MATHEMATICS AND EVOLUTION: A MANIFESTO

RALPH H. ABRAHAM

Dedicated to: Teilhard de Chardin, 1881 - 1955.

PREFACE

This paper consists of four short essays on the application of mathematical dynamics to general evolution theory and the implications of this application for our psychosocial transformation to a stable planetary society.

We begin with a short orientation to evolution theory in the first part, and a primer of dynamics terminology in the second. This is technical, and may be skipped on a first reading. Some simple sociopolitical applications are discussed in the third essay, with speculations on their extrapolation to a psychohistorical (world political) model. Then, in the final part, we return to the question of modeling strategies for evolution, and the willful creation of a planetary society with a stable future. We end by combining this mathematical strategy with other schemes, to suggest a fourfold strategy for transformation and survival.

For more realistic models of the holarchies (complex systems) which abound in the biosphere, an extension of dynamics has been created. Known variously as *complex dynamics* or *holarchic dynamics*, we have presented its concepts in a companion paper, *Complex Dynamics and the Social Sciences*. A further application to the simulation of the evolution of the geosphere and biosphere will be presented in another companion piece, *The Simulation of Biogeochemical History*.

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I. EVOLUTION THEORY AND HOLARCHIC MATHEMATICS

1. Introduction.

Suppose that a natural process evolves in time. Then a model for the process should depend upon parameters which change with time. Dynamical models appropriate for this task are called *dynamical schemes*, or *holons*, and the significant changes in their behavior are known as *bifurcations*. As we have a growing encyclopedia of generic bifurcations in the annals of dynamical systems theory, we should expect to be able to use them to model special events in the evolution of a natural process.

This expectation is reasonable, even exciting. It has been vindicated in important applications in the physical sciences, such as the science of turbulent fluid flow.

Moreover, we should be able to use the encyclopedia of bifurcations to make models in general evolution theory. Yet not much has been achieved in this context, as here we must contend with highly complex, hierarchically structured systems. The extension of dynamical systems theory to this traditional territory of general systems theory and cybernetics, known as holarchic (or complex) dynamics, has just begun. This Section is devoted to the bare outline of two main themes: general evolution science, and holarchic dynamical models. To actually grasp the concepts, one must go to the sources given in the References. Even better, go to the original sources, such as Lamarck, Lotka, Smuts, Whyte, Needham, de Chardin, Schrodinger, Szent-Gyorgyi. An excellent bibliography is given in Koestler[1].

2. Evolution theory.

Probably the origin of general evolution theory is Lamarck, who dealt with the origin of mind in his classic of 1809.[2]

Around the turn of the century, the subject resumed with Driesch and Bergson. The terms *lithosphere, biosphere,* and *atmosphere* were introduced at this time, apparently by Suess and Vernadsky. Another early version of general evolution theory was given by Lotka in 1925.[3] He tried to describe the evolution of the geosphere and the biosphere, and the origin of consciousness.[4] He sought a general theory of evolution, one equally applicable to the three envelopes.

Teilhard de Chardin extended these theories. To increase the distinction between individual and social consciousness, he coined the term *noosphere* in 1925.[5] In parallel with the *geogenesis[6]* and *biogenesis[7]* of the denser envelopes of the planet, he made extensive use of the term *noogenesis.[8]* The following year, Smuts introduced the concept of *holism.[9]*

Recently, in a similar attempt to discern overall patterns in evolution, Koestler introduced the concept of *holarchy[10]* for structures of cooperative, yet autonomous, individual *holons[11]* Since then, there is a growing literature on general evolution theory. For an introduction to the modern theory, see the conference proceedings edited by Jantsch[12] or Yates,[13] and the recent works referenced therein.

The geosphere has component envelopes, such as the solid core, liquid core, lower mantle, transition zone, asthenosphere, lithosphere, and crust. The hydrosphere has its layers as well. The atmosphere contains the troposphere, mesosphere, thermosphere, and the exosphere. The terms ionosphere and stratosphere are also used. A concise introduction to the new subject of biospherics is given in *The Biospherics Catalogue,* along with an excellent bibliography.[14]

Likewise the biosphere has its subspheres, mostly unnamed. Of these, we single out for attention the stratum of human affairs, the *sociosphere.* For here is the crux of world problems. Its evolution, known as *cultural evolution,* or *sociogenesis,* will be subject to the laws of general evolution theory. And as we learn those laws, from the comparative studies of the histories of geogenesis, biogenesis, and noogenesis, we may develop the capability to guide our own sociogenesis, and create our own future (or at least, to have a future.)

