From Metaphors to Models: Broadening the Lens of the Hunter Warrior

CSC 1999

Subject Area - General

Executive Summary

Title: From Metaphors to Models: Broadening the Lens of the Hunter Warrior Experiment with a Complex Adaptive System Tool

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Thesis: Complex systems theory can help to answer specific combat experimentation questions using an agent-based simulation model built around complex adaptive system (CAS) principles.

Discussion: Military analysts have used simulation models and field experiments for years to gain insight into the fundamental dynamics of combat. Each research methodology has its traditional advantages and disadvantages. Past simulation efforts have traditionally focused on the "science" of war at the expense of the "art" of war. The nonlinear interdependencies, feedback, and "soft" factors of combat (like cohesion or trust) have just been too difficult to model.

The "new" or nonlinear sciences provide a totally different framework for analysts to work within. Specifically, the field of the nonlinear sciences referred to as complex systems theory has encouraged military scientists to build analytic tools from a bottom-up approach rather than a traditional top-down approach. This approach coupled with advances in programming and computing power allow agent-based simulation models to be built that allow analysts to examine forces in combat as a complex adaptive system. These models are now being built to capture the actions of individual soldiers (agents) and allow forces to learn, adapt, plan, and re-direct efforts and resources within broadly defined behavior boundaries. Unanticipated and unexpected relationships often result from this modeling approach, which can make it a superior tool for "broadening the lens" of various warfare scenarios.

Field experiments like the Marine Corps' Hunter Warrior experiment often raise more questions than they answer. CAS-principled agent-based models can be used to answer follow on questions in a more thorough, expansive, and enlightening fashion than previously realized with top-down, design-constrained models. The SWarrior agent-based model is highlighted as an example of how complex systems theory principles can be implemented to provide analysts with the capability to broaden the lens of previous experimentation. This paper proposes an experimental design that could efficiently answer several of the operational questions that resulted from the Hunter Warrior Advanced Warfighting Experiment.

Conclusion: The ability of future agent-based simulation models to replicate the learning, adaptation, and goal-directed behavior of forces in combat will be a powerful analytic tool with

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE
From Metaphors to Models: Broadening the Lens of the Hunter Warrior Experiment with a Complex Adaptive System Tool

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
United States Marine Corps,Command and Staff College, Marine Corps University,2076 South Street, Marine Corps Combat Development Command,Quantico,VA,22134-5068

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**113**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

many different applications. Course of action analysis, decision making training, resource allocation analysis are just a few examples. With such tools, military analysts will not only be able to examine specific conflicts like Hunter Warrior, but they will now be able to more efficiently explore the implications of different tactics, techniques and procedures for future combat environments. These tools can help shape our understanding of military operations other than war, urban warfare, and Operational Maneuver From The Sea.

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Chapter 1

Nonlinear Sciences: Where are we in application?

> *And there will be other ways and means which no one can foresee at present, since war is certainly not one of those things which follow a fixed pattern; instead it usually makes its own conditions in which* ***one has to*** *adapt oneself to changing situations.*[1] --Thucydides

The nonlinear sciences qualify as "other ways and means" where studying the patterns of conflict is concerned. As Thucydides so clearly captured thousands of years ago, adaptation is a primary requirement for all who participate in war. Neither Thucydides nor Clausewitz could see the "other ways and means" of the nonlinear sciences, but today, the nonlinear sciences can help us experiment with the process of adaptation that is so critical to success in combat. The following introduction and review will highlight a few nonlinear science concepts that have been appreciated and understood by some of the senior leadership in the Marine Corps. Several new doctrinal publications even reflect a nonlinear science approach to warfare. Institutionally, the understanding of this new approach to military science is just beginning, but there is much to be accomplished in applying the principles to gain practical utility.

[1]Strassler, Robert R., Crawley, and Victor Davis, *The Landmark Thucydides: A Comprehensive Guide to the Pelopponesian War,* Free Press, 1996, 106.

In 1992, Alan Beyerchen's publication of *Clausewitz, Nonlinearity, and the Unpredictability of War* clearly illustrated that modem nonlinear scientific concepts are in perfect accord with Clausewitz's world-view and offer many useful metaphors.[2] The first chapter sub-headings of the Marine Corps capstone Warfighting manual, Marine Corps Doctrinal Publication 1 (MCDP 1), reflect that the Marine Corps continues to formally recognize the role of such important issues as friction, uncertainty, fluidity, disorder, and complexity. Direct application of complexity theory concepts are also evident in the Marine Corps Doctrinal Publication on Command and Control (MCDP 6). The next step is to continue to pursue a full understanding of these pervasive realities and how we can operate more effectively in the midst of them.

The nonlinear sciences "make up a rapidly growing trans-disciplinary field that seeks to discover new insights and concepts governing natural phenomena and 'complex adaptive systems.' These systems are composed of numerous independent agents that interact with each other, co-evolve from this interaction, and adapt to their changing environment. Examples of such complex adaptive systems include biological processes, economic systems, and human behavior -- to include our behavior in military operations. In complex systems, unpredictable occurrences and emerging properties arise from the

[2] Dr Chris Bassford, a former professor at the Marine Corps university, considers Clausewitz' perspective on war so pertinent and applicable that he is working toward the development of a new version of *On War*, to be called *On War 2000*. Like Clausewitz' classic, it will describe the complex and uncertain manner in which real-world events unfold, taking into account both the frailties of human nature and the complexity of the physical and psychological world. After more than a century and a half, Clausewitz's work remains the most comprehensive, perceptive, and modem contribution to political-military thought. Bassford's goal is the synthesis of nonlinear science and Clausewitz's words to form a powerful, and contemporary message. He aims to recast Clausewitz's book in a form that citizens and soldiers alike will find both readable and perceptibly relevant to the emerging world of the twenty-first century. Bassford's effort is just one of many ongoing initiatives that increasingly prove that the concepts and principles of the nonlinear sciences are here to stay. http://www.mnsinc.com/cbassford/SWZHOME/Complex/Proposax.htm.

interaction and adaptation. Combat veterans recognize that there is nothing more unpredictable than the interaction of opposing wills in armed conflict. Thus, it is natural that nonlinear sciences might provide powerful and profound insights about warfare."[3] In fact, in a recent interview, Lieutenant General P.K. VanRiper said that he thought "understanding the implications of nonlinear dynamics is the real Revolution in Military Affairs (RMA)."

General Krulak provides a good overview of how the nonlinear sciences currently fit into our study of warfare in his preface to Maneuver Warfare Science 1998.

> The nonlinearity of war is based on the fundamental essence of the physical and psychological processes that occur in actual combat which give rise 1] to its long-term unpredictability. The introduction of randomness and chance in war reflects its nonlinear nature and magnifies the impact of minor events and unforeseen factors that Clausewitz introduced to us as 'friction.' Rather than a deterministic, predictable, and methodical world seen through a Newtonian worldview, the nonlinear sciences provide the closest scientific perspective approaching warfare as we currently understand it. One of the more revolutionary aspects of the nonlinear sciences includes new techniques and tools for military operations research and analysis. Many of our models and combat simulations are now outdated and inappropriate for tomorrow's forces. Modeling an adaptable enemy, with a will of his own and with the capacity to evolve new tactics and reactions, requires more than we can derive from formulae-driven computer algorithms. Nonlinear sciences are not about a single technological innovation or scientific discipline. They represent a distinct revolutionary shift in how to approach both the study of physical properties and human behavior. They have the potential to profoundly impact the way we look at, think about, and model warfare.[4]

[3] United States Marine Corps, *Maneuver Warfare Science 1998,* Marine Corps Combat Development Command, Quantico, VA: 1998, Preface.

[4] Maneuver Warfare Science 1998, Preface.

Maneuver Warfare Science 1998

The nine articles in the Marine Corps Combat Development Command's (MCCDC's) Maneuver Warfare Science 1998 publication[5] contain some excellent nonlinear science research summaries and provide an indication of where the Marine Corps is heading with the nonlinear sciences. This collection reviews the current and future links between nonlinear sciences and warfighting. Lieutenant General Rhodes provides appropriate perspective in his introductory comments,

> A maneuver warrior is one who exploits the fact that warfare is nonlinear. In warfare, outputs are not always proportional to effort. The whole fighting force is not equal to the sum of its parts. Initial conditions and intangibles influence the outcome. In other words, warfare is nonlinear. *To exploit these facts, we must better develop our understanding of the nonlinear nature of warfare. But we are now only in the very be ginning stages of exploring warfare in the context of the nonlinear sciences.* The exploration of the nonlinear sciences holds promise as a catalyst and perhaps as a vehicle for movement toward MCCDC's general analytic goals.[6]

Research Focus

This paper attempts to meet Lieutenant General Rhodes' challenge to "explore warfare in the context of the nonlinear sciences". It will illustrate how the Marine Corps can continue to move from useful metaphors to useful models. Rather than focus on the *general* application of nonlinear science to military science, this research provides an overview of some *specific* applications of nonlinear science with the emphasis on a specific, practical application of the nonlinear sciences for the warfighter. Using an agent-based simulation model, this paper examines how complex systems theory can help

[5] Maneuver Warfare Science, 1998, Foreword. Part I contains three background articles that help to lay the groundwork for terms, concepts, and a recent history of the nonlinear sciences. Part II contains three articles that examine key combat issues with an emphasis on how metaphors from the nonlinear sciences help us to develop a new perspective from which to understand the issues. Finally, the three articles in Part III of the collection focus on agent-based models which have demonstrated significant potential to capture basic nonlinear principles and use them to improve the usefulness of combat models.

to answer specific combat experimentation questions. In particular, it attempts to broaden the lens of the Hunter Warrior Advanced Warfighting Experiment (AWE) with a complex adaptive system tool to demonstrate specific utility to the warfighter.

[6] Maneuver Warfare Science, 1998, Foreword.

Chapter 2

Nonlinear Sciences Review

> *The aim of science is not things themselves, as the dogmatists in their simplicity imagine, but the relations among things; outside these relations, there is no reality knowable.* -- H. Poincare

Before proceeding with a discussion of several military applications, this chapter presents a brief review of the interesting field of the nonlinear or "new" sciences. This review will not necessarily provide sufficient background information to make the uninitiated totally comfortable with all the underlying concepts. The intent is to set the stage for the chapters that follow. The works listed in the enclosed bibliography (especially Waldrop and Holland) can provide further background information. The following quotes are provided to motivate our review:

> 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. The term nonlinearity is adopted as a convenient umbrella for all of the various terms 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, 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.[7]

[7]Czerwinski, Tom. *Coping with the Bounds: Speculations on Nonlinearity in Military Affairs.* Washington, D.C.: National Defense University Command and Control Research Program, 1998, Introduction.

Nonlinear sciences, or the "new science", is in its infancy, and it is more about biology than about physics. It is approximately twenty years old, and it could only be discovered with the advent of the computer. This science has its own unique terminology such as phase states, bifurcations, strange attractors, emergence, criticality and path-dependence. The new science is founded on a whole new set of concepts that are considered to be post-Newtonian. The following quote helps to explain what it means to be post-Newtonian and how that impacts the way we examine problems.

> Within the Newtonian scientific framework, the arrangement of nature, life and its complications was assessed to be predominantly a linear phenomenon where inputs are proportional to outputs. Under this paradigm, careful planning assisted prediction; success by detailed monitoring, and control; and a premium placed upon linear reductionism. 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; that is where the test of wills, the conflict of interests, and the collision of agendas are largely absent. Under a post-Newtonian framework, the arrangement of nature, life and its complications, such as warfare are considered to be nonlinear; where inputs and outputs are not proportional. This perspective sees where phenomena are unpredictable, but within bounds, 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. Where rewards go to those who excel in coping with the bounds in order to command and manage--not on prediction and control.[8]

Complex Adaptive Systems (CAS)

Under the post-Newtonian framework of the nonlinear sciences, there has been a strong and growing interest in an interdisciplinary field referred to as the Science of Complexity over the past several years. Complex Systems Theory is just one of several research areas that currently falls under the heading of the nonlinear sciences. This field covers a wide variety of interests that focus on the analysis of systems that exhibit nonlinear interactions among system components.

> Complexity theory is rooted in the fundamental belief that much of the overall behavior of ostensibly diverse complex systems (natural ecologies, fluid flow, the human brain, etc) in fact stems from the same basic set of underlying principles.[9]

Such systems with interesting emergent behavior are referred to as *complex systems.* Those complex systems with the additional property that the basic elements that make up the system can change their properties, or evolve over time, are often called ***complex adaptive systems*** **(CAS).**[10] In the military environment, these basic elements are human combatants who use time, resources, and weapons differently over time to accomplish their goals. Originally coined by Dr John H. Holland, the term CAS has been used to describe social, economical, and biological systems, to name just a few. In CAS literature, the ant colony is a common example of a natural, social system that is governed by relatively few simple rules yet self-organizes to create complex behavior that achieves a common goal. Holland used the following four properties and three mechanisms to describe systems as complex adaptive:

- Properties: aggregation, nonlinearity, flow, and diversity
- Mechanisms: internal models, adaptation, coevolution[11]

Holland uses simple examples to demonstrate how each of these properties and mechanisms create and characterize complex adaptive systems. Military units in conflict clearly exhibit every one of these properties and mechanisms. This is why much current research and modeling is approaching the study of combat from a CAS framework.

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[8]Czerwinski, Introduction.
[9]Ilachinski, Andy, "ISAAC: An artificial life approach to land combat", http://www.cna.org/isaac.
[10]Stonier, Russell and Xing Huo Yu, "Mechanism of Adaptation", Introduction, *Complexity International*, (Vol 2:1995) Charles Sturt University. http://www.csu.edu.au/ci/vol2/intro942.html.

This paper will use the term "complex adaptive system" to refer to a system with the following properties:

- Contains a collection of basic elements, called "agents"
- Exhibits interactions among agents and between agents and their environment
- Unanticipated global properties often result from the interactions
- Agents adapt their behavior to other agents and environmental constraints
- As a consequence, system behavior evolves over time[12]

The concept of an "agent" is simply an extension of the "object" in object-oriented modeling and simulation. For programmers to create effective simulations, they create all the important objects that define a system of interest. They do this by writing code that captures all the essential characteristics of the object in a definition module. They also write code that captures all the different ways this object interacts with other objects and with its environment (implementation module). Once a base object (or agent) type is created, multiple copies can be created within the simulation to populate the system. Each object or agent will be different based on variations (programmed and/or random) in characteristics or parameters. For example, from a base mortar object, a programmer can easily create 60mm, 81mm, and 120mm mortars or 155mm howitzer variants simply by changing characteristics. Each of these would obviously have different ranges, weights, effective casualty radii, employment doctrine, and ammunition types. The use of the term "agent" vice object usually means that the element of the system that is being modeled can actually learn, communicate, and adapt behavior over time. With current advances in programming, the ability to more effectively capture the complexities of

[11]Holland, John H. ***Adaptation in Natural and Artificial Systems.*** Cambridge, Massachusetts: MIT Press, 1992, 10.

[12] Forrest, Stephanie and Terry Jones. "Modeling Complex Adaptive Systems with Echo", *Complexity International,* (Vol 2:1995) Charles Sturt University. http://www.csu.edu.au/ci/col2/ci2.html (Download from the INTERNET in Oct 1998).

reasoning, goal-directed behavior, and adaptation allow us to produce more effective system analysis tools.

> The basis of adaptation rests on the premise that there is some condition of operation or performance that is better than any other. Moreover, to be called *adaptive*, self-organizing features must exist in the system to enable performance to be optimized. Of particular interest are those systems for which there are no governing physical laws. These occur, for example, in natural ecological systems, social systems and, of course, the brain. In its simplest description, adaptation usually implies that the system is capable of accommodating unpredictable changes or disturbances, whether these arise within the system or are external to it in the environment. Adaptation is clearly a fundamental characteristic of all living organisms since they attempt to maintain physiological equilibrium in the midst of changing environmental conditions.[13]

The ability to adapt to changing conditions is very important to military units as well as living organisms. With DoD's current focus on Network-Centric Warfare, the potential for rapid adaptation at all levels of combat should improve. As LtGen Rhodes, USMC, has said, "Network-Centric Warfare stresses rapid decision making, decentralized command, and self-synchronization rather than directive control."[14] The wide availability of important information on a networked battlefield will theoretically encourage more rapid adaptation. A well-known nonlinear science researcher named Stuart Kauffman discovered that network connectivity was a key variable for encouraging adaptation. As Dr Kauffman varied the connectivity parameter in his generic networks, he discovered (as expected) that

> a system where few agents influenced each other was not very adaptable to changes in the system. The soup of connections was too thin to transmit an innovation. The system would fail to evolve. As Kauffman increased the average number of links between nodes, the system became more resilient, "bouncing back" when perturbed. The system could maintain stability while the environment changed. It would then evolve. The completely unexpected finding

[13] Complexity International, Volume 2 Introduction.
[14] Rhodes, LtGen John E., "Network Centric Works for Marines" *Proceedings*, (September 1998): 2.

> was that beyond a certain level of linking density, continued connectivity would only decrease the adaptability of the system as a whole.[15]

During a research trip to the Santa Fe Institute[16], the author heard Dr John Holland discuss the body's immune system as an excellent example of a CAS. In the midst of talking about how our immune system is able to distinguish its host from such a wide variety of foreign intruders over time, Dr Holland introduced the concept of a CAS **lever point.** Using the immune system example, Dr Holland explained that a vaccine is a way to get at a critical lever point in the immune system. The vaccine serves as a catalyst (or lever) of sorts in prompting the system to produce a totally new and effective set of antibodies. In this sense, a relatively simple action (vaccination) introduced at the right point in a system can produce large and sometimes critical results. Major Thomas Moore, USMC further pursues the applicability and potential importance of lever points in the CAS of combat. In his research, which will be reviewed later, Major Moore examines "communications" as a lever point that might be better used to create large, directed changes in the behavior of units in combat.

Additional CAS research in the military arena is being conducted by Dr Andy Ilachinski at the Center for Naval Analyses (CNA). The central thesis of Dr Ilachinski's comprehensive and persuasive work, "Land Warfare and Complexity, Part II: An Assessment of the Applicability of Nonlinear Dynamics and Complex Systems Theory to the Study of Land Warfare", is that *land combat is a complex adaptive system.* One of

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[15] Kelly Kevin. *Out of Control.* New York: Addison-Wesley Publishing, 1994, 399.

[16] The Santa Fe Institute is located in Santa Fe, New Mexico and is considered to be the origin of many nonlinear science concepts.

many effective tables in that work highlights the key characteristics of land combat as a CAS in Table 1 below.

Generic Property of Complex Systems	Description of Relevance to Land Combat
Nonlinear interaction	Combat forces composed of a large number of nonlinearly interacting parts; sources include feedback loops in C2 hierarchy, interpretation of (and adaptation to), enemy actions, decision making process and elements of chance
Nonreductionist	The overall "fighting ability" of a combat force is not a simple aggregate function of the fighting ability of individual combatants
Hierarchical structure	Combat forces organized in a command and control hierarchy
Decentralized control	There is no master "oracle" dictating the actions of each and every combatant
Self-organization	Local action, which often appears "chaotic" induces long-range order
Nonequilibrium order	Military conflicts, by their nature, proceed far from equilibrium
Adaptation	In order to survive, combat forces must continually adapt to a changing environment
Collective dynamics	There is a continual feedback between the behavior of (low-level) combatants and the (high-level) command structure

Table 1. Land Combat as a Complex Adaptive System[17]

Modeling and Simulation to Gain Insight into CAS[18]

We must capitalize on the gains realized through our new training initiatives and exploit the opportunities resident in modeling and simulation to increase our warfighting efficiency and effectiveness. --General C.C. Krulak

One way to obtain insight into the evolution and adaptive processes of complex systems is through modeling and simulation (M&S) where a computer model is created

[17] Ilachinski, Andy, "Land Warfare and Complexity, Part H: An Assessment of the Applicability of Nonlinear Dynamics and Complex Systems Theory to the Study of Land Warfare", Center for Naval Analyses Research Memorandum 96-68. http://www.cna.org/isaac/downref.htm

to represent a given system. The general question of definition and structure for modeling complex systems has been studied by several researchers; for example, John Holland in *Adaptation in Natural and Artificial Systems* and John Casti in *Reality Rules I: Picturing the World in Mathematics - the Fundamentals.*

The interactions and relationships between agents within various complex systems are currently being examined through the creation and study of self-contained artificial worlds. By creating systems that can maintain themselves in a natural environment, researchers can more thoroughly study how agents adapt by processing local information. For a biologist, the agents might be ants, for a doctor the agents might be viruses, and for an economist the agents of interest might be companies. The military analyst, on the other hand, is interested in studying combatants and the systems they use to shoot, move, and communicate.

