IDA

Complex Adaptive Systems
in Military Analysis

Keith L. Green

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INSTITUTE FOR DEFENSE ANALYSES

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1. Complex Adaptive Systems in Military Analysis

From the battlefield adjutants he had sent out, and orderlies from his marshals, kept galloping up to Napoleon with reports of the progress of the action, but all these reports were false, both because it was impossible in the heat of battle to say what was happening at any given moment and because many of the adjutants did not go to the actual place of conflict but reported what they had heard from others; and also because while an adjutant was riding more than a mile to Napoleon circumstances changed and the news he brought was already becoming false. Thus an adjutant galloped up from Murat with tidings that Borodino had been occupied and the bridge over the Kolocha was in the hands of the French. The adjutant asked whether Napoleon wished the troops to cross it? Napoleon gave orders that the troops should form up on the farther side and wait. But before that order was given—almost as soon in fact as the adjutant had left Borodino—the bridge had been retaken by the Russians and burned...[1]

War and Peace is of course a narrative fictional account, but having served in the Russian Army, Tolstoy was conveying in this passage not just hypothetical knowledge gained through his study of history, but to some extent his personal experience in the Crimean. One wonders what Tolstoy might have written had he witnessed the use of technology by the First-World militaries of today. There exists that data allows commanders to know within tolerable error where their units are in near or near-real time; radios permit them to make inquiries of field units and communicate orders in seconds; Unmanned Aerial Systems provide real-time reconnaissance of an area many miles from their headquarters. And yet soldiers still die, and battles may still be won while campaigns are lost. Confusion reigns. Sometimes military analysts cannot answer except with anecdotal evidence or gut feeling what seems a simple question: *Are we winning or losing?* Moreover, military analysts often cannot answer credibly and convincingly whether a particular action has helped or harmed the cause. War differs from the subjects that traditional technical analysis is well-suited to address; however, in attempting to address the complex problems of war, analysts often attempt to apply traditional techniques by making simplifying assumptions invalid in the real world. In effect, the analysts ignore the complexities of war altogether. War displays archetypical features of complex adaptive

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[1] Leo Tolstoy, *War and Peace* Project Gutenberg, Book 10, Chapter XXXIII, accessed at <www.gutenberg.org/files/2600/2600.txt> 24 Aug 2010.

systems—systems comprising agents that make decisions based on local, sometimes erroneous or dated information in which interactions produce patterns that could not have been calculated or derived beforehand.

The mission space for the US military has been dominated in recent years by tasks that were not the focus of the military during much of the twentieth century, when major combat operations against other major powers was the primary concern. These new tasks cut across what has been described as the range of military operations and the problems associated with these tasks cannot be adequately addressed by traditional, fixed responses. Such problems require generalized adaptive strategies and capabilities. Today's military prevents genocide, delivers humanitarian assistance, counters insurgents, trains foreign militaries, assists reconstruction, and supports civil authorities in a range of missions, from disaster relief to combating drug trafficking. Mission outcomes can be strongly influenced by factors that have nothing directly to do with logistics or kinetic operations. Local economic, political, and social factors exacerbate inherent complexity—as can the economic, political and social factors in the United States and around the world. A US Marine Corps manual states explicitly, *War is a complex phenomenon.*[2]

A. Overview

For the past several years, the Institute for Defense Analyses (IDA) has hosted an informal lecture series on complex adaptive systems, funded by IDA's Central Research Program (CRP). Typically an invited expert discussed a particular aspect of complexity during a "brown bag" lunch session. Sometimes the speaker was an IDA employee, but more often the speaker was an expert from academia, government, or industry. This paper synopsizes what was learned.

To provide such a synopsis, this paper will describe complex adaptive systems, explain how they can be of value to commanders and military analysts, and give examples of applications that demonstrate how the emerging field of complexity can contribute to military analysis.

