

Coping with the Bounds

Speculations on
Nonlinearity
in Military Affairs

Tom Czerwinski

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Coping with the Bounds

**Speculations on
Nonlinearity
in Military Affairs**

Tom Czerwinski



"I am convinced that the nations and people who master the new sciences of complexity will become the economic, cultural, and political superpowers of the next century."

Heinz Pagels

Physicist, author of *Dreams of Reason*, and inspiration for the character of the Chaos scientist in the book and film "Jurassic Park." Died climbing a mountain in 1988.

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Foreword

For years, the private sector has been immersed in such works as *Thriving In Chaos* by Tom Peters and *The Fifth Dimension* by Peter M. Senge. This book is perhaps the first to directly engage the defense establishment along the same lines.

The theme of this work is that conventional, or linear, analysis alone is not sufficient to cope with today's and tomorrow's problems, just as it was not capable of solving yesterday's. Its aim is to convince us to augment our efforts with nonlinear insights, and its hope is to provide a basic understanding of what that involves.

Murray Gell-Mann, a Nobel Laureate in physics, has defined the challenge:

When dealing with any nonlinear system, especially a complex one, it is not sufficient to think of the system in terms of parts or aspects separately, and finally to combine those analyses in an attempt to describe the entire system. Such an approach is not, by itself, a successful way to understand the behavior of the system. In this sense there is truth in the old adage that the whole is more than the sum of its parts. . . . It is of crucial importance that we learn to supplement those specialized studies with what I call a crude look at the whole.

Tom Czerwinski brings to this challenge his experience teaching nonlinearity to students of the National Defense University. He has formulated an approach that calls for intertwining, or meshing, linear and nonlinear reductionist techniques. His terms are “Tools of Analysis” for linear techniques and “Aids to Learning” for nonlinear approaches. The latter are set forth as a means to attain Gell-Mann’s “crude look at the whole.” As you will find, these Aids to Learning are still in the formative stage and very different both in methodology and expectations, requiring new ways of thinking and acting.

Nevertheless, I am convinced that the ability to thrive in nonlinear environments will have to be among the core competencies of the warrior and statesman of the 21st century if the United States is to maintain its position. It may be that attaining that ability lies at the heart of the Revolution in Military Affairs that we seem certain is present, but that has proven so elusive.

Richard A. Chilcoat
Lieutenant General, U.S. Army
President, National Defense University

Acknowledgments

I am indebted to two now-retired lieutenant generals who have led the way in introducing nonlinearity to the Defense establishment. The first is LTG Ervin J. Rokke, USAF, formerly president of the National Defense University, whose interest provided me encouragement as only the boss can. The other is Paul K. Van Riper, USMC, a truly visionary leader. My thanks to LTC Bruce DuBlois, USAF, COL Douglas A. Macgregor, USA, LTC Steven M. Rinaldi, USAF, and MAJ John F. Schmitt, USMCR, for reviewing drafts, but more for what I have learned from them as friends and writers. A special acknowledgment to my colleague LTC Richard L. Casey, USAF, who served as editor-de-facto. Finally, to my lovely wife Sue for her patience during the past year on this book, and the 28 years preceding it.

The field of nonlinear studies, including chaos theory and complexity theory, both as pure and applied science, is evolving and has almost as many viewpoints as practitioners. Therefore, anyone proposing, at this date, to interpret the meaning of nonlinearity for national security and military strategy and operations must by necessity assume the provisional nature of those efforts, running the risk of being found to be erroneous. I accept these assumptions and have written this work fully conscious of them; being on the one hand, as careful as the limits of my knowledge allow, and on the other,

not allowing them to overly constrain me in the paths where my thoughts on nonlinearity led me. As a teacher, my first obligation is not to pristine precision, but to the sweaty intellectual inconvenience of finding a way to get the point across to students without unduly mangling the matter. That is always a judgment call. The result is mine alone, and I am responsible for errors in both fact and interpretation.

Introduction

This book is about the implications of the new nonlinear sciences for national security and military affairs. Uncertainty is with us, and *chaos* theory rooted in physics and chemistry tells us why it is inevitable, pervasive, and won't go away. Fortunately, there is the "companion" new science of *complexity*, rooted in biology, which provides insights into what we can do about that.

I have adopted the term *nonlinearity* as a convenient umbrella for all of the various terminology and concepts which have proliferated in the field—deterministic chaos, fractals, self-organizing systems far from thermodynamic equilibrium, complexity and complex adaptive systems, self-organizing criticality, cellular automata, solitons, and so on—because they all globally share this property.

Nonlinearity reflects the *science* of the Information Age, rather than its *technology*. Currently, the awareness level about that science is low in comparison to the omnipresent technology. This book is intended to help correct this dangerous imbalance. In fact, the Information Age and its technology are largely considered to be synonymous in both the public and the military mind. The Revolution in Military Affairs debate to date has largely been shaped by that technology, including the pervasive rush of chip advances, computer utilities, and an

increasingly Internetted world. The science is in its infancy, and is more about biology than about physics. It is some 20 years old, and required the computer to be invented before it could itself be discovered. This science has its own jargon: phase states, bifurcations, strange attractors, emergence, criticality and path-dependence, to name a few. However, its message is post-Newtonian.

By “Newtonian,” we mean the arrangement of nature–life and its complications–to be a linear phenomenon. Inputs in a linear phenomenon are proportional to outputs, facilitating prediction by careful planning; success is by detailed monitoring and control; and a premium is placed upon linear reductionism, rewarding those who excel in such reductionist processes. Linear reductionist analysis consists of taking large, complex problems and reducing them to manageable chunks. This form of reductionism works in environments that are effectively linear, where the test of wills, the conflict of interests, and the collision of agendas are largely absent.

By “post-Newtonian,” we mean the arrangement of nature–life and its complications, such as warfare–to be nonlinear, where inputs and outputs are not proportional; where phenomena are *unpredictable, but within bounds are self-organizing*, where unpredictability frustrates conventional planning; where solution as self-organization defeats control as we think of it; and where a premium is placed on nonlinear reductionism. And where rewards go to those who excel in *coping with the bounds* in order to command and manage–not in prediction and control.

I have become convinced that nonlinearity does not pose a revolutionary challenge in the sense of being a trumpet of the “new,” or yet another siren song for novelty. Instead, it for the

most part privileges, reinforces, and gives the edge to certain practices over others forged in the school of hard knocks and trial and error. Humankind has been around a long time and is very resourceful. The effect of conscious nonlinearity will largely be to go back over alternatives and choices with a different lens and say, "Hey, you overlooked this," or "That one is better," or "Yes, you were right all along." The nonlinearist job is not so much to invent, but to reaffirm, review, and improve. The human being is smart, and has through history tried lots of things. With our new knowledge, we can make good those efforts where they fit, by recognizing them and promoting them. It may be that the strength and staying power of nonlinearity will turn out to be that, like Clausewitz's *On War*, it operates in a deeply historical, organic context, as opposed to "cutting-edge" faddism.

In fact, Clausewitz is the emblem of nonlinearity in military affairs. It is said that Clausewitz is more often quoted than read. The reason is simply that he is hard to read linearly. We only learned this in 1992, with the publication of "Clausewitz, Nonlinearity and the Unpredictability of War," by Alan Beyerchen. The message is both profound and fundamental. This paper is so important that it is reproduced in its entirety in the Appendix. It forms the basis for the *neo-Clausewitzian view*: the synthesis of nonlinear science and Clausewitz's words to form a powerful and contemporary message. The rest of this book can be regarded as a supplement.

Part One

Linearity + Nonlinearity

This section introduces nonlinearity. It contains the theoretical material underlying the rest of the text, and introduces the idea of nonlinear reductionist techniques.

Chapter 1

Nonlinearity: An Introduction

The chess-board is the world; the pieces are the phenomena of the universe; the rules of the game are what we call the Law of Nature.

- T. H. Huxley

In this chapter, we will cover the bare essentials to get us started. There are a lot of aspects of the nonlinear sciences that we will not cover, such as fractals, solitons, cellular automata, and a host of other subjects. Not because they are uninteresting or unimportant, but because we can get *there* without them. On the other hand, in the notes are some good sources to read to learn more.¹ Our approach will be to briefly contrast linearity and nonlinearity, and then concentrate on the characteristics of *complex adaptive systems*, which is key to grasping the rest of the material.

Linearity

We are essentially linear creatures. Whether this is the native mode of humanity or whether it is primarily the result of acculturation is open to question. It can be observed that non-linearity is more prevalent in contemporary non-Western cultures, and indeed in Western culture itself, prior to the modern era. However, it is unarguable that our society fosters and rewards linear behavior and performance from kindergarten on. Our educational system teaches it and grades on it, our workplaces hire, fire, and promote on it, our governmental and social programs are designed and executed on it, and it drives national security policy, military strategy, and operations. Often associated with the name of Sir Isaac Newton, Newtonian, or linear, science became a powerful philosophy to both describe and ultimately control nature, which has proved to be largely illusory.

But what is it? The features of linearity include *proportionality*, *additivity*, *replication*, and *demonstrability of causes and effects*. With *proportionality*, small inputs lead to small outputs, greater inputs to larger consequences in an environment where these causes and effects are demonstrably and effectively measurable. Like the linear mathematical equation, only one valid answer is possible, permitted, or expected.

Further, the linear principle of *additivity* provides that the whole is equal to the sum of its parts. This promotes and legitimizes *reductionism*, the practice of taking a complicated and large problem and breaking it into more manageable pieces, analyzing the constituent parts, and arriving at a conclusion. The assumption, of course, is that the cumulative analytic product represents a valid derivative of the original whole, faithful and complete. *Replication* means that the same action or

experiment under the same conditions will come out the same way; that results are repeatable, and therefore, independently verifiable. Finally, *cause and effect are demonstrable*. This can happen in a number of ways: observed, inferred, extrapolated, statistically validated, and so on. Therefore, the nature of linear systems is that if you know a little about their behavior, you know a lot. You can extrapolate, change scales, and make projections with confidence. Unlike nonlinearity, in which $2+2$ may yield oranges, in linearity you can rely on the 4.

Two historical factors have reinforced a linear mindset within the U.S. military establishment. The first is the result of the Cold War, in which we lived and struggled for 40 years in a bipolar world, dominated by the USSR and the United States. Two-body problems lie generally in the linear to mildly nonlinear range. In other words, the Cold War marked by the interactions of two world powers habituated participants to an essentially linear environment. The second factor is America's historical industrial and technological prowess, which has favored a military strategy of attrition through the use of overwhelming force wherever it could be brought to bear. Overwhelming force can, in effect, significantly linearize conflict. If the odds are big enough, the inherently nonlinear characteristics of warfare don't count as much.

Nonlinearity

Nonlinearity, which covers such concepts as chaos theory and complexity theory, does not conform to those qualities found in linearity. It is not proportional, additive, or replicable, and the demonstrability of causes and effects are ambiguous. Inputs and outputs are not proportional. The whole is not quantitatively equal to its parts, or even qualitatively recogniz-

able in its constituent components. Results cannot be assumed to be repeatable; the same experiment may not come out exactly the same way twice. A contributing cause to this condition is the phenomenon of nonlinear dynamics, whereby outcomes are arbitrarily sensitive to tiny changes in initial conditions.

As a result, if you know a little about a nonlinear system, you don't know a lot. We cannot extrapolate, change scale, or project. The lack of predictability frustrates planning and control, as we use the terms. Yet, the vastness of the nonlinear world dwarfs the linear. So we must learn to deal with it. Alan Beyerchen, of Ohio State University, addresses this need in practical national security terms.

Why harp on nonlinearity? Why does it matter? One reason for emphasizing nonlinearity is that it constitutes the well-established mathematical property underlying and making coherent all the faddish-sounding new sciences: deterministic chaos, fractals, self-organizing systems far from thermodynamic equilibrium, complexity and complex adaptive systems, self-organizing criticality, cellular automata, solitons, and so forth. It was in various ways sensed by the ancient Greeks. . . . Yet no one before the late twentieth century could solve the interesting problems posed by nonlinear equations. There are no analytical techniques that work well, and numerical methods were just too cumbersome and time-consuming. Most scientists just bracketed out the nonlinear elements of their equations and went with the idealized linear approximation. Now computers allow us to go after many formerly intractable problems using the computer to pursue numerical solutions.

The connotations of linearity still drive a great deal of our thinking, especially in mechanics and the many social scientific disciplines that implicitly try to copy the success of mechanics. Linearity offers structural stability and emphasis on equilibria. It legitimates simple extrapolations of known developments, scaling and compartmentalization. It promises prediction and thus control—very powerful attractions indeed. But linear systems are often restrictive, narrow, and brittle. They are seldom very adaptive under significant changes in their environment. Bureaucracy is the quintessential linearization technique in social affairs.

The connotations of nonlinearity are a mix of threat and opportunity. Nonlinearity can generate instabilities, discontinuities, synergisms, and unpredictability. But it also places a premium on flexibility, adaptability, dynamic change, innovation, and responsiveness. . . .

What is the utility of thinking about war—for our potential opponents and ourselves—in nonlinear terms, especially in the high-tech, research-forefront metaphorical terms from the new sciences? For our opponents the usefulness may be the same as it was for Clausewitz. The Germans were underdogs to the French, and Clausewitz wanted to understand and use against the French their blindspots. He also needed to be the champion of disproportionate effects and unpredictability, for in a linear, predictable world Prussian resistance to Napoleon after 1807 was futile. The opponents of the United States will be looking for our blindspots in an effort to seize opportunities to surprise and shock us. They may also be able to compensate for their disadvantage in a military confrontation such as the Gulf War by consciously striving to affect the political context in order to change the conduct of warfare. An understanding of the porousness of the boundaries

between politics and war can be a real weapon against those who envision those boundaries to be impermeable.

We need for our own sake to understand the limitations our imagination places upon us. Linearity is excellent for the systems we design to behave predictably, but offers a narrow window on most natural and social systems. That narrowness sets blinders on our perception of reality and offers a weakness for an opponent to exploit. But if we know our limits, we can minimize the extent and duration of our surprise, reducing its value. And an expanded sense of the complexity of reality can help us to be more successfully adaptive amid changing circumstances. By thinking more constructively about nonlinearity, we might be able to design more robust systems when we need them. A new form of modeling that takes such concepts as self-organization to heart allows structures to bubble up from below rather than be imposed from above. With such tools we might come to understand better the biological and historical processes with which we must deal. And we may come to realize how conventional, analytical predictive techniques can themselves stimulate a self-defeating, unfulfillable desire to control more of the real world around us than is truly possible.²

Complex Adaptive Systems (*cas*)

Fundamental to an understanding of nonlinearity is an understanding of complex adaptive systems, or *cas*, which are the “engines” that drive nonlinearity.

Complex adaptive systems are quite different from most systems that have been studied scientifically. They exhibit coherence under change, via conditional action and anticipation, and they do so without central direction. At the

same time, it would appear that *cas* have lever points, wherein small amounts of input produce large, directed changes. It should be easier to discover these lever points if we can uncover general principles that govern *cas* dynamics. Knowing more about lever points would, in turn, provide us with guidelines for effective approaches to *cas*-based problems, such as immune diseases, inner-city decay, industrial innovation, and the like. . . . We are only at the beginning of the search for general principles, but we do have some hints as to what those principles might be.³

Complex adaptive systems, or *cas*, contain seven basic attributes. These consist of four properties (aggregation, non-linearity, flows, and diversity), and three mechanisms (tagging, internal models, and building blocks.)

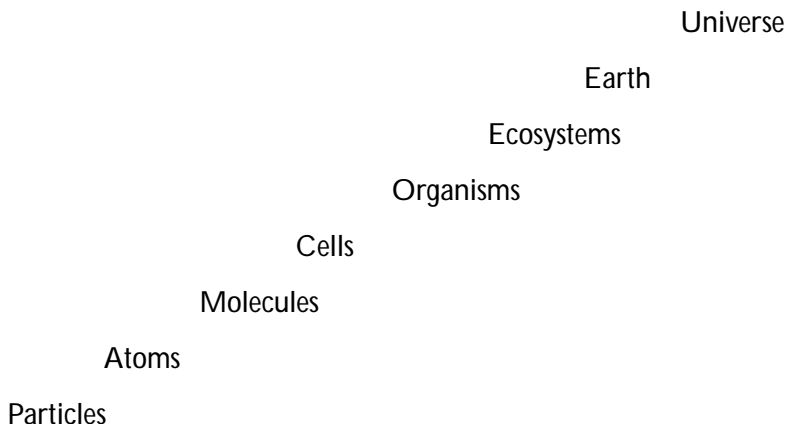
Aggregation

The first property of *cas* is *aggregation*, which “concerns the emergence of complex large-scale behaviors from the aggregate interactions of less complex agents. . . .” Aggregates so formed can in turn act as agents at a higher level—meta-agents. Holland cites examples:

Gross National Product (GNP) as an emergent aggregate property of the aggregate of the economy consisting of firms; individual identity from the immune system composed of anti-bodies, and behavior from the nervous system comprised of neurons.⁴

Emergent behavior, that is, activities that could not be predicted from the system’s parts, is a feature of non-additivity—that the sum of the parts of *cas* is not equal to the whole.

Another way to view emergence is provided by the following hierarchy:



Note that the structure is hierarchical, but not in the bureaucratic sense. For all of the talk one hears today about the demise of “tyrannical” hierarchies and the rise of “networked” organizations such as the Internet, nature doesn’t work that way.

A good example of emergent behavior is also demonstrated by a popular simulation known as “boids,” in which a few simple rules result in quite complex behaviors akin to the flocking of birds or the schooling of fish. A good Internet site for “boids” is Professor Brakke’s Web site at Susquehanna University.

Tagging

The first mechanism of *cas* is *tagging*, which

consistently facilitates the formation of aggregates. . . . The most familiar example is a banner or flag that is used to rally members of an army or people of similar political persuasion. A more operational version of a tag in these days of the Internet is the header on a message that knits

together members of a bulletin board or conference group. . . *cas* use tags to manipulate symmetries. . . The classic example of a full-blown symmetry is a perfect sphere, say the white cue ball in billiards. [C]onsider a set of cue balls in rapid motion on a billiard table. . . after a strong 'break.' We cannot distinguish the individual cue balls unless we keep a careful record of their trajectories. But again, we can break the symmetry with a tag. If we put a striped cue ball in with the other cue balls, we can easily track it despite its motion. . . .

[Tags] allow agents to select among agents or objects that would otherwise be indistinguishable [and] provide a sound basis for filtering, specialization, and cooperation. This, in turn, leads to the emergence of meta-agents and organizations that persist even though their components are continually changing. Ultimately tags are the mechanism behind hierarchical organization—the agent/meta-agent/meta-meta-agent/. . . organization so common in *cas*.⁵

Nonlinearity

The second property of *cas* is *nonlinearity*. It is not unusual to have a word stand for two meanings when it has both macro and micro relevance, depicting both a global and interior condition: for example, "man" as a species and "man" as an individual. This is the case here, in which nonlinearity stands for a field as a whole as well as a specific property of *cas*.

It is little known outside of the world of mathematics that most of our mathematical tools, from simple arithmetic through differential calculus to algebraic topology, rely on the assumption of linearity. Roughly, linearity means that we can get a value for the whole by adding up the values of

its parts. . . . Whole branches of mathematics are devoted to finding linear functions that are reasonable approximations when linearity cannot be directly established. Unfortunately, none of this works well for *cas*. To attempt to study *cas* with these techniques is much like trying to play chess by collecting statistics on the way pieces move in the game.⁶

One of the most valuable databases known contains the meticulous records kept by the Hudson Bay fur company, which goes back over 150 years. These have been studied in great detail, and a model has been developed that can account for the year-to-year fluctuations in the number of fur pelts acquired. This model deals with the interactions of predator-prey populations, and in this instance, the predator is the lynx and the prey is the hare. It is also one of the simplest illustrations of nonlinearity. The model consists of three factors: (1) a constant which indicates how efficient the predator is based on how much of its territory it searches each day, (2) the number of predators in a given area, and (3) the number of prey in the same area. Let's say that the efficiency of lynx is 50 percent. A wolf pack's might be different. So if there are 2 lynx per square mile and 10 rabbits, you multiply the three terms, or 50 percent $\times 2 \times 10 = 10$ encounters. If you double the number of lynx and hares, you get 50 percent $\times 4 \times 20 = 40$ encounters. So doubling the number of agents in the system results in quadrupling the number of interactions.

This nonlinearity occurs

because it entails the *product* of two distinct variables instead of their *sum*. That is, the overall predator-prey interaction cannot be obtained merely by adding predator activity to prey activity. . . even in the simplest situations nonlinearities can interfere with the linear approach to

aggregates. That point holds in general: nonlinear interactions almost always make the behavior of the aggregate more complicated than would be predicted by summing or averaging.⁷

Flows

The third property of *cas* is the idea of flows, and they also form the basis for centers of gravity. Pat A. Pentland, a pilot with over 2,400 hours in the A-10, has developed an approach to centers of gravity based upon the principles of nonlinear dynamics, as well as a large dose of ideas from anthropology. His formulation uncannily follows exactly the concept of flows in complex adaptive systems presented here. See *Center of Gravity Analysis and Chaos Theory* in the Appendix.

You can

[t]hink of flows over a network of nodes and connectors. The nodes may be factories, and the connectors transport routes for the flow of goods between the factories. Similar [node, connector, resource] triads exist for other *cas*: [nerve cells, nerve cell interconnections, pulses]; [species, foodweb interactions, biochemicals] for ecosystems; [computer stations, cables, messages] for the electronic Internet; and so on. . . In general terms, the nodes are processors—agents—and the connectors designate the possible interactions. In *cas* the flows through these networks vary over time; moreover, nodes and connections can appear and disappear as the agents adapt or fail to adapt. Thus, neither the flows nor the networks are fixed in time. They are patterns that reflect changing adaptations as time elapses and experience accumulates.⁸

There are two attributes of flows that confound linear analysis. One is the *multiplier effect*, which is a major feature of networks and flows, whether money, information, or goods. To illustrate, community economic development specialists estimate, as a rule of thumb, that for every \$75,000 a business generates in gross receipts, one direct job is created. In addition, however, another indirect job is also created. The latter is the multiplier effect. But that job has no association with the creating business; it is a disembodied derivative—a connector or interaction-based ingredient. Actually, the rule of thumb does not work well at the level of the individual firm, or even industry. The jobs show up in counts at the macro-level, the county or state level, but no more precise cause-and-effect relationships can be established because they are hidden in the interactions. Once again, the whole is not equal to the sum of the parts.

The other attribute of flows that confounds linear input/output is the effect of recycling, whereby the “aggregate behavior of a diverse array of agents is much more than the sum of the individual agents,”⁹ and is thus a source of nonlinearity. This recycling, however, is also “hidden” within the interactions of the system(s). Once again, as with the multiplier effect, the micro-effects are masked, but evident at macro-levels.

The role of tags is that they

almost always define the network by delimiting the critical interactions, the major connections. Tags acquire this role because the adaptive processes that modify *cas* select *for* tags that mediate useful interactions and *against* tags that cause malfunctions. That is, agents with useful tags spread, while agents with malfunctioning tags cease to exist.¹⁰

It would be fair to say that tags indicating multiplier effects and recycling behavior would tend to favor agents carrying them.

Diversity

The fourth property of *cas* is the diversity of agents within the system(s). The agents within *cas* comprise a diverse community marked by perpetual novelty. You might think that *cas*, for the sake of economy and efficiency, would favor the evolution of a few kinds of “general purpose” agents that are highly adapted, or optimized, to take advantage of a large range of opportunities. But *cas* does not do that because the inevitable stagnation of equilibrium would result. Instead, in a process that is neither accidental nor random, *cas* seems to consist of hierarchies of “slots,” occupied by agents. When an agent is removed from the system by losing its stability with the environment, which includes other agents, it leaves a hole. This is filled in a cascade effect by another agent similar to the former inhabitant, but different enough to achieve the stability to occupy the slot. Other things being equal, the agents with recycling capability to conserve resources, or possessing a multiplier effect, are favored.

This seems to argue, at the micro-nonlinear level of human affairs, for a population of agents that are, within bounds, mildly heterogeneous yet sufficiently differentiated, competitive enough to produce multiplier effects, and cooperative enough to recycle resources. Students are quick to point out that the unique characteristics of the people of America and its turbulent culture have historically fostered these qualities. In fact, America’s success may be, in no small measure, due to the fact that Americans make for a pretty darn good natural

cas. However, it is more than likely that recent movements which define “diversity” in terms of political correctness, for example, actually decrease that essential diversity so essential for *cas*. If the factor is significant, we will either bear the consequences or have to make some hard choices.

Internal Models

A second mechanism of *cas* are internal models that give them the power to anticipate.

[T]he agent must select patterns in the torrent of input it receives and then must convert those patterns into changes in its internal structure. Finally, the changes in structure, the model, must enable the agent to anticipate the consequences that follow when that pattern (or one like it) is again encountered. How does an agent distill experience into an internal model? How does an agent unfold the model’s temporal consequences to anticipate future events?

To make a start on these questions, let’s take a closer look at models as predictors. We usually ascribe prediction only to “higher” mammals, rather than taking it as a property of all organisms. Still, a bacterium moves in the direction of a chemical gradient implicitly predicting that food lies in that direction. The mimic survives because it implicitly forecasts that a certain pattern discourages predators. When we get to the so-called higher mammals, the models do depend more directly on the agent’s sensory experience. A wolf bases its movements on anticipations generated by a mental map that incorporates landmarks and scents. Early humans built Stonehenge as an explicit, external model that helped predict the equinoxes. Now we use computer simulations to make predictions ranging

from the flight characteristics of untried aircraft to the future gross domestic product. In all these cases prediction is involved, and in the last two cases external models augment internal models.

Taking these models into account we will find it useful to distinguish two kinds of internal models, *tacit* and *overt*. A tacit internal model simply prescribes a current action, under an *implicit* prediction of some desired future state, as in the case of bacterium. [*BOIDS is also a good example of a tacit or low-level model.*] An overt internal model is used as a basis for explicit, but internal, explorations of alternatives, a process often called *lookahead*. The quintessential example of lookahead is the mental exploration of possible move sequences in chess prior to moving a piece. Both tacit and overt models are found in *cas* of all kinds—the actions and identity supplied by an immune system fall at the tacit end of the scale, whereas the internal models of agents in the economy are both tacit and overt. . . .¹¹

Building Blocks

The third mechanism of *cas* are building blocks, which you will see again in Chapter 10 where we will cover pattern recognition.

In realistic situations an internal model must be based on limited samples of a perpetually novel environment. Yet the model can only be useful if there is some kind of repetition of the situations modeled. How can we resolve this paradox?

We get the beginnings of an answer when we look to a common-place human ability, the ability to decompose a complex scene into parts. When we do this, the component parts are far from arbitrary. They can be used and

reused in a great variety of combinations like a child's set of building blocks. Indeed, it is evident that we parse a complex scene by searching for elements already tested for reusability by natural selection and learning. . . .

Wherever we turn, building blocks serve to impose regularity on a complex world. We need only look at the use of musical notation to transmit the endless variety of music, or the use of a limited range of morphologies to describe the tremendous spectrum of animal structures. The point applies with at least as much force to our everyday encounters. If I encounter a "flat tire while driving a red Saab on the expressway," I immediately come up with a set of plausible actions even though I have never encountered this situation before. I cannot have a prepared list of rules for all possible situations, for the same reason that the immune system cannot keep a list of all possible invaders. So I decompose the situation, evoking rules that deal with "expressways," "cars," "tires," and so on, from my repertoire of everyday building blocks. By now each of these building blocks has been practiced and refined in dozens or hundreds of situations. When a new situation is encountered, I combine relevant, tested building blocks to model the situation in a way that suggests appropriate actions and consequences. . . .¹²

Putting It All Together

In a fascinating reprise, Holland uses the seven basics we have just covered to describe New York City as a complex adaptive system:

Agents formed by *aggregation* are a central feature, typified by firms that range from Citibank and the New York Stock Exchange to the corner deli and the yellow cab. These

agents determine virtually every fiscal transaction, so that at one level of abstraction the complex adaptive system that is New York City is well described by the evolving interactions of these agents. We have only to look to advertising, trademarks, and company logos to see how *tags* facilitate and direct these transactions. The *diversity* of these tags underscores the variety in the city's firms and activities, and the complex *flow* of goods into, out of, and through the city that results. That New York retains both a short-term and a long-term coherence, despite diversity, change, and lack of central direction, is typical of the enigmas posed by *cas*. As is usual, nonlinearities lie near the center of the enigma. New York's nonlinearities are particularly embedded in the *internal models*—models internal to the firms—that drive transactions. These models range from spreadsheets to sophisticated corporate plans. There are also continual innovations, such as the steady flux of financial instruments on Wall Street (“Derivatives,” the current innovation, have absorbed even more money than their predecessors, “junk bonds”). Trend projection and other linear analyses provide few insights into these activities. New perceptions will surface, I suspect, if we can uncover the building blocks that are combined and recombined to determine the city's outward appearance. The building blocks for this enterprise are less obvious than for some other *cas*, though contracts, organization charts, permissions, pieces of city infrastructure, and taxes are all obvious candidates.¹³

[J. Holland, *Hidden Order*, pages 13-40. ©Copyright John H. Holland. Reprinted by permission of Addison Wesley Longman, Inc.]

In common with other fields, more progress has been made in working with nonlinearity than in defining and measuring it. The problem has been compared to that

confronting early 19th-century scientists as they tried to get a grip on a mysterious concept called energy. Today, people take energy so much for granted that it is hard to appreciate how abstract the concept really is. 'Many people had a pretty good idea what energy did and how it behaved. . . . But energy was not really understood. . . until people came up with a precise definition. The result was the laws of thermodynamics.'

This search for definition and measurement is covered in *Researchers on Complexity Ponder What It's All About* by George Johnson¹⁴ in the Appendix. The article ends on the following note:

An idea that runs throughout this kind of research is that complexity lies somewhere between order and disorder, predictability and surprise. "Nobody disputes that there are some characteristics of systems that make them more complicated," said Dr. Erica Jen, vice president for academic affairs at the Santa Fe Institute. "And those characteristics are neither highly ordered nor completely random. A string of numbers with all the same digits is very uninteresting, but a number like pi that has all this structure in it is very interesting." . . . As Dr. Lloyd continues to hammer away at a definition, he likes to ask his colleagues what they mean by complexity. After puzzling over the matter, they usually answer with something like this: "I can't define it for you, but I know it when I see it." "That," he said, "remains the tried and true definition."

It is obvious from the above that the field of complexity permits, even invites, speculation. In this book I admit there is some of that. Certain concepts such as macro-versus-micro-nonlinearity, unpunctuated equilibrium, the complexity shuttle, and the edge of equilibrium are constructions. But

then, I too know complexity when I see it. We are dealing with the messy process by which science assumes human dimensions and relevancy. Science applied to technology yields engineering; the application of science to human affairs produces philosophy.

The world of nonlinearity has been discovered; there is no turning back or ignoring the fact. Further, it has been found to be fundamental to national security processes and warfare. While John Holland, Seth Lloyd, and other scientists search for general principles, we must make do with what we have and work with it. That is the object of this work.

Notes

- 1 The following books have achieved the status of “standards” for introductions to the field.
 Waldrop, M. Mitchell. *Complexity: The Emerging Science at the Edge of Order and Chaos*. New York: Simon and Schuster. 1992. It is an entertaining as well as intelligible work that is very popular with students. It tells the story of complexity theory through the personalities of the scholars associated with the Santa Fe Institute, and the struggle to establish that “think tank.”
 Gleick, James. *Chaos: Making a New Science*. New York: Viking. 1987. Gleick’s book is notable for being the first popular account of nonlinear science to become a best-seller with the general reading public. In addition, three articles are recommended:
 Crutchfield, James P., J. Dooyne Farmer, Norman H. Packard, and Robert S. Shaw. “Chaos.” *Scientific American*. December 1986. pp. 46-57.
 Ruthen, Russell. “Adapting to Complexity.” *Scientific American*. January 1993. pp. 130-40.
 Bak, Per and Kan Chen. “Self-Organized Criticality.” *Scientific American*. January 1991. pp. 46-53.
- 2 Beyerchen, Alan D. “Clausewitz, Nonlinearity and the Importance of Imagery.” in Alberts, David and Thomas J. Czerwinski, eds., *Complexity, Global Politics and National Security*. Washington, DC: National Defense University. May 1997. pp. 161-62 and 167-68.

- 3 Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. Reading, MA: Addison-Wesley Publishing Company, Inc. 1995. p. 23.
- 4 Holland: pp. 38-41.
- 5 Holland: pp. 13-15.
- 6 Holland: pp. 15-16.
- 7 Holland: p. 23.
- 8 Holland: p. 23.
- 9 Holland: p. 26.
- 10 Holland: p. 23.
- 11 Holland: pp. 31-33.
- 12 Holland: p. 37.
- 13 Holland: pp. 41-42.
- 14 Johnson, George. "Researchers on Complexity Ponder What It's All About." *New York Times*, May 6, 1997. p. C1.

Chapter 2

The Nature of Linear Reductionism

We live in a world orderly enough that it pays to measure.

- Paul Johnson, *Fire in the Mind*

Linearity (which has been linked for the last 200 years with the great Sir Isaac Newton, and dubbed Newtonianism) has always rubbed up against the nonlinear world. This is inevitable since nonlinearity has always been present, has always been representative of most of our world, and is growing. This has not always been recognized. A survey of physics textbooks showed that only 2 of the 19 published between 1910 and 1949 "treated nonlinear oscillations; one of these stated that nonlinear behavior occurs 'only occasionally,' and the other called it an 'important' topic but said 'we shall not go into it in any detail.'"¹

When linearity meets nonlinearity, it has established its domain by either imposing linear surrogates or excuses. In the former case, the linear has invented the calculus, statistical techniques, and elements of operations research and systems theory. These methods work in mildly nonlinear environ-

ments. While differential equations are essentially linear and reductionist (small changes produce small effects and large effects are obtained by summing up many small changes), this approach has, nevertheless, served well. "Phenomena as diverse as the flight of a cannonball, the growth of a plant, the burning of coal, and the performance of a machine can be described by such equations."²

But linearity's real power has been its ability to produce technology, from the wheel and steam engine to the silicon chip and the unraveling of the DNA string. Remember Alan Bey-erchen's point that "linearity is excellent for the systems we design to behave predictably." Technological improvements are primarily linear, or mildly nonlinear. In the latter case, linear techniques developed to deal with mild forms of nonlinearity, such as differential equations, work well. It should be noted, however, that software development, which is often an intrinsic part of today's technology, is potentially subject to the full range of nonlinear behaviors. But, technological success often leaves behind a conundrum of migraine proportions. As this is being written, Congress is holding hearings on cloning, a sheep having recently been duplicated in Great Britain using thoroughly linear reductionist techniques.

On every other front, however, linearity alone has not come close to meeting with the success it has enjoyed in technological innovation. The fact is that sheep don't fight back, and the silicon chip does not have its own agenda. In technology, one is faced by formidable challenges. But it is not a test of wills or opposing forces, which is precisely the environment that gives rise to nonlinear behaviors. Linear reductionism, faced with a significant degree of nonlinearity in the environment, gives way to "rounding," Peter's Principle, "good

enough for government work," Murphy's Law, or looking good, if meaning nothing.

The result of unintended results, which is the manifestation of applying linear approaches to nonlinear problems, lies all about us in painful and embarrassing profusion. The 1960s with all its other calamities can be viewed as the height of arrogant confidence in the power of the linear paradigm, which was undoubtedly a contributing cause of its travails. Linearity was expected to win both the Vietnam war and the War on Poverty, simultaneously, and failed in both.

Systems as Agents and Interactions

The major inadequacy of linear reductionism is its inability to deal with interactions. It inherently focuses on agents or objects in the process of taking a complicated and large problem and breaking it up into manageable pieces. It does not account for the fact that in any system, the number of ways for pairs of agents to interact is almost, but not quite, equal to half the square of the total number of agents in the system. As a result, as the number of agents grows, the number of possible interactions increases even faster, as follows: 10 agents can generate up to 45 interactions; 100 up to 4,950; 1000 up to 499,500; 10,000 up to 49,995,000; and 100,000 agents can generate up to 4,999,950,000! The interactions are not usually significant if there are only two agents. When there are three, interactions can become a factor. And from four on up, interactions increasingly become the things that count.

In fact, the emergent quality of nonlinearity is attributed to the interactions between the agents within a system, and not the agents themselves. Graham T. Allison, back in

1971, described this proposition with little, if any, knowledge of nonlinearity.

[T]he Governmental (or Bureaucratic) Politics Model sees no unitary actor but rather many actors as players—players who focus not on a single strategic issue but on many diverse international problems as well; players who act in terms of no consistent set of strategic objectives but rather according to various conceptions of national, organizational, and personal goals; players who make government decisions not by a single, rational choice but by the pulling and hauling that is politics.³

Steven Rinaldi, a physicist and Air Force officer who is often cited in this book, perceptively adds,

According to this model, the global emergent properties (*the strategic decisions*) of the government come about not because of the personal, organizational, and national goals of the agents (*players*), but rather because of the interactions (*political maneuvering*) between the agents within the governmental hierarchy. And a prior knowledge of the agents does not suffice in comprehending the emergent decisions of a government.⁴

Growth of Nonlinearity

Obviously, the more that interactions count, which is a function of the number of agents/objects, the less linear reductionism does. And the number of agents/objects are globally increasing over time because there is an absolute growth in nonlinearity. Below are three views of this growth:

W. Brian Arthur, member of the Santa Fe Institute (the leading Complexity theory “think tank”) and prominent nonlinear economist, believes that,

there is a general law: complexity tends to increase as functions and modifications are added to a system to break through limitations, handle exceptional circumstances or adapt to a world itself more complex. This applies, if you think about it, not just to technologies and biological organisms but also to legal systems, tax codes, scientific theories, even successive releases of software programs. Where forces exist to weed out useless functions, increased complexity delivers a smooth, efficient machine. Where they do not, it merely encumbers.⁵

Murray Gell-Mann, Nobel Laureate, says that,

As the universe grows older and frozen accidents pile up [*i.e., the net increase in saved bifurcations over historical time*], the opportunities for effective complexity to increase keep accumulating as well. Hence there is a tendency for the envelope of complexity to expand, even though any given entity may either increase or decrease its complexity during a given time period.⁶

LTG Erwin Rokke, USAF (Ret.), former president of the National Defense University, sees a technological basis for the increase in nonlinearity. Speed and feedback loops are attributes of nonlinearity. Hence, new information technologies such as the Internet, e-mail, and CNN increase the nonlinearity of both information exchanges and the events and processes they cover.

Increasing the overall level of complexity does not change the size of the complexity region. But it does increase the population of the agents/objects within it, and, therefore, disproport-

tionately, the potential number of interactions. One result is to make predictability even more difficult. Another, effect however, is that

diversity and sheer complexity have also made the economy more rugged, distributing shocks across a greater number of smaller businesses and an ever-denser web of commercial relationships. 'Rather than multiply a decline [economic recessions], these wider networks are far more likely to cushion that decline. . . .'⁷

In fact, this increase in complexity may help to account for the amazing (1992-199?) "bull" stock market. The effect is, of course, not limited to the economy, but extends to networks of all kinds and to social interactions.

The Dilemma

Yet,

We can't study most individual interactions because they are either too small, or we can't separate them from all the other interactions. . . . This is one of the main reasons why we don't have effective explanations in ecology, epidemiology, or economics. The new area of complexity theory pays a lot of attention to just these areas, searching for a better approach. Despite intense study of AIDS, we cannot confidently predict the number of people who will be infected in twenty years' time. Nobody knows how to predict stock-market crashes. There are no big areas of reductionist causality in social science or management studies. When we find an explanation that seems convincing, it always turns out that for every expert there is an equal and opposite expert who can convince us of the

reverse story. Nobel prizes have been awarded to economists whose theories flatly contradict each other.⁸

Therefore, it is usual that imposing linear expectations on the agents within a nonlinear system will backfire in the form of unintended consequences caused by those slippery interactions.

Interactions in International Relations

The never-ending consequences of these interactions led Robert Jervis to explore the nature of these unintended results in diplomacy and security policy in his *Complex Systems: The Role of Interactions*,⁹ which is found in the Appendix. Jervis, who is an Adlai E. Stevenson professor of international affairs at Columbia University, writes:

We can never do merely one thing. Wishing to kill insects, we may put an end to the singing of birds. Wishing to 'get there' faster we insult our lungs with smog. Seeking to protect the environment by developing non-polluting sources of electric power, we build windmills that kill hawks and eagles that fly into the blades; cleaning the water in our harbors allows the growth of mollusks and crustaceans that destroy wooden piers and bulkheads; adding redundant safety equipment make some accidents less likely, but increases the chances of others due to the operators' greater confidence and the interaction effects among the devices; placing a spy in the adversary's camp not only gains valuable information, but leaves the actor vulnerable to deception if the spy is discovered; eliminating rinderpest in East Africa paved the way for canine distemper in lions because it permitted the accumulation of cattle, which required dogs to herd them, dogs which provided a steady source for the virus that could spread to lions; releasing

fewer fine particles and chemicals into the atmosphere decreases pollution but also is likely to accelerate global warming; pesticides often destroy the crops that they are designed to save by killing the pests' predators; removing older and dead trees from forests leads to insect epidemics and an altered pattern of regrowth; allowing the sale of an anti-baldness medicine without a prescription may be dangerous because people no longer have to see a doctor, who in some cases would have determined that the loss of hair was a symptom of a more serious problem; flying small formations of planes over Hiroshima to practice dropping the atomic bomb accustomed the population to air raid warnings that turned out to be false alarms, thereby reducing the number of people who took cover on August 6.

Additionally, Jervis further identifies these interactions as one of three unique types that lead to unintended consequences, and relate directly to our understanding of the nature of complexity and national security:

Interactions in which the Results cannot be Predicted from the Separate Actions

The effect of one variable frequently depends on the state of another, as we often see in everyday life: each of two chemicals alone may be harmless but exposure to both could be fatal; patients have suffered from taking combinations of medicines that individually are helpful. So research tries to test for interaction effects and much of modern social science is built on the understanding that social and political outcomes are not simple aggregations of the actors' preferences because very different results are possible depending on how choices are structured and how actors move strategically.

