Chaos, Complexity and Conflict

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Abstract

Developments in complexity theory provide new opportunities for viewing non-linear systems that operate under high levels of certainty. Models of warfare and conflict meet these conditions and are suitable for these new techniques. A model of conflict is adapted from Colonel John Warden's theory of the air campaign that outlines conflict as a complex adaptive system. The model incorporates the inherent interdependence between the participants in any conflict. Practical applications of the model for the decision maker are presented and discussed.

From Sun Tzu to Clauswitz, our models of conflict and warfare have been shaped by the scientific and intellectual trends of each era. These trends have led to the more refined models of conflict we use today. A modern example of this influence from external intellectual schools of thought is Colonel John Warden's development of his theory of the air campaign from systems theory, a concept first introduced in the 1920's to address biological problems.

Our day-to-day management of our military resources also borrows concepts from the private sector. Examples of management theories incorporated into the military culture include Total Quality Management and Management by Objectives. Of course, some of these ideas are adopted with more success than others; however, the transference of intellectual theories is a natural and necessary process for a modern military organization.

Over the past fifteen years a trend has developed in the literature on military strategy and doctrine that parallels developments in the scientific and management disciplines. That trend has been to describe warfare in terms of systems theory and chaos theory. If we continue to follow the developments in the scientific sectors, the next logical step for these trends is to develop a model of warfare based on complexity theory. More specifically, an extrapolation of the trend would show that warfare and nation-states complex adaptive systems (CAS) and appropriate models can be developed to enhance our understanding of warfare and the conduct of nation-states.

While complexity theory is still under development, it is mature enough to apply to our current models of conflict. Complexity models provide description of difficult problems involving high degrees of uncertainty and interdependence. In this vein, this article develops a model of conflict that uses Colonel John Warden's concepts of the air campaign as a beginning and then extends that model to incorporate modern complexity theory. These improvements shed light on some of the more difficult problems of modern conflict including adaptation of the enemy to the methods employed by the attacker. The article concludes with practical applications of the model for decision makers.

Systems Theory

Before getting into the basics of complexity theory, a discussion of the developments leading up to complexity theory is necessary. As mentioned above, the predecessors of complexity theory are systems theory and chaos theory. Understanding these two concepts will make the discussions of complexity theory more meaningful.

Systems theory is a "science of wholeness."[1] To understand the systems idea it helps to contrast it with the typical approach of the traditional scientist, or reductionist method. A reductionist approach tries to understand the world by breaking the problem into ever-smaller pieces (e.g. molecules, atoms, and quarks). Greene articulates the reductionist viewpoint when he argues that the primary roadblock to understanding the operation of the universe is simply a "calculational impasse."[2] According to Greene, if we had a large enough computer to understand the behavior of every elemental particle in the universe, we could then predict the behavior of any system.[3]

Realizing that Greene's "calculational impasse" was likely to last indefinitely, scientists looked for other means to understand complex phenomena. The history of systems theory reaches back to Ludwig von Bertalanffy in the 1920's. Bertalanffy wanted to develop a general theory for attacking scientific problems, initially biological, which seemed to be resistant to typical reductionist methods. As systems theory reached some success in modeling various scientific problems it was incorporated into other disciplines.[4] One of the most successful qualitative adaptations of this theory has been in the management literature. Most recently, authors such as Peter Senge, Checkland and Holwell, and Gharajedaghi have popularized systems thinking as a discipline required for success in today's complex economic and technological environment.[5]

Systems theory approaches a problem by looking at the larger system as a whole rather than dissecting the parts. As such, systems theory is not a tool for all occasions. Checkland and Holwell point out that a systems approach is "not usually concerned with well-defined problems - such as how to maximize the output from a manufacturing facility - but with the ill-structured problem situations with which managers of all kinds and levels have to cope - such as what to do about researching new products given competitors' innovations, and how to plan, resource, carry out, monitor and control that activity."[6] Modern warfare is also another area of ill-structured problems that has benefited from systems analysis.