Our ability to analyze complex systems has been directly related to the great advances in computation. The increased speed of parallel processing allows one to observe the behavior of such systems on a realistic time scale. Evolutionary paradigms like genetic algorithms have arisen out of studies made possible by parallel computation. Results have had great application to search and optimization problems in a variety of fields. The current understanding of Chaos has shattered an old view that "simple systems exhibit simple behavior" and "complex systems exhibit complex behavior". Simple, deterministic, nonlinear systems *can* exhibit complicated behavior. Further, system

[18] Complexity International, Volume 2 Introduction. Typical research in the area of CAS covers both theory and applications and are often organized loosely into four categories: Artificial Life, Evolution and Complexity, Classification, Heuristic Search and Computation, Neural Networks, Chaos and Fractals.

solutions may be very sensitive to small changes in initial conditions. For an overview of the popular concept of Chaos, see Appendix A. Additionally, new neural network techniques have been used with success in pattern classification and recognition, prediction, function approximation and optimization. All of these are important tools for the military modeler as he attempts gain insight into a system's dynamics from the results of agent-based modeling.

Utility of Agent-based Modeling (ARM)

The emergent patterns that result from interacting agents in a complex adaptive system are difficult to analyze by traditional tools of science. The science of complexity involves the search for new theoretical frameworks and methodological tools for understanding complex systems. The main tool currently being used in this research is a computer-based microworld where agents interact and adapt to their evolving environment without explicit programmer direction.[19]

Agent-based modeling (ABM) promises to provide new insights into military operations by asking fundamentally different questions about the dynamics of military interactions. ABM techniques have their roots in complex systems theory. Unlike most approaches to computer simulations, ABM techniques simulate a situation from the bottom up. By assigning key behavioral characteristics to individual agents (i.e. infantrymen, individual tanks, UAVs, or infantry squads) agent-based models track every interaction between individual agents and between the agents and their environment.

Agent-based simulations are constructed from a number of low level entities, which interact with each other according to a (sometimes evolving) set of behavioral boundaries to produce emergent higher level behaviors. While traditional modelers assumed that complicated, and therefore difficult to model, behavior drives the actions of individuals and small units, agent-based techniques assume that the behavior of individual agents is relatively simple and can be approximated by a limited number of rules or behavioral boundaries. It is the interaction of these agents and their ability to learn and adapt that generates the complex system that we know as combat.

The agent-based approach to ground combat focuses on how the behaviors of low level entities change under differing circumstances, and under the same circumstances over time. Agent-based modeling thus contrasts to comparable traditional models of the same fidelity, which focus more exclusively on the performance parameters of the modeled entity. Like traditional models, agent-based models begin with certain entity performance parameters. For example, ground combat agents are ascribed a set of physical characteristics (speed, endurance, range of available weapons, sensor capabilities, etc). The agents are also defined by the methods and procedures with which they interact with each other and their respective environments.

In contrast with traditional models, however, the agent is also given one or more sets of simple behavioral characteristics. These include the following: (1) doctrinal

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[19]Casti, John L. *Would-Be Worlds: How Simulation is Changing the Frontiers of Science.* New York: John Wiley & Sons, Inc.,1997. 34.

instructions, so that agent behavior is generally in accordance with existing doctrine, (2) the commander's concept of the operation and how agents should behave in particular circumstances, and (3) variable parameters describing the human (or personality) dimension of that agent. For example, when a Marine is surprised or when his squad-mates are dying around him, his behavior is likely to be different than when his unit is whole and the enemy appears only where and when expected. Much current research and modeling applications are being pursued to develop the algorithms needed to capture more and more of this behavioral differential. All of the agent characteristics are adjustable within the model. Those models that most thoroughly capture the dynamic interactions of a complex adaptive system are those where each and every agent adapts and learns from other agents and its environment.

Other common aspects of an agent-based simulation are stochastic effects, grouping of agents into like units, and parallel computations. In military agent-based models, such as SWarrior, the actions of each squad, Marine, or UAV is likely to be generated stochastically according to specified behavior rules or boundaries. This is a powerful and natural way to incorporate such effects as individual fatigue, communication link imperfections, or differences in training and skill levels between individuals, into a realistic model. It is also one of the few techniques available that addresses connectivity among units and allows one to leverage combined arms synergies. The individual warrior agents are modeled separately, but are also considered members of a group, originally called a "swarm", since these models were first used to study behaviors of social insect colonies. In some models, individual agents can be easily aggregated and de-aggregated.

Modeling the behavior of every combatant or small unit would not have been possible in the past because of the computational resources required. The increase in computing power over the past decade, and the promise of more in the future, makes high-fidelity, agent-based simulations of combat operations viable on a large scale. Additionally, it makes it possible to execute such simulations a large number of times to explore the "solution space" for particular combinations of model variables and assumptions. As processing power increases another thousand-fold over the next decade, agent-based simulations of combat will be increasingly important as larger, more complex simulations will become possible.[20] As modeling and simulation developments and technology advances continue to allow us to study larger problems in more detail, the requirement to carefully decide what output data needs to be collected and analyzed becomes more critical. Efficient solution space search techniques become more valuable.

Utility of New Solution-Space Searching Techniques

The idea of searching for a desired solution among a collection of candidate solutions is so common in computer science that it has given rise to the term "search space". In this environment, the term "search space" refers to some (usually very large) collection of candidate solutions to a given problem and some idea of distance between

[20] SAIC, *SWARRIOR Draft User's Manual,* Produced for the Office of the Secretary of Defense (Net Assessment) in support of MCCDC, Quantico, VA: November 1998.

candidate solutions.[21] The goal of the analyst is usually to find some way to intelligently and efficiently search the very large search space for "good" solutions to a problem. This is the driving motive behind a computer science construct called a genetic algorithm. Genetic algorithms (GAs) are one of a number of methods of computation that use the principles of natural selection to "evolve" solutions to complex optimization problems. See Appendix B for further explanation and background on GAs and other different computational methods. GAs are particularly useful on problems that have many local maxima, where more traditional optimization techniques can be weak. The selection of a military tactic for a given domain could be characterized as such a problem -- one that is characterized by many dimensions, with multiple local maxima, and where traditional optimization techniques are not very effective. It is possible that, by using genetic computation techniques in the context of a sophisticated agent-based military model, future research could make progress towards literally "evolving" new tactics. In its search for institutional innovation and adaptation, this is a very promising arena where the Marine Corps should continue to take the lead.

The Marine Corps has stated its commitment to maximizing the effectiveness of its forces by the use of modeling and simulation. This vision is presented in both the Marine Corps Modeling and Simulation Master Plan and the Marine Corps Modeling and Simulation Investment Plan. More recently, General Krulak emphasized the importance of modeling and simulation in his Commandant's Planning Guidance. He states that effective training is the key to maintaining our warfighting edge in an era of scarce

[21] Mitchell, Melanie. *An Introduction to Genetic Algorithms,* MIT Press, Cambridge MA, 1996, 6.

resources and that the use of simulation can make subsequent field training more effective.[22]

Modeling and Simulation (M&S) presents real life situations in a simulated environment with the aid of computers. The computer has been, and will continue to be, used as a training and analysis tool for individuals, staffs, and units to fight battles without the extensive cost of manpower, equipment, and other necessary support resources. M&S is an effective and economical means of providing research and realistic training at all levels of command.

The Marine Corps expects to use M&S to develop and maintain military skills at the tactical, operational, and strategic levels of war through the use of synthetic environments with realistic interactions. It will assist the warfighter and analyst at all levels, in problem solving and decision making across the entire spectrum of defense issues. Models and simulations will provide insights otherwise unavailable to procedural, structural, and technological changes in areas such as precision strike, dispersion tactics, information dominance, force projection, and joint readiness. The Marine Corps has taken a series of significant steps over the past few years to accelerate M&S employment and is a key participant in all the major joint modeling programs[23], but our current ability to gain new insights into combat as a CAS is limited. The following section highlights

[22] Kelly, Major John F., USMC, "Maximizing Training with High Resolution Modeling", MSTP, Quantico, VA, http://www.mstp.quantico.usmc.mil/TSB/documents/maxtrain.htm. (Download from the INTERNET 1 Dec 1998).

[23] Marine Corps, "Modeling and Simulation", *Marine Corps Intelligence Activity Note*, CBRS Support Directorate, (July 1998): 1.

some of the major research and development initiatives in the M&S arena that hope to resolve that limitation.

Current Nonlinear Science Research and Development Initiatives

Appendix C contains a broad review of some of the larger DoD research and modeling initiatives and then focuses on service and non-DoD research. The appendix highlights just a few examples of the many conventional models that could be significantly enhanced with the integration of advanced behavior representation technology and CAS principles. As will be discussed later, these enhancements will allow computer-generated forces (CGF) to adaptively choose a proper course of action based on a continuously changing battle situation. This, in turn, will allow future models to leverage the benefits inherent to a complex adaptive systems approach to analysis. Appendix D provides two examples of how corporate companies have been successful in leveraging the benefits inherent to a complex adaptive systems approach to analysis. The DoD modeling and simulation community is working to obtain these benefits.

> Currently, DoD Modeling and Simulation (M&S) systems for representing human-like behavioral characteristics are not capable of meeting the needs of DoD. For example, during the Synthetic Theater of War (STOW) Advanced Concept Technology Demonstration (ACTD) opposing force (OPFOR) operations could have been conducted with far fewer personnel if fully automated, learning-capable company commanders were available. With extensive man-in-the-loop participation, the STOW OPFOR CGF technology and architecture simply facilitated human step by step instructions at the platoon level.[24]

[24] Kwak David S., *"A Multiple Paradigm Behavior Architecture: COREBA (Cognition Oriented Emergent Behavior Architecture* ". SIW98F Conference: 1998, Introduction.

This is a typical description of the state of current DoD entity based simulation, and demonstrates the need for a new way to implement human behaviors in simulation systems.

CGF behavior development is expensive and difficult. Current CGF technologies do not provide the required level of realism and sophistication necessary to meet future analysis needs. For all of the CGF models briefly described in Appendix C, the current state of their CGF behaviors could be characterized as:

- Too low-level (thus, they require too many human operators)
- Too machine-like (easily predictable), and
- Too difficult to use (neither flexible nor intuitive)

CGF behavior implementation will be the major stumbling block for further progress in the area of battlefield simulation. Many feel that there is a real danger that research and development in other areas (synthetic environments, distributed simulation, etc) will be wasted due to the unbalanced progress of behavior implementation technologies as a whole.[25]

Simulation technology is growing rapidly, and the Marine Corps must keep pace by leveraging its benefits and optimizing its inherent training value. These types of tools are not meant to be replacements for field training, but can significantly enhance staff and commander decisionmaking, Tactical Decision Games (TDGs), and other existing training methods significantly. The following quote from a senior OPFOR commander at the U.S. Army's National Training Center (NTC) supports the concept that simulations

[25] Kwak, Introduction.

can enhance, but not replace field training. Other pertinent and interesting comments from the NTC staff can be found in Appendix E.

> Units/command and staff teams trained predominantly in virtual and constructive simulations are much less effective than those who trained not only with simulations, but extensively in the field under tough, realistic conditions, particularly through battalion task force level. From our point of view, there appears to be no effective substitute for training the combined arms team as one team under realistic, field conditions.[26]

The Marine Corps' MAGTF Staff Training Program's (MSTP's) experience with high-resolution modeling illustrates the immense potential of this technology in enhancing the combat effectiveness of our Corps. Using any of the many interactive, man-in-the-loop simulation models has consistently demonstrated that there are real benefits available from modeling technology advances. These advances lie not in improved predictive ability, but in providing more realistic and more available decision-making training.

USMC Initiatives

Turning from a brief look at the DoD world of research and development, this introduction will now focus on the Marine Corps Combat Development Command's (MCCDC's) current efforts to explore the implications and applications of the nonlinear sciences. Focusing on synthesis vice reductionism, MCCDC's 'Project Albert'[27] is essentially an umbrella for three distinct research arenas that are being pursued to help achieve MCCDC's general analytic goals, which are:

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[26] NTC Observations, e-mail from Col Brown, Doctrine Div, Dec 23.
[27] Project Albert originated with Dr Brandstein, MCCDC Chief Scientist.

- Developing a conceptual model of maneuver warfare at a level of clarity and specificity to allow for detailed analysis.
- Developing a more quantitative basis for concepts, doctrine, organization, training, equipment, and support.
- Demonstrating the true value of a force in readiness.[28]

The general theme of Project Albert is to capture the intangibles of warfare in order to better study and understand it. Project Albert is pursuing MCCDC's goals through the following three mutually supporting research areas: (1) an initiative to research the possibilities of a concept called **generative analysis** (2) an initiative to examine the benefits of **agent-based simulation,** and (3) an initiative to explore the wealth of information to be found through various **data farming** and supporting visualization techniques. Appendix F further defines each of these research areas.

From Metaphors to Models[29]

You don't see something until you have the right metaphor to let you perceive it.[30]
-- Thomas Kuhn

As Alan Beyerchen so clearly demonstrated in his Marine Corps University essay *"Why Metaphors Matter"*, the proper and timely use of a good metaphor is an extremely powerful tool. Aristotle wrote, "The greatest thing, by far, is to be a master of metaphor.[31] It is the one thing that cannot be learned; and it is also a sign of genius." Metaphors surround us in everyday conversation. They are illustrative of networks of meanings that expand or limit both our perceptions and conceptions. Clausewitz

[28] Maneuver Warfare Science, 1998, Foreword, LtGen Rhodes.
[29] Maneuver Warfare Science, 1998,21. This was part of the title of LtGen Van Riper's article.
[30] llachinski, Land Warfare and Complexity, Part II, 43.
[32] Ilachinski, 43. Etymologically, metaphor (the Greek metafora, "carry over") means "transfer" or "convey," the transference of a figurative expression from one area to another. According to the 3d edition of the American Heritage Dictionary, a metaphor is "a figure of speech in which a word or phrase that ordinarily designates one thing is used to designate another, thus making an implicit comparison.

understood that, when a particular aspect of war could not be adequately defined directly, metaphors were often a superior form of description. Newtonian, linear, mechanistic metaphors have dominated military science thinking for decades. By using linear metaphors when describing combat, the military encourages a linear mind-set and inadvertently constrains itself. If, on the other hand, the military is able to realize that there are better, more accurate sources of metaphors (such as complexity theory) there is greater potential for new insight and understanding.[32]

When asked in a recent interview[33] how the Marine Corps should best proceed in the area of understanding and applying the concepts and principles of complexity theory, LtGen Van Riper said that only when we are successful in changing the metaphors of the masses will institutional understanding and acceptance follow. He knows that there is no way to force widespread understanding or acceptance of these principles into this or any other institution. He advocated the deliberated education and exposure of these new concepts with the understanding that eventually a "critical mass" of understanding and acceptance would arise. Then and only then will the Marine Corps be able move from using not only metaphors but models as well. Then we will be able to fully explore all the possible advantages to training, equipping, and operating within this new paradigm. Referring to the eight tiers of applicability listed in Table 2 on the next page, this paper provides insight into how the Marine Corps might continue to move from Tier 1 to Tier 7 and Tier 8— a move from metaphors to models.

[32] Lt Sparling, Robert F. James, "Complexity of War", *Surface Warfare*, Jan/Feb 98,7.

Tier of Applicability	Description	Examples
I. General Metaphors for Complexity in War	Build and continue to expand base of images to enhance conceptual links between complexity and warfare	nonlinear vice linear synthesis vice analytical edge-of-chaos vice equilibrium process vice structure holistic vice reductionism
II. Policy and General Guidelines for Strategy	Guide formulation of policy and apply basic principles and metaphors of CST to enhance and/or alter organizational structure	Use general metaphors & lessons learned from complex systems theory to guide and shape policy making; use genetic algorithms to evolve new forms
III. "Conventional" Warfare Models and Approaches	Apply tools and methodologies of CST to better understand and/or extend existing models	chaos in Lanchester equations chaos in arms-race models analogy with ecological models
IV. Description of the Complexity of Combat	Describe real-world combat from a CST perspective	power-law scaling Lyapunov exponents entropic parameters
V. Combat Technology Enhancement	Apply tools and methodologies of CST to certain limited aspects of combat, such as intelligent manufacturing, cryptography and data dissemination	intelligent manufacturing data compression cryptography IFF computer viruses fire ants
VI. Combat Aids	Use CST to enhance real-world combat operations	autonomous robotic devices tactical picture agents tactics / strategy evolution via genetic algorithms
VII. Synthetic Combat Environments	Full system models for training and / or to use as "research laboratories"	agent-based models
VIII. Original Conceptualizations of Combat	Use CST-inspired basic research to develop fundamentally new conceptualization of combat	pattern recognition controlling / exploiting chaos

Table 2. Eight Tiers of Applicability of Complex Systems Theory to Warfare[34]

33 Interview with LtGen P.K. VanRiper, 18 Feb, MCRC.

34 Ilachinski.

Before examining how we might continue to move "from metaphors to models", a short look at previous USMC research in this area might be beneficial. An overview of two pertinent Marine Corps research efforts is provided in Appendix G. In his 1995 Marine Corps War College paper tided, "The Complexity of War: The Application of Nonlinear Science to Military Science", Colonel Glenn M. Harned was one of the first Marines to synthesize the historical military classics under a complex systems theory framework. The second effort reviewed in Appendix G is Major Thomas C. Moore's 1997 Command and Staff College thesis titled "Foglamps of War? Can a Complex Systems Tool Light the Way to Understanding the Nature of Warfare?"

Building on this previous research, this paper will now review a recent military field experiment to set the stage for further discussion. Before this paper can broaden the lens that was used in the Hunter Warrior Experiment, it must first provide a clear picture of the baseline.

Chapter 3

Hunter Warrior AWE: Follow Up Experimentation Needed

The Marine Corps, as it has always done when faced with uncertainty and challenge, is turning to our unequaled ability to innovate and adapt. Just as we did at Culebra prior to World War II, we are today, turning to experimentation. Our engine for experimentation is called Sea Dragon. Sea Dragon is a process; not a solution. It will use three Advanced Warfighting Experiments, each of which will test a range of concepts and equipment in very different operating environments.[35] -- General C.C. Krulak

In its current stage of development and application, complex systems theory consists almost entirely of some form of modeling, simulation, or the design of simulation engines.

> Quite literally, much of leading-edge complex systems theory is practiced by (1) choosing a real-world system to understand, (2) building a model of it, and (3) watching and interacting with the model as it runs on a computer (while looking for patterns that might provide some deeper insight into what the real-world system itself really does).[36]

In order to be useful, a model needs to not only simplify the real system in an appropriate way and provide a shortcut solution to a given problem, it also must be ***developed in a well-defined context.***[37] The well-defined context that this paper will use to illustrate the practical utility of complex systems theory is the Hunter Warrior

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[35] United States Marine Corps, *Exploiting Hunter Warrior,* Marine Corps Combat Development Command, Quantico, VA: 1998,2.

[36] Ilachinski, Andy, "Land Warfare and Complexity, Part II: An Assessment of the Applicability of Nonlinear Dynamics and Complex Systems Theory to the Study of Land Warfare", Center for Naval Analyses Research Memorandum 96-68. http://www.cna.org/isaac/downref.htm, 29.

Advanced Warfighting Experiment (AWE). Within this framework, this paper hopes to advance our institutional transition from metaphors to models. Before discussing the objectives, conduct, and results of the Hunter Warrior experiment, some background information is appropriate.