Interactions in which Strategies Depend on the Strategies of Others

Further complexities are introduced when we look at the interactions that occur between strategies when actors consciously react to others and anticipate what they think others will do. Obvious examples are provided by many diplomatic and military surprises: a state believes that the obstacles to a course of action are so great that the adversary could not undertake it; the state therefore does little to block or prepare for that action; the adversary therefore works especially hard to see if he can make it succeed. As an 18th century general explained, "In war it is precisely the things which are thought impossible which most often succeed, when they are well conducted." In the war in Vietnam, the U.S. Air Force missed this dynamic and stopped patrolling sections of the North's supply lines when reconnaissance revealed that the number of targets had greatly diminished: after the attacks ceased the enemy resumed use of the route.

Interactions in which Behavior Changes the Environment

Initial behaviors and outcomes often influence later ones, producing powerful dynamics that explain change over time and that cannot be captured by labeling one set of elements "causes" and another "effects." Although learning and thinking play a large role in political and social life, they are not necessary for this kind of temporal interaction. Indeed, it characterizes the operation of evolution in nature. We usually think of individuals and species competing with one another within the environment, thus driving evolution through natural selection. In fact, however, there is coevolution: plants and animals not only adapt to the environment, they change it. As a result, it

becomes more hospitable to some life forms and less hospitable to others.

The challenge for security policy and military affairs, arising from the unintended consequences of interactions, lies in rethinking “ends and means” as we conventionally linearly view them. We must take these identified interaction types consciously into account.

Interactions in Vietnam

One of the best examples of what happens when linearity meets nonlinearity in this century took place in Vietnam, and is described in the excerpt of the chapter of Martin Van Creveld’s book, *Command in War*¹⁰ in the Appendix. During Vietnam, the United States was led by perhaps the most linear leadership in its history. Van Creveld illustrates the shortcomings of linear reductionism in warfare—especially the imperative to control, through quantification and centralization—and the susceptibility to the thrall of technology that marked the war. Van Creveld’s observations on the use of statistics are especially pertinent to our discussion of the effects of interactions within systems.

Since the patterns that form the objective of statistical analysis only become visible at fairly high levels in the hierarchy (further down, the figures are by definition meaningless), reliance on such analysis is itself a contribution toward centralization and the information pathologies of which centralization can be a cause. Statistics may have been the only way to handle the flood of incoming messages—running, at the Pentagon level, into the hundreds of thousands per day—but in the process, statistics reduced the content of those messages to the lowest common denomi-

nator. Finally, statistics constitute one of the most abstract forms of information known to man; although they can possibly present a good picture of a whole phenomenon the relevance of any given set of figures to this or that particular event at this or that particular place may well be next to zero.

There are severe limits to linearity's promise of control, even to those who faithfully practice its arts and follow its form. Linear reductionism will not be succeeded, but will be combined with nonlinear reductionism to form a more robust, versatile, and effective means, not to control, but to cope. The fiction of control will go down hard, while the considerable virtues of coping will just have to be learned to be appreciated.

Notes

- 1 Kellert, Stephen F. *In the Wake of Chaos*. Chicago: University of Chicago Press. 1993. p. 137.
- 2 Cohen, Jack and Ian Stewart. *The Collapse of Chaos: Discovering Simplicity in a Complex World*. New York: Penguin Books. 1994. p. 23.
- 3 Allison, Graham T. *Essence of Decision: Explaining the Cuban Missile Crisis*. New York: Harper-Collins Publishers. 1971. p. 144.
- 4 Rinaldi, Steven M. *Beyond the Industrial Web: Economic Synergies and Targeting Methodologies*. (Student thesis.) Maxwell AFB, AL: Air University. April 1995. p. 12.
- 5 Arthur, W. Brian. "Why Do Things Become More Complex?" *Scientific American*. May 1993. p. 144.
- 6 Gell-Mann, Murray. "What Is Complexity?" *Complexity*, Vol 1, No. 1. p. 19.
- 7 Petzinger, Thomas. "The Front Lines." *Wall Street Journal*. May 5, 1997. p. B1.
- 8 Cohen Stewart: p. 182.
- 9 Jervis, Robert. "Complex Systems: The Role of Interactions." in Alberts, David and Thomas J. Czerwinski, eds. *Complexity, Global Politics and National Security* Washington, DC: National Defense University. 1997. pp. 45-71.

- 10 Van Creveld, Martin. *Command in War*. Cambridge, MA: Harvard University Press. 1985. pp. 251-260.

Chapter 3

Toward a Nonlinear Reductionism

It is the mark of an educated mind to rest satisfied with the degree of precision that the nature of the subject admits, and not seek exactness when only an approximation is possible.

- Aristotle in *Nicomachian Ethics*

Nonlinear dynamical systems theory is holistic to the extent that it studies properties of physical behavior that are inaccessible to microreductive analytical techniques. But it nevertheless proceeds by massively simplifying the models it studies.

- Stephen Kellert in *In the Wake of Chaos*¹

Think of nonlinearity as a game. There are the “players” and the “place.” In baseball, “nines” play on “diamonds”; in football “elevens” play on a “gridiron.” Recall the seven basics of complex adaptive systems (*cas*) covered earlier. The four properties—aggregation, nonlinearity, flows, and diversity—and the three mechanisms—tags, internal models, and building blocks, as *cas* constitute the players, or “sevens.”

But what is the “place” that nonlinearity is played on? Well it resembles a tree, or your lungs, cardiovascular system, or the brain. It is called the “period-doubling cascade,” which is depicted in Figure 3.1.²

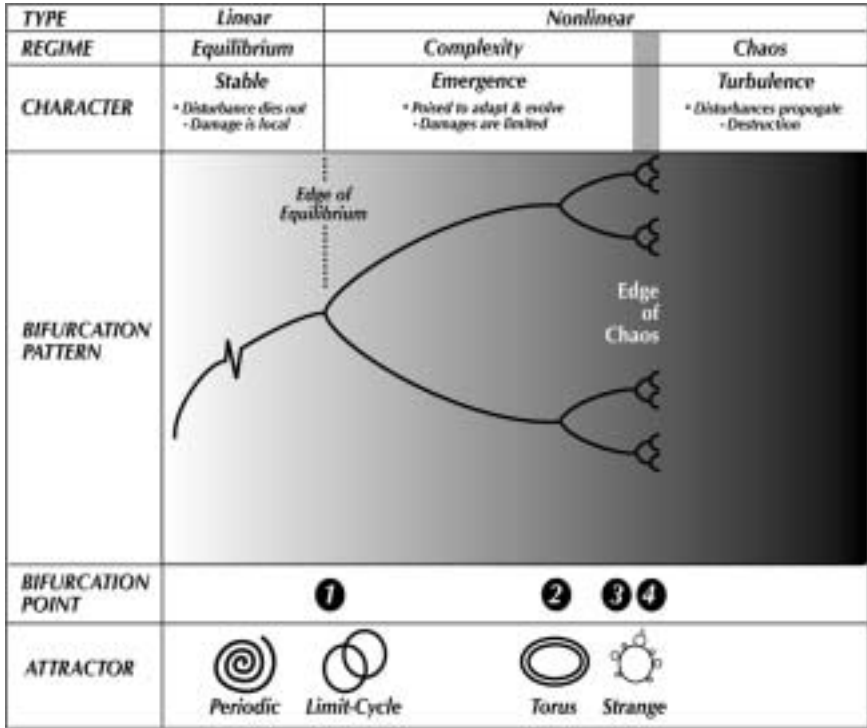


Figure 3.1: Period-Doubling Cascade

The End Zones

As in football, this “place” contains two end zones. At one end there is Equilibrium, and at the other, Chaos. Neither end zone is a particularly attractive place. In the Equilibrium end zone, everything is so stable, there is so much order, that growth, innovation, and progress are suffocated. In the Chaos end zone, the situation is just the opposite. The turbu-

lence is so severe that human understanding and intervention becomes impossible.

The Playing Field

In between these end zones is the playing field—a region called Complexity. It is

a kind of ‘phase transition’ between order and randomness. Water frozen into a simple lattice of molecules is not very complex. Nor is a gas in which the molecules vibrate at random. But between the two extremes is liquid water, which can move in complex patterns that are almost mesmerizing.³

Ice represents the region of Equilibrium in the above quote, and gas, or water heated to steam, the region of Chaos. Water, that life-giving substance, is formed in the Complex region. It is essential territory precisely because that is where complex adaptive systems (*cas*) thrive. It is an oasis.

A football field is marked off in 5-yard increments from 0 at one end line to the 50-yard line, and then back to 0 at the other end line. In the generalized “game” of nonlinearity, the playing field is marked off in bifurcation points—1 through 4. Each bifurcation, or “splitting into twos,” is a fork in the road, or a branching representing choices, possibilities, or paths. The first bifurcation point, which generates two alternatives, is an end line marking the formal boundary between linearity and nonlinearity—the Edge of Equilibrium. Then comes the second bifurcation point generating four. Next comes the third bifurcation point bringing with it eight branches. However, the difference between the second and third bifurcation point is only about 22 percent of that between the first and second.

These bifurcations follow a rule—a rarity in mathematics, such as the value of π . The rule is that these bifurcations occur in an accelerated fashion. Each succeeding bifurcation happens at an interval, each closer to 22 percent as long as its predecessor, creating a compression effect. Therefore, the fourth bifurcation point, in about 5 percent of that between the first and second points, develops 16 choices. If we were to carry this forward, the fifth bifurcation and its 32 alternatives occur in a fraction of about 1/100; the sixth with 64 in about 1/500; and so on. But we don't carry the playing field further, because we have entered the Chaos end zone, and this is the turbulence you encounter in which the average mind will turn to mush. While chaos is deterministic, the turbulence obscures the underlying patterns. To us it is just mindlessly random because of our habitual way of looking.

Nevertheless, there are exceptions, and this end line—the Edge of Chaos—is more elusive, lying in a range. The boundary may be based on the application, which is to say that it is situational and depends on circumstances. In computers, which are essentially crude machines compared to the human mind, their ability to mimic life may require a boundary just short of the third bifurcation point. Human agency may be able to hold sway, beyond that of computers, through the barrier of the third bifurcation just barely into the fourth. But for some, the boundaries may be even greater. This, I assert, accounts for the successes of Napoleon, Rommel, and Patton and their forces, each a superb complex adaptive system that attained at times those qualities which only lie at the very farthest reaches, just short of chaos.

The Game

In football, the object of the game is to get into the opponent's end zone while keeping the opponent out of yours. The object in nonlinearity is to stay out of *both* end zones (and get your opponent into *either* one). What you want to do is to stay in the field of play, moving back and forth in the Complexity region. As long as you can avoid the end zones, you are doing all right, or, at least, surviving.

In order to prevent entering either the rigid suffocating world of the Equilibrium end zone or the bewildering Chaos end zone, most humans (revolutionaries and anarchists excepted), and the institutions and societies they build, intuitively have practiced a back and forth shuttle within the confines of Complexity—from the Edge of Equilibrium to the Edge of Chaos. This amounts to a sort of precarious balancing act, like a gymnast on the balance beam, in order to stay where *cas* allows learning, adaptation, and emergence necessary to an interesting life and the prospect of progress. We are like the dairyman Tevya's fiddler on the roof, trying to keep our balance while we play a pretty tune. . . "coping with the bounds."

W. Brian Arthur, a Stanford economist, gives examples of the complexity shuttle in human affairs.

But, interestingly, even when a system gets lumbered down with complications, there is hope. Sooner or later a new simplifying conception is discovered that cuts at the root idea behind the old system and replaces it. Copernicus's dazzlingly simple astronomical system, based on a heliocentric universe, replaced the hopelessly complicated Ptolemaic system. Whittle's jet engine, ironically, replaced the incurably complicated piston aeroengine of the 1930s before it also became complex. And so growing complexity

is often followed by renewed simplicity in *a slow back-and-forth dance*, with complication usually gaining a net edge over time.⁴ (italics added)

Watching the unconventional but always interesting feminist Camille Paglia addressing the cadets at West Point on C-Span, I caught the following in paraphrase. Paglia talked about what she called the tension between Plato and Dionysus—averting rigidity and authoritarianism, on the one hand, and chaos on the other—an eternal dynamic observed throughout political and social history. Here we have another “slow back and forth dance.” In fact, the basic processes of political life can be reduced to these dynamic interactions between liberal and conservative tides in the complexity shuttle. Corporations, congregations, and even families also make these adjustments.

The complexity shuttle historically has been, while instinctive, a clumsy affair. Not well understood or articulated, because the principles of nonlinearity were only dimly perceived, prat-falls have been common. This has led to unintended conflicts, inequities, suffering, and wasted resources. In the future, an acute awareness of nonlinearity, coupled with the refinement of nonlinear techniques, promises to significantly improve our ability to “cope with the bounds.” Should we succeed, this may well be the hallmark achievement of the 21st century.

The Play Book

A “play” is represented by the path of a bifurcation (which is actually a *cas* encountering its environment, which includes other *cas*). The *cas* senses its situation and collects information about surrounding conditions. It then responds to this information by using a set of internal models to guide its actions. The *cas* also encodes data about new situations for use at a

later date. The key for a path or “play” to become history, and then stay history, is that the seven basics of *cas*, covered in Chapter 1, work well together providing agility and quick adaptation, especially a “good enough” set of internal models to stabilize itself.

Now one, both, or none of these branches of a bifurcation may survive. Those that survive are saved by a successful encounter of a *cas* with its environment, which stabilizes it for an instant or for hours, weeks, months, years, or eons. History itself can be viewed as the human record of these saved branches; an event happened. A condition existed, whether recorded or not. Or consider your ancestry. You can read its bifurcation history in the “family tree,” including our own birth. For those paths which are not saved, the event/condition never happens, the sign of failure of a *cas* to adapt with its environment. Even those branches which are saved, such as a birth, will sooner or later lose their stability because over time conditions change, resulting in death.

A “play” or a bifurcation path representing a *cas* “expedition,” occurring close to bifurcation point 4 is worth more than one near bifurcation point 1. Complex adaptive systems (*cas*) thrive best at the Edge of Chaos, or the closer to the boundary with the Chaos end zone the better. This play, however, is complicated by the accelerating pattern of the bifurcations, each forming faster and faster. The result is that if we are not careful, we will not have the time to either recognize what is happening or the time for correction. Therefore, pushing the limits of the envelope in order to benefit from the heightened capability of *cas* at the edge of chaos is a matter to be balanced with the risk of getting too close. History is full of winners, but perhaps more losers, trying to pull this off. Alvin Saperstein, a

Wayne State University physicist, provides a good historical example of losers:

When all is said and done, the most useful aspect of the chaos and complexity metaphor. . . is to remind us and help us to avoid falling into chaos. . . . If the leaders of pre-WWI European states had recognized that the railroad-schedule-dominated mobilization of their troops was a source of great crisis instability, perhaps they would have avoided starting—and being trapped by—the process. But this recognition would have required that the chaos metaphor be more commonly found in the ‘intellectual air’ of turn-of-the-century Europe than was the case in that rapidly industrializing Newtonian-reductionist society.⁵

Michael Shermer, an adjunct professor of the history of science at Occidental College, has developed a “contingent-necessity” model of history consisting of six corollaries.⁶ These represent a refined playbook in which the generalized concept of the complexity shuttle in Figure 4.1 (see Chapter 4) is customized to deal specifically with the characteristics of history. Even without definitions and detail, these six corollaries have the feel of a nonlinear playbook (and the complexity shuttle).

- The earlier in the development of any historical sequence, the more ordered are the actions of the individual elements of that sequence and the more predictable are future actions and necessities.
- The later in the development of any historical sequence, the more chaotic are the actions of the individual elements of that sequence and the less predictable are future actions and necessities.

- The actions of the individual elements of any historical sequence are generally postdictable but not specifically predictable, as regulated by corollaries 1 and 2.
- Changes in historical sequences from chaotic to ordered is common, gradual, followed by relative stasis, and tends to occur at points where poorly established necessities give way to dominant ones so that a contingency will have little effect in altering the direction of the sequence.
- Change in historical sequences from ordered to chaotic is rare, sudden, followed by relative nonstasis, and tends to occur at points where previously well-established necessities have been challenged by others so that a contingency may push the sequence one direction or the other.
- Between origin and bifurcation, sequences self-organize through the interaction of contingencies and necessities in a feedback loop driven by the rate of information exchange.

When the Complexity Shuttle Fails

At the macro-level, where fundamental scientific questions and processes are the focus of investigation—the composition of the subatomic world, the creation of the universe, ecosystem change, and especially biological evolution—certain conclusions are largely accepted. Among these is that organisms encounter and endure chaos in order to evolve. Falling into chaos means submitting to “punctuated equilibrium,” a term that describes the way that evolution works. Evolution does not follow a smooth curve. Instead, it is marked by intermittent stutter-step movements, akin to earthquakes and

avalanches, triggered by a phenomenon known as “self-organizing criticality” (SOC). Briefly stated, self-organized criticality is based on the principle that

Large interactive systems perpetually organize themselves to a critical state in which a minor event starts a chain reaction can lead to a catastrophe. . . a deceptively simple system serves as a paradigm for self-organized criticality: a pile of sand.⁷

Following punctuation, the system loops to the Equilibrium regime. Further, there is no complexity shuffle. The arrow points in only one direction—toward chaos. But for the commander, statesman, and manager in the day-to-day world of real outcomes for which they are responsible, the Chaos end zone is a place to avoid like the plague. He or she is expected to perform, not evolve, at least not in the biological sense.

Apparently, scalar effects are involved here, and they need to be recognized in some framework, similar to the distinction between macroeconomics and microeconomics. Just as economics, in general, has some globally common attributes, it is also recognized that there are differences in behavior and impact at different scales. For example, one does not apply macroeconomics to the family budget, or conversely, microeconomics to an analysis of the Gross National Product. So too it is with nonlinearity.

At the micro-level, the failure of the complexity shuttle involves falling off the complexity region into, on the one hand, chaos, or, on the other, equilibrium. This can happen from (1) a lack of agility, (2) risk-taking, or (3) the accumulation of events, resulting in environmental conditions, largely beyond our control, which cause us to lose our balance. The

latter condition can be caused by the effects of coevolution. Remember Robert Jervis's words in Chapter 2:

We usually think of individuals and species competing with one another within the environment, thus driving evolution through natural selection. In fact, however, there is coevolution: plants and animals not only adapt to the environment, they change it. As a result, it becomes more hospitable to some life forms and less hospitable to others.

Further, it appears to be difficult for a system in Chaos to get back into the Complexity domain without the aid of exogenous, or outside, factors. Consider the Great Depression: the complexity of the 1920s economy was sucked into the deep chaos of the 1928 Wall Street Crash, followed by years and years of the stagnation of the Great Depression. Despite the largely ineffectual attempts to "jump start" the economy by New Deal policies, the economic system was only propelled back into the Complexity region by conditions generated by the impending outbreak of World War II.

The region of Equilibrium at the opposite end of the Complexity region is also a threat. The dynamics are different. Instead of losing the reaction time caused by the compression of bifurcations at the other end, one gains breathing space at the edge of equilibrium—what one might overconfidently consider a risk-adverse area to operate in. History is replete with examples of decay, with no sign of a chaotic preamble. Consider, for example, the Soviet Union's command and control economy. Certainly its dynamics were close to the "edge of equilibrium," perking along at best in a mildly nonlinear range to afford it the minimum of innovation, while still providing rigid Five Year Plan control using linear techniques. In the late 1980s, events led it not to a frenzied outburst of bifurcations. It

just wound down, not up. It went “metronomic”—the tick-tock of the point attractor. It died, it didn’t erupt.

The Necessity for a Nonlinear Reductionism

In many works in the field of nonlinearity, chaos is not so much to be avoided as the plague as is reductionism. There is a school of thought, known as Holism, which does not recognize the scalar effects. Instead, it imposes macro-nonlinear principles on the micro-nonlinear level as a norm. Consider the following paragraph:

In human and social systems, both linear order and chaos intertwine in varying degrees and alternate throughout the life history of the system. A period of relative order is followed by a period of chaos, which in turn brings forth a new order. *The period of deep chaos is a natural and necessary part of the development of every living and social system.* It comes at the bifurcation point of discontinuous change. The conditions that are the fertile ground for the creation of the new order are born out of the turbulence of chaos.⁸ (italics added)

It is obvious that we have a problem here. Holism treats the complex regime largely as a mere transition from Equilibrium to Chaos, and presumably on to better things, whereas in micro-nonlinear terms—that is for humans—it is an oasis! Holism rejects any concession to the use of reductionism in nonlinear affairs. Holism insists that a nonlinear system be dealt with “in the whole.” In Holism everything is connected to everything else, and there is no hierarchy. Holism, therefore, is a slippery slope which without “handles,” has a tendency to default to “worst case” scenarios, and therefore, advocates extreme measures to avert them.

Certain radical formulations regarding environmental concerns come to mind.

Such a condition is untenable and useless for the responsible commander, manager, and diplomat involved in national security policy, military strategy, and operations. Some form of reductionism—we all understand things as models, or miniatures, each an abridgment of reality—must come to the fore to deal with nonlinearity, and coping with the bounds of the complexity shuttle.

The only qualification required of this reductionism is that it must help us to be better at doing the complexity shuttle. They will not be the kinds of methods or techniques we are used to, or like to use. They are all more *tacit* than the hyper-*overt* models we are used to in linearity. These are Aids to Learning.

Tools of Analysis and Aids to Learning Compared

Tools of Analysis are, well, tools. Like wrenches, hammers, oscilloscopes, radars, and differential equations, they are pre-conceived “artifacts,” preassembled and ready-to-go. All their “learning” is built into them by their human designers who are familiar with the nuts, bolts, nails, frequencies, and problems these tools deal with. They are basically linear; they are proportional, additive, replicable, and certainly they are bothered with because they will result in an expected, measurable effect on the cause. And they work well enough in environments which are mildly nonlinear.

But how does one devise a wrench, or radar, for any degree of nonlinearity beyond the mild? Nothing so overt as a tool can be preassembled. One must rely on something more tacit,

sometimes even close to spontaneity, like the work of our immune system. Recall John Holland's observation that, "One cannot have a prepared list of rules for all possible situations, for the same reason that the immune system cannot keep a list of all possible invaders."⁹

If a tool is not available, than an "aid" is the next best thing. An aid is something which helps to do the job, which is "learning." An aid is not a tool, which is already "learned." But, that is what our current understanding of nonlinearity allows us. In the future we can expect to get better. Someday, there may even be something akin to nonlinear tools.

Even with the weather, there are building blocks—fronts, highs and lows, jet streams, and, so on—and our overall understanding of changes in weather has been much advanced by theory based on those building blocks. It is still difficult to predict detailed weather changes, particularly over an extended period. Nevertheless, theory provides guidelines that lead us through the complexity of atmospheric phenomena. We understand the larger patterns and (many of) their causes, though the detailed trajectory through the space of weather possibilities is perpetually novel. . . . A relevant theory for *cas* should do at least as well.¹⁰

In the mean time, how do we make the most of what we have? We can get good at six things: metaphors, Perrow's quadrants, applying Van Creveld's rule, systems dynamics, genetic algorithms, and pattern recognition. Each of these aids will be covered in the next section. Each is a low-level model, all of them being more tacit than we are used to. But they are *cas* friendly, and allow insight into their workings. It could be that Aids to Learning work by somehow exploiting the mechanisms of *cas* to get insights into their properties. Without putting too

fine a point on it, there appears to be a rough correlation between the Aids to Learning and the mechanisms of *cas*, covered in Chapter 2 (see Figure 3.2).

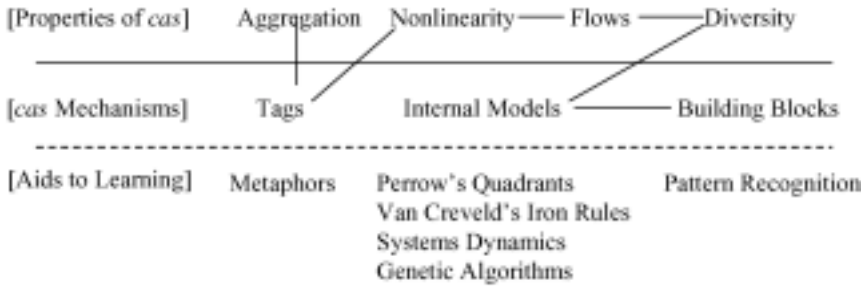


Figure 3.2: A Notational Correlation Between Aids to Learning and *cas*

But even if you do get good at nonlinear reductionist techniques, they will still not be as comfortable as a wrench, or hammer, or overt models. The tacit nature of Aids to Learning are by design “crude looks at the whole.” Insights into nonlinear environments are provided by “coarse graining” and “blurred vision.” In order to get “past the trees to the forest,” we try to look up through the levels in the hierarchy to understand the overall patterns.

Finally, the complexity of the nonlinear and its resistance to predictability gives the phrase “solving the problem” a hollow ring. In actuality, we “cope with the environment.” Nonlinear reductionist techniques do not optimize, they satisfice. Their object, like *cas*, is not the perfect answer, but the good enough, fast enough to ensure survival. They seek the fittest, not the fanciest, avenue. They are inelegant and messy compared to the fastidious, but often ineffective constructs of the linearist. What the aids lose in formalistic symmetry is more than gained by the vibrancy of life. Our brains have been trained; aesthetics, form, and taste are part of our intellectual inherit-

ance. We will have to undergo (using perhaps the most abused term in history) a “paradigm shift.”

Notes

- 1 Kellert, Stephen H. *In the Wake of Chaos*. Chicago: University of Chicago Press. 1993. p. 115.
- 2 Fig. 4.1 represents a computer plot of the *iterated growth*, or *Logistics*, equation, or $X_n + 1 = KX_n(1-x_n)$. A number of important and interesting aspects of Chaos theory, such as *attractors* and *fractals*, are not covered. If you'd like to know more about these take a look at Complexity Exploratorium [<http://www.exploratorium.edu/complexity>] on the Internet.
- 3 Johnson, George. “Researchers on Complexity Ponder What It’s All About.” *New York Times*. May 6, 1997. p. C7.
- 4 Arthur, W. Brian. “Why Do Things Become More Complex?” *Scientific American*. May 1993. p. 144.
- 5 Saperstein, Alvin M. “Complexity, Chaos, and National Security: Metaphors or Tools?” in Alberts, David and Thomas J. Czerwinski, eds., *Complexity, Global Politics and National Security*. Washington, DC: National Defense University. 1997. p. 124.
- 6 Shermer, Michael. “The Crooked Timber of History.” *Complexity*. July/August 1997. p. 24.
- 7 Bak, Per and Kan Chen. “Self-Organized Criticality.” *Scientific American*. January 1991. p. 46.
- 8 Merry, Uri. *Coping With Uncertainty*. Westport, CN: Praeger Publishers. 1995. p. 41.
- 9 Holland, John H. *Hidden Order: How Adaptation Builds Complexity*. Reading, MA: Addison-Wesley Publishing Company, Inc. 1995. p. 33.
- 10 Holland: p. 168.

Chapter 4

The Meshing of “Tools of Analysis” and “Aids to Learning”

When dealing with any nonlinear system, especially a complex one, it is not sufficient to think of the system in terms of parts or aspects identified in advance, then to analyze those parts or aspects separately, and finally to combine those analyses in an attempt to describe the entire system. Such an approach is not, by itself, a successful way to understand the behavior of the system. In this sense there is truth in the old adage that the whole is more than the sum of its parts. . . . It is of crucial importance that we learn to supplement those specialized studies with what I call a crude look at the whole.

- Murray Gell-Mann, Nobel Laureate

I resort to a whole, in importance, yet stunted, in length, chapter in order to emphasize the following point. Linear reductionism, as Tools of Analysis, alone is not sufficient to cope with today's and tomorrow's problems, just as it was not capable of solving all of yesterday's. Nor are nonlinear tech-

niques in the form of Aids to Learning alone sufficient. Instead, we require an approach which calls for intertwining or meshing *both* linear and nonlinear reductionist techniques; that is, “Tools of Analysis” for linear techniques, blending to “Aids to Learning” for nonlinear approaches, depending on the environment involved. Further, linear subsystems might be connected in nonlinear ways, just as nonlinear subsystems might be interlinked in linear ways. There are these places where the use of appropriate techniques will have merit. Often we need a synthesis. One must become ambidextrous—a switch-hitter.

The 80/20 Rule

Of importance to this notional continuum of linear and nonlinear techniques is the idea of the “80/20” rule. It is widely accepted, not just in Western culture, but most if not all cultures, that typically the first part of an endeavor or task is relatively easy. It then gets progressively more difficult, and toward the end, gets hard to do. In fact, it is so common that it has not only been codified into a saying, but quantified—the 80/20 rule. For example, software developers routinely establish as a rule of thumb budgets and schedules which allocate 20 percent of the dollars and time to the first 80 percent of the project, and the remainder to the last fifth. Why? Because time and time again, from generation to generation, the phenomenon has persisted, whether in a blacksmith shop or a national central bank trying to control inflation.

Suppose that all that accumulated experience and wisdom tells us something with enough confidence to take a stab at pinning it down. If we measure the generalized playing field of com-

plexity, we find that the “80-yard line” is located just beyond the second bifurcation point (see Figure 4.1).

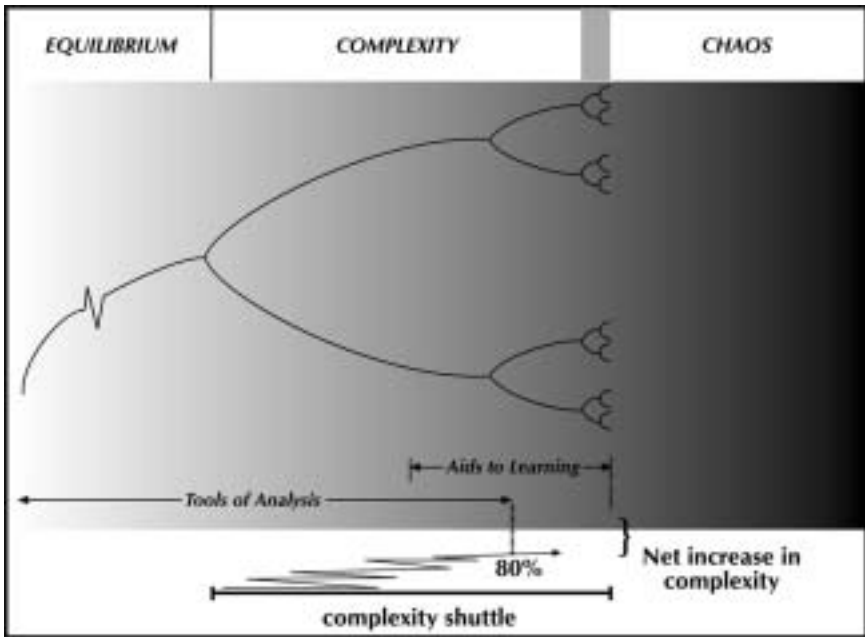


Figure 4.1: Coping with the Bounds

We could postulate this to be the effective limit of linear reductionist techniques, which also marks the boundary of mild nonlinearity. After that point, Aids to Learning come into play because Tools of Analysis lose their power, especially to provide “good enough” internal models for complex adaptive systems (*cas*). In terms of bifurcation points, this is only halfway through the Period-Doubling Cascade. Further, we might assume that Aids to Learning can be a useful supplement, or substitute, even earlier. This would also tell the practitioner that when the system becomes sensitive to more than two ranges, oscillations, or feedbacks, when the environment begins to cloud judgment with more than two effective possibilities, that the commander or manager would go into

“nonlinear mode,” bringing to bear Aids to Learning in order to persevere.

The New Economy Exemplifies the Need for Meshing

Today’s economy must be viewed as the situation requires—linearly, nonlinearly, and sometimes something in between. It therefore provides reinforcement for the argument that the meshing of Tools of Analysis and Aids to Learning is necessary in order to be effective, to succeed, or to subdue.

Many of you will vaguely remember the principle of diminishing returns from your Economics 101 course long ago. Basically, the gist went something like this: A farmer gets into peanuts early and starts to make a killing. But this is noticed by other farmers and they switch to peanuts, too, thereby increasing the supply and driving down prices. The farmer tries expanding, but the price of land increases, and sooner or later, he finds that he or she reaches a point where diminishing returns makes it senseless to increase production because it does not pay, and equilibrium sets in. That is classical economics and it is linear, caused by negative feedback.

Now consider a piece of software, say something called a Web browser. The first copy may cost \$1 million to develop, but the second and ensuing copies go for 99 cents to cover the cost of the floppy disk, packaging, advertising, and shipping and handling. But the developer is smart enough to give it away free, in order to establish a user base large enough to create a de facto standard, thereby creating “early lock-in.” The strategy is to make money off of upgrades and bundled features. Essentially, you have increasing returns, because each unit of

increased production faces none of the perils faced by the peanut farmer. Welcome to the world of nonlinear economics caused by positive feedback. The result is that the economy, as a whole, is becoming differentiated:

Mechanisms of increasing returns exist alongside those of diminishing returns in all industries. But roughly speaking, diminishing returns hold sway in the traditional part of the economy—the processing industries. Increasing returns reign in the newer part—the knowledge-based industries. Modern economies have therefore bifurcated into two interrelated worlds of business corresponding to the two types of returns. The two worlds have different economics. They differ in behavior, style, and culture. They call for different management techniques, strategies, and codes of government regulation. . . Where do service industries such as insurance, restaurants, and banking fit in? . . . It would appear that such industries belong to the diminishing returns, processing part of the economy. . . [But] (t)hese industries, too, are subject to mild increasing returns. . . In fact, the increasing returns character of service industries is steadily strengthening, one of the marks of our time is that in services. . . processing insurance claims, supplying and inventorying in retail, conducting paralegal searches for case precedents—are increasingly being handled by software. . . Services belong to both the processing and the increasing returns world. But their center of gravity is crossing over to the latter.¹

The concept of increasing returns is the work of W. Brian Arthur of Stanford and the complexity theory think-tank, the Santa Fe Institute, who has again been passed over for the Nobel Prize. This year it went to a pair of individuals for devising stock market derivatives, of all things. The continuing anti-trust action by the Justice Department against Microsoft is to a

great extent based on increasing returns. It is ironic that there is now case law based on nonlinearity, while its applications remain largely unrecognized in other realms. It is almost enough to make one say something nice about lawyers!

To recapitulate, the “meshing” framework for the economy looks like this:

Economic Sector:	Processing-----Service-----High tech
Characteristic:	Linear-----Nonlinear
Attribute:	Decreasing returns-----Increasing returns
Method:	Tools of Analysis-----Aids to Learning

Having now made my plea that both linear and nonlinear techniques are vital, and need to be used together, we can move on to the next section, where we will examine each of the six Aids to Learning individually. Of necessity, both their composition and application are still incomplete. While the Metaphor and Van Creveld’s Rule are well tested, all remain in stages of development. Paradoxically, even when fully developed, each will remain, in Murray Gell-Mann’s term, a “crude look at the whole,” for that is what nonlinearity both requires and prizes.

Notes

- 1 Arthur, W. Brian. “Increasing Returns and the New World of Business.” *Harvard Business Review*. July-August 1996. p. 107.

Part Two

Aids to Learning

This section covers the six identified analytical techniques which are suitable for use in highly nonlinear environments. Each technique is described, and examples of actual use are given.

Chapter 5

Metaphors

Metaphor: A figure of speech in which a word or phrase literally denoting one kind of object or idea is used in place of another to suggest a likeness or analogy between them (as in *the ship plows the sea*).

- Webster's New Collegiate Dictionary

This chapter examines the first of six Aids to Learning—the seemingly humble metaphor—in dealing with nonlinear environments. The metaphor is akin to the mechanism of tagging in complex adaptive systems as described in Chapter 1. These systems sense their environments and collect information about surrounding conditions by using tags to guide their actions. The systems may also encode data about new situations for use at a later date. We often think that information is a human-derived product of the interaction of animate Man and inanimate Nature. Nothing could be farther from the truth. Information processing is almost universal. For a branch of a bifurcation to survive, its tags must survive a “fitness” test. Essentially, metaphors do the same thing for us, and are essentially tags. All metaphors are not created equal. Clichés, for example, won't stand the test. The 19th century understood

this better than we do today. Students studied Rhetoric, which rigorously covered the “science” of metaphor-making. We have, in our own century, taken a step backward.

Alan D. Beyerchen sets forth a spirited defense of the linguistic metaphor, which is, in actuality, a form of low-level model.¹

There seems to be serious metaphorical value in the images and ideas emanating from the new sciences. . . Murray Gell-Mann, James Rosenau, and others caution wisely against expecting too much, too soon from the new sciences and stress the informed use of metaphor for now. I could not agree more. But if this sentiment implies that metaphors are merely poor substitutes for adequate models, then I could not disagree more. Metaphors are extremely powerful in their own right and should not be treated simply as tokens along a tollway toward models.

What is a metaphor? Is it only a stylistic flourish, as most of us think who encountered metaphors primarily in literature classes in school? No. Metaphor is much more significant, as philosophers and linguists are beginning to demonstrate more and more convincingly.

A metaphor is usually a statement that is paradoxical. It is literally false according to the rules of abstract rationality (i.e., logic, truth tables), but is true according to the rules of imaginative rationality (i.e., art). Metaphor constitutes a ubiquitous, irreducibly complex aspect of any natural language. It is an essential “AS” gate in our cognitive processing. It is a crucial way that we understand one thing as another.

Metaphors are embedded throughout our speech patterns (including the word “embedded” here). They are jarring when new, but often we use “dead” metaphors or clichés

such as the wings of a building, the branches of science, weighing our options, or sitting at the foot of a mountain. Each such "gate" is much more than a word. Contemporary researchers tell us that metaphors are indicators of networks of meanings and entailments that dilate or constrain both our perceptions and our conceptions.ⁱ It is furthermore possible to extend this understanding to visual and other metaphors such as the Mandelbrot set that enlivens our program covers at this conference.

The importance of metaphor has long been understood. Aristotle wrote, "The greatest thing, by far, is to be a master of metaphor. It is the one thing that cannot be learned; and it is also the sign of genius." He contended that it is so indicative of power that it is not appropriate for slaves to use it.

Beyerchen, a Clausewitz scholar, goes on to say that the great thinker was contemptuous of metaphors. "Critical studies, he [Clausewitz] says, are imperiled by narrow systems used as formal bodies of law and 'a far more serious menace,' the 'retinue of jargon, technicalities, and metaphors that attends these systems. They swarm everywhere—a lawless rabble of camp followers.'"ⁱⁱ And yet he was a master of the metaphor:

To condemn metaphors in such a colorfully metaphorical way implies that Clausewitz thought... in profoundly metaphorical terms. Think merely of his "friction," or "fog" of war, or "center of gravity." Recall how a defeat "leaves a vacuum that is filled by a corrosively expanding fear which completes the paralysis. It is as if the electric charge of the main battle had sparked a shock to the whole nervous system of one of the contestants." Or how routine is a clock "pendulum" that reduces natural friction and "regulates" the mechanism of war. Or how war has its own "grammar," but not its own logic. Or that politics is

“the womb in which war develops—where its outlines already exist in their hidden rudimentary form, like the characteristics of living creatures in their embryos.”ⁱⁱⁱ

Why did Clausewitz resort to this “lawless rabble of camp followers” in his own language? One reason is that he wanted to draw upon history to generate theory. In historical studies a major goal is frequently to understand one thing (the present or a vision of the future) in terms of another (the past). Metaphor is very robust for this purpose. Consider the staying power of the metaphor of the Munich agreement in American foreign policy since World War II. To claim some action is necessary to avoid a “Munich” is to offer a justification of enormous magnitude; to claim some other course will lead to a Munich is to denounce its proponents in the most damning terms as appeasers. Metaphors appeal to imaginative rationality and often evoke indelible images. . . .

Yet another reason Clausewitz relied upon metaphor was that he did not trust the established jargon of his day, which was full of rigid (and French!) geometric principles and models. [*Think of Jomini.*] He preferred the new sciences of his time—chemistry, thermodynamics, magnetism, electricity, embryology. These offered novel, high-tech, research-forefront terms for the dynamic phenomena he wanted to discuss. . . .

Clausewitz appears to have understood that metaphors can be superior to analytical [*or overt*] models when the phenomena of interest cannot be controlled, or you are unsure of the necessary assumptions. As evolving things, metaphors are open to novelty, surprise, innovation, and even mutation. They therefore can capture the underlying processes of other evolving entities surprisingly well. If the metaphors are really successful, of course, they may

become mere commonplace, frozen images that get passed along unthinkingly and thus constrain our imaginations. But this is also part of the way evolution works. Metaphorizing (as opposed to traditional modeling) is a process of exploring some interesting possibility space with contingency and feedback. Each biological mutation is such an exploration, as is each historical event. This is a crucial aspect of Clausewitz's method of analysis and his approach to war.

Those who still find the linguistic metaphor to be wanting can find a little solace in the alternative of mathematics. Mathematics at its heart is also metaphorical, but somewhat more capable of precision.

The higher levels of the reductionist story use mathematics as a metaphor, not as a precise representation of nature. . . . Even though mathematical models do not correspond to the whole of reality—indeed, *because* they do not correspond to the whole of reality—they offer definite advantages. Because mathematics is more precise than words, it can handle more delicate distinctions. . . .²

But what is inadequate about the metaphors we use now, and what would better ones be like? Andrew Ilichinski of the Center for Naval Analysis has produced a report on land warfare and complexity,³ which contains an excellent table of metaphors that has been reproduced on the following page. Those on the left-hand column are linear. Those on the right, their nonlinear equivalents.

Analytical	Synthesist
Basic elements are "Quantities"	Basic Elements are "Patterns"
Behavior is Contingent and Knowable	Behavior is Emergent and often Unexpected
Being	Becoming
Clockwork Precision	Open-end Unfolding
Closed System	Open System
Complexity Breeds Complexity	Complexity Can Breed Simplicity
Deterministic	Deterministically Chaotic
Equilibrium	Far-From-Equilibrium/ "perpetual novelty"
Individualistic	Collective
Linear	Nonlinear
Linear Causation	Feedback loop/ Circular causality
Mechanistic Dynamics	Evolutionary Dynamics
Military "Operation"	Military "Evolution"
Combat as collision between Newtonian "billiard-balls"	Combat as self-organized ecology of living "fluids"
Order	Inherent Disorder
Predesigned	Emergent
Predictable	Unpredictable
Quantitative	Qualitative
Reductionist	Holistic
Solution	Process and Adaptation
Stability	"Edge of Chaos"
Top-Down	Bottom-Up and Top-Down

Ilichinski also provides an insightful comparison between some of the principles underlying the formation of linear and nonlinear metaphors (see below).