If one can accept that some level of systems thinking is necessary to understand the environment under discussion, then one must look at what a systems approach to the problem would constitute. Checkland, one of the most renowned systems theorists, lists the most important ideas of the systems approach as emergence, hierarchy, communications, and control. Each of these ideas is central to the development of any model of warfare as a system and subsequently as a complex adaptive system.[7]

The first of Checkland's concepts, emergence, refers to the development of ideas from within and without the system that have a significant impact on our operation. Frequently, emergence of these ideas results in turbulence for the leadership of an organization. Development of new technologies is one example of a source of turbulence for leaders and military commanders. Emergence of new tactics and doctrine also adds to the uncertainty associated with the system of a given conflict.

Hierarchy and the level at which we choose to view the system also shapes whether we are able to grasp the true nature of the system. An example of Warden's ideas will help illustrate this dilemma. Warden views the enemy as a system unto itself for his model of the air campaign. He could have viewed the fielded forces as a system, but he chose a higher level by including the civilian infrastructure and political institutions.[8] However, in the eyes of some, his model still falls short because it is not viewed at an even higher level. Ware provides the most compelling argument for this position when he argues that Warden's concept of the enemy as a system "fails to grasp the enemy's true nature." Some believe that this is a condemnation of the systems approach. In reality, what Ware shows is that Warden fails to view the system at the appropriate level. Ware argues that Warden's "five ring analysis is problematical for a representation of the enemy as a social construct [and] it is even more problematical for a representation of the enemy as a system." As the dialogue from Ware demonstrates, frequently the systems argument comes down to a choice of the appropriate level for analysis.[9]

Checkland's third element of a system is communication. This element is the method in which we transmit our desire for direction and change. It is fundamental that we be able to communicate among the various levels of a system to make the systems model effective.

Finally, the fourth element of control is the method with which we interact with the system. Hopefully, our feedback into the system provides the appropriate input to shape the future direction of the system. Of course, the wrong control inputs can bring unintended consequences quickly.

Now that some of the basics have been discussed, one must explore the applicability of systems theory to military problems. It seems intuitive that a military organization constitutes a system, but the subject does bear some discussion. Some contend that our entire mental construct and our thoughts are systems. Since our organizations are collections of people, each with his or her own mental construct, an organization would constitute a system.[10]

The history of the systems idea for organizations dates to nineteenth century engineering practices. The early mechanical engineering community realized that labor unrest and other human factors were important design considerations. The idea "that organizations are systems is an idea with strong roots in organizational theory."[11] Other authors compare the organization to human ecology, industrial economics, and systems practices, all of which are non-linear complex systems. This demonstrates the complexity of understanding the nature of the system, but none of these discussions leads to a formal proof of the systemic nature of organizations.[12] Even without the formal proof, many authors do accept that military organizations constitute systems including Warden, Gorman,[13] and Scales.[14]

Chaos Theory

If one can agree that the concept of warfare constitutes a system, then the next logical question is how can one model the behavior of the system? Chaos theory lends important insights for systems that exhibit significant non-linear tendencies. Warfare, of course, is one of the most non-linear of enterprises. Some authors blur the distinction between the colloquial definition of chaos as randomness and disorder and the scientific definition of chaos as non-linear systems with defined characteristics; however, for the purposes of this paper, chaos refers to the more scientific concept. Resnick quotes Bateson's insight on the usefulness of these phenomena with his observation that "any study which throws light upon the nature of 'order' or 'pattern' in the universe is surely nontrivial."[15]

Of course, it is not just enough to show that warfare is a non-linear undertaking. It must be shown that warfare exhibits chaotic behavior. Nicholls and Tagarev have researched the previous work in this area and reached the following conclusion:

> There is evidence that warfare might also be chaotic. First, strategic decision making, an integral part of war, has been found to be chaotic. Second, nonlinearity, which is a requirement for chaotic behavior, appears to be a natural result of Clausewitzian friction. Third, some computer war games and arms race simulations have been found to exhibit chaotic behavior. Fourth, previous work done by the current authors [Nichols and Tagarev] applied several tests for chaos to historical data related to war. Those tests demonstrated that warfare is chaotic at the grand strategic, strategic, and operational levels.[16]

If one can agree that warfare constitutes a chaotic system, then one can begin to explore the characteristics of that system. One of the first characteristics applicable for warfare is extreme sensitivity to initial conditions, also known as the "butterfly effect." This popular name refers to the idea that weather patterns exhibit such extreme non-linear tendencies that the movement of a butterfly's wings in China will affect the weather on some other continent in the world.[17] In the realm of warfare, defining initial conditions can be equally as difficult as defining atmospheric initial conditions. Initial conditions include the state of the international economy, the state of the enemy's and our own political landscape, culture, as well as the state of many individual minds. However, Nicholls and Tagarev point two key differences concerning the initial conditions of warfare compared to the weather. "First, unlike weather forecasters, we have some ability to change the initial conditions. Specifically, if we find ourselves in a region of great uncertainty, we could determine which conditions would have to be changed to move the system to a position where the outcome was predictable and desirable. Second, we could use our model to determine which initial conditions and which variables had the most profound effect on our predictions. This would aid in identifying centers of gravity and information that we needed to know precisely. That is, it would tell us where to concentrate our attack and what intelligence information was most critical."[18]

A second property of chaotic systems that has some research applicability is the idea of boundaries. Chaotic systems are interesting precisely because they are not completely random. If chaos (in the mathematical sense) equated to complete randomness there would be no point in exploring the idea further. However, chaotic systems exhibit certain tendencies that can be mapped with persistent examination. The primary useful idea behind this behavior is that the system will exhibit randomness within certain boundaries.[19] Therefore, the crucial question becomes boundary definition for modern warfare. At what point does this system (i.e. the conflict or warfare condition) approach the boundary condition, or likewise what conditions will cause a puncture of our boundary conditions. (Nicholls and Tagarev explore the nature of these boundaries in depth, so we will not do it here).

Complexity Theory

As chaos theory became more generally regarded in fields other than physics, scientists began to explore ways to map this non-linear behavior in more general terms. Gell-Mann was a pioneer in this effort as were many other academics such as Robert Axelrod (Game Theory)[20] and Kenneth Arrow (Economics)[21]. These efforts led to the development of complexity theory. In short, complexity theory describes the behavior complex adaptive systems (CAS). The primary influence of complexity theory is the addition of the feedback or control mechanism to a system (normally chaotic). While systems theory and chaos theory have an implicit idea of feedback, complexity theory makes feedback mechanisms explicit. This focus on feedback also highlights the interdependencies throughout any given system.

Of course mapping these ideas of complexity theory to a broader genre outside theoretical physics leads to a certain ambiguity that can be troubling at times. Rothman and Sudarshan admit, "There is still no consensus in many circles on what is a complex system or an emergent phenomenon."[22] Further, Gell-Mann concedes that complex adaptive systems mean different things to different researchers.[23] Despite these doubts and uncertainties, complexity theory has grown in its reach over the past decade. The ideas of complexity theory show how systems adapt to randomness and the external environment. These ideas will give us insights into dealing with uncertainty in warfare.

Even though there are many opinions on the nature of complex adaptive system, a working definition of a complex adaptive system must be found to orient our efforts. For this purpose we will use Gell-Mann's general characteristics of a CAS:

> 1. Its experience can be thought of as a set of data, usually input?output data, with the inputs often including system behavior and the outputs often including the effects on the system.
>
> 2. The system identifies perceived regularities of certain kinds in the experience, even though sometimes regularities of those kinds are overlooked are random features misidentified as regularities. The remaining information is treated as random, and much of it often is.
>
> 3. Experience is not merely recorded in a lookup table; instead, the perceived regularities are compressed into schema. Mutation processes of various sorts give rise to rival schemata. Each schema provides, in its own way, some combination of description, prediction, and (where behavior is concerned) prescriptions for action. Those may be provided even in cases that have not been encountered before, and then not only by interpolation and extrapolation, but often by much more sophisticated extensions of experience.
>
> 4. The results obtained by a schema in the real world then feed back to affect its standing with respect to the other schemata with which it is in competition.[24]