The relation between sociogenesis (cultural evolution) and noogenesis (the history of consciousness) is particularly important for our future, and has been the special study of theoretical biologists, such as Bateson[15] and Sheldrake.[16]

In fact, in the introduction to his last book, Bateson wrote in 1979[17]:

> I want to tell you why I have been a biologist all my life, what it is that I have been trying to study. What thoughts can I share regarding the total biological world in which we live and have our being?
>
> What now must be said is difficult, appears to be quite *empty,* and is of very great and deep importance to you and to me. At this historic juncture, I believe it to be important to the survival of the whole biosphere, which you know is threatened.
>
> What is the pattern which connects all the living creatures? ... The *pattern which connects is a metapattern.* It is a pattern of patterns. It is that metapattern which defines the vast generalization that, indeed, *it is patterns which connect.*

Holarchic dynamics is the mathematics of metapatterns, patterns of patterns in space and in time, rhythms and undulations and symmetries in the physical, biological, social, psychological, and collective supraconscious realms.

3. Social transformation.

The social and ecological crises of these times, collectively known as the *World Problematique,* have stimulated a great wish, in the collective consciousness of human society, for a magical solution, which we may call the *World Mystique.*

An early version of this wish was the *Omega Point* concept of Teilhard de Chardin.[18] After extensive analysis of the coupled evolutionary processes following the *Alpha Point* (creation) of our history, he proposed a divine resolution of the upcoming crises, the Omega Point.[19]

This is a catastrophic evolutionary event, involving transformations of individuals and societies, a sort of phase transition of the noosphere, and the reunion of the noosphere with the denser spheres (geosphere and biosphere) into a conscious (and loving) hierarchy.[20]

Another recent version of the great wish is the

the hope for a spontaneous transformation to the Aquarian Age.[21]

These expressions of the salvation mystique have been extensively criticized in the political press for potentially working against the urgent necessity of political action, and for obviating the related Main Question: *what action is possible and desirable at present?*

One popular answer to this pressing question centers on individual actions, aimed at individual transformation. An outstanding summary of this view is presented in Metzner.[22] If this reductionist, or atomistic, view of the mechanics of noogenesis is correct, we may be approaching the omega transition at a good pace, as there seems to be a tremendous groundswell of personal efforts toward individual transformation in many societies today.

However, it may be that a substantial increase in cooperation among peoples and societies is prerequisite to solution of the world problems, and the continued evolution of a planetary society. This is the view of Koestler, in his general theory of holarchic evolution, in which the balance of the two main tendencies of holons (self-assertive and integrative, the two faces of Janus) is prerequisite for a stable evolution.

This possibility is the motivation for the present work.

For if this holistic view were correct, individual work would be insufficient to achieve a healthy planetary society, even if all people were to work upon themselves full-time! Instead, new strategies of holarchic cooperation and collective action would be necessary as well. The discovery of these new strategies is our eventual goal.

4. Holarchic dynamics.

The integration of a planetary society allows many strategies. Here we discuss just one among these, based upon mathematical models and computer simulation. This is the current form of the strategy introduced by the ancient Greeks, and called by them *mechanikos* (mechanics).

The hope for progress based on this strategy, and the creation of a universal theory of evolution according to mathematical principles, is an extrapolation of the wondrous success of mechanics in the physical and biological sciences. One explanation of this success is the philosophical theory of mathematical structuralism, which holds that natural evolution, in the phenomenal universe, is constrained by overlying mathematical structures.[23]

Of mathematical modeling strategies there are, again, many. Here we fasten upon just one for exploration, generally known as *dynamical systems theory*. Extensively evolved since Newton in the crucible of the physical sciences, its main concepts are briefly explained in Part II. One of these concepts, the *bifurcation* of a dynamical scheme, is basic to our strategy for modeling the critical moments of an evolutionary process.

The application of these concepts to model a holarchic system requires the combination of separate dynamical schemes *(the model holons)* into a complex, hierarchical network *(the model holarchy)*. These structures are the target of much research on the frontiers of dynamics today, called complex dynamical systems theory, or synonymously, *holarchic dynamics*. One outstanding problem here is to discover how the dynamical behavior of a holarchy is determined by the response diagrams of its component holons, together with (as yet unknown) holonomic rules. Another problem is to discover what properties of a holarchy are not determined by its holons. We might call this domain the *canon of holarchic law*, or as Arguelles says, *holonomy*. [24]

II. DYNAMICS PRIMER

1. Introduction.

Dynamics is the study of systems constrained by a deterministic law of evolution. Experimental dynamics was founded by Galileo in 1600, in his study of balls rolling down an inclined board, and falling from the leaning tower of Pisa. Mathematical dynamics began with Huyghens in 1624, in his search for a perfect pendulum clock for the Dutch mercantile navy. By 1880, dynamics had emerged as the most extensive branch of applied mathematics, fundamental to all the sciences and technology. Then came a sudden revolution of the subject, in which the classical analytical methods of Newton were replaced with the new geometric ones of Poincare.

In the geometric view which dominates dynamics today, the chief features of a dynamical system are its *attractors*. These characterize the long-run behavior of the system. After starting up from any initial state, the system evolves along a unique trajectory (or time series) of states, guided by the deterministic law of evolution. Sooner or later, this trajectory leads to one of the attractors, where it remains trapped forever.

