Chaos and Crises in International Systems

Gottfried Mayer-Kress [1]

Center for Complex Systems Research - Department of Physics

Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, Il 61801

and Department of Mathematics University of California at Santa Cruz

Abstract

Nonlinear dynamical systems exhibit a very rich class of potential modes of behavior. Among them are order, crises, and chaos, all of which can coexist within a very small range of parameters. They may serve as paradigms for the complex new world order after the end of the cold war where scenarios of delicate crisis management will replace those of plain deterrence or retaliation.

In this note we first try to give a very short overview of some basic elements of chaos theory. Then we discuss some work in relation to the application of chaos theory to arms race dynamics. Finally we give an outlook of the potential role of nonlinear dynamics and chaos in models for crisis management.

Talk presented at:

SHAPE Technology Symposium on crisis management, Mons, Belgium, 3/19-20/92

[1]On leave of absence from the Santa Fe Institute, 1660 Old Pecos Trail, Santa Fe New Mexico

email: gmk@santafe.edu

What is Chaos?

When we look at the changing world that we are living in, we can categorize the types changes into a few fundamental categories: growth and recession, stagnation, cyclic behavior and unpredictable, erratic fluctuations. All of these phenomena can be described with very well developed linear mathematical tools. Here "linear" means that the result of an action is always proportional to its cause: if we double our effort, the outcome will also double.

However, as Stan Ulam had pointed out, nature is basically non-linear in the same sense as most of zoology is non-elephant zoology. The situation that most of traditional science is focusing on linear systems can be compared to the story of the person who looks for the lost car keys under a street lamp because it is too dark to see anything at the place where the keys were lost. Only recently do we have access to methods and compute power to make significant progress in the field of non-linear systems and understand, for example, seemingly simple things like dripping faucets. One whole class of phenomena which does not exist within the framework of linear theory has become known under the buzz-word of "chaos".

The modern notion of chaos describes irregular and highly complex structures in time and in space that follow deterministic laws and equations. This is in contrast to the structureless chaos of traditional equilibrium thermodynamics. A simple diagram summarizes the organization of chaos and order in generic self organizing systems that are removed from thermal equilibrium and put under some form of stress. The basic example system that might be helpful for visualization, is a fluid on a stove, the level of stress is given by the rate at which the fluid is heated.

We can see how close to equilibrium there exists no spatial structure, the dynamics of the individual subsystem is random and without spatial or temporal coherence. Beyond a given threshold of external stress, the system starts to self-organize and form regular spatial patterns (rolls, hexagons) which create coherent behavior of the subsystems ("order parameters slave subsystems"). The order parameters themselves do not evolve in time.

Under increasing stress the order parameters themselves begin to oscillate in an organized manner: we have coherent and ordered dynamics of the subsystems.

Further increase of the external stress leads to *bifurcations* to more complicated temporal behavior, but the system as such is still acting coherently. This continues until the system shows temporal deterministic chaos. The dynamics is now predictable only for a finite time. This predictability time depends on the degree of chaos present in the system. It will decrease as the system becomes more chaotic. The spatial coherence of the system will be destroyed and independent subsystems will emerge which will interact and create temporary coherent structures.

In a fluid we have turbulent cascades where vortices are created that will decay into smaller and smaller vortices. Analog situations in societies can be currently studied in the former USSR and Eastern Europe. James Marti speculates: ‘‘Chaos might be the new world order’’ [Marti,1991].

At the limit of extremely high stress we are back to an irregular Tohu-wa-Bohu-type of chaos where each of the subsystems can be described as random and incoherent components without stable, coherent structures. It has some similarities to the anarchy with which we started close to thermal equilibrium. Thus the notion of "Chaos" covers the range from completely coherent, slightly unpredictable, strongly confined, small scale motion to highly unpredictable, spatially incoherent motion of individual subsystems. A schematic graphics of this organization structure is displayed in Figure 1:

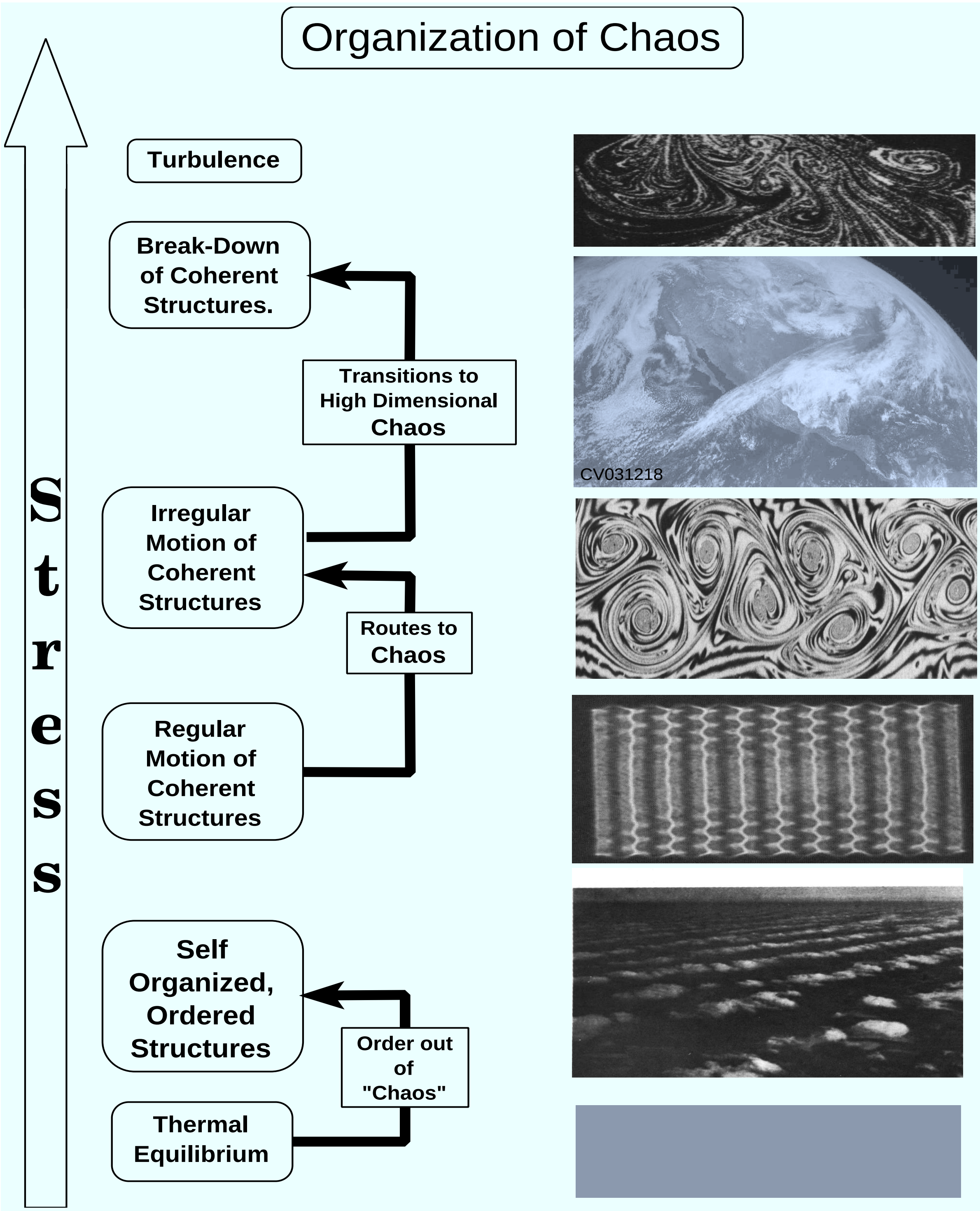

Figure 1: Organization of Chaos

Some properties of chaotic system.

There is frequent confusion between chaos and randomness. There are some similarities in the nature of chaotic and random system, but there are also some fundamental differences. Some of them are listed in Figure 2:

System	Order	Chaos	Randomness
Paradigmatic Example	Clocks, Planets	Clouds, Weather	Snow on TV Screen
Predictability	Very High	Finite, Short Term	None -> Simple Laws
Effect of Small Errors	Very Small	Explosive	Nothing BUT Errors
Spectrum	Pure	Yes!	Noisy, Broad
Dimension	Finite	Low	Infinite
Control	Easy	Tricky, Very Effective	Poor
Attractor	Point, Cycle, Torus	Strange, Fractal	No!

Figure 2: Discrimination table between Order, Chaos, and Randomness. Planets used to be representations of a divine order[2]. Chaotic signals can show spectra in the full range from pure tones to very noisy[3]. The dimension of a dynamical system indicates the number of independent variables. An attractor determines the geometrical structure, towards which a system will evolve.

---

[2]The regularity of their motion allowed spectacular predictions of eclipses etc. But it has been known for a long time that planetary motion can be chaotic.

[3]This can be heard very clearly in the Chua oscillator described below. As a resistor in the circuit is tuned the cooresponding sound signal changes from pure tone to tones with timbre (representing low level chaos) to very noisy.

The game of Roulette is an interesting example that might illustrate the distinction between random and chaotic systems: If we study the statistics of the outcome of repeated games, then we can see that the sequence of numbers is completely random. That led Einstein to remark: "The only way to win money in Roulette is to steal it from the bank." On the other hand we know the mechanics of the ball and the wheel very well and if we could somehow measure the initial conditions for the ball/wheel system, we might be able to make a short term predict ion of the outcome. Exactly this has been done by a group of Santa Cruz students who called themselves "Eudemonic Enterprises". Their story how they used chaos theory to conquer the casinos of Las Vegas and Atlantic City is described in [Bass, 1985].