Applicability of CAS theory to Warfare

The previous section outlined the basics of complexity and its associated theory and the discussion established the basic framework for exploring the question of warfare as a complex adaptive system. There are three basic questions to be answered to ascertain the applicability of complexity theory to modern warfare. The first is whether or not warfare is a system. Secondly, does the system exhibit chaotic behavior? Finally, can we classify warfare and more generally conflict situations of many types as a complex adaptive system? The first two questions have been explored previously in the literature as outlined in this article. The final question is the crux of our discussion.

Some previous work in this area has been done; however, this work falls short of the overall model of warfare as a complex adaptive system. That is not to say that the previous literature is not useful; however, this paper tries to explore the applicability of complexity theory to a higher-level analysis. Scales points out that militaries can be considered complex adaptive systems. Gorman takes the analysis further with a discussion of strategy as a complex adaptive system in the World War II environment. Gorman's choice of a World War II situation provides interesting insights into our subject matter, but leaves many unanswered questions about asymmetric warfare, peacekeeping operations, and other more recent developments.[25]

The areas where previous explorations fall short tend to be in the discussion of interdependencies of the elements of the system. An example would be the influence of the tactics of the North Vietnamese military on the civilian population of the U.S. This type of interdependency is difficult to analyze with traditional tools. In order to develop this model further, each thesis of Gell-Mann's definition of a complex adaptive system will be expanded.

The first characteristic of a complex adaptive system looks for data, more specifically input/output data.

> Its experience can be thought of as a set of data, usually input--output data, with the inputs often including system behavior and the outputs often including the effects on the system.

For warfare the input data can be troops, money, political negotiations, or other resources. Also considered input to the system can be more abstract entities such as the organizational structures of the participants and the rules of engagement defining the combat environment. Output data would be the results of the conflict including casualties, equipment losses, or political actions of either party. Understanding the input/output nature of the system is the first step to modeling the behavior of the system.

The second characteristic as defined by Gell-Mann is:

> The system identifies perceived regularities of certain kinds in the experience, even though sometimes regularities of those kinds are overlooked are random features misidentified as regularities. The remaining information is treated as random, and much of it often is.

The idea of regularity or predictability is key to this approach to managing uncertainty in interorganizational relationships. As discussed previously, a totally random world would not yield results from any modeling methodology. That is not to say that there is no randomness in the system, nor does it say that the non-random elements can be completely understood. Instead this method assumes that there is sufficient predictability to make a successful input to the system. An example of this phenomenon is discussed in the modeling of economic situations using complexity theory. Certain scholars have "started to look at economic fluctuations under the hypothesis that a relevant portion of them can be explained as a deterministic phenomenon, endogenously created by the interaction of market forces, technologies and preferences. In particular, it is conjectured that deterministic periodic cycles affected by small stochastic forces and/or ‘noisy’ chaotic paths generated by dynamical systems of relatively small dimensionality, can account for a relevant portion of the observed fluctuations of most of the important macroeconomic variables."[26] The most common dissuasion in the theory of warfare that equates to this discussion revolves around Clausewitz’s concept of the fog and friction of war. Discovering which inputs are random and which are chaotic gives the decision maker a chance to make meaningful inputs into the system.

Gell-Mann goes on to list the third characteristic as:

> Experience is not merely recorded in a lookup table; instead, the perceived regularities are compressed into schema. Mutation processes of various sorts give rise to rival schemata. Each schema provides, in its own way, some combination of description, prediction, and (where behavior is concerned) prescriptions for action. Those may be provided even in cases that have not been encountered before, and then not only by interpolation and extrapolation, but often by much more sophisticated extensions of experience.