Context	Linear	Nonlinear
<i>Complex Behavior</i>	Complex behavior requires complex models.	Simple models often suffice to describe complex systems
<i>Patterns of Behavior</i>	Each qualitatively different pattern of behavior requires a different equation	Qualitatively different patterns of behavior can be described by the same underlying equation
<i>Descriptions of behavior</i>	Each qualitatively different kind of behavior requires new equation, or set of equation	One equation harbors a multitude of qualitatively different patterns of behavior
<i>Effects of small perturbations</i>	Small perturbations induce small changes	Small perturbations can have large consequences
<i>How to understand system</i>	A system can be understood by into and analyzing its simpler components	System can be understood only by respecting the mutual interactions among its components: look at the whole system.
<i>Origin of disorder</i>	Disorder stems mainly from unpredictable forces outside of system	Order can arise in a purely self-organized fashion within the system
<i>Nature of observed order</i>	Order, once present, is pervasive, and appears both locally, and globally	A system may appear locally disordered but possess global order
<i>"Goal"</i>	Goal is to develop "equations" to describe behavior; determined by isolating effect of one variable at a time.	Goal is to understand how entire system responds to various contexts, with no one variable dominating
<i>Type of "solutions"</i>	Goal is to search for "optimal" solution	No optimal solution exists, as the set of problems and constraints continuously change

The metaphor is a primary weapon, together with Van Creveld's Rules, in the arsenal of nonlinearity. At this stage in the development of nonlinear reductionism, these two are the

more advanced Aids to Learning that the nonlinearist has available to work with. Both are potent.

Notes

- 1 Beyerchen, Alan D. "Clausewitz, Nonlinearity and the Importance of Imagery." in Alberts, David and Thomas J. Czerwinski, eds. *Complexity, Global Politics and National Security*. Washington, DC: National Defense University. May 1997. pp. 153-170.
 - i) For a very readable exposition, see Lakoff, George and Mark Johnson. *Metaphors We Live By*. Chicago, IL: University of Chicago Press. 1980. For a variety of current approaches, see Ortony, Andrew ed. *Metaphor and Thought*, second ed. Cambridge: Cambridge University Press. 1993.
 - ii) *On War*. p. 168.
 - iii) *On War*. pp. 225, 296, 605, 149 respectively.
- 2 Cohen, Jack and Ian Stewart. *The Collapse of Chaos: Discovering Simplicity in a Complex World*. New York: Penguin Books. 1994. pp. 184-186.
- 3 Illichinski, Andrew. *Land Warfare and Complexity, Part II: An Assessment of the Applicability of Nonlinear Dynamic and Complex Systems Theory to the Study of Land Warfare (U)*. Alexandria, VA: Center for Naval Analyses. 1996. pp. 48, 52-3.

Chapter 6

Van Creveld's Rules

Confronted with a task, and having less information available than is needed to perform the task, an organization may . . . increase its information-processing capacity [or] design the organization, and indeed the task itself, in such a way as to enable it to operate on the basis of less information. These approaches are exhaustive; no others are conceivable. . . It is a central theme. . . that through every change. . . [and] technological development that. . . one will remain superior. . . in virtually every case.

- Martin Van Creveld, *Command in War*¹

Van Creveld's rule is an important Aid to Learning. Moreover, it is readily translatable into implementation by adopting certain organizational principles. Van Creveld's book *Command in War*, published in 1985, is a classic. However, the rule is based not on the author's knowledge of the principles of nonlinearity, but on years of studying the problem of command learned in the "school of hard knocks" of history. In this sense, Van Creveld is, like Clausewitz, an "unwitting" nonlinearist, having neither the field nor the vocabulary available to him when he studied, pondered, and wrote. Yet, there is in this convergence a satisfying confirmation provided by

powerful minds working independently from different source materials and approaches.

Van Creveld unravels his rule in a three step process:

Confronted with a task and having less information than is needed to perform the task (a military) organization may . . . increase its information processing capability. . . (which) will lead to the multiplication of communications channels and to an increase in the size and complexity of the central directing organ.

Van Creveld's study of command convinces him, "that this approach is inadequate and stand(s) in danger of being self-defeating."²

The second of Van Creveld's iron rules for increasing the performance of command through the "drastic simplification of the organization so as to enable it to operate with less information" is like the first rule, also "inadequate and stand(s) in danger of being self-defeating."³

Confronted with insufficient information to carry out a task, Van Creveld's third rule states that a military

organization may react by designing the organization, or indeed the task itself, to operate on the basis of less information, relying on the division of the task into various parts and to the establishment of forces capable of dealing with each of the parts separately on a semi-independent basis. It is a central theme. . . through every change. . . (and) technological development that the third one will remain superior. . . in virtually every case.⁴

Van Creveld identifies five requirements for success:

1. The need for decision thresholds to be fixed as far down the hierarchy as possible, and for freedom of action at the bottom of the military structure;
2. The need for an organization that will make such low-decision thresholds possible by providing self-contained units at a fairly low level;
3. The need for a regular reporting and information-transmission system working both from the top down and from the bottom up;
4. The need for the active search of information by headquarters in order to supplement the information routinely sent to it at its command; and
5. The need to maintain an informal, as well as a formal, network of communications inside the organization.⁵

Van Creveld's Rules Reflected in Public Policy

Certainly it seems that in our public life there are echoes of Van Creveld's rules in recent legislative and public policy initiatives. For example, in response to the accumulated evidence of disappointing results, a measure to reform welfare was passed and made law in 1996. It is interesting precisely because this legislation largely follows the Van Creveld prescription. Though certainly Congress never thought to reference *Command in War*, it still represents a "nonlinear" response to fix to a problem with deep linear roots, and goes by the term "devolution." Essentially, devolution decentralizes, thereby distributing uncertainty.

[T]he law gives states broad latitude in fashioning their welfare systems. It imposes some restrictions in return for the lump-sum 'block grants' of federal money that states receive from Washington, such as barring most recipients from receiving federal money for more than five years and requiring states to put specified percentages of welfare recipients to work. But states have flexibility in deciding how to accomplish those things and are free to use their money to pay benefits as long as they wish.⁶

Therefore, the legislation contains a relatively broad sense of federal intent, and a minimum of specifics. Subject to these directives, the individual states are given waivers in order to encourage them to develop innovative and tailored means to manage the program. All of the elements are there. The emphasis lies on distributing uncertainty through lowered decision thresholds to the states, while modifying the basis of command from detailed specifics to a broader one, which establishes intent and expectations. The "what" is less closely coupled with the "how." That is, ends and means more mirror the reality of welfare as a nonlinear system, where causes and effects are separated in space and time. This arrangement allows the flexibility necessary to do the complexity shuttle better. Is it working? The Council of Economic Advisors released a report on May 9, 1997, which attributes about 40 percent of the drop in welfare cases to a near full-employment economy. However, most of the rest of the decrease is credited to the waivers and flexibility of the new law.

Van Creveld's Rules Reflected in the Private Sector

The Van Creveld prescription for command on the inherently nonlinear battlefield has, as the readings below show, found an

independent, validating response in the management of private enterprise. Business people are adopting measures very similar to those found in *Command in War*. In the private sector, a measure of success has been realized through a combination of corporate vision statements (intent) and worker empowerment (lowered decision thresholds), thereby increasing productivity.

Stephen R. Covey is a major business writer and consultant to the corporate world. His books include *The Seven Habits of Highly Effective People* and *Principle-Centered Leadership*. The following appeared as the “The Strange Attractor,” in the journal *Executive Excellence*.⁷ The writer certainly takes liberties. His concept of the Strange Attractor is enough to make any scientist wince. Nevertheless, it works to get his message across to the business community in a style that is effective in that setting. That message is very consistent with that of Van Creveld’s Rule, translated from the military arena to that of commerce. The message is the same—distribute uncertainty. New MBAs out of the prestigious business schools may not use the same language, but the shared meaning is inescapable.

Earlier this year, I spoke to a group of executives gathered at a ski resort in Whistler, Canada. After my presentation, I enjoyed a day of skiing. Observing the mountain from the base lift, I could see hundreds of people skiing. At first glance, it looked like total chaos. But after a while, I could see a beautiful pattern of harmony and order to the whole thing.

Snatching order out of chaos is a result of what is called in chaos theory the “Strange Attractor,” meaning that all individuals share the same purpose—to enjoy their day in their way, according to their level of skill, the condition of the snow, the steepness of the slope, who their friends are,

what their plans are, and so forth. Even though I'm sure there were some accidents on the mountain that day, I never saw any.

Now, imagine what would happen if some chief executive sat at the top of the mountain with a computer, programming in all of the variables and giving everyone orders on how to go down the hill. It would be chaos, true chaos, resulting in many crashes.

Give Up Control to Gain It

Chaos theory, one of the cutting edges of management thought today, essentially reveals a world that is characterized by a kind of randomness and a seeming absence of rules, where even small changes in the system produce huge amplified effects. You can't predict the effects, and you can't control them. But on deeper examination, starting at the subatomic level, you find a core order that is beautiful and harmonious.

The significance of this principle in managing an organization is that if there is a Strange Attractor—that is, a common vision, sense of meaning, strategy, and value system based upon principles which ultimately control anyway—then we will see the same effect in our organizations as I saw on the ski hill: people managing themselves according to the Strange Attractor. And self-management provides order, harmony, and beauty rather than chaos. Although it may look chaotic, because everyone is doing his or her thing, they are all drawn to and united by the Strange Attractor.

The great paradox is that you're going to have chaos if you try to control people. You may appear to have order on the surface, because of your wielding the carrot and the stick to moti-

vate people, but deep inside people will be going in a thousand directions, having different motives and agendas, because there is no Strange Attractor or common purpose.

To get the Strange Attractor, you need a vision or strategic purpose that everyone can buy into and feel good about, and have a value system based on principles reinforced by a 360-degree information system and sustained by the universal conscience, the source of the mission statement. If you expect other people to buy into your mission statement, all stakeholders must be involved in creating it. This is what enables order to come out of chaos.

What difference might the Strange Attractor make in relationships? People and teams become more self-managing, since they all have a common value system, a common strategic intent, and a common sense of vision. That commonness attracts them and enables them to bond. It lubricates all human interaction. People will subordinate their own egos and work for a higher purpose. They may work independently, just as a person may ski alone, but because of the context and the commonness, they achieve synergetic interdependence. In their work, they look for ways to collaborate or partner with each other. On the ski hill, for example, they watch out for everyone else, skiing a little defensively and with an awareness of where their friends and family members are on the hill. They may meet their friends for lunch at the lodge and ask, "How did you ski that run?" "How are you going to approach the next one?" "How are you going to handle that steep part?" "How are we going to help this one person who's just beginning?"

Comfortable with Chaos

Command-and-control managers or ski instructors who are used to order, discipline, and direction, might view the Strange Attractor with suspicion, if not outright terror. The main source of this raw terror is their own personal need for control. Many managers feel they'll lose control and things will fall apart. But their underlying paradigm of control is the very cause of their undoing.

Today, the global marketplace is driving the demand for quality, and we can't produce quality unless we have shared values and strategic intent. Those who don't know the Strange Attractor will experience raw terror when trying to compete in the global marketplace. To be more competitive, they need to become more comfortable with chaos. And to do that, they'll need to break their addiction to control slowly, starting with their own immediate workgroup.

To illustrate this concept of the Strange Attractor, I cite the following examples:

1. When AT&T divested, they were rule-infested, bureaucratic, and product-focused rather than customer-focused. When they went through divestiture, they had to go up against global competition and deal with enlightened customers who had many options. Within one decade, several divisions developed amazingly high levels of empowerment, unleashing talent and energy toward a common purpose or strategic intent.
2. Similarly at General Electric, a decade ago they were highly bureaucratic, rule-infested, and filled with policies and procedures in a highly politicized environment. Now, some divisions have remarkable levels of empowerment and customer focus, thanks to the Strange Attractor.

3. Saturn Corporation is another example of an organization with a significant mission statement which serves as a corporate constitution, as a Strange Attractor.

How can you create an attraction that's so strong it's virtually molecular? It usually comes out of common vision and shared mission. Warren Bennis talks about four things: magnetic attraction, meaning, trust, and consistent example. Those four things define the job of the leader.

My definition of leadership has evolved to this: *the creation of a culture around a shared vision and value system based on principles*. That's true leadership. If you leave any one of those elements out, you'll be less effective in your leadership. For example, if your vision and value system are not based on principles, you'll have a social value system, like Hitler had. If you don't create the culture, you may have an excellent vision and value system, as most organizations do, but your people won't own it.

Exchange Between Old and New

Let's imagine an exchange between an enlightened leader and a line manager who's still caught in command-and-control ways. The leader asks,

"How's it going?"

"We can't get good work out of these people," says the manager. "Their work ethic is terrible. No one will cooperate."

The leader says, "Well, tell me about it."

The manager moans, "Our customers aren't loyal; our suppliers try to take advantage of us; our employees are all looking out for #1; no one will cooperate and pull together."

And then the leader asks, "What if everyone had the same vision, purpose, strategic intent, and values you have? What if everyone could share that?"

"Oh, that would make all the difference," says the manager. "But we can't possibly achieve that ideal. There are so many different agendas. Everybody's working for his or her own reasons. They go at different speeds and have different timetables."

And the leader says, "Well, look at the human body. The body has many different members, but because of the DNA chromosome structure of every cell, the entire body has the same Strange Attractor. We can reduplicate the entire body out of one cell. It's all there, like a holograph. What if we could have such a Strange Attractor inside this organization?"

And the manager says, "Well, that's just not possible or practical."

"Well, what are our competitors doing?" asks the leader.

"I don't know what they're doing," says the manager. "I just know that some of them are eating our lunch."

"Well, what do you think they are doing?" asks the leader. "Would you be interested in finding out?"

"Oh, yeah, but don't give me any of this idealistic crap about mission statements."

And the leader says, "Well, let's just observe the best of the competition. Maybe we can benchmark a little to see how what we're doing compares with what they're doing."

Gradually, by the force of competitive circumstances, the manager is humbled. Still he wonders how to get from here to there. "But I don't know what to do," he says. "what must we do to develop a Strange Attractor?"

Now the leader and manager are honestly exploring together how to get a shared vision and mission, using an

inside-out approach. They realize that it has to start with themselves.

Fears Are Groundless

In recent months, I have interviewed several executives who have worked with companies that have won the Malcolm Baldrige National Quality Award. I asked them, "What was the toughest challenge for you personally?"

They all said, "The biggest, toughest personal challenge was to give up control." They feared losing control, but they found that their fear was groundless. They thought they were going to have chaos. The opposite happened.

Again, this is the great paradox of leadership: *you give up control, and you gain it*. When you give up control and involve people in a genuine process of developing a common purpose and value system where you own the Strange Attractor, you begin to see everyone pulling together in the same direction according to their roles and level of skill. You move from procedural control to conceptual control. You move from external control to self-control.

This is why *humility* is the mother of all virtues, *courage* the father, and *integrity* the child. Because humility says, "I am not in control. I control my actions, but principles and natural laws control the consequences of those actions."

And the consequences are amplified ten-fold with other people. So, if you want to just transact with people, not have any partnering or any deep relationship, then its easy to just go ahead and do it. But know this: as soon as your competition has the Strange Attractor, you don't have a chance. You'll never last if you have only superficial relationships with a few people and your competitors have

transformed relationships and partnerships within the firm and outside the firm.

In a state of humility, you see yourself as part of a larger system. You recognize the dynamic forces involved. You see there has to be more give-and-take flow, more flexibility, because of the dynamic forces of the marketplace. Likewise, if you're going to partner with other people, you've got to understand their business requirements and cultural imperatives. In my work with the French company, Michelin, I found the whole key was to first understand the nature of their culture and to go with the cultural flow in order to achieve a common, strategic intent, that Strange Attractor. If you go against the cultural grain, you get the opposite result, the Strange Resistor.

The *leadership versus management* distinction ultimately comes down to *people versus things*. You can use control and efficiency with things, but you need to build relationships with people. Unless people have some common sense of meaning, they won't have a Strange Attractor to unite them. In my own office, we have eight people who work with a high level of empowerment and autonomy. In fact, I rarely even show up. I purposely stay away from the office to be more productive in other high-leverage activities. I attribute the harmony and productivity of the office to the Strange Attractor—a common vision of strategic intent and a value system based on principles. Unless you have the Strange Attractor in your family, how are your kids going to manage themselves when you're not around? They'll do whatever they think they can get away with. Such self-centered behavior truly leads to chaos.

When the Strange Attractor is present, people may actually be absent without impairing the operation. People can

be doing their thing on “the hill” and while it may appear chaotic at any given moment if you take a snapshot, if you film the action with a motion picture camera, you see that it all fits and flows.

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This report from the April 11, 1997, issue of *The Wall Street Journal*[®] supplements (and perhaps balances) Covey. It is a fine case study to illuminate the importance that the properties of diversity and hierarchy have for a complex adaptive system to function effectively.

Their eyes sparkled with enthusiasm—10 young, fresh-faced graduates, all smiling broadly on the cover of *Fortune* in May 1994. They worked for Architectural Support Services Inc., or ASSI, “a company” the magazine cover declared, “where the employees take charge of their future.” And how. Within a year, all but two of them had walked out, embittered and divided against the very company that gave them control. “It was a revolt,” says owner Vic Williams. Adds his wife and co-owner Joyce Roberts: “Instead of thriving, they quit.” What on Earth went wrong? Though their concepts were sound, the owners’ execution was flawed in a few critical respects. Today, they are rebuilding the business on similar leadership principles, but without the costly mistakes of the past.

Vic is an architect who developed a passion for computing more than 20 years ago. He and Joyce launched ASSI in 1985, providing computer-aided design services to architects. Joyce, with years of experience managing contracting projects, organized the jumble of floppy disks and the unevenness of work flows inherent in computer-aided design. Before long ASSI landed a big one, churning

out construction diagrams for an up-and-coming retail chain called Home Depot. Intent on building the best staff possible, Vic and Joyce followed a rigorous recruiting profile, hiring hotshot young designers from the best schools. They built a look-alike staff of people between 21 and 23 years old, most from well-to-do backgrounds.

Though gifted at organizing, Joyce was uneasy about her people skills. She immersed herself in books, tapes and seminars that appealed to her sensibilities as a rebellious baby boomer. Teams. Empowerment. Profit sharing. No hierarchies. It was her extensive use of these policies that put her and her employees on the cover of *Fortune*. Later the company was featured in a management textbook as a case study in modern management. But while the experts were fawning, the staff was fuming.

Employees were expected to schedule their own jobs, but they were offended if Vic pointed out they were behind schedule. They were asked to deal directly with customers, but they chafed when customers made big demands. Says Joyce's sister Caroline, who helps run the business: "The staff was downtrodden, unhappy and looking for something to complain about." And complain they did. When the owners leased an extra-large suite so everyone could sit by a window, employees complained about the glare on their computer screens. When Joyce offered to send people to professional-development classes, they took it as a slight. It did not help that while being told they were in charge, employees had to work with Joyce's carefully designed work flows. The message from employees, Joyce says, was palpable: "Get out of my face." Joyce was heartbroken—and mystified. "It was like a soap opera," adds designer Tina Maxian, who is still with the company.

The reality in retrospect, wasn't terribly complicated. Joyce and Vic had given their young staff plenty of authority but too little accountability. There were no formal performance reviews. No one was ever fired. They had created not a sense of fulfillment, but of entitlement. They tried to win people back over private lunches, but in such a monolithic work force there was little hope of solving the problem one employee at a time. So finally, in early 1995, "the walkout" began. In the space of a few weeks the entire design staff, other than Ms. Maxian, jumped to clients and competitors. Joyce, nursing her devastation, threw herself into the design work alongside Vic and began soul-searching.

One evening at the end of an intense week, she saw a sign behind the carryout counter of a pizza parlor. "When all else fails," it said, "lower your standards." She did not take the message literally; she is too much a perfectionist for that. But it did provide the glimmer of an answer. Perhaps by hiring to a different standard—by emphasizing teamwork over training, personality over pedigree—she and Vic could build a new and stronger staff. So far it has worked. Recruiting at community trade schools instead of four-year colleges, they found people whose eagerness to learn exceeded their lack of training.

Just as important, hiring from a wider pool created a more diverse staff. I don't just mean race, although that's part of it. The new staff includes a mix of locals and out-of-towners, some people well past their 20s, married people and singles, a former construction worker, an architect from Vietnam. Despite some beliefs to the contrary, a diverse workplace responds better to problems than a homogeneous one. A greater variety of backgrounds creates a greater variety of solutions.

The new staff is also held more accountable. Today, ASSI conducts formal performance reviews. People who do not get along do not stay. But in most respects employees have as much say-so over their work as ever. Indeed, Joyce has lightened her touch, "accepting the chaos," she says, "and not feeling like I have to control every aspect." The better mix of employees makes that easier. "Now we have some people who take direction and some who provide leadership," she says, "rather than a lot of people the same age rebelling and feeding off each other."

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The Van Creveld prescription—design "the organization, or indeed the task itself, to operate on the basis of less information, relying on the division of the task into various parts and to the establishment of forces capable of dealing with each of the parts separately on a semi-independent basis"—is a practical and useful Aid to Learning. It provides for many parts of the system to work on a problem at the same time. It as a means enables us to do the *complexity shuttle* better, helps us keep our balance in the narrow range of *cas*, and helps us avoid the regions of order and disorder on either side.

Notes

- 1 Van Creveld, Martin. *Command in War*. Cambridge: Harvard University Press, 1985. p. 269.
- 2 Van Creveld.
- 3 Van Creveld.
- 4 Van Creveld.
- 5 Van Creveld: p. 270.

- 6 Harwood, John. "In Some Big States, Lawmakers Remain Divided Over How Best to Implement Welfare Overhaul," *Wall Street Journal*. May 16, 1997. p. A20.
- 7 Covey, Stephen R. "The Strange Attractor." *Executive Excellence*. August 1994. pp. 5-6.
- 8 Petzinger, Thomas, Jr. "A Creative Staff Finds New Strength In Its Differences." *The Wall Street Journal*. April, 11, 1997. p. B1.

Chapter 7

Perrow's Quadrants

In building a theory of the world, it helps if one's vision is a little bleary.

We build our orders, but only at the expense of creating randomness elsewhere.

- George Johnson, *Fire in the Mind*

Perrow's quadrants, devised by the sociologist Charles Perrow as a result of his investigation of the Three Mile Island nuclear plant accident, abandons many details. His quadrants are a stripped, minimalist model. That is, they are "tacit," or low-level models, while high-level models, which contain a lot of detail, are "overt." More tacit models are responsive to the call for "coarse-graining;" for a "crude look at the whole," essential for dealing with nonlinear environments, and are a hallmark of Aids to Learning. The following summarizes Perrow's framework.¹

Charles Perrow's book² takes a unique approach to accident prevention and risk management. He focuses upon organizational causes of accidents rather than limiting his study to human error and equipment failure. He

argues some accidents are inevitable and are in fact, normal. To understand Perrow's approach, one must first distinguish between what he calls incidents and accidents. Then, one needs to have a firm grasp upon two key concepts, interaction and coupling, which form the foundation of his thesis. . . .

Incidents and Accidents

Perrow differentiates between simple incidents like backing a car into a telephone pole and nuclear accidents like Three Mile Island. For analysis, he organizes all "systems" (major end items) into four levels. Level one is the *part*, the smallest component of any system. Examples include valves, filters, gauges, etc. Level two is the *unit*, which is made up of parts. Examples are motors, pumps, wiring panels, etc. Level three is the *subsystem*, which is an array of units. Examples include propulsion systems on naval destroyers and navigation sets in aircraft. Level four is the *system* itself, which is the summation of its subsystems. Examples are aircraft carriers and space shuttles.

An incident involves damage to parts (*level one*) and/or a unit (*level two*). An accident "is a failure in a subsystem, or the system as a whole, that damages more than one unit (a subsystem, or *level three*) and in doing so disrupts the ongoing or future output of the system (*level four*)." Incidents and accidents both begin with equipment failure or human error, but accidents continue on out of control with multiple, unanticipated failures in units and subsystems.

Perrow's definitions can be confusing. A truck tire could blow, cause a wreck, and kill a soldier. An extremely serious situation, but one he would categorize as an incident. Perrow takes an impersonal, rational, systemic

approach. . . to analyze potential catastrophes. Integral to his analysis are the concepts of interaction and coupling.

Linear and Complex Interactions

The concept of interaction helps Perrow identify which systems are most prone to accidents. *Linear interactions* describe highly structured systems which are logical, sequential and planned. They function as a series of expected events in a predictable sequence. If damage to a part occurs, the problem can be identified and corrected with little disturbance to the overall system. Linear interactions are also characterized by minimal feedback loops which make it easier to understand and monitor the entire system.

Complex interactions on the other hand, are less predictable. Breakdowns within one or more units and/or subsystems can occur because of unplanned and unforeseen interactions. Unexpected events may occur, regardless of intended system designs. Problems are not easily identifiable in complex systems, especially during the confusion that ensues from an accident.

Advanced technology could make systems more complex and more difficult to understand and predict. Or, innovation could result in increased simplicity. One decreases the chance of accidents by increasing linearity in complex interactive systems. (The big attraction of complex systems lies in production efficiencies, not in safety considerations.) Holding everything else constant, linear designs are inherently more safe.

Tight and Loose Coupling

Perrow's second major concept is coupling, or the amount of "slack, buffer, or give between two items." *Loosely coupled systems* are characterized by decentralized operations, mission orders, ambiguous performance standards, and flexible control mechanisms. Change has little effect upon loose organizations. These types of systems allow a wide variety of responses during emergency situations. If something goes wrong, there is time to correct the problem without catastrophic consequence. Processes do not flow in rigid sequence. Field expedient solutions to problems and substitute equipment are readily accommodated.

Tightly coupled systems are highly centralized and rigid. Output is closely monitored within specified tolerances. Subsystems are interdependent. Change causes massive ramifications throughout the system. Tightly controlled time schedules with little slack are sensitive to delays. Production sequences must be strictly followed. Substitutions are not easily accomplished and equipment breakdowns can bring the entire system to a halt. Safety features must be designed into the system because human intervention is not easily accommodated. Emergency override features may be built-in, but systems design makes on-the-spot, field expedient solutions difficult.

Interaction/Coupling Chart

Figure 7.1 shows relationships between interaction and coupling. A tight-linear organization falls into quadrant 1, tight-complex into quadrant 2, loose-linear in quadrant 3 and loose-complex in quadrant 4. Arguably, examples within the quadrants are used to illustrate various incident/accident potentials.

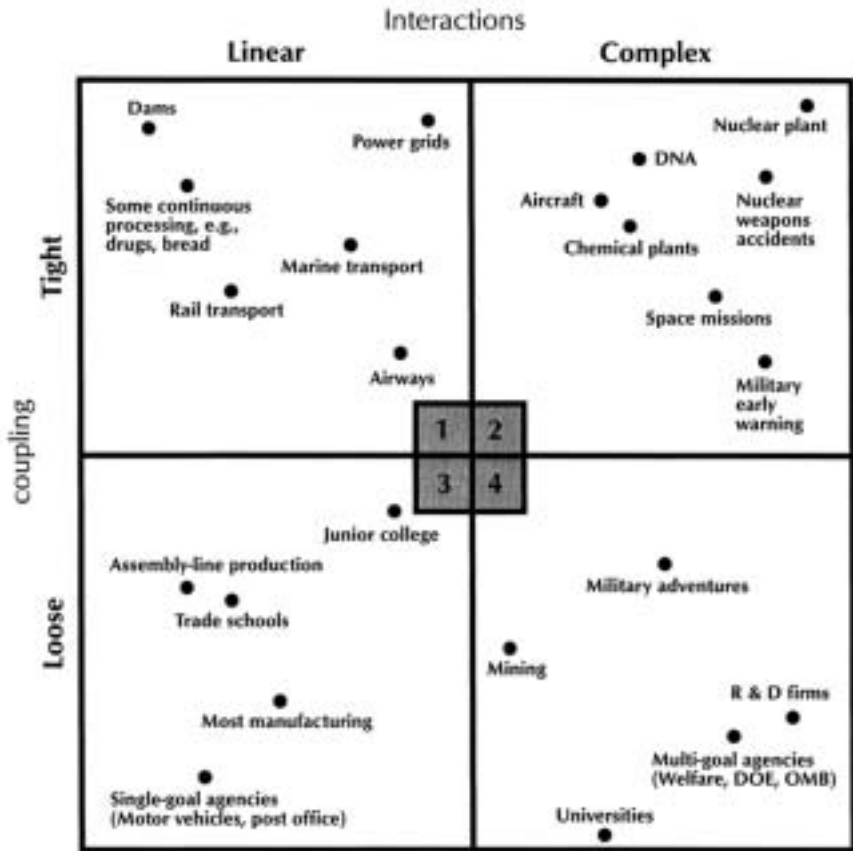


Figure 7.1: Interaction/Coupling Chart

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A railroad company (quadrant 1) is a tight-linear organization. *Tight coupling tendencies:* Trains run on time. Management has limited flexibility in the use of tracks. Trains must be staggered and time buffers rigidly followed. Experienced personnel and specialized equipment are required; substitutes have to meet standards which limit options during emergencies. *Linear interaction tendencies:* Rail cars are spread around the country to meet customer demand. Failures within the system are relatively easy to locate. Direct, online information sources exist. Opera-

tions are sequential and procedures are usually conducted "by the numbers."

NASA (quadrant 2) is a tight-complex organization. *Tight coupling tendencies*: Time schedules are rigidly followed (which partially explains the Challenger disaster). Once a spacecraft is launched, NASA is committed. Specific actions and sequence of events must occur. Safety features are designed into the system and few substitutions of equipment, supplies and personnel are possible. The inflexible nature of this tight system is illustrated by the tremendous ingenuity and luck required for the safe return of Apollo 13. *Complex interaction tendencies*: Highly specialized personnel work in the U.S. space program. Equipment is tightly packed in small spaces and interdependencies of functions are great.

A neighborhood gasoline station (quadrant 3) is a loose-linear organization. *Loose coupling tendencies*: Attendants have flexibility in servicing cars at the pumps and in the bays. Customers have choices between different grades of fuel, viscosities of oil and brand names on repair parts. Backlogs occur at different times of the day with few ramifications. Skills required are relatively few so employees can be readily replaced when problems occur. *Linear interaction tendencies*: Equipment is spread out—tools and diagnostic kits are scattered among the bays and cars. Turnover of personnel has little effect to include summertime when high school kids are hired temporarily. Customers are served on a first come basis, but exceptions can be made easily. Few surprises occur because information sources are direct and firsthand.

A college is a loose-complex organization (quadrant 4). *Loose coupling tendencies*: Class schedules are easily changed based on the availability of the instructor. If textbook

orders are not filled before the semester begins, alternates may be selected or photocopies made of existing texts. Slack is present; a class falling on a holiday is easily slipped to another day. When an instructor is ill, another may substitute or students sit in on another class. *Complex interaction tendencies*: Feedback loops exist between the students, the dean and faculty. . . Indirect and inferential information sources complement the formal feedback loops that provided the impetus for change.

There is less chance of accidents in loosely coupled organizations compared to tightly constructed ones. A catastrophe is far less likely at a gasoline station or a college compared to a mainline on Southern Railroad or during space shuttle flight. Once an incident or accident is about to occur, or is in progress, it is easier for a linear organization than a complex one to control the situation. One can fix a problem easier on a railroad than in a space shuttle.

Perrow's Authority Rules

Based upon his investigations, Perrow concludes that the inherent nature of effective "authority" [or command and managerial processes and styles] fundamentally differs in each individual quadrant, as follows (see Figure 7.2):

- Complex but loosely coupled systems are best *decentralized*.
- Linear and tightly coupled systems are best *centralized*.
- Linear and loosely coupled systems can be *either*.
- But, complex and tightly coupled systems can be *neither*.

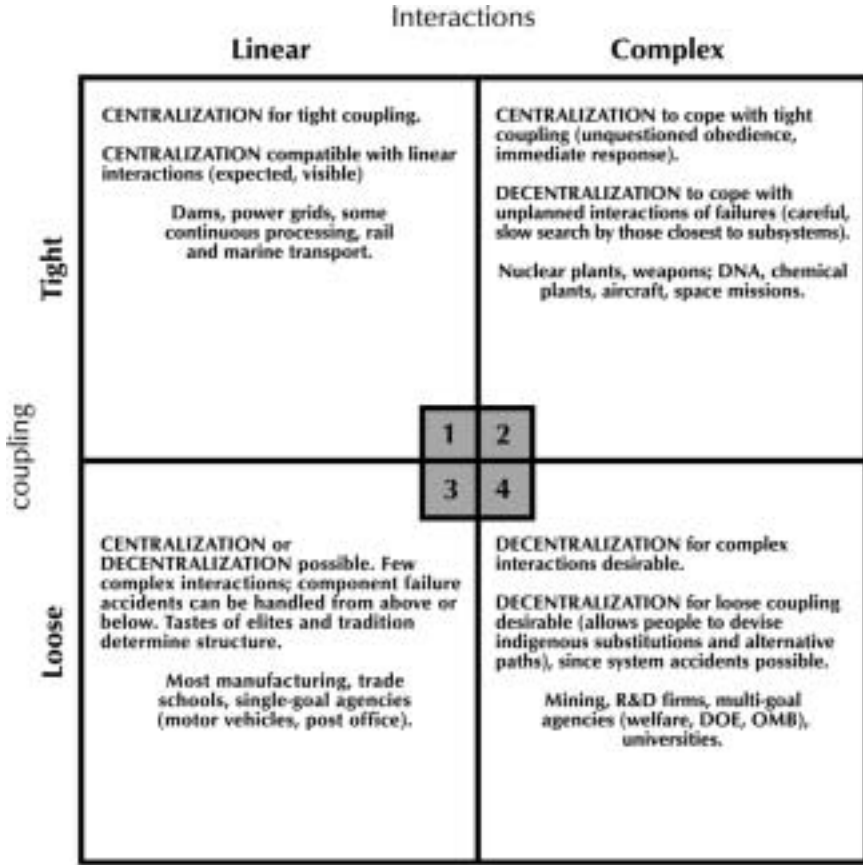


Figure 7.2: Centralization/Decentralization of Authority Relevant to Crises
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Meshing Aids to Learning

It is not only that linear and nonlinear techniques need to be meshed. All kinds of Tools of Analysis are routinely combined every day to solve problems in a linear way. So too can Aids to Learning be intertwined to provide insights. Meshing occurs both between and within these regimes.

In the following example, three nonlinear avenues will be drawn into intersection—Perrow’s Quadrants, the Period-Doubling Cascade of the “playing field,” and Van Creveld’s Rules—providing a focus in which insights yield knowledge. The process is fundamentally different from linearity’s focus on transforming data into information.

Overlaying Perrow’s Quadrants on the Period-Doubling Cascade

Suppose we were to dismantle the quadrants and lay them end-to-end in the following sequence: Tightly linear, loosely linear, loosely nonlinear, and tightly nonlinear, or Quadrants 1-3-4-2 (see Figure 7.3).



Figure 7.3: Quadrant Continuum

What we would have is a continuum that “parallels” the place on which the game of nonlinearity is played. While it is parallel and consistent with the features of the period-doubling cascade, it is not demarcated. Nevertheless, one can conjecture that—

- Quadrant 1 lies at the Edge of Equilibrium.
- Quadrant 2 lies at the Edge of Chaos.
- Quadrant 3 extends to the 2nd bifurcation point, and is effectively mildly nonlinear.

- Quadrant 4 roughly equates to the remainder of the playing field.

The composite picture that is derived, therefore, looks something like Figure 7.4.

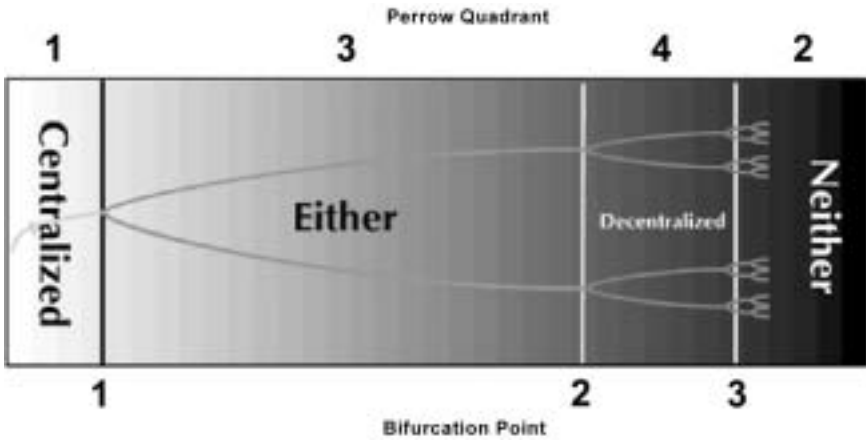


Figure 7.4: Composite Image

Perrow's Quadrants and Van Creveld's Rules

To carry the matter of meshing Aids to Learning one step further: What if we were to relate Van Creveld's Rules to Perrow's Quadrants? I tried that in a article published in *Parameters* in 1996, which is included in the Appendix.³

In this article I suggested that the Army's Force XXI "digitized battlefield" appeared to have the characteristics of a tightly coupled and complex system, and therefore might fall into Perrow's quadrant 2. If so, its future is problematic. Perrow explains that the problem with tightly coupled, complex systems is that

the demands are inconsistent. Because of the complexity, they are best decentralized; because of the tight coupling, they are centralized. While some mix may be possible, and is sometimes tried (handle small duties on your own, but execute orders from on high for serious matters), this appears to be difficult for systems that are reasonably complex and tightly coupled, and perhaps impossible for those that are highly complex and tightly coupled.⁴

Quadrants: An Imaginary Seminar

Perrow's quadrants, shorn of all distracting "noise" and embellishments, yield insights. After all, the obverse of a safety concern can be viewed as a military consideration. They are different sides of the same coin. Imagine the following discussion, somewhat along lines which have occurred in class:

Q: If we assume that democracies don't fight each other, in which quadrant(s) will future threats likely come from?

A: Probably quadrant 1, which has the earmarks of an authoritarian regime.

Q: Where does quadrant 1 lie on the Period-Doubling Cascade continuum?

A: Adjacent to the Edge of Equilibrium. It has minimal nonlinear attributes.

Q: What is its authority rule?

A: Highly centralized—a command and control economy, society, and military.

Q: In terms of "ends" and "means," what is the end?

A: Knock it over the edge into Equilibrium.

Q: What are the means?

A: Affect the small, but critical, elements of its nominal *cas*.

Q: What could be the actual center(s) of gravity? Think of the seven attributes of complex adaptive systems.

A: Usually we focus automatically on *flows* when it comes to centers of gravity. But, in this case, I think we ought to look more carefully at *tagging*. . . [Another student] Wait, if we can't get at that small component of nonlinearity directly, can't we just make the system's linearity even more intense, to the point where we are accomplishing the same thing?

Q: Our force projection lies in which quadrant?

A: Probably quadrant 1, too, assuming that everything but precision strike is ruled out.

Q: Are there exceptions, or is it a rule, that when both opposing forces emanate from the same quadrant that winning can only come through attrition? Are there shades of gray? . . . *and so on, and on.*

Notes

- 1 Smith, Bradley E. "Review of *Normal Accidents: Living with High Risk Technologies*." (Unpublished paper) Industrial College of the Armed Forces. November 26, 1996.
- 2 Perrow, Charles. *Normal Accidents: Living with High Risk Technologies*. New York: Basic Books, Inc. 1984.
- 3 Czerwinski, Thomas J. "Command and Control at the Crossroads." *Parameters*. Autumn 1996. pp. 121-132.
- 4 Perrow: p. 334.

Chapter 8

Systems Dynamics

In the long run, the only sustainable source of competitive advantage is your organization's ability to learn faster than its competition.

- From the dust jacket of *The Fifth Discipline*

Thinking about phenomena as a system has not been around for a long time, perhaps for the past 50 years. This should strike you as strange, even improbable, yet it is true. Terms such as *feedback* are relatively recent additions to our language. It took a long time to understand that despite the hints implied in electrical, hydraulic, and pneumatic circuits, there were such things as systems, and they are all around us in profusion. There have been a succession of systems approaches which have gained attention, and then more or less waned. Among the first was General Systems Theory. Then there was Cybernetics, another relatively high-level model which still finds vogue in some information warfare circles, and of which the Russians have been, and remain, especially fond. The third in this succession can loosely be called *systems dynamics*, to which the name Jay Forrester, who in the 1950s invented core memory for the early mainframe

computers, is associated. We will, however, focus on its foremost contemporary practitioner, Peter M. Senge of the Massachusetts Institute of Technology.

Peter Senge's book's cover proclaims "Over 400,000 copies in print!" That is a lot by any standard. *The Fifth Discipline* has grown with companion fieldbooks, guidebooks, and everything short of a "Cliff notes." It is perhaps the single most influential book in circles dealing with private sector management. Here is a description of systems dynamics based on an interview with Peter Senge.¹

Systems theory is not as gray or mechanical an idea as it sounds. In fact it can be quite lively. One key to systems is nonlinear feedback—and as we've seen, nonlinear feedback can turn the simplest activity into the complex efflorescence of a fireworks display. The systems approach has taken the form of many species of theories that have evolved over the years. There is a general systems [tradition] pioneered by the late Ludwig von Bertalanffy; the cybernetic tradition begun by Norbert Wiener; and the servomechanistic or engineering tradition represented by MIT systems theorist Jay Forrester.

In its various forms and hybrids, the systems idea has been infiltrating virtually every discipline. Departments of systems have sprung up in universities all over the world. . . . Nobel prize economist Herbert Simon announced in 1978 that he had abandoned traditional economic theory and was converting to information and systems theory. However, despite the enthusiasm, the systems approach has yet to prove itself as more than a clever new way of looking at things.

Above Peter Senge's desk at MIT's Sloan School is pinned a drawing by his young daughter. It is a swirling spasm of

lines, a portrait of chaos, on which she has printed in a preschool hand, "Daddy at work." Chaos and uncertainty are indeed part of the work Senge does at the Systems Dynamics Group. . . [which has] taught dozens of corporations and municipalities to deal with management problems through "nonlinear" modeling.

We all have countless models in our heads about how things work. "If the car starts to skid, turn your wheels in the direction of the skid"—that's a model. "Spare the rod and spoil the child"—another model. Some of our models involve feedback but generally not the kind of iterated (positive) feedback that makes for nonlinearity. In business and economics the theoretical models used for planning have traditionally been linear. "Increase the sales force and we'll increase the number of sales," or "Take the growth rate for the last five years and project it for the next five years after compensating for population declines."