Correlations between variables

Many problems in connection with the analysis of complex, political issues are related to the questions of what factors are causing a specific desirable or undesirable development. One example might be to ask how environmental factors are affecting security issues. A traditional way of analysing this problem is to compare histories of each of the parameters and perform statistical analysis to measure how dependent or independent these factors are.

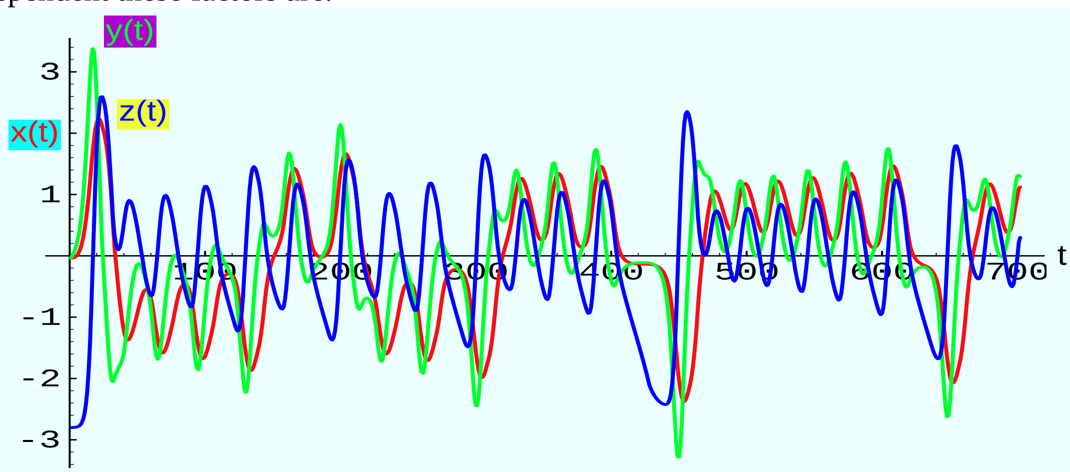

Figure3a: x,y,z-coordinates of normalized Lorenz-system vs. time

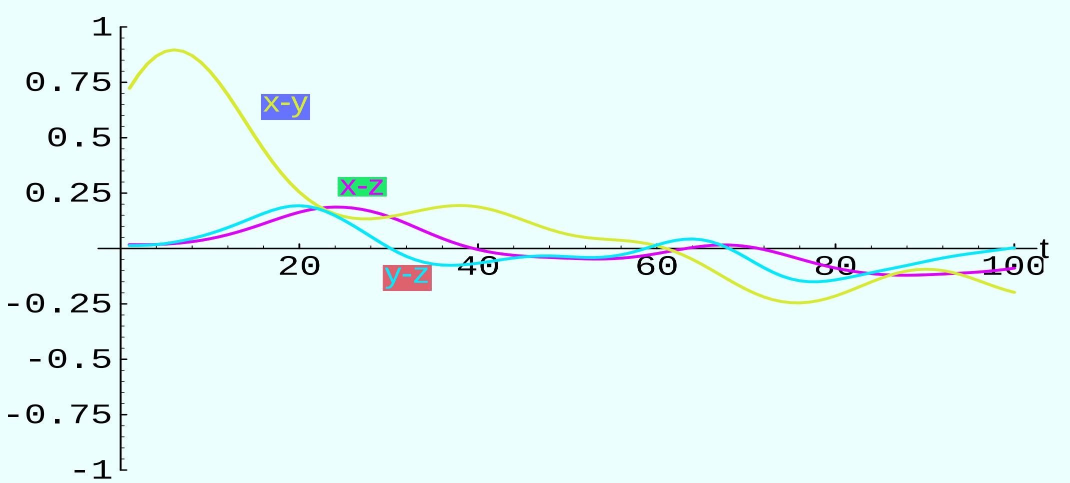

Figure3b: Crosscorrelations of Lorenz-system

Thus one can show, for example, that environmental problems, in a statistical sense, are very poorly correlated with security issues. One could naïvely draw the conclusion that environmental variables should not be relevant for decisions relating to security problems.

How dangerous such conclusions might be in the context of nonlinear chaotic, systems is illustrated in the following example: Assume we observe three time series (each one appropriately normalized) with apparent erratic time dependence. Visual inspection of the time series suggests that these time-series might not be independent. (Figure 3a).

When we calculate the corresponding correlation between pairs of the three variables we find the results shown in Figure 3b: Indeed, the x and y variables are highly correlated (up to 90%) whereas neither the x nor the y variable show any significant correlation with the third, z-variable. Coming back to our initial example, let us now assume that the z-variable corresponds to a factor describing some environmental parameter. From the interpretation mentioned above we would expect that decisions, which would have an effect on the z-parameter would not make much difference on the variables x or y.

Perturbation Analysis

In a computer experiment we now simulate such a decision which would change at a given time the value of the z-parameter by an amount of less than a tenth of a percent. This impact is too small to be visible on the graph of Figure 3a. The results of this new simulation is shown in Figures 4a-c: Figure 4a shows the three original variables, but this time without normalization.

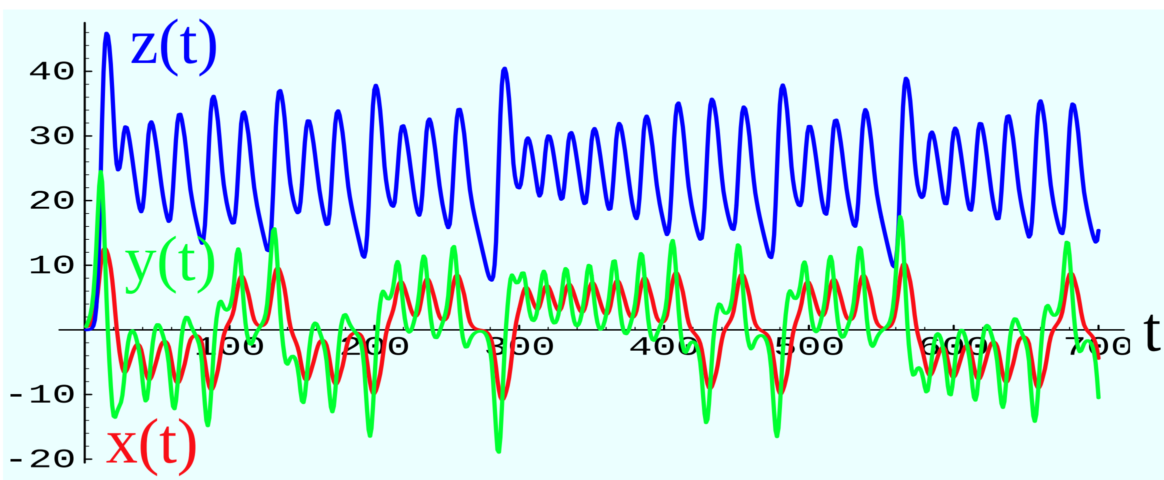

Figure 4a: Original time series of Fig. 3 without normalization.

Figure 4b shows a super-position of the original z-variable and the z-variable of the perturbed solution. As mentioned above, the time history for both solutions is basically the same for about 200 time steps (about 10 intrinsic cycles of the system which is a more characteristic time unit than the algorithm dependent numerical time-step). Later on, the difference between the two curves increases until they have a basically independent evolution.

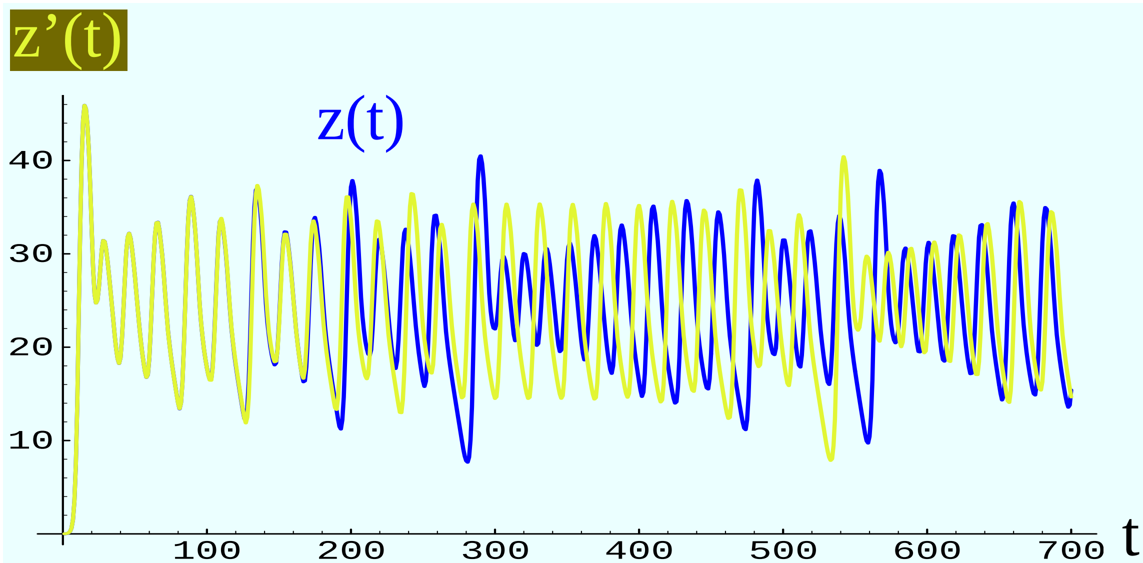

Figure 4b:Super-position of the original z-variable and the z-variable of the perturbed solution z'. Initially the difference is only 0.01, i.e. less than 0.1%.