Background: Sea Dragon

> The Marine Corps Warfighting Laboratory (MCWL) is a military applications laboratory. It applies the scientific method to military operations. This is not to imply that the Lab is making the art of war into science. Instead, it simply means that experiments are approached scientifically. However, military operations contain two aspects that scientific experiments do not. First, human beings, who are unpredictable, are the core of conflict between opposing forces. Second, success in conflict requires actions that, from a scientific standpoint, are illogical. Innovation, creativity, uncertainty, and unpredictability are unwanted factors in controlled science experiments. They are essential, however, in military operations. In other words, military experimentation contains elements of both science and art. An effective military applications laboratory must take both into account.[38]

Hunter Warrior was a large-scale field experiment conducted by the Marine Corps to gain insight into future warfighting operational concepts, organizations, and doctrine. It was the Marine Corps Warfighting Lab's first attempt to enhance the Marine Air Ground Task Force's capability to *adapt* to future battlefield challenges. Most of the specific topics of exploration in the Hunter Warrior research design emerged from the Marine Corps Warfighting Lab as they sought to explore new operational concepts.

The concepts and forces explored through Hunter Warrior were the result of an analysis of the emerging Revolution in Military Affairs by each of the services, Joint

[37] Ilachinski, 29.

Staff organizations, and numerous DoD agencies. In a broad sense, Hunter Warrior was one aspect of a rapidly expanding recognition and analysis of fundamental warfare transformations that are currently in progress. These transformations have recently been examined through a combined effort of the services and the Office of the Secretary of Defense for Net Assessment (OSD/NA). "Its near-term policy and doctrinal implications are reflected in Joint Vision 2010, the Navy's implementation of this vision for littoral operations, as expressed in Forward From the Sea (FFTS), and Operational Maneuver From the Sea (OMFTS)."[39]

AWE Conduct and Objectives

Hunter Warrior was composed of a large number of simultaneously conducted smaller experiments, called Limited Objective Experiments, that were loosely linked together. Complementary experimental tracks were developed as part of the experimental design. One track focused on more efficient command and control. A second track focused on the Marine squad leader in order to *encourage adaptation* where combat is occurring. The experiments addressed both centralized and decentralized operations on the battlefield.[40] Hunter Warrior experimentation ended with an AWE that examined 37 experimental objectives where dispersed operations were the centerpiece. Conducted in southern California from 1-12 March 1997, the AWE was an instrumented, free-play, force-on-force experiment.

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[38]Exploiting Hunter Warrior, 2.
[39]Exploiting Hunter Warrior, 3.
[40]Exploiting Hunter Warrior, 8.

The Special Purpose MAGTF(X) that was the main experimental force for Hunter Warrior operated from a simulated over-the-horizon seabase. The command element was located at Camp Pendleton, simulating a force at sea. Its ground combat element (GCE), a reinforced infantry battalion, operating in dispersed squads, was "inserted" onto the battlefield at Twenty-Nine Palms, California, more than 150 miles away. The opposition force was a 4,500 man, reinforced, mechanized regiment, made up of elements of the 7th Marines.[41]

At the squad leader level, the Lab focused on the training, tactics, and technology necessary for dispersed small unit operations. This decentralized focus is important because the Marine squad leader is the key individual involved in actual combat. He coordinates tactics, techniques, and technology and *must possess the ability to adapt to the local situation.*[42]

Within the framework of the dispersed operations objective, the friendly (blue) squad patrols were trained and equipped to conduct reconnaissance, surveillance, and target acquisition. Their objective was to shape the battlefield through detection, targeting, and precise long-range fires. The squads, backed by a range of other sensors, employed massed fires from dispersed assets to engage enemy (red) forces. The squad patrols were not to seek direct enemy engagement.[43]

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[41] Exploiting Hunter Warrior, 8.
[42] Exploiting Hunter Warrior 8.
[43] Exploiting Hunter Warrior, 9. An interesting factor in the Hunter Warrior experiment was the fact that the OPFOR commander, who was a Marine, knew the blue forces would be more likely to sleep during the night. He knew that they had limited range night vision capability. This and other knowledge about his opposition determined his tactical decision. This highlights the importance of being able to adequately

An Experimental Combat Operations Center (ECOC) continuously maintained a common operating picture of operations ashore and tracked the engagements between the two forces. These engagements tested the potential capabilities of the Special Purpose MAGTF(X) and provided a rich data base to use in further analysis.

Summary and Conclusions

The MCWL produced a 50 page document titled "Exploiting Hunter Warrior" in August 1997 that sets the stage and then describes the full conduct and analysis of the Hunter Warrior experimentation. For each of the experimental concepts[44] that were pursued through various objectives, that document presents a well-organized summary. Each of the experimental concepts is described by the following: (1) a brief description of the experiment and its result, (2) a list of the critical enabling actions in terms of tactics, techniques, technologies, and procedures needed to develop the required capability, (3) a description of key observations relating to experimental results, and (4) a description of selected actions planned to exploit the results. For example, within the Dispersed Operations concept, a critical enabling activity was "improve small unit training in the use of digital communications devices." A key observation was "small units operating with stealth tactics can survive on a dispersed noncontiguous battlefield".

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model the intelligence level of opposing forces and how that can and will affect OPFOR actions in combat models.

[44] SAIC, "Hunter Warrior Workshop and Assessment", Prepared for Wargaming Division, Marine Corps Combat Development Command, Quantico, VA: April 1998, Section 2, 9-25. The experimental concepts for Hunter Warrior were: (1) Dispersed Operations, (2) Small Unit Training, (3) Cellular Command Element, (4) Engagement Coordination, (5) Tactical Aviation, (6) Shared Information Environment, (7) Battlefield Visualization, (8) Sensor Integration and Management, (9) Enhanced Targeting, and (10) Seabased Logistics.

Finally, an example of a **specific recommended action** for further exploiting results from this portion of the experiment was *"use* ***simulation to further examine alternative concepts and tactics for dispersed operations."***[45]

The overall results of the Hunter Warrior AWE indicated that "a light force, such as a Marine Expeditionary Unit, arriving early on scene in a conflict can seize the initiative from a larger, more capable enemy force when supported by long-range precision weapons. Furthermore, such a force appears to be capable of dominating the battle-space through integration of fires from organic and supporting weapons, and significantly reducing a foe's combat power, thereby increasing the likelihood that heavier follow-on forces will be able to decisively defeat the threat."[46]

Hunter Warrior Follow-on Experimentation Questions

In March and April of 1998, OSD/NA sponsored a series of Hunter Warrior Workshops as part of the overall DoD process of defining the emerging RMA through field experimentation and analysis. This particular group of workshops was designed to examine the organizational and operational concepts that had been investigated by the Marine Corps. Of the three primary innovations that were tested during the Hunter Warrior AWE (dispersed operations, application of digital technology, and the flattening of traditional command architectures), this paper focuses on the workshop questions that arose from a review of the dispersed operations concept. The workshop questions were

[45] Exploiting Hunter Warrior, 9.
[46] Exploiting Hunter Warrior, 9.

numerous and varied and were intended to help form the basis for the development of *possible future experiments.*

Two specific questions from the "dispersed operations" workshop can now be uniquely addressed with a nonlinear science approach to simulation experimentation. They are:

1. What are the advantages and/or disadvantages of having small units equipped to employ heavy direct fire weapons (HMG, TOW, etc) within the Hunter Warrior type of dispersed operations?
2. What are the advantages and/or disadvantages of providing mobility assets for the teams? What type of mobility asset is optimal?

The following quote summarizes a workshop discussion that revolved around these two follow-on questions,

> It is apparent the Long Range Contact Patrols could have used some type of dedicated organic mobility. The size and weight of the individual combat loads seriously hindered the mobility of the patrols. Lack of mobility was also cited as a factor in not giving the teams a direct fire capability. Mobility shortfalls made ingress and egress, and massing and de-massing problematic. An added benefit of providing the teams with mobility assets is that they often come with advanced targeting and communications capabilities. Possible solutions to the mobility problem include a series of agile UGVs, HMMWVS, LAVs, dune buggies, or unit air mobility assets. Like a direct fire capability, though, increased mobility might also decrease team survivability by making the teams more difficult to hide and therefore less stealthy.[47]

Hunter Warrior: The **Next Step?**

In addition to the Hunter Warrior Assessment, which actually called for further experimentation, several recent articles in the Marine Corps Gazette have highlighted the need to further pursue the issues that arose during Hunter Warrior.

> Hunter Warrior examined infestation (dispersed operations) doctrine through a very narrowly defined lens. Subsequently, the Corps must pursue

[47] Hunter Warrior Workshop Assessment, 9.

> further experimentation and study before any final conclusions are drawn... .If the Marine Corps fails to further test the concept, we will have thrown the proverbial baby out with the bath water. Infestation (dispersed ops) may or may not constitute the future of the Corps, but it deserves the same sort of thorough testing that our predecessors gave to amphibious doctrine six decades ago. Hunter Warrior must not be the end of the experiments and arguments, but only the beginning.[48]

Given LtCol Hoffman's challenge in the previous quote and the fact that the Warfighting Lab already has a full plate for the next couple of years (Urban Warrior, Capable Warrior), what options does the Marine Corps have to follow up on the many issues that came out of Hunter Warrior? Though several serious problems currently exist in military M&S[49], the answer lies in the rapidly developing world of modeling and simulation. As recommended in the post-exercise assessment the Marine Corps needs to ***"use simulation to further examine alternative concepts and tactics for dispersed operations".*** Relatively recent advances in behavior generation algorithms and increased computing speed and memory continue to make silicon experimental combat labs a robust and realistic option. As summarized earlier and illustrated in Appendix C, both DoD and the corporate sector are now rushing to apply the principles of complexity theory to the way they study and operate within their respective systems.

What the Marine Corps needs is a more fully developed system of experimentation that closely integrates agent-based modeling results with field exercises such as Hunter Warrior. Using models that are created from a bottom-up (CAS)

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[48] Hoffman, J.T., Marine Corps Gazette, Dec 1998, 59.

[49] Potential Failures and Disasters for DoD's M&S. http://www.nas.edu/cpsma/nsb/ms3.htm. Two causes of concern are (1) an inadequate research base, and (2) the inherent complexity of emerging military systems and operations. One basic problem is that DoD's high-visibility work on M&S is dominated by content-neutral computer and software technologies with little investment in the knowledge base needed to determine the *substantive* content of such M&S initiatives.

perspective rather than a top-down perspective will allow Red and Blue forces (modeled as adaptive agents) to sense, assess, learn, and adapt to each other and their environments. This will allow analysts to examine a much broader region of possible responses than standard top-down simulation models of the past. A silicon laboratory built around CAS principled, agent-based simulation models could be used to experiment with force structure, doctrinal deviations, resource allocation schemes, and much more. Under an appropriate experimental design umbrella, intelligent, inexpensive, and insightful analyses could be rapidly conducted. Such analyses could precede, augment, replicate, reinforce, expand, or follow-up field experiments. In the Hunter Warrior case, the next step is to examine all the questions that came from the field experiment with a sophisticated agent-based model. After thorough experimentation is conducted with these models, and once the key dynamics involved in each different course of action are better understood, the MCWL could then take a force and doctrine of choice back into the field for validation and further experimentation. A good example of what that follow-on field experimentation might look like was captured in another recent Marine Corps Gazette article that described one of the few Army-Marine Corps exercises at the Army's Joint Readiness Training Center (JRTC).

During a recent combined training exercise at the Army's JRTC, the OPFOR's insurgent operations partially replicated the type of infestation tactics evaluated by SPMAGTF(X) during Hunter Warrior. Although the small OPFOR teams only had limited indirect fire support (from individually employed 81mm mortars), they were able to inflict major (sometimes catastrophic) damage on Blue Forces that significantly outnumbered and outgunned them.

> At JRTC, smart, motivated, well-led, well-trained Americans operating in small teams routinely defeat or at least hold their own against smart, motivated, well-led, well-trained Americans employing large unit tactics. One can easily guess what the outcome would be if the small teams also had the advantage in air support and firepower that a real American force would bring to the battlefield. The JIRTC can provide a perfect forum for future tests that would pit an infestation-style force against an Army Brigade or Marine MEF(Forward).[50]

Exercises of this type would provide an extremely valuable addition to the original Hunter Warrior experiment <u>after</u> thorough experimentation with an adaptive force simulation model.

A recent modeling effort by a local contractor has brought us a step closer to reaching the particular goal of a high-resolution, semi-autonomous force model that will allow us to conduct the type of experimentation previously described. The SWarrior model that will be discussed next provides <u>just one example</u> of how we can leverage the principles of complexity theory to provide a more thorough examination of the dynamics and results when two independent wills collide in combat. Other current agent-based models like CNA's well-developed EINSTein[51] model promise to give the military analyst a whole new range of useful tools with which to study combat issues.

[50] Hoffman, LtCol Jon T., USMCR. "Hunter Warrior", *Marine Corps Gazette*, (February 1999): 34-36.
[51] Ilachinski, Andy, http://www.cna.org/isaac/einsteinpage.htm. EINSTein stands for "Enhanced ISAAC Neural Simulation Tool". It is currently under development by Dr Ilachinski at the Center for Naval Analyses. It is a very promising artificial-life "laboratory" for exploring self-organized emergent behavior in land combat.

Chapter 4

The SWarrior Project

Science Applications International Corporation (SAIC) has developed a Swarm-based[52] Marine Infantry Combat Model called SWarrior. SWarrior is a new breed of analytical tool that uses agent-based simulation to provide insight into the dynamics of combat operations.

The SWarrior model was commissioned and funded by the Office of the Secretary of Defense (Net Assessment) and the Marine Corps Combat Development Command to explore the utility of agent-based modeling techniques to address specific warfighting issues. SWarrior is an agent-based model that simulates the dynamics of light, dispersed, highly mobile forces. SWarrior development was based on the operations and forces employed by the Marine Corps during its 1997 Hunter Warrior field experiment. In support of MCCDC, SWarrior employs baseline red and blue forces that resemble the forces used in Hunter Warrior in their number, capabilities, and behavior. In addition, the

[52] The Swarm simulation system is a software package for multi-agent simulation of complex systems developed by Christopher Langton at the Santa Fe Institute. He intended Swarm to be a useful tool for researchers in a variety of disciplines. It was built around the mechanism by which ants, bees, birds and other organisms exhibit collective behavior, such as in group foraging for food or flying in pattern. Swarm is a general-purpose simulation package for the investigation of such concurrent, distributed systems. It provides a wide spectrum of generic artificial worlds populated with generic agents, a large library of design and analysis tools, and a kernel to drive the simulation. This simulation package is being used to

simulated terrain used in SWarrior is constructed from a database of the 29-Palms exercise area in which Hunter Warrior was conducted. The model can thus be partially validated by the correspondence between the exercise and the emergent behaviors of the simulated model agents.

More importantly, the model allows analysts to perform multi-run sensitivity analyses on many of the conditions and assumptions within which Hunter Warrior was conducted. In this manner, SWarrior can deepen our understanding of the insights provided by Hunter Warrior. It can suggest the range of conditions for which specific findings are valid, and it can provide new insights about results that did not emerge because the combination of factors producing them were beyond those available to Hunter Warrior. The careful use of SWarrior and interpretation of its results can thus help an analyst identify outcomes which hold across a variety of conditions and distinguish them from results which appear to hold only across a narrow context.

SWarrior was designed around a subset of the Hunter Warrior field experiments that can be described as follows:

- Blue dispersed squad-sized teams (Long Range Contact Patrols: LRCP) of foot-mobile Marines dispersed throughout the desert terrain and used pre-positioned supplies. The primary function of the teams was to act as scouts and call in remote fires from the offshore Enhanced Combat Operations Center (ECOC).
- The 29-Palms exercise area itself was intended to simulate a sparsely populated semi-arid and hilly coastal region. The exercise area was wide open and provided ample terrain for LRCP concealment.
- Blue units were supported by low-flying dragon drone UAVs with video cameras. Blue used approximately 10 of these UAVs to provide continuous coverage of the

model systems within ecology, anthropology, chemistry, economics, military and political science among others. Santa Fe Institute, http://www.santafe.edu/sfl/research.
[53]SAIC, SWARRIOR Draft User's Manual.

exercise area, with two in the air at any given time. These UAVs transmitted video feed to and were controlled from the ECOC, but could accept surveillance flight requests.

- Small Red teams mounted in tanks and/or HMMWVs entered the exercise terrain in a dispersed fashion with the objectives of (1) sweeping the area for and destroying opposition forces, (2) occupying the terrain by operating throughout it, and (3) securing the port and airfield objectives at the far end of the battlespace.
- Because of concern over Blue long-range precision fires, Red attempted to remain dispersed and to move in a semi-random fashion, rather than proceeding directly to its objectives. Red thus adopted a strategy of moving from laager position to laager position by relying on mission orders rather than electronic communication between units.[54]

SWarrior employs agent-based modeling techniques to simulate unit behavior using the Hunter Warrior baseline described above. The agent-based approach is used because it provides significant advantages in its representation of military operations. Additionally, it provides the foundation from which to analyze and understand those operations from a new, nonlinear perspective. The relatively new techniques of agent-based modeling represent only a few of the many advances that are being made in response to a clear requirement for further sophistication in military science. This requirement is spelled out in the following section.

Defense Science Board Recommended Changes to DoD analytic culture

In the summer of 1996, the Defense Science Board (DSB) recommended several fundamental changes to the analytic culture of the Department of Defense (see Table 3). These recommendations provided additional catalysis to the process that had been evolving in the Marine Corps' analytic community. Stimuli for the Marine Corps' process came from the realization that traditional simulations were incapable of representing many of the attributes of the world required to help explore contemporary military issues. Additionally, it was observed that advances in computer science could, if applied properly, provide data and insight for more appropriate abstractions which would be useful in addressing many military questions.[55]

[54] SWARRIOR Draft User's Manual.

[55] Maneuver Warfare Science 1998, 95.

What Currently Is	What Should Be
Closed	**Open**
--Bureaucratic review	--Peer review
--Accredited Analysis	-- Competitive Analysis
Model Orientation	**Subject Matter Oriented**
--Mechanical	-- Meaningful
--Data poor	-- Data rich
--Rigid approvals	-- Learning & Adaptation
--Stable algorithms	-- Unstable phenomenon
Suppresses Uncertainty	**Illuminates Uncertainty**
--Suppresses Risk	--Illuminates Risk
Cold War Oriented	**Oriented to the future**
--Few accredited scenarios	-- Broad range of scenarios
-- Point Threat Estimates	-- Robustness to threat variations

Table 3. Defense Science Board recommended changes to military analytic culture.[56]

The SWarrior Solution for Hunter Warrior

SWarrior is a recent example of a DoD modeling effort that is attempting to incorporate some of the recommended changes mentioned above. SWarrior uses the following technical solution in order to leverage the utility of Agent-based modeling techniques to represent and explore the operational concepts employed in Hunter Warrior:

- The model builds upon the foundation of the Swarm software package for Agent-based modeling. Swarm provides a wide variety of pre-existing utilities which SWarrior is able to leverage. These include base classes, which allow agents to be represented as objects in the source code, including the ability to probe and change the characteristic variables of those agents.
- Based on its Swarm foundation, SWarrior is built to run in the Unix operating environment. The core model is coded in Objective C.
- SWarrior front-end interfaces are Java applications and applets, thus providing the potential for the model to be indirectly accessed and run over the Web.
- SWarrior is modular software. It consists of the core simulation engine plus several interface modules. The Builder-Monitor System (BMS) provides the

[56] Ibid.

capability to set up a scenario, to include creating individual agents and defining their attributes and connectivity. It also allows you to view model run5.[57]

Figure 1 shows a Builder-Monitor screen with one of the Hunter Warrior scenarios loaded.