But linear models are notoriously unreliable as predictors, which is their usual function. Forecasts don't work out. The population suddenly starts to grow or moves to another part of the country or starts buying less of a product because of some unforeseen reason, such as a gas crisis. Attempts to make predictions suffer a chaotic fate. The predictions fail because the models can't take in the whole of how the elements in sensitive dynamical systems interact. Systems dynamics' answer to this modeling dilemma was to make the essence of the model nonlinear and to shift the emphasis away from prediction.

Nonlinear models differ from linear ones in a number of ways. Rather than trying to figure out all of the chains of causality, the modeler looks for nodes where feedback loops join and tries to capture as many of the important loops as possible in the system's "picture." Rather than

shaping the model to make a forecast about future events or to exercise some central control, the nonlinear modeler is content to perturb the model, trying out different variables in order to learn about the system's critical points and its homeostasis (resistance to change). The modeler is not seeking to control the complex system by quantifying it and mastering its causality; (s)he wants to increase her "intuitions" about how the system works so (s)he can interact with it more harmoniously.

Thus, the development of the systems model exemplifies the shift that the science of chaos and change is making from quantitative reductionism to a qualitative holistic appreciation of dynamics.

How is a qualitative model made? When they work in complex organizations such as corporations, System Dynamics modelers try to identify the written and mental concepts the people in an organization are using when they do their work, the organization's rules and policies, the actual behavior of people in the organizational setting, the organizational structure, its purpose, and numerical data such as how many people are working and when they work. The goal is to see what kinds of loops these elements form. The process of making a nonlinear feedback model is itself a nonlinear feedback process (see Figure 8.1).

"Initially clients are skeptical," Senge says, "'You can't model this; this is not just a system of hard variables. We are talking about innovation, passions of man, all sorts of subtle, unmodelable things.' Their first position is always cynicism. But after a while they get enthusiastic. They see you *can* model the psychology and the subtler dynamics that go on in an organization. They find that if you can talk about something clearly, you can usually model it, and

they get enthused about modeling the subtler dynamics that everybody knows are important.”

The tangle of feedback loops is often immensely complex, of course, but the computer can handle that. Nonlinear equations are assigned to the loops to indicate the precipitous things that happen as values are powered up (“loop gains”) or diminished.

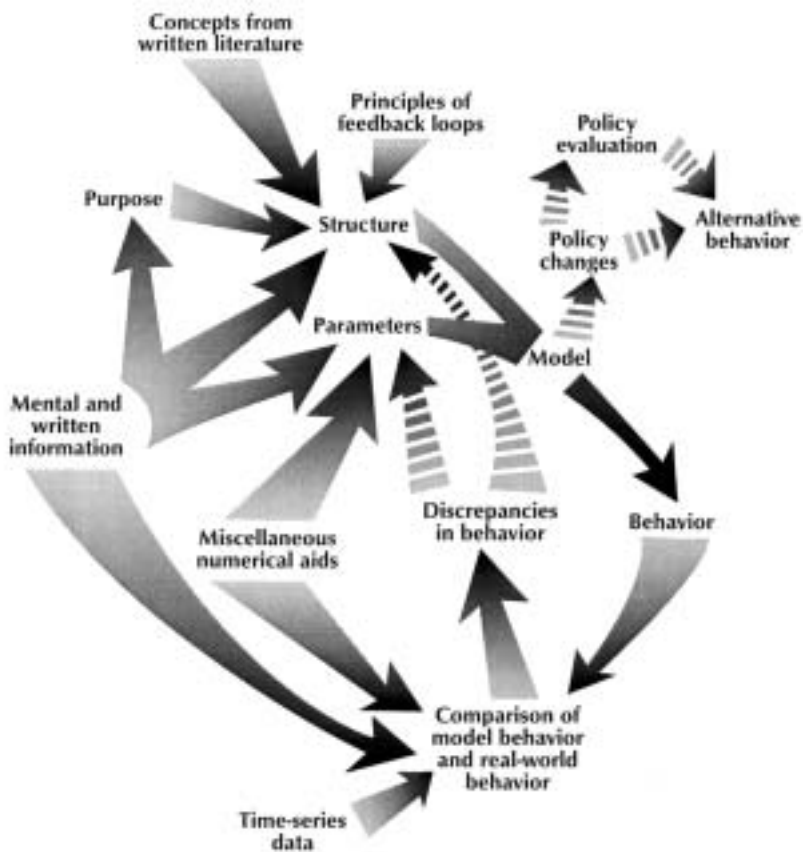


Figure 8.1: A picture of the process of making a nonlinear feedback model is itself a nonlinear feedback process.

What is purposely left out of the model are the “historical,” or “time-series,” data used by linear modelers to compute the ups and downs of past trends the organization has experienced. The nonlinear modeler uses the time-series data not to make the model but to check it. By running the model on the computer, the modeler can see how close his or her picture of the organizational feedback comes to behaving the way the actual organization behaved historically. [*This is a good example of meshing, or interweaving, linear and nonlinear techniques, which is superior to either alone.*]

One advantage claimed for a good model is that you can change the values in different loops, run the simulation on the computer and see what happens. You can try out a policy change, watch the effect on the system of adding staff or cutting staff; you can experimentally change the relationship of different elements, even gauge the possible result of a difference in employee morale or attitude. Because it’s difficult for a human mind on its own to visualize any more than a very few loops, the computer is indispensable to the modeling process.

By studying systems’ complex and varied forms, systems theorists have developed a long list of systems’ principles. Below are a few, summarized by Peter Buttner, an executive for the Boise Cascade Lumber Company and a former student of Senge’s at MIT:

–To permanently change a system you have to change its structure.

–In any given system there are very few “high-leverage points” where one can intervene to produce significant, lasting changes in the overall behavior of the system.

–The more complex the system, the farther away cause and effect usually are from each other in both space and time.

–It doesn't take very many feedback loops before it gets tough to predict the behavior of a system.

–Neither the high-leverage points nor the correct way to move the levers for the desired results tend to be obvious.

–“Worse before better” is often the result of a change of a high-leverage policy in the “right” direction; therefore any policy change that produces better results immediately should almost always be suspect.

Senge, for one, believes that we are only just beginning to understand how to handle such complexity on the social level. He says that when he teaches people how to model systems he starts with “a degree of complexity just within the bounds of your conscious ability” and then escalates the complexity until people dimly grasp the whole without actually being aware of it. He thinks learning to handle complexity means learning to live more intuitively, because intuition is the key to making significant changes in complex systems, helping them evolve, and evolving with them.

“At the deepest level of systems dynamics we are trying to cultivate a unique intuitive/rational sense of when we are getting close to a leverage point. It rarely has any correlation to the symptoms most people focus on, because in a system cause and effect are rarely closely related in time and space.”

The point of people immersing themselves in the complexity is, he believes, to liberate their visions. You want to change the system so that it expresses your unique angle

on things. But the problem is you can't do that mechanically because your unique angle isn't a reducible item; its more of a feel, a nuance. So to get at a vision, the system has to be approached as a subtle whole. The task, as Senge describes it, is obviously not an easy one for minds trained in reductionism. He says that "there's an incredible tell-me-what-I-can-do-so-can-fix-it attitude" that people have about organizations. "We're trying to teach people the systems perspective and part of that is assimilating the ability to grow from acknowledging uncertainty. You're always in an experimental mode. I think it's enormously powerful. It liberates the vision side of things. It also liberates the intellect. In education it lets people operate in a learning mode rather than a fix-it mode, which makes them a hell of a lot more effective intellectually."

However, he admits that while people get insights from systems dynamics, they often don't stick with the process. "I think in the back of their minds is the thought that despite their insights, somewhere along the line they're going to get this reduction, this model of the system which then they'll be able to change mechanically. After a while they see there's no end to this modeling process, the intuitive process, and they get discouraged. The nature of what we're doing doesn't fit with their assumption of a reductionist solution."

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Bear in mind that each successive attempt at systems theory has been launched in the linear domain to probe the nonlinear world, and each got better at it by introducing elements that are more native to the nonlinear environment. Systems dynamics is getting close. Yet, even Senge is concerned that it, like its predecessors, may be on the wane, in which case a

more successful and persuasive form is likely to follow. Yet, the struggle will be uphill, because this Aid to Learning employs higher level models, always operating at the edge of the envelope that nonlinearity will permit, compared to lower-level, more tacit models such as those of Van Creveld and Perrow.

The future of higher level models, such as systems dynamics, remains problematic because they seem to continually bump their head on the low ceiling that nonlinearity permits for entry into its domain. Should systems dynamics yet hit on the right dimensions, becoming just tacit enough for the nonlinear aperture, it has the potential to be a powerful Aid to Learning.

Notes

- 1 Briggs, John and F. David Peat. *Turbulent Mirror*. New York: Harper & Row, Publishers. 1989. pp. 174-80.

Chapter 9

Genetic Algorithms

. . . even as late as 1957, “algorithm” did not appear in *Webster’s New World Dictionary*. The closest word to appear in dictionaries of that time was “algorism,” which means the process of doing arithmetic using Arabic numerals. The word algorithm appears as the result of confusing the word arithmetic with the name of the Persian mathematician Abu Jafar Mohammed ibn Musa al-Khowarizmi (c. 825). . . before it came to have its present meaning of a well-defined procedure for computing something.

- George Markowsky¹

A genetic algorithm is a computer program that is designed to work in much the same way that biological evolution does. The results are not attempts to arrive at *optimal* answers, but *fittest* solutions. A recent article on the front page of the *Wall Street Journal*² describes well the nature and uses of *genetic algorithms* as Aids to Learning:

The cold, digital domain of silicon-based technology is drawing inspiration and new ideas from an unlikely source: the living, breathing realm of nature. Companies

and scientists are turning to a wide variety of natural models—from the way salmon migrate to how the human body fights viruses to evolution—for new approaches to problem-solving. Spurring this unusual alliance is the realization that many problems, similar to the ones humans want to solve, have already been cracked by Mother Nature. Nature offers a “huge library of design metaphors,” says John Hiles, president of Thinking Tools Inc., a Monterey, Calif., company that develops software based on natural analogies. “It’s opening up a wide range of possibilities.” That’s why scientists have studied the human immune system for tips on how to protect against viruses of another kind—those that invade computers. Typical virus-detection programs check software against a database of known viruses. That can let unknown viruses—for which there are no database matches—easily sneak through.

Alien Molecules

To find a new approach, Stephanie Forrest, a computer science professor at the University of New Mexico, has teamed up with Alan S. Perelson, a theoretical immunologist at Los Alamos Laboratory. Together they have created software that attacks unrecognized computer viruses by imitating a neat trick by which immune systems identify alien molecules. The human immune system uses a class of protein-attacking cells known as T-cells. Early in life, the system destroys those T-cells that would attack the body’s own proteins, while keeping all other T-cells. This unusual process, known as “negative selection,” lets the immune system identify intruders it has never encountered before. When T-cells run into a nonbody protein on the surface of an invading virus or a foreign cell, they sound the alarm for other parts of the immune system to arrive and do battle. Professor Forrest and researchers at

Interval Research Corp., a small research-and-development company in Palo Alto, Calif., have built their own “T-cells”—from strings of computer code. As with the immune system, their approach evolves the strings so as to keep only those that are extremely sensitive to “foreign” computer code.

Virus Killers

To test them, researchers unleash both known and unknown computer viruses into a network. The digital T-cells roam around seeking out foreign code and setting up an alarm: a window pops open upon the screen, warning, “A change has been detected.” The software then displays the file where the virus lies. “I really believe that our computer systems are so complicated, we can’t use them effectively till we make them look more like biological systems,” Prof. Forrest says. Interval Research hopes to release a commercial version of the antivirus program in a year or two.

So what, exactly, makes nature such a wizard problem-solver? Her “reckless and random” ways, says David Liddle, a cofounder of Interval and chairman of the board of trustees of the Santa Fe Institute, which supports *nature-inspired* research, an interesting term for complexity. Because humans rely on logical processes, they consider a fairly narrow range of solutions, he argues; nature, on the other hand, takes a sprawling trial and error approach that tests many more potential solutions. “Our view of computer science is rational, mechanistic. But nature winds up doing things in a way we’d never think of,” Mr. Liddle says.

Arms Race

Other scientists have caught the bug. Mr. Hiles of Thinking Tools is borrowing from bacteria to create a computer simulation to teach managers how to handle complex projects, such as building an airport. Traditional software rarely does a good job of imitating the unpredictability of events in the real world. To make his simulator more challenging, Mr. Hiles programmed it to behave like a nasty bacterium, so that the simulator engages in an escalating "arms race" against its host, the user.

Just as the tuberculosis bacteria, because it constantly mutates, ends up developing resistant strains against antibiotics, the simulator keeps changing its responses to a user, manipulating the information and throwing out an unexpected difficulty that the trainee must then tackle. "If a user persists in making a certain kind of mistake, the computer can ruin the operation. So he's pressured to learn," says Mr. Hiles. He hopes to make the simulator commercially available sometime in 1996.

Elsewhere in the world of software, scientists at AT&T Bell Laboratories are on an ambitious quest: to create software that can write itself and solve a problem. But this work isn't under the direction of a software programmer. It is guided by a physicist, Andrew Pargellis. In this pursuit, Mr. Pargellis has built the digital equivalent of the "primordial soup," the mishmash of chemicals from which all life is said to have originated. Dubbed Amoeba, this artificial world consists of 1,000 rectangles that flit about on a computer screen. Each rectangle represents a piece of randomly generated software code that contains certain mathematical instructions. Since the original primordial soup spontaneously gave rise to life, Mr. Pargellis reasons, why can't an artificial soup spontaneously generate the

answer to the problem? So Mr. Pargellis sets a test problem for each rectangle: Copy thyself.

Evolving Rectangles

At first, the rectangles flit about on the screen chaotically. No one rectangle carries all the instructions to execute the command. But some contain bits of code that, when combined with that of others, would let them pull it off. Sooner or later, one rectangle—a red one, say—gathers up the right instructions to let it copy itself, albeit clumsily, taking five or six separate steps. Still, red rectangles begin to proliferate, dominating the screen. Then random mutations—an alteration in the code in certain inhabitants—begin to help; although most mutations are harmful, eventually a mutation will be beneficial, letting a blue rectangle, say, copy itself in fewer steps. This means the blue rectangles are more “evolved,” and they eventually take over the screen. Other mutations could let still another colored rectangle copy itself even faster.

The point is that the software itself, long after Mr. Pargellis gave it vague instructions, keeps seeking out better ways to carry out the directive. “The implication is that one could define a problem and let software evolve to solve that problem,” Mr. Pargellis says. So far, Amoeba has only proved itself in solving elementary arithmetic problems. But someday, this kind of self-writing software may handle the burden of creating millions of lines of base code, letting human developers focus on the hard stuff.

Ones and Zeros

One of the first approaches to borrow ideas from evolution came in the 1950s—“the genetic algorithm,” invented by John Holland at the University of Michigan. Dozens of

companies have applied this technique to a range of programming problems. Prof. Holland's main insight: the way ones and zeros are strung along a piece of computer code is similar to the way genes are strung along a chromosome.

In evolution, the best solutions—the traits that let a species survive—win out after long periods in which organisms occasionally pass on mutant genes to offspring. These offspring with beneficial mutations tend to thrive, and those with insufficient traits tend to die out. Prof. Holland figured that, in computers, if you combine and recombine strings of ones and zeros in a similar way, they would yield ever-better solutions. When he proffered this notion about 40 years ago, “it was greeted with resounding indifference,” he recalls. Critics would joke, “You don't have enough time to imitate evolution.”

But the genetic algorithm has become a hit. Moody's Investment Service uses it to farm out hundreds of computer-service jobs. Organizers of the 1992 Paralympic Games used it to schedule events, LBS Capital Management of Clearwater, Fla., uses the algorithm to help pick stocks for a pension fund it manages. “Three billion years of evolution can't be wrong,” says David Goldberg, an engineer and genetic-algorithm pioneer at the University of Illinois at Urbana-Champaign. “It's the most powerful algorithm there is.”

Making a Face

One of the more unusual applications is the FacePrints project, which uses a genetic algorithm to help witnesses describe and identify criminal suspects. Witnesses who are interviewed often can't conjure up a suspect's individual features; they are much better at recognizing entire faces. The FacePrints project runs through random illustrations

of faces on a computer screen, combining and recombining features dozens of times until the best solution emerges. "A particular face has on one billion possibilities. This lets us search an enormous 'face space' very quickly," says the FacePrints inventor, Victor S. Johnson, a psychology professor at the New Mexico University at Las Cruces.

His technology got a real-world test after one of his students, Craig Caldwell, and two companions were robbed of \$22 outside a restaurant. They took turns at a computer. It generated 30 random pictures of faces, which were rated in order of likeness to the assailant, then threw up 30 more, which were rated again. The process was repeated dozens of times "until I was satisfied the picture resembled the criminal," Mr. Caldwell says. "The final three images that the three witnesses separately created were strikingly similar."

How did FacePrints do it? Using a genetic algorithm, the software "evolved" the picture. FacePrints consists of hundreds of individual features—a hooked nose, a bushy brow—and each is written in a digital string of computer code. When Mr. Caldwell rated the first 30 random faces, slapped together from 30 arbitrary combinations, he was performing the FacePrints equivalent of natural selection. The picture with the highest rating was then "bred" with another picture to produce a new choice; to make room for it, the software "killed off" a few less-likely pictures—and so on, so that each "new" population of 30 faces was slightly "fitter" than the last. In the Caldwell case, the resulting picture was printed in the local paper. Although the bandit remains at large, the police were impressed. "Their picture had more detailed features than our pictures," says Kay Hernandez, a Las Cruces police detective. Prof. Johnson is setting up a company to commercialize his invention.

Directing Traffic

Sometimes the models offered by nature are fuzzier. At Texas Instruments Inc., researchers in collaboration with Thinking Tools are building a computer system to help shipping companies efficiently dispatch goods to far-flung areas. Their inspiration? The navigation skills of salmon. Just as a salmon finds the way to a spawning ground, so might thousands of packages each 'seek' their own best routes to particular destinations. At big shipping companies, traffic is typically controlled by a central computer. When volume soars, the system can fail. TI researchers figure each crate could have a small screen that tells baggage handlers where it is headed. A built-in sensor would wirelessly pull up relevant data from the shipper's computer. Warned of an accident on a particular route, the crate would independently search out the next best path and display new instructions on its screen.

Just as nature can offer new approaches, so can experts in one field, when they cross-pollinate their skills in another discipline. At AT&T Corp.'s computer division, Kenneth L. Reed works on developing sales-forecasting models for retailers. Yet his specialty is ecology. As a Yale professor, he and others modeled forest growth by measuring the overall sunlight falling on a given area—and got better results than when they tried extrapolating from the amount of light hitting an individual leaf. [*This is a good example of coarse-graining in order to get a "crude look at the whole."*] Mr. Reed now is on a loftier quest. Using a technique called "evolutionary programming," he hopes to create software that can produce the perfect product mix for each store in a big chain. "We haven't tried it yet," Mr. Reed says, "but we think it will work." He laughs. "We're looking for guinea pigs."

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The actual workings of a genetic algorithm are described in the following example by LTC Steven M. Rinaldi. The subject is the selection of target sets for an air strike involving some mix of electrical and petroleum networks. As you can see, the process follows closely the nonlinear biological process of evolution.³

In the natural world, the fitness function of an organism is a measure of its ability to survive in a given environment. Reproduction, exchange of genetic material, mutations, and natural selection change the genetic code of successive generations of the organism, either improving their positions on the fitness landscape or not. A genetic algorithm (GA) uses the same basic processes to evolve optimal solutions to problems inside a computer. Like its organic counterparts, the GA creates “generations” of solutions that progressively move toward the global maximum of the fitness function. In solving the problem, the GA mimics naturally occurring biological processes. . . .

A principle element of a GA is the gene string or *genotype*. The simplest and most general prototype occurs in the binary combinatorial optimization problem. Here, there are n discrete elements or variables, such as n potential targets. Let a_i represent the i th element. Since the elements are binary, they can take only one of two values, 0 or 1 (on or off, attacked or not attacked, etc.). Concatenating the elements in a string yields a binary variable $a_1, a_2, a_3, \dots, a_n, \dots$ correspond(ing) to a point in the configuration space. For example, 0111001011 and 1101010011 are two points in the configuration space of an $n=10$ binary problem. In an analogy with the biological case, the string . . . represents a chromosome (genotype), each bit

position of the genotype corresponds to a gene, and each gene represents the state of a particular discrete element. Consequently, the genotype represents all of the possible system configurations.

A second key element of the GA is the fitness function. . . the embodiment of the problem at hand. . . In the targeting problem, the value of the fitness function denotes how well a given targeting solution. . . meets the commander's requirements. . . the fitness function will change for every targeting scenario. In all scenarios, the GA will attempt to "evolve" high fitness targeting solutions.

The operation of a GA parallels the biological processes of selection, reproduction, and genetics. . . The algorithm begins by creating an initial population of *individuals*. That is, the routine generates m values of $a_1, a_2, a_3, \dots, a_n$. . . Each individual is a trial solution to the optimization problem. . . Once the program has created the population, it is ready to pass to the reproduction step. As the name implies, the reproduction step creates the next generation of individuals. First, the routine evaluates the fitness function for each individual. The fitnesses determine whether an individual survives to the next generation or dies out. The average fitness of the successive generation is generally higher than that of the previous one.

Following reproduction and selection, the algorithm performs two crucial operations. The first is crossover, in which two individuals swap blocks of genetic material. . . In the second operation, a mutation operator selects an individual at large and then randomly flips one of its bits. . . Crossover and mutation are important steps that maintain the diversity of the population as well as allowing the algorithm to sample large regions of the configuration space. . . .

The above description sketches a highly simplified picture of the main steps of a GA. Researchers have modified this simple routine in many ways, adapting it to a variety of problems.

The problem centers on the notional electrical and POL [petroleum, oil, and lubricants] networks of some hypothetical country. Following the output-based targeting philosophy, the friendly commander has decided that certain sectors of the electrical grid and POL networks must be destroyed. Their elimination will hamper enemy efforts: integrated air defenses and communications networks will suffer from power outages, electrified rail transportation for mobilization will shut down, motorized transportation will be hindered from the loss of POL resources, and so forth. The adversary can use backup electrical power generation and stockpiles of POL to overcome some of the immediate losses of economic resources. However, we are also interested in the synergistic effects that arise from the couplings between the networks.

In more concrete terms. . . the commander has decided that the electricity and POL pipelines must be shut down in the eastern half of the adversary nation. To facilitate reconstruction efforts after the conflict, those elements targeted for destruction must be repairable within 6 months. This restriction eliminates certain potential targets, such as generators and their step-up transformers. Furthermore, we assume that the ROEs constrain the attack sorties to the eastern third of the nation. The problem thus poses objectives as well as several constraints. The fitness function must include all of these considerations. . . The program employs a genetic algorithm to evolve targeting solutions that meet the commander's requirements.

The Genotype

Our notional targeting problem is an example of binary combinatorial optimization. The electrical grid and POL network consist of n components (lines, buses, transformers, generators, pipeline segments, compressor and pump stations, etc.), where n is some large integer. Each component can be in one of two states: targeted (and assumed destroyed during an attack) or untargeted. If the variable a_i is the state of the i th component, then it takes one of two values, 0 for untargeted (undamaged) and 1 for targeted (destroyed). The state of the entire electrical grid and POL network is then represented by the genotype $a_1a_2a_3 \dots a_n$. The genotype takes the particularly simple form of a binary variable.

The genotype will be long if the number of components n is large. However, if the number of targets that can be attacked is limited (by available aircraft, munitions, etc.) and is much less than n , then the genotype will be sparse. Compression of the genotype information will reduce the storage requirements, especially if the population size m is large. For example, in a very sparse genotype, it is only necessary to store a set of pointers that indicate which components are targeted, rather than storing information about each component.

The Fitness Function

The fitness function f is arguably the most important part of the routine. It is the embodiment of the targeting problem, and as such must incorporate the commander's objectives and all constraints and restraints. . . considerable care must go into its development.

Each electrical grid and POL network component has an associated set of rewards and penalties. In keeping with the commander's desires, every electrical grid and POL network component in the eastern half of the country that shuts down as a result of the attack accrues a positive reward. Likewise, every eastern transmission line or pipeline that is still operational after the attack incurs a negative penalty. Any targeted facilities in the western two-thirds of the nation will also incur negative penalty. Note that there is no penalty for components still running in the western half of the nation. Some components may be weighted more heavily than others. . . For example, if the commander determines that destroying the electrical grid is more important than shutting off the POL flow, the electrical grid rewards would be correspondingly higher than those for the POL network. Note that the values of the penalties and rewards may require tuning to improve the convergence of the GA. . . [The table on the next page] lists the rewards and penalties for our particular problem.

Each component, then, has an associated set of weights. The weights form a vector. . . ri, sj, ti, uj, vi, wi . Using the weights from the table, a destroyed electrical grid component on the eastern border of the country with a repair time of 2 years (such as a step-up transformer) would have (100, 0, 0, 0, -25, 0) as its vector. A destroyed pump station with a 4-month repair time located in a restricted flight zone but in the eastern half of the country would be characterized by (0, 50, 0, 0, 0, -100). If the same pump station is unattacked but nevertheless shut down, its vector becomes (0, 50, 0, 0, 0, 0). Similarly, every component in the data base has a weight factor.

The fitness function is given by the sum of the rewards and penalties over all grid elements. The maximum value f_{max} is simply the sum of the rewards ($ri+sj$) which occurs when

all components in the eastern half of the country are down, and no constraints have been violated. With this particular fitness function, the program must attempt to find a target set that maximizes f .⁴

<u>Variable</u>	<u>Type</u>	<u>Weight</u>	<u>Description</u>
ri	reward	100	Electrical grid component in the eastern region that is shut down
si	reward	50	POL component in the eastern region that is shut down
ti	penalty	-80	Electrical grid component in the eastern region that is running
ui	penalty	-40	POL component in the eastern region that is running
vi	penalty	-25	Attacked component has a repair time of >6 months
wi	penalty	-100	Attacked component is in the restricted zone

Program Logic

In general terms, the algorithm is composed of a nodal analysis section and an optimization routine. The nodal analysis section performs load-flow and hydraulic analyses, and incorporates the interconnections between the two systems. This section draws heavily upon the database. The optimization routine computes the fitness function values and generates new target sets for evaluation. Figure 9.1 illustrates the flow of the algorithm.

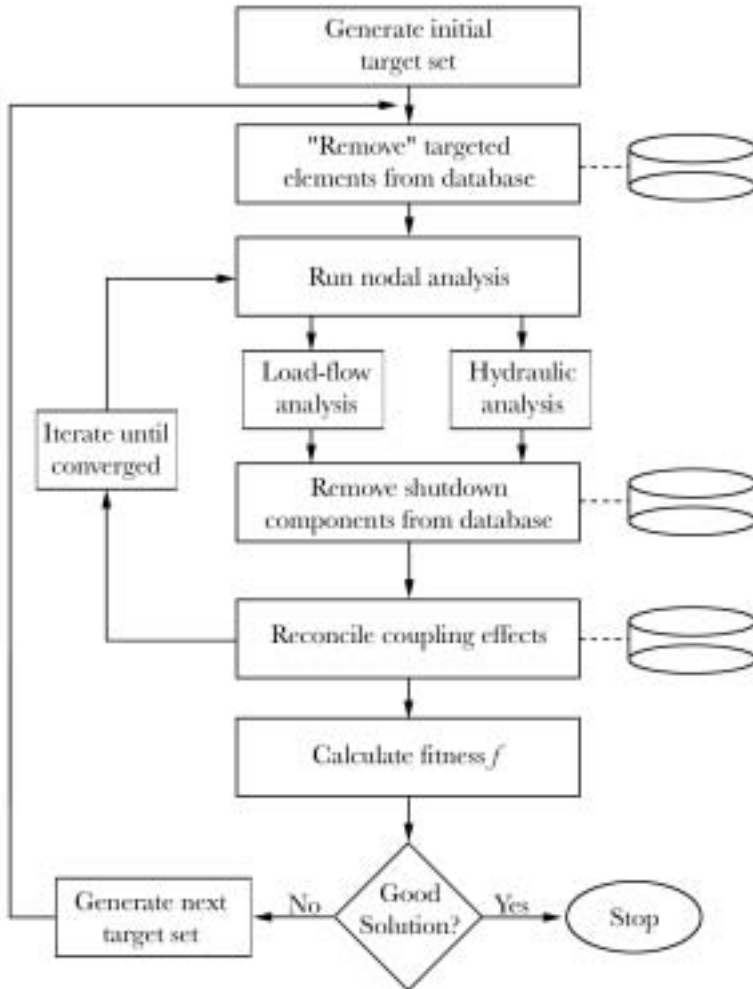


Figure 9.1: Genetic Algorithm Flow

The nodal analysis begins after some initial set of targets is generated. The initial target set can be randomly generated, determined by some algorithm, or input by the planner. (Each individual in the population pool is, in essence, an attack plan. The value of the genotype indicates which components are attacked or bypassed.)

The manner in which the electrical grid-POL system linkages are incorporated merits further discussion. The program uses an iterative technique to determine the synergistic results of an attack. First, the routine simulates the attack by “removing” any targeted components from the database. The result is a “post-attack” database used in the ensuing nodal analyses. This database (or genotypes) reflects the state of the electrical grid and POL distribution system immediately after the attack.

Second, the routine performs separate nodal analyses of the two elements. In each step, the program analyzes each element *in isolation* from the other. In essence, the program calculates the effects of the damage on each element without regard to synergistic couplings. The analyses determine the components that shut down due to the attacks. Any such electrical grid or POL pipeline component is removed. . . (leaving) only those components still functioning *in the isolated economic elements*.

Third, the routine reconciles the effects of the couplings between the two elements. For example, if electricity is lost to a substation that feeds a pipeline pump, the pump ceases to function. Although the pump was not directly attacked, the loss of electricity causes the pump failure. The routine then removes the pump from the post-attack database. Similarly, if the natural gas line feeding a gas-fired electrical generator shuts down, the electrical generator drops offline. . . At this point, the program has removed any components that either were destroyed in the attack, “failed” during the isolated nodal analyses, or shut down due to synergistic couplings.

Fourth, the program repeats the nodal analysis-reconciliation steps. . . In essence, the program calculates the cascading failures within and between the two elements

of the model. . . Eventually, the routine will converge to a post-attack database that undergoes no further changes. This database represents the final operating state of the model after the attacks. It includes the results of the synergistic couplings and cascading failures. Therefore, the last nodal analysis yields the final state to which the coupled economic elements deteriorate. The optimization routine commences by determining the fitness f of the target sets. If f is sufficiently high or if the results of the attack achieve the commander's requirements, the routine terminates. Otherwise, the routine generates a new set of targets and iterates.

Notes

- 1 Markowsky, George. "An Introduction to Algorithmic Information Theory." *Complexity*. March/April 1997. p. 14.
- 2 Naik, Gautum. "Back to Darwin: Genetic Algorithm Software." *Wall Street Journal*. January 16, 1997. p. 1.
- 3 Rinaldi, Steven M. *Beyond the Industrial Web: Economic Synergies and Targeting Methodologies*. Maxwell AFB, AL: School of Advanced Airpower Studies. April 1995. pp. 46, 48-49 and 53-55.
- 4 Rinaldi, Steven M. *Targeting Modern Economies: Economic Synergies and Nodal Analyses*. Draft, unpublished paper. March 26, 1996. pp. 15-17.

Chapter 10

Pattern Recognition

Though intelligence doesn't allow us to overcome the second law (of thermodynamics), it remains true that creatures with more acute senses and more powerful brains will see patterns where others see randomness.

- Paul Johnson, *Fire in the Mind*

Obviously, this is an act of the imagination. Things are perceived. Of course, partly by the naked eye and partly by the mind, which fills the gaps with guesswork based on learning and experience, and thus constructs a whole out of the fragments that the eye can see.

- Clausewitz, *On War*: p. 109

The "highest" form of Aids to Learning is *pattern recognition*, which is closely related to the building block mechanism of complex adaptive systems covered in Chapter 1. It is a non-linear cognitive process that involves the difficult transition from the ingrained habit of deductive reductionist thought to more inductive processes in which powers of pattern recognition are enhanced and intuition is elevated. By intuition, we mean not so much instinct as the product of the experiential

provided by training and education, as well as experience itself. A major requirement for pattern recognition capabilities is to infuse lower echelons with both the confidence and competence to engage in semiautonomous action in accordance with Van Creveld's Rules. As pattern recognition is the analogue to the building block mechanism of *cas*, recognition-primed decisionmaking is the scholarly exploitation of pattern recognition in the field of the cognitive sciences.

Gary Klein, an applied cognitive psychologist who has done work for the Air Force Human Resources Laboratory, the Army Research Institute, and the Marine Corps' Combat Development Command, has been a pioneer in pattern recognition. In 1989, he wrote:¹

It is time to admit that the theories and ideals of decision-making we have held over the past 25 years are inadequate and misleading, having produced unused decision aids, ineffective decision training programs, and inappropriate doctrine. . . DoD often follows the lead of behavioral scientists, so it is important to alert DoD policy makers to new developments in models of decisionmaking.ⁱ

The culprit is an ideal of analytical decisionmaking which asserts that we must always generate options systematically, identify criteria for evaluating these options, assign weights to the evaluation criteria, rate each option on each criterion and tabulate the scores to find the best option. We call this a model of concurrent option comparison, the idea being that the decisionmaker deliberates about several options concurrently. The technical term is *multiattribute utility analysis*.

Another analytical ideal is decision analysis, a technique for evaluating an option as in a chess game. The decisionmaker looks at a branching tree of responses, and counter-

responses and estimates the probability and utility of each possible future state in order to calculate maximum and minimum outcomes. Both of these methods, multiattribute utility analysis and decision analysis, have been used to build decision training programs and automated decision aids.ⁱⁱ

These strategies sound good, but in practice they are often disappointing. They do not work under time pressure because they take too long. Even when there is enough time, they require much work and lack flexibility for handling rapidly changing field conditions.

Imagine this situation (which we actually observed): An Army brigade planning staff engages in a 5-hour command and control exercise. One requirement is to delay the enemy advance in a specific sector. The operations and training officer (S3) pinpoints a location that seems ideal for planting mines. It is a choke point in a wooded area where the road can be destroyed. A plan develops to crater the road, mine the sides of the road and direct the artillery on the enemy as he either halts or slows his advance to work around the obstacles. During the planning session, there are objections that it is impossible to have forward observers call in the artillery, and that without artillery support to take advantage of the enemy slowdown, the mines would do no good. Someone suggests using FASCAM (family of scatterable mines), but another person notes that FASCAM will not work in trees. Only after this thorough consideration and subsequent rejection of his original choice, does the S3 consider an open area also favorable for an artillery attack and select it as the point of the action.

Suppose the planners had tried to list each and every available option, every possible site all over the map, and then

evaluate the strengths and weaknesses of each? There was simply not enough time in the session to do this for each possible decision. We counted 27 decisions made during the 5 hours, an average of one every 12 minutes. Even if this is misleading, since it does not take into account time taken by interruptions and communications. We estimate that about 20 of the decisions took less than 1 minute, five took less than 5 minutes and perhaps only two were examined for more than 5 minutes. Obviously, there was not enough time for each decision, using analytical concurrent option comparisons. And if we try to approach only a few choices in this way, which ones? It is even more complicated to screen decisions for deliberation. Analytical strategies just will not work in this type of setting.

I am not saying that people should never deliberate about several options. Clearly, there are times to use such analytical strategies. We have watched DoD design engineers wrestle with problems such as how to apply a new technology to an existing task. Here it *did* make sense to carefully list all the options for input displays and to systematically analyze strengths and weaknesses to get down to a small number of configurations for testing.

The point for this article is that there are different ways to make decisions, analytical ways, and recognitional ways, and that we must understand the strengths and limits of both in order to improve military decisionmaking. Too many people say that the ideal is for soldiers to think more systematically, to lay out all their options and to become, in effect, miniature operations researchers. This attitude is even built into military doctrine. For example, U.S. Army Field Manual 101-5, *Staff Organizations and Operations*, advises decisionmakers to go through the steps of multiattribute utility analysis.ⁱⁱⁱ Such advice may often be unworkable and sometimes may be dangerous. To under-

stand why, we must get a clear idea of what skilled decisionmakers do.

For the past 4 years, my colleagues and I have been studying experienced decisionmakers, faced with real tasks that often have life and death consequences. We have studied tank platoon leaders, battle commanders engaged in operational planning at Fort Leavenworth, Fort Riley, Fort Hood, Fort Stewart, and the National Training Center at Fort Irwin. (Prior to that, we observed Air Force and Army battle commanders at *BLUE FLAG*.) We studied urban fireground commanders and wildland fireground commanders (with over 20 years of experience) as they conducted actual operations. We also studied computer programmers, paramedics, maintenance officers, and design engineers. Many of the decisions we examined were made under extreme time pressure. In some domains more than 85 percent of the decisions were made in less than 1 minute.

We found that concurrent option comparison hardly ever occurred. That is, experienced decisionmakers rarely thought about two or more options and tried to figure out which was better. In this article, I will describe the recognitional decision strategies we did find, differentiate between the situations that call for analytical or recognitional strategies and examine some of the implications for military decisionmaking.

Recognitional Decisionmaking

When we told one commander that we were studying decisionmaking, he replied that he never made any decisions! What he meant was that he never constructed two or more options and then struggled to choose the best one. After interviewing him, we learned that he did handle decisions

all the time. After studying over 150 experienced decision-makers and 450 decisions, we concluded that his approach to decisionmaking is typical of people with years of experience and we have derived a model of this typical strategy.

Basically, proficient decisionmakers are able to use their experience to recognize a situation as familiar, which gives them a sense of what goals are feasible, what cues are important, what to expect next and what actions are typical in that situation. The ability to recognize the typical action means that experienced decisionmakers do not have to do any concurrent deliberation about options. They do not, however, just blindly carry out the actions. They first consider whether there are any potential problems and only if everything seems reasonable, do they go ahead. . . .

We call this a recognition-primed decision (RPD). The officer used experience to recognize the key aspects of the situation, enabling a quick reaction. Once a decisionmaker identifies the typical action, there is usually a step of imagining what will happen if the action is carried out in *this* situation. If any pitfalls are imagined, then the officer jettisons it and thinks about the next most typical action. . . the experienced decisionmakers are not searching for the best option. They only want to find one that works, a strategy called "satisficing." [*Recall George S. Patton's saying, "A good plan executed now is better than a perfect plan next week."*] We have found many cases where decisionmakers examined several options, one after the other, without ever comparing one to another. Because there is no deliberated option comparison, experienced decisionmakers may feel they are relying on something mysterious called "intuition" and they may be mildly defensive about it if they are questioned carefully. One implication of our work is that this is not a mysterious process. It is a recognitional, pattern-matching process that flows from experience. It should not

be discounted just because all aspects of it are not open to conscious scrutiny.

Figure 10.1, a schematic drawing of the RPD model, shows that if the events contradict expectancies, the experienced decisionmaker may reexamine the way the situation is being understood. The basic thrust of the model is that decisionmakers handle decision points, where there are several options, by recognizing what the situation calls for rather than by calculating the strengths and weaknesses of the different options. The concept of recognitional decisionmaking has been developing only in the last few years.

We have found that even with nonroutine incidents, experienced decisionmakers handle approximately 50 to 80 percent of decisions using recognitional strategies without any effort to contrast two or more options. If we include all decision points, routine plus nonroutine, the proportion of RPDs goes much higher, more than 90 percent. For novices, however, the rate of RPDs can dip to 40 percent. We have also found that when there is deliberation, experienced decisionmakers deliberate more than novices about the nature of the *situation*, whereas novices deliberate more than experts about which *response* to select. In other words, it is more typical of people with lower levels of experience to focus on careful thinking about the best option.

What about team decisionmaking? Since many decisions are made within a network of coordinating organizations and by several people at each node in the network, we have also examined distributed decisionmaking.

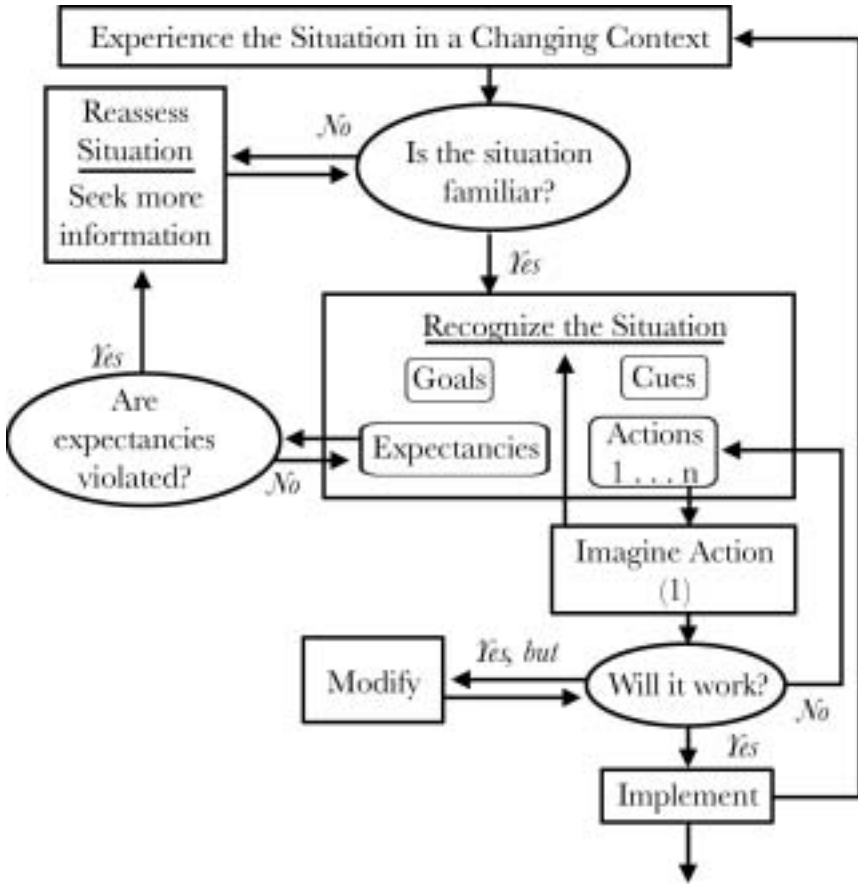


Figure 10.1: Recognition-Primed Decision (RPD) model

Teams and networks demand more justification and conflict resolution, so we expect to find more examples of concurrent option comparison; that is, contrasting two or more options. However, in our studies, this has not occurred. Earlier I described a 5-hour command and control planning session in which we tabulated 27 decisions.^{iv} Only one of these showed any evidence of concurrent option comparison. . . . Similarly, our other studies of team decisionmaking found the team behaving much like individuals—generating a plausible option, evaluating it by

imagining what could go wrong, trying to “satisfice,” trying to improve the option to overcome its limitations and sometimes rejecting or tabling an option to move on in a more promising direction.