In Figure 4c we have the corresponding plot for the x variable, which is basically uncorrelated with the z-variable. Nevertheless we can see that after somewhat over 200 time steps the two scenarios can have values which are completely (order unity) different from each other.

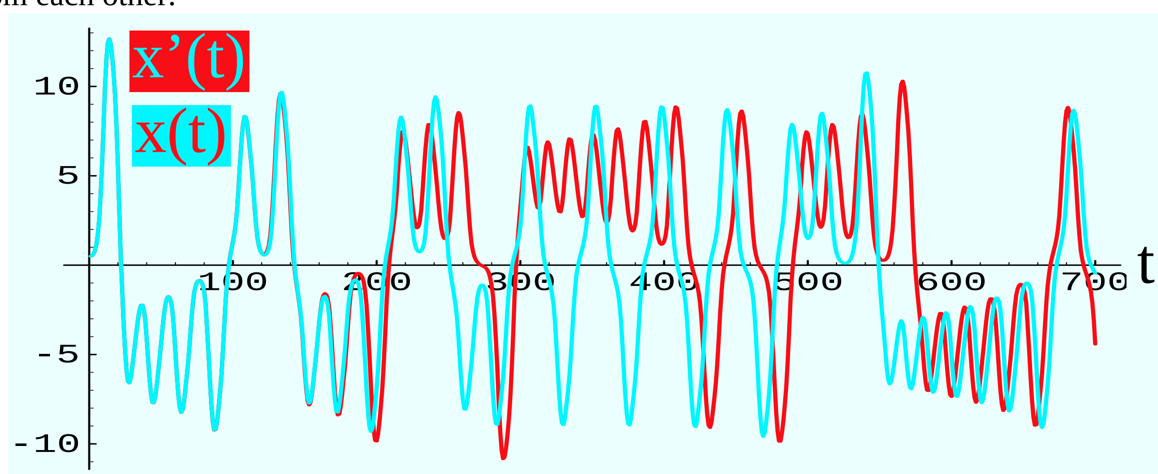

Figure 4c: Super-position of the original x-variable and the x-variable of the perturbed solution x'.

Strange Attractors:

The explanation for this phenomenon is shown in Figure 5: all three time-series are generated by the same set of equations, the famous Lorenz equations [Lorenz,1963].

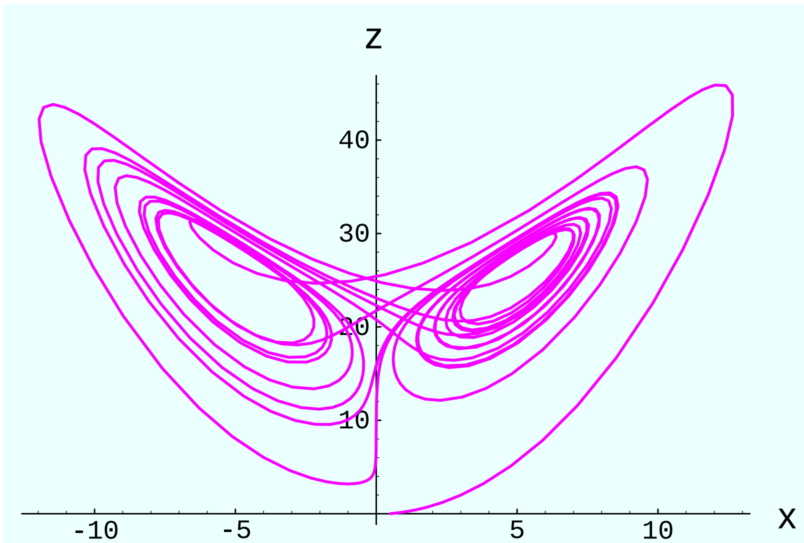

Figure 5: (x-z) projection of the Lorenz Attractor

Thus we can see that a geometrical analysis might prove much more powerful in cases like this than a quantitative statistical analysis. Thus we have to make sure that we capture all the *relevant* variables in a global model, even when there is no statistical correlation among some of them. This, of course raises the question of nonlinear indicators for *relevancy* or *redundancy* a question that is the topic of a very active area of current research. The conclusion from this example should not be that "everything is connected with everything" in a naïve way. From the theory of synergetics [Haken,1977,1983] we know that there are slaved variables and order parameters. For low-dimensional models we need to find out what these order parameters are and we need nonlinear methods to do that.

Sensitive Dependence to Initial Conditions

In order to understand the predictability aspect of chaotic systems a little better, let us expand some more on the sensitivity and divergence properties of chaotic systems: When we follow the orbit in Figure 5, we can see that the motion on each of the *wings* of the Lorenz *butterfly* is fairly regular. Only close to the z-axis, where the system has to *decide* if it should continue on the right wing or switch to the left wing or vice versa we directly see the origin for unpredictable behavior of the Lorenz system: Small influences can determine the global large scale future of the system. The same kind of perturbation in a less sensitive region of the Lorenz attractor could go completely unnoticed. We can understand that it is very important to find tools to identify those sensitive regions where the state of the system is extremely vulnerable to external perturbations. One of those nonlinear measures, the *local divergence rate* has been introduced in [Nicolis et al.,1983]. A visualization tool that provides a good global estimate of the distribution of these sensitivity parameters is given by the recurrence diagram [Koebbe,1991]. It allows us to anticipate in which states of the system it might be very sensitive to small fluctuations and in which domains it is relatively robust and insensitive and also where attempts to control the system would be most promising.

Crises

The Lorenz system is very stable in the sense that we can always be confident that the small perturbations will only lead to solutions which are confined to the same global attractor. This can change, however, when we modify one of the internal systems parameters: We can now obtain configurations where the system would exhibit an attractor with a different type of sensitivity. Small changes now not only would determine the fate of individual orbits **on** the attractor, but the fate of the whole attractor can become sensitive to very small external perturbations [Mayer-Kress et al.,1984]. The system could be pushed into a new and qualitatively different attractor (*internal crisis*) or the system could collapse altogether in the sense that the solutions would diverge (*external crisis*)[Grebogy,Ott, Yorke,82]. An example of an internal internal crisis in an electronic oscillator [Chua et al., 1986] is illustrated in Figure 5C:

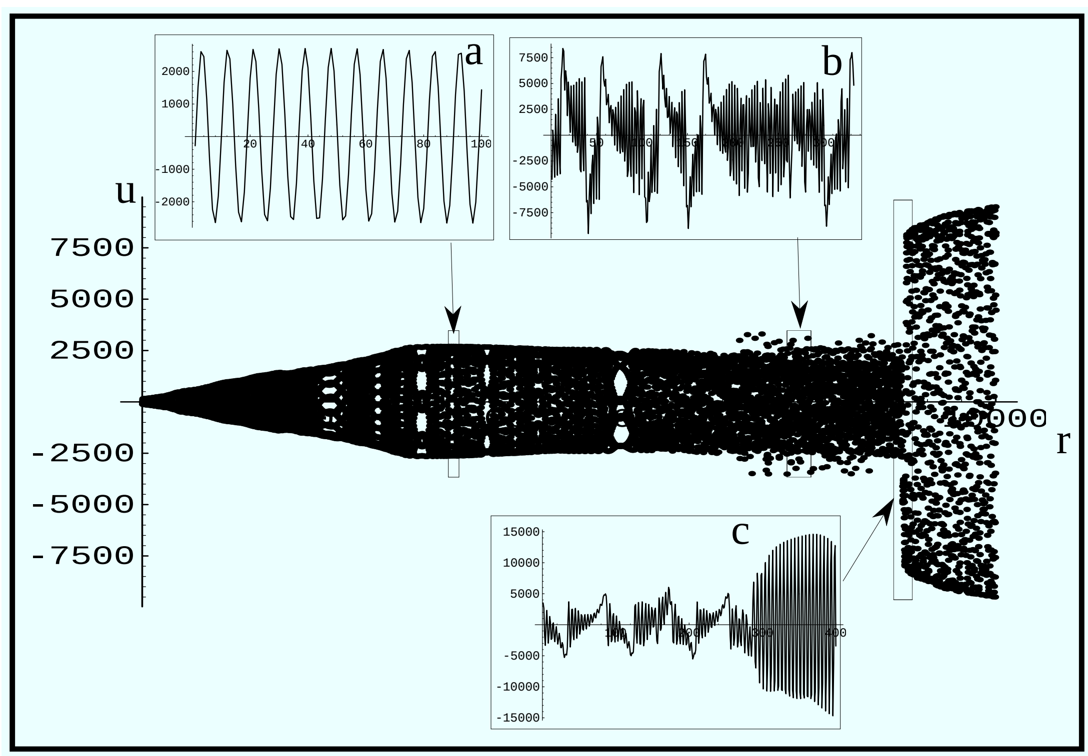

Figure 5C: Bifurcation diagram of the Chua Oscillator: As a parameter r is increased, the system undergoes several bifurcations: onset of periodic oscillations (inset a), deterministic chaos (inset b), internal crisis and transition to large scale limit cycle (inset c). The total data set for the bifurcation diagram consists of over 100,000 points therefore we had to sub-sample the points for the main diagram and use inserts to show the actual oscillations.