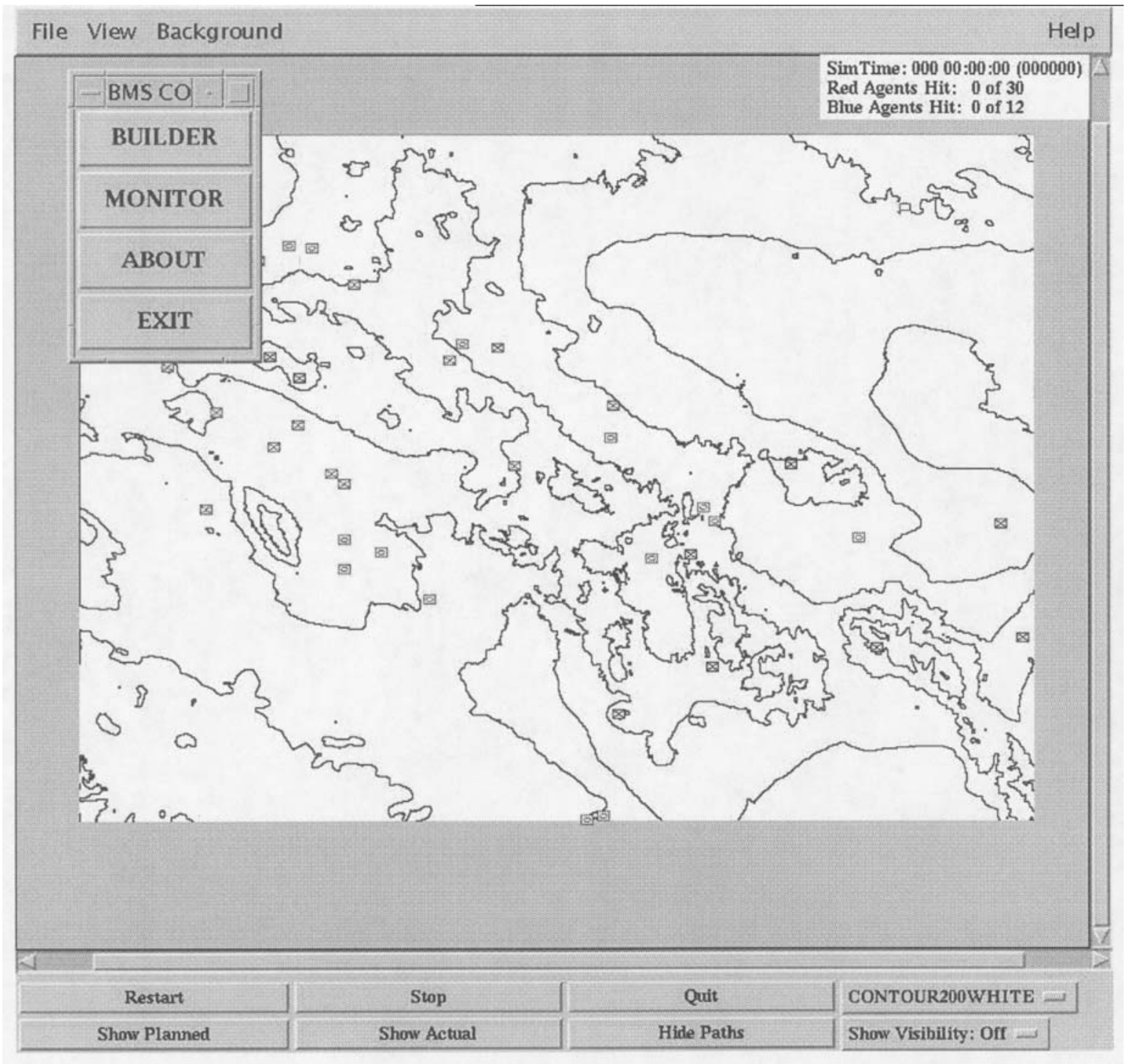

Figure 1. SWarrior Builder Monitor Screen With Hunter Warrior Terrain

The intuitive graphical user interface of modern simulation models like SWarrior make it very easy to use. For example, the contour button on the lower right hand of

[37]SWARRIOR Draft User's Manual.

Figure 1 allows the user to easily change the terrain contour display of the 29 Palms exercise area.

Underlying Architecture and Design

The SWarrior simulation system is comprised of integrated components which work together to perform multiple-run simulation and analysis. The Builder-Monitor System tool is used to develop a desired scenario that begins with the basic environmental conditions and terrain data to be used. Once the baseline scenario has been set up, the scenario is populated with the desired red, blue, and neutral agents of various types. Agents are not only placed in desired starting positions, but they are provided maneuver goals and a communications structure. After desired agents are created, each agent's default value parameters may be changed to create the desired heterogeneous force or unit. For each agent, one may uniquely change values for position, visibility, training, weapon system, and other variables.

The basic dynamics simulated in SWarrior are inspired by the small unit tactics explored in Hunter Warrior. Blue agents are dispersed throughout the theater trying to find red agents and call in fires against them via the ECOC. Blue agents are squad-sized foot mobile forces, which augment their search capabilities with a network of ground-based sensors and UAVs. Red agents, in turn, are small units of tanks and/or HMMWVs who move in a semi-random fashion from laager position to laager position with the simultaneous goal of sweeping the area for hostile forces and eventually occupying the designated port and airfield objectives. The combination of the attributes of each type of agent and its respective objective generates the behavior boundaries that ultimately determine its behavior in the simulation.[58]

SWarrior Agent Types

The basic agent types used in SWarrior are: Friendly (Blue) Squad also referred to as a long range reconnaissance patrol, Enhanced Combat Operations Center (ECOC), Mechanical Ground Sensor, Unmanned Aerial Vehicle (UAV), Enemy (Red) Tank, Enemy HMMWV, and Neutral Vehicle. The primary dynamics of the model currently revolve around movement, visibility, and detection, but each agent type is distinct in its functions and capabilities. The behavior of each of these agent types is discussed in turn in Appendix H.

[58] SWARRIOR Draft User's Manual.

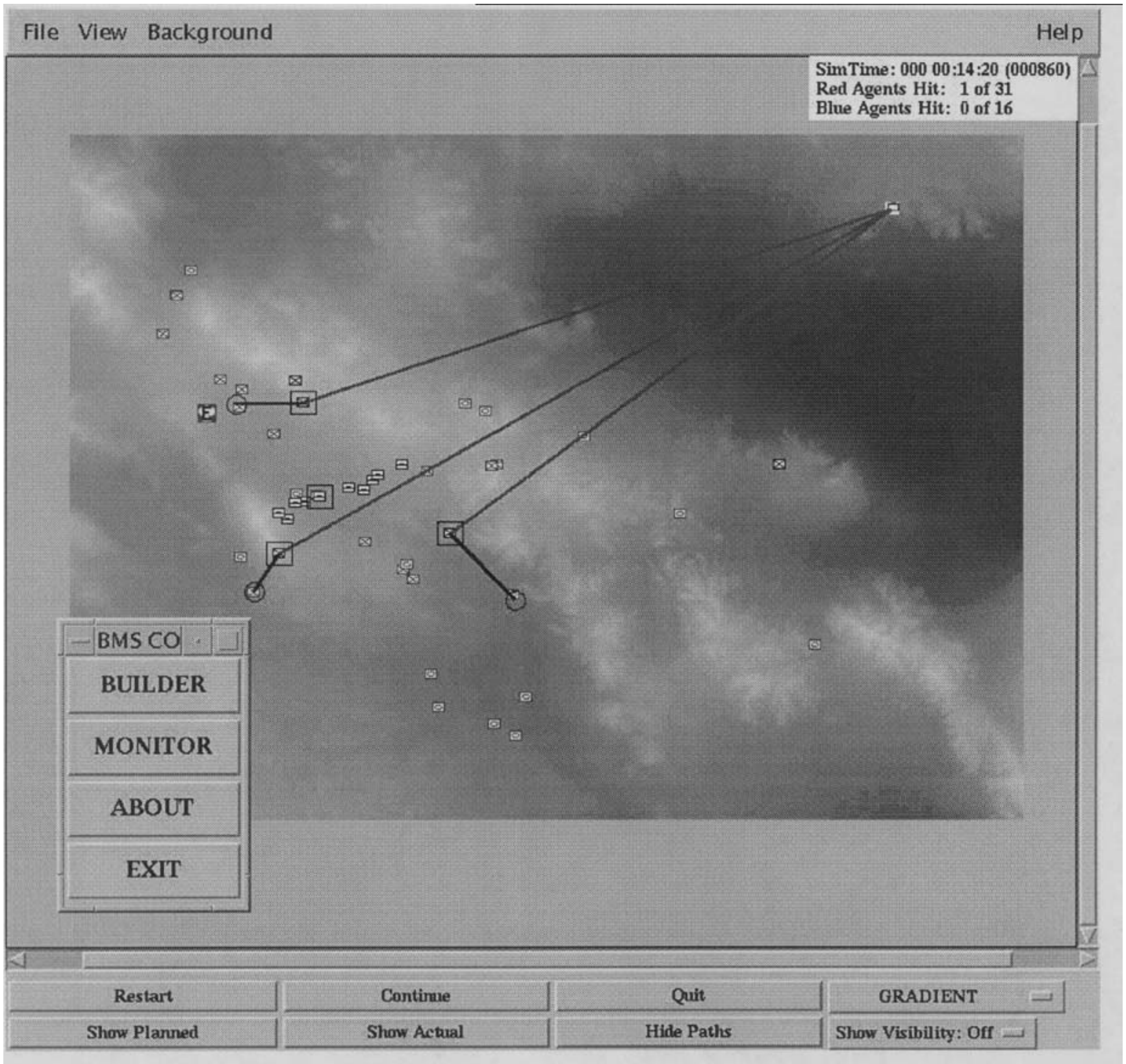

Figure 2. Hunter Warrior Patrols Sensing Red Units and Communicating to ECOC

Figure 2 was captured from a Hunter Warrior simulation playback that experimented with a mechanical ground sensor string to augment the Blue squad's sensing capabilities. Without the color screen, it is difficult to distinguish between Red and Blue units, but this screen shows three Blue squads (with boxes around them) communicating back to the ECOC (upper right) after sensing Red units (with circles) moving within their sensing zone. Appendix H discusses engagements, communications, and other simulation activities.

The SWarrior Solution for Hunter Warrior: Enhancements Required

Although the current version of the SWarrior model is very capable of providing insight into certain aspects of the Hunter Warrior experiment, it lacks the sophisticated algorithms that will allow a given squad (agent) to "learn" and "adapt" to the environment it senses. Without this capability, we cannot fully explore the full breadth of the possible response space or "fitness landscape" (See Appendix G) for any given experimental design. At this point of development, SWarrior agents are only able to react in limited fashion to the input they receive throughout a given simulation.

Imagine a Hunter Warrior squad (or collection of Marine agents) which has to accomplish numerous missions (global goals) in the complex, dynamic environment of 29 Palms. An example might be a particular squad that has been tasked to reconnoiter several valleys and engage any enemy units that are detected. What actually is "the most appropriate" or the "the most relevant" next action that the squad should take at a particular moment? It is difficult to programmatically define the best course of action in a particular situation. Nevertheless, some of the characteristics that an improved action-selection mechanism should demonstrate are:

- it favors actions that are goal-oriented, in particular, actions that contribute to several goals at once,
- it favors actions that are relevant to the current situation, in particular it exploits opportunities and is adaptive to unpredictable and changing situations,
- it favors actions that contribute to the ongoing goal or plan (unless another action rates a lot higher) unless there is a good reason to start working on something different

- it looks ahead (or plans) in particular to avoid dangerous situations and handles interacting and conflicting goals,
- it is robust (exhibits a graceful degradation when any of its components fail), and it is reactive and fast.[59]

In addition to these improved action-selection mechanisms, each agent should have a different view of the dynamic risk space that would affect their respective decisions and actions. This capability is not yet implemented in SWarrior, though the "tools" or programming advances that are needed to enhance a standard model like SWarrior currently exist. Many are being successfully integrated into DoD and corporate models to allow a CAS analysis approach to their respective systems. In the next chapter, this paper will now examine a few of these tools that can help to take us the next step in realizing the practical utility of the nonlinear sciences (integrating adaptation into combat models).

[59]Maes, Pattie, *"Designing Autonomous Agents: Theory and Practice from Biology to Engineering and Back's* Cambridge, Mass: MIT Press, 1990, 52.

Chapter 5

Current Research: New Tools Ready for Application

Much work continues to be done to further implement algorithms in the modeling and simulation world that allow analysts to better examine combat issues through a "complex adaptive system" lens. An agent-based model, like SWarrior, could greatly benefit from any of these enhancements. Much of the most promising work appears to be in the areas of learning, knowledge structure and memory, behavior generation, decision making, and human factor issues (fear, trust, cohesion, etc).

Building Complexity into Existing Models

In a recent Marine Corps Gazette article about the Gulf War, General Myatt said, "The moves and countermoves of a conflict all originate in the intellect, and are not generally subject to prediction or modeling."[60] Since the most interesting and critical aspects of combat do indeed take place in the minds of the combatants, the challenge for military modelers is to capture those that are the most important. A model that is too simple might not capture enough of the dominant variables to be useful, but a model that

[60] Myatt, MajGen J. M., USMC, "Comments on Maneuver", *Marine Corps Gazette,* (October 1998): 40-42.

is too complex might take too long and cost too much to create. Additionally, such a complex model would probably be too difficult to understand or interpret. Human interactions and relationships, especially in combat, can be tremendously complex. They are not easy to analyze and include many random characteristics. They are difficult to comprehensively model and simulate with high degrees of fidelity and predictive accuracy. "The complexities of the human system that make it so hard to model have been successfully managed by various complexity reduction techniques such as abstraction, domain restriction, simplifying assumptions, effects aggregation, order reduction, lookup tables and rules-of-thumb."[61]

On the other end of the spectrum, once a *simple* model is built and effectively used to study a system, one often needs to add additional capabilities. Complexity can be added to increase a model's scope and usability and explore second and higher-order effects. In models built to capture human thoughts and decisions, complexity is often added to "simulate anticipatory and delayed responses, feedback modulation, and other important natural human capabilities such as noise filtering, prediction and pattern recognition."[62] Other sources of human complexity such as multitasking, communications, decision making and motivation make the agent-based modeler's job a difficult one. The opportunities for continued research in any one of these areas abound.

The following elements of model complexity are areas that can be explicitly addressed in an agent-based model, like SWarrior or EINSTein, to further explore the

[61] Reardon, Matthew. "Building Complexity into Biomedical Models" *Phalanx* Vol. 31 No. 4 (December 1998): 16-17.

nature and dynamics of complex adaptive systems: number of variables, nonlinearity and interaction, time invariance, causality, feedback, uncertainty, optimization, stress, and noise filtering.[63] Further insight into how each of these can enhance a simulation is provided in Appendix I.

Problems associated with implementing elements such as those listed above do not negate the usefulness of complex models. They can still be useful for testing concepts and generating hypotheses that can be specifically tested in focused studies. "The concept of using relatively simple first order models as a building block for more complex models is sound and well documented."[64] As basic response models are being built from constituent elements, they can be enhanced with additional complexity to enhance their capabilities and scope of application.[65] Recent modeling developments in the areas of learning and adaptation promise to provide the capabilities needed to fully leverage the bottom-up approach characteristic of agent-based modeling.

Learning, Adaptation, and Emergent Behavior

A new view of learning and learning-based systems has emerged over the last few years. This view advocates that the understanding (or design) of systems capable of complex, robust, open-ended learning and cognition requires a structure where intelligence is shared among multiple, possibly dissimilar agents. These agents interact with each other and with their environment in a fashion that encourages adaptation. This

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[62] Reardon, 16-17.
[63] Reardon, 16-17.
[64] Reardon, 16-17.

approach shifts the emphasis from static structures and distinct operations to a process of continuous change. It places cognition in the same domain as the brain, body and environment and is concerned with the principles of self-organization. The critical question for distributed systems has been shown to be an understanding of the relation between local mechanisms and the learning process of the whole. A few examples of key questions being investigated by countless researchers across the country are (1) How does a network of agents learn to behave differently than do the agents individually (co-evolving learning on both sides)? and (2) How do we facilitate, detect, analyze, and leverage the emergence of cooperative learning?[66]

If there is a single, unifying thread to the whole discussion of modeling combat as a complex system, it is the important concept of adaptation. Success in combat and success as an institution requires continued adaptation over time. "In any environment characterized by unpredictability, uncertainty, fluid dynamics and rapid change, the system that can adapt best and most quickly will be the system that prevails."[67] In order to use a model that can truly serve as an experimental laboratory, that model needs to be able to create and examine alternative environments and actions by itself. This capability often falls under the heading of machine learning (ML). The agents that interact in these types of models have to be able to adapt to changes without programmer, or man-in-the loop, guidance. The challenge of enhancing intelligent agents appears to reside mainly in the following two areas:

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[65] Reardon, 16-17.
[66] Santa Fe Institute, http://www.santafe.edu/sfi/researcb/focus/whatissfi.html.
[67] Schmitt, Major John F., USMC. "Command and (Out of) Control: Military Implications of Complexity Theory", *Surface Warfare*, (January/February 1998): 8-12.

- There needs to be improved techniques for representing the domain knowledge that the agents will draw upon.
- There needs to be improved methods for reasoning about the knowledge, real time, during the simulations.[68]

Implementation of various new techniques and methods to meet the challenges listed above have allowed new agent behaviors to emerge in the middle of a simulation.

One way of meeting the challenge of machine learning is to have a Knowledge Based System (KBS) "discover" the knowledge required for logical decisions and then construct a plan by itself.

> There are many different techniques that are considered ML, but they all can be characterized into one of four major categories: Analytic Learning, Inductive Learning, Neural Network Learning, and Genetic Algorithm (or selectionist) Learning. Depending on the problem, each approach offers certain unique advantages and disadvantages. When it comes to the general problem of tactical decision making, a strong case can be made that selectionist learning techniques are the most appropriate.[69]

The next sections provide an overview of some promising research in the areas of **learning** and **adaptation.** Specifically, these are the types of programming enhancements that, if added to a model like SWarrior, would significantly increase the model's usefulness as a tool to study complex systems like Hunter Warrior combat.

COREBA

Created by Dr. S. David Kwak at Lockheed Martin, the Cognition Oriented Emergent Behavior Architecture (COREBA) is a Computer Generated Force (CGF) technology to significantly enhance future CGF models. It does not have many of the

[68] Leddo, John and James Kolodziej, *"Simulation-Based Intelligent Agents"*, Research Development Corporation, Herndon, VA. 1998, Introduction.
[69] Ilachinski, 90.

fundamental limitations that are usually associated with conventional behavior implementation technologies. Through the use of this new paradigm, it makes possible the construction of a CGF whose behavior closely resembles that of a human combatant. The COREBA's unique cognition oriented paradigm, proven theories, and architecture allows for the construction of CGF behaviors that are continuously adaptive while maintaining military rationality.[70] This particular behavior architecture has extremely strong potential to provide the flexible, autonomous, goal-directed behavior that models like SWarrior could benefit from.

COREBA utilizes advances in artificial intelligence tools to help create the flexible, goal-directed behavior necessary to allow adaptation within a model.

> One of the results of research in the area of artificial intelligence has been the development of techniques that allow the modeling of information at higher levels of abstraction. These techniques are embodied in languages (or tools) that help build programs to closely resemble human logic in their implementation. By design, these tools are easier to develop and maintain. These programs, which emulate human expertise in well-defined problem domains, are called **expert** systems. The availability of expert system tools, such as CLIPS, has greatly reduced the effort and cost involved in developing an expert system.[71]

Appendix J provides more background information on expert systems and CLIPS.

Integrated Knowledge Structure (INKS)[72]

Non-human agents are central to many simulations. Unfortunately, many simulation users complain that such agents are easy to spot, behave stupidly, and are therefore easy to game. The key is to make agent behavior realistic and consistent with the training,

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[70] Kwak, abstract.
[71] CLIPS, "What Are Expert Systems?", http://www.ghgcorp.com/clips/ExpertSystems.html.

mission, or other objectives of the simulation. Research Development Corporation has developed an intelligent agent model based on the psychological formalisms of reasoning, problem solving and decision-making behaviors. The heart of these intelligent agents is an Integrated Knowledge Structure (INKS (tm)) model of domain problem solving that is independent of a specific simulation scenario. The result is that these agents, like humans, can be dropped into a scenario and act based on the situational cues provided. Because the INKS (tm) model is independent of the simulation, it makes the intelligent agent architecture generic enough to be integrated into a wide range of simulation models. This technology was demonstrated in constructive and virtual simulations for military operations in urban terrain (MOUT). Two demonstrations of their robustness and realism were conducted. Review by military experts found behaviors exhibited by the intelligent agents to be virtually indistinguishable from behaviors exhibited by human controlled simulation agents. This technology is advertised to be especially useful in large-scale exercises where the number of computer generated forces increases and the need for quality intelligent agents becomes central to the effectiveness of the exercise.[73]

Composable Behavioral Technologies (CBT)

The development of behaviors for simulated entities in Semi-Automated Forces (SAF) systems is a labor-intensive process that often neglects valuable input from the end user. There is a great need for applications that will allow the end user to compose new behaviors as required. The objective of the Composable Behavioral Technologies (CBT)

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[72] Leddo.

project is to explore a solution to the problem of allowing users of a SAF system to create custom behaviors for simulated entities. Company-level Rotary Wing Aircraft behaviors have been identified as the behavioral domain for the initial focus of the CBT project. Though Modular Semi-Automated Forces (ModSAF) is being used for the purposes of the prototype development and demonstration, to the greatest extent possible, CBT will focus on solutions that can be applied to SAF systems in general.