This description of a CAS is fundamental to most management, organizational and leadership undertakings. Military strategists regularly develop various models for viewing the strategic and tactical landscape. Likewise, the management book publishers provide a steady stream of schema for almost every considerable organizational quandary. These publications as well as the academic literature provide the fundamental building blocks for developing new views of our situation and the many diverse approaches provide critical insights into complex phenomena. Gell-Mann points out that "even among schemata, competition leavened with cooperation is sometimes both possible and advantageous. In the realm of theories for instance, competing notions are not always mutually exclusive; sometimes a synthesis of several ideas comes much closer to the truth than any of them does individually."[27]

Interestingly, the CAS approach is also a schema but at the meta-level. CAS is an approach that allows us to create better models. A key element of these CAS models will be that they adapt and learn with the organizations and the environment. "A learning-less model can be used to anticipate the near-future where evolutionary change is minimal; but to predict an evolutionary system--if it can ever be predicted in pockets--will require the requisite complexity of a simulated, artificial evolutionary model."[28] Argyris (1999, p. 1) lists the ideal notions of a learning organization as "organizational adaptability, flexibility, avoidance of stability traps, propensity to experiment, readiness to rethink means and ends, and inquiry orientation"[29] among others. Surely these ideals apply to effective model development for complex adaptive systems and our military doctrine and strategy.

Once our model is developed, these learning ideals can be put forth in the Gell-Mann's last characteristic of a CAS:

> The results obtained by a schema in the real world then feedback to affect its standing with respect to the other schemata with which it is in competition.

Economic entities have a built-in feedback mechanism: financial performance. Unfortunately, military feedback mechanisms for warfare are not normally available until execution, although wargaming technology does provide some useful data. This means that history becomes our guide as competing schema are evaluated through historical analysis. Warfare ensures the survival of the fittest. Of course, the reason for the CAS approach is to ensure that our organization is the 'fittest' as opposed to the enemy.

These feedback systems also provide control mechanisms to ensure continued top performance. Information technology plays a role in these control systems. "Information processing and reciprocal communication [i.e. feedback] are twin activities. Information processing is essential to all purposive activity, which is by definition goal directed and must therefore involve the continual comparison of current states to future goals."[30] On the other hand, a limit to the feedback systems for complex systems is that "direct feedback models can achieve stabilization--one attribute of living systems--but they can't learn, grow, or diversify--three essential complexities for a model of changing culture or life. Without these abilities, a world model will fall far behind the moving reality."[31]

The last point concerning the characteristics of a complex adaptive system is implicit in Gell-Mann's definition, but never stated for the record. That point is that in a complex adaptive system the relationships between the elements of the system are fundamental to the nature of the system. This means that in conflict not only is the number of troops a factor, but also how those forces relate to each other. These relationships frequently exist independently of the actual participants in the system. For example, some military units retain a particular character over long periods of history. This character survives even when there has been complete turnover of personnel (though overlaps of personnel do occur).

The Model

Now that a foundation of complexity theory has been constructed, the CAS model of conflict can be developed. The model developed for this article is one of a two-adversary system. I have used Warden's five rings model for a starting point. My objection to Warden's model is that the interaction is assumed to be one-way. Interdependencies between the actors in the conflict are not readily apparent in the five rings model. Gilster brings this issue to the forefront under a different name: substitution. He shows that under prolonged conflict, enemies are able to adapt to our tactics to minimize the effect of our actions.[32]

Fittingly enough, the model presented here (Figure 1) is not static. The model is built upon a continuum of interdependency. As the actors in a conflict become more interdependent the points of intersection become greater. This means that the actions taken by one party affect the aggressor and the defender. This was true for example in Vietnam. The military tactics including bombing campaigns had affects on our civilian population causing unrest and demonstration. Certainly there were many complex interactions taking place during the Vietnam conflict and these effects would not have been readily predicted by the original five rings model.