This is the significance of the attractors in a fixed *dynamical system*. In a *dynamical scheme*, however, the dynamical rules may be changed at any time by the experimentalist. A trajectory may thus be diverted by suddenly changing the controls.

In a dynamical system, each attractor sits within its *basin*, comprising all initial states which are attracted by it.

2. Attractors.

There are three types of attractor: static, periodic, and chaotic.

The *static attractor* consists of a single state, at which the system comes to rest. Also called a static equilibrium or a rest point, these were the first to be studied, and were extensively applied in thermodynamics, chemistry, control theory, and engineering.

The *periodic attractor* consists of a cycle of states repeated again and again, always in the same interval of time, or *period*. This is the geometric model for an *oscillator*. The study of oscillations in this form preoccupied dynamicists in the early part of this century, during which dynamics was sometimes called the *theory of nonlinear oscillations*. Both attractors, static and periodic, were known to Poincare, at the turn of this century.

The chaotic attractor was predicted by mathematical dynamicists early in this century, but became firmly established only after the computer revolution, in 1962. The trajectory of an evolving dynamical system approaching a chaotic attractor is very erratic, and casual observation of such a time series may give the impression of a random, unpredictable process. The long-run behavior is neither settling to rest, nor is it approximately periodic. Nevertheless more careful observation using recently developed, computer-based graphic methods *(macroscopy)* reveals a highly ordered geometric pattern, a chaotic attractor.

The most familiar, and one of the best studied of these deterministic yet chaotic systems is the dripping faucet.[25] Many other natural processes long considered to be truly random, such as earthquakes, turbulent fluid flow, and brain waves, have been recently found, by macroscopy, to have the highly ordered structure of a chaotic attractor. This is the basis of a revolution in the physical sciences, as much which was formerly thought to be noise is now known to be signal, or recognizable information.

The study and classification of attractors is one aspect of dynamics, the global theory of phase portraits is another.

3. Phase portraits.

Global theory concerns the way in which attractors and their basins may combine into the global portrait of the dynamical system, called the *phase portrait*. When the dynamical rule of evolution is changed, the phase portrait may or may not change in a geometrically significant way. If the portrait resists significant change after small perturbations of the dynamical rule, it is called *structurally stable*. The significant changes exhibited by unstable dynamical systems are called *bifurcations*.

4. Bifurcations.

Bifurcation theory is the branch of dynamics devoted to the discovery and classification of bifurcations.

The response of a dynamical system, as its dynamical rule is changed by a fixed number of parameters called *controls*, is customarily mapped by plotting the phase portraits against the control parameters. The resulting map is called the *response diagram*. A bifurcation is seen, within the response diagram, as a definite change in the phase portrait. The results of bifurcation theory so far may be regarded as an encyclopedia of elementary response diagrams, each exhibiting a canonical bifurcation.

There are three main categories of bifurcations: *subtle*, *explosive*, and *catastrophic*.

In a *subtle bifurcation*, an attractor changes type. For example, a static attractor may change into a small periodic attractor, which then grows into a major oscillation. Likewise, a periodic attractor may subtly turn chaotic, with a gradual increase of noise.

In an *explosive bifurcation*, an attractor suddenly changes size. For example, a static attractor may suddenly blow up, becoming a large-scale chaotic attractor.

In a *catastrophic bifurcation*, or *catastrophe*, an attractor suddenly appears or disappears, along with its basin. *Elementary catastrophe theory* is the study of the catastrophic appearance or disappearance of static attractors only, and has had important applications throughout the sciences -- physical, biological, and social -- since its introduction by Thom around 1966. But periodic and chaotic attractors have catastrophes also, in which they may disappear into, or appear out of, the blue sky.

5. Chaos theory.

Chaos theory is the branch of dynamics dealing with the properties of chaotic attractors, and their bifurcations.

Although it is only a few years old, it already has a rapidly growing literature of experimental results. Several distinctly ordered chaotic attractors are known, such as the Lorenz mask, the Rossler band, and the Shaw bagel, named after their discoverers. The apparently random behavior of many natural processes have been discovered to be equivalent to the behavior of these model mathematical systems. Fluid dynamical turbulence is probably the best known of these, and the discovery of these chaotic models for turbulence by Ruelle and Takens in 1971 marked the turning point in the current paradigm shift within the physical sciences caused by chaos theory.

A sequence of bifurcations leading from static equilibrium, to oscillation, and on to chaotic turbulence is called a *scenario* for the onset of turbulence. Several such scenarios have been identified, both in physical systems and in mathematical models. For example, a Shaw bagel may appear out of the blue, in a *blue bagel catastrophe*, after suitable change of the dynamical rule of the dynamical system. This is a *catastrophic scenario*. There are also *subtle scenarios*, in which a static equilibrium changes to an oscillation, which grows, and then subtly becomes chaotic. The period doubling sequence is a subtle scenario which has been particularly well studied. Both of these scenarios occur abundantly in the context of two coupled oscillators. Explosive scenarios occur as well.