Goal-Directed Planning

Research abounds with titles like goal-directed behavior, goal-directed programming, goal-directed reasoning, etc. Past research shows that the goal of a knowledge-based system is not only to produce a solution to a problem situation it faces, but also to construct, implicitly or explicitly, a situation-specific model that can explain the rationale behind a given solution.

Many techniques of goal-directed re-planning, behavior, and dynamic goal creation have been created for application to Semi-Automated and Computer-Generated Forces. These techniques are used to generate behaviors that are reactive to local situations but incorporate the more global intent of a mission. At the heart of this work is a goal representation that captures desired aspects of a mission and constrains the selection of actions within the battlefield environment. Goals have general types (e.g. survival, conservation, and destination) and a hierarchy based on their association with units within a simulation. General rules governing the selection of actions use these goals to

[73] Research Development Corporation, Projects, http://www2.dgsys.com/~rdc/projects.html.

restrict behavior to that which furthers the intent of the mission. Dynamic goal creation is used to create new goals "on the fly" as unusual situations arise.[74] These techniques provide a good balance between reactive and purposeful behavior, making them well suited to represent decision-making above the individual agent or vehicle level.

Enhancement Summary

If the Hunter Warrior follow-on questions are to be effectively examined, a model like SWarrior needs sophisticated algorithm and architecture enhancements like those described in this chapter. If any one of these new approaches were integrated into SWarrior, then SWarrior would be ready to explore an experimental design like the one described in the following chapter. Hunter Warrior follow-on questions could then be explored with forces that are capable of creating and pursuing goals while composing new behaviors and adapting to new situations.

[74] A model that applies these techniques was developed, implemented, and tested with an example company team scenario employing one mechanized infantry platoon and two tank platoons assaulting a defended bill.

Chapter 6

Proposed Experimental Design

Nunquam ponenda est pluralitatis sine necessitate.
("Thou shalt not seek an explanation based on more complex mechanisms, until you are satisfied that simpler mechanisms will not do!") --William of Ockham, 14th century

Objective: Characterize Dynamics vice Predict Results

After reviewing the current state of the SWarrior model in Chapter 4 and then examining a few of the recommended model enhancements in the last chapter, this paper will now examine the type of experimentation that could be possible if a more sophisticated model was available to Marine Corps analysts. With a model that truly exhibited bottom-up adaptation, learning, and composable behavior, analysts would be capable of examining the Hunter Warrior follow-on questions described in Chapter 3. Analysts would not be interested in predicting combat results but gaining further insight into the essential dynamics of a given situation.

In the newer agent-based models, the focus has been to determine the simple or "low-level" rules that appear to govern the individual agents within the system. From these low-level rules, the important properties of the system as a whole often emerge. In the microworlds or "bottom-up" models that complex system theorists use, the analyst relies upon knowledge of the agents and their interactions with each other. This then generates a pattern at a higher level than the agents themselves. Such a pattern is often called an *emergent* phenomenon, since it emerges out of the aggregate interactions between the individual agents in the system. In the design of an agent-based experimental design, we want to encourage interactions, adaptation, and emergent phenomenon that will provide the system insight we desire.

One often questions the degree to which analysts can employ agent-based simulation models as surrogates for the slice of reality they want to represent. Typical questions include:

- How do these simulated worlds relate to their real-world counterparts?
- What types of behaviors can emerge from the interaction of agents in their electronic environment?

A challenge to any agent-based model is the tracking and description of the interactions among the agents, each of whom can learn from past behavior and thereby change the mode of their interaction with other agents and their environment as the simulation progresses. Because of the historical, technological challenges of tracking individual agent interactions, modelers have tended to focus their efforts on what we might call aggregated or high-level models.

> These types of high level models predict patterns like the final score of a football game not from first principles, like the decisions of individual players and coaches, but from higher-level properties like yards gained passing and rushing by the two teams. In these models, instead of following the activities of individual agents, medium-level quantities, like yardage gained and turnovers, are combined by various statistical techniques to come up with a projection of how many points

> these factors contribute to a team's overall total. A microworld analysis is not the only, or even the better, way to go. It is just one way that can sometimes shed useful light on a situation that can't be obtained through a less detailed look at a system.[75]

Just as there are different types of models, there are different ways the models can be used. Some models are predictive, some are explanatory, and some are designed to be prescriptive. The focus of SWarrior and the following proposed experimental design is as an *explanatory* model where we are interested in the way various factors affect a force's ability to successfully *move, shoot, and communicate.*

The mere duplication of the real world in a model, an experimental model, is in no way an indication that the microworld is a good model of its macroworld counterpart. Therefore, complete fidelity in a model is certainly far from a sufficient condition to deem the model a good representation of reality. It is not just the model of a system that an analyst is concerned with but a more complete understanding of the essential dynamics and lever points of the real system.

Like good paintings, a good model captures the essence of its subject. The structure and agents of the model need to be sufficiently defined to ask the questions about the slice of reality that the model represents. A first test is that our model provides convincing answers to the questions we ask of it. Although answering questions is the essence of a good model, there are other characteristics that tend to separate the good from the bad. These characteristics of good models are simplicity, clarity, bias-free, and

[75] Casti, 6-9.

tractability. The structure and characteristics of any given model depend on the nature of the questions that the analyst wants answered. Additionally, the results of any model will obviously depend on how much the designers actually know about the underlying laws that determine the ways the various parts of the system interact with each other.[76]

As a reminder, the questions that the Hunter Warrior Assessment wanted to investigate were:

1. What are the advantages and/or disadvantages of having small units equipped to employ heavy direct fire weapons (HMG, TOW, etc) within the Hunter Warrior type of dispersed operations?
2. What are the advantages and/or disadvantages of providing mobility assets for the teams? What type of mobility asset is optimal?

Though these questions are simple ones and anyone with a basic knowledge of force-on-force dynamics might be able to provide generic, common sense answers, we are interested in seeing if any surprising dynamics are revealed when these new factors are introduced into the experiment.

With these questions and the model principles reviewed above in mind, this paper recommends taking an existing agent-based model, like SWarrior or EINSTein, and significantly improving it as an analytical tool with some combination of the advanced capabilities described in Chapter 5. This new complex adaptive system tool, which would be created within the specific context of the Hunter Warrior AWE, would then be ready to examine a broad range of force protection and mission accomplishment issues.

[76] Casti, 6-31.

Experimental Design: Examine the Hunter Warrior Follow-on Questions

The outline of a generic combat experimental procedure might look like the following:

1. Create an artificial battlespace with space, time, and units that can be located, within reason, to certain "points" in the overall structure of space and time within that space. Then allow these units to determine their own behavior according to their own doctrine and tactics and internal state in concert with the recurrent sensing of the state of their world.
2. Within this artificial battlespace, create a number of objects or mechanisms that will serve to observe, record, and analyze data produced by the behavior of the units as they interact in the artificial battlespace implemented in step 1.
3. Run the simulation, moving both the environment and observation objects (agents) forward in time under some explicit model of concurrency.
4. Interact with the experiment via the data produced by the instrumentation objects to perform a series of controlled experimental runs of the system.
5. Depending on what is observed in stage 4, alter the experimental or instrumental "apparatus" and go back to 3.

Given an enhanced version of the SWarrior model (or any other agent-based model), an analyst would have a simple, yet sufficient battlefield environment within which to conduct valid experiments. The essential elements of our silicon battlefield that we want to ensure are modeled with sufficient clarity are those elements that will affect the functions of *move, shoot, and communicate.* These elements are traditionally:

- the environment (day/night, terrain, and weather),
- the units (personnel, equipment, and weapons),
- communications (command and control structure, equipment, doctrine),
- and warfighting doctrine (tactics, techniques, and procedures).

As a small initial experiment, the specific Hunter Warrior questions that this paper proposes to answer are the following:

- What is the difference in #Red casualties when Blue has mobility vice no mobility?
- What is the difference in #Blue casualties when Blue has mobility vice no mobility?

- What is the difference in #Red casualties when blue has LAV-25 vs. HMMWV?
- What is the difference in #Blue casualties when blue has LAV-25 vs. HMMWV?
- What is the size of the Blue force required to prevent Red from reaching objective?

The difference in casualties is used here to represent the benefits (or lack of benefits) of providing enhanced ground mobility to the long-range reconnaissance patrols. In an agent-based simulation, though, the real benefit will be found in observing the underlying dynamics of how the blue units learn to use any given ground mobility to their advantage. As agents are given new resources to use, they can explore how best to use them to reach their overall goal(s). Without specific, top-down directive guidance inherent in a limited behavior space, the Blue agents (long range reconnaissance patrols) in Hunter Warrior might develop or "adapt" a totally new way to "employ" a TOW HMMWV or an LAV-25. This is where the real power of this new perspective is realized. By allowing the agents to learn and adapt at the lowest level with only broad behavior boundaries, we can see new behavior emerge that might provide great insight into the essential dynamics of our "system" of combat.

Likewise, as Blue forces are provided UAVs and ground mechanical sensors with varying capabilities, an analyst can examine multiple simulation runs to sec if/how the different capabilities change the tactics employed and the combat results.

Measures of Effectiveness (MOEs)

The following MOEs are just a few of the many that could be easily collected and used in examining the dynamics of combat as it plays out over a broad fitness landscape. Though these are predominantly oriented toward capturing the effects of mobility and direct fire weapons capability, many more could be derived in an attempt to "farm" more data from the simulation environment.

- # Blue casualties
- # Red casualties
- # Red Kills with Blue direct fire weapons
- # Red Kills with Blue indirect fire weapons
- Average distance covered by Blue Agents
- Average Blue Distance moved by day
- Average Blue Distance moved by night
- # transmissions to ECOC
- # transmissions to other Blue Agents
- # Red (Blue) Agent detections during day
- # Red (Blue)Agent detections during night
- Max range Blue engages Red (and Red engages Blue)
- Min range Blue engages Red (and Red engages Blue)
- Average range Blue engages Red (and Red engages Blue)
- # Red detected but not engaged
- Time for Red to reach objective
- # times Red detects Blue but does not engage successfully because Blue moves

Once the model was verified to be executing as programmed, we would check to see if the created agents were in fact demonstrating logical, rational, adaptive behaviors within the broadly defined behavior boundaries (as defined by user based on doctrine, tactics, etc). The first set of experimental runs would entail initiating the simulation with the exact number and location of Blue and Red agents as was realized during Hunter Warrior. Approximately 100 iterations of the baseline scenario (Blue with foot mobility only) would be executed for the first series of runs. MOEs would be collected for each iteration. Three-dimensional surface plots (such as Figure 3 on the next page), or other creative visualization techniques, depicting various variable relationships would be examined to glean insight on trends, minimums, maximums, smoothness/roughness to indicate stability, etc. The next 100 iterations would use the same random number seed sequence; but with this set, each blue squad would have access to three HMMWVs. Two TOW variants and one .50 caliber variant (or any other mix) would provide the firepower and mobility needed to move each squad as the squad deemed appropriate. Blue agents would be "free" to utilize new mobility and direct fire assets within the behavioral boundaries set upon initiation.

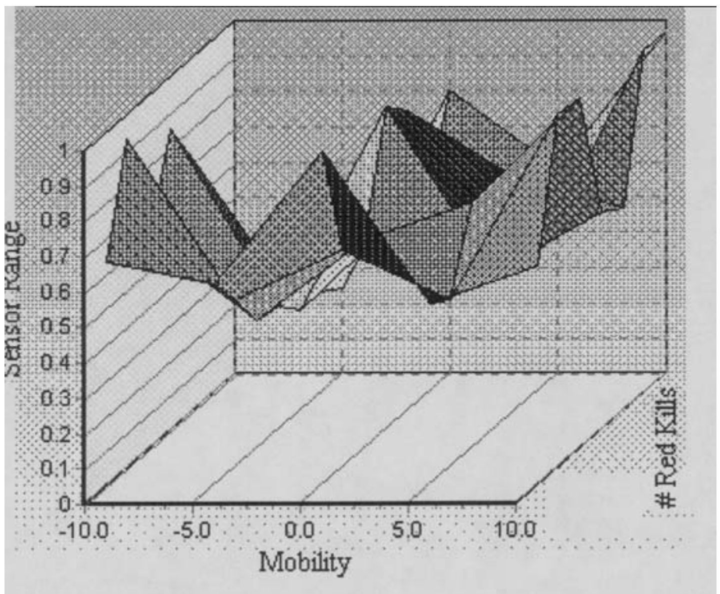

Figure 3. Notional Surface Plot of Hunter Warrior MOEs

With mobility and direct-fire capabilities, the Blue agents would not be constrained to rely on naval surface fire support (NSFS) coordinated through the ECOC to engage Red forces. Because the long time of flight for NSFS prevented Blue from engaging mobile targets with this asset, many engagement opportunities were passed up during Hunter Warrior. With an adaptive force that can learn from each experience, an analyst could observe how a force "learns" to integrate direct and indirect fire assets to maximize enemy destruction while minimizing the threat to friendly units. Improved tactics and procedures just might be discovered.

The wide range of possibilities in establishing appropriate behavior boundaries for adaptive forces can provide a rich source of varied experimental runs. For example, the criteria or "doctrine" for Blue to move from a given hide site might not be specified at all in one set of runs and then explicitly prescribed in another. The second set of runs might describe the withdrawal doctrine as a function of Red encroachment range (i.e. In the model's current configuration, Blue agents withdraw to an alternate hide site if Red approaches within 1000 meters, with more than a 4 to 1 force ratio).

Proposed Sensitivity Analysis

Most traditional models focus on looking for equilibrium solutions among some set of (pre-determined) aggregate variables like "attrition rate" which might be used to represent the success or failure of an entire force. The outcome of a battle is said to be "understood" when the equilibrium state has been explicitly solved for. In contrast, agent-based models tend to focus on understanding the kinds of emergent patterns that might arise while the overall system is out of (or far from) equilibrium[77] though they will still need to collect performance statistics or measures of effectiveness to visualize these patterns.

[77] Ilachinski, ISAAC, http://www.cna.org/isaac/downref.htm, MOBS pdf.

What can we hope to learn with a model that by design does not fully correspond to a specific, real environment like desert combat? We can study patterns of behavior. For example, how resources flow through different stages of a re-supply network, how co-operation among agents can arise through evolution, and arms races. We can also use such models to identify parameters or collections of parameters that are critical; that is, to perform sensitivity analysis. As with any simulation tool, it is much easier to run hypothetical 'what-if experiments than to conduct experiments on a real system. If models like EINSTein and SWarrior are built and used correctly, they will allow analysts to build deep intuitions about how different aspects of a military unit or command and control system affect one another. They will reveal important dependencies and an appreciation of how small unit adaptation interacts with the ongoing dynamics of a combatsituation.[78]

Obviously with the very large number of behavior and distribution parameter permutations possible, there are countless interesting options for sensitivity analysis in the given Hunter Warrior example. Several proposed additional experiments that would provide further insight into the effects of mobility and direct fire capability would be the following:

- Alternate the speeds available with HMMWV and LAV-25 assets
- Alternate weapons mixes on vehicles
- Alternate weapon max effective ranges
- Alternate IR, dust, and smoke signatures of vehicles

[78] Forrest.

The proposed experimental design illustrated in this chapter is obviously just one of many that could be pursued with a sophisticated agent-based model. Furthermore, the analyst's learning during the experimental process will lead to changes and additional explorations via data farming. If a model like SWarrior were enhanced with some of the concepts and capabilities discussed in the previous chapter, simulated units would be able to learn from mistakes and use available resources in new and potentially beneficial ways. Hunter Warrior follow-on questions could be quickly and cost-effectively researched without putting units back into the field. The ability to foster logical and realistic "adaptation" at the lowest level in simulation programs has opened up a whole new realm of possible applications for the Marine Corps to pursue. Several of these additional applications are reviewed in Appendix K. The Appendix provides more examples of how the application of the nonlinear sciences can provide practical utility to the warfighter in the areas of wargaming, course of action analysis, and decisionmaking training.

Chapter 8

Conclusions

The nature of conflict and the human will have not changed since Thucydides penned his classic history of the Peloponnesian Wars. What has changed is the way that the art and science of war are being studied through a new lens. The relatively new and rapidly growing field of the nonlinear sciences continues to demonstrate practical utility for the warfighter. The Marine Corps has begun the metaphors-to-models journey toward this new way to explore combat dynamics, but there is much work to be done. Continuing to explore the questions that resulted from Hunter Warrior is a great place to begin.

Thanks to the availability of affordable, high-quality computing capabilities, we can now construct silicon surrogates for complex, real-world processes like combat. We can use these surrogates as laboratories for carrying out useful experiments. Continuous experimentation is needed to be able to explore viable theories of complex physical, social, biological, and behavior processes that affect combat.[79] To better leverage current and future progress m the nonlinear sciences, the Marine Corps will benefit from a continued, focused effort to integrate the necessary expertise and resources in the area of

[79] Casti, 35.

analytical modeling and simulation. As described earlier, there are many DoD combat-modeling initiatives that utilize man-in-the-loop decisions to add the requisite experience and realism desired by users. There are inherent disadvantages in relying solely on manpower intensive man-in-the-loop models. In order to take full advantage of the data farming possibilities that are surveyed in MCCDC's Project Albert, the Marine Corps needs to aggressively support advances in agent-based simulation, behavior generation, and knowledge representation.

The current view within DoD is that nonlinear science and traditional methods will be used in complementary fashion in the future. Enhanced hybrids of linear and nonlinear tools will offer the ability to more creatively and effectively examine those operations that are not modeled well now. Military Operations in Urban Terrain is one specific arena that will lend itself to research as a very challenging complex adaptive system. As the Marine Corps Warfighting Lab returns from the Urban Warrior AWE in California[80], there will be many follow-on questions that need to be researched. The right agent-based simulation model (allows learning and adaptation) can greatly facilitate further exploration of the key factors and dynamics of operating in an urban environment. It can provide a realistic environment for the warfighter to explore various "what-if' scenarios in a more thorough manner than is currently possible.

Another challenging arena that lends itself to study as a complex adaptive system is Military Operations Other Than War (MOOTW). In the post-Cold War environment

[80] Urban Warrior is the second of the three Advanced Warfighting Experiments that comprised the original Marine Corps Sea Dragon experimentation plan.

where non-traditional foes abound, it is evident that we will not be facing readily identifiable enemy forces in direct confrontation. If our new enemies are warlords, terrorists, charismatic demagogues and the militaries of rogue states as Ralph Peters and others suggest, then the military should use every tool available to explore the implications of operating in such an environment. New agent-based simulation models can provide a useful tool for this exploration.

A final arena that could greatly benefit from more effective experimentation is the shape of future expeditionary warfare. As the Navy and Marine Corps continue to explore the supporting concepts for Operational Maneuver From The Sea (OMFTS), they will need an enhanced capability to efficiently and inexpensively experiment with new doctrinal concepts. Intending to move from limited, voice radio *nets* to widely available digital *networks*, OMFTS will stress the need for "highly trained individuals and cohesive teams capable of operating in fluid and ambiguous environments. Such individuals must be capable of confidently employing new technologies while decisively conducting military operations in tomorrow's risky three-block war" .[81]

Adaptation at the individual and institutional level is critical for survival and success. Advances in complex adaptive system analytic tools can help facilitate the Services ability to adapt to new challenges as demonstrated with the Hunter Warrior example. Institutionally, the Department of Defense needs to continue to foster an environment of experimentation as the Services adapt to the uncertainties of chaos in the world's littorals.