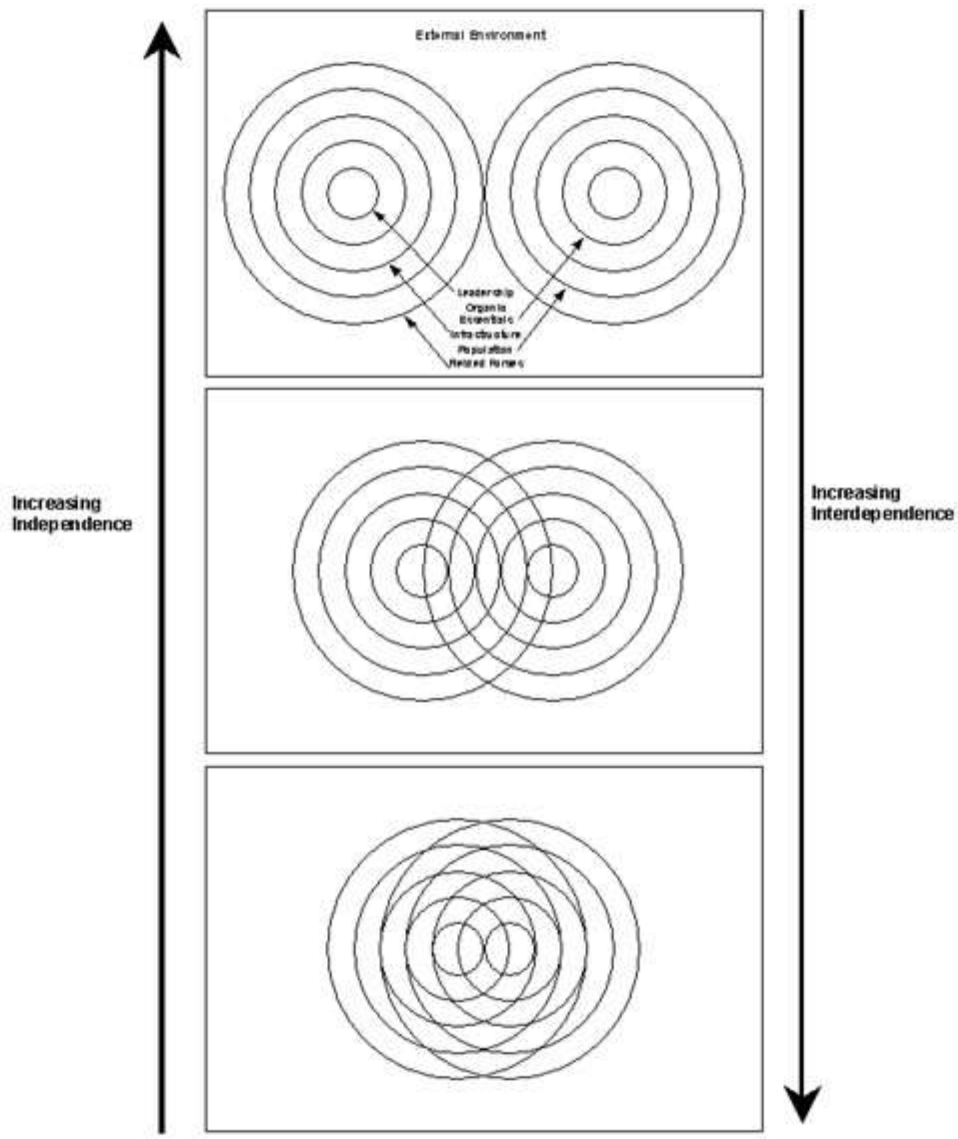

Figure 1

Complex Adaptive System Model of Warfare

Adapted from Colonel John Warden's Five Rings

Applying the Model

Now that the model has been presented, its applicability for modern leaders needs to be analyzed. Before direct application is explored though, a key question must be answered. How much interdependence is inherent in the interaction between the participants? Assessing the level of interdependence establishes the basis for further analysis. It is important to note that most of the recent conflicts have been fought using a coalition and not undertaken by a single player. Therefore, interdependence between coalition members must also be considered. Factors affecting interdependence include:

1. Historical and Cultural Ties: These factors include common religions or historic relationships. These relationships may mean that members of the population have family ties with the adversary. Examples of these ties include Israel and Western Europe for the U.S.
2. Trade Relationships: The trading relationship between participants in a conflict may be the cause of the conflict or it may only be a secondary consideration. Middle Eastern oil is an obvious example of a trade relationship affecting the nature of a conflict.
3. Information Flow: The level of information infrastructure available to each participant and its corresponding population directly impacts the level of interdependence. This information infrastructure includes everything from access to CNN to Internet access. Personal communications methods such as e-mail, cell phones, and normal wired telephones also contribute to the overall information flow.

The assessment of the level of interdependence of the participants then leads to a more detailed consideration of a strategy. For example, the most interdependent of conflicts would be a civil war. In today's era of globalization, a completely independent conflict would be difficult to imagine. The adaptable nature of this model provides some general insights for planning that should prove scalable for many scenarios. Some of the initial principles inherent in this model for future planning are:

1. Study of history and the effective use of intelligence sources are critically important given the extreme sensitivity to initial conditions inherent in our complex adaptive system
2. Our military and political actions during a conflict affect our own institutions as well as those of the enemy. We must understand the interdependencies of our actions to the maximum extent possible.
3. An incrementalist strategy for warfare is risky given that it may allow for breaching of the boundaries established by the initial model
4. A return to the blitzkrieg concept is warranted given that the longer the conflict lasts, the more likely that the enemy will be able to adapt to any advantages enjoyed by the attacker.[33]

Conclusion

In the past, the CAS literature has been descriptive in nature. Systems are designated as behaving as a CAS after observation. Future research in warfare as a complex adaptive system must strive to be predictive in nature. One must collect data on the general principles that can be extrapolated for complex adaptive systems application in warfare. Since each conflict is unique, the generalized CAS principles provide an excellent framework for developing the infinite varieties of relationships that can be created. The improved technologies of the information age will require new techniques to understand the interdependencies created by tomorrow's conflicts.

"We must in the end, bring about the two most direct ways to the truth about CAS: to try to build them and to try to study them."[34] Complex adaptive systems are being built every day, either consciously or unconsciously, and this includes military organizations and other elements of our politico-military environment. Beinhocker says, "What's needed is a model of a world where innovation, change, and uncertainty are the natural state of things."[35] Complexity theory gives us the tools to build that model.

Suggested Further Reading

Systems Theory

The Fifth Discipline by Peter Senge.

General System Theory by Ludwig von Bertalanffy

Systems Thinking, Systems Practice by Peter Checkland

Chaos Theory

Chaos by James Gleick

Leadership and the New Science by Margaret Wheatley

Complexity Theory

Complexity: The Emerging Science at the Edge of Order and Chaos by M. Mitchell Waldrop

The Quark and the Jaguar by Murray Gell-Mann

Endnotes

1. Ludwig von Bertalanffy, General System Theory: Foundations, Development, Applications, (New York: George Braziller, 1968), 37.
2. B.R. Greene, The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory, (New York: Vintage, 1999), 17.
3. It is interesting to note that even if we were able to overcome Greene's calculational impasse, Heisenberg's "Uncertainty Principle" states that the best