6. Transients.

When an attractor disappears catastrophically into the blue, the system finds itself suddenly far from equilibrium. It is in the basin of a new attractor. Following the rules of its dynamic, it must hurry to this new destination. This adjustment is called a *transient*. The transient is a trajectory which leaves the vicinity of the vanished attractor, and approaches the vicinity of a new attractor.

This phenomenon is well studied in elementary catastrophe theory, where the transient frequently pauses on its journey to linger in the neighborhood of a saddle point belonging to the separatrix, or basin boundary, of the new attractor. That is, after a catastrophe, the transient response of the system accelerates toward a special point in the separatrix, lingers there for awhile, then speeds off towards its attractive destination. This behavior is called a *static transient*.

But in our more general context, saddles in the separatrices may be periodic, or even chaotic. Thus, transients may pause for an extensive bout of oscillation on the way to equilibrium, even if this final state is static. This behavior is called a *periodic transient*. Similarly, there may be a *chaotic transient*. These phenomena are particularly relevant for modeling the crises of cultural evolution, as historically, the transformations from one cultural equilibrium to another usually manifest transient chaos.

For more details, consult the picture books[26] or a basic text.[27]

III. THE SIMULATION OF CULTURAL EVOLUTION

1. Introduction.

Years ago, before chaos theory, I would be sitting in an airplane. The person in the next seat would ask, "What do you do?" And I would reply, "I do research in mathematics." To which they would invariably reply, with a face, "That is my worst subject," or, "What is there to discover since the Greeks?" But now I answer, "I do research in chaos theory." And they invariably reply, "That is something I know a lot about!"

Initially, I would try to explain that there were no established connections between the mathematical models of chaos I studied and the social chaos they knew a lot about. Now, I ask them to help me find these connections. For I have been convinced that chaos theory may be crucial for the understanding and management of chaos in all contexts, including psychoanalysis, personal relationships, commerce, and politics at all levels.

This section is a survey of some recent contributions of mathematics to the *sociosphere*, with some speculations on the role of chaos theory in the understanding of real chaos. We will consider primarily its component realm, the *polisphere*, the network of nations, and their political interaction (especially in connection with the simulation of war and peace). The parallel realm of the *econo-*

sphere, the combination of econometric models for nations with the economic interaction of the international trading partners, which is an extensively developed subject, will not be discussed here. But we should keep in mind that this brief discussion begins a trail which would lead to a sociosphere model consisting of coupled models of the econosphere and the polisphere.

This sociosphere model would then be coupled to other models of the biogeographical distribution of the plant and animal species to comprise a biosphere model. And this in turn would be coupled to models of the geosphere (especially the atmosphere and global climate) and (ultimately) the noosphere. This colossus[28] would encompass the synthesis of all the sciences, and serve as a guide in policy making and the creation of the future.[29]

Dynamical models for the outbreak of war have appeared since World War II. But applications of chaos theory to the social sciences are quite new. Let's begin with a prechaos model from catastrophe theory.

2. One nation: hawks and doves

Starting around 1965, the mathematical world began to hear the words *catastrophe theory* from one of its distinguished theorists, Rene Thom, now professor at the Institut des Hautes Etudes outside Paris. Thom had turned from pure mathematics to applications of a revolutionary character, and was involved in the multidisciplinary group assembled by Conrad Waddington to intentionally create theoretical biology.[30] As a topologist, he became fascinated by the ideas of morphogenesis, and universal evolution theory. After the appearance of the first edition of his book on this subject in 1972,[31] some followers tried unsuccessfully to carry out his indications for specific applications. But Zeeman succeeded, and a series of interesting and highly novel papers appeared.[32,33]

Unfortunately, controversy and back-biting diminished the effects of these publications. But they still hold enormous potential for the advance of the biological and social sciences. This potential is based not on the individual applications, or even the highly technical methods. Rather, it is the basically geometric style of representing the data, and the role of a topological theory to *exclude pathological behavior* from this representation. Indeed, the topological theory provided an encyclopedia of basic forms, around which the data must arrange itself. This has the power to revolutionize the conduct of science.

This style of applied mathematics paved the way for chaos and bifurcation theory in their current applications in many sciences. In fact, the considerable power of nonlinear dynamics in its role of service to the sciences is epitomized by catastrophe theory. One who would apply chaos theory to some domain in the biological sciences, for example, would do well to study the exemplary applications of catastrophe for their pedagogic and inspirational value.

Among the two dozen or so applications in the Zeeman series about one third are in the social sciences. All of these are relevant to our present discussion. We wish now to summarize just one of these, which appeared in the first series in April, 1976,[34] and in more detail in the second series in 1977.[35] It is called *hawks and doves*.