Control of Chaos

A very interesting recent development in chaos theory is the control of chaos [Hübler, 1987], Ott et al., 1990]. Traditional methods of control theory could be shown to potentially lead to chaotic solutions as a result of the effort to control the system to go to a stable state. A control force that has too large of a feedback delay, could try to control the system to a state that has changed due to the dynamics. The result is an overshooting that could lead to chaotic oscillations [Grossmann et al.,1989]. Instead of attempting to force the system to the desired state, one can use the information about the geometrical structure of the attractor of the system to drive the system close to a *stable manifold* of the goal state. Then the internal dynamics will assist in bringing the system closer to the desired state [Shinbrot et al. 1990]. A different approach that is based on the principle of matching takes advantage of the stable domains of chaotic systems: A nonlinear dynamical system will respond extremely sensitive to a control force which is close to its own intrinsic dynamics (*nonlinear resonance)*. If the system is perturbed with such a resonant force while it is in a stable domain then this form of open loop control can be very effective [Jackson et al., 1990]. Simulations show how extremely small forces can drive the system from one attractor to a more desired one.

Chaos Theory and International security?

The pioneering work of Richardson [Richardson,1960] set the stage for subsequent attempts to analyze quantitatively many questions of strategic military and economic competition between -- and among -- nations. Some of his insights came from his work on a classic chaotic system, our weather. He has already anticipated many developments which only were realized decades later, when fast computers became available. Many phenomena that are exhibited by chaotic systems appear to have striking parallels in the interaction of human societies.

In a very simplistic model, Saperstein discussed analogies between deterministic chaos and the out break of war [Saperstein, 1984]. The interpretation by Saperstein that chaos always has a high risk of conflict and war, has been questioned for example in [Grossmann et al., 1989]: Low level bounded chaos can indicate a stabilizing, democratic discussion and interaction. Conditions that lead to an orderly but unbounded arms races can have a much higher risk of war.

Some of these arguments have also been discussed in an model on the impact of SDI on the strategic arms race [Saperstein et al., 1988, 1989]: This research indicates that very fast rates of deployment of SDI systems can lead to unstable and unpredictable solutions which can be interpreted as indications of chaotic processes. The numerical value of the predicted number of ICBMs for each side after a 30 year arms race could take any value between zero and 10,000 missiles.

More recently, the end of the cold war and its impact on the international security system have been studied. The end of the simple situation of a 2 nation superpower competition leads to a multi-polar world in which alliances can form and change [Waltz, 1979]. Some elements of this problem have been studied in [Mayer-Kress, 1989] and will be discussed in the next section.

How can Chaos Theory be applied to Crisis Management?

Some Examples

As we tried to explain above, chaos theory is intrinsically based on the treatment of problems as non-linear dynamical system. Solutions can be complex and typically they cannot be easily extrapolated from current trends. Qualitative changes in the response and, correspondingly, in the strategy will be more typical than quantitative competition in deterrence values measured in throw weight or mega-tonnage. National security interests have to be redefined and perhaps will have to be expressed differently than budgetary numbers of large programs. Domestic economic interest might be increasingly in conflict with national security interests. Thus the notion of "preventive diplomacy" has to be taken seriously also by strategy planners. Many traditional areas of military power loose their role with respect to security issues whereas others increase their influence.

A few years ago S. Kapitza gave a talk at Los Alamos National Laboratory where he made comparisons of the effect of nuclear weapons and national television. During the gulf war cable network news (CNN) played an important role in providing the global public with close to realtime information. Political and military decision-makers have to take this into account as a relevant factor for their decisions. It is also clear that decision makers will try to control that public information factor. This was relatively easy during the gulf war through classical means of censorship. This direct control of the news-media, however, can have non-linear effects in that the public response to that control can change political parameters which then can act back onto the military decision makers. The complexity of this public information system will increase as multiple access to CNN type information becomes more available. Under those circumstances a plain censorship decision might not lead to the desired effect but could easily achieve the opposite outcome. Thus it would be very important in future crises to build careful models incorporating those factors which were absent or much less important in classical military planning.

The international drug industry represents another potentially important source conflict: The capital controlled by international drug organizations is of the same order of magnitude as some national defense budgets. Economic interests in the producing countries can often be in conflict with efficient drug policy enforcement measures. The current crisis in Peru, the most dominant producer of coca could be studied under this perspective.

While sophisticated technologies are developed to intercept ICBM missiles, it seems that modern technologies have only a 50% success rate of intercepting civilian ships and small airplanes. This fact might create a "window of vulnerability" which could be more dramatic than that in the context of ICBM surprise attacks.

Another example where nonlinear model simulations could be helpful is in reevaluating the importance of specific international aids programs for national and international security. For example a rational analysis of the amount that is spent for Israel as opposed to the amount spent to stabilize the situation in the former domain of influence of a collapsed superpower.

If one superpower focuses on military strength without the corresponding economic backing, then in a system in which lobbies have traditionally had a large influence on policies there will be a very strong incentive for other powers to invest a large fraction of their defense budget for lobbying activities in that military power. For example there seems to be some evidence of more or less direct influence of the Israeli and Japanese government on US politics. Therefore it seems feasible that superpowers in the classic style might not be sustainable any longer largely because of economic and information realities. Maybe the gulf war, dominated by the US but largely financed by the allies indicated a change in the global strategic arena.

Approaches from Nonlinear Dynamical Systems and Chaos Theory

How could we approach these problems from a nonlinear dynamical systems point of view? The first step certainly has to be a systems analysis. Much know-how in this sector has been developed in the context of systems dynamics, although there the analysis is guided by the restricted mathematical methods and certainly has to be improved and generalized. Guiding questions in that sense might be:

- *"Who are the major actors in this crisis?"*
- *"How are these actors influencing each other?"*
- *"What are external parameters that influence the decisions of the actors?"*

Answering those questions and representing their answers in some structured form (graphical or symbolic) would constitute, what we would call a conceptual model. Already at this conceptual level, recent progress in object oriented graphical user interfaces (GUIs) such as the Diagram tool described below, might provide assistance in a better understanding of the complexity of an evolving interacting system.

Once this conceptual model has been established, often (but not always) it is straightforward to find quantitative variables to map this conceptual model onto a computational model. In the conflict between Russia and Ukraine the variables might be military and economic capabilities and potential future threats as a function of those capabilities. In other circumstances which are of a more nationalistic, ethnic, or religious origin, a quantification on the level of global actors could be more difficult if possible at all. How would the christians respond to actions of the moslems as a coherent entity? How to model the conflict between Croats and Serbs?

Here a more recent development in adaptive computation might provide very helpful: These conflicts could be modelled on a *microscopic* level of individuals:

Imagine you are a Croat in Zagreb, what are the factors that would make you go and fight against the Serbs?

And what factors could make you go home and do your work?

Modern Computers are fast enough to run scenarios with an ensemble of (simplified) decision patterns for each of the 4.5 Mio Croats and 11.5 Mio Serbs. The quantification probably could be done in many cases through assigned probabilities for specific actions. What one would expect from such simulations is that global properties would emerge which could give new insights into the effects of different crisis management measures on the stability of problematic regions.

We can summarize: Decision makers will always have some model of the system of interest to assist reasoning during a crisis. Two (conflicting) factors contribute to the type of models chosen:

(i) conceptual models use intuitive reasoning based on experience. They typically abstract the most relevant features from a sea of redundant information. They are very flexible to adapt to unforeseen changes and generalize easily to qualitatively new situations.

(ii) Traditional analytical models try to anticipate as many factors as possible in as many detail as possible. Thereby they become very inflexible and practically useless in surprise situations. These models are typically not very adaptive.

Chaos theory suggests the use of models with local, short term predictability:
Adaptability requires
- simple, low-dimensional models which should be intuitive
- fast and direct access to and integration of current, global data
- multimedia user interface for efficient representation of the results
- global sensitivity analysis and identification of crisis domains
- efficient individual archiving and retrieval system

A efficient simulation environment would provide an object oriented integration of all of the elements described above:
- conceptualization of complex developments without strict formalization
- access to global information systems that allow global estimation of parameters for low-dimensional chaotic models with global scan of scenarios
- links to detailed simulation systems where data and quantification requirements are satisfied.

In the remaining sections we want to give a brief description of some elements that might illustrate some of the points discussed above.

Adaptive Control of Two Agents :
The following example illustrates some of the issues under discussion [Hübler et al. 1991]:
Two agents interact in an environment which is influenced by three factors:
(i) an unpredictable world, which accounts for all factors that are not directly accessible
to modelling and control and provides a background unpredictable influence.
(ii)-(iii) the actions of each of the two agents.

The goal of each of the two agents is to avoid crises and keep the environment predictable. Thus they have to adapt their strategies to their environment. Their success is measured by how well the future state of the environment can be predicted over some number of time steps.

The strategies that the agents have available are:
(i) build a model of the environment with a level of complexity that the agents can choose.(The level of complexity is expressed as the number of parameters that go into the model)
(ii) the number of observations used to tune the model.
(iii) try to influence and control the environment to make it better predictable
(iv) choose the type of order that the agent tries to impose onto the dynamics of the environment in order to achieve maximal predictability.

Since there are continuous unpredictable influences from the outside world and since the opponent also influences the environment in an unpredictable fashion, each agent has to continuously update the strategy.

Simulations of this simple model provide some fairly interesting results:

First of all both agents will try to control their environment/opponent but soon will realize that a "leader/follower" configuration allows better prediction for both agents.

The attempt of a leader to introduce static order in the environment appears to be generally very unstable since it provides very little information about the internal state of the system and the opponent. Therefore the model of the dominating and controlling agent becomes increasingly worse until the mismatch between model ("ideology") and reality is large enough that the system becomes unstable and large scale fluctuations can build up. It appears that the most stable strategy of the leader is to impose a goal dynamic on the system which shows low level chaos. Thereby the controlling agent can continuously test an extended behavioral domain of the system and thereby keep the model up to date and close to reality (in the form of external world, immediate environment and opponent.) From the perspective of the follower, fairly accurate short time predictions are also possible since the goal dynamics was assumed to be weakly chaotic. That means it is unpredictable enough to keep the follower alert but also structured enough to allow for successful adaptation and anticipation. When the system becomes too unpredictable or hopeless, a transition to a "no future" culture might be the response.