Complex adaptive systems theory and techniques provide insights into the nature of adaptation and how it might operate. For example, military institutions recognize the need for leaders who can adapt, but struggle with exactly how to teach or train them to do so. One example here will show how understanding complex adaptive systems theory enabled a commander to be more adaptable and to succeed in his mission.

In some cases, complex systems theory provides methods for recognizing structure and hypothesizing reasons for that structure. The discovery of scale-free structure in a

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[2] US Marine Corps, *Warfighting* MCDP 1 (Washington, DC: Dept of the Navy, 20 June 1997), 12, <www.dtic.mil/doctrine/jel/service_pubs/mcdp1.pdf> accessed 8 Sept 2010.

hierarchical organization can indicate similar causes or analogous opportunity. *Scale-free structure* means that the structure is repeated at different levels of the organization, from the smallest scale to the largest. This repeated similarity of structure can in some instances indicate similarity of causes. Identifying this deep structure could supply input to other models, or insights that allow commanders to shape engagements.

Complex adaptive systems are implicit search agents that are always looking for better results. The implicit target for the search is improved survivability, which is determined by the ability of a potential solution to locate points of leverage that produce desired outcomes. The behavior of these systems is analogous to biological evolution. Therefore, military analysts might be able to exploit the ability of evolutionary systems to explore possibilities for continuous improvement.

B.   What makes a system complex and adaptive?

The greatest obstacle to discovering the shape of the earth, the continents and the ocean was not ignorance but the illusion of knowledge.[3]

To recognize a complex adaptive system for what it is, one ought to first distinguish it from what it is not. While a common dictionary may define *complex* and *complicated* as synonyms,[4] the scientific definitions are distinct. A modern jet is a complicated product of technological expertise and engineering design, but it is not a complex system in the technical sense of the term. First, its functional behavior falls within prescribed operating parameters that can be reasonably understood through analysis and simulation. Next, the plane will not of its own accord spawn new, unexpected behaviors or modes of operation. However, the human institutions that collectively develop and produce modern jet aircraft may constitute a complex adaptive system.

There are many familiar examples of complex adaptive systems and most of them are of interest in one way or another to the military. Keeping a few of these in mind helps one recognize the common structure and properties that "define" complex adaptive systems. Many systems are complex and adaptive—living organisms, immune systems, ecologies, societies, economies, political systems, communications networks (including their users' behaviors), military organizations, and war itself. Individual living cells are complex adaptive systems, as are human brains. The entire ecosystem of the Earth is also a complex adaptive system. Thus, a complex adaptive system can be composed of complex adaptive systems or be an element of an even larger complex adaptive system.

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[3]   Daniel J. Boorstin, *The Discoverers: A History of Man's Search to Know His World and Himself, New York*, Random House, 1983, p.86.

[4]   *American Heritage Dictionary*, entries for *complex* and *complicated*, <http://dictionary.reference.com/browse/complex> accessed 21 Aug 2010.

Although there is as yet no universally accepted definition of complex adaptive systems, Elgazzar and Hegazi offer a usable definition: A complex adaptive system consists of inhomogeneous, interacting adaptive agents. Adaptive means capable of learning.[5] In this instance, the ability to learn does not necessarily imply awareness on the part of the *learner*; only that the system has memory that affects its behavior in the environment. In addition to this abstract definition, complex adaptive systems are recognized by their unusual properties, and these properties are part of their *signature*. Complex adaptive systems all exhibit non-linear, unpredictable, emergent behavior. They are self-organizing in that their global structures arise from interactions among their constituent elements, often referred to as *agents*. An agent is a discrete entity that behaves in a given manner within its environment. In most models or analytical treatments, agents are limited to a simple set of rules that guide their responses to the environment. Agents may also have memory or be capable of transitioning among many possible internal states as a consequence of their previous interactions with other agents and their environment. The agents of the human brain, or of any brain in fact, are called neurons, for example. Rather than being centrally controlled, control over the coherent structure is distributed as an emergent property of the interacting agents. Collectively, the relationships among agents and their current states represent the state of the entire complex adaptive system.