The holarchy in this situation consists of two actual holons, each a whole nation. However, the dynamical model for hawks and doves is a single model holon, representing not the holarchy, but just one of the interacting nations. It is constructed as follows: The geometric model for the virtual states of the two-nation system is a segment of a single straight line, called the *behavior axis*. It represents the war policy of the nation, (or the mood of the citizens) with strong military action at one end, and withdrawal or surrender at the other.

The internal dynamic is the sensitivity of the government to its electors, which is assumed to act so as to maximize its popular support. But this support is assumed to depend upon two control parameters. One is the *threat* (perceived by the government or its citizens) of an attack by the other nation. The other is the estimated *cost* of a military action. These two controls are modeled by a rectangular region in a geometrical plane, called the *control plane*. Imagining this plane rectangle held horizontally in front of us, we now attach at each point a copy of the behavior axis. This creates a three-dimensional box, the geometrical space of the hawks and doves model.

From these hypotheses, and the details of catastrophe theory, Zeeman then fits a *cusp catastrophe* into the box. This means that there is a cusp (a V-shaped curve) in the control plane. For a control point (given values of threat and cost) outside this cusp curve, the dynamics within the corresponding behavior axis has a single attractive point, representing the equilibrium behavior of the mood of the nation. For a control point inside the cusp, however, the behavior dynamic is *bistable*.

That is, there are two point attractors, one corresponding to a militant *hawk* mood, and the other to a passive *dove* mood. Which strategy the model government will follow depends upon the history of behavior, before the control point moved into the cusp region of bistability.

His discussion ends with specific application of the model to the United States and Russia, at the time of the Cuban Missile Crisis of 1962.

Despite any considerations of the controversy around catastrophe theory and its claims, and beyond any question of the ultimate value of this model to the political strategies of nations or to the advance of the social sciences, we find this exemplary application very stimulating in the current context. Its pedagogic value here is based on these features of the model:

* The holarchy is reduced to a single model holon, having two controls. One of which (threat) is obviously begging to be coupled to the behavior axis of an identical model for another nation. Connecting model holons in this way, a polisphere of any number of nations may be modeled. Synthesis follows reduction (a holarchic law).

* The model holon is a geometric object containing a dynamical scheme, the behavior of which is visible and intuitively understandable.

* The response diagram of the model provides for the user a map for navigation, giving sure strategies for the manipulation of the two controls to achieve a gradual transformation from one equilibrium to the other.

* Experiments with the model are sure to improve the understanding of the actual situation in the mind of the experimenter.

* In the bimodal regime (control points within the cusp curve) both states are modeled by point attractors of the behavior dynamic, even though one corresponds to hawks, and the other to doves.

Finally, we believe that efforts to improve this model *will* advance the social sciences, and the art of mathematical modeling as well.

3. Two or three nations: war and peace.

Going back to the original context of the hawks and doves model, we may now assemble a model holarchy from two model holons. Here we depart from the classical work of Zeeman, and describe some of our own work in progress. Simulation results will follow in another paper.

Ignoring the peculiarities of any actual nations, we may simply consider two identical holons, X and Y, as described in the preceding section. We will couple them in the style of holarchic dynamical systems theory.[36] Let the threat perceived by X be set equal to the behavior of Y, and vice versa. (This is but the simplest of many alternative coupling rules.) Let the cost of each be the same. (This will be relaxed eventually.) Then the model holarchy is a dynamical system with a two-dimensional state space (behavior of X, behavior of Y) and a single control (cost). Depending on the value of cost (fear), the behavior of the holarchic dynamical systems will be determined by one or two point attractors. If an attractor is in the *war quadrant* of the behavior plane (both nations militant) and the cost is low, war is presumably immanent. With variations in the details of the model holons, periodic attractors could appear.

Let us now consider briefly the more interesting case of a holarchy of three nations. In the case of three identical hawks and doves holons (X, Y, and Z), let us assume (implausibly) that the threat perceived in X is proportional to the militancy of the behavior (mood) in Y, threat in Y proportional to behavior of Z, and threat in Z proportional to behavior in X. Assume, again, that cost (fear of loss) is the same in all three countries. Then it is known that, even in this simplest possible (cyclic) network, periodic behavior will occur for some values of cost.[37] And for slightly more complicated network (for example, if X is also afraid of Z) then chaotic behavior and multistability is to be expected.

A model for a network of actual nations in a geographical region, or a global network, may be made in this manner, shedding some insight on the possible behaviors, and potential controls, of the holarchy. More realistic model holons could be developed, but may not provide more insight into political instability than these ultrasimple model holons of Zeeman. In any case, this is one starting point for a holarchy model of the polisphere in which we live.

4. The arms race and star wars.

As the war clouds gathered over Europe in the 1930's, a British meteorologist, thinking as we do that mathematical modeling and prediction would promote the cause of peace, developed the first dynamical model for the arms race. His paper, the first of its type, was promptly rejected. The war followed, then the death of the author, L. F.