[81] Rhodes, 2.

Appendices

Appendix A

Chaos Theory for the Practical Military Mind[82]

> *"...all action takes place, so to speak; in a kind of twilight, which, like fog or moonlight, often tends to make things seem grotesque and larger than they really are."* Clausewitz

People often interpret Chaos to mean something is random, unpredictable, and uncontrollable. True mathematical Chaos (spelled here with a capital "C" to distinguish from general chaos) occurs in real, physical systems. Some key concepts critical to understanding why **Chaos theory is relevant to the military** are the following:

(1) Chaos is not randomness and it does not arise from the same stochastic forces that cause random behavior.
(2) Instead, Chaos arises from the same completely knowable conditions that give rise to ordered, thoroughly predictable behavior, despite the disorder of Chaos itself;
(3) As a result, Chaotic systems can often be mistaken for random systems, and the potential for well-behaved systems to become Chaotic is often not realized;
(4) There is an underlying structure to Chaotic systems that sometimes allow us to make predictions about its long-term trend and very short-term behavior.
(5) Some chaotic systems can be driven in or out of Chaos; that is, Chaos can occasionally be controlled.

Examples of Chaos are turbulence, lasers propagating through the atmosphere, weather, electrical circuits, brain activity, and the rhythm of the beating heart. The mathematical aspects of Chaos have only been recognized in the last few decades. Previously, order and randomness were seen as the only two worldviews available. Chaos is a fundamentally different way of viewing reality; it is a type of behavior that has characteristics in common with both order and randomness, but is not either. It is still being developed in a mathematical sense and still has a long way to go. See James Gleick's classic book, *Chaos: Making a New Science* for a thorough introduction. Chaos theory is a mathematical theory, and like most tools of 'hard' science doesn't readily lend itself to 'soft' science application.

[82] ACSC Thesis, Maj Susan E. Durham, PhD, Mar 97

The scope of Major Durham's thesis work is quite narrow; it focuses on those aspects of Chaos which specifically deal with issues of predictability. Let's begin by looking at a well-behaved system that becomes Chaotic. In population biology, the logistics equation is commonly used to predict fluctuations in wildlife populations. The equation allows us to predict variations in populations based on only two factors:

1. the average number of offspring per adult (a constant), and
2. the initial population

A key aspect of the equation, however, is a feedback factor. What is most important about this feedback factor is that it introduces nonlinearity into the system. Linear equations contain only addition, subtraction, multiplication or division by constants. Nonlinear operations involve exponents, trigonometric functions, and' logarithms. Many Chaotic systems become so because they are subject to this type of nonlinear feedback, which the system can't compensate for.

When a system can't compensate for nonlinear feedback there is often a sudden change in the character of the output. This is known as a **bifurcation,** which is another term that frequently appears when defining Chaos. A bifurcation simply means a drastic change in the pattern, or the quantitative state of a system. In Major Durham's bass population example, an offspring rate change from 2 to 3 to 3.6 are all OK, but when the rate is changed to 4, the system goes into Chaos. Feedback is a major factor in driving many systems into Chaos. The nonlinearities, which are manifest in feedback to the system, already exist and small changes in the physical conditions of a system can mean the difference between thoroughly characterizable systems and Chaotic systems.

Chaos is often mistaken for randomness. Before Chaos theory, the only options available to a system were (1) total predictability based on deterministic, characterizable, conditions, or (2) disorder, based on random, stochastic processes. Chaos results from completely known, deterministic, conditions. Chaos is not caused by random events and Chaotic systems do not behave randomly. Chaos frequently "sets-in" to systems that have only minor differences in the physical conditions, or parameters, of completely predictable systems. In the bass population example, the control parameter was the number of offspring per adult bass.

According to Major Durham's research, **basic truths of Chaos** are:

1. all Chaotic systems are nonlinear
2. all chaotic systems are deterministic
3. all chaotic systems are sensitive to initial conditions.. .in short, the slightest variation during the time-evolution of the system result in vastly different outcomes...the butterfly doesn't cause the hurricane. The system must already have enough energy in it to produce a hurricane.
4. chaotic systems are unpredictable except in terms of long-term trends and occasionally in the very short term

5. chaotic systems often have the multi-foci attractors in phase-space called strange attractors
6. all trajectories of chaotic systems exhibit mixing in phase-space
7. all chaotic systems are bounded ... even though the data swirls around lobes in an unpredictable way, it still stays within the bounds

Phase-space is simply a way of graphically representing the way a system behaves. A more complete way to describe the system is to examine how the time and space-dependent properties, or variables, of the system evolve. Graphing the way the variable change with respect to each other is called representing the system in phase-space. All periodic behavior shows up as closed loops in phase-space. An attractor is the focus of the phase-space orbit. It is a virtual point about which the trajectory orbits. The attractor literally attracts or 'draws' the trajectory in phase-space to it. One can think of the attractor of a periodic system as that point that the system would eventually collapse to 'n' phase-space if no external forces act upon it.

Chaos is not randomness. Random events have equal probability of being in any state they can be in, from one moment to the next, independent of the previous state. A random system has no structure in phase-space. Chaotic systems do have structure in phase-space.

What Ed Lorenz[83] called an 'orderly disorder' in normal space reveals a decided structure in phase-space. In phase-space, the trajectory seems to be 'drawn' to , or attracted to orbiting around two distinct lobes, one to the left of center and one to the right. The very fact that chaotic data has structure in phase-space, and random data does not, is why we can make some predictions about chaotic data. Wild meandering around in phase-space is called mixing. Chaotic data never falls into a repetitive pattern, though sometimes small portions of the data form patterns that are extremely similar to other portions.

There is a definite difference between Chaos, randomness, and periodicity. Lyapunov exponents are a measurement of how fast the trajectories represented on a phase-space plot diverge from each other.

In summary, Chaos Theory is a mathematical description of deterministic

instability.

[83]Lorenz, Edward N. *Essence of Chaos.* London: University College London Press Limited, 1993.

Appendix B

Tools and Concepts of Complexity[84]

Genetic Algorithms

Genetic algorithms are a class of heuristic optimization methods and computational models of adaptation and evolution based on natural selection. In nature, the search for beneficial adaptations to a continually changing environment (i.e. evolution) is fostered by the cumulative evolutionary knowledge that each species possesses of its forebears. This knowledge, which is encoded in the chromosomes of each member of a species, is passed from one generation to the next by a mating process in which the chromosomes of 'parents' produce 'offspring' chromosomes. Genetic algorithms mimic and exploit the genetic dynamics underlying natural evolution to search for optimal solutions of general combinatorial optimization problems. They have been applied to the traveling salesman problem, VLSI circuit layout, gas pipeline control, the parametric design of aircraft, neural net architecture, models of international security, and strategy formulation.

Fitness Landscape

A fitness landscape consists of a fitness function mapping objects in a search space to their fitness, and a neighborhood relation defining neighboring objects in the search space.In biological contexts the neighboring objects are called mutants. Fitness landscapes are important aid to understanding optimization.

Machine learning is a family of computational algorithms that mimic that ways humans seem to learn. There are two kinds of machine learning: supervised, and unsupervised.
Supervised learning involves determining the relationship between two variables, say X and Y, given a set of data consisting of (X, Y) pairs. For example, X might represent market conditions, and Y might represent stock volatility. (So the goal of supervised learning in this case is to determine if there is a relationship between these two variables, and if so what that relationship is.) Unsupervised learning involves discovering patterns in unlabeled data (i.e. a set of X's). For example, if X represents stock market conditions, it might discover two distinct kinds of X's corresponding to 'bullish' and 'bearish' markets.

Neural Networks

Neural networks represent a new approach to computational problem solving. The methodology they represent can be contrasted with the traditional approach to artificial intelligence (AI). Whereas the origins of AI lay in applying conventional serial processing techniques to high-level cognitive processing like concept-formation, semantics, symbolic processing, *etc.* -- or in a top-down approach -- neural nets are designed to take the opposite -- or bottom-un -- approach. The idea is to have a human-like reasoning emerge op the macro-scale. The approach itself is inspired by such basic skills of the human brain as its ability to continue functioning with noisy and/or incomplete information, its robustness or fault tolerance, its adaptability to changing

[84] http://www.biosgroup.com/bgcomplex.htm

environments by learning, etc. Neural nets attempt to mimic and exploit the parallel processing capability of the human brain in order to deal with precisely the kinds of problems that the human brain itself is well adapted for.

Gaussian Processes
Gaussian processes are a relatively new approach to problems in supervised learning. To learn the relationship between X and Y from a data set consisting of (X, Y) pairs, a Gaussian probability distribution is defined directly over the possible relations between X and Y. Gaussian processes have been shown to be equivalent to single layer neural networks with an infiinte number of neurons. They are computationally more efficient than neural networks when little data is available.

Simulated Annealing
A mathematical technique for general optimization problems. The name comes from the physical process of annealing, during which a material is first heated and then slowly cooled. During annealing, the component atoms of a material are allowed to settle into a lower energy state so that a more stable arrangement of atoms is maintained throughout the cooling process. Simulated annealing is a new algorithm that has been applied with success to a wide variety of optimization tasks.[85]

Multi-objective Optimization
Multi-objective optimization is the task of maximizing or minimizing a number of criteria simultaneously. Multi-objective optimization is more difficult than most kinds of optimization problems because the trade-offs between the multiple objectives may be unknown. In this case the best that can be done is to find Pareto optimal solutions. There are a number of new algorithms used to solve multi-objective optimization problems, including modifications to genetic algorithms.

Bayesian Networks
Bayesian networks are graphical representations of complex probability distributions. The nodes in the graph represent random variables, and edges between the nodes represent logical dependencies. A significant advantage of Bayesian networks over other machine learning techniques is their simple interpretation and ability to include prior knowledge.

Decision Trees
Decision trees are tree-shaped classification structures. Branch points in the tree represent decision points (i.e. If X < 100 do one thing, and if X> 100 do something else). Terminal nodes of the tree represent classes (i.e. the terminal node of the X < 100 branch might designate class A, and the terminal node of the X> 100 branch, class B). For complex problems, decision trees can be quite large. A decision tree might be used to classify income ranges (e.g. class A = income between 0 and $25 00, class B income between $25 000 and $50 00, class C = income greater than $50 000) based upon categorical demographic data like age, gender, sex, *etc.*

[85] http://www.biosgroup.com/definitions/simulation%20annaeling.htm

Clustering
Clustering is an unsupervised learning technique used for discovering patterns in unlabeled data. For example, it might discover that a set of data is well described by three distinct clouds of points. Clustering is often used for dimension reduction whereby complex data is understood in terms of simpler objects with only a slight loss in accuracy. Simple algorithms exist to cluster high-dimensional data efficiently.

Agent-based Model
In an agent-based model, the system is represented as a collection of autonomous, interacting entities referred to as *agents.* Agents' behavior is determined by their current circumstances according to a set of internal rules. The rules may be simple if-then clauses or sophisticated machine learning algorithms such as neural networks or Bayesian networks. Sample agent behaviors include producing, consuming, buying, fighting and selling. Parameters of the model are set to represent a situation of interest, and the model is run for a given number of iterations. At the end of the run, its internal dynamics and external output give the user a good idea of how the real system would behave under the conditions portrayed in the model.

Adaptation
Any change in the structure or function of an entity (e.g. a biological organism, or human organization) that allows it to survive and reproduce more effectively in its environment.

Optimization
Optimization is the task of maximizing or minimizing some variable such as cost or time. Algorithms used for this purpose include simulated annealing, genetic algorithms, and gradient descent.

Time
One the most important differences between an experiment in the "real" world and an experiment inside of a computer is the nature of time.

In the real world, everything in one's experimental setup is moved forward in time via a natural concurrency, courtesy of the laws of physics. In a computer experiment, however, the experimenter has to explicitly move every object in his artificial universe forward in time, making sure that everything remains within some well-understood state of synchronization. Many fundamental problems in computer science have arisen in the course of trying to understand how to control and use concurrency. Therefore, a very important aspect of setting up an experiment in a computer is how one weaves the multiple threads of time that must be woven together coherently in order to produce reliable, repeatable results.[86]

[86] http://www.santafe.edu/projects/swarm/swarmdocs/overbook/swarm.overview.mag2.chapter.html

Appendix C

Current Research and Development Initiatives

DoD Joint Research Initiatives. JCATS, JTLS, JTS, JSIMS, JWARS

The Joint Conflict and Tactical Simulation **(JCATS)** is a multi-sided, interactive, entity level, joint conflict simulation. JCATS capabilities will include the ability to conduct Joint Task Force level exercises across the entire spectrum of war, to include Operations Other Than War and highly specialized operations. JCATS' training focus will include the strategic through tactical levels and will be an extremely effective tool for training, analysis, and mission planning and rehearsal. Among the unique capabilities to be provided by JCATS is very detailed modeling of small group tactics in rural or urban terrain and modeling day or night operations with artificial lighting. JCATS will also allow for dynamic aggregation and de-aggregation of units during the game allowing the user to play at the JTF level with larger numbers of entities with fewer players. The current model proponent and configuration control organization for JCATS is the Joint Warfighting Center (JWFC). JCATS is being developed and will be enhanced, maintained, and supported by the Conflict Simulation Laboratory (CSL) at Lawrence Livermore National Laboratory (LLNL).

The Joint Theater Level Simulation **(JTLS)** is an interactive, computer-assisted simulation that models multi-sided air, ground, and naval combat, with logistical, Special Operation Force (SOF), and intelligence support. As an interactive model, it requires human decisions to manage the processes and entities. A component of the Modern Aids to Planning Program (MAPP), JTLS was designed as a tool for use in the development and analysis of joint and combined (coalition) operation plans, but is frequently used as a training support model. JTLS is theater-independent and does not require programming knowledge.

JTS is a high-resolution model developed by Lawrence Livermore National Laboratories that can simulate all MAGTF weapons and systems. It allows for multiple sides to interact (friendly, OPFOR, neutral). Attrition is based on individual weapon versus target algorithms. JTS can provide an extremely detailed terrain playbox with complex MOUT scenarios that include multistory buildings with specific floor plans. JTS is also capable of simulating fatigue in personnel and can produce the effects of suppression from direct and indirect fire. It also allows personnel to surrender and be captured. Post processing utilities can graphically display system movements, direct and indirect fire and system kills. The system also tracks and displays loss exchange ratios and weapons usage data. There is also a capability to replay simulations at various speeds.

The Joint Simulation System **(JSIMS)** is envisioned to fulfill the simulation needs of all users when fielded (Full Operational Capability 2003). The primary simulation currently used to support Marine Corps exercises is the MAGTF Tactical Warfare Simulation (MTWS). MTWS is the replacement for the Tactical Warfare Simulation, Evaluation and Analysis System (TWSEAS) and can cover the complete range of MAGTF operations. It is a member of the Aggregate Level Simulation Protocol (ALSP) confederation and can therefore interface with numerous models used by the other services. MTWS is currently fielded at Quantico, Camp Lejeune, Camp Pendleton, Okinawa, Twenty-Nine Palms and USACOM. While MTWS meets many of the Marine Corps' simulation needs, it has some inherent limitations. Since it is an aggregate level model it cannot accurately depict individual systems with a great deal of detail. When used to support a MEF level exercise, this is not a significant problem. However, there are many Marine Corps missions that require more detail in a simulation. This is especially true of MEU-SOC missions such as non-combatant evacuations, amphibious raids etc. Additionally, simulation support for battalion and company operations requires higher resolution in order to provide the necessary degree of realism. A high-resolution model (HRM) is a computer simulation that can model entities at the individual level (i.e. tank, aircraft, or infantryman). There have been numerous HRM's developed for various agencies. The U. S. Army has used JANUS for several years and the Joint Conflict Model has been used extensively in the joint community. While these models may have the desired degree of resolution, they have only limited capability to support Marine Corps simulation needs. MITRE corporation recently briefed MCCDC on the status of their work towards creating Autonomous Command Entities (ACE) for JSIMS. Their goals in this work are: represent collaborative decision making behavior, offload a portion of the cognitive burden of decision making, enhance command and control effectiveness, and reduce manpower requirements for executing scenarios.[87]

The Joint Warfare System **(JWARS)** is being developed by the Office of the Secretary of Defense (OSD), at the direction of the Deputy Secretary of Defense as the next-generation theater warfare model. It is being designed to be capable of analyzing a full range of scenarios from an MRC to a MOOTW. It is a closed form, analytic model being developed for use in addressing joint questions. Its applications include the evaluation of alternative courses of action, force structure, and resource allocation issues. JWARS is being developed using an object-oriented software design approach. It will be a faster-than-real-time discrete event simulation with user-selectable deterministic and stochastic properties. It is estimated that JWARS will be comprised of approximately 2,500 classes containing 50,000 methods and will be programmed primarily in the Smalltalk programming language.[88]

Non-DoD Initiatives

ECHO was designed to capture the essential features of ecological systems in an agent-based model. All of the entities and interactions in Echo are highly abstract, and it

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[87] MITRE, Autonomous Command Entities (ACE) for JSIMS, In-Progress Review, Dr John Tyler, 9 March 1998.

[88] JWARS Project Overview, http://www.stic.org/Adventure/B0l0.htm

is not yet known whether Echo can be used to model real world phenomena effectively. Many CAS can be viewed as ecologies, but the focus in this research is on the analogy with natural ecologies. Echo resembles some other CAS models. Echo extends classical genetic algorithms in several important ways: (1) fitness is endogenous, (2) individuals (called agents) have both a genome (set of chromosomes with respective "genetic" material) and a local state that persists through time, and (3) genomes are highly structured. In Echo, an agent replicates (makes a copy of itself, possibly with mutation) when it has acquired enough "resources" to copy its genome. The local state of an agent is exactly the amount of these resources it has stored. Agents acquire resources through interactions with other agents (combat or trade) or from the environment. This mechanism for "endogenous" reproduction comes much closer to the way fitness is assessed in natural settings than conventional "fitness functions" in genetic algorithms. Along with these extensions to the evolutionary component, Echo specifies certain structural features of the environment in which agents evolve.[89]

Coac**H** is an evolutionary simulator developed to investigate strategies for teams in a competitive environment. It has been used to research some of the issues surrounding the evolution of co-operation and communication among team members. A situation that requires both co-operation and communication is the interaction and group dynamics of players participating in a team sport like volleyball. This environment provides an ideal opportunity to investigate such phenomena. The investigation is realized through the study of teams interacting in a simulated sporting environment by means of computer-based artificial evolution.[90]

One example of a corporate firm that has been developed specifically to apply aspects of complexity theory to solve real problems is BIOS. This new corporation is a partnership founded by the ***Ernst & Young Center*** ***for Business Innovation*** and Dr. Stuart Kauffman, a ***Santa Fe Institute*** external Professor and MacArthur Fellow, and one of the foremost scientists in the field of complexity. Inspired by success stories (see Appendix D) of the application of complexity theory to real world business problems, and recognizing the immense potential of this approach, *Bios Group* has put together a group of outstanding scientists, programmers, and business leaders eager to exploit paradigm-shifting scientific breakthroughs of the last two decades for the benefit of business. The BIOS mission is to apply research in complexity to the development of a set of powerful new tools for solving the kinds of problems and situations encountered by companies and organizations. The tools that BIOS is developing and applying fall into the following three main categories: Optimization, Data Mining, and Modeling.

[89] Forrest.

[90] http://www.csu.edu.au/ci/vol2/raik/node1 .html

Appendix D

Complexity Theory Application Success Stories

GENERAL MOTORS

"Factories are havens of erratic behavior," according to Dick Morley, one of the creators of the floppy disk, and father of the programmable logic controller. His solution has been to develop factory control systems drawing from complexity theory.

In 1992, one of Morley's computer systems was put to the test in the paint shop of a *General Motors* assembly plant in Fort Wayne, Indiana. In the past, unpainted truck bodies rolled off the assembly line and were routed to one of ten paint booths by a centralized controller. The highly interconnected system had worked fine as long as nothing went wrong, but when any one part faltered, everything else was thrown off.