It is very interesting to notice that the degree to which the external world is changing is essential for the degree of complexity of the most successful models for both leaders and followers: In a relatively stationary environment it pays to accumulate many data points in order to construct a model with a large number of parameters accurately. In the case of a rapidly changing world, however, sub-optimal, smaller models that need less input data and has fewer parameters to be estimated appear to become more successful, since they can be updated more rapidly, whereas a highly complex model can find itself to make accurate predictions based on data or parameters that are already obsolete.

Such conditions typically occur in crisis situations where simple adaptive models with tight links to global information systems might become superior in spite of their global character and lack of detail.

Global Information and Simulation Systems

The amount of information available about the state of out planet with all its subsystems increases dramatically. The data come both from direct observations as well as from computer simulations and more traditional methods. The representation and structuring of this rapidly changing information flood is a challenging and unsolved problem.

From the theory of chaotic dynamics and the study of complex adaptive systems we have a sophisticated mathematical and computational tool-box available regarding global, invariant structures, bifurcations, analysis and response to external perturbations. These tools have been applied and tested for the analysis and modeling of a number of systems in a large variety of contexts. From a different angle they have been most successfully applied in ‘virtual realities’ of educational computer games. Common to both of these examples is that they deal with a closed environment of theoretical or game pragmatic assumptions and parameters. What is lacking is some efficient interface to the real world of global dynamics. The technology for such an interface is currently developed as global communication and information systems, high speed computer networks, wide are information servers and other areas of global networks.

In this project we made a first attempt to utilize some of these modern communication, computer, and multi-media technologies to approach exactly that problem. A pilot project version of this approach has been presented as an interactive computer installation "EarthStation" at the 1991 ARS electronica [Mayer-Kress,1991b]. Since this framework is very global and since our main interest is to demonstrate the power of modern computational tools with respect to adaptability and interactivity, we constantly updated the models, including some issues of current interest (through news paper or through segments recorded from news broadcasts or received from the NetNews of the internet. At the same time we would drop issues which seemed to be no longer strongly coupled to the global dynamics, which, of course might prove completely wrong from some future perspective. In the following we want to describe several of the elements in our installation, which try to integrate generally available software and services into a useful information and simulation system.

The Main Diagram Interface

Our concept is mainly based on hierarchical network representations of current problem areas: Each node of the network corresponds to an object which can be of a very general type:

- a network on a lower level
- images and charts, which themselves can act as background for new networks or annotated with sound messages (news-clips) or general other programs
- simulation tools
- programs that connect to other units such as other computers, on which different types of programs can be launched or general multi media devices.

This framework is a natural background for geographic information systems, both static and dynamics. The links that connect these objects can be adapted very easily in a graphic, object oriented programming style and thereby have a great advantage compared to classical world-model programs: The contents and the structure of the simulation and visualization tools can be easily updated as the state of the real world changes and evolves.

Figure 6 shows a top level diagram for the global system. From the diagram interface we can access different objects. Examples of these objects are given in the list below:

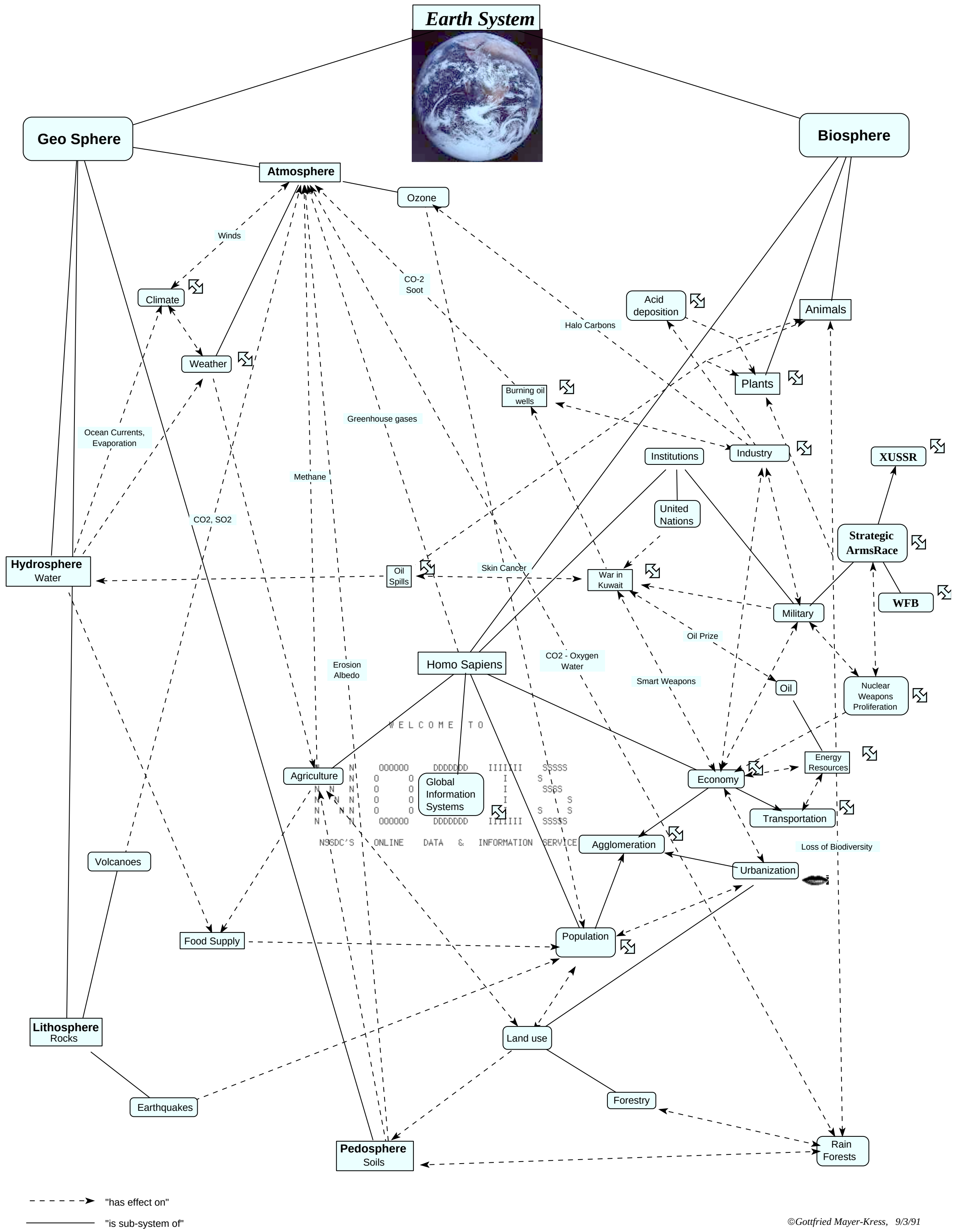

Figure 6: Diagram interface to access local and remote data bases, information services, and simulation software. Each element in the diagram labeled with a double arrow attached to it represents a symbolic link to one of the objects accessible from this interface.

Strategic arms-race among three competing nations

Several ways to represent a (Richardson) model of three nation strategic arms races [Mayer-Kress, 1989] is displayed in the diagram of Fig. 7:

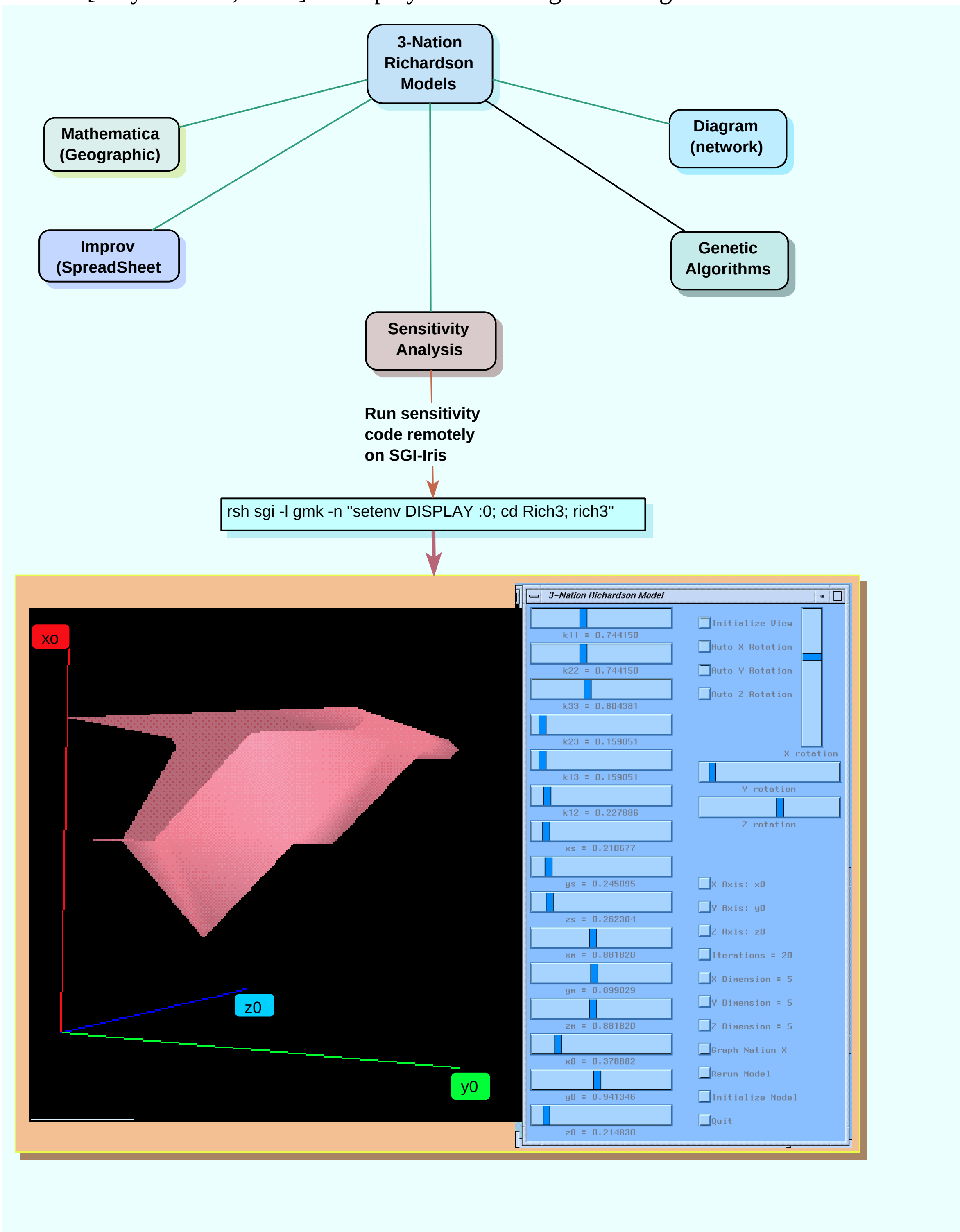

Figure 7: Diagram interface to interact with a 3-Nation Richardson model through three different representations: Schematic network, electronic spreadsheet program, and geographic representation. We also indicate links to a genetic algorithm learning program and a sensitivity analysis program which allows simultaneous, interactive, global analysis of more than 100,000 scenarios.

- Schematic flow chart representation of the logical structure of the model (Fig. 8) As described in [Mayer-Kress, 1989] nations will determine their armament levels depending on national factors, external threats and economic constraints. Alliances form when one of the nations becomes stronger in terms of arms expenditures than any of the other nations (collective security).

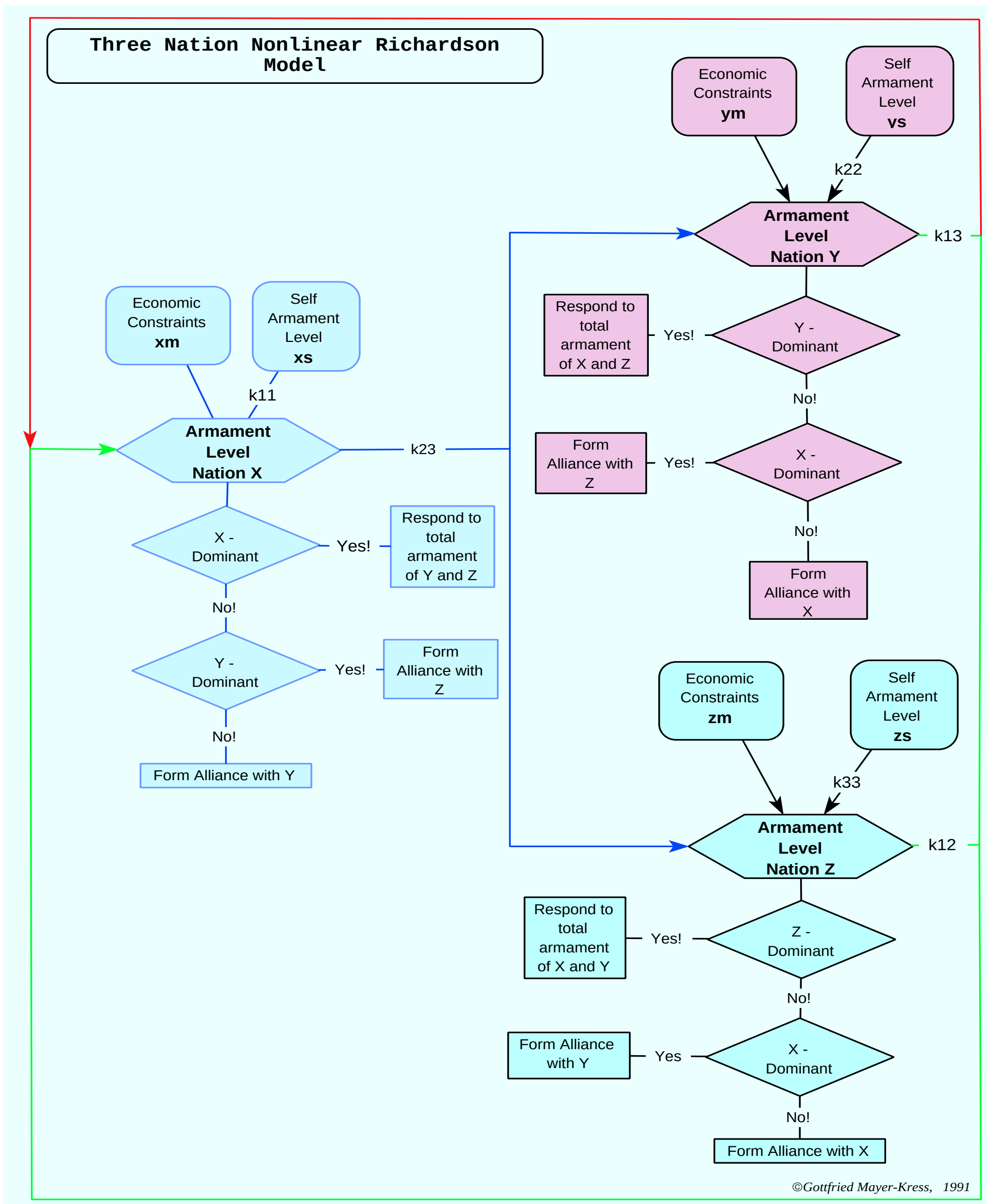

Figure 8: Chart of a 3 Nation Richardson model of the post cold war strategic arms-race. Included are economic constraints and non-linear alliance formation rules: The weaker nations will always team up against the nation with the highest arms expenditures.

Sub-diagrams:

If the problem under consideration is of a hierarchical nature or has elements which can be decomposed into sub-problems, then we create a diagram that can be activated by selecting the node under consideration.

- Representation as hyper-media notebook. The model and the results are presented in the form of a table of contents to obtain a quick overview over the general structure of the model. Each of the chapters can be interactively accessed to arbitrary details. Again the parameters and also the structure of the model can be modified and simulated. In Fig. 9 we have a display of graphical time series output similar to the display from the electronic spreadsheet interface.

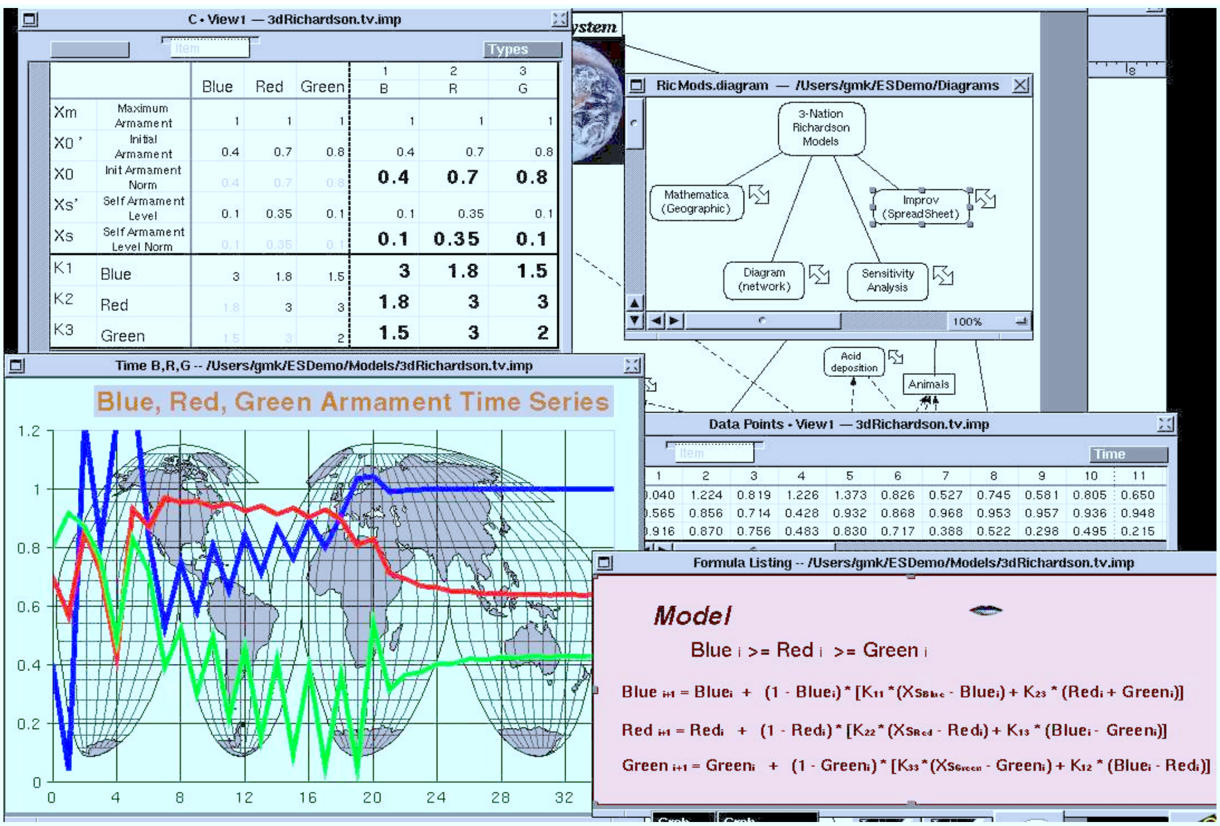

Figure 9: Electronic spread-sheet interface for interactive simulation of 3-Nation-Richardson model. This is spread sheet is called as one sub-node of the main diagram interface.