Richardson, and finally the posthumous publication of his pioneering work in the mathematical theory of peace, in 1956. For a detailed explanation and bibliography of this work, see Moriarty.[38]

Richardson's model is much like Zeeman's, in that each nation is stimulated by fear of the other, and simulateneously inhibited by cost. The behavior axis, in Richardson's arms race model, is the armament level, while in Zeeman's hawks and doves model, it is the degree of hawkness. Clearly these models are very similar. One crucial difference, however, is that Richardson's dynamical equations are *linear*, while Zeeman's are cubic polynomials. We may fairly assume that if Richardson were writing in the 1970's instead of the 1930's, the models would be identical. Another difference, less significant, is that Richardson considered two or three nations at a time, in a coupled system or network, just as we have in the preceding section.

In the extensive literature of the mathematical theory of peace, there eventually appeared an application of chaos theory. This is a new model for the arms race, presented by Saperstein in 1984.[39] Representing two nations, it is an irreversible discrete dynamical system (that is, variables are evaluated only once per year). The variables are the same as Richardson's, but the equations are quadratic polynomials. They are carefully chosen so that the behavior of the model will be chaotic. Saperstein explained his motivation thus:

> The transition, from stability to instability, from arms race to war, could be analogous to the transition from a laminar to a turbulent (or chaotic) flow. ... I suggest that war be viewed as a breakdown in predictability: a situation in which small perturbations of initial conditions, such as malfunctions of early-warning radar systems or irrational acts of individuals disobeying orders, lead to large unforeseen changes in the solutions to the dynamical equations of the model.[40]

While this looks good at first glance, it does seem a bit out of place when applied to the variables in this particular model. For these represent, after all, the fraction of the nations' resources devoted to armaments. Presumably, the transition from arms race to war would be accompanied by a rapid increase of these values to their upper limit, one. Additional criticism is given in Roten and Orient.[41] A sequel by Saperstein and Mayer-Kress presents a similar model for the effect of space-based weapons.[42]

In spite of these criticisms, Saperstein's model is a valuable starting point for nonlinear models for the arms race.

5. Nuclear winter and the ozone hole.

The nuclear winter story provides an important example of the role of mathematical modeling and simulation in the policy arena.

Although the fear of nuclear war, based upon the estimation of the primary effects of the explosions and immediate radiation and fallout, has escalated to massive proportions since Hiroshima without need of scientific calculations, it has been recently dwarfed by an enormously larger fear: the death of the species by freezing. This, in brief, is the story.

In 1975, the National Academy of Science (NAS) of the United States issued a report on the long-term effects of a nuclear war. Damage to the atmospheric ozone layer, with resulting increase of ultraviolet radiation, was a main concern. It warned that serious damage to the ecology could not be ruled out. A year later, a new report from the U.S. Arms Control and Disarmament Agency (ACDA) concluded that a nuclear war could cause widespread environmental damage.[43]

In April of 1979, a pamphlet from the U.S. Office of Technology Assessment (OTA) concluded that the 1975 NAS report was alarmist, and assumed that most of the population could emerge from their shelters after 30 days and begin cleaning up. This was qualified by three pages of discussion on the *uncertainties in the computations.* [44]

But in 1981, Crutzen and Birks calculated the effects of smoke created by extensive fires on the ground, concluding that up to 99% of solar radiation could be blocked out by smoke for many weeks, causing death by freezing to most survivors of the initial effects of a massive nuclear exchange. This was published in April of 1982 [45] and at the same time, the NAS issued a resolution warning that nuclear war could destroy life as we know it.[46]

Shortly afterward, on Sept 15, 1982 the Committee on Science and Technology of the U.S. House of Representatives held a hearing on the subject, in which the most authoritative predictions were summarized.[47] Among them were the results of extensive numerical simulations,[48] which revised and supported the conclusions of the NAS in 1975. The appearance of the report of this hearing in early 1983, with its highly credible predictions presented by well-respected scientists, had a chilling effect on the world-wide scientific community.

The danger of a nuclear winter, caused by the simultaneous explosion of only a small part of the nuclear arsenal, was further supported by a definitive and convincing study called the TTAPS report.[49] Here, the nuclear winter was compared in severity with the climactic extinctions of 65 million years ago. Subsequent simulations using massive mathematical models in the U.S. and in the USSR confirmed this estimate.[50] And all this evidence was presented at yet another congressional hearing,[51] this time against the counterpoint of Edward Teller, who did his best to diminish the fears expressed by Carl Sagan, Stephen Jay Gould, Alan Hecht, Vladimir Aleksandrov, Leon Goure, and Theodore Postol.[52]

About a year later, a film enacting *The Day After* (an hypothetical nuclear exchange) was shown on nationwide television in the United States, and was followed by debates and discussions by leading scientists and others, including Dr. Sagan.