By *inhomogeneous*, the authors means that each agent is an individual in the system. Any agent may (and generally does) have data elements (called *properties*) with at least some values that differ from the data element values of all other agents in the system. Furthermore, the system may comprise different kinds of agents. For example, the components of a police "system" may include human military police agents and also K-9, or dog, agents. These different kinds of units may have not only different data element values but different data elements altogether.

In a complex adaptive system, the large number of agents interacting over time generates unpredictable and distinct large-scale patterns that often suddenly change. From different starting conditions or environmental situations, the same complex adaptive system might exhibit very different long-term, large-scale patterns and different sequences of transition from one pattern to another. This formation of large-scale structure and tendency to transition from one pattern to another is often referred to as *emergence*. Emergence is possible because agent interactions lead to runaway feedback spreading throughout the entire system.

Some military units are capable of emergent self-organization. US Navy Sea Air Land (SEAL) team members may not plan or be directed into specific formations, but a formation will result as a result of each team member's being cognizant of his own abilities and

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[5] E. Ahmed, A.S. Elgazzar, A.S. Hegazi "An overview of complex adaptive systems," in Mansoura J. Math, 28 June 2005; <http://arxiv.org/PS_cache/nlin/pdf/0506/0506059v1.pdf> accessed 21 Aug 2010.

range of observation as well as that of his fellow team-members.[6] While emergence is a powerful and often surprising occurrence, it is not necessarily good for all parties concerned. Nature provides numerous examples of emergent behaviors that benefit one class of agent and not another. For example, the ichneumon wasp[7] implants its egg in a caterpillar, inside of which the egg hatches as a larva. The larva feeds on the inside of the caterpillar, feeding on the least necessary parts first so as to keep the host alive as long as possible. This emergence is useful for the propagation of ichneumonoidea, but not so much for the caterpillars.

A given computer model of a complex adaptive system does not generally reproduce exactly the same patterns and sequence of patterns given identical initial conditions. Slightly different initial conditions are likely to generate widely divergent patterns, while very different initial conditions can general similar patterns. Characterizing the common emergent patterns and properties of the transitions among patterns is often the most predictable, understandable, and useful aspect of complex adaptive systems analysis. The analysis of these patterns requires new branches of mathematics and statistics such as fractals and fat-tailed distributions that violate typical probabilistic assumptions.

Nonlinearity is a fundamental characteristic of complex systems and can manifest in systems in two ways and is important because emergence cannot happen without nonlinear effects. Nonlinearity occurs when the effect produced by a change in two or more variables does not equal the sum of the effects produced when the variables are changed individually. In some cases, the effect of changes in two variables acting in unison can amplify; in others, they can cancel each other out—or even cause an opposite effect. For example, Sodium (Na) and Chlorine (Cl) are poisonous; however, when they are combined into NaCl (table salt), they are an essential nutrient. A hypothetical military example might be developers noting that outfitting a soldier with a new kind of individual weapon marginally increases his life expectancy, and that putting more armor on the individual also increases his life expectancy. It could be that upgrading both of these would increase life expectancy even more, or it could be that increasing the soldier's load so much adversely affects his mobility and reduces his life expectancy. In this kind of nonlinearity, effects are not additive. Multiple changes that are good individually, may not be so good when added together—they may even be harmful. This form of nonlinearity is often called synergy—though the word is commonly used positively, synergy in this sense may be negative.

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6. Capt Todd Veazie, lecture to Complex Adaptive Systems Group, Institute for Defense Analyses, Alexandria, Virginia, 27 Nov 2007.
7. Stephen J. Gould, "Nonmoral Nature," The Unofficial Steven J. Gould Archive, <www.stephenjaygould.org/library/gould_nonmoral.html> accessed 30 Aug 2010.