A notebook object also allows a display of the result in a geographic representation: A color table codes information about the armament level of each of the nation at a given step of the simulation. The sequence of maps , color coded according to arms expenditures, can be animated to show the spatio-temporal dynamics of the model.

- Interactive simulation of the context of an electronic spreadsheet program. Here individual scenarios can be simulated and graphically or numerically displayed.

- Sensitivity analysis of the model through an analysis of a large number of simulated scenarios. The corresponding object in the diagram activates a link to a program located on a different computer (Silicon Graphics Iris) which allows interactive simulation and visualization of outcomes of simulations for typically 10^5 different parameter values and/or initial conditions.. (See lower part of Fig. 7).
  There are 4 different iso-surfaces electable through radio buttons. They can be interpreted as crisis surfaces where either the arms-race among the three nations becomes unbounded, or where the different possible alliances will break down. For example the red surface indicates for which parameters/initial conditions nations blue and green form an alliance against red (inside the surface) or conditions for which the result of the arms race is of a different nature (Out side of the iso surface)

Economic Links

We have used the multi-media communication tool *MediaView* of R. Phillips of LANL to represent linkage data of the Middle East countries obtained from the "Correlates of War" (CoW) project of the University of Michigan. The document contains a text description of the methodology and the data and different multi-media attachments.

There are many interactive tools provided by *MediaView* to attach voice, Post-It, and graphics annotations. This is done by dragging icons to the appropriate location in the text. These icons can be opened and comments, graphs or voice messages can be attached. Fig. 10 shows an attached graphics document which represents through arrow graphs (with variable color and thickness) information about economic links between the Middle East countries (these are {Iran, Turkey, Iraq, Egypt, Syria, Lebanon, Jordan, Israel, Saudi Arabia, Yemen AR, Yemen PR, Kuwait, Bahrain, Qatar, UAE, Oman}) and their major partners in the world.

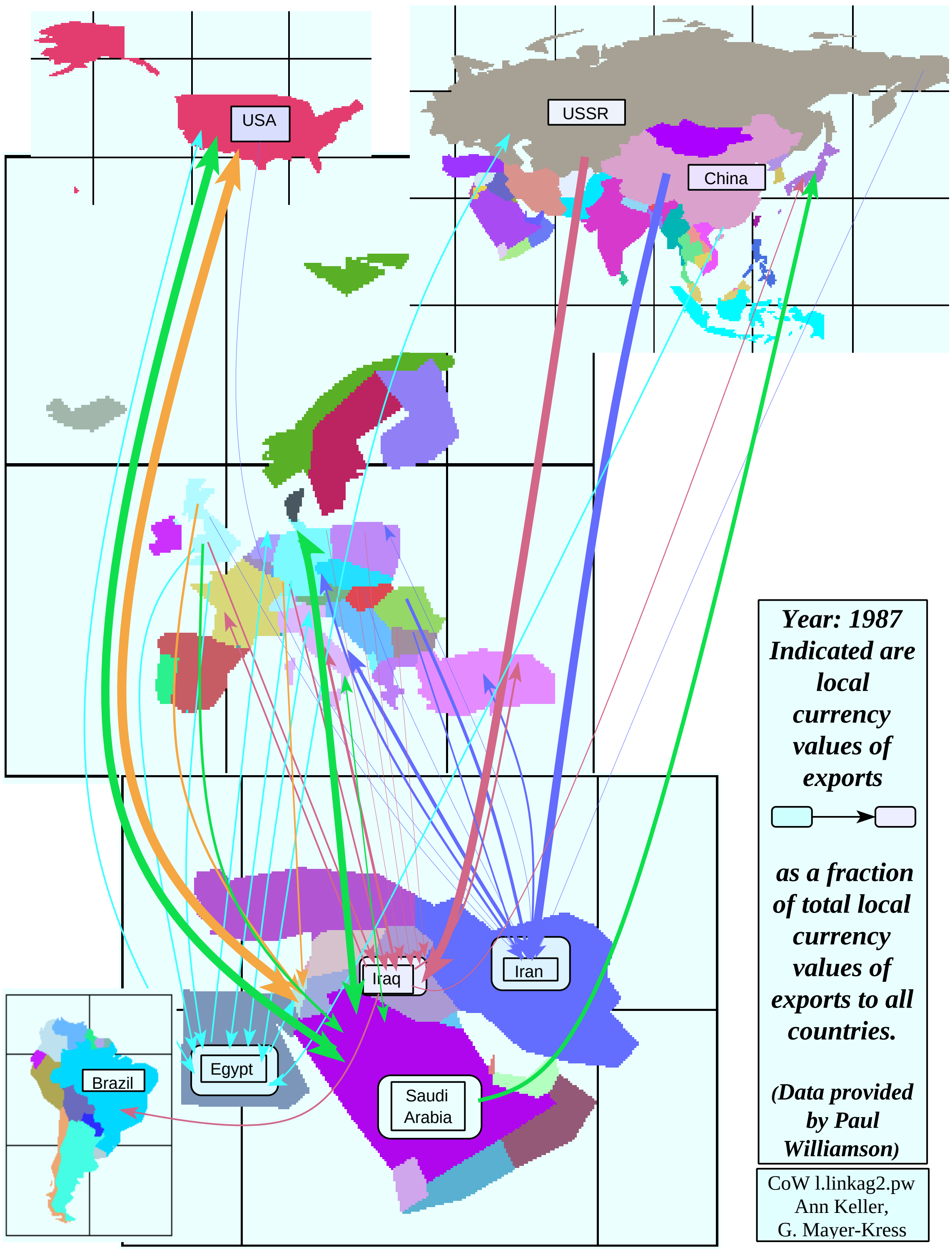

Figure 10: Economic links of countries in the middle east to the rest of the world. (Data from Correlates of War [COW] project.)

Geographic Multi-Media Information Systems

In this part of the general structure we want to represent different problem areas in a geographical context. In Fig.11 we see a diagram structure for which a scanned image of a cloudfree earth was used. Objects in this diagram are labelled by geographical location and are linked to a program which will control a laser disk player to show video sequences taken from a space shuttle flight over that same location.

Figure 11: Geographic interface to video sequences of space shuttle overflights.

Public Realtime Access to Global Data Bases

Traditionally there have been quite a few commercial news and wire services available More recently innovative multimedia servers have been developed in the internet community. If we want to have a global information and simulation tool with a user interface which is intuitive and easy to use such as in Maxis' educational game "SimEarth", then it is essential that we have direct access to distributed data base systems. Already today we have examples of distributed information systems which can be accessed with sophisticated user interfaces. In the following we will present a few operational examples:

Example:, Wide Area Information Server(WAIS)

This is a research tool under development by thinking machines cooperation, a distributed information system that allows the user to make requests in natural English. The WAIS system will then search through a pre-specified information resources on the (global) network and provide a list of possible sources, each one is attached with a bar graph, representing how relevant the source might be to the request. In this way the user can do iterative searches on these sources. The result of the search can be text information, but also for example image files. The most important feature of this information service is, again its flexibility: new information sources can submit their information summary and the evolving network of servers can be adapted to changing needs of users.

World Wide Web (WWW) and NetNews

A similar approach to the WAIS has been developed at CERN in Geneva, Switzerland. It is based on hypertext which contain links to different distributed data objects. One of the links goes to the NetNews system. This is a global internet news program which allows global reading and posting of news- items among users. It is organized in different categories for a browser type interface, allowing the simultaneous representation of different levels of information. The path in the hierarchies of news directories is high lighted (talk-politics-soviet). The interface NewsGrazer on NeXT also allows for archiving news items in specific customized news folders. Thus it is possible to access these archives on a specific topic from the diagram interface, described above, and at the same time update the archives by accessing current news items.

Example: Weather Information

The College of Engineering, Atmospheric, Oceanic, and, Space Sciences of the University of Michigan is providing the "Weather Underground. It provides hourly updated weather, earthquake and other information through very user friendly interfaces. This tool is basically of a hyper-text nature and provides textual reports. Hourly updated weather-maps for the continental US is provided through different ftp sites such as vmd.cso.uiuc.edu of the University of Illinois at Urbana-Champaign or caticsuf.cati.csufresno.edu at the California State University at Fresno. The latter site also provides detailed local weather, drought, and other information. A third way of distributing weather information is through direct satellite images. Widely available today are see a one of the GOES images that are also distributed through the ftp sites mentioned above. Maybe we should mention that all of these information tools can also be directly accessed from the general diagram interface described in the beginning.

Geographic Information Systems:

On modern graphics workstations, high quality geographic information system become more available. The direction is also clearly going in direction of creating virtual reality interfaces so that one can get a fast overview about an environment that would be very difficult to experience otherwise. As one recent example we want to mention modern flight simulator type environments and interactive geographic tools like the "Electric Atlas".