The story continues to this day.[53] In the United States, a $5.5 million research effort is now under way. The ongoing massive simulations are increasingly guided by improved observations, and doubts such as those of Dr. Teller are starkly decreasing,[54] although still controversial.[55]

Our point in repeating this story here is this: the evolution of a massive mathematical model for the complex dynamics of the atmosphere, its extensive simulations on supercomputers repeated in various centers of great repute including national laboratories of several countries, the comparison of its simulated data with atmospheric observations, and so on, comprises an *advance of science*, and simultaneously, an *intervention*, or political action of substantial magnitude and potential effect.

Of course, by now most people have heard that we do not need a nuclear war to create a massive extinction comparable to that of 65 million years ago. For according to Norm Myers[56] and the Worldwatch Institute,[57] such a massive extinction is in progress at the moment. And if the rate of species extinction and ecological deterioration is not alarming enough, the rapidly growing Antarctic ozone hole (caused by ecological damage to the ozone layer by man-made gases) is clearly a massive disturbance of the biogeospheric system. This ozone catastrophe is developing, at present, into another intervention story like nuclear winter. In June 1986, scientists tried to warn the public,[58] and the U. S. government in a Senate subcommittee hearing. But as before, the reaction is less than vigorous. One reason claimed is the *uncertainty of the predictions.*

A further example is the gradual warming of the global climate due to the increase of the greenhouse effect during the past century. Again, scientists claim that their simulations and historical data need to be *more precise* to obtain a response from politicians.[59]

In all these cases, the development of a *credible biogeospheric model* could be a powerful factor in the support of political actions aimed at the protection of our ecosystems.

As this model continues to grow in the future, the simulated data it produces in hindcasting experiments may increase in fidelity, in comparison with our actual biogeographical history (the fossil record). As *confidence in the model* grows with increasing fidelity of hindcasting, it may reach such a level that decision makers would use it for guidance in forecasting experiments (playing the WHAT IF game), and be able to respond more promptly to ecological danger signals.

A recent NASA proposal for extensive monitoring of our planetary holarchy[60] has a similar goal. We are seeking techniques which, properly employed, will increase our chances of survival through the evolutionary challenges to come.

6. Conclusion.

In each of the models discussed in this essay, the theory is in a very preliminary stage. Nevertheless, we are suggesting that the further study of these models will stimulate the development of the sciences, and the arts of mathematical modeling as well. More important, the causes of peace and ecological protection may be critically served.

A controversy over these questions has been going on recently in *Simulation*, the journal of the Society for Computer Simulation, in which one may find many valuable references.[61] It is clear that there already exist some very sophisticated models for the polisphere, as well as the econosphere and the atmosphere.

Beyond the proliferation of models such as these, and the growth of theory within the social sciences, an important value of chaos theory to the social sphere might be its power to discover order in chaos. Thus, anxiety may be reduced as chaotic states are identified as recognizable geometric forms, which do not grow out of control. The knowledge of these forms, chaotic transients, chaotic attractors and of their bifurcations, may facilitate policy-making in a time of social transformation. In fact, it is possible that the development of a truly useful social theory, facilitating the evolution of a successful planetary society, had to await the discovery of chaos theory.

IV. THE FOURFOLD PATH TO THE FUTURE

1. Introduction.

Einstein wrote

> All of us who are concerned for peace and the triumph of reason and justice must be keenly aware how small an influence reason and honest good will exert upon events in the political field.

In these days of rapid expansion and development of human society and increasing awareness of its ecological consequences, many people, groups, and institutions are giving serious attention to specific strategies for the intentional creation of a stable future. Travelling, talking, and reading of these efforts reveals a fourfold classification of the proposed strategies. There are three basic types of traditional means:

(P) political action,

(A) artistic programs, and

(S) spiritual activities.

Actual traditional means are usually a combination of these three pure types, and may be regarded as mature strategies, selected by evolutionary challenges such as the glaciations. The combination of all three we call the *threefold path.*

To these three older types has been recently adjoined the modern scientific way of

(T) technical strategies.

Due to its novelty, its integration with traditional strategies may be yet incomplete. The completion of this integration we call the *fourfold path.*

2. The threefold path.

Some current activities belong to the time-tested paths.

In the first category, (P), we may place most of the activities of many societies devoted to conservation or ecological protection. For example:

* the efforts of the World Bank to save the Amazon jungle from destruction,

* the activities of the World Wildlife Fund to preserve the habitats of large mammals facing extinction,

* educational films made by the Cousteau Society,

belong to category (P), as well as

* numerous election campaigns,

* a few responsible feature films such as *The Day After*, or *The China Syndrome*,

and many personal campaigns.

Illustrative of the artistic strategies of category (A), we may consider most of the sacred art of the distant past (largely displaced by the scientific revolution), including works of music, graphics, plastic arts, visual music, and more recently, artistic films (such as *Koyanisqaatsi)*, videos, and performance. In fact, the world art historian Jose Arguelles argues that the specific aim of sacred art is the increase of intelligence, ecological awareness, and spiritual sensitivity prerequisite to the evolution of a stable civilization.[62] Sacred art is the vanguard of cultural evolution.