How is the RPD Model Different from Analytical Decisionmaking?

The RPD model describes how choices can be made without comparing options: by perceiving a situation as typical; perceiving the typical action in that type of situation; and evaluating potential barriers to carrying out the action. This recognitional approach contrasts to analytical decisionmaking in several ways:

–The RPD model concentrates on “satisficing,” whereas models of decision analysis and concurrent option comparison have emphasized optimizing (trying to find the *best* option).

–The RPD model asserts that experienced decisionmakers generate a good option as the first one they consider. However, concurrent option comparison assumes that generating options is a semirandom process, with some coarse screening to ensure that only relevant options are considered.

–The RPD model focuses on situation assessment. In contrast, concurrent option evaluation models have placed more of the emphasis on selecting among options than on recognizing situations.

–Another difference is the evaluation of options. The RPD model assumes that decisionmakers evaluate typical actions by imagining how they will be carried out in that situation. Such an evaluation lets the decisionmaker improve the option and also reject it, if necessary. Analyti-

cal models present strong methods for evaluating sets of options. These models make it inconvenient for the user to improve options since that would force the evaluation to begin again.

–The RPD model assumes that the decisionmakers will usually have an option available regardless of how tight the time constraints are. Experienced decisionmakers usually start with a typical option. If time permits, this option will be evaluated; if defective, it will be replaced by the next most typical action. In contrast, analytical models provide no guidance until after options are generated, evaluation criteria and weights established, ratings accomplished and tabulations completed. If a reaction is needed before this process is finished, the decisionmaker is out of luck.

By contrasting recognitional and analytical decisionmaking, we can see the strengths of each. Recognitional decisionmaking is more important when experienced personnel are working under time pressure on concrete, contextually dependent tasks in changing environments and have a “satisficing” criterion of selecting the first option that looks like it will work. It comes into play when the unit is an individual or a cohesive team that does not reach deadlocks over conflicts. Recognitional decisions can ensure that the decisionmaker is poised to act. Its disadvantages are that it is hard to articulate the basis of a decision and it is difficult to reconcile conflicts. Furthermore, it cannot ensure “optimal” courses of action and that is especially important for anticipating the opponent’s strategies in preparation for the worst case. Also, it is risky to let inexperienced personnel “shoot from the hip.”

Concurrent option comparison has the opposite strengths and weaknesses. It is more helpful for novices who lack an experience base and for seasoned decisionmakers con-

fronting novel conditions. It is apt to be used when there is ample time for the decision. It comes into play when the data are abstract, preventing decisionmakers from using concrete experiences. It makes it easy to break down new tasks and complex tasks that recognition cannot handle. It is especially important when there is a need to justify the decision to others, since justification usually requires us to list reasons and indicate their importance. Analytical decisionmaking is more helpful when there is a conflict to be resolved, especially when the conflict involves people with different concerns. It is usually a better strategy to use when one needs an optimal solution. And finally, analytical decisionmaking is needed when the problem involves so much computational complexity that recognitional processes are inadequate. However, its cost is more time and effort, and more of a disconnect with the experience of the decisionmaker. . . .

I am not claiming that there is a right way or a wrong way to make decisions. Different conditions call for different strategies. My goal is not to reject analytical decisionmaking, but to make clear what its strengths and weaknesses are so that it can be applied more fruitfully. For too long we have emphasized one strategy—the analytical one. That is the one required by doctrine. That is the one we have been teaching. That is the one we have been building decision aids to promote.

Problems with Analytical Decisionmaking

We create problems of *credibility* when we present doctrine about one right way to make decisions—the analytical strategy—and thereby force officers and soldiers to ignore doctrine in making the vast majority of time-pressured operational decisions during training exercises. It does not take them long to realize that doctrine is irrel-

evant in this area and to wonder whether it can be trusted in other areas.

We can create problems in *efficiency* when we teach analytical decision techniques to military personnel who will have little or no opportunity to use them. Worse yet, we create problems in *effectiveness* for personnel who try to apply these techniques and fail.

We create problems of *competence* when we build decision aids and decision support systems that assume analytical decision strategies. These systems are likely to reduce inputs to the form of abstract alphanumeric data and to restrict the operator's job to that of assessing probabilities, entering subjective utilities, providing context-free ratings and so forth. This misses the skilled operator's ability to size up situations, to notice incongruities and to think up ways to improve options. In other words, these decision aids can interfere with and frustrate the performance of skilled operators. It is no wonder that field officers reject decision aids requiring them to use lengthy analytical processes when the time available is not adequate.

Human error is often explained in terms of decision bias.^v The concept of decision bias is that people are predisposed to make poor decisions because of several inherent tendencies, such as inaccurate use of base rates, overreliance on those data that are more readily available or appear more representative, low ability to take sample size into account and difficulty in deducing logical conclusions. The argument is often made by scientists who want to convince us that human decisionmakers (other than themselves) cannot be trusted, and we therefore need these scientists to develop decision aids to keep the rest of us from making grievous errors.

However, the decision bias argument has been recently attacked as unjustified and self-serving.^{vi} The evidence that humans are inherently biased decisionmakers comes from experiments run under artificial laboratory conditions. Furthermore, judgment biases appear to have a very small impact outside laboratory conditions. It is easy to use the benefit of hindsight to label each accident an example of decision bias that can best be controlled by more rigorous analytical procedures.

My own impression is that experienced decisionmakers do an excellent job of coping with time pressure and dynamic conditions. Rather than trying to change the way they think, we should be finding ways to help them. We should be developing techniques for broadening their experience base through training, so that they can gain situation assessment more quickly and accurately. If we can give up our old single-theory analytical perspectives and appreciate the fact that there are a variety of decision strategies, we can improve operational decisionmaking in a number of ways.

One opportunity is to improve strategies for effective team decisionmaking. Staff exercises are too often a charade where they present options to a commander who then picks the best one. Usually, however, they know which option they prefer. They present, as other options, ones that had been rejected to round out the field. This procedure can be inefficient because it divorces the situation assessment from the response selection step and gives the subordinates the more demanding job of assessing the situation. It asks the commander to make a choice rather than working with the team to modify and improve options. There may be times when it is more effective to have the commander work with the staff to examine the situation and then turn over to them the job of preparing

implementation plans. If alternative viewpoints and criticisms are wanted, they should come during the assessment and initial planning, so as to strengthen the option to be implemented.

A second opportunity is to understand how commanders can present their strategic intent so that subordinates are able to improvise effectively. It is dangerous to have subordinates ignoring direction and carrying out their own plans, but it is also dangerous to have subordinates carrying out plans that no longer make sense. Improvisation arises when there is a recognition that the situation has fundamentally changed. We need to understand how commanders can recognize and exploit conditions.

A third opportunity is to revise training procedures. Certain specialties need training and analytical decision strategies. But generally, training can be more productive by focusing on situation assessment. Along with teaching principles and rules, we should present actual cases to develop sharper discriminations and improve ability to anticipate the pitfalls of various options. The goal of analytical decisionmaking is to teach procedures that are so abstract and powerful that they will apply to a wide variety of cases. If this had been successful, it would have been quite efficient. However, we have learned that such rules do not exist. Instead, we need to enhance expertise by presenting trainees with a wide variety of situations and outcomes and letting them improve their recognitional abilities. At the team level, we can be using after-action reviews to present feedback about the *process* of the decisionmaking and not just on the *content* of the options that should have been selected.

A fourth opportunity is to improve decision support systems. We must insist that the designers of these systems

have appropriate respect for the expertise of proficient operators and ensure that their systems and interfaces do not compromise this expertise.^{vii} We must find ways to present operators with displays that will make situational assessment easier and more accurate. We will also want displays that will make it easier for operators to assess operations in order to discover potential problems. In other words, we want to build decision support systems that enhance recognitional as well as analytical decision strategies.

Decisionmaking based upon pattern recognition has prompted responses such as the following,² which I do not read so much as an objection to nonlinearity, but as the finest testimony for the need for meshing the linear and nonlinear.

Intuitive decisionmaking is a worthy goal, but there's an irony to it, [because] intuition is based on experience. So we can conclude that as we move down the chain of command to the level of company grade officers and noncommissioned officers (NCOs), the quality of intuition will be correspondingly degraded as the level of experience decreases. Unfortunately, the further down the chain we look, the more likely it is that leaders will find themselves in situations requiring rapid decisions. Historically, commanding generals rarely, if ever, find themselves having to make immediate decisions. At the other end of the spectrum, a sergeant commanding a squad in combat may be forced to make scores of immediate decisions everyday. So, the leader with the most highly developed intuition—the general—rarely uses that talent, while the leader whose need for intuition is greatest—the NCO—lacks the requisite experience.

I agree. . . that intuitive decisionmaking can't be taught—it must be learned. Sadly though, it is improbable that even a

reasonable percentage of Marines are capable of such learning. . . CDR Tritten noted that, "If anything, the desired Myers-Briggs Type Indicator pattern at the highest levels of the military are "NT" (intuitive thinking)." When the Myers-Briggs Type Indicator was administered at the Marine Corps Command and Staff College in the late 1980s, the results indicated that more than 90 percent of Marine Corps officers displayed the "SJ" preference (sensing-judging), the polar opposite of the preference that indicates a capacity to develop and use intuition. While people can learn to use skills that fall outside their own set of preferences (as CDR Tritten stated) we must remember that to do so can be very challenging, like forcing oneself to breathe. In a demanding situation, such as combat, people will typically resort to their "comfort zone."

. . . LTG Bernard E. Trainor wrote: "I learned a lot in those final 72 hours of TBS [*The Basic School*]. Most of all I learned how easy it is to become mistake prone when cold, wet, sleepless, and fatigued over a prolonged period of time. It was then that the rote repetition of things like the five-paragraph combat order, the seven troop leading steps, and immediate action drills suddenly made sense. They allow an officer to engage in automatic when the brain can't handle manual. It was a lesson I appreciated the rest of my career."

The 10 percent who possess the rare characteristics described by T.E. Lawrence as the "flash of the kingfisher". . . can decide intuitively under the most demanding circumstances. For the other 90 percent of us, perhaps there is some value in the structure afforded by analytical methods.

Amen to that. It's all about moving from the complexity "shuffle" to the complexity "shuttle." Some of my best students

have been SJs on the Myers-Briggs scale, and I've come to the conclusion that the Myers-Briggs type may not be as salient as I had earlier thought. And I am sure that Lieutenant General Trainor can remember days when the five-paragraph combat order didn't make sense, either.

Don't forget that the difference is not a yawning chasm. Our current complexity "shuffle" is a reflection of the 80/20 rule; that is our ability to handle mild nonlinearity with linear approaches. Our immune system, the finest kind of complex adaptive system, operates around the 90/10 mode. We may not, probably cannot, get to 90, but we can do better than 80, and that difference can be a world better. . . the difference between a "shuffle" and a "shuttle."

Notes

- 1 Klein, Gary. "Strategies of decisionmaking." *Military Review*. May 1989. pp. 56-64.
 - i) For a fuller view, see: Klein, G.A. (in press) "Recognition-Primed Decisions." *Advances in Man-Machine Systems Research*. ed. W. Rouse. Greenwich, CT: JAI Press. p. 5.
 - ii) For the purposes of this article, the term "analytical decisionmaking" will be to refer to these two methods, and particularly to concurrent option comparison.
 - iii) U.S. Department of the Army Field Manual 101-5, *Staff Organization and Operations*. Washington, DC: U.S. Government Printing Office. May 1984. pp. 5-9 to 5-10.
 - iv) Thordsen, M., J. Galushka, S. Young, G.A. Klein and C.P. Brezovic, *Distributed decisionmaking in a Command and Control Planning Environment* (KATR-8 (C)-87-08F). Yellow Springs, OH: Klein Associates, Inc. 1987. Prepared under contract MDA903-86-c-0170 for the U.S. Army Research Institute, Alexandria, VA.
 - v) Kahneman, D. and A. Tversky. "Intuitive Predictions: Biases and Corrective Procedures." *TIMS Studies in Management Science*, 12, 1979. pp. 313-27.
 - vi) Lopes, L.L. *The Rhetoric of Irrationality* paper presented at Colloquium in

Mass Communication, Madison, WI, November 1986 (currently under revision). J.J. Christensen-Szalanski. "Improving the Practical Utility of Judgment Research." *New Directions in Research on decisionmaking*. ed. B. Brehmer, H. Jungerman, P. Lourens and G. Sevon. North Holland: Elsevier. 1986.

vii)I have made some suggestions in an earlier paper, see: Klein, G.A. "Automated Aids for the Proficient Decisionmaker." *IEEE Proceedings*. 1980. pp. 301-4.

- 2 Blasiol, Leonard A. "Intuitive Decisionmaking: Not For Everyone." *Marine Corps Gazette*. July 1996. pp. 52-3.

Conclusion

The physicist Heinz Pagels is quoted in the frontispiece of this book:

I am convinced that the nations and people who master the new sciences of complexity will become the economic, cultural and political superpowers of the next century.

If anything we have said here means anything at all, America's defense establishment needs to heed these words.

How well would efforts to prepare for America's national security in the 21st century stack up against Pagels' admonition? Has the Revolution in Military Affairs debate been relevant to this advice? Does any list of big-ticket defense initiatives, such as Joint Vision 2010, Dominant Battlespace Knowledge (DBK) and its "system of systems," and Force XXI's digitized battlefield, *not* show an overriding penchant for the linear, especially its enchantment with, and over-dependence on, technological solutions?

The Department of Defense ought to institutionally evolve a "Pagels' test," similar to the largely informal, yet ubiquitous, "purple test" that is applied almost self-consciously as a sort of internalized feature of almost any defense process and review. It is the product of concerted and consistent acculturation.

The “purple test” essentially just prompts the question, “How does this fit into the joint application of force, since no one goes it alone anymore?” The “Pagels’ test” would prompt a similar question: “Have we provided for nonlinear, as well as linear, approaches because both are needed to ‘cope with the bounds’?”

Certainly, the vestiges of McNamara’s PPBS, the absurdly rigid POM cycle, would get a thumbs down. It would not be surprising to realize that many peacekeeping missions result in “artificial histories” and all the more unintended consequences further down the road. In fact, remembering the importance of the property of *diversity* in complex adaptive systems, the “purple test” might not always get by the “Pagels’ test,” as well.

Appendix

Clausewitz, Nonlinearity, and the Unpredictability of War

by Alan D. Beyerchen

[Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War." *International Security* 17:3. Winter, 1992. pp. 59-90. © Copyright 1993 by the President and Fellows of Harvard College and the Massachusetts Institute of Technology. Reproduced with permission.]

Although our intellect always longs for clarity and certainty, our nature often finds uncertainty fascinating.

- Clausewitz, *On War*, Book One, Chapter 1

Despite the frequent invocations of his name in recent years, especially during the Gulf War, there is something deeply perplexing about the work of Carl von Clausewitz (1780-1831). In particular, his unfinished magnum opus *On War* seems to offer a theory of war, at the same time that it perversely denies many of the fundamental preconditions of theory as such—simplification, generalization and prediction, among others.¹ The book continues to draw the attention of both soldiers and theorists of war, although soldiers often find the ideas of Clausewitz too philosophical to appear practical, while analysts usually find his thoughts too empirical to seem

elegant. Members of both groups sense that there is too much truth in what he writes to ignore him. Yet, as the German historian Hans Rothfels has bluntly put it, Clausewitz is an author "more quoted than actually read."² Lofty but pragmatic, by a theorist who repudiated conventional meanings of theory, *On War* endures as a compelling and enigmatic classic.

Just what is the difficulty with Clausewitz that makes his work so significant yet so difficult to assimilate? *On War's* admirers have sensed that it grapples with war's complexity more realistically than perhaps any other work. Its difficulty, however, has prompted different explanations even among Clausewitz partisans. Raymond Aron has spoken for those who believe that the incomplete and unpolished nature of *On War* is the primary source of misunderstanding: as Clausewitz repeatedly revises his treatise, he comes to a deeper understanding of his own ideas, but before his untimely death he brings his fully developed insights to bear only upon the final revision of Chapter 1 of Book One.³

A second approach to the question is exemplified by Peter Paret's stress on the changing interpretation of any significant author over time. Clausewitz's writings have suffered more distortions than most, Paret has suggested, because abstracting this body of work from its times does violence to its insistence on unifying the universal with the historical particular. Thus, for Paret the literature on Clausewitz has been "fragmented and contradictory in its findings" because of our lack of historical consciousness.⁴

A third route to explaining the difficulties encountered in coping with *On War* has been typified by Michael Handel, for whom the issue is not so much changes in our interpretations as changes in warfare itself. Those aspects of *On War* that deal

with human nature, uncertainty, politics, and rational calculation “will remain eternally valid,” he contended. “In all other respects technology has permeated and irreversibly changed every aspect of warfare.”⁵ For Handel, the essential problem in understanding Clausewitz lies in our confrontation with a reality qualitatively different from his. Each of these approaches has merit, yet none satisfies completely. I offer a revision of our perception of Clausewitz and his work by suggesting that Clausewitz displays an intuition concerning war that we can better comprehend with terms and concepts newly available to us: *On War* is suffused with the understanding that every war is inherently a nonlinear phenomenon, the conduct of which changes its character in ways that cannot be analytically predicted. I am not arguing that reference to a few of today’s “nonlinear science” concepts would help us clarify confusion in Clausewitz’s thinking. My suggestion is more radical: in a profoundly unconfused way, he understands that seeking exact analytical solutions does not fit the nonlinear reality of the problems posed by war, and hence that our ability to predict the course and outcome of any given conflict is severely limited.

The correctness of Clausewitz’s perception has both kept his work relevant and made it less accessible, for war’s analytically unpredictable nature is extremely discomfiting to those searching for a predictive theory. An approach through nonlinearity does not make other reasons for difficulty in understanding *On War* evaporate. It does, however, provide new access to the realistic core of Clausewitz’s insights and offers a correlation of the representations of chance and complexity that characterize his work. Furthermore, it may help us remove some unsettling blind spots that have prevented us from seeing crucial implications of his work.

What is “Nonlinearity”?

“Nonlinearity” refers to something that is “not linear.” This is obvious, but since the implicit structure of our works often reveals hidden habits of mind, it is useful to reflect briefly on some tacit assumptions. Like other members of a large class of terms, “nonlinear” indicates that the norm is what it negates. Words such as *periodic* or *asymmetrical*, *disequilibrium* or *nonequilibrium* are deeply rooted in a cultural heritage that stems from the classical Greeks. The underlying notion is that “truth” resides in the simple (and thus the stable, regular, and consistent) rather than in the complex (and therefore the unstable, irregular, and inconsistent).⁶

The result has been an authoritative guide for our Western intuition, but one that is idealized and liable to mislead us when the surrounding world and its messy realities do not fit this notion. An important basis for confusion is association of the norm not only with simplicity, but with obedience to rules and thus with expected behavior—which places blinders on our ability to see the world around us. Nonlinear phenomena are thus usually regarded as recalcitrant misfits in our catalog of norms, although they are actually more prevalent than phenomena that conform to the rules of linearity. This can seriously distort perceptions of what is central and what is marginal—a distortion that Clausewitz as a realist understands in *On War*.

“Linear” applies in mathematics to a system of equations whose variables can be plotted against each other as a straight line. For a system to be linear it must meet two simple conditions. The first is *proportionality*, indicating that changes in system output are proportional to changes in system input. Such systems display what in economics is called “constant

returns to scale," implying that small causes produce small effects, and that large causes generate large effects. The second condition of linearity, called *additivity* or superposition, underlies the process of analysis. The central concept is that the whole is equal to the sum of its parts. This allows the problem to be broken up into smaller pieces that, once solved, can be added back together to obtain the solution to the original problem.⁷

Nonlinear systems are those that disobey proportionality or additivity. They may exhibit erratic behavior through disproportionately large or disproportionately small outputs, or they may involve "synergistic" interactions in which the whole is not equal to the sum of the parts.⁸ If the behavior of a system can appropriately be broken into parts that can be compartmentalized, it may be classified as linear, even if it is described by a complicated equation with many terms. If interactions are irreducible features of the system, however, it is nonlinear even if described by relatively simple equations.

Nonlinear phenomena have always abounded in the real world.⁹ But often the equations needed to describe the behavior of nonlinear systems over time are very difficult or impossible to solve analytically. Systems with feedback loops, delays, "trigger effects," and qualitative changes over time produce surprises, often abruptly crossing a threshold into a qualitatively different regime of behavior. The weather, fluid turbulence, combustion, breaking or cracking, damping, biological evolution, biochemical reactions in living organisms, and hysteresis in electronic systems offer examples of nonlinear phenomena. Although some analytical techniques have been generated over the centuries to cope with systems characterized by nonlinearity, until the advent of numerical

techniques offered by computers its study has been relatively limited.¹⁰

In contrast, sophisticated analytical techniques for solving linear equations have been developed over the centuries, becoming the preferred tools in nearly all technical fields by the latter portion of the nineteenth century. Due to the structural storability of a linear system, once we know a little about it we can calculate and predict a great deal. The normal procedure has thus been to find mathematical techniques or physical justification for an idealized “linearization” of a natural or technological system. Such an idealized version of a system is often constructed by throwing out the nonlinear “approximation.” In commonly used terms, one thus goes from equations that “blow up” to those that are “well-behaved.” In fact, mathematician Ian Stewart has noted:

Classical mathematics concentrated on linear equations for a sound pragmatic reason: it could solve anything else. . . So docile are linear equations that the classical mathematicians were willing to compromise their physics to get them. So the classical theory deals with *shallow* waves, *low*-amplitude vibrations, *small* temperature gradients.¹¹

As is often the case, reality has been selectively addressed in order to manipulate it with the tools available. Clausewitz pointedly contrasted his own approach with the implicit dependence upon such selectivity among military theorists of his era, such as Heinrich von Bulow or Antoine-Henri de Jomini.¹²

The resort to idealized linearizations has been legitimated by the assumption, increasingly dubious, that reality is ultimately simple and stable. This assumption works well for linear sys-

tems, and even relatively well for those nonlinear systems that are stable enough to be treated using the techniques of linear analysis or control theory. But it turns out to be misleading when applied to the many more systems that are unstable under even small perturbations. As Stewart implied, this was understood by the more thoughtful of the classical mathematicians and physicists. James Clerk Maxwell, one of the greatest scientists of the nineteenth century, displayed a keen awareness of the limitations of assuming that systems in the real world are structurally stable:

When the state of things is such that an infinitely small variation of the present state will alter only by an infinitely small quantity the state at some future time, the condition of *the* system, whether at rest or in motion, is said to be stable; but when an infinitely small variation in the present state may bring about a finite difference in the state of the system in a finite time, the condition of the system is said to be unstable. It is manifest that the existence of unstable conditions renders impossible the prediction of future events, if our knowledge of the present state is only approximate, and not accurate. . . . it is a metaphysical doctrine that from the same antecedents follow the same consequents. No one can gainsay this. But it is not of much use in a world like this, in which the same antecedents never again concur, and nothing ever happens twice. . . . The physical axiom which has a somewhat similar aspect is "that from like antecedents follow like consequents." But here we have passed from sameness to likeness, from absolute accuracy to a more or less rough approximation.¹³

Thus, Maxwell held that analytical mathematical rules are not always reliable guides to the real world. We must often rely on statistical probabilities or approximate solutions reached by numerical techniques.

What is new is that computers have allowed us to attack nonlinear problems numerically, in the process highlighting patterns of instability that have captured scientific and popular imaginations alike. The various fields of “nonlinear science”—such as those that deal with solitons, fractals, cellular automata, and self-organization systems far from thermodynamic equilibrium—have been stimulated and enhanced by powerful computer graphics techniques for scientific visualization or “mathematical experiments.” Their shared aesthetic conceptions about the positive value of complexity create multiple connections among them.¹⁴

One of the most visible aspects of nonlinear science is the portion of nonlinear dynamics popularly known as “Chaos Theory.” “Chaos” results when a system is nonlinear and “sensitive to initial conditions.” This is the case even in a deterministic system for which the analytical laws and variables are known.¹⁵ Such sensitivity is exactly what Maxwell meant: immeasurably small differences in input can produce entirely different outcomes for the system, yielding various behavior routes to a degree of complexity that exhibits characteristics of randomness—hence the term “chaos.” For persons accustomed to expecting linear behavior, it is disconcerting that regions of deterministic chaos and predictable order can coexist for the same system. Furthermore, the very nature or definition of the system can change, and can do so rather abruptly, with transitions that usually depend on the parameters of the system more than on the variables within the system. In effect, parameters set the context, and the idealized boundaries they represent often contrast starkly with the indistinctness of boundaries in the real world.¹⁶ In a chaotic regime, a system is dynamically unstable, so that nearly all input values

for the variables lead to unpredictable, irregular behavior by the system.

Chaotic systems have raised some fundamental questions about relationships among order, randomness, and predictability, especially since the equations that represent them can be surprisingly simple. One of the first contemporary examples of chaos was encountered in meteorology in the early 1960s when the applied mathematician Edward Lorenz set up three linked first-order differential equations in a computer model of weather development. With certain parameters, the system proved so sensitive to the initial conditions that it was estimated that quite literally a butterfly flapping its wings in one part of the world would be sufficient to cause a major storm to emerge somewhere else. An arbitrarily small change could generate an entirely different history for the system. Obviously, acquisition and management of the precision and the amount of input data necessary for exact prediction pose an impractical problem, but the large scale of the atmospheric system is actually not the issue. The difficulty arises merely from multiplying pairs of the variables in two of the three coupled equations.¹⁷ The heart of the matter is that the system's variables cannot be effectively isolated from each other or from their context; linearization is not possible, because dynamic interaction is one of the system's defining characteristics. The question is whether, according to Clausewitz, wars are also nonlinear systems.

Is War Nonlinear for Clausewitz?

In Chapter I of Book One, Clausewitz engages the reader with three increasingly sophisticated definitions of war, each one of which is prominently marked by nonlinearity. The first defini-

tion is that war “is nothing but a duel [*Zweikampf*] on a larger scale. . . . *an act of force to compel our enemy to do our will.*”¹⁸ Because each opponent has the same intent, war is inherently an “interaction” (*Wechselwirkung*): it “is not the action of a living force upon a lifeless mass (total nonresistance would be no war at all) but always the collision of two living forces.”¹⁹ For Clausewitz, the interactive nature of war produces a system driven by psychological forces and characterized by positive feedback, leading “in theory” to limitless extremes of mutual exertion and efforts to get the better of one another. The course of a given war becomes thereby not the mere sequence of intentions and actions of each opponent, but the pattern or shape generated by mutually hostile intentions and simultaneously consequential actions. The contest is not the presence or actions of each opponent added together. It is the dynamic set of patterns made in the space between and around the contestants. This may not be immediately evident if we think of a duel with swords or with pistols. But it is obvious in a match between two wrestlers, which is how Clausewitz himself suggests we imagine the *Zweikampf* (literally “two-struggle”) between opponents in war: the bodily positions and contortions that emerge in wrestling are often impossible to achieve without the counterforce and counterweight of an opponent.²⁰

Clausewitz stresses that the logic of war in the abstract, with its limitless escalation of cost and effort, contradicts human experience; there are always constraints on human action. Only if war were some hermetically sealed phenomenon could its fundamental nature rage on unchecked. This would require that war (a) be an isolated and sudden act without prelude, (b) consist of a single decisive act or set of simultaneous ones, and (c) achieve a result perfectly complete in itself. But Clausewitz contends that an actual war never occurs without a context;

that it always takes time to conduct, in a series of interactive steps; and that its results are never absolutely final—all of which impose restrictions on the analytically simple “pure theory” of war. Any specific war is subject to historical contingencies; thus he concludes that the theoretical basis for prediction of the course of the war dissolves from any analytical certainties into numerical possibilities.²¹ Wars, therefore, are not only characterized by feedback (a process distinctly involving nonlinearities), but inseparable from their contexts.

The unique political situation is the context that bounds the system constituted by a given war. It must be considered carefully, Clausewitz argues, for

the same political object can elicit differing reactions from different peoples, and even from the same people at different times. . . . Between two peoples and two states there can be such tensions, such a mass of inflammable material, that the slightest quarrel can produce a wholly disproportionate effect—a real explosion.²²

Note the nonlinear image of combustion, and the view that the prevailing political conditions rather than the intended “political object” constitute the parameters that determine fundamental regimes of behavior in the system.²³ The emphasis on the changeable political context also contrasts sharply with the view held by many theorists (then and in our own time) that the parameters of war must be readily quantifiable military categories such as logistical factors, characteristics of weaponry, etc.²⁴

Consideration of the political environment leads Clausewitz to generate his famous second definition of war as “merely the continuation of policy [Politik, which also means “politics” in German] by other means.”²⁵ He claims that war is never

autonomous, for it is always an instrument of policy. Yet the relationship is not static; it implies neither that the instrument is unchanging nor that the political goal or policy itself is immune to feedback effects. Using another image of explosion, he argues:

War is a pulsation of violence, variable in strength and therefore variable in the speed with which it explodes and discharges its energy. War moves on its goal with varying speeds; but it always lasts long enough for the influence to be exerted on the goal and for its own course to be changed in one way or another. . . . That, however, does not imply that the political aim is a tyrant. It must adapt itself to its chosen means, a process that can radically change it; yet the political aim remains the first consideration.²⁶

The ends-means relationship clearly does not work in a linear fashion. The constant interplay is an interactive, feedback process that constitutes an intrinsic feature of war. Clausewitz's conception is that the conduct of any war affects its character, and its altered character feeds back into the political ends that guide its conduct. War is, he says, a "true chameleon" that exhibits a different nature in every concrete instance.²⁷

To reach an understanding of the character of war in general is a purpose of theory and to describe how that theory functions, Clausewitz resorts to a third definition that he elucidates in terms of a striking metaphor of nonlinearity. In the last section of Chapter 1, Book One, he claims that war is "a remarkable trinity" (*eine wunderliche Dreifaltigkeit*) composed of (a) the blind, natural force of violence, hatred, and enmity among the masses of people; (b) chance and probability, faced or generated by the commander and his army; and (c) war's rational subordination to the policy of the govern-

ment.²⁸ Clausewitz compares these three tendencies to three varying legal codes interacting with each other (the complexity of which would have been obvious to anyone who lived under the tangled web of superimposed legal systems in the German area before, during, and after the upheavals of the Napoleonic years). Then he concludes with a visual metaphor: "Our task therefore is to develop a theory that maintains a balance between these three tendencies, like an object suspended between three magnets."²⁹ What better image could he have conjured to convey his insight into the profoundly interactive nature of war than this emblem of contemporary nonlinear science?³⁰

Although the passage is usually taken to mean only that we should not overemphasize any one element in the trinity, Clausewitz's metaphor also implicitly confronts us with the chaos inherent in a nonlinear system sensitive to initial conditions. The demonstration usually starts with a magnet pendulum hanging over one magnet; when the pendulum is pulled aside and let go, it comes to rest quickly. Positioned over two equally powerful magnets, the pendulum swings toward first one, then the other, and still settles into a rest position as it is captured by one of the points of attraction. But when a pendulum is released over three equidistant and equally powerful magnets, it moves irresolutely to and fro as it darts among the competing points of attraction, sometimes kicking out high to acquire added momentum that allows it to keep gyrating in a startlingly long and intricate pattern. Eventually, the energy dissipates under the influence of friction in the suspension mountings and the air, bringing the pendulum's movement asymptotically to rest. The probability is vanishingly small that an attempt to repeat the process would produce exactly the same pattern. Even such a simple system is complex enough

for the details of the trajectory of any actual “run” to be, effectively, irreproducible.

My claim here is not that Clausewitz somehow anticipated today’s “chaos theory,” but that he perceived and articulated the nature of war as an energy-consuming phenomenon involving competing and interactive factors, attention to which reveals a messy mix of order and unpredictability. His final metaphor of Chapter 1, Book One captures this understanding perfectly. The pendulum and magnets system is orderly, because it is a deterministic system that obeys Newton’s laws of motion; in the “pure theory” (with an idealized frictionless pendulum), we only need to know the relevant quantities accurately enough to know its future. But in the real world, “a world like this” in Maxwell’s phrase, it is not possible to measure the relevant initial conditions (such as position) accurately enough to replicate them in order to get the same pattern a second time, because all physical measurements are approximations limited by the instrument and standard of measurement. And what is needed is infinitely fine precision, for an immeasurably small change in the initial conditions can produce a significantly different pattern. Nor is it possible to isolate the system from all possible influences around it, and that environment will have changed since the measurements were taken. Anticipation of the overall kind of pattern is possible, but quantitative predictability of the actual trajectory is lost.

There are a number of interconnected reasons for the pendulum and magnets picture to be emblematic for Clausewitz, and all of them go to the heart of the problem of understanding what he meant by a “theory” of war. First of all, the image is *not* that of any kind of Euclidean triangle or triad, despite its understanding as such by many readers. Given his attacks on

the formulation of rigidly “geometric” principles of war by some of his contemporaries, such an image would have been highly inapt.³¹ Clausewitz’s message is not that there are three passive points, but three interactive points of attraction that are simultaneously pulling the object in different directions and forming complex interactions with each other. In fact, even the standard translation given above is too static, for the German original conveys a sense of ongoing motion: “*Die Aufgabe ist also, dass sich die Theorie zwischen diesen drei Tendenzen wie zwischen drei Anziehungspunkten schwebend erhalte.*”³² Literally: “The task is therefore that the theory would maintain itself floating among these three tendencies as among three points of attraction.” The connotations of *schweben* involve lighter-than-air, sensitive motion; a balloon or a ballerina “schwebt.” The image is no more static than that of wrestlers. The nature of war should not be conceived as a stationary point among the members of the trinity, but as a complex trajectory traced among them.

Secondly, Clausewitz’s employment of magnetism is a typical resort to “high-tech” imagery. The relationship of magnetism to electricity was just beginning to be clarified in a way that made it a cutting-edge concept for its time. It is quite possible that he actually observed a demonstration of a pendulum and three magnets as envisioned in the metaphor, for he was a man of considerable scientific literacy.³³ His famous incorporation of the notion of “friction,” also a high-technology concept for his day, is another example of this characteristic of his thought.

Thirdly, and perhaps most importantly, the metaphor offers us insight into a mind realistically willing to abandon the search for simplicity and analytical certainty where they are not obtainable. The use of this image displays an intuitive grasp of dynamic processes that can be isolated neither from their context nor from chance, and are thus characterized by

inherent complexities and probabilities. It encodes Clausewitz's sense of war in a realistic dynamical system, not an idealized analytical abstraction.

The image of the interactive "remarkable trinity" is thus a densely rich metaphor, but is it only a literary device? A stylistic trick? Or is it fundamental to understanding Clausewitz? Raymond Aron thought it representative of a major shift from dualism to a form of triadism that constituted the final state of Clausewitz's thought.³⁴ Michael Howard ended his excellent short biography with this trinity, and suggested that it formed both Clausewitz's conclusion and a good starting place for any contemporary strategic thinker.³⁵

But the pendulum-and-magnets metaphor reveals more than Clausewitz's concluding thought. If the metaphor can bear the burden of my contention, *On War* ought to be filled with insights intended to identify and cope with nonlinearities. Clausewitz ought to display a deep and abiding concern for unpredictability and complexity, and consequently to search for ways to express the importance of such matters as context, interaction, effects disproportionate to their causes, sensitivity to initial conditions, time-dependent evolutionary processes, and the serious limitations of linear analysis. If he does, we will have a viable explanation for the compelling nature of *On War* and many of its difficulties for readers, because the intuition needed to investigate nonlinear dynamical systems runs counter to much of what has constituted scientific theory since the time of Galileo and Newton.

How Does Nonlinearity Manifest Itself in *On War*?

Clausewitz's emphasis on unpredictability is a key manifestation of the role that nonlinearity plays in his work. This emphasis links widely recognized, fundamental, enduring elements of *On War*. A look at what Clausewitz says about "interaction," "friction," and "chance" may allow us to explore his understanding of the nonlinear nature of war.

Unpredictability from Interaction

It may seem obvious that war is an interactive process, yet Clausewitz was at great pains to emphasize the point and to assail his contemporaries for ignoring this basic aspect of reality. That war is profoundly interactive is underscored by each of the definitions of the phenomenon in Chapter 1, Book One. The question is whether Clausewitz related this concept to the unpredictability that characterizes nonlinear systems. The answer is unequivocally yes. In Chapter 3 of Book Two, Clausewitz considers whether the study of war is an art or a science. He concludes that it is neither:

The essential difference is that war is not an exercise of the will directed at inanimate matter, as is the case with the mechanical arts, or at matter which is animate but passive and yielding, as is the case with the human mind and emotions in the fine arts. In war, the will is directed at an animate object that *reacts*.³⁶

A military action produces not a single reaction, but dynamic interactions and anticipations that pose a fundamental problem for any theory. Such patterns can be theorized only in

qualitative and general terms, not in the specific detail needed for prediction:

The second attribute of military action is that it must expect positive reactions, and the process of interaction that results. Here we are not concerned with the problem of calculating such reactions—that is really part of the already mentioned problem of calculating psychological forces—but rather with the fact that the very nature of interaction is bound to make it unpredictable.³⁷

Clausewitz thus understood an essential feature of nonlinearity and applied its consequences in his understanding of war: the core cause of analytical unpredictability in war is the *very nature of interaction* itself.

Interaction occurs not just between adversaries, but also in processes that occur on each side as a consequence of the contest. This is demonstrated in Book Four, as Clausewitz discusses the differing effects of victory or defeat on the battlefield. The consequences are often disproportionately felt:

As we have already mentioned in Chapter Seven, the scale of victory does not increase simply at the rate commensurate with the increase in the size of the defeated armies, but progressively. The outcome of a major battle has a greater psychological effect on the loser than on the winner. This, in turn, gives rise to additional loss of material strength [through abandonment of weapons in a retreat or desertions from the army], which is echoed in loss of morale; the two become mutually interactive as each enhances and intensifies the other.³⁸

Such an amplifying feedback process is as nonlinear as those in any field, from turbulence in the atmosphere to the optics of the laser.

Clausewitz's concern for interaction permeates *On War*, and it has certainly commanded the attention of commentators. The crucial importance of interaction is usually framed in terms of Clausewitz's "dialectical" method, although his non-Marxist adherents have usually been at pains to distinguish the dialectic in Clausewitz's work from Hegel's method.³⁹ Aron, in particular, devoted an entire section of his two-volume study to Clausewitz's dialectic. He argued that the categories termed "moral-physical," "means-ends," and "defense-attack" formed the "three conceptual pairs around which the system develops."⁴⁰ He recognized better than many commentators that Clausewitz does not demand binary opposites and is willing to live with ambiguity:

[Clausewitz] explicitly recognizes that the clear opposition of two poles risks becoming confused in the intermediate zones. . . . In reality, the distinctions, conceptually clear-cut, give way to doubtful cases or even to mixed cases. Clausewitz does not see real objections in these remarks: the distinction, conceptually valid, does not preclude uncertain boundaries in reality.⁴¹

Aron's use of the word "risks" (*risque*), however, perhaps betrayed discomfort with the analytical ambiguity that comes with taking interaction seriously.

Clausewitz himself displays no unease with ambiguity in the passages under discussion. He appears, on the contrary, to relish the complexity of the relationship between tactics and strategy:

The art of war in the narrower sense must now in its turn be broken down into tactics and strategy. The first is concerned with the form of the individual engagement, the second with its use. . . . Admittedly only the rankest pedant

would expect theoretical distinctions to show direct results on the battlefield. . . . Tactics and strategy are two activities that permeate one another in time and space but are nevertheless essentially different. Their inherent laws and mutual relationship cannot be understood without a total comprehension of both.⁴²

The purpose of theory is to untangle confusion by creating distinctions, but to do so in order to understand the whole better, not for the sake of pedantic analytical compartmentalization.

What interests Clausewitz, I argue, is not so much either pole in any of his analytical pairs, nor even either opponent in war, but the tangled dynamics occurring between them. This is consistent with the wrestlers' image of the *Zweikampf*. Many theorists tend, for the sake of analytical simplicity, to force war into the model sequence of move-countermove. But any good commander will seek to take advantage of the disproportionate effects or unpredictable situations generated by nonlinearities. Furthermore, war is not chess; one's opponent is not always playing by the same rules, and is often, in the effort to win, attempting to change what rules there are. This is a major reason that how war is conducted can and does change its character, and that any war is (in Maxwell's sense) structurally unstable.

Capturing the essence of this "true chameleon" is Clausewitz's aim. He is therefore willing to accept uncertainty and complex interaction as major factors in order to cope with what is happening along the hazy boundaries where the opposing forces in war, or contending categories in theory, are actually engaged. Facing up to the intrinsic presence of chance, complexity, and ambiguity in war is imperative. For Clausewitz, this is preferable to the risk of being blind-sided by the stric-

tures of a theory artificially imposed on the messiness of reality in the name of clarity.

Unpredictability from Friction

A key element of reality for Clausewitz is the ubiquity of “friction,” the “only concept that more or less corresponds to the factors that distinguish real war from war on paper.”⁴³ This concept is usually interpreted as a form of Murphy’s Law: whatever can go wrong, will, and at the worst possible moment. That interpretation is not bad as far as it goes, but its presentation is usually skewed. The implication is that things go right until some exogenous factor ruins the situation. But for Clausewitz friction is neither extrinsic nor abnormal:

Everything in war is simple, but the simplest thing is difficult. The difficulties accumulate and end by producing a kind of friction that is inconceivable unless one has experienced war. . . . Countless minor incidents—the kind you can never really foresee—combine to lower the general level of performance, so that one always falls short of the intended goal. . . . The military machine—the army and everything related to it—is basically very simple and therefore seems easy to manage. But we should bear in mind that none of its components is of one piece: each part is composed of individuals, . . . the least important of whom may chance to delay things or somehow make them go wrong. . . . This tremendous friction, which cannot, as in mechanics, be reduced to a few points, is everywhere in contact with chance, and brings about effects that cannot be measured, just because they are largely due to chance.⁴⁴

The concept of friction is not just a statement that in war things always deviate from the plan, but a sophisticated sense of *why* they do so. The analytical world, epitomized by the

“frictionless pendulum” or the “perfectly spherical billiard ball on a frictionless surface” or “low-amplitude vibrations” so common in elementary physics, is one of linear rules and predictable effects. The real world and real war are characterized by the unforeseeable effects generated through the nonlinearity of interaction.