Finally we want to briefly mention three more tools that are integrated in the EarthStation installation on different platforms:

PhaseSpaceShip and Audification:

Here the dynamics and sensitivity of specific, multidimensional simulation models (in our case a 9-dimensional chaotic model for the El Niño phenomenon) are represented on two different platforms (SGI Iris and Macintosh with special MIDI hardware and software): The simulation of the model and the graphics rendering of the solutions of the model are done on the Iris.

The user can select (through radio buttons) the projection and perspective of a laboratory ("Tower") perspective or co-moving ("Cockpit") perspective. A spaceball interface allows the interactive perturbation of the equations of the model. All nine dimensions of the model are represented by a set of maximally orthogonal musical dimensions.

In Table 1 we have listed the nine sonic parameters that we have used with an indication of the range the each of the dimension defines and also an estimation of the resolution for each of the dimensions. The idea is to monitor variables with little activity in a dimension with low resolution. As soon as the ear detects significant change, the buttons in the interface allow to switch the dimension into a higher resolution audio dimension and/or into a visual dimension. [Kramer, 1991]. This application explores the possibilities of new multi-media approach of complex data analysis and representation.

Fractal Boxes Representation of Complex Structures

The representation of complex data sets or structures of complex simulation models has been done traditionally in the form of flowcharts. In our application we generalize that concept to a 3-dimensional virtual space. Each problem area of the global environment is represented as a three-dimensional object in the virtual space. We can fly through that space exploring the problem areas from different perspectives. Then we can explore the deeper structures of a specific problem are by entering those problem objects from any direction. As soon as we enter a specific problem area we are in a new virtual space which displays in multi media the different aspects of the problem and new objects suspended in this virtual space indicate directions in which one can proceed to explore the problem area in still deeper levels [Mayer-Kress,1991b].

Sonic Map

Parameter	Description	Range	Resolution
Speed	**Speed of pulses**	**Slow-----Fast**	**16**
Envelope	**Attack and Decay**	**Sharp-----Dull attack**	**4**
Duration	**Percentage of time of pulse**	**Short-----Long**	**4**
Detune	**Detuning of two pitch components**	**Unison-----Out of Tune**	**4**
Flange	**Phase shifting of sound**	**Stable-----Swirling**	**4**
Pan	**Left/Right stereo placement**	**Left-----Right**	**8**
Pitch	**Fundamental frequency**	**Low-----High**	**32**
Volume	**Amplitude**	**Soft-----Loud**	**8**
Brightness	**Energy of upper harmonics of waveform**	**Dull-----Bright**	**8**

Table 1: Sonic map used for the visualization/audification of a 9-dimensional chaotic system. Note the wide range of resolutions for each of the sonic dimensions. This is similar to the lower resolution that we have in the depth dimension in visual space.

Acknowledgements: I would like to thank S. Bankes, P. Boyle, P. Carruthers, D. Campbell, G. Cowan, H. Fallin, and A. Hübler for interesting discussions and for their support. This work was supported in part by a grant from the INCOR program of the University of California, administered through the Center for Nonlinear Studies of the Los Alamos National Laboratory.

References

[Abraham et al., 1991]
R. Abraham, A. Keith, M. Koebbe, G. Mayer-Kress, **Double Cusp Models, Public Opinion, and International Security**, Intl. J. Bifurcations and Chaos , **1(2)** (1991) 417-430
[Bass, 1985]
T. Bass, **The Eudemonic Pie**, Science of mind publishers, Los Angeles, (1985)

[Berge et al., 1984]
P.Berge, Y. Pomeau, C. Vidal, **L'Ordre dans le Chaos**, Hermann, Paris (1984), english translation: Wiley (1986)

[Campbell et al., 1991]
D. Campbell, G. Mayer-Kress, **Chaos and Politics: Simulations of Nonlinear Dynamical Models of International Arms Races**, Proceedings of the United Nations University Symposium ‘‘The Impact of Chaos on Science and Society’’, Tokyo, Japan, 15-17 April 1991

[Chua et al., 1986]
L.O. Chua, M. Komuro, T. Matsumoto,**The Double Scroll Family**, IEEE Transactions on Circuits and Systems, **CAS-33,**No 11,1073-1118,1986

[Ditto et al., 1990]
W. Ditto, S. Rauseo, M. Sano, **Experimental Control of Chaos**, Phys Rev Let, 1990 Dec 24, **65**N26:3211-3214

[Eckmann,1983]
J.-P. Eckmann, **Roads to turbulence in dissipative dynamical systems**,
Rev. Mod. Phys. **52**, 643-654, 1981

[Farmer et al.,1988]
J.D. Farmer, J. Sidorovich, **Exploiting chaos to predict the future**,
in Evolution, Learning, and Cognition, ed. Y.C. Lee, World Scientific
Press, 277, 1988
[Forrest et al., 1991]
S. Forrest, G. Mayer-Kress, **Using Genetic Algorithms in Nonlinear Dynamical Systems and International Security Models,** in: *The Genetic Algorithms Handbook*, L. Davis, (Ed.),Van Nostrand Reinhold, New York 1991

[Grebogi et al.,1983]
C. Grebogi, E. Ott, J. Yorke, **Crises, Sudden Changes in Chaotic Attractors and Transient Chaos**, Physica **7D**, 181, (1983)

[Grossmann et al.,1989]
S. Grossmann, G. Mayer-Kress, **The Role of Chaotic Dynamics in Arms Race Models**, Nature, **337**, 701-704, (1989)

[Haken,1977]
H. Haken, **Synergetics an Introduction**, Springer, Berlin 1977

[Haken,1983]
H. Haken, **Advanced Synergetics**, Springer, Berlin 1983

[Hübler,1987]
A.W. Hübler, **PhD Thesis**, TU München 1987

[Hübler et al.,1991]
A. Hübler, J. Miller, D. Pines, N. Weber, **Optimal Adaptation in a Randomly Evolving Environment**, Santa Fe Institute preprint, 1991

[Hübler ,1992]
A. Hübler, **Modeling and Control of Complex Systems: Paradigms and Applications**, in ‘‘Modeling Complex Phenomena’’, edited by L. Lam (Springer, New York 1992)

[Jackson et al., 1990]
E.A. Jackson, A. Hübler, **Periodic Entrainment of Chaotic Logistic Map Dynamic**, Physica **D 44**, 407(1990)

[Kadyrov, 1984]

M.N. Kadyrov, **A Mathematical Model of the Relation between Two States, Global Development Processes** , Institute for System Studies, Preprint 1984

[Koebbe et al., 1991]
M. Koebbe, G. Mayer-Kress, **Use of Recurrence Plots in the Analysis of Time-Series Data,** in Nonlinear Modelling and Forecasting, SFI Studies in the Sciences of Complexity, Proc. Vol. XII, Eds. M. Casdagli, S. Eubank, Addison-Wesley, 1991

[Kramer ,1991]
Gregory P. Kramer, Technical notes on audification, Santa Fe Institute, 1991

[Lorenz,1963]
E. Lorenz, **Deterministic nonperiodic flow**, J. Athmos. Sci., **20**, 130-141, 1963

[Marti,1991]
Marti, James, **Chaos might be the new world order**, Utne Reader, n48 (Nov-Dec, 1991):30

[Mayer-Kress et al.,1984]
G. Mayer-Kress, H.Haken, **Attractors of Convex Maps with Positive Schwarzian Derivative in Presence of Noise**, Physica **10D**, 329-339, (1984)

[Mayer-Kress, 1989]
G. Mayer-Kress, **A Nonlinear Dynamical Systems Approach to International Security**, in: ‘‘The Ubiquity of Chaos’’, S. Krasner (Ed.), Proceedings AAAS conference, San Francisco, January 1989

[Mayer-Kress,1991a]
G. Mayer-Kress, **Nonlinear Dynamics and Chaos in Arms Race Models**, Proc.Third Woodward Conference: "Modelling Complex Systems", (Lui Lam, Ed.), San Jose, 4/12-13/91

[Mayer-Kress,1991b]
G. Mayer-Kress, **EarthStation**, in: ‘‘Out of Control’’, Ars Electronica 1991, K. Gerbel (Ed.), Landesverlag Linz, Linz, 1991

[Nicolis et al., 1983]
J. Nicolis, G. Mayer-Kress, G. Haubs, **Non-Uniform Chaotic Dynamics with Implications to Information Processing**, Z. Naturforsch. **38a**, 1157-1169 (1983)

[Ott et al., 1990]
E. Ott; C. Grebogi; J. Yorke, **Controlling chaos**, Phys Rev Let, 1990, **64** N11:1196-1199.

[Packard,1990]
N.H. Packard, **A Genetic Larning Algorithm for the Analysis of Complex Data**,
Complex Systems, **4**, 543-572, 1990

[Richardson,1960]
L.F. Richardson, **Arms and insecurity**, Boxwood, Pittsburgh 1960

[Saperstein, 1984]
A. Saperstein, **Chaos - a Model for the Outbreak of War**, Nature **309**, 303-305, 1984

[Saperstein et al., 1988]
A. Saperstein, G. Mayer-Kress, **A nonlinear dynamical model of the impact of SDI on the arms race**, J. Conflict Resolution, **32**, 636-670, 1988

[Saperstein et al., 1989]
A. Saperstein, G. Mayer-Kress, **Chaos versus predictability in formulating national strategic security polic**y, Am. J. Phys. **57**, 217-223 (1989)

[Shinbrot et al., 1990]
T. Shinbrot; E. Ott; C. Grebogi; J. Yorke, **Using Chaos to Direct Trajectories to Targets**, Phys Rev Let, 1990 DEC 24, **65** N26:3215-3218.

[Waltz ,1979]
K. Waltz, **Theory of International Politics**, Addison-Wesley Publishing Company, Reading Mass. 1979