Morley's system completely changed the game by enabling the ten paint booths to act as free agents with a simple goal: paint as many trucks as possible using as little paint as possible. Each booth electronically 'bids' for the right to paint a certain truck. Bids are based on several factors, including what color the booth is set up to paint, and how long the line in front of the booth is. As a truck rolls off the assembly line, each booth makes a bid which is placed immediately in its computer. Bids from the computers are compared, and the truck is assigned to the 'winner.' During its first year of operation, the system saved $1 million a year in paint alone and reduced software needs by nearly 100%.

JOHN DEERE

Farmers order over a million different permutations of planters from *John Deere.* Some want 4-row planters, others 24-row planters, and others something in between. Some want planters that apply liquid fertilizer, others want dry fertilizer, others no fertilizer at all. Orders used to be filled by shipping planters in pieces for assembly by local dealers. In 1992, *Deere* began assembling planters at the factory in order to enhance quality and decrease inventory. Workers were organized into self-directed teams, each devoted to a particular system of planter. Problems soon arose. Half-assembled machines were bunching up at one station, while another station remained idle. A new approach was sorely needed. Complexity theory provided a solution. Now, every night before the factory closes, a genetic algorithm program running on a PC artificially 'breeds' generation after generation of assembly schedules. The best schedules of each generation participate in the next round of breeding. The process results in the production of more than 600,000 schedules each night. Planters now flow smoothly through the production line, and monthly output has increased sharply.[91]

[91] http://www.biosgroup.com/business.html

Appendix E

National Training Center (NTC) Observations[92]

The following comments were sent to Colonel Brown of the Marine Corps' Doctrine Division in Quantico, VA by a senior officer at the Army's National Training Center.

With the continuing decline in knowledge, skill, and abilities of leaders and units at every level, coupled with the fact that damn few units are training above company/team level in the field these days, maybe NTC should return to the building block approach. Instead of jumping straight in to brigade operations, maybe it makes sense to gain proficiency at battalion task force level first, then pull the brigade back together at the end of the rotation. Performance levels are probably at an all time low at NTC.

NTC OPFOR has been fighting and adapting tactics and techniques in response to Force XXI capabilities at the National Training Center since Spring 1994. What follows is a short compilation of OPFOR observations, deductions, conclusions, and opposing tactics! techniques the past 4 years, associated with defeating Force XXI technology, capabilities, and units.

Technology is worthless in the hands of commanders, staffs, and soldiers who have not mastered the fundamentals of battle command, planning operations, setting conditions for synchronization of the combined arms team, getting every dog in the fight at the right time and place, and the ability of soldiers and units to perform individual and collective tasks to established performance standards. You can't fight fast with precision until you learn how to fight. Mastery of fundamentals at every level-blocking and tackling-must be achieved first before Force XXI capabilities can make any difference at all.

Units/command and staff teams trained predominantly in virtual and constructive simulations are much less effective than those who trained not only with simulations, but extensively in the field under tough, realistic conditions, particularly through battalion task force level. From our point of view, there appears to be no effective substitute for training the combined arms team as one team under realistic, field conditions.

The first step towards defeating a Force XXI-equipped unit is to gain information dominance. Focus lookers and shooters to find and destroy/disrupt critical communications systems upon which the flow of information depends; MSE nodes and command posts. Take these stationary and easily acquired systems off the battlefield and the ability to maintain situational awareness/execute precision fires evaporates. The screens go blank. At the same time, find and jam critical FM command and fire direction

[92] Col Brown, forwarded e-mail from MCCDC Doctrine Div, 23 Dec 1998.

nets. Work hard to stop the flow of electrons/digits across the battlefield. If achieved, units appear to have serious problems reverting to analog capabilities.

Active and passive force protection measures are vital to preserving combat power, such as: protect the force from observation by targeting radars, thermal optics, and other acquisition systems which can precisely locate our forces; protect the force from the effects of direct/indirect fires through dispersion, obscuration, terrain masking, speed, and agility. Additionally, a force equipped with a vast array of intelligence collection systems, JSTARS, UAV, LONGBOW, KIOWA WARRIOR, etc, is more susceptible to deception, and places a premium on our ability to deceive. Deception equipment, positions, thermal signatures, obstacles, march units, and deceptive communications are critical to preserving our combat power and neutralizing Force XXI capabilities. Through deception, aimed at HUMINT observers behind the camera lens, surprise can be achieved.

Find and strike enemy high payoff targets(critical capabilities) simultaneously through the depths of the battlefield; it imposes paralysis.

Move the high payoff targets frequently, *move dispersed, move fast, concentrate rapidly, disperse quickly after striking a decisive blow.* The ability to do this is critical to preserving combat power and defeating an enemy with real time intelligence.

You can defeat a Force XXI-equipped force by being more flexible and agile. Agility and flexibility-produced by our disciplined deliberate planning process, detailed wargaming of courses of action, our ability to establish HUMINT observers through the depths of the battlefield, and troopers and leaders who have mastered tactical fundamentals and understand the commander's intent-have been the source of success.

Appendix F

Project Albert Research

The three distinct but mutually supporting research areas of Project Albert that are currently being pursued to further MCCDC's goals are: (1) an initiative to research the possibilities of a concept called **generative analysis** (2) an initiative to examine the benefits of **agent-based simulation,** and (3) an initiative to explore the wealth of information to be found through various **data farming** techniques.

Through a contract with Los Alamos National Laboratory, MCCDC is studying the possibilities offered by ***generative analysis.*** Generative analysis is a process that seeks to automatically generate constraint-composable agent-based simulations for exploring a particular scenario space.[93] Using an agent-based simulation model called **JIVES** to examine the essential dynamics of combat in urban terrain, analysts at Los Alamos Lab are working to automate much of the experimental design process to facilitate more rapid, thorough, and efficient use of agent-based simulation models.

Agent-based simulations provide the next extremely promising research area of Project Albert. MCCDC and the Center for Naval Analyses (Dr Andy Ilachinski) used this nonlinear approach to explore behavior implementation and genetic algorithms in a model called ISAAC. **ISAAC,** and its follow-on **EINSTein,** are simple multi-agent-based models of land combat being developed at CNA to illustrate how certain aspects of land combat can be viewed as emergent phenomena. These phenomena result from the collective, nonlinear, decentralized interactions among notional combatants. These models use a bottom-up, synthesist approach to the modeling of combat, vice the more traditional top-down, or reductionist view, and represent a first step toward developing a complex systems theoretic analyst's toolbox (or "conceptual playground") for exploring high-level emergent collective patterns of behaviors arising from various low-level (i.e., individual combatant and squad-level) interaction rules. The idea is not to model in detail a specific piece of hardware (M16 rifle, Ml0l 105mm howitzer, etc.), but to provide *an understanding of the fundamental behavioral tradeoffs involved among a large number of notional variables.* In ISAAC and EINSTein, the final outcome of a battle -- as defined, say, by measuring the surviving force strengths -- takes second stage to exploring how two forces might *co-evolve* during combat. The basic element of ISAAC is an ISAAC Agent, which represents a primitive combat unit (infantryman, tank, HMMWV, etc) that is equipped with the following characteristics:

- Doctrine: a default local rule set specifying how to act in a generic environment
- Mission: goals directing behavior
- Situational Awareness: sensors generating an internal map of environment

[92] Generative Analysis Brief, Los Alamos National Laboratory, Steve Upton, 17 Oct.

- Adaptability: an internal mechanism to alter behavior and/or rules.[94]

The current version of Einstein represents a significant step toward developing an inherently complex systems theoretic model of land combat. It is motivated by a desire to extend the largely conceptual links between complex systems theory and land combat, as outlined very well in the reference and in Table 1 of Chapter 2, to create a set of practical connections as well. Planned future enhancements include more realistic offensive and defensive capabilities, an enhanced internal value-system, added environmental realism, and providing individual agents with both a memory of, and a facility to learn from, their past actions (using both neural-network and reinforcement learning techniques).[95]

The third area currently covered by the Project Albert umbrella is data analysis research. Advances in computing power enable us to significantly increase the volume of data available to study. We now have the opportunity to explore entire fitness landscapes instead of just a small subset of possible experimental outcomes. These advances in our ability to organize, analyze, and visualize scientific data enable analysts to actually *"farm data".* Many analysts believe that agent-based models have the promise of eventually bringing entire response landscapes to light by revealing some of the key elements of conflict. The agent-based models allows one to "grow" more pertinent data and increase understanding through more simulation iterations, a more detailed look at data areas of interest, and examining other parameters. If one considers the degree to which a unit or agent effectively accomplishes a given mission its "fitness", then the multiple results obtained over a certain modeling parameter space will define a fitness landscape that can reveal many new insights.

The *data farming* technique can perhaps be better understood through the following metaphor. One **fertilizes** the minds of military professionals and other experts with ideas on how to capture the important aspects of conflict which we have not captured well in the past such as morale, momentum, leadership, cohesion, trust, and many others. One then **cultivates** ideas from these professionals concerning what issues or elements might be the most important in a given situation. One then **plants** these ideas in models to the degree made possible by current advances (artificial intelligence, fuzzy logic, neural nets) in algorithm development and run the models over a landscape of possibilities to investigate variables of interest. One then **harvests** the data output from the model with organization, statistical, and visual techniques that continue to be developed in order to better understand the dynamics at work. The large amount of harvested data allows the analyst to continually re-focus on the question at hand and "grow" subsequent data, which promises to add to our understanding of the dynamics of combat.[96]

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[94] http://ww.cna.org/isaac/extabs.htm
[95] http://www.cna.org/isaac/downref.htm, MORS pdf.
[96] ManeuverWarfare Science, 1998, 98-99.

Appendix G

Recent Marine Corps Nonlinear Science Research

Colonel Harned's work is one of the earliest Marine Corps research efforts to explore the extent to which complexity theory and other emerging aspects of nonlinear science apply to the art and science of war. After providing a good background discussion of terms, scope and significance, Colonel Harned reviewed the work of some great Western military theorists. The analogies of Clausewitz, Jomini, Foch, Fuller, and Johnston are used to reinforce the working hypothesis that war, as a social phenomenon, is a nonlinear dynamical system whose study can benefit from the application of nonlinear science. Colonel Harned concludes with a review of the applicability of chaos and complexity theory and makes a clear case for viewing war as a clash of complex adaptive systems. Drawing on Dr Brian Arthur's noted studies of economies as complex adaptive systems, Colonel Harned identified the following four principles for economic and political policy-making that also appear to apply to military decision-making:

(1) Observe the system continually and don't expect circumstances to last.
(2) Use the natural nonlinear dynamics of the system to apply available force to the maximum effect; don't waste it.
(3) Forget about optimization, because it is meaningless in an ever-changing, interlocking, nonlinear world.
(4) Search for recognizable themes and patterns in order to adapt and retain the competitive edge.[97]

These same principles are found to be fundamental to the Marine Corps' new doctrinal view of command and control that is outlined so well in MCDP 6.

In the second work mentioned in Chapter 2, Major Thomas Moore,USMC, reviewed a majority of the well-known works in the growing field of the nonlinear. He summarized and defined most of the key new concepts of chaos, complexity, and reductionism and compared them to historical views of war and the study of war.[98] Major Moore's focus was on demonstrating Dr Ilachinski's ISAAC Model as one example of how some of the current nonlinear science concepts are helping the M&S community within DoD to better examine the complexities of land combat.

[97] Harned, The Complexity of War, 50.
[98] Maj Moore, Foglamps of War. His thesis chapters were: An Art of War, Newton's Legacy, Combat Models, A New Science, A New Model of Combat, A Mobile Cellular Automaton Model, and Conclusions.

Appendix H

SWarrior Agent Types

Friendly Squads

The primary function of friendly squads is to search for red targets, communicate detections to the ECOC, and use shared information about the battlespace (such as impending encroachment) to decide when to relocate and to where. As is discussed below, friendly squad visibility and target recognition is governed by position in relation to surrounding terrain, available equipment (such as night vision goggles), time of day, weather conditions, and levels of training. As implemented in the current version of SWarrior, communication of detects is directly through the ECOC.

ECOC

The Enhanced Combat Operations Center receives detections of targets (and decoys) from two sources: friendly squads and UAVs. Communication links between each agent and the ECOC must be specified in order for these detections to reach the ECOC. The ECOC responds through an algorithm which prioritizes target detections according to size and perceived realism, then fires missiles at high-priority suspected targets. The ECOC represents an offshore Naval asset and does not use its own visibility or movement capabilities for the purposes of the current experimental design.

Mechanical Ground Sensor

Mechanical sensors are pre-placed, non-moving mechanisms(such as REMBASS) which are located on teh ground to detect Red targets. Mechanical sensors generate detect messages to the friendly squads to which they are linked in the communications network. These detections are based on simulated acoustic detection, which is relatively independent of time of day or training levels. The reports of mechanical sensors to the blue squads either reinforce existing detections by the blue squads, or add to the detections already made by the blue squads, thus increasing the effective detection range of the blue squad in an irregular fashion.

Unmanned Aerial Vehicle (UAV)

UAVs are unmanned blue airborne visual and infrared sensor aircraft launched from and controlled by the ECOC. UAVs fly from the ECOC to a fixed piece of airspace and commence a monitoring pattern of flight that consists of flying over progressive "strips" of airspace until the area has been covered. UAV movement is dictated by the patrol pattern and area to be patrolled in a given sortie, as well as the rate of speed of the aircraft, and the width of coverage possible during a sensor sweep. UAVs transmit detections back to the ECOC, which may act on them as it acts on other incoming detection data. Because UAV sensing is primarily visual, target detection is limited by time of day, and weather conditions. UAV altitude, however, obviously means that terrain is less an impediment to visibility.

Enemy Tank

Enemy tanks move from a starting position in the battlespace, toward a series of successive laager positions within larger "laager zones". Enemy tanks choose a new laager position to move to upon arriving in a new laager zone, based on the steepness and roughness of the terrain (including basic footing data), whether the position is already occupied, and the imperative to avoid being seen by blue agents. The tank maximum speed parameter governs the rate of movement of the tank squad. As with blue squads, red tanks also have visibility parameters, which are dictated by the surrounding terrain, onboard equipment, weather, time of day, and levels of crew training. Enemy tank squads also have firing capabilities. In an enemy tank squad observes a blue squad within its weapons ranges, it will fire on the blue squad until it destroys it.

Enemy HMMWV

Enemy HMMWV squads move and make detections in a manner similar to enemy tank squads. Their movement, however, is both more rapid, but more sensitive to the roughness of surrounding terrain.

Understanding Detection

The ability of blue and red agents to detect enemy agents employs a common detection algorithm based on a Gaussian probability distribution. A cumulative probability-of-detection curve begins at 100% at range 0, and falls according to the normal curve as distance approaches infinity. The variables used to define the agent determine where the distance approaches infinity. The variables used to define the agent determine where the distance correspondence to a "90% probability of detection" lies at any given point in time. A target at a distance corresponding to this 90% threshold has a 90% likelihood of being seen by the detecting agent. Detection versus no detection is a discrete outcome that is determined stochastically through a Monte Carlo simulation using the specified underlying probability distribution (here 90%). As range to the target decreases, probability of detection increases. At either range, any particular target would be either detected or not detected, but over a large number of targets, the greater odds would mean a higher percentage of closer targets would be detected.

Visual, infrared, and acoustic detection mechanisms each use the probabilistic algorithm outlined above, but the determinants of how "far out" the detection probability curve is stretched varies greatly from one target and sensor to the next. For example, the 90% detection distance for a squad is based on a standard visual range, which is then adjusted by multipliers which reflect the impact of levels of training, time of day, weather condition, and available equipment (such as IR goggles). Distance is also a function of whether the target is moving or not, with the baseline detection distance being greater for moving targets. Detection distance is also affected by relative target size and target contrast with the surrounding terrain (or target heat signature in the case of IR-based detection).

Understanding Engagements.

Currently the engagement criteria modeled in SWarrior are very simplistic. If an agent "senses" an enemy agent within its sensor range during a particular simulated time step (currently modeled at 10 seconds), then the blue squad agents send a message to the ECOC indicating that they have an enemy in sight. Because of the time of flight issue with the off-shore weapon systems currently modeled, moving targets are not engaged with long range naval surface fires. This is where the Hunter Warrior Assessment Team wanted very much to see the combined advantages and effects of direct fire weapons and mobility when provided to the long-range reconnaissance patrols.

Understanding Communications.

Like the engagement criteria and other aspects of the current version of SWarrior, the information that is exchanged in current communication exchanges is limited to that required to model the dynamics of interest. In this case, the majority of information passed from the blue squads to the ECOC in simulated digital burst transmissions related to enemy locations and activities. Additional communications embellishments would be needed to provide the adaptation and learning desired in a more powerful agent-based model. Large-scale research efforts obviously abound in the arena of command and control theory and modeling. This is a very complex arena that promises to continue to provide many opportunities for complexity theory application.

Understanding Movement

Each agent generally has its own uniquely tailored movement algorithm. As noted earlier, the ECOC and ground based sensors do not move, so this section will focus on movement algorithms for friendly squads, UAVs, and enemy tanks and HMMWVs.

Friendly Squad Movement. Friendly squads are assumed to be pre-positioned in observation positions at the outset of the simulation, and move only to improve visibility, or if encroached upon. When an enemy agent enters the encroachment zone of a friendly squad, and if the friendly squad sees the enemy squad, the friendly squad may attempt to re-locate before being seen by the enemy squad. The point at which the friendly squad will move is currently a simple function of the size of its encroachment zone. This zone varies as a function of the discipline of the squad. Thus, because movement actually increases the likelihood of being seen, a higher setting for the squad's discipline parameter means that it will have a smaller encroachment zone, and will allow red to come closer before vacating its position.

UAV Movement. UAVs are currently launched from a user-defined UAV launch center and fly to a pre-designated patrol area. The UAV agent then proceeds up and down the defined patrol area in successive swaths, with the width of each swath corresponding to the search radius of the UAV.

Enemy Tank and HMMWV Movement. Enemy tanks and HMMWVs proceed forward to user-defined laager positions at their rated speed. If traveling to a laager position, the vehicles choose specific laager positions based on the accessibility and amount of concealment offered by the position. En route to the new position, the specific direction of vehicle movement at each time-step is based on a number of imperatives. All units employ terrain driving when moving from one position to the next. Tank and vehicle commanders employ an algorithm comparing the slope of the next 100 meter square to the distance they will be to their goal when that movement is completed. Based on a weighting factor that the user sets, the vehicle will follow terrain en route to its objective.[99] It is in areas like movement programming where goal oriented planning and re-planning issues need to be addressed and integrated.

[99] SWARRIOR Draft User's Manual.

Appendix I

Elements of Complexity

The following "elements of model complexity" are areas that can be explicitly addressed in an agent-based model to further explore the nature and dynamics of complex adaptive systems:

- **"Number of Variables:** Additional dependent variables can expand the scope of a model's usability, but does not itself improve a model's resolution
- **Non-linearity and Interaction:** In dynamic response models, closed-form solutions can be very difficult to obtain. Results from numerical methods cannot be directly verified.
- **Time Invariance:** Human I/O processing mechanism is usually not time invariant because responses to inputs typically differ as functions of time of application of stimuli.
- **Causality:** Causal systems generate outputs based on current, or previous, but not future, or anticipated, inputs. Because humans naturally formulate and use mental models to facilitate estimation, prediction and decision making, situational responses are functions of not only present and past exposures but also of predicted future events. In this sense, human system responses involving cognitive processing are not always causal.
- **Feedback:** Systems often contain or are part of feedback mechanisms... A soldier, for example, utilizes direct sensory and model-based feedback to direct and adjust behavior and achieve objectives and specified levels of performance despite changes in internal parameters. Hence, closed loop soldier models are preferred over their open loop alternatives for high fidelity, constructive soldier-based simulations.
- **Uncertainty:** Human response models that only use mean values for coefficients and parameters in response functions are effectively deterministic. Human responses to identical sequences of conditions and events typically vary considerably between individuals. Sources of such interpersonal variances include the many differences between individuals in basic characteristics and experience as well as differences in sensitivity to changes in external and internal variables on cognitive, affective and physiological responses.
- **Optimization:** Humans act instinctively in attempts to optimize state trajectories based on qualitative minimization or maximization of various subjective functions of sensations and potential consequences. For example behavior patterns are directed toward minimizing effort, energy, task completion time, distance, expense, inconvenience, stress, distress, etc. Behavior is usually driven by efforts to simultaneously minimize adverse consequences and maximize beneficial ones.
- **Stress:** Software-implemented soldier models typically act deterministically according to scripts or prescribed rules. However, real soldiers are more complex and tend to act in ways that minimizes effort and exposure to stressors. Humans attempt

to efficiently reach objectives by qualitatively optimizing a subjectively weighted sum of gain and cost functions.