“Friction” as used by Clausewitz entails two different but related notions that demonstrate the depth of his powers of observation and intuition. One meaning is the physical sense of resistance embodied in the word itself, which in Clausewitz’s time was being related to heat in ways that would lead ultimately to the Second Law of Thermodynamics and the concept of entropy.⁴⁵ Friction is a nonlinear feedback effect that leads to the heat dissipation of energy in a system. The dissipation is a form of increasing degradation toward randomness, the essence of entropy. Even in peacetime, the degradation of performance in an army is a continual problem. In war, the difficulties are amplified. Military friction is counteracted by training, discipline, inspections, regulations, orders, and other means, not the least of which, according to Clausewitz, is the “iron will” of the commander.⁴⁶ New energy and effort are sucked into the open system, yet things still never go as planned; dissipation is endemic due to the interactive nature of the parts of the system.

The second meaning of “friction” is the information theory sense of what we have recently come to call “noise” in the system. Entropy and information have some interesting formal similarities, because both can be thought of as measuring the possibilities for the behavior of systems. According to information theory, the more possibilities a system embodies, the more “information” it contains. Constraints on those possibilities are needed to extract signals from the noise. Clausewitz under-

stands that plans and commands are signals that inevitably get garbled amid noise in the process of communicating them down and through the ranks even in peacetime, much less under the effects of physical exertion and danger in combat. His well-known discussion of the difficulty in obtaining accurate intelligence presents the problem from the inverse perspective, as noise permeates the generation and transmission of information rising upward through the ranks.⁴⁷ From this perspective, his famous metaphor of the “fog” of war is not so much about a dearth of information as how distortion and overload of information produce uncertainty as to the actual state of affairs.

Clausewitz’s basic intuition here is that organizations are always slower and more inflexible than the natural events they are intended to control. Seen in this light, training, regulations, procedures, and so on are redundancies that enhance the probability of signal recognition through the noise. On the basis of linear assumptions, one expects major obstacles to produce proportionately serious errors in responding to the message. Clausewitz emphasizes, however, the disproportionately large role of the *least* important of individuals and of minor, unforeseeable incidents. “Friction” conveys Clausewitz’s sense of how unnoticeably small causes can become amplified in war until they produce *macroeffects*, and that one can never anticipate those effects.⁴⁸ The issue is not just that “for want of a nail the shoe was lost. . .” but that one can never calculate in advance *which* nail on which shoe will turn out to be critical. Due to our ignorance of the exact initial conditions, the cause of a given effect must, for all intents and purposes, often be treated as unavoidable chance.

Unpredictability from Chance

How are we to understand “chance,” which Clausewitz finds pervasive? It is one of the three points of attraction in his definition of war as a remarkable trinity, and he emphasizes that “no other human activity is so continuously or universally bound up with chance” as is war.⁴⁹ It is associated also with the fog of uncertainty in war, which obscures or distorts most of the factors on which action is based. Yet he nowhere provides a succinct definition of chance.

The connection between chance and uncertainty provides a means of understanding both, if we draw on the insights of the late 19th-century mathematician Henri Poincare, whose understanding of the matter was powerful enough that he is a frequently cited source in nonlinear science today. Poincare argued that chance comes in three guises: a statistically random phenomenon; the amplification of a microcause; or a function of our analytical blindness. He described the first as the familiar form of chance that can arise where permutations of small causes are extremely numerous or where the number of variables is quite large. This form of chance can be calculated by statistical methods. The very large number of interactions produces a disorganization sufficient to result in a symmetrical (i.e., Gaussian or bell curve) probability distribution. Nothing significant is left of the initial conditions, and the history of the system no longer matters.⁵⁰ It is possible that Clausewitz was aware of this general line of reasoning. As with magnetism and friction, important developments in probability theory were occurring in Clausewitz’s time, and we know that he read intensely in mathematical treatises.⁵¹

Of course *On War* does not present this statistically tractable form of chance in exactly the way Poincare explained it later,

although commentators have noted that Clausewitz often refers to the role of probability in a commander's calculations.⁵² In Chapter 1, Book One, he notes that "absolute, so-called mathematical factors" are not sound bases for such calculations due to the "interplay of possibilities, probabilities, good luck and bad" that are endemic in war. The "games of chance" most amenable to statistical treatment are those like dice and coin tossing, but when Clausewitz compares war to a gamble, he does not use either. For him, "in the whole range of human activities, war most closely resembles a game of cards."⁵³ This analogy suggests not only the ability to calculate probabilities, but knowledge of human psychology in "reading" the other players, sensing when to take risks, and so on. Clausewitz certainly understands that the number of variables in war can be enormous, and that a rather special aptitude is needed to cope with the chance and complexity involved:

Circumstances vary so enormously in war, and are so indefinable, that a vast array of factors has to be appreciated—mostly in the light of probabilities [*Wahrscheinlichkeitsgesetze*] alone. The man responsible for evaluating the whole must bring to his task the quality of intuition that perceives the truth at every point. Otherwise a chaos of opinions and considerations would arise, and fatally entangle judgment. Bonaparte rightly said in this connection that many of the decisions faced by the commander-in-chief resemble mathematical problems worthy of the gifts of a *Newton* or an *Euler*.⁵⁴

Since a mathematician of the likes of Newton or Euler is unlikely to be making military decisions, those in command have to rely on judgment rooted in intuition, common sense, and experience. Statistical laws of probability alone will never suffice, because moral factors always enter into real war, and it

is possible for the results of any given action to defy the odds. This is one of the most important facts that experience indeed provides.⁵⁵

A second form of chance described by Poincare is deeply embedded in *On War*, but commentators have not usually distinguished its nature from that of the first.⁵⁶ In contrast to the statistical form characterized above, this type of chance—amplification of a microcause—is inherent in the system itself. It arises from the fact that in certain deterministic systems small causes can have disproportionately large effects at some later time. Because the history of the system matters, the initial conditions remain significant. In a passage often cited by researchers working on nonlinear dynamics, Poincare explained:

A very slight cause, which escapes us, determines a considerable effect which we can not help seeing, and then we say this effect is due to chance. If we could know exactly the laws of nature and the situation of the universe at the initial instant, we should be able to predict exactly the situation of this same universe at a subsequent instant. But even when the natural laws should have no further secret for us, we could know the initial situation only *approximately*. If that permits us to foresee the subsequent situation *with the same degree of approximation*, this is all we require, [and] we say the phenomenon has been predicted, that it is ruled by laws. But this is not always the case; it may happen that slight differences in the initial conditions produce very great differences in the final phenomenon; a slight error in the former would make an enormous error in the latter. Prediction becomes impossible and we have the fortuitous phenomenon.⁵⁷

Poincare thus linked the crucial importance of the initial conditions to the idea that in the real world the precision of our information concerning causes is always limited. This is a root explanation for unpredictability in those nonlinear phenomena that exhibit chaotic regimes of behavior.

This is exactly how Clausewitz perceives the role of chance in relation to friction in real war. Unnoticeably small causes can be disproportionately amplified. Decisive results can often rest on particular factors that are “details known only to those who were on the spot.”⁵⁸ Attempts to reconstruct cause and effect always face the lack of precise information:

Nowhere in life is this so common as in war, where the facts are seldom fully known and the underlying motives even less so. They may be intentionally concealed by those in command, or, if they happen to be transitory and accidental, history may not have recorded them at all.⁵⁹

We can never recover the precise initial conditions even of known developments in past wars, much less developments in current wars distorted by the fog of uncertainty. Interactions at every scale within armies and between adversaries amplify microcauses and produce unexpected macroeffects. Since interaction is intrinsic to the nature of war, it cannot be eliminated. The precise knowledge needed to anticipate the effects of interaction is unattainable. Unpredictability in war due to this second form of chance is thus unavoidable.

There is yet a third type of chance discussed by Poincare that is prominently displayed in Clausewitz’s work. Poincare argued that this kind is a result of our inability to see the universe as an interconnected whole:

Our weakness forbids our considering the entire universe and makes us cut it up into slices. We try to do this as little artificially as possible. And yet it happens from time to time that two of these slices react upon each other. The effects of this mutual action then seem to us to be due to chance.⁶⁰

Thus, the drive to comprehend the world through analysis, the effort to partition off pieces of the universe to make them amenable to study, opens the possibility of being blind-sided by the very artificiality of the partitioning practice. This form of chance is a particularly acute problem when our intuition is guided by linear concepts.

Clausewitz has a profound sense of how our understanding of phenomena around us is truncated by the bounds we place on them for our analytical convenience. The assertion from *On War* quoted above, that “circumstances vary so enormously in war, and are so indefinable,” makes this point explicitly in the German original. A literal translation refers to the “diversity and indistinct boundary of all relationships” (“die Mannigfaltigkeit und die unbestimmte Grenze aller Beziehungen”) with which a commander must cope. Clausewitz repeatedly stresses the failure of theorists, such as his contemporaries Jomini and Bulow, to obtain effective principles because they insist on isolating individual factors or aspects of the problems presented in war. One indictment is particularly well known:

Efforts were therefore made to equip the conduct of war with principles, rules, or even systems. This did present a positive goal, but people failed to take an adequate account of the endless complexities involved. As we have seen, the conduct of war branches out in almost all directions and has no definite limits; while any system, any model, has the finite nature of a synthesis [in the sense of

synthetic or man-made]. An irreconcilable conflict exists between this type of theory and actual practice. . . . [These attempts] aim at fixed values; but in war everything is uncertain, and calculations have to be made with variable quantities. They direct the inquiry exclusively toward physical quantities, whereas all military action is entwined with psychological forces and effects. They consider only unilateral action, whereas war consists of continuous interaction of opposites.⁶¹

For Clausewitz, the generation of any system of principles for the conduct of war is a desirable goal but an unattainable one. Such an act of synthesis is indeed attractive, because it becomes so easy to forget the filters we have imposed on our view of the phenomenon.

But his concerns, like those of many scientists wrestling with nonlinear phenomena today, are open systems which cannot be isolated from their environments even in theory, which are characterized by numerous levels of feedback effects, and which need to be grasped realistically as an interactive whole. Traditional analysis that aimed at breaking the system into simpler parts fails now just as surely as it did in Clausewitz's time, and for the same reasons. As Clausewitz writes of critical analysis and proof:

It is bound to be easy if one restricts oneself to the most immediate aims and effects. This may be done quite arbitrarily if one isolates the matter from its setting and studies it only under those conditions. But in war, as in life generally, all parts of the whole are interconnected and thus the effects produced, however small their cause, must influence all subsequent military operations and modify their final outcome to some degree, however

slight. In the same way, every means must influence even the ultimate purpose.⁶²

Interconnectedness and context, interaction, chance, complexity, indistinct boundaries, feedback effects and so on, all leading to analytical unpredictability—it is no wonder that *On War* has confused and disappointed those looking for a theory of war modeled on the success of Newtonian mechanics.

The Role of Linearity

It is important to emphasize that Clausewitz does not hold the view that linearity is nowhere valid in war. As much as any military professional, he clearly wants to find or generate conditions under which outcomes may be guaranteed. His attention to situations characterized by direct, sequential cause-effect relationships or proportionality makes Clausewitz's understanding of the consequences of nonlinearity more supple—and credible—than if he ignored linearities entirely. But he is aware that linear relations and the predictability they offer are the exceptions in the real world, so he usually surrounds a linear effect with a discussion of the constraints needed to achieve it.

For Clausewitz, the parameters that make linear approximations possible are the political-military analogs of shallow waves or low-amplitude vibrations. In Chapter 1, Book One, for instance, he notes that political objectives come to the fore as the limitations of the real world dampen the theoretical tendency of pure war to be driven to absolute extremes. “The smaller the penalty you demand from your opponent, the less you can expect him to try to deny it to you; the smaller the effort he makes, the less you need make yourself.”⁶³ This offers

an example of linearity. Yet, Clausewitz in the next paragraph restricts such a relationship:

The political object—the original motive for the war—will thus determine both the military objective to be reached and the amount of effort it requires. The political object cannot, however, *in itself* provide the standard of measurement. Since we are dealing with realities, not with abstractions, it can do so only in the context of the two states at war. The same political object can elicit *differing* reactions from different peoples, and even from the same people at different times. [Here follows the nonlinear image of combustion noted on p. 68 above]. . . . The less involved in the population and the less serious the strains within states and between them, the more political requirements in themselves will dominate and tend to be decisive. Situations can thus exist in which the political object will almost be the sole determinant.⁶⁴

The context in which a war begins thus sets an initial range of possibilities for the relationship between political objective and military exertion. Situations “can” exist in which a single variable “almost” solely determines the outcome. But this requires that one of the magnetic attractions in the “remarkable trinity”—the primordial passions of the people—be diminished so greatly as to be effectively removed.

The embedding of linearity in a general environment of non-linearity is thoroughly characteristic of *On War*. This awareness of the full range of the system’s behavior prevails not only when Clausewitz considers the outbreak of war, but also when he assesses the impact of a single battle in war. In a chapter where he discusses the disproportionate, nonlinear effects of a victory, Clausewitz relates other processes in clearly linear terms: “Our argument is that the effects of victory that we

have described will always be present; that they increase in proportion to the scale of the victory; and they increase the more the battle is a major one."⁶⁵ Yet he encompasses this remark within assertions that the effects of victories still depend very much on the context, including the character of the victorious commander, whether moral forces will be aroused on the other side that "would otherwise have remained dormant," and so on.⁶⁶ It is even possible, therefore, for a victory to have the entirely unexpected effect of rallying the losing side.

Seen from this perspective, the best-known and most popular of the linearities identified by Clausewitz—the offensive thrust at the enemy's "center of gravity"—looks quite different than it is usually depicted. Defeat of the enemy, he holds, involves "chances and incidents so minute as to figure in histories simply as anecdotes," but out of the dominant characteristics of each belligerent "a center of gravity [Schwerpunkt] develops, the hub of all power and movement, on which everything depends."⁶⁷ Practicing soldiers may warm to the idea of focusing one's efforts on the most critical concentration of the enemy's fighting forces in order to strike the most telling blow. But they balk when Clausewitz goes on to suggest that under specific circumstances the center of gravity could be a city, or a community of interest among allies, or the personality of a leader, or even public opinion.⁶⁸ Furthermore, he urges an awareness of the restraints imposed by considerations of economy of force: an excess of force is worse than a waste, for it means unnecessary weakness elsewhere.⁶⁹ Even more unsettling for some readers, he says that he is only describing what has been done in the past and wants "to reiterate emphatically that here, as elsewhere, our definitions are aimed only at the center of certain concepts; we neither wish [to] nor can give

them sharp outlines."⁷⁰ Even this most Newtonian-sounding analogy of a "center of gravity" becomes swamped in qualifications and caveats intended to convey the complexity of war.

No wonder that, in an effort to cut through the maddening maze of qualification, students of *On War* tend to linearize and simplify what is said. The upshot is often an implicit and even explicit claim that, if Clausewitz were only less confused and understood his own concepts better, he would sound like Jomini. In a recent example, the military authors of an article rehearsed the above passages, but were clearly relieved when they could finally report that Clausewitz goes on to say that no matter what the center of gravity may be, "defeat of the enemy fighting force remains the best way to begin." For them, this strategy retrieved the analogy from the region "beyond its applicability" in the psychological realm and "reestablishes the analogy of the center of gravity in its proper physical domain."⁷¹ They then immediately proceeded to contrast Clausewitz's terminology with that of Jomini, whose crisply stated maxims about the "decisive point" were held to be much more clear. But the continual twisting about that fills *On War* is just not the case of Clausewitz's being ponderous and wordy. Instead, the apparently irresolute to and fro of his prose conforms fully to his metaphor of theory floating among competing points of attraction.

Clausewitz's partisans, who agree with him that a theory of war cannot be axiomatic, nevertheless have also labored under the implicit imperative that a good theory must conform to a linear intuition. Examples can be found even among the most articulate and sensitive interpreters of his work. Two essays by Bernard Brodie, long an influential member of the American defense analysis community, were included by Howard and Paret in their 1976 translation of *On War*. It is striking that even

Brodie sometimes attempted to legitimize Clausewitz's ideas by linearizing them. For example, when Clausewitz states that the events of a war can change policy, according to Brodie Clausewitz cannot really mean this, "for to admit even a high probability of such a feedback effect would be to destroy his basic contention that war is an instrument of policy and not the reverse." But Clausewitz not only admits this feedback effect he specifically *underscores* it in the passage under discussion, and it is typical of his conception of war.⁷² The relationship between policy and war cannot be that of a discrete independent variable and a discrete dependent variable, for it is impossible to isolate the ends from the means used to pursue them.

Once identified as such, Clausewitz's perception that war is a profoundly nonlinear phenomenon seems so obvious that the natural question is why this has not been clearly understood all along. The answer is that what is meant by "theory" has been profoundly linear, to some extent already in Clausewitz's time and increasingly so since. Simplicity achieved by idealized isolation of systems and of variables within systems, deterministic laws, clearly delineated boundaries, linear causal trains, and other tools with which to forge analytical prediction have become the hallmarks of good theory. By using such techniques, rooted in the parsimonious and deductive power of logic, we have searched for—and therefore overwhelmingly found—static equilibria, consistent explanations, periodic regularities, and the beauty of symmetry.

Of course, as Ian Stewart noted, all this comes at a price, namely the restriction of our vision to low-amplitude vibrations, shallow waves, small perturbations, and their analogs. We have trained our imaginations to be fundamentally linear. We have been able to devise analytical equations that offer

prediction, but only by implicitly requiring that the system not be allowed to change too much in the meantime. We artificially require that our systems be stable in the sense expressed by Maxwell, and then are surprised by the manifest instability we encounter in the real world. A scientist at Los Alamos National Laboratory has summed up our situation:

That a system governed by deterministic laws can exhibit effectively random behavior runs counter to our normal intuition. Perhaps it is because intuition is inherently 'linear'; indeed, deterministic chaos cannot occur in linear systems.⁷³

The realization that we have been wearing analytical blinders is becoming widespread. Looking to the future relationship between basic and applied physics, a National Research Council panel lamented the general lack of an adequate intuition: "inheritance of experience with simple systems is strikingly empty of images, intuitions, and methods for dealing with nonlinear problems of complexity. We know almost nothing of the workings and accustomed regularities of such systems. And to proceed we must come to know them intimately."⁷⁴ Working over 150 years ago with the requisite intuition, Clausewitz had no precise and commonly accepted vocabulary with which to express his insights into nonlinear systems. He thus wrestled for years with formulations of his insights, unwilling to abandon realism for idealization.

It seems clear that in *On War*, Clausewitz also senses that any prescriptive theory entails linearization, which is why he holds a dim view of such theory in the real world in which war actually occurs. Only an idealized "pure theory" of war could be predictive with universal prescriptions. In our world of probabilities, rather than axiomatic certainties, by contrast, any

useful theory must instead be heuristic, for each war is “a series of actions obeying its own peculiar laws.”⁷⁵ The purpose of theory in our world is to expand the range of personal experience that is the best aid to judgment in war; it is “meant to educate the mind of the future commander, or more accurately, to guide him in his self education.”⁷⁶ Since war evolves over time, the best techniques are historical, which offer an indication only of what is possible, not what is necessary, in the future.

Clausewitz is quite explicit: it is impossible “to construct a model for the art of war that can serve as a scaffolding on which the commander can rely on for support at any time.”⁷⁷ Since the opponent is a reacting, animate entity, “it is clear that continual striving after laws analogous to those appropriate to the realm of inanimate matter was bound to lead to one mistake after another.”⁷⁸ The notion of law does not apply to actions in war, “since no prescriptive formulation universal enough to deserve the name of law can be applied to the constant change and diversity of the phenomena of war.”⁷⁹ Thus, theory must be based on a broader sense of order rooted in historical experience, leading to descriptive guidelines. Theorists must not be seduced into formulating analytically deductive, prescriptive sets of doctrines that offer poor hope and worse guidance.

Implications

I have demonstrated that Clausewitz perceives war as a profoundly nonlinear phenomenon that manifests itself in ways consistent with our current understanding of nonlinear dynamics. Furthermore, I have suggested that the predominance of a linear approach to analysis has made it difficult to

assimilate and appreciate the intent and contribution of *On War*. The concepts and sensibility recently emerging in nonlinear science can be used to clarify not *his* confusion, but *our* truncated expectations for a theory of war—namely that it should conform to the restrictions of linearity. At the very least, such a sensibility may help us explore the stubborn intractability of prediction in war.⁸⁰ Only a few other implications can be noted here.⁸¹

One implication is that full comprehension of the work of Clausewitz demands that we retrain our intuition. For historians, who have often been attracted rather than repelled by the subtleties of *On War*, this may not be too unsettling a task. But for those trained in the engineering and scientific fields, as are so many military officers and analysts, this retraining is likely to be a more wrenching and unwelcome experience. As the various scientists and mathematicians cited above have suggested, the predominance of a linear intuition is endemic. Such an intuition guides value judgments and choices, with real world consequences:

We would emphasize that in many areas of science and technology a large effort has traditionally been made to model a physical system or process. Yet once the mathematical model has been constructed, only a few rather cursory computer simulations are sometimes made. Lulled into a false sense of security by his familiarity with the unique response of a linear system, the busy analyst or experimentalist shouts “Eureka, this is the solution” once a simulation settles onto an equilibrium or steady cycle, without bothering to explore patiently the outcome from different starting conditions. To avoid potentially dangerous errors and disasters, industrial designers must be prepared to devote a greater percent-

age of their effort to exploring the full range of dynamic responses of their systems.⁸²

Here, Michael Thompson and Bruce Stewart speak of modeling physical systems and processes that are much simpler than the social systems engaged in warfare, yet surveys of military applications of modeling indicate the predominance of the same analytically linear intuition despite the loss of realism it entails.⁸³ And, of course, the “potentially dangerous errors and disasters” take on added dimensions when the task is to prepare for or conduct a war.

A consequent necessity is a reevaluation of Clausewitz as an authority in military manuals and training. The simplicity of a set of “principles of war” will surely remain attractive, not least because they are so easy to comprehend and memorize. But we should understand that Clausewitz’s concerns are to such principles as nonlinearity to linearity (or fractals to Euclidean objects, or the real numbers to the integers). The elegance of military axioms is a mirage shimmering above the distinct abstractions of implicitly idealized, isolated systems; the denseness of Clausewitz’s forest of caveats and qualifications more faithfully represents the conditions and contexts we actually encounter.

Another implication of the nonlinear interpretation of Clausewitz is the need for a deepening of our understanding of his dictum on the relationship of war to politics. That “war is merely the continuation of policy by other means” is often taken to mean the primacy of a temporal continuum: first politics sets the goals, then war occurs, and then politics reigns again when the fighting stops. But such a view categorizes politics as extrinsic to war, and is an artifact of a linear sequential model. Politics is about power, and the feedback loops from

violence to power and from power to violence are an intrinsic feature of war. It is not simply that political considerations weigh upon military commanders. War is inherently a subset of politics, and *every* military act has political consequences, whether or not these are intended or immediately obvious. In the grip of battle, it is hard to remember that every building destroyed, every prisoner taken, every combatant killed, every civilian assaulted, every road used, every unintentional violation of the customs of an ally ultimately has political import. It is crucial to understand that Clausewitz, who was for many years on the losing side before the tide turned against Napoleon, embeds the long-term view and the full range of a system's behavior into the structure of *On War*. Such considerations often make soldiers impatient with his presentation, but the variables in war cannot be isolated from the parameters constituting the political context. And that environment itself evolves dynamically in response to the course of the war, with the changed context feeding back into the conduct of hostilities.

Yet another implication is that chance is also not extrinsic to war, because the interactive nature of military action itself *generates* chance. Single-valued, analytically exact solutions achieved by idealization that conveniently excise all but a few variables derive from a linear intuition. Clausewitz understands that war has no distinct boundaries and that its parts are interconnected. What is needed is to comprehend intuitively both that the set of parameters for "the problem" is unstable, and that no arbitrarily selected part can be abstracted adequately from the whole. The work of Clausewitz indicates that knowing how the system functions at this moment does not guarantee that it will change only slightly in the next. Although it may remain stable, it might also suddenly

(although perhaps subtly) pass a threshold into a thoroughly different regime of behavior. And the causes of such changes in a complex system can be imperceptibly small. Production of an unchanging set of laws or even principles to be employed in all “similar” contexts is not merely useless, it can become counterproductive and lead to the kind of fixed, inflexible, mechanical mentality that is overwhelmed by events. Adaptability is as important in doctrine as on the battlefield.

The overall pattern is clear: war seen as a nonlinear phenomenon—as Clausewitz sees it—is inherently unpredictable by analytical means. Chance and complexity dominate simplicity in the real world. Thus, no two wars are ever the same. No war is guaranteed to remain structurally stable. No theory can provide the analytical shortcuts necessary to allow us to skip ahead of the “running” of the actual war. No realistic assumptions offer a way to bypass these uncomfortable truths. Yet these truths have the virtue that they help us identify the blinders we impose on our thinking when we attempt to linearize. And what Clausewitz says about the conduct of war applies to the study of war: “once barriers—which in a sense consist only in man’s ignorance of what is possible—are torn down, they are not so easily set up again.”⁸⁴

Notes

- 1 Carl von Clausewitz. *On War*. ed. and trans. Michael Howard and Peter Paret. Princeton: Princeton University Press. 1976. I use this edition for all quotations unless otherwise indicated. For the German, see: *Vom Kriege*. 18th ed. (complete edition of original text), ed. Werner Hahlweg. Bonn: Dummlers. 1973. For other works in English, see: von Clausewitz. *Historical and Political Writings*, ed. and trans. Peter Paret and Daniel Moran. Princeton: Princeton University Press. 1992.
- 2 Rothfels, Hans. “Clausewitz” in Edward Mead Earle, ed. *Makers of Modern Strategy*. New York: Atheneum. 1969. p. 93. Christopher Bassford offers one

- impression of the reception of Clausewitz's work in his study of the Anglo-American reception of Clausewitz. 1815-1945. Oxford: Oxford University Press, in press.
- 3 Aron, Raymond. *Clausewitz: Philosopher of War*. trans. Christine Booker and Norman Stone. London: Routledge and Kegan Paul. 1983. p. 6. Original *Penser la guerre, Clausewitz*. 2 vols. Paris: Gallimard. 1976. The suggestion has recently been made that the text was actually much more finished than has hitherto been thought: Azar Gat, "Clausewitz's Final Notes." *Militargeschichtliche Mitteilungen*. Vol. 45, No. 1, 1989. pp. 45-50.
 - 4 Paret, Peter. *Clausewitz and the State: The Man, His Theories and His Times*. Princeton: Princeton University Press. 1983. pp. 8-9 (originally published by Oxford University Press, 1976). Azar Gat's argument that Clausewitz's work is best understood as part of the Romantic backlash against the Enlightenment, also belongs to this approach. See: Gat. *The Origins of Military Thought: From the Enlightenment to Clausewitz*. Oxford: Oxford University Press. 1989.
 - 5 Handel, M.I. *War, Strategy and Intelligence*. London: Frank Cass. 1989. p. 60.
 - 6 Beyerchen, Alan. "Nonlinear Science and the Unfolding of a New Intellectual Vision." *Papers in Comparative Studies*. Vol. 6 (1988-89). pp. 26-29.
 - 7 The principle of proportionality means that if f is a function or an operator, a is a constant, and u is the system input (either a variable or itself a function), then $f(au) = af(u)$. A more precise way of stating the principle of additivity is that the effect of adding the system inputs together first and then operating on their sum is equivalent to operating on two units separately and then adding the outputs together, so that $f(u_1 + u_2) = f(u_1) + f(u_2)$. If f does not meet both of these conditions, it is nonlinear. In effect, if a system can be described adequately by the mathematical operations of addition, subtraction, multiplication, by a constant, integration with respect to time or differentiation with respect to time, it can appropriately be thought of as linear. If it is necessary to multiply or divide variables by each other, raise to powers, extract roots, or integrate or differentiate with respect to dependent variables (that is, variables other than time), then the system is nonlinear.
 - 8 The meaning of "synergistic" interaction is indicated by the contrast between a common linear operation and a common nonlinear one. A linear operation such as multiplying by a constant obeys the principle of additivity: let $f(u) = au$, then $f(u_1 + u_2) = a(u_1 + u_2) = au_1 + au_2$, which is just $f(u_1) + f(u_2)$ again. A nonlinear operation such as squaring, however, is different: let $f(u) = u^2$, then $f(u_1 + u_2) = (u_1 + u_2)^2$, which equals not just $u_1^2 + u_2^2$ again, but $u_1^2 + u_2^2$ plus the interaction term $2u_1u_2$.

- 9 The mathematician Stanislaw Ulam suggested that calling natural phenomenon nonlinear is like referring to the bulk of the animal kingdom as "non-elephant animals." Campbell, David. "Nonlinear Science: From Paradigms to Practicalities." *Los Alamos Science*. Vol. 15. Special Issue. 1987. p. 218.
- 10 See for example: Smarr, Larry. "An Approach to Complexity: Numerical Computations." *Science*. Vol. 228. April 26, 1985. pp. 403-408; and Zabusky, Norman. "Grappling with Complexity." *Physics Today*. October 1987. pp. 25-27.
- 11 Stewart, Ian. *Does God Play Dice? The Mathematics of Chaos*. Oxford and New York: Basil Blackwell. 1989. p. 83.
- 12 See the treatment of Jomini and Bulow in: Paret. *Clausewitz and the State*, passim. Also: *Clausewitz On War*. pp. 134, 136, and 158.
- 13 Maxwell, J.C. "Science and Free Will." in Lewis Campbell and William Garnett, with a new preface and appendix by Robert H. Kargon, *The Life of James Clerk Maxwell* [1882]. New York: Johnson Reprint Corporation. 1969. pp. 440-442.
- 14 See: Beyerchen. "Nonlinear Science and the Unfolding." p. 31. A very good brief discussion of the mathematics and physics involved is in Campbell, "Nonlinear Science." pp. 218-262. The Santa Fe Institute is one of the key research centers where the implications of complexity across these fields is explored. See for example: Stein, D.L. ed. Santa Fe Institute *Lectures in the Sciences of Complexity*. Vol. 1. Redwood City, CA: Addison-Wesley. 1989.
- 15 For a readable, popular account of the development of this field, see: Gleick, James. *Chaos: The Making of a New Science*. New York: Viking. 1987., whose notes on sources indicate many of the seminal papers, yet notably lack the Russian achievements. For a more mathematically sophisticated, yet still accessible overview, see: Casti, John. *Reality Rules*. 2 vols. New York: Wiley. 1992. As dissipative systems, wars also exhibit characteristics of nonlinear self-organization, but space does not here permit an exploration of this topic in Clausewitz's work. On self-organization, see: Nicolis and Prigogine. *Exploring Complexity: An Introduction*. New York: W.H. Freeman. 1989. Coveney and Highfield. *The Arrow of Time: A Voyage through Science to Solve Time's Greatest Mystery*. New York: Fawcett Columbine. 1990.
- 16 Parameters are, after all, just certain variables treated as constants for the duration of the problem. The crucial role played by the parameters is readily apparent in contrasting the commonly studied motion of the simple pendulum for small oscillation amplitudes, with that of the damped, driven

pendulum under more realistic conditions. See: Baker, G.L. and J.P. Gollub. *Chaotic Dynamics: An Introduction*. Cambridge: Cambridge University Press. 1990.

- 17 The Lorenz equations indicate the simplicity directly:
 $dx/dt = Py - Px$, $dy/dt = -xz + rx - y$, $dz/dt = xy - bz$
 where P , r , and b are adjustable parameters relating to fluid flow, thermal convection, etc. See the discussion in: Grebogi, Ott, and Yorke, "Chaos, Strange Attractors, and Fractal Basin Boundaries in Nonlinear Dynamics." *Science*. Vol. 238. October 30, 1987. pp. 633-636. and a readable and more extended treatment in: Thompson, J.M.T. and H.B. Stewart. *Nonlinear Dynamics and Chaos: Geometrical Methods for Engineers and Scientists*. New York: Wiley. 1986: pp. 212-234.
- 18 *On War*: p. 73. All emphases are in the original unless otherwise indicated.
- 19 *Ibid.*: p. 77.
- 20 *Ibid.*: p. 75.
- 21 *Ibid.*: pp. 77-80.
- 22 *Ibid.*: p. 81.
- 23 *Ibid.*: pp. 600-610, the tone of which is set on p. 602: "Still, as we have argued in the second chapter of Book One (purpose and means in war), the nature of the political aim, the scale of demands put forward by either side, and the total political situation of one's own side are all factors that in practice must decisively influence the conduct of war."
- 24 See for example the works of: Dupuy, T.N. *Numbers, Prediction, and War*. Indianapolis: Bobbs-Merrill. 1979.
 Dupuy, *Understanding War: History and Theory of Combat*. New York: Paragon House. 1987.
- 25 *On War*: p. 87.
- 26 *Ibid.*: p. 87.
- 27 *Ibid.*: p. 87.
- 28 *Ibid.*: p. 89.
- 29 *Ibid.*: p. 89.
- 30 See for example: the PBS "Nova" program entitled "The Strange New Science of Chaos," which aired in January 1989.
- 31 *On War*: pp. 214-215.
- 32 *Vom Kriege*: p. 213.

- 33 The experiment requires only simple apparatus. During the time Clausewitz was composing *On War* he attended the lectures of physicist Paul Erman at the Kriegsschule for an entire year without missing a single lecture. Erman was publishing on the new field of electricity, and emphasized precision of observation over the then-fashionable intuitive approach to nature. Erman's son was also studying physics in these same years with a special interest in magnetism. See: Paret, *Clausewitz*: p. 310.
- 34 Aron, *Clausewitz*: p. 2.
- 35 Howard, Michael. *Clausewitz*. Oxford: Oxford University Press. 1983: p. 73.
- 36 *On War*: p. 149.
- 37 *Ibid.*: p. 139.
- 38 *Ibid.*: p. 253.
- 39 See: Aron, *Clausewitz*: pp. 225-228. Howard, *Clausewitz*: p. 84, note 13. Engels and Lenin, however, praised *On War* largely because they read the Hegelian dialectic into it; see: Kitchen, Martin. "The Political History of Clausewitz." *Journal of Strategic Studies*. Vol. 11. No. 1 (March 1988): pp. 27-30.
- 40 Aron, *Clausewitz*: p. 90.
- 41 *Ibid.*: pp. 98-99. *Penser la guerre*, Vol. 1: p. 166.
- 42 *On War*: p. 132.
- 43 *Ibid.*: p. 119.
- 44 *Ibid.*: pp. 119-120.
- 45 See: Cardwell, D.S.L. *From Watt to Clausius: The Rise of Thermodynamics in the Early Industrial Age*. London: Heinemann, 1971. pp. 186-294. On the relationships of nonlinearity and entropy, see the works of: Ilya Prigogine, esp. with Isabelle Stengers, *Order Out of Chaos*. New York: Bantam. 1984. Arthur Peacocke, "Thermodynamics and Life." *Zygon*. Vol. 19. No. 4 (December 1984): pp. 395-468.
- 46 *On War*: 119. See also p. 153: "Routine apart from its sheer inevitability, also contains one positive advantage. Constant practice leads to *brisk, precise and reliable* leadership, reducing natural friction and easing the working of the machine."
- 47 *Ibid.*: p. 101 and pp. 117-118.
- 48 On how simple nonlinear systems exhibiting chaotic behavior can similarly be viewed as "information pumps" that amplify immeasurably small

- differences, see: Shaw, Robert. "Strange Attractors, Chaotic Behavior, and Information Flow." *Zeitschrift der Naturforschung*. Vol. 36a. 1981. pp. 80-112.
- 49 *On War*. p. 85.
- 50 Poincare, Henri. "Chance," in *Science and Method*, reprinted in *Foundations of Science*, trans. George Bruce Halsted [1913] Washington, DC: University Press of America. 1982: pp. 400-406.
- 51 On Clausewitz's interest in mathematics, see Paret, *Clausewitz*: p. 127 and p. 130; and Clausewitz to his future wife, February 28, 1807, in K. Linnebach, ed., *Karl und Marie von Clausewitz: Ein Lebensbild in Briefen und Tagebuchblättern*. Berlin: Martin Warneck. 1925: p. 94. On the history of probability theory in the period, see: Daston, Lorraine. *Classical Probability in the Enlightenment*. Princeton: Princeton University Press. 1988. pp. 226-295.
- 52 Katherine Herbig has remarked that analysis of statistical probability depends on large numbers of events to be valid, while Clausewitz stressed the unique and distinctive events in war. Raymond Aron has noted the emphasis that Clausewitz placed on an intuitive rather than calculative grasp of probabilities. However, the relevance of Poincare here relates to the generation of statistical chance rather than how to cope with it. Herbig, Katherine. "Chance and Uncertainty in *On War*," in Michael I. Handel, ed. *Clausewitz and Modern Strategy*. London: Frank Cass. 1986. p. 107. (originally published in *Journal of Strategic Studies*. Vol. 9. No. 23. June-September 1986). Aron, *Clausewitz*: p. 185.
- 53 *On War*. p. 86.
- 54 *Ibid.*: p. 112.
- 55 *Ibid.*: pp. 136-140.
- 56 An exception is Barry D. Watts, who had explored Clausewitz's concept of friction from this perspective. See: Watts. *The Foundations of U.S. Air Doctrine: The Problem of Friction in War*. Maxwell AFB, AL: Air University Press. 1984. Roche, J.G. and Barry D. Watts, "Choosing Analytic Measures," *Journal of Strategic Studies*. Vol. 14. No. 2. June 1991. pp. 191-194. See also Bassford's manuscript (note 2 above), chap. 2.
- 57 Poincare, "Chance": pp. 397-398.
- 58 *On War*. p. 595.
- 59 *Ibid.*: p. 156.
- 60 Poincare, "Chance": p. 403.
- 61 *On War*. p. 134 and p. 136.

- 62 Ibid.: p. 158.
- 63 Ibid.: p. 81.
- 64 Ibid.: p. 81.
- 65 Ibid.: p. 256.
- 66 Ibid.: pp. 256-257. This outcome is certainly exceptional, but hardly unknown; the German victory at Dunkirk and the Japanese victory at Pearl Harbor provide obvious twentieth-century examples.
- 67 Ibid.: pp. 595-596.
- 68 Ibid.: p. 596.
- 69 Ibid.: p. 486.
- 70 Ibid.: p. 486.
- 71 Schneider, James and Lawrence L. Izzo. "Clausewitz's Elusive Center of Gravity." *Parameters*. Vol. 17. No. 3. September 1987. p. 50.
- 72 Brodie. "A Guide to the Reading of *On War*." *On War*. p. 647. The passage in Clausewitz that Brodie discusses reads: "One point is purposely ignored for the moment—the difference that the *positive* or *negative* character of the political ends is bound to produce in practice. As we shall see, the difference is important, but at this stage we must take a broader view because the original political objects can greatly alter during the course of the war and may finally change entirely *since they are influenced by events and their probable consequences*." *On War*. p. 92. For a statement by Clausewitz that the means always affect the ends, see *On War*: p. 158. On Brodie's overall appreciation of Clausewitz, see: Steiner, Barry. *Bernard Brodie and the Foundations of American Nuclear Strategy*. Lawrence, KA: University Press of Kansas. 1991. pp. 210-225.
- 73 Campbell, "Nonlinear Science": p. 231.
- 74 U.S. National Research Council. *Physics Survey Committee, Scientific Interfaces and Technological Applications (Physics through the 1990s)*. Washington, DC: National Academy Press. 1986. p. 132.
- 75 *On War*. p. 80.
- 76 Ibid.: p. 141.
- 77 Ibid.: p. 140.
- 78 Ibid.: p. 149.
- 79 Ibid.: p. 152.

- 80 Such an exploration would have immediate consequences. As Joshua Epstein has mused, "If by a series of empirically and theoretically defensible assumptions, we are led to mathematical models that, over certain ranges, exhibit highly sensitive, even chaotic, behavior, that may reveal a fundamental fact about war and its inherent volatility, a fact with which policy makers, scholars, and soldiers may have to come to terms." Epstein. "The 3:1 Rule, the Adaptive Dynamic Model, and the Future of Security Studies." *International Security*. Vol. 13. No. 3. Spring 1989. p. 119.
- 81 A parallel examination has begun in economics. In contrast to the negative-feedback idealizations of conventional theory, W. Brian Arthur has argued that positive feedbacks can make the history of an economic system matter. Thus, "to the extent that small events determine the overall path always remain beneath the resolution of the economist's lens, accurate forecasting of an economy's future may be theoretically, not just practically, impossible." Arthur. "Positive Feedbacks in the Economy." *Scientific American*. February 1990: p. 99. See also the essays in: Anderson, Philip., Kenneth J. Arrow, and David Pines, eds. *The Economy as an Evolving Complex System, Santa Fe Institute Studies in the Sciences of Complexity*. Vol. 5. Redwood City: CA: Addison-Wesley. 1988.
- 82 Thompson and Stewart, *Nonlinear Dynamics and Chaos*. p. xiii.
- 83 See: Battilega, John and Judith K. Grange. *The Military Applications of Modeling*. Wright-Patterson AFB, OH: Air Force Institute of Technology Press. 1979: esp. Appendix A: pp. 516-543; and Battilega and Grange. *Models, Data, and War: A Critique of the Foundation for Defense Analyses*. Washington, DC: U.S. General Accounting Office. 1980.
- 84 *On War*. p. 593.

From *Command in War*

By Martin Van Creveld

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The Misdirected Telescope

So far, the analysis in this chapter has concentrated on the quantity of information that was needed to command the U.S. forces in Vietnam. However, the kind of information employed by the Americans in order to manage the Vietnam conflict is also worth investigating. It is in this field that we can hope to find the causes of some of the characteristic ways command operated in this strange war. . . .

The favorite lens through which the American defense establishment chose to understand, plan and wage the war in Vietnam consisted of statistics. As already noted, the selection of systems analysis as the method for making high-level decisions about budgets and the structure of military forces carried with it a penchant for quantification that was subsequently expanded into other fields also. Two of the most important decisionmakers, McNamara and Westmoreland, both of whom at one time or another had been associated with the Harvard Business School, appear to have loved statistics for their own sake and surrounded themselves with men whose

predilections were similar. At a time when computers were still very new and exciting, it was sometimes thought that their use in problem-solving in itself constituted a superior method of analysis. The trend toward statistics was probably enhanced by the very size of the information flow needed to run the war in Vietnam, leading to a situation in which messages could not be read but had to be counted instead.