outcome would be to assign probabilities to the possible states of nature inherent within the system.
4. Bertalanffy.
5. See for example: Peter Senge, The Fifth Discipline: The Art & Practice of the Learning Organization, (New York: Currency Doubleday, 1994); P. Checkland and S. Holwell, Information, Systems, and Information System: Making Sense of the Field, (Chichester: John Wiley & Sons, 1998); J. Gharajedaghi, Systems Thinking: Managing Chaos and Complexity: A Platform for Designing Business Architecture, (Boston: Butterworth Heineman, 1999).
6. Checkland and Holwell, 157.
7. Peter Checkland, Systems Thinking, Systems Practice, (New York: John Wiley & Sons, 1993), p. 19.
8. John A. Warden, "The Enemy as a System," Airpower Journal (Spring, 1995). Found on-line at airchronicles/apj/warden.html.
9. Lewis Ware, "Some Observations of The Enemy as a System," Airpower Journal, (Winter, 1995). Found on-line at airchronicles/apj/ware.html.
10. David Bohm, Thought as a System, (London: Routledge, 1994).
11. Yehouda Shenhav, "From Chaos to Systems: The Engineering Foundations of Organization Theory, 1879-1932." Administrative Science Quarterly, Vol. 40 (1995), 578.
12. W.G. Astley and A.H. Van de Ven, "Central Perspectives and Debates in Organization Theory," Administrative Science Quarterly, Vol. 28 (1983), 245-273.
13. G. Scott Gorman, Endgame in the Pacific: Complexity, Strategy, and the B-29, The Fairchild Papers, (Maxwell AFB, Alabama: Air University Press, 2000).
14. Major General Robert H. Scales, Jr., "Adaptive Enemies: Dealing with the Strategic Threat After 2010," Strategic Review, Vol. 27 (Winter 1999), 5-14.
15. Mitchell Resnick, Turtles, Termites, and Traffic Jams: Explorations in Massively Parallel Microworlds, (Cambridge, Massachusetts: MIT Press, 1994), p. 3.
16. David Nicholls and Todor Tagarev, "What Does Chaos Theory Mean for Warfare?" Airpower Journal, Fall 1994, available online at airchronicles/apj/apj94/nichols.html.
17. James Gleick, Chaos: Making a New Science, (New York: Penguin Books, 1987).
18. Nicholls and Tagarev.
19. Ibid.
20. Robert Axelrod, The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration, (Princeton: Princeton University Press, 1997).
21. Kenneth Arrow, The Limits of Organization, (New York: Norton, 1974).

22. Tony Rothman and George Sudarshan, Doubt and Certainty, (Reading: Perseus Books, 1998), p. 143.
23. Murray Gell-Mann, "Complex Adaptive Systems," In G. Cowan, D. Pines, and D. Meltzer (Eds.), Complexity: Metaphors, Models, and Reality, (Reading: Perseus Books, 1994, 17-45), 18.
24. Ibid, pp. 17-18.
25. G. Scott Gorman, "Endgame in the Pacific: Complexity, Strategy, and the B-29," The Fairchild Papers, (Maxwell AFB, Alabama: Air University Press, 2000).
26. M. Boldrin, "Oscillations and Chaos in Dynamic Economic Models," In P.W. Anderson, K.J. Arrow, and D. Pines (Eds.), The Economy as an Evolving Complex System, (Reading: Perseus Books, 1988, pp. 49-75), p. 50.
27. Murray Gell-Mann, The Quark and the Jaguar, (New York: W.H. Freeman and Company, 1994), p. 242.
28. Kevin Kelly, Out of Control: The New Biology of Machines, Social Systems, and the Economic World, (Reading: Addison-Wesley), 448
29. Chris Argyris, On Organizational Learning (2nd ed.), (Oxford: Blackwell, 1999).
30. J.R. Beninger, The Control Revolution, (Cambridge, Massachusetts: Harvard University Press, 1986), p. 434.
31. Kelly, 448.
32. Herman L. Gilster, "Desert Storm: War, Time, and Substitution Revisited," Airpower Journal, Spring 1996, 1-10.
33. Ibid, 2.
34. Peter Anderson, "The Eightfold Way to the Theory of Complexity: A Prologue," in G. A. Cowan, D. Pines, and D. Meltzer (eds.), Complexity: Metaphors, Models, and Reality, (Reading: Perseus Books, 1994, 7-16), 13.
35. Eric Beinhocker, "Strategy at the Edge of Chaos," The McKinsey Quarterly, 1997 (No. 1), 28.