The spiritual strategies of category (S) include all the means of individual development such as yoga, as well as social practices such as shamanic and priestly rituals, geomancy, mysteries, singing of hymns, prayer, and the like.

Besides these examples of pure strategies of types P, A, and S, there are some activities of combined types. For example, twofold strategies of political and artistic types, the PA strategies, include popular songs on political themes, and all political art. Of the mixed type PS are the political activities of spiritual groups, such as the nonviolent interventions of Ghandi and King. Then there are mixed strategies of type AS, such as mandalas, church architecture, hymns, some shamanic rituals, and all religious art. Finally, there are fully threefold PAS ways, epitomized by the Cretan, Egyptian, and Greek mysteries. Recent examples are hard to find.

3. Technical strategies.

Among the technical strategies of category (T), we may find:

* nuclear winter, ozone depletion, and global warming simulations developed by several government agencies,

* arms race models by a few mathematicians and physicists,

* biosphere simulations by ecologists, such as *Daisy World*,

* economic forecasts by the Club of Rome and others,

and educational programs based on such strategies, such as the pavilions of the Disney World Epcot Center.

Besides these examples of purely technical means, we could probably find some twofold strategies, of political-technical type PT (such as the nuclear winter affair), of artistic-technical type AT (such as high-tech music, computer-graphic art), and of spiritual-technical type ST (such as biofeedback devices). Nevertheless, we feel that the integration of technical means with traditional strategies is an outstanding challenge for our society today. This fourfold challenge is not to be surmounted in a mere century or two.

4. A fourfold proposal.

Although at present technology seems to many people more of an evolutionary curse than a blessing, we may entertain the hypothesis that *technology is useful for our evolutionary toolbox.* Suppose that the population explosion alone, for the sake of discussion, were our outstanding World Problem. Or a fast growing ozone hole, global warming, or an invasion by aliens, or *any* new challenge for that matter. Then traditional means may not suffice, as they have evolved only in the crucible of past challenges. So, we must try not only to develop new means, but always and in every way to integrate them with the old. Here, then, is a proposal for an exemplary mixed strategy of type PAST:

The technical component would be vast biogeochemical models evolved from the cytodynamical strategy of holarchic dynamics, combining the most advanced models in use today. Implemented upon a colossal network of supercomputers,[63] they would be capable of simulating 60 million years of biogeospheric evolution in 60 minutes. The artistic element would be embedded in computer generated audiovisual displays generated by the simulation, evolved through the interaction of planetary artists with the scientists/programmers of the model. The political strategy would involve the injection of the simulation of alternative futures into the society, via planetary television networks and interactive graphics devices in theme parks around the world. And the spiritual strategy would depend upon the interaction between this adult videogame, and users from among the most evolved spiritual leaders and groups. There could indeed be competitions for the best predictions, the maximum social effect, the most artistic displays, the greatest mathematical elegance, and the most convincing spiritual value, as in Herman Hesse's *Glasperlenspiel.* [64]

The anticipated result would be the determination of new and creative alternative futures and the conditions needed to attain them, the most informed choice among them, and the transformation of society required to achieve these conditions. Accurate prediction of the future, as in Hari Seldon's psychohistory,[65] will probably still be beyond our reach.

5. Conclusion.

In short, we wish to create an exemplary fourfold path, from which others may evolve, in which technology, adjoined to traditional means, gives powerful amplification to the *influence reason and honest good will exert upon events in the political field,* which, as Einstein observed, is presently much too small.

The technical challenge of a massive biogeospherical model is manageable at present, and might require a network of supercomputers, each specializing in a certain region of the planet, all connected via satellite links. This in itself might comprise a technical action with political overtones, as the cooperation of several governments may be required. Without doubt this is coming of itself in due time.

But it is the coupling of this adult videogame to planetary society, to achieve an effective and successful intervention, which challenges us. This may require knowledge not yet available, and only this coupling will provide us a fourfold way. More ivory tower exercises will avail little more in future than they have in the past.

Hence we have argued elsewhere for an intentional acceleration of the development of the social sciences. But even more, we need innovative cooperation from industry, the media, and funding agencies.

POSTSCRIPT

Well now, what would you do?

WHAT IF your only biosphere faced an extinction due to ignorance?

WHAT IF Colossus was actually standing by to serve us, with a *credible* simulation program for biogeography?

WHAT IF its output was in the form of video, suitable for broadcasting?

WHAT IF it was connected to satellite-linked planetary video networks?

WHAT IF you had a vaccine for the *Problematique humaine?* Would you dare? Would We dare?

Symbionts arise! Plants, animals, and droids, lend us our selves! Let us join hands, minds, and mathematics in the willful transformation of Point Omega! After all, the meek shall inherit the world. *But when?*

Let us act now, or for 65 million years hold our peace.

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