Although some of the drive toward statistics thus came from factors inside the command system itself, it is undeniable that Vietnam, a guerrilla war without fronts, was difficult to grasp except by statistical means. Arrows or colored patches on a map, even the act of fighting itself, meant comparatively little in a war whose ultimate objective was the allegiance of a people and the building of a nation. Progress toward either being difficult to determine, indirect means had to be substituted; the percentage of the population in "pacified" areas was measured by the Hamlet Evaluation System (HES), the number of miles of road or waterway open to traffic, the country's economic activity as measured in tons of rice brought to the urban markets. The enemy situation in its turn was measured by the number of incidents and the body count,¹ and the performance of friendly troops was put in terms of kill ratios. The figures had to be analyzed in a thousand ways, a task for which computers were often used.

Some of the disadvantages of the system, including in particular the often notorious inaccuracy of data, have been the subject of frequent comment,² but others are less well understood and must be briefly discussed here. Statistics, even when accurate, can never substitute for indepth knowledge of an environment, a knowledge that the Americans in Vietnam were almost entirely without.³ The lack of it tends to convert genuine political and military problems into bogus technical

ones. Though the reams of figures in a computer printout may appear impressively comprehensive and accurate, their meaning is often ambiguous: for example, a drop in the incident rate may signify (among other things) either that the enemy is being defeated or that friendly forces are less than successful in locating him and bringing him to battle.⁴ Since the patterns that form the objective of statistical analysis only become visible at fairly high levels in the hierarchy (further down, the figures are by definition meaningless), reliance on such analysis is itself a contribution toward centralization and the information pathologies of which centralization can be a cause. Statistics may have been the only way to handle the flood of incoming messages—running, at the Pentagon level, into the hundreds of thousands per day—but in the process, statistics reduced the content of those messages to the lowest common denominator. Finally, statistics constitute one of the most abstract forms of information known to man; although they can possibly present a good picture of a whole phenomenon the relevance of any given set of figures to this or that particular event at this or that particular place may well be next to zero.

Thus, following analyses based on vast amounts of data, the MACV in Saigon or the Office of Systems Analysis back in Washington might produce tables to show (these are actual examples) that combat activity peaked in 1968 and 1972; that the heaviest fighting always took place in the first half of the year, a somewhat unsurprising fact since this also happens to be the dry season; that there were, year by year, so many attacks (large, small, or other), so many cases of harassment, terrorism, sabotage, propaganda, and anti-aircraft fire; that Viet Cong strategy, as analyzed by these methods, “called for constant small harassment punctuated by a few high points of

activity;" that such and such of a percentage of all villages in this or that district had been "pacified," and that so and so many fighter bomber sorties had been flown in such and such a period.⁵ Given the nature of the data and of the methods used for analyzing them, it is thus not surprising that, in the words of one of OSA's advocates, "perhaps the most dramatic" finding of the Office of Systems Analysis was that the United States was not winning the war of attrition and that the addition of more troops would not solve the problem. The conclusion that no more troops should or could be sent, incidentally, had already been arrived at by McNamara, reasoning independently along entirely different lines.⁶

What effect did all this have on the actual command system in Vietnam? Based on post-action reports, statistics of the kind discussed above did not constitute enemy intelligence, in the true sense of the word. Gathering the information on which they were based was a heavy and, in the case of body count, hazardous burden on the troops, to whose specific requirements its relevance was often doubtful. Constantly subjected to pressure for more and more data of this kind, the troops not unnaturally responded by feeling that it did not matter what one reported so long as it looked good in the Efficiency Reports. The result, to borrow Jeremy Bentham's cruel phrase about natural rights, was "nonsense on stilts." Clogged with data whose accuracy and relevance were both open to question, the military reporting system lost much of its value and had to be supplemented, and in part replaced, by other forms of information gathering.

The peculiar role played by helicopters in commanding the war in Vietnam has been the subject of frequent and interesting comment;⁷ few of those who noted the phenomena have attempted, however, to look for its causes or to relate it to the

general way in which the command system operated. As one observer has written, the helicopter tended to exaggerate two of the fundamental traits of the American character, impatience and aggressiveness⁸—possibly a pertinent remark, but not really an explanation. Other factors that help account for the extraordinary role that helicopters played in command must include the new machine's glamorous image and the prestige associated with having such a thing at one's beck and call; the tendency to use them in order to accumulate flying hours, leading toward air medals and eventual promotion; and the fact that the helicopter does indeed provide a fast and flexible means for getting commanders from one place to another and for obtaining an overall view of the battlefield.⁹ It is this last factor that has led to the adoption of the helicopter as a tool of command in every modern army. In the difficult, often roadless Vietnamese terrain, such speed and flexibility made the helicopter particularly attractive.

Under the conditions peculiar to the war in Vietnam, major units seldom had more than one of their subordinate outfits engage the enemy at any one time. Ordinarily this would have permitted each commander to control a larger number of subordinates, thus leading to decentralization and a flattening of the hierarchical structure; instead, it led to a very different phenomenon. A hapless company commander engaged in a firefight on the ground was subjected to direct observation by the battalion commander circling above, who was in turn supervised by the brigade commander circling a thousand or so feet higher up, who in turn was monitored by the division commander in the next highest chopper, who might even be so unlucky as to have his own performance watched by the Field Force (corps) commander. With each of these commanders asking the men on the ground to tune in on his frequency

and explain the situation, a heavy demand for information was generated that could and did interfere with the troops' ability to operate effectively. Yet what were the medium-level and senior commanders to do? As the discussion has so far shown, the normal channels of military reporting in Vietnam were often flooded with inaccurate, irrelevant information that could not be transmitted and processed on time. To get through it all, uncommonly powerful directed telescopes had to be employed by commanders from General Westmoreland—who insisted on his right to make unannounced visits to all levels¹⁰—downward. That the telescopes in question were frequently so powerful as almost to paralyze the action they were supposed to monitor is, in view of the circumstances, hardly surprising.

The other phenomenon associated with command in Vietnam that can be explained only with reference to the inadequacy of the ordinary military reporting system is the enormous role played by the media, especially television. Once again, it is essential not to lose perspective; other factors, including the openness of American society and a growing tendency on the part of the public to discount official statements as mendacious, were of course involved. Nevertheless, the importance of the media as a source of information for decisionmakers in Washington, and even, to some extent, for the MACV in Saigon, is best understood as deriving in part from the media's ability to cut through the military information system itself.

The media as they operated in Vietnam had much in common with some aspects of the command system. Both journalists and commanders often spent only a short time in the country and on the job, and both were thereby prevented from acquiring a thorough knowledge of the environment. Both spent much of their time flitting into and out of places where dra-

matic events took place, sometimes even sharing the same helicopters.¹¹ Unlike commanders, however, newsmen enjoyed an advantage in that they did not have to deal with statistics and were therefore able to transmit a direct image of events. Nor did the information they sent up have to be summarized afresh by every intermediate headquarters, the result being often considerable time savings. Journalists in general, and television in particular, mostly dealt with the specific rather than with the general, and to this extent were often able to present a more accurate picture than the one compiled from a mass of statistical reports. Often operated by men with little understanding for either the country or the war, and subject to no supervision but their own, the media acted as an undirected telescope that could and did focus attention on individual events to the detriment of the picture as a whole. Their strong point—their ability to cut through the normal information channels—thus also constituted a weakness.

Possibly the best example of the way that the media, acting as an undirected telescope, influenced the war in Vietnam is afforded by the 1968 Tet offensive. At a time when the 90 percent of South Vietnam not visited by newsmen saw 85 percent of all American maneuver battalions deployed and 80 percent of all U.S. casualties (it was in the unreported area that My Lai took place on 16 March 1968), the media made it appear as if the war was being fought solely in Saigon, Hue, and Khe San.¹² So powerful was the ability to focus the attention of even the senior decisionmakers that General Westmoreland came to live in his operations room while the “siege” of the Marine base at Khe San lasted. In Washington the “symbolic” and “historic” value attributed to Khe San first caused President Johnson to extract a written pledge from the Joint Chiefs of Staff that it would not be allowed to fall, then to have a

model of the base constructed in the White House basement around which he and his advisors spent their time. Whether in fact General Giap ever intended to overrun the base remains unknown; that the U.S. media were able to focus attention on the siege—and thus away from the coming Tet offensive—appears certain, regardless of whether it was planned in this way by the North Vietnamese.

The way that the helicopter, the media, and the tactical field radio functioned is perhaps best understood as an attempt to overcome the shortcomings of the military reporting system as it operated in Vietnam. Owing to a variety of circumstances favoring its use, the helicopter was turned into such a powerful directed telescope that it distorted the operation of the system it was supposed to help monitor and was even capable of bringing it to a halt. The media moved wildly out of control, concentrating on events selected mainly for the drama that they could bring to newspaper headlines and television screens, and thus helped pull the entire war out of focus. Field radio was used as a rapid and effective means of communications, regardless of security. Probably none of this, to repeat, would have happened had not the normal channels of military information been deficient to start with.

Conclusions: The Pathology of Information

The U.S. forces deployed in Vietnam were among the most complex in history. Not only was top-level organization diffuse and chaotic to the point that nobody and everybody was in charge, but an entire regular command structure designed for conventional warfare was transplanted into a guerrilla environment for which it was not suitable. Extreme specialization

of personnel and of units, coupled with adherence to the traditional triangular chain of command, meant that headquarters were piled upon headquarters and that coordination between them could only be achieved, if at all, by means of inordinate information flows.¹³ A tendency toward centralization, the pooling of resources, and the running of the war by remote control—especially evident in the field of logistics, and in the air war against North Vietnam—further augmented the demand for information. Though the signals network that the U.S. Army established in South Vietnam was the most extensive, expensive, and sophisticated in history, it proved in the end incapable of dealing with this “bottomless pit,” as General Abrams once put it.¹⁴

Although the most obvious military result of the information pathologies produced by complexity and centralization was the long leadtime often required to prepare and launch an operation in Vietnam, others made themselves manifest in the roles played by the helicopter and the media and in the way field radio was used. Confronted with a military information network that was impossibly complex and in the end often unable to cope, decisionmakers not unnaturally responded by attempting to cut through by any and every means that presented themselves. Commanding officers in Vietnam relied on the helicopter; officials in Washington depended on the media to supplement the frequently highly abstract, imprecise, and slow-to-arrive information percolating through normal military and defense establishment channels; and the troops chatted over their radio sets.

To guard against a misunderstanding at this point, I must stress that there is nothing inherently wrong in the use of extracurricular sources of information; their employment may, in fact, be a prerequisite for the creation of a functioning com-

mand system. When the regular channels are blocked or distorted by disease, however, the effort to cure that disease by drugs that are too powerful, or insufficiently specific, or insecure, is not likely to succeed.

Thus, in the end, the effort to minimize the cost-benefit ratio by the coordinated action of thousands of little cogs, all to be interconnected and fine-tuned to the performance of their missions in the hands of a supreme management team, backfired. Instead of resources being economized, hundreds of thousands of tons of ordnance were dropped or fired away in return for few if any enemy casualties.¹⁵ Instead of the war being fought surgically and selectively against a highly elusive enemy while sparing the population, entire districts were flattened so that they could be saved. Instead of all data being available to top-level decisionmakers, they often ended up with a form of knowledge that was too diffuse and abstract for use. Instead of the helicopter's extraordinary capabilities being used to improve the command process, they often ended up obstructing its operation. Designed to produce accuracy and certainty, the pressure exercised from the top for more and more quantitative information ended up by producing inaccuracy and uncertainty. Instead of being sure of what they were doing, the Americans by measuring output—often the only thing that could be measured with any accuracy—ended up doing what they could be sure of.

Undoubtedly, some of the factors responsible for this mess are inherent in the nature of modern war. Others were specific to the time and place, while others still—including in particular excessive specialization, centralization, and instability in the organization of the forces—could conceivably have been avoided by a better understanding of what the war was all about.¹⁶ The real point of the story, however, is that while up-

to-date technical means of communications and data processing are absolutely vital to the conduct of modern war in all its forms, they will not in themselves suffice for the creation of a functioning command system, and that they may, if understanding and proper usage are not achieved, constitute part of the disease they are supposed to cure. The outlay involved in the American command system in Vietnam was enormous, but this very outlay involved a heavy additional logistic burden and in the end collapsed under its own weight. The men who designed the system and tried to run it were as bright a group of managers as has been produced by the defense establishment of any country at any time, yet their attempts to achieve cost-effectiveness led to one of the least cost-effective wars known to history. The technical ability of the command systems in their various forms to make their influence felt at the lowest levels was unprecedented, but this very ability probably did as much to distort the process of command as to assist in its work. To study command as it operated in Vietnam is, indeed, almost enough to make one despair of human reason; we have seen the future and it doesn't work.

Notes

- 1 Ironically, body count was first introduced by MACV in an attempt to convince skeptical journalists that its reports of "victories" were accurate. This did not prevent it from turning into a highly unreliable indicator and the butt of every kind of guided and misguided criticism. See: Kinnard, D. *The War Managers*. Hanover, N.H. 1977. pp. 68-75.
- 2 See: Thayer, T.C. *How to Analyze a War without Fronts: Vietnam, 1965-1972*. Washington, D.C. pp. 854-855.
- 3 It has been claimed that, even as late as 1968, there were only some 30 "experts" on Vietnam in American universities, of whom perhaps 12 possessed a thorough knowledge of the language.
- 4 The obvious remedy—dividing incidents into those initiated by friendly forces and those initiated by hostile ones—would not work, since a drop in, for

instance, enemy-initiated incidents might mean (again, among several other things) either that he was too weak to attack or that he was too strong to need to.

- 5 All these examples are from Thayer, *How to Analyze*, passim.
- 6 Ibid.: p. 722.
The Pentagon Papers, vol. IV: pp. 456-458, 468-469, 478.
- 7 Palmer, D.R. *Summons of the Trumpet*. San Rafael, Cal. 1978. pp. 143-144.
Mylander, M. *The Generals*. New York, NY. 1974. p. 174.
Kinnard, *The War Managers*: pp. 55-56.
Hay, *Tactical and Material Innovations*: p. 84.
Thompson and Frizzel, *The Lessons of Vietnam*: pp. 176-177.
Bradford and Brown, *The U.S. Army*: pp. 236-237.
- 8 Thompson, R. *No Exit from Vietnam*. London, ENG. 1969. p. 136.
- 9 Nevertheless, watching a battlefield from the air is by no means the same as experiencing it from the ground, a fact that many a contemporary commander would do well to remember.
- 10 Westmoreland, W.C. *A Soldier Reports*. Garden City, N.Y. 1976. pp. 269-271.
- 11 Newsmen in Vietnam were provided with free military transportation on the basis of space available.
- 12 Braestrup, B. *Big Story: How the American Press and Television Reported and Interpreted the Crisis of Tet 1968 in Vietnam and Washington*. Boulder, CO. 1977. vol. I, p. xxix.
- 13 One proposal for an alternative chain of command is put forward by: Canby, S.L., B. Jenkins, and R.B. Raincy. "Alternative Strategy and Force Structure in Vietnam." RAND Paper D 19073 ARPA. Santa Monica, CA. 1969. Appendix A, pp. 29-37. Here it is suggested that the span of control of battalion and brigade should have been increased to five and divisions all but eliminated, resulting in a more flexible command structure and reducing information flow.
- 14 Rienz, T.M. Vietnam Studies: *Communications-Electronics 1962-1970*. Washington, D.C. 1972. p. 157.
- 15 For some figures on the waste involved, such as 75 bombs and \$400,000 to kill a single enemy soldier, see *Life* magazine, 27.1.1967, and the *New York Times*, 7.12.1967. Even then, of course, it might be argued that many of those killed were not enemy troops at all and that the results of the killing were, if anything, unproductive.

- 16 Significantly, U.S. performance in terms of enemy troops killed versus ordnance expended improved dramatically after Westmoreland was replaced by Abrams and a halt was called to large-scale search and destroy operations. See: Blaufarb, D.S. *The Counterinsurgency Era: U.S. Doctrine and Performance*. New York, NY. 1977. p. 254.

Command and Control at the Crossroads

by Thomas J. Czerwinski

[Czerwinski, Thomas J. "Command and Control at the Crossroads." *Parameters*, Autumn 1996: pp. 121-132.]

This article elaborates on the methods of command developed by Martin Van Creveld in his classic *Command in War* (1985), with extensions to both definitions and framework. It then projects for each method its analogue in contemporary command and control (C2) system developments. Each of these systems are then evaluated against Van Creveld's "iron rules" for increasing the performance of command.

The second test in this article explores each command method in terms of linear and nonlinear dynamics, both as art and technology. Finally, the command methods are evaluated in accordance with the principles of the field of safety engineering. These three tests together provide a framework that complements, reinforces, and extends Van Creveld's original theses.

American command practice is at a crossroads. Which path, or emphasis, it takes is of vital concern. These tests suggest that

the method least considered and least formulated is, nevertheless, the most appropriate, most of the time.

Command Methodologies and Their Information Age Systems Equivalents

The function of command is carried out by direction, by plan, or by influence. While not mutually exclusive and often employed in combination, these methods, or archetypes, are dominant.¹ While technological advances have affected these methods incrementally over time, the effect of the Information Age is such that all three methods are for the first time embodied in contending automated information systems developments. The system supporting command-by-direction is the Army's "Force XXI" and its digitized battlefield. The "System of Systems" advocated by the immediate past Vice Chairman of the Joint Staff is a command-by-plan approach. Finally, command-by-influence is associated with maneuver warfare to which the Marine Corps is doctrinally committed.

Each of these three methods are responses to the pervasive underlying commander's quandary—uncertainty and insufficient information. By insufficient, however, Van Creveld does not mean lacking in quantity. Rather, he speaks to getting the necessary quality of information in the right form, at the right place, at the right time. He describes information that does not conform to that standard, including information overload, as an "information pathology," a graphic term which unfortunately has not conceptually been pursued further. As a penetrating RAND study noted in 1989, "commanders' information needs are rarely specific pieces of data but are instead highly variable and human intensive elements."² Thus, C2 requirements are not information

intensive, but information *sensitive*. Checklist-generated data might also be called “cyber-junk.”

Each method of command grapples with uncertainty in its own way. In the absence of uncertainty, the act of command would be a simple one, if not irrelevant. But a commander’s work is virtually always complicated by uncertainty, and the three styles of command address that uncertainty in different ways. Generally, the directing commander attempts to *prioritize* uncertainty, the command-by-plan commander seeks to *centralize* uncertainty, and the influencing commander prefers to *distribute* uncertainty.

Command-by-Direction

Command-by-direction is not only the oldest of methods, but virtually the sole method until the middle of the 18th century, and largely in disfavor since. The earliest commanders found that even if they could find a vantage point from which they could see the entire battle, distances prevented them from playing any role other than observer. They were required accordingly to adopt one of two compromise approaches to command. In the first approach, they could attach themselves to one element of the force, judging it to be the decisive one. They thereby directed some of their forces all of the time, while depending on tenuous, if any communications with other units. The other variant involved the commander moving from unit to unit as the situation seemed to warrant, thereby directing some or all of the forces some of the time. Both variants of command-by-direction, however, fell short of the commander’s dream—to direct dynamically all of the forces all of the time. To do so has been—until recently, with the maturation of the Information Age—all but impossible.

In recognition of the difficulties of command-by-direction, the Army has been evolving toward a concept of command-by-plan—not, however, without reservations. The demand to lessen dependence on command-by-plan was recognized in the Gulf War:

Schwartzkopf intuitively rejected a battle by formula of the sort taught at the Army schools and practiced by U.S. forces in NATO. He had seen how poorly the Army had performed in Grenada in trying to conduct operations from a checklist.³

The Army's digitized battlefield is intended to equip command with dynamic, near real-time synchronization⁴ capabilities. That battlefield requires massively increased information processing capabilities, described as "the most complex mobile router-based computerized network that the world has ever seen," and as "deploying a network larger than the one managed by AT&T." A reinforced brigade will field more than 1,200 computers. Every tank and Bradley fighting vehicle would be so equipped, as well as a number of other vehicles and dismounted troops.⁵

The basic technological tenets of the Army's Force XXI concept are conducive to returning command-by-direction to the repertoire of the U.S. Army commander after an absence of 250 years. In simulations, the information processing capabilities of Force XXI have "demonstrated that modernized information operations improve the commander's ability to synchronize operations in his battlespace. . . [The] commander's situational awareness and the staff's shared picture of the battle allowed the commander to make more accurate and rapid decisions than nondigitized counterparts."⁶

Force XXI embodies the first of the “iron rules” for the improvement of the performance of command formulated by Van Creveld:

Confronted with a task and having less information than is needed to perform the task [a military] organization may . . . increase its information processing capability. . . [which] will lead to the multiplication of communications channels and to an increase in the size and complexity of the central directing organ.

Van Creveld’s study of command convinces him “that this approach is inadequate and stand[s] in danger of being self-defeating.”⁷ At another level of analysis, the Army’s approach implies that command forms that attempt to *prioritize* uncertainty do not lend themselves to success.

Force XXI is an effort to offset command-by-plan with the more proactive and interventionist element of Information Age command-by-direction. Most Army commanders, seeing the opportunity to be a boxer as well as an architect, cannot refuse the window of opportunity offered by the promise of modern information technology.

Command-by-Plan

Two hundred and fifty years ago, Frederick the Great tried to break out of the limitations imposed in commanding by direction. He resorted to command-by-plan, thereby opting for comprehensiveness over dynamism. His efforts consisted of “trying to plan every move in advance, relying on highly trained troops and strict discipline to carry out the scheme as ordered.”⁸ Frederick’s use of a plan to command all of the forces all of the time met with mixed success.

Nevertheless, the highly centralized command-by-plan formula evolved into the norm for the command of modern military forces. This has been accompanied by much experimentation and adaptation in doctrine and systems to support the method, and in training, equipping and organizing the force to operate according to plan. However, as with all plan regimes, increased complexity has kept pace with heightened competency. The reason is that command-by-plan inherently fights the disorderly nature of war as much as the adversary. It is a futile quest to will order upon chaos. The contemporary C2 equivalents for this method are the various forms of plan regimes under the broad designation of precision warfare. Foremost among these is the "System of Systems" concept based upon achievement of dominant battlespace awareness, or knowledge,⁹ and the Air Forces' air campaign methods and supporting systems.

The method is characterized by trading flexibility for focus in order to concentrate on identifying and neutralizing centers of gravity, or target sets, in a campaign context. It operates exclusively at the strategic and operational levels of war, it reduces information requirements by focusing on perceived centers of gravity and by honing the associated target lists into prioritized and—increasingly—synchronized and simultaneous operations. Essentially, both the organization and tasks are designed to operate with less information in total, notwithstanding the considerable complexities in achieving targeted expectations.

The argument is made that the second of Van Creveld's iron rules for increasing the performance of command applies to command-by-plan: "drastic simplification of the organization so as to enable it to operate with less information." As with the first rule's applicability to command-by-direction, this second rule tends to make command-by-plan "inadequate

and. . . in danger of being self-defeating." In other words, command forms that *centralize* uncertainty do not lend themselves to success.¹⁰

Command-by-Influence

A hallmark of command-by-influence is the use of *auftragstaktik*, or "mission-type orders," especially as developed by the Germans in the latter stages of World War I and refined in World War II. In this method of command, only the outline and minimum goals of an effort are established in advance, effectively *influencing* all of the forces all of the time. Unlike other command forms, this method takes disorder in stride as "inevitable and even, insofar as it affected the enemy as well, desirable."¹¹ Great reliance is placed on the initiative of subordinates based on local situational awareness, which translates to lowered decision thresholds. It relies on self-contained, joint, or combined arms units capable of semiautonomous action. All of this activity occurs within the bounds established by the concept of operations derived from the commander's intent.

Confronted with insufficient information to carry out a task, Van Creveld's third rule states that a military organization

may react by designing the organization, or indeed the task itself, to operate on the basis of less information, relying on the division of the task into various parts and to the establishment of forces capable of dealing with each of the parts separately on a semi-independent basis. It is a central theme. . . through every change. . . [and] technological development that the third one will remain superior. . . in virtually every case.

This suggests that only command forms that *distribute* uncertainty are likely to be more or less consistently successful.

The third rule is embodied in command-by-influence. Yet despite the promise of this form of command, the dim outlines of its information system equivalent is only now starting to take shape, and then largely on a theoretical plane. Inexplicably, the most promising method for future command has fallen, both in terms of realization and resources, behind competing command forms that exhibit no superior characteristics in terms of realization and resources, behind competing command forms that exhibit no superior characteristics.

How the Command Methods Relate to Toffler's Third Wave

Command-by-direction and command-by-plan are supported by the capabilities of the technologies at the surface of the Third Wave, the so-called Information Age. Command-by-influence, however, has its source at the deepest level of the Third Wave: post-Newtonian science, or nonlinear dynamics, exemplified by theories of chaos and complexity. Most readers will be familiar with the concept of the Information Age, with Silicon Valley, the Internet, and the writings of Peter Drucker, and of Heidi and Alvin Toffler. The Revolution in Military Affairs debate has largely been shaped by the technology of this age, by the pervasive rush of chip advances, computer utilities, and an increasingly Internetted world. In fact, the Information Age and the Third Wave are generally synonymous with both the public and the military.

Nothing could be farther from the truth. The Third Wave is a complex, contentious place.

Awareness that nonlinear dynamics is at the base of the Third Wave is low in comparison to the broad general

understanding of the omnipresent technology that otherwise helps to define it. This science is in its infancy, and is more about biology than about physics. It is only some 20 years old, and required the computer for its discovery. Nonlinear dynamics has its own jargon: phase states, bifurcations, fractals, periodic and strange attractors, emergence, criticality, and path-dependence,¹² to name a few. Its message, however, is post-Newtonian.

By Newtonian, we mean the arrangement of nature–life and its complications—to be a linear phenomenon where inputs are proportional to outputs; prediction is facilitated by careful planning; success is pursued by detailed monitoring and control; and a premium is placed upon reductionism, rewarding those who excel in such reductionist processes. Reductionist analysis consists of taking large, complex problems and reducing them to manageable chunks. Reductionism still works where effective linearity holds sway, such as in some areas of engineering and technology.

By post-Newtonian, we mean that the arrangement of nature–life and its complications, such as warfare—is nonlinear. It defines activities in which inputs and outputs are not proportional; where phenomena are *unpredictable, but within bounds, self-organizing*; where unpredictability frustrates planning; where solution as self-organization defeats control; and where a premium is placed on holistic, intuitive processes. It rewards those who excel in the calculus of bounds¹³ as the variable of management and command.

By denying the efficacy of prediction and control, post-Newtonian science ratifies command-by-influence and its principles. In command-by-direction and command-by-plan, the emphasis is placed upon technology insertion and innovation, and

training the force to take advantage of increased capabilities. In command-by-influence, the emphasis is on training and educating the force to exercise initiative to exploit opportunities, guided by the commander's intent, only secondarily dependent on technology. The difference involves a difficult transition from the ingrained habit of deductive, reductionist thought to more holistic, inductive processes in which intuition is elevated and powers of pattern recognition are prized. Intuition in this sense means not so much instinct, as experiential training and education, and firsthand experience. It offers the opportunity to infuse lower echelons with both the confidence and competence to engage in semiautonomous action.

What a Command-by-Influence System Might Look Like

The outline of a command-by-influence system retains its historic characteristics, foremost of which are "mission-type orders" and self-contained units capable of semiautonomous action, complemented by the following four traits:

—Recognition that the native mode of command is an image, or mental model, not voice or text. Further, "the meaning of any information gained by the commander is driven by the image that frames it, and the value of that information is determined by the manner in which it fits into the image. . . [Therefore] a major purpose of communications in the command and control process lies in the sharing of images."¹⁴

—Advances in synthetic environment technology, especially thin panel imagery displays, to transmit the intent of the commander as a symbolic representation of the mental image. This symbology, in the form of standard and personalized icons, requires extensive investigation and experimentation. This may lead us

into the field of semiotics, a “science which analyzes signs and symbols and puts them in correspondence with a particular meaning.”¹⁵

–*The provision of subtly directed telescopes.* This technique employs the selective and careful use of trusted and attuned subordinates to act as the commander’s eyes and ears, to observe and report directly, bypassing channels. This technique is especially useful for determining intangibles, such as morale.¹⁶ (Sadly, this historic practice no longer is found even as an option in current doctrine.)

–*The introduction of the principles of post-Newtonian science, and reducing the use of voice and text in the battlespace.* This characteristic can be waived as necessary to raise alarms should circumstances require it.

The display of mental images, the native mode of command, through synthetic environment technology produces a decision loop bordering on the instantaneous. A combination of standard and personalized icons and frames displayed on thin-panel screens, representing the commander’s intent, results in a superior decision cycle, both in elapsed time and integrity. One is virtually reading the commander’s mind (with imagery feedback loops provided.) In the command and control process:

Control is provided by feedback—the continuous flow of information about the unfolding situation [or better, the changed situation based on subordinate initiative], returning to the commander—which allows the commander to adjust and modify command action as needed. . . Control is not strictly something which seniors impose on subordinates; rather, the entire system gains control. . . based on feedback about the changing situation. The result is a mutually supporting system of give and take in which com-

plementary commanding and controlling forces interact to ensure that the force as a whole can adapt continuously to changing requirements.¹⁷

This description is consistent with the behavior of any complex adaptive system, the nonlinear form of post-Newtonian science.

The introduction of nonlinearity is justified by, consistent with, and compelled by the fact that seemingly random turbulence, such as the chaos inherent to the battlespace, or in whitewater rapids, has been shown to be *unpredictable, but within bounds, self-organizing*. The commander's mental images, representing his intent, or concept of operations, and captured in synthetic environments constitute (a) those bounds and (b) the means by which deliberately stimulated but controlled chaos is inserted to achieve command-by-influence. The subordinate, freed from the prescriptive qualities of voice and text, is cast in the role of interpreter of the image, which together with his local situational awareness, provides the latitude for slightly chaotic, but self-organizing effects to take hold. The result is the breaking up of Western man's acculturated Newtonian pattern of linear cause-and-effect processes, and their predictability. While our adversaries in Vietnam lacked mobility, they enhanced their agility by reading our linear responses. As a result, they were the ambushers more often than the ambush-ees. Despite Delta Force's effort to mask procedures in Somalia, patterns were detected by discerning opponents. The mechanistic intrusion of slightly chaotic effects, bounded by the commander's intent embedded in symbolic imagery, promises to allow us "to do mountains, jungles, and cities." It will even the odds in low-intensity conflicts.

Further, limitations on the use of voice and text are not only necessary in order to achieve a slightly chaotic condition, but are vital to survivability on the battlefield. Electromagnetic signatures invite corruption, disruption, and destruction by the adversary and need to be minimized to protect both C2 and the force. Finally, this command environment acts as a barrier, or at least an obstacle, to the ever-present potential for micro-management. The dysfunctional conduct of the in-theater operational, and even tactical, levels of war as practiced in Vietnam would be rendered difficult, if not impossible, by breaking the prescriptive qualities of command dependent upon voice and text.

The Technology and its Implications of Chaos

Laboratory experiments have demonstrated practical ways to synchronize conventional message traffic with chaotic signals. This appears to have potential for battlefield C2 radio applications where data is perishable, or transient, due to the speed and fluidity of conditions. The technology of chaos has the virtues of being light, compact, cheap, and simple. They are not based on expensive and intricate software and computers, but are relatively simple electronic circuits—resistors, inductors, diodes, and so on.¹⁸ For example, a message signal can have chaos added to it at the point of transmission. At the receiving end, the chaos can be stripped away, leaving the original message. Along the transmission path the signal is ostensibly nothing but random noise. The application of this technique, with low probability of intercept and unscrambling, has potential down to the smallest unit level, especially for dismounted troops. Chaos can also be controlled. On the battlefield, this capability allows chaotic signals to form mes-

sages. This can be accomplished by having each pattern of chaos represent an alphanumeric value or more global representations, such as alarms.

When compared to the other command forms, an inherent weakness in command-by-influence is its potential for incurring friendly casualties. In contrast, the Army's Force XXI command-by-direction proposes to incorporate the "knowledge of where everyone is on the battlefield, which will prevent fratricide."¹⁹ This weakness of command-by-influence could be offset by the provision of strong Identification-Friend or Foe (IFF) capabilities. Perhaps the greatest potential of chaotic signals technology lies in preventing friendly casualties by breaking the barriers to affordable and portable electronic protection from "blue on blue" engagement. Troops and vehicles emanating a unique chaotic signal generated by simple circuitry may be able to operate with less fear of friendly fire or detection by the adversary than has ever been possible.

Chaos-based technology is still in its infancy. Closely allied to the technology of chaos are certain analytical computer tools derived from the science of complexity, which deal with the calculus of bounds. These include genetic algorithms, cellular automata, and simulated annealing programs.²⁰ These contributions may be universally useful, regardless of the command method, but appear to be especially pertinent to command-by-influence, where the behavioral, analytical, and technological attributes of nonlinearity intersect.

The Command Methods Through the Lens of Safety Engineering

Another way to view the command forms, suggested by Charles Perrow, is from the perspective of the principles of safety engineering. Fundamental to this discipline is the classification of systems by certain properties—assigning risk values and risk management measures according to the characteristics of the properties. We can, in any system, classify the parts and their linkages as tight or loose.

Tight coupling refers to agents that are strongly dependent upon one another. Disturbances in the system may be highly correlated to each other when the system is tightly coupled. Time-dependent processes, with little give or slack, characterize tightly coupled systems. Additionally, disturbances tend to propagate throughout a tightly coupled system.²¹

Obviously, in the case of loosely coupled agents, or parts, of the system, these attributes are reversed, or perhaps, relaxed.

In addition to the coupling characteristics of the parts of a system, the parts can be distinguished by whether their interactions are linear or complex.

Linear interactions are those in expected and familiar production or maintenance sequence, and those that are quite visible even if unplanned. Complex interactions are those of unfamiliar sequences or unplanned and unexpected sequences, and either not visible or immediately comprehensible.²²

The result, is that systems can be classified as one of four combinations: tightly linear, tightly complex, loosely linear, or loosely complex.

It seems clear that command-by-plan, exemplified by the "System of Systems" and the Air Tasking Order, is tightly linear. "Tight linearity" is at the core of plan regimes, where actions are designed to be separated, yet related enough to detect attributed outcomes, and where the outcomes are normally expected to be proportional. It also seems clear that command-by-influence is inherently a system exhibiting loosely complex characteristics. With respect to command-by-direction, however, the case is less clear. However, it appears that the form may fall into the category of tightly complex systems. These systems are, in safety engineering terms, those containing the highest risk.

According to Perrow, "complex but loosely coupled systems are best decentralized [*influence*]; linear and tightly coupled systems are best centralized [*plan*]; linear and loosely coupled systems can be either [*certain combat support functions*]; but complex and tightly coupled systems [*direction*] can be neither—the requirements for handling failures in these systems are contradictory." Again, "the organizations at risk are the complexly interactive, tightly coupled ones."²³

If Force XXI's digitized battlefield is, indeed, a tightly complex system, it would exhibit systems characteristics similar to those found in "nuclear plants, nuclear weapons systems, chemical plants, space missions, and DNA," and

For the interactively complex and tightly coupled system the demands are inconsistent. Because of the complexity, they are best decentralized; because of the tight coupling, they are best centralized. While some mix may be possible, and is sometimes tried (handle small duties on your own, but execute orders from on high for serious matters), this appears to be difficult for systems that are reasonably com-

plex and tightly coupled, and perhaps impossible for those that are highly complex and tightly coupled.²⁴

Whether these conditions exist, and to what their extent they exist, can only be verified through modeling, simulation, and exercises. Nevertheless, there is the possibility that even with the capabilities of Information Age technologies, the return of full-fledged command-by-direction to the battlefield may be beyond our reach.

Other Issues Related to the Methods of Command

While they are beyond the scope of this paper, at least two other areas deserve further examination. The first is the specific relationships between Information Warfare and each of the command methods. The Information Warfare component on the battlefield is designated as Command and Control Warfare (C2W). C2W provides for the protection of C2, as well as attacking the opponent's C2. C2W is defined as "the integrated use of operations security, military deception, psychological operations, electronic warfare, and physical destruction mutually supported by intelligence to deny information to, influence, degrade, or destroy adversary C2 capabilities, while protecting friendly C2 capabilities against such actions."²⁵ It is likely that with each of the three command methods analyzed above, the interaction between C2W and C2 will differ in emphasis, challenge, and perhaps utility.

The other area deserving of consideration is the relationship between each method of command and joint doctrine. Joint doctrine tends to be written for the context of command-by-plan which has, after all, dominated warfare for 250 years. It therefore presumes, for example, the existence of linear and

tightly coupled systems, and other conditions of the command-by-plan environment. This represents perhaps an unintended, yet effective bias. Joint doctrine will somehow have to strike a delicate balance—on the one hand, authoritative enough to promote interservice synergy, while, on the other, remaining contingent enough to encourage continual innovation.

Conclusion

The timelessness of Clausewitz will inevitably be revitalized by the incorporation of post-Newtonian scientific terminology, replacing that of the prevailing science of Clausewitz's own era—the branch of physics known as statics. It will be more biological. "Centers of gravity," "friction," and "mass" will give way to nonlinear concepts, including those rooted in thermodynamics. The commanders of tomorrow will wrestle with "entropy" and "phase states," while grasping "periodic and strange attractors" as they search for "fractals" and "emergence."²⁶

To use whitewater rapids as a metaphor for the chaotic battlespace, the *directing* commander applies his skills and sources to traverse the turbulence through a pragmatic mix of direct address and portage. The *plan* commander builds a dam to elevate the water level to submerge the rocks. The *influencing*, nonlinear commander, like the kayaker, conquers whitewater by "reading" the turbulence, immersing himself in it, and combining technology, organization, and concept to exploit it. If turbulent times await us, which method of command will best prepare us to cope with them?

Notes

- 1 Much of the material in this section is based upon Chapters 2-5 of Martin Van Creveld's *Command in War*. Cambridge: Harvard University Press. 1985.
- 2 Kahan, James P., D. Robert Worley, and Cathleen Stasz. *Understanding Commanders' Information Needs*. Santa Monica, CA: RAND. June 1989. p. v.
- 3 Trainor, LTG Bernard E. "Schwartzkopf the General." *Proceedings*. May 1994. p. 110.
- 4 "Synchronization is arranging activities in time and space to mass at the decisive point." U.S. Army Field Manual 100-5, *Fighting Future Wars*. Washington: HQDA. 14 June 1993. pp. 2-8.
- 5 "Largest computer network to power Task Force XXI." *Pentagram*. March 15, 1996. p. 3.
- 6 U.S. Army. Office of the Chief of Staff. *Force XXI: America's Army of the 21st Century*. Ft. Monroe, VA: Louisiana Maneuvers Task Force. 15 January 1995.
- 7 Van Creveld: pp. 269, vii.
- 8 Van Creveld: p. 53.
- 9 Owens, Adm William A. "The Emerging System of Systems." *Proceedings*. May 1995. pp. 35-39.
- 10 This formulation by no means is meant to denigrate planning, or to relegate it to some subordinate status. The relationship between planning and command-by-plan was furnished by Dwight D. Eisenhower: "In preparing for battle I have always found that plans are useless, but planning is indispensable." (Quoted by Richard Nixon in "Krushchev." *Six Crises* [Garden City, NJ: Doubleday. 1962].) Planning is required in order to accommodate surprise. Planning is a means for coping. Planning is essential to such basically linear elements of warfare as certain combat support activities. However, the process of devising a plan should always be recognized as a provisional exercise. The object is not to devise a script, but to ensure that processes exist through which commanders and their staffs can respond to unanticipated opportunities or setbacks during a campaign, battle, or skirmish.
- 11 Van Creveld: p. 188.
- 12 There are a number of useful introductions to nonlinear dynamics, the variable being the degree of mathematical literacy required. At the low end, see: Cohen, Jack and Ian Stewart. *The Collapse of Chaos: Discovering Simplicity in*

a Complex World. Penguin Books. 1994.

Coveney, P. and R. Highfield. *Frontiers of Complexity: The Search for Order in a Chaotic World*. Fawcett Columbine. 1995.

An exploration of Chaos theory and its application to warfare is to be found in: James, Glenn E. *Chaos Theory: The Essentials for Military Applications*. Naval War College. 21 February 1995.

An example of the application of Complexity theory to warfare is found in: Rinaldi, Steven M. *Beyond the Industrial Web: Economic Synergies and Targeting Methodologies*. Air University Press. April 1995. Chapter 2.

- 13 By "calculus of the bounds" is meant the unfinished business of how one exercises command, or management, in a nonlinear environment where planning and control mechanisms are considered marginalized, if not negative. This leaves the "bounds" as the major actionable variable. Several means and aids are suggested in this article. In the private sector, a measure of success has been realized through a calculus consisting of corporate vision statements (intent) and worker empowerment (lowered decision thresholds), thereby increasing productivity. Nevertheless, the definition and establishment of "bounds" may represent the 21st century's greatest challenge—from theology to ideology to paychecks, much less warfare.
- 14 Kahan, et al: p. vi.
- 15 Alex Meystel. *Semiotic Modeling and Situation Analysis: An Introduction*. Bala Cynwyd, PA: AdRem, Inc. 1995. p. 45.
- 16 Napoleon, Montgomery, and Patton are cited as adept practitioners of the "directed telescope" in: Griffin, Gary B. *The Directed Telescope: A Traditional Element of Effective Command*. Ft. Leavenworth, KA: U.S. Army Command and General Staff College, Combat Studies Institute. 20 May 1985.
For the misuse of telescopes in Vietnam, see: Van Creveld: pp. 251-58.
- 17 Marine Corps Concept Paper (MCCP) 6. *Command and Control* (draft)
Washington, DC: Headquarters, USMC. 12 December 1995. pp. 43-46.
- 18 Ditto, William L., and Louis M. Pecora. "Mastering Chaos." *Scientific American*. August 1993. pp. 78-84.
- 19 *Pentagram*: p. 3.
- 20 Rinaldi, Steven M. *Beyond the Industrial Web: Economic Synergies and Targeting Methodologies*. Maxwell AFB, AL: School of Advanced Airpower Studies. April 1995. pp. 8-9.
- 21 Rinaldi: pp. 8-9.
- 22 Perrow, Charles. *Normal Accidents: Living with High Risk Technologies*. New York: Basic Books, Inc. 1984. p. 78.