- **Noise Filtering:** Humans routinely filter sensory input to reduce the effects of noise and improve the effective signal to noise ratio. Therefore, agent-based models can be made more realistic by appropriately including this capability. Filtering noisy input improves dynamic performance."[100]

[100] Reardon, 16-71.

Appendix J

Expert Systems[101]

Conventional programming languages, such as FORTRAN and C, are designed and optimized for the procedural manipulation of data (such as numbers and arrays). Humans, however, often solve complex problems using very abstract, symbolic approaches which are not well suited for implementation in conventional languages. Although abstract information can be modeled in these languages, considerable programming effort is required to transform the information to a format usable with procedural programming paradigms.

One of the results of research in the area of artificial intelligence has been the development of techniques that allow the modeling of information at higher levels of abstraction. These techniques are embodied in languages or tools that allow programs to be built that closely resemble human logic in their implementation and are therefore easier to develop and maintain. These programs, which emulate human expertise in well-defined problem domains, are called expert systems. The availability of expert system tools, such as CLIPS, has greatly reduced the effort and cost involved in developing an expert system. Rule-based programming is one of the most commonly used techniques for developing expert systems. In this programming paradigm, rules are used to represent heuristics, or "rules of thumb," which specify a set of actions to be performed for a given situation. A rule is composed of an "if' portion and a "then" portion. The "if' portion of a rule is a series of patterns which specify the facts (or data) which cause the rule to be applicable. The process of matching facts to patterns is called pattern matching. The expert system tool provides a mechanism, called the inference engine, which automatically matches facts against patterns and determines which rules are applicable. The if portion of a rule can actually be thought of as the whenever portion of a rule since pattern matching always occurs whenever changes are made to facts. The then portion of a rule is the set of actions to be executed when the rule is applicable. The actions of applicable rules are executed when the inference engine is instructed to begin execution. The inference engine selects a rule and then the actions of the selected rule are executed (which may affect the list of applicable rules by adding or removing facts). The inference engine then selects another rule and executes its actions. This process continues until no applicable rules remain.

FuzzyCLIPS is an enhanced version of CLIPS developed at the National Research Council of Canada to allow the implementation of fuzzy expert systems. The modifications made to CLIPS contain the capability of handling fuzzy concepts and reasoning. It enables domain experts to express rules using their own fuzzy terms. It allows any mix of fuzzy and normal terms, numeric-comparison logic controls, and uncertainties in the rule and facts. Fuzzy sets and relations deal with fuzziness in

[101] http://www.ghgcorp.com/clips/ExpertSystems.html

approximate reasoning, while certainty factors for rules and facts manipulate the uncertainty. The use of the above modifications is optional and existing CLIPS programs still execute correctly.

Appendix K

Future Applications of Nonlinear Science in Agent-based Models

> *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

The use of a CAS tool like SWarrior to conduct an experiment such as the one illustrated in chapter six is just one example of how the warfighter can "fill the gap" and benefit from nonlinear science concepts. If decentralized execution will continue to be central to the success of modem day combat units, we need to remain at the forefront of analysis and experimentation that will allow us to better prepare and train our junior leaders and staffs. A large part of this challenge lies in the area of pattern recognition and decision-making. If our leaders can practice making time-sensitive decisions when provided realistic combat scenarios, they will be better prepared to understand the uncertain environment they will be expected to operate in. They will more easily recognize critical patterns unfolding as conflicting wills collide. Three areas, then, where agent-based models will have additional utility are (1) wargaming, (2) resource allocation analysis, and (3) decision-making training.

MAGTF Staff Training Program

The MAGTF Staff Training Program (MSTP) is one Marine Corps organization that could directly benefit from the development of more robust agent-based simulation. The first aspect of MSTP's training program that could be greatly improved with the addition of an easily modified, agent-based combat model is in the area of **Course of Action Analysis.** The critical third step of the Marine Corps Planning Process, Course of Action Analysis pits a human red cell against the training audience's Operational Planning Team (OPT) and their selected courses of action in a step-by-step wargame. Depending on the experience, training, preparation, and motivation of the red cell, this wargaming interaction can provide widely varying degrees of benefit to the OPT. Intended to provide realistic and challenging counteractions to proposed friendly actions, the red cell's reactions are often naturally constrained by our operational paradigms.

The perspective of most Marines is typically very linear. One of the principle considerations in developing courses of action *is* determining the enemy's most likely and most dangerous courses of action. These are normally derived from a "linear extrapolation of enemy capabilities and doctrine."[102] To avoid the inevitable surprises that result from linear expectations, we need a more efficient, thorough, and nonlinear method to challenge our proposed courses of action. We can expect better results with a "red-cell-in-silicon" that has been programmed with actual enemy doctrine, resources, and behavioral boundaries at the autonomous agent level. One is bound to be challenged with some very interesting and widely varying reactions to proposed friendly courses of action as these adaptive agents explore reactions that we might not normally consider. The author's vision is a system that automates and facilitates a much more effective Course of Action Analysis stage in the Marine Corps Planning Process.

One of the many aspects of training a MEF staff that MSTP is concerned with is the MEF's use of resources, both human and physical. Similar to any well designed combat simulation experiment, an agent-based combat simulation will allow an analyst or staff to quickly examine potential effects of different **resource allocation schemes** within a proposed operational plan. The significant advantage that a bottom-up, agent-based model can provide is that a much larger region or landscape of possible effects will automatically be examined within each iteration or simulation run. The traditional exploration boundaries of a top-down design no longer exist. If designed properly with appropriate measures of effectiveness, a multiple run, agent-based simulation analysis of different resource allocations will provide a much more robust feel for inherent advantages, disadvantages, and risks involved with each allocation scheme. Going back to the data farming metaphor presented in Chapter 2, an analyst will now be able to visualize much richer 3-dimensional effects landscapes. These result graphs will not just reflect logical, program-driven results, but will reflect a broader area of the possible response area than could have been imagined or programmed. By allowing the agents to interact, learn, adapt and operate within broad behavioral boundaries, the analyst will be able to see a more realistic response space. The potential to learn about the underlying dynamics of "the system” is much higher with this new approach.

Decisionmaking

In addition to wargaming advances, adaptive agent simulation models have tremendous potential to facilitate decision-making training. Our current professional military education system attempts to complement real world experiences and enhance commanders' abilities to make sound and timely decisions. There are two basic theories about how we make decisions. They frame the extreme boundaries of what we currently recognize as the decision-making spectrum.

- **analytical decision making :** methodical and time consuming -- reasoning matters more than experience
- **intuitive decision making:** relies on experience and intuitive ability to recognize key elements of particular problem and arrive at the proper decision. Intuitive decision-making thus replaces methodical analysis with an intuitive skill for

[102] Moore, Thomas C., Maneuver Warfare Science 199S, 37.

> pattern-recognition based on experience and judgment. It aims to "satisfice" rather than optimize.[103]

Each approach has different strengths and weaknesses and their use depends on many factors: nature of situation, amount of time and information available, etc. For example, the analytical approach may be more appropriate for pre-hostility decisions where more time is available. Problems with a strictly analytical approach are explored in Appendix L. The intuitive approach is thought to be more appropriate for the vast majority of typical tactical or operational decisions where conditions are rapidly changing and time and uncertainty are critical factors. Here creativity and speed are desirable traits. The Marine Corps' command and control system is thus built around mission command and control that allows us to create tempo, flexibility, and the ability to exploit opportunities but which also requires us to decentralize and rely on low-level initiative.[104] The command and control spectrum and different concepts of command are reviewed in Appendices M and N. The mission oriented command and control philosophy is further amplified in FMFM 1, "Whoever can make and implement his decisions consistently faster gains a tremendous, often decisive advantage. Decision making thus becomes a time-competitive process, and timeliness of decisions becomes essential to generating tempo."

After observing countless force-on-force exercises, a senior officer at the Army's National Training Center recently made a statement that sheds interesting light on the complementary principles of maneuver warfare, mission oriented command and control, and adaptation while indirectly supporting several of the issues discussed in this paper.

> You can defeat a Force XXI-equipped force by being more flexible and agile. Agility and flexibility produced by our disciplined deliberate planning process, detailed wargaming of courses of action, our ability to establish HUMINT observers through the depths of the battlefield, and troopers and leaders who have mastered tactical fundamentals and understand the commander's intent-have been the source of success.[105]

Fully understanding "commander's intent" is central to the mission-oriented command and coordination philosophy that is central to maneuver warfare. It relies on the use of mission tactics where seniors assign missions and explain the underlying intent but leave subordinates as free as possible to choose the manner of accomplishment.[106]

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[103] MCDP 6, 102.

[104] MCDP6, 102-104.

[105] NTC Observations from e-mail, from Col Brown, Doctrine Div, Dec 23.

[106] MCDP 6, 112-114. "Commanders seek to exercise a sort of command by influence. Mission command and control relies on **lateral coordination** between units as well as communications up and down the chain. We seek to minimize coercive methods of command and control with spontaneous, self-disciplined cooperation based on **low-level initiative**, a commonly understood **commander's intent, mutual trust,** and **implicit understanding and communications.** Low-level initiative hinges on distributing the authority to decide and act throughout an organization rather than localizing it in one spot. This places a special burden on subordinates, requiring that they always keep the larger situation in mind and act in consonance with their senior's intent. Initiative distributed throughout an organization is a source of great

This freedom leverages the situational awareness of the small unit leader. As MCDP 2 explains, "Maneuver warfare requires decision and action based on situational awareness -- a keen understanding of the **essential factors** that make each situation unique -- rather than on preconceived schemes or techniques."

All military decision-makers must demonstrate intuitive, analytical, and creative skills that are the products of experience, intelligence, boldness, and perception. When time is not critical, we need to understand the factors that favor an analytical decision. While intuitive decision making skills are paramount, we should be able to adopt an analytical approach or to reinforce intuitive decision-making with more methodical analysis when necessary.

Artificial intelligence and other new programming advances can help in the modeling and testing of courses of action, but in the end it is only software. What matters is the "wetware"[107] in the commander. To help train that "wetware", the commander needs to have countless vicarious experiences in peacetime (crossing the river, moving through the mountain pass, attacking the fortified bunker complex, etc). When the real opportunity comes, he can then intuitively recognize critical opportunities while minimizing friction enroute to a quick decision.[108] Situation assessment is a critical capability in the intuitive decision-making process. This capability can be enhanced through tactical decision games.

Silicon Tactical Decision Games (TDG)

Tactical decision games on paper have proven a relatively quick and efficient way to expose military leaders at all levels to challenging decision-making scenarios. These are particularly useful for junior leaders since a lack of experience is the most common cause of errors in situations that require intuitive decisions. One of the hidden benefits of this type of drill is that it encourages the development of important discernment and pattern recognition skills.[109] As General Krulak recently said, "The inescapable lesson of

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strength and energy, especially in times of crisis. The **commander's intent** pulls various separate actions of the force together. It provides topsight and the logic that allows subordinates each to act according to their unique circumstances while maintaining harmony with one another and the higher commander's aim. Mutual trust is the cornerstone of cooperation. Implicit understanding and communication do not occur automatically. They are abilities we must foster and are the product of a common ethos and repeated practice."

[107] E-mail discussion with Maj John Koenig, USMC.

[108] Koenig.

[109] Czerwinski, 139-140. "The highest form of Aids to Learning is pattern recognition, which is closely related to the building block mechanism of complex adaptive systems. It is a nonlinear 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. A major requirement for pattern recognition capabilities is to infuse lower echelons with both the confidence and competence to engage in semi-autonomous action in accordance with Van Creveld's rules. The culprit is an ideal of analytical decision making 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

Somalia, and of other recent operations, whether humanitarian assistance, peacekeeping, or traditional warfighting, is that their outcome may hinge on *decisions* made by small unit leaders and by actions taken at the lowest level.[110] The natural next step in preparing these "strategic corporals" is computer aided tactical decision games where leaders are challenged by an autonomous enemy (intelligent, adaptive agent-based enemy) to consider a broad range of decisions.[111] This type of training environment can efficiently develop the recognitional decision-making skills of any leader.

Recognitional Decision Making

"Experts see what others don't see. They are able to make judgments and act on subtle cues."[112] Proficient decision makers are able to use their experience to recognize a situation as familiar, which gives them a sense of what goals are feasible, what to expect next, and what actions are typical in that situation. The ability to quickly recognize the set of required actions in a situation means that the experienced decision-makers do not have to do any concurrent deliberation about options. In decision theory language, this is called a recognition-primed decision (RPD). When officers are able to use experience to recognize the key aspects of the situation, a quick reaction is enabled. Once a decision-maker identifies a typical action in his mind, he usually imagines what will happen if the action is carried out in this situation. This is where agent-based models can assist. If any problems are anticipated, then the leader usually eliminates that course of action and thinks about the next most typical action. The experienced decision-makers are not searching for the best option. They only want to find one that works. This strategy is commonly called "satisficing". "Studies have found that even with non-routine incidents, experienced decision makers handle approximately 50 to 80 percent of decisions using recognitional strategies without any effort to contrast two or more options."[113]

It is an irony of the chain of command that the leader with the most highly developed intuition as a result of vast experience (the general) rarely uses that talent in time compressed situations. Meanwhile, the leader whose need for intuition is the greatest (the NCO and junior officer) lacks the requisite experience to have developed that same

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comparison. The idea is that that decision maker deliberates about several options concurrently. The technical term is multi-attribute utility analysis."

[110]Krulak, General Charles C., USMC. *Marines Magazine*, (January 1999): 26.

[111]A system currently being developed to support the Marine Corps Warfighting Lab in their Sea Dragon experiments is known as the Integrated Marine Multi-Agent Command and Control System (IMMACCS). It provides an agent-based decision support system to assist the user in both planning and shaping of the battle space and situation awareness. The human- Integrated Collaborative Decision Support (ICDS) interface uses expert agents to assist decision making by the MAGTF Commander and his staff provides greater situation awareness, and rapid decision making based on information with a higher degree of accuracy. Thus, accelerating the commander's capability to execute the Plan, Decide, Execute (PDE) decision cycle, an out- execute an adversary.

[112] Klein, Decision Makers in Action, http://www.decisionmaking.com/applications/applications.html.

[113] Czerwinski, 139-140.

level of useful intuition.[114] Fortunately as a result of Hunter Warrior, decision-making training systems are being developed for the Marine Corps junior leaders.

New tools and new approaches to training are giving small unit leaders unprecedented experience in cuffing-edge leadership and decision-making. Hunter Warrior proved that small unit leaders can perform at a much higher level if given the proper training and equipment. A Combat Squad Leader's Course[115] was developed by WFL to build on the idea of pushing combat decision making down to the small unit level. Quicker, confident decisions and faster execution generate a tempo that can overwhelm an opponent. The Combat Decision-making Range (CDR) is a key component of the Squad Leader's Course success. The intent of the CDR is to enable trained squads to maneuver and make rapid, opportunistic decisions (adaptation at the lowest level). Applying this principle throughout a force, senior commanders can seize and exploit the momentum gained by the initiative of hundreds of confident, small unit leaders. Similar to the silicon tactical decision games described earlier, this training will allow leaders to confidently say, "I have seen this sort of situation before and I know what to do."[116]

In summary then, training decision-makers and enhancing the staff planning process are two more practical areas where a transition from using nonlinear metaphors to nonlinear models can provide benefits to the warfighter.

[114]Czerwinski, 154.
[115]New York firefighters identified three main components required to operate in chaotic, rapidly changing situations: **communications, situational awareness,** and **realistic training.** Agreeing with their assessment, the Warfighting Lab developed Marine battle scenarios and a facilitator package to integrate these same three components. The Combat Decision-making Range (CDR) that was created is now an integral part of the Combat Squad Leader's Course. The scenarios vary so that in the span of a 30-45 minute training session (one scenario) a squad leader must make 15 to 30 rapid fire decisions while sending situation reports and orders up and down the chain of command.
[116]Sullo, Capt Mark, USMC. "Combat Decision Range Training" *Marine Corps Gazette,* (Feb 1999): 37.

Appendix L

Problems with Analytical Decision Making

"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 irrelevant 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. Rather than trying to change the way military leaders 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 decision making in a number of ways. One opportunity is to improve strategies for effective team decision making. Staff exercises are too often a charade, where they present options to a commander who then picks the best one."[117]

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 decision making 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 military leaders with a wide variety of situations and outcomes, and letting them improve their recognition abilities. A fourth opportunity is to improve decision support system. We want to build decision support systems that enhance recognition as well as analytical decision strategies.[118]

[117] Czerwinski, 150-152.
[118] Czerwinski, 153-154.

Appendix M

The Command and Control Spectrum

The two basic responses to the fundamental problem of uncertainty in war are to pursue certainty for effective command and control or accept it as fact and learn to function in spite of it. These responses result in the varying approaches often referred to as 'detailed command and control' or 'mission command and control'. Mission command and control accepts the turbulence and uncertainty of war. It supports spontaneity. Subordinates are guided not by detailed instructions and control measures but by their knowledge of the requirements of the overall mission. In such a system, the commander holds a loose rein, allowing subordinates significant freedom of action and requiring them to act with initiative. Mission command and control tends to be decentralized, informal, and flexible. It seeks to increase tempo and improve the ability to deal with fluid and disorderly situations. These two approaches mark the theoretical extremes of the spectrum. In practice, most commanders use a combination.[119]

Dr Gary Klein and associates have been conducting fascinating research in the decision making arena for many years. Well known and respected in the Marine Corps, his company has made great strides in educating leaders and staff in countless corporate, civil, and military organizations about the human cognitive process and how we seek and use information in our decision making. The research his company continues to conduct has relevance across at least two different threads that the author has discussed in this paper and direct application to the application of complexity theory to warfighting. If we can better understand the dynamics and principles of our own analytical and intuitive decision-making processes, we can better train our decision-makers and we can better integrate that process in our combat models. For example, in a research project conducted for the National Defense University to study decision making and cognitive demands of commanders of Operations Other than War (OOTW), they uncovered important expertise by looking for the critical cognitive aspects of the commander's job. These aspects included: perceptions, judgments, situation assessments, and decisions about the events, critical needs, and problems and solutions of the environment the commanders were working in. Examples of probe questions that were generated during interviews with former OOTW commanders were:

- How did you know that?
- What made you think that would be important?
- What other information did you need? Where did you seek it?[120]

[119] MCDP-6, 77.
[120] Commander's Cognitive Demands in OOTW, Klein Associates, Inc.

Appendix N

Concepts of Command[121]

Command-by-Direction: Specific top-down guidance is provided. Structure facilitates command and control of as much of system as possible from a central location.

Command-by-Plan: Command-by-plan opts for comprehensiveness over dynamism. This approach inherently fights the disorderly nature of war as much as the adversary. Approach is characterized by trading flexibility for focus. Dwight Eisenhower furnished a good relationship between planning and command: "In preparing for battle, I have always found that plans are useless, but planning is indispensable." 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.

Command-by-Influence: The hallmark here is mission type order. This method of command takes disorder in stride. Great reliance is placed on the initiative of subordinates based on local situational awareness. The outline of a command-by-influence system is founded on mission type orders and self-contained units capable of semi-autonomous action complemented by four traits:

- Recognition that the native mode of command is an image, or mental model, not voice or text.
- 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.
- The provision of subtle directed telescopes.
- The introduction of the principles of post-Newtonian science, and reducing the use of voice and text in the battlespace.

In MCDP-6, this form of command encourages traditional "control" to take the form of feedback. Control is not strictly something that seniors impose on subordinates; rather, the entire system comes 'under control', based on feedback about the changing situation. The result is a mutually supporting system of give and take in which complementary commanding and controlling forces interact to ensure that the force as whole can adapt continuously to changing requirements.

[121] Czerwinski, Surface Warfare, Jan/Feb 1998.

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