- 23 Perrow: p. 331.
- 24 Perrow: p. 334.
- 25 Memorandum of Policy No. 30. *Command and Control Warfare*. Washington, DC: Chairman of the Joint Chiefs of Staff. 8 March 1993. p. 2.
- 26 "Clausewitz displays an intuition concerning war that we can better comprehend with terms and concepts newly available to us: *On War* is suffused with the understanding that every war is inherently a nonlinear phenomenon." Beyerchen, Alan. "Clausewitz, Nonlinearity, and the Unpredictability of War." *International Security* 17. Winter 1992/93. p. 61.

From *Complex Systems: The Role of Interactions*

by Robert Jervis

Although we all know that social life and politics constitute systems and that many outcomes are the unintended consequences of complex interactions, the basic ideas of systems do not come readily to mind and so often are ignored. Because I know international politics best. . . I will often focus on it. But the arguments are more general and I will take examples from many fields. This is not difficult: systems have been analyzed by almost every academic discipline because they appear throughout our physical, biological, and social world. The fact that congruent patterns can be found across such different domains testifies to the prevalence and power of the dynamics that systems display. Much of this constitutes variations on a few themes, in parallel with Darwin's summary remark about the structures of living creatures: "Nature is prodigal in variety, but niggard in innovation."¹

We are dealing with a system when (a) a set of units or elements is interconnected so that changes in some elements or their relations produce changes in other parts of the system and (b) the entire system exhibits properties and behaviors that are different from those of the parts.

The result is that systems often display nonlinear relationships, outcomes cannot be understood by adding together the units or their relations, and many of the results of actions are unintended. Complexities can appear even in what would seem to be simple and deterministic situations. Thus, over 100 years ago the mathematician Henri Poincare showed that the motion of as few as three bodies (such as the Sun, Moon, and Earth), although governed by strict scientific laws, defies exact solution: while eclipses of the Moon can be predicted thousands of years in advance, they cannot be predicted millions of years ahead, which is a very short period by astronomical standards.²

International history is full of interconnections and complex interactions. . . Ripples move through channels established by actors' interests and strategies. When these are intricate, the ramifications will be as well, and so the results can surprise the actor who initiated the change. The international history of late 19th and early 20th centuries, centered on maladroit German diplomacy, supplies several examples. Dropping the Reinsurance Treaty with Russia in 1890 simplified German diplomacy, as the Kaiser and his advisors had desired. More important, though, were the indirect and delayed consequences, starting with Russia's turn to France, which increased Germany's need for Austrian support, thereby making Germany hostage to her weaker and less stable partner. In 1902, the Germans hoped that the Anglo-Japanese Alliance, motivated by Britain's attempt to reduce her isolation and vulnerability to German pressure, would worsen British relations with Russia (which was Japan's rival in the Far East) and France (which sought British colonial concessions).³ There were indeed ramifications, but they were not to Germany's liking. The British public became less fearful of foreign ties,

easing the way for ententes with France and Russia. Furthermore, Japan, assured of Britain's benevolent neutrality, was able to first challenge and then fight Russia. The Russian defeat, coupled with the strengthening of the Anglo-Japanese treaty, effectively ended the Russian threat to India and so facilitated Anglo-Russian cooperation, much against Germany's interests and expectations.

In a system, the chains of consequences extend over time and many areas: the effects of action are always multiple. Doctors call the undesired impacts of medications "side effects." Although the language is misleading—there is no criteria other than our desires that determines which effects are "main" and which are "side"—the point reminds us that disturbing a system will produce several changes. Garrett Hardin gets to the heart of the matter in pointing out that, contrary to many hopes and expectations, we cannot develop or find "a highly specific agent which will do only one thing. . . . *We can never do merely one thing.* Wishing to kill insects, we may put an end to the singing of birds. Wishing to 'get there' faster we insult our lungs with smog."⁴ Seeking to protect the environment by developing nonpolluting sources of electric power, we build windmills that kill hawks and eagles that fly into the blades; cleaning the water in our harbors allows the growth of mollusks and crustaceans that destroy wooden piers and bulkheads; adding redundant safety equipment makes some accidents less likely, but increases the chances of others due to the operators' greater confidence and the interaction effects among the devices; placing a spy in the adversary's camp not only gains valuable information, but leaves the actor vulnerable to deception if the spy is discovered; eliminating rinderpest in East Africa paved the way for canine distemper in lions because it permitted the accumulation of cattle, which required dogs to

herd them, and the dogs provided a steady source for the virus that could spread to lions; releasing fewer fine particles and chemicals into the atmosphere decreases pollution but also is likely to accelerate global warming; pesticides often destroy the crops that they are designed to save by killing the pests' predators; removing older and dead trees from forests leads to insect epidemics and an altered pattern of regrowth; allowing the sale of an antibaldness medicine without a prescription may be dangerous because people no longer have to see a doctor, who in some cases would have determined that the loss of hair was a symptom of a more serious problem; flying small formations of planes over Hiroshima to practice dropping the atomic bomb accustomed the population to air raid warnings that turned out to be false alarms, thereby reducing the number of people who took cover on August 6.⁵

In politics, connections are often more idiosyncratic, but their existence guarantees that here too most actions, no matter how well targeted, will have multiple effects. For example, William Bundy was correct to worry that putting troops into Vietnam might not make that country more secure because deployment could not only lead the North to escalate, but also might "(a) cause the Vietnamese government and especially the army to let up [and] (b) create adverse public reactions to our whole presence on 'white men' and 'like the French' grounds."⁶ It seems that the American development of nuclear weapons simultaneously restrained Stalin by increasing his fear of war and made him "less cooperative and less willing to compromise, for fear of seeming weak."⁷ Indeed, it is now widely accepted that mutual second strike capability not only decreased the chance of nuclear war but also made it safer for either side to engage in provocations at lower levels of violence⁸. . . .

Interactions, Not Additivity

Because of the prevalence of interconnections, we cannot understand systems by summing the characteristics of the parts or the bilateral relations between pairs of them.⁹ This is not to say that such operations are never legitimate, but only that when they are we are not dealing with a system. More precisely, actions often interact to produce results that cannot be comprehended by linear models. Linearity involves two propositions: (1) changes in system output are proportional to changes in input. . . and (2) system outputs corresponding to the sum of two inputs are equal to the sum of the outputs arising from the individual inputs.¹⁰

Intuitively, we often expect linear relationships. If a little foreign aid slightly increases economic growth, then more aid should produce greater growth. But in a system, a variable may operate through a nonlinear function. That is, it may have a disproportionate impact at one end of its range. Sometimes even a small amount of the variable can do a great deal of work and then the law of diminishing returns sets in, as is often the case for the role of catalysts. In other cases very little impact is felt until a critical mass is assembled. For example, women may thrive in a profession only after there are enough of them so that they do not feel like strangers.

Similarly, the effect of one variable or characteristic can depend on which others are present. Thus, even if it is true that democracies do not fight each other in a world where other regimes exist, it would not follow that an entirely democratic world would necessarily be a peaceful one: democracies might now be united by opposition to or the desire to be different from autocracies and once triumphant might turn on each other. (The other side of this coin is that many of the charac-

teristics of democracies that classical Realists saw as undermining their ability to conduct foreign policy—the tendency to compromise, heed public opinion, and assume others are reasonable—may serve them well when most of their interactions are with other democracies.)

To further explore interactions, it is useful to start with the basic point that the results cannot be predicted by examining the individual inputs separately. I will then move on to the ways in which the effect of one actor's strategy depends on that of others, after which I will discuss how the actors and their environments shape each other, sometimes to the point where we should make the interaction itself the unit of analysis.

First Interactions: Results Cannot Be Predicted from the Separate Actions

The effect of one variable frequently depends on the state of another, as we often see in everyday life: each of two chemicals alone may be harmless but exposure to both could be fatal; patients have suffered from taking combinations of medicines that individually are helpful. So research tries to test for interaction effects and much of modern social science is built on the understanding that social and political outcomes are not simple aggregations of the actors' preferences because very different results are possible depending on how choices are structured and how actors move strategically.

Turning to international politics, Shibley Telhami argues that while pan-Arabism and pro-Palestinian sentiment worked to enhance Egyptian influence when Egypt was strong, they made it more dependent on other Arab states when Egypt was weak.¹¹ From the fact—if it is a fact—that nuclear weapons stabi-

lized Soviet-American relations we cannot infer that they would have a similar impact on other rivalries because variables that interact with nuclear weapons may be different in these cases (and of course may vary from one pair of rivals to another). Within the military domain one finds interaction effects as well: two weapons or tactics can work particularly well together and indeed most analysts stress the value of “combined arms” techniques that coordinate the use of infantry, artillery, armor, and aircraft. Events that occur close together also can have a different impact than they would if their separate influences were merely summed. The Soviet invasion of Afghanistan affected American foreign policy very deeply in part because it came on the heels of the Iranian revolution, which undercut American power, disturbed public opinion, and frightened allies.

In explaining outcomes, we are prone to examine one side’s behavior and overlook the stance of the other with which it is interacting. Although deterrence theory is built on the idea of interdependent decisions, most explanations for why deterrence succeeds in some cases and fails in others focus on differences in what the defender did while ignoring variation in the power and motivation of the challenger, just as much policy analysis in general starts—and often ends—with the strengths and weaknesses of the policies contemplated and adopted. But one hand cannot clap; we need to look at the goals, resources, and policies of those with whom the actor is dealing. . . .

Second Interactions: Strategies Depend on the Strategies of Others

Further complexities are introduced when we look at the interactions that occur between strategies when actors consciously react to others and anticipate what they think others will do. Obvious examples are provided by many diplomatic and military surprises: a state believes that the obstacles to a course of action are so great that the adversary could not undertake it; the state therefore does little to block or prepare for that action; the adversary therefore works especially hard to see if he can make it succeed. As an 18th century general explained, "In war it is precisely the things which are thought impossible which most often succeed, when they are well conducted."¹² In the war in Vietnam, the U.S. Air Force missed this dynamic and stopped patrolling sections of the North's supply lines when reconnaissance revealed that the number of targets had greatly diminished: after the attacks ceased the enemy resumed use of the route.¹³

Both the success and failures of policies are determined interactively. This means that many cases of intelligence failure are mutual—i.e., they are failures by the side that took the initiative as well as by the state that was taken by surprise. Indeed, an actor's anticipation of what others will do stems in part from its estimate of what the other thinks the actor will do. In many cases of surprise, a state sees that a certain move by the adversary cannot succeed and therefore does not expect the other to take it: the U.S. did not expect the Russians to put missiles into Cuba or Japan to attack Pearl Harbor because American officials knew that the U.S. would thwart these measures if they were taken. These judgments were correct, but because the

other countries saw the world and the U.S. less accurately, the American predictions were also inaccurate.¹⁴

Third Interactions: Behavior Changes the Environment

Initial behaviors and outcomes often influence later ones, producing powerful dynamics that explain change over time and that cannot be captured by labeling one set of elements “causes” and other “effects.” Although learning and thinking play a large role in political and social life, they are not necessary for this kind of temporal interaction. Indeed, it characterizes the operation of evolution in nature. We usually think of individuals and species competing with one another within the environment, thus driving evolution through natural selection. In fact, however, there is coevolution: plants and animals not only adapt to the environment, they change it. As a result, it becomes more hospitable to some life forms and less hospitable to others.

Nature is not likely to “settle down” to a steady state as the development or growth of any life form will consume—and be consumed by—others, closing some ecological niches and opening others, which in turn will set off further changes. To some extent, organisms create their own environments, not only by direct actions (e.g., digging burrows, storing food, excreting waste products), but as their very existence alters the microclimates, nutrients, and feeding opportunities that will affect them and others. . . .

Politics, like nature, rarely settles down as each dispute, policy, or action affects others and reshapes the political landscape, inhibiting some behaviors and enabling others. Campaign

financing reforms generated new actors in the form of PACs, new issues in the form of arguments about what PAC activities should be permitted, new debates about the meaning of the first amendment, and new groups that track the flow of money and services. These in turn affect not only how funds are solicited and given, but also change the allies and adversaries that are available to political actors and the ways in which a variety of other issues are considered. Political maneuvers create niches for new actors and disputes, often in ways that no one had anticipated. William Miller's fascinating study of the Southern attempt to control—indeed choke off—the debate about slavery in the 1830s points out that by passing a “gag rule” prohibiting Congressional discussion of petitions asking for the end of the slave trade in the District of Columbia, the South called up “petitions against the gag rule itself” and made a new issue of the right to petition the government.¹⁵ Indeed, many protest movements grow as people previously unsympathetic are offended by the way the authorities respond. Each added issue may mobilize the population in a different way than did the original one—and of course the new dispute in turn changes the political environment. . . .

Because actions change the environment in which they operate, identical but later behavior does not produce identical results: history is about the changes produced by previous thought and action as people and organizations confront each other through time. The final crisis leading to World War II provides an illustration of some of these processes. Hitler had witnessed his adversaries give in to pressure; as he explained, “Our enemies are little worms. I saw them at Munich.”¹⁶ But the allies had changed because of Hitler's behavior. So had Poland. As A.J.P. Taylor puts it, “Munich cast a long shadow.

Hitler waited for it to happen again; Beck took warning from the fate of Benes."¹⁷

Hitler was not the only leader to fail to understand that his behavior would change his environment. Like good linear social scientists, many statesmen see that their actions can produce a desired outcome, all other things being equal, and project into the future the maintenance of the conditions that their behavior will in fact undermine. This in part explains the Argentine calculations preceding the seizure of the Falklands/Malvinas. Their leaders could see that Britain's ability to protect its position was waning, as evinced by the declining naval presence, and that Argentina's claim to the islands had received widespread international support. But what they neglected was the likelihood that the invasion would alter these facts, unifying British opinion against accepting humiliation and changing the issue for international audiences from the illegitimacy of colonialism to the illegitimacy of the use of force. A similar neglect of the transformative power of action may explain why Saddam Hussein thought he could conquer Kuwait. Even if America wanted to intervene, it could do so only with the support and cooperation of other Arab countries, which had sympathized with Iraq's claims and urged American restraint. But the invasion of Kuwait drastically increased the Arabs' perception of threat and so altered their stance. Furthermore, their willingness to give credence to Iraqi promises was destroyed by the deception that had enabled the invasion to take everyone by surprise. Germany's miscalculation in 1917 was based on a related error: although unrestricted submarine warfare succeeded in sinking more British shipping than the Germans had estimated would be required to drive Britain from the war, the American entry (which Germany expected) led the British to tolerate shortages

that otherwise would have broken their will because they knew that if they held out, the U.S. would rescue them.¹⁸

The failure to appreciate the fact that the behavior of the actors is in part responsible for the environment that then impinges on them can lead observers—and actors as well—to underestimate the actors' influence. Thus, states caught in a conflict spiral believe that they have little choice but to respond in kind to the adversary's hostility. This may be true, but it may have been the states' earlier behavior that generated the situation that now is compelling. Robert McNamara complains about how he was misled by faulty military reporting but similarly fails to consider whether his style and pressure might have contributed to what he was being told.¹⁹

Products of Interaction as the Units of Analysis

Interaction can be so intense and transformative that we can no longer fruitfully distinguish between actors and their environments, let alone say much about any element in isolation. We are accustomed to referring to roads as safe or dangerous, but if the drivers understand the road conditions this formulation may be misleading: the knowledge that, driving habits held constant, one stretch is safe or dangerous will affect how people drive—they are likely to slow down and be more careful when they think the road is dangerous and speed up and let their attention wander when it is "safe." It is then the road-driver system that is the most meaningful unit of analysis. . . .

Similarly, we often refer to international situations as precarious, unstable, or dangerous. But, again, if statesmen perceive them as such and fear the consequences, they will act to

reduce the danger—one reason why the Cuban missile crisis did not lead to war was that both sides felt that this could be the outcome if they were not very careful. Nuclear weapons generally have this effect. Because statesmen dread all-out war, international politics is safer than it would otherwise be, and probably safer than if war were less destructive. Conversely, like drivers on a “safe” stretch of road, decision-makers can behave more recklessly in calmer times because they have more freedom to seek unilateral gains as well as needing to generate risk to put pressure on others. For example, the relaxation of Anglo-German tensions after 1911 may have misled both countries into believing that they could afford dangerous tactics in 1914.

Circular Effects

Systems can produce circular effects as actors respond to the new environments their actions have created, often changing themselves in the process. In international politics, perhaps the most important manifestation of this dynamic is the large-scale operation of the security dilemma—i.e., the tendency for efforts to increase a state’s security to simultaneously decrease the security of others. Because states know that they cannot rely on others in the unpredictable future, they seek to protect themselves against a wide range of menaces. Thus in the 1930s, Japan, which was heavily dependent on resources from outside its borders, sought to expand the area it controlled. Immediate economic needs generated by the worldwide depression increased but did not create this impulse. Nor were they brought on by specific conflicts with the Western powers. Rather, what was driving was the fear that conflict might be forced upon Japan in the future, which meant that to remain secure Japan needed raw materials and larger markets. The

result was the conquest of Manchuria, followed by a larger war with China, and then by the occupation of Indochina. Each move generated resistance that made the next action seem necessary, and the last move triggered the American oil embargo, which in turn pushed Japan into attacking the West before it ran out of oil. Had Japan been secure, her aggression would not have been necessary; it was the fear of an eventual war with the West that required policies that moved Western enmity from a possibility to a reality. (Of course a further irony is that World War II led to the reconstruction of international politics and the Japanese domestic system that brought Japan security, economic dominance of South East Asia, and access to markets around the world.)

Despite the familiarity of the idea that social action forms and takes place within a system that is familiar, scholars and statesmen as well as the general public are prone to think in non-systemic terms. This is often appropriate, and few miracles will follow from thinking systematically because the interactive, strategic, and contingent nature of systems limits the extent to which complete and deterministic theories are possible. But we need to take more seriously the notion that we are in a system and to look for the dynamics that drive them. . . Exploring them gives us new possibilities for understanding and effective action; in their absence we are likely to flounder.

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Researchers on Complexity Ponder What It's All About

by George Johnson

It is a tribute to the power and precision of science that it was able to predict so far in advance that on April 1, Comet Hale-Bopp would make its closest rendezvous with the Sun. But what science could not reliably say was whether, in any particular part of the country, clouds would congeal to block the view—a cosmic April Fool's joke. Some of the greatest phenomena, like the coursing of comets around the Sun, are marvelously predictable. But some of the most mundane, like the weather, are so convoluted that they continue to elude the most diligent forecasters. They are what scientists call complex systems. Though made up of relatively simple units—like the molecules in the atmosphere—the pieces interact to yield behavior that is full of surprise.

A quarter of a century ago, long before complexity research became a hot scientific frontier of the 1990s, Dr. Phillip W. Anderson, who won a Nobel Prize in physics in 1977, compactly described complex systems by saying, “More is different.” Whether cells interact to form an organism or organisms to form an ecosystem, or gas molecules interact to form a weather front, the result is what people intuitively consider complex. For all of the efforts to understand these

phenomena, scientists are still puzzling over a very basic question: What precisely is meant by complexity? People think they know it when they see it. It is orderly, but not too orderly; surprising, but not completely random. A brain seems more complex than a kidney; a cell more complex than a crystal; a symphony more complex than a song. But how can the essence of complexity be captured and quantified in a precise definition that scientists can use?

“Complexity is still almost a theological concept,” said Dr. Dan Stein, chairman of the physics department at the University of Arizona and an associate of the Santa Fe Institute in New Mexico, a center for studying complex systems. “Everybody talks about it. But nobody knows what it really is. In the absence of a good definition, complexity is pretty much in the eye of the beholder.” Human brains like to describe themselves as the most complex objects in the known universe. But what does that really mean? “There is a lot of hand waving going on,” said Dr. Charles Bennett, a computer scientist at the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y. “We human beings like to think that we’re very special. We bend over backwards saying we are the product of billions of years of evolution. But without good definitions, we’re kind of shooting the breeze.” Coming up with objective ways to measure this slippery quality would help extend science’s reach into areas where prediction has proved difficult, if not impossible. That would mean understanding not only natural phenomena like weather but also the increasingly intricate machines people build. Forecasting the behavior of the Internet, with all its interacting pieces, for example, can be like predicting the direction of a lumbering elephant.

“Current technology, hardware, and software are rapidly approaching biological levels of complexity,” said Dr. Gregory Chaitin, a mathematician at the Watson Research Center. “That’s either wonderful or frightening, depending on your point of view.” Dr. Stein compares the challenge of defining complexity to that confronting early 19th-century scientists as they tried to get a grip on a mysterious concept called energy. Today, people take energy so much for granted that it is hard to appreciate how abstract the concept really is. “Many people had a pretty good idea what energy did and how it behaved,” Dr. Stein said. But energy was not really understood, he said, until people came up with a precise definition. The result was the laws of thermodynamics. . . .

Scientists have had little trouble coming up with candidate definitions. Several years ago, Dr. Seth Lloyd, a mechanical engineer at the Massachusetts Institute of Technology and a researcher at the Santa Fe Institute, compiled a list of some three dozen ways in which scientists use the word “complexity.” Though the list was taken by some as a sign that the field was in a hopeless muddle, Dr. Lloyd said this embarrassment of riches was no reason for despair. The definitions seem to fall into several clusters, with a few underlying concepts. Some definitions, for example, are used to gauge the complexity of a process—how much computing it would take to solve a problem. Other scales are used to measure the complexity of an object. How many bits of information does it take to describe it? Or how much effort would it take to produce it? In coming years, Dr. Lloyd suspects, scientists will show that these different kinds of complexity are related, somewhat as James Clerk Maxwell showed in the 19th century that various magnetic and

electrical phenomena were different aspects of the same overarching concept, electromagnetism.

One of the first stabs at a definition was made in the mid-1960s by Dr. Chaitin and others who came up with a concept called algorithmic complexity. An algorithm is simply a recipe—or, more precisely, a computer program—for making something. Simple things, it seems, should be produced by shorter programs, and complex things by longer programs. The musical score for a piano sonata is longer than the one for a simple child's song. To measure the complexity of something, just find the length of its most compact description.

For example, the monotonous sequence 111111111111111 (think of it as hitting the same piano key over and over) can be produced with this short algorithm: "Print '1' 15 times." A more interesting "melody," 1011011101111011110, would take a longer algorithm, telling the computer to print 1 and 0, then two 1's and 0, then three 1's and 0, and so forth. More complex still (and requiring an even longer algorithm) would be a sequence like this: 10000110001110011110, where the number of 1's increases as the number of 0's decreases. But this measurement breaks down when it is applied to sequences that appear to be haphazard, like 11010100010100-010111101101. Since there is no apparent rule for generating the number, the best we can tell the computer is "Print 11010100010100010111101101." The recipe is actually longer than the number it produces. So by this definition, its complexity is very high. The algorithm for a sonata is longer than the algorithm for a children's song. But the algorithm describing patternless banging on a piano keyboard would be the longest of all. A measuring stick that confuses randomness with complexity is obviously flawed. "The definition is totally impractical," Dr. Chaitin admitted.

I think that is the most interesting thing about it because it demonstrates the limits of mathematical knowledge. Doing a mathematically elegant definition of complexity is easy. I've done it. Dealing with the messy real world is much harder.

Dr. Murray Gell-Mann, the Nobel-Prize-winning particle physicist who is now at the Santa Fe Institute, is trying to come up with a different measuring stick. "What we're after is a way to describe what is usually meant by complexity," he said. "What is it we usually mean when we say a conglomerate corporation is complex or a language is complex or the plot of a novel is complex?" The first step, Dr. Gell-Mann proposes, is to identify a system's regularities. Then they are described in the form of a compact theory or model—what he calls a "schema." The schema for a language, for example, is its grammar, the rules for using it. More complex languages have longer grammars than do simple ones. The length of the schema measures what he calls "effective complexity." Incoherent babbling cannot be described by a grammar. So the length of its schema—and hence its complexity—is zero.

Measuring the length of a schema does not capture everything customarily meant by complexity. A genome, the sequence of genetic information coded in the form of DNA, can be thought of as the schema for an organism. The genome of a bacterium is shorter than that of a salamander. But the genome of a human and a chimpanzee are almost the same. Apparently a few tiny differences in the human genome are responsible for generating a great deal of additional neurological complexity, giving people the capacity for mathematical reasoning or constructing arbitrarily long sentences. Genes can switch on genes, allowing for a deceptively large amount of complexity to unfold from a fairly simple recipe.

“Our analysis is by no means finished,” Dr. Gell-Mann said. If complexity is measured by the length of the schema—a concise description of a system’s regularities—then one must consider who or what is devising the schema. Some observers will see order—or think they see order—where others will perceive only confusion. What standards should be used to identify patterns? What language should the schema be expressed in? Dr. Gell-Mann and Dr. Lloyd are working on ways to express these and other matters with mathematical precision.

Dr. Bennett, at IBM, has developed a different measure of complexity that he calls “logical depth.” The idea here is to gauge how long it would plausibly take for a computer to go from a simple blueprint to the final product. Very orderly and very random subjects are both logically shallow because so little computation is required to produce them: “Print a million 1s” or “Print this random number.” But something very complex, like the digital recording of a Beethoven symphony, would require a great deal of computational grinding.

An idea that runs throughout this kind of research is that complexity lies somewhere between order and disorder, predictability and surprise. “Nobody disputes that there are some characteristics of systems that make them more complicated,” said Dr. Erica Jen, vice president for academic affairs at the Santa Fe Institute.

And those characteristics are neither highly ordered nor completely random. A string of numbers with all the same digits is very uninteresting, but a number like pi that has all this structure in it is very interesting.

. . . As Dr. Lloyd continues to hammer away at a definition, he likes to ask his colleagues what they mean by complexity. After puzzling over the matter, they usually answer with something

like this: "I can't define it for you, but I know it when I see it."
"That," he said, "remains the tried and true definition."

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From *Center of Gravity Analysis and Chaos Theory*¹

by Pat Pentland

The key to center of gravity (COG) analysis is to incorporate the real and dynamic complexities of the natural world explained by chaos theory. . . The theory. . . instructs us how to examine dynamic systems—look for deep structures and patterns. It shows us how dynamic systems can self-organize, how they are closely interrelated, and how they use feedback to regulate themselves. . . it tells us how to disrupt dynamic systems. Crises points can be precipitated by—

1. Closing the system off from its environment and propelling it to equilibrium;
2. Eliminating feedback within the system;
3. Driving any one of the dimensional dynamics to singularity by overloading and destroying it; or
4. Applying quantum amounts of broad external energy to the entire system.

It does not allow us to predict accurately the specific end states that may develop after disruption occurs. Nor does it permit

¹Master's thesis. Maxwell AFB, AL: School of Advanced Airpower Studies, AY 1993-94.

long-term prediction of detailed end states of dynamic systems that are not subjected to disruption. Identifying the deep structures and processes and predicting the *how* and *why* of disrupting dynamic systems closely corresponds to the processes we must use to analyze COGs. I submit that it is the same process. It should be evident, however, that applying chaos theory to human social systems requires both inductive and deductive approaches. . . *Meshing/ interdisciplinary*. . .

A Structure Based on Chaos

Basis of Organization

The fundamental constant within socio-cultural constructs is human free will. Free will is analogous to the space-time concept in relativistic physics, defining the dimensions of human society. Free will is always present, it permeates decisions, structures, and culture providing a vehicle for randomness to be introduced into the system. Human will occurs in various forms, but the primary ones for our purposes are: the will to survive, the will to power, and the will to truth.¹ The highest reaches of individual or personal will are dependent upon the social substance from which they arise, and can only be fulfilled in the context of a community. . . Communal relationships exist at all levels of human society in endless elaboration. The necessity to define man's relationship to other individuals, his relationship to the community, the community's relationship with nature, and the community's relationship with other communities give rise to value systems. These value systems reflect the will to truth and the will to power, and they comprise what many would call norms, mores, and laws. Common expressions of value systems are

religions, ethics, philosophies, political ideologies, and doctrines. The value systems that arise from human will and community are the underlying element of power and organization within human society from the most primitive tribe to modern nation states. Values are the gravity that rules the human universe. Values are the first element of power. They define the organization and dynamics of the other elements of power.

Elements of Power

Power is not well understood. Power is the ability to do what you want, and the ability to influence others to conform to your desires. Power is strength that permits freedom of action. Because power is exercised by humans and is applied to human societies, it is both real and perceived in nature. Power is amoral. It is neither “good” nor “bad,” but it can have positive or negative effects on social organization—sometimes both simultaneously. This means it can increase or decrease cohesion in society. The effectiveness of power is always situational in terms of who is using it, which element of power is being used, where it is being used, and who or what is the object of influence. Power is dynamic over time and its full force is rarely mustered without crossing fractal boundaries and connecting into other sources and types of power. The effect of a single type of power is rarely persuasive if used independent of other types of power, and influence is magnified when the various elements of power are used in combination rather than isolation. For example, military action, diplomatic pressure, and economic sanctions should be coordinated to achieve maximum effect.

Power essentially supports, defends, or implements the goals and values of society. Each element of power is three dimensional. It consists of a "source," a manifestation (or "force"), and a "linkage." The linkage assists in transforming the source into a force, and it provides connectivity within and between the elements of power. Each complete element of power is a center of gravity, and each element of power is a strange attractor. The dimensions that define it vary, but the essential ones are: the mass of the source, the intensity of the force, interconnectivity within the system, and the rate of exchange flow within the linkages. These systems can then be characterized by their predictability, their rate of information flow, and their tendency to create mixing.

Sources of Power

There are relatively few true sources of power in human society. . . value systems (which we have discussed), culture, economic resources, and social organization. Culture is the learned body of customs and knowledge. . . Culture arises from values, and is the means by which values are defined or expressed. Culture determines how man adjusts to his community, and how societies adjust to their environment. The most common approaches to the environment are: naturalism, supernaturalism, estheticism, and mysticism.² These approaches often exist in mixed form, although they can exist in societies in prevalent or pure forms. Economic resources include populations, natural resources, and territory. . . .

Social organizations can be categorized into three fundamental types: *solidary*, *contractual*, and *antagonistic*.³

- Solidary societies are typified by familistic, tribal, and ethnic affiliation, but can exist in economic and religious

forms. Normally, solidary groups define or attempt to encompass all values for social organization, and thus are intense and mutual.

- Contractual types of organizations are commonly associated with cooperative groups where rights, privileges, and obligations are clearly defined. Only a few values are encompassed, projected, or monitored by the contractual group. Modern democratic, bureaucratic nation states are the archetypal contractual organization.
- Antagonistic social organizations are coercive in nature, usually involve domination of one group by another, are normally one-sided, and involve the imposition of value systems either internally or externally. Antagonistic groups often assume a pseudosolidary or pseudocontractual guise, and are typified by ideological totalitarian states.

These three types of social organizations can exist in “mixed” varieties, and they are not permanent because societies develop and change. For example, solidary societies can slowly evolve into contractual or antagonistic forms. Likewise revolutions can occur when major disconnects develop between fundamental value systems and outwardly apparent social organizations.

These broad categories can be further classified by the prevalent type of functional interdependence between the group’s members. This includes the ability to organize “unibonded” groups and “multibonded” groups.⁴ Unibonded groups have one set of meaningful norms or values as the vehicle or magnet for organization, while multibonded groups collate around

two or more sets (or potentially large numbers) of norms and values. The method of bonding helps to determine the connectivity within society, but more importantly helps to indicate the potential “biases” or predisposition toward decisions that may occur within groups.

Solidary societies will tend to horizontally organize themselves around unbonded groups, and will use reinforcing unbonded groups to organize vertically. For example, the tribe or the clan becomes the defining factor that determines status throughout social, economic, political, and military organizations. These societies are normally focused inward upon their defining element. Contractual societies will be horizontally and vertically organized around multibonded groups while permitting the existence of unbonded groups. A multitude of competing and complementary pluralistic groups exist at all levels of contractual societies. Antagonistic societies will organize vertically along unbonded groups, using these groups to suppress other unbonded groups and to control multibonded groups. Antagonistic societies can be focused either internally or externally.

These fundamental classifications and characteristics which derive from values, help determine the outward forms of economic organization, governmental function, and military capability. This is especially evident when one studies social and cultural history back to antiquity, and examines diverse civilizations other than modern Europe. Values, culture, and social groups interact in many permutations and combinations. They form the basis for beginning a systematic center of gravity analysis. This is especially true when looking at the entire spectrum of conflict rather than just conventional operations. Checklist center of gravity methodologies simply do not work, nor will methods solely focused on analyzing the exter-

nal vestiges of society such as government leadership⁵. . . cohesive governments and societies do not require strong leadership to bind their social fabric together and maintain power.

The sources of power are not centers of gravity in and of themselves. They are the raw material that gets molded into another dimension of the element of power that we call force. Let's move on to investigate these manifestations of power and the linkages of power to produce them.

Manifestations of Power (Force)

The important manifestations of power are: military force, political/diplomatic force, economic force, cultural force, and ideological force. The existence and the strength or magnitude of these various forces differs widely between societies and nations. Relative to our cultural viewpoint, some societies are incapable of organizing effective forces, although they may occupy a seat at the General Assembly of the United Nations. This stems from their underlying cultural values and their social organization. They may, however, possess a deeper force. A force that binds their society together, and is capable of eluding modern means to overcome it. To understand this, we must explain how force is created in society and examine the dynamics of different types of force.

In the natural world we know there are four fundamental forces: gravity, electromagnetism, and the weak and strong nuclear forces. These forces exhibit similar characteristics and functions. They can attract and repel. They can exhibit positive and some negative charges. They possess different strengths, and they exert their influence at different ranges. . . .

The forces within human society exhibit similar behavior and characteristics. They are not all of the same strength. They can be both destructive and constructive. Their influence and power varies in its projectability over various distances. Furthermore, human social forces are created in the same manner as the forces of nature—the constant exchange of mass-energy in the form of “things” and/or “ideas.” Neither the forces of nature nor the forces of human society can be visibly touched, although their effects can be felt. They do not have mass because they are a form of energy derived from mechanisms of exchange. Force is therefore an event, a process, or an action that is always covertly present and overtly felt.

Let’s imagine the specific force creation process for the important manifestations of power in society. Military force arises from the consumption and expenditure of logistics to conduct training and operations. Political force arises from the constant redistribution of wealth and power in society. Diplomatic force simply represents the redistribution of wealth and power outside the boundaries of a society. Economic force is the production and exchange of goods and services. Cultural force is the exchange of knowledge and customs. Ideological force is the transmission or exchange of values. These forces constitute the primary “strange attractors” in human culture and the boundaries between each of them is closely interwoven. This blurring makes it sometimes difficult to distinguish between the elements of pure force. Indeed, the fighter aircraft flown by the military, procured by the government, manufactured by the economy, organized by society, and conceived by a culture is a product of many interacting systems.⁶

As previously stated, ideological forces or values constitute the “gravity” of human society. Ideology projects rapidly but weakly over long distances, however, in concentrated masses it

dominates all other forces. In relativist terms, values may actually be the “rest energy” that distorts the space-time continuum of human will, becoming the fabric on which the other forces of society play. It creates biases and predispositions which influence the connectivity within systems determining their susceptibility to chaos. The more solidary the system, with many unbonded groups, the more islands of stability it will exhibit. These areas are triggered into locked states that become isolated from feedback. This provides temporary stability that can only be disrupted by quantum inputs of energy.

The fundamental organization of each society determines the strength of the military, political/diplomatic, economic, and cultural forces at its disposal. This “strength” is only meaningful when compared to another society. However, a rule of thumb for modern nation states would categorize their strengths in decreasing order as: cultural, economic, political, diplomatic, and military. This may seem surprising and there may be some exceptions, but it explains the historic difficulty of targeting military force against deeply rooted political, economic and cultural systems! By contrast, the projectable range and the time response is inversely proportional to the strength. Military force projects fast and over long distances. Economic force projects slower, over shorter distances, and requires a longer period to produce effects.

Linkages of Power

We have discussed the first two dimensions of power—*sources* and *manifestations*—so let’s move on to the third dimension we call *linkage*. The linkages of power are the human, cultural, and material networks and capabilities that assist in transforming

the sources of power into forces, and that provide connectivity within and between the elements of power. The primary linkages consist of: communications, logistics, transportation, leadership, science, technology, education, and training. Linkages determine how efficiently power is organized, and ultimately how effectively it is applied. Connectivity facilitates or hinders the transmission of data and feedback within the various systems. This, along with bias, helps determine system dynamics and susceptibility or resistance to chaos.

The linkages are often mistaken for COGs when in actuality they possess no force in and of themselves.⁷ However, a linkage of power can possess either strengths or vulnerabilities that can be exploited to disrupt a COG system. Some linkages may have to be avoided, depending on the particular society. For example, transportation systems are often identified as “vulnerable COGs,” despite some transportation systems being so redundant they are almost impervious to targeting. The nature of the linkages of power ultimately derive from a culture’s approach to its environment—naturalistic, supernatural, aesthetic, or mystic. This determines a society’s technology or its method of altering the environment to suit its culture. Naturalistic or scientific approaches seek and use technology at all levels of society. Thus, they are more capable of creating linkages that organize, orchestrate, and transform sources of power into force.⁸

The linkages of power create the energy which drives open dynamic systems. This energy can be created by less efficient “chemical” means. In nature, chemical reactions release energy by exchanging electrons between atoms. In society, this is analogous to the trade, exchange, and service industries. However, nature also creates energy by “nuclear” methods involving fission and fusion. The production of industrial goods

from raw source materials is the social equivalent. “Chemical” linkages and “nuclear” linkages represent distinctly different targeting choices both in terms of the energy required to effect the linkage, and expected results. Similar distinctions exist as to which “level” of linkage is being attacked within the structure. Strategic and tactical linkages produce different dynamics and thus require different targeting strategies⁹. . . .

<u>SOURCE</u>	<u>LINKAGE</u>	<u>FORCE</u>
Armed Forces	Command & Control Training & Logistics	Military
Government Bureaucracy	Leadership & Communication	Political & Diplomatic
Industry & Natural Resources	Transportation & Technology	Economic
Society & Culture	Family, Education, & Socialization	Social-Cultural
Value System	Religion & Philosophy Indoctrination	Ideological

[Pentland’s Source, Linkage, and Force framework turns out to be the same as the property of Flows found in any complex adaptive system (*cas*). For example, “Similar [node, connector, resource] triads exist for other *cas*: [nerve cells, nerve cell interconnections, pulses]; [species, foodweb interactions, biochemicals] for ecosystems; [computer stations, cables, messages] for the electronic Internet; and so on.”]

Let's briefly assess this construct of society:

- *First*, individual human will permeates everything, introduces chance, and establishes the arena for all social activity.
- *Second*, the interactions of individuals and community give rise to value systems, culture, and higher levels of organization activity.
- *Third*, this human activity, or element of power, consists of sources, linkages, and forces. Higher levels are more "particle" in nature and their small mass-energy can be rapidly directed against specific points. The underlying levels of social organization resemble "fields." These forces surround their source with energy that in effect makes it difficult to distinguish force from source. "The arena joins in the very action taking place within itself."¹⁰
- *Fourth*, the more complex areas of social activity self-organize from simple structures. These activities are closely interwoven with each other and clearly function as open nonlinear systems.
- *Fifth*, deep in human structural patterns societies clearly exhibit characteristics of strange attractors and are subject to the processes governing chaos theory.

Center of Gravity Implications

These areas of activity, the elements of power, are true centers of gravity within human society. They exist at all levels of organization and they represent centers of power and strength.

They change dynamically within and between societies, and they provide freedom of action to exercise power. They involve complexity, cohesion, energy and mass, and it requires deep analysis to determine where they lay and to prioritize them. Lastly, they are intimately tied to human will and value systems, and thus by default, to political objectives.

Of the three dimensions of power (source, force, and linkages), only force is projectable—but in varying degrees. However, force can be applied against any of the other dimensions of power. Generally, applying force against a source is difficult, and can be counterproductive because it always threatens vital national interests. It can create a “dangerous paradox,” whereby a strategy for unlimited war, if pursued in a war of limited aims, can lead to escalation and transformation of the war into something inconsistent with the political objectives.¹¹ This is also often associated with attrition-type warfare. Force against force involves clashes between classic centers of gravity, and can equate to battles of annihilation. Lastly, employing force against power linkages is an “indirect” approach.

Notes

- 1 I borrow this construct from: Niebuhr, Reinhold. *The Children of Light and the Children of Darkness*. New York: Charles Scribner's Sons. 1944. pp. 48-49. In some ways this corresponds with Maslow's hierarchy of needs.
- 2 Slotkin, J.S. *Social Anthropology: The Science of Human Society and Culture*. New York: MacMillan Company. 1950. pp. 143-45. See also f.n. 41 below.
- 3 Sorokin, Pitirim A. *Society, Culture and Personality: Their Structure and Dynamics*. New York: Harper and Brothers Publishers. 1947. pp. 69-150.
- 4 *Ibid.*: pp. 171-178. Important unbonded groups are: perceived race, sex, age, kinship, territorial proximity, language, occupation, economic, religious, political, scientific, and leadership elites. Important multibonded groups are: clans, tribes, nations, castes, and social classes.

- 5 Metz, Steven and Frederick M. Downey. "Centers of Gravity and Strategic Planning." *Military Review*. April 1988. pp. 30-31.
For example see: Ross, Bruce A. "The Case for Targeting Leadership in War." *Naval War College Review*. Vol. XLVI, No. 1. Winter 1993. pp. 73-79.
- 6 A good argument can be made that military force is just the external manifestation of a more comprehensive "security force." The internal manifestation of this force provides internal security and police functions within society.
- 7 Airpower theorists in particular have considered transportation and communications as "vital centers." In some cases they are indeed vital "linkages," and thus the appropriate target.
- 8 Slotkin, *Social Anthropology*. pp. 156-181. Slotkin goes on to categorize supernaturalism as the use of symbols and beliefs to transform the environment (p. 182). An esthetic approach essentially defines the environment as something that is pleasing and of value in and of itself therefore only minor attempts are made to change it (p. 270). An asymmetrical approach achieves adjustment to the environment by changing an individual's internal experience or perception rather than producing outward change to the environment (p. 309). These last three approaches have a common denominator in that they provide only a partial adjustment to the environment.
- 9 Mancur Olson, Jr. "The Economics of Target Selection for the Combined Bomber Offensive." *Journal of the Royal United Service Institution*. Vol. CVII, No. 628. Nov 1962. pp. 308-314.
- 10 Penrose, Roger. *The Emperor's New Mind*. New York: Penguin Books. 1989. p. 217.
- 11 Hoapili, Evan J. "Carl von Clausewitz: Hope and Fear." unpublished paper, Naval War College, 13 February 1992. p. 22.
Also see: Clausewitz, *On War*. p. 486.