Another form of nonlinearity occurs when a change in a variable and its effect are not proportional. For example, humans need water, but imbibing too much can be deadly (an effect called hyperhydration). To modify the previous example to illustrate this concept, suppose that increasing a soldier's body armor by 10 percent increases survivability approximately 1 percent and increasing body armor 20 percent increases survivability nearly 2 percent. It could be that increasing armor by 30 percent would decrease the probability of survival, because a 30 percent increase slows him down and wears him out. In this kind of nonlinearity, effects are not proportional. More of a good thing is not always better, nor is less of a bad thing.

Complex adaptive systems must be nonlinear since linearity would imply that combinations of different input conditions would simply lead to combinations of the individually known consequences. This would preclude emergence and the other unpredictable aspects of a complex adaptive system's behavior.

Linear systems are easier to analyze; on the other hand, they are also less interesting and often misleading when used as proxies for understanding nonlinear behaviors.

C. The value of studying complex adaptive systems

It is generally accepted that complexity is better handled through adaptive responses than fixed ones and that "[W]ar is … a process of continuous mutual adaptation …",[8] but Freeman and Burns write, "*… we have found no scientifically acceptable metrics, in the military or other domains, which would validate current efforts to train or develop adaptability. Thus, to this point, there is no consensus on how to train adaptability, particularly within the world of behavioral and social scientists who have been most engaged in pursuing adaptability development."*[9] Even recognizing that one is in a situation where adaptation is required can be a challenge. "*Adaptability requires being able to recognize an altered situation that requires a change in response, but it also requires the ability to recognize when the situation demands committing to well established means for carrying out a task.*"[10]

Recognizing when one needs to adapt is often elusive, even for very intelligent, very well-trained people. The case of the Eighth Air Force in World War II illustrates this.

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[8] US Marine Corps, *Warfighting,* 3.

[9] William R. Burns, Jr. and Waldo D. Freeman, *Developing an Adaptability Training Strategy and Policy for the DoD Interim Report*, IDA Paper P-4358 (Alexandria, VA: Institute for Defense Analyses, October 2008), 21. The Department of Defense subsequently sponsored a limited experiment, with metrics, demonstrating that training can enhance adaptability. However, efforts to train and measure adaptability remain in their infancy. Waldo D. Freeman and William R. Burns, Jr., *Developing an Adaptability Training Strategy and Policy for the DoD* IDA Paper 4591 (Alexandria, VA: Institute for Defense Analyses, August 2010.)

[10] William R. Burns, Jr. and Waldo D. Freeman, *Developing an Adaptability Training Strategy and Policy for the DoD Interim Report*, IDA Paper P-4358. p. 42.

Prior to the war, military leaders had developed a strategy based on the assumption that it was possible to conduct long-range bombings using massed bombers (300 or more) and that the bomber pilots could accomplish their mission with few losses—even without long range fighters as escorts. The leaders maintained this strategy long after it had been shown to be a complete failure. It wasn't until new leadership took over that the Eighth Air Force was able to recognize the problem and change to a more appropriate strategy.[11]

1. Recognizing structure

Complex adaptive systems theory also provides methods for recognizing structure in data that may otherwise appear random. If, for example, aspects of data can be described by certain probability distributions, it might suggest underlying conditions that could cause that kind of distribution. Commanders and analysts can then look for processes and relationships that would generate those conditions. If those relationships are robust in varying conditions, the process must be a dominant one that shapes virtually all outcomes. That is, CAS theory can generate hypotheses about the nature and cause of the similarity between organizational levels. This kind of information is useful both for understanding how the system arrived at its current configuration and how the system might respond to perturbations. Is it more likely to break or to reform itself according to its former order? Thus, deviations from a common scaling relationship or shifts in its parameters have broad operational implications.

2. More effective search methods

Many complex adaptive systems are effectively systems that search. Biological evolution, for example, can be viewed as a non-targeted, opportunistic search for genes and transmitted behaviors that are better adapted to survive. A central challenge is that defining goals of a search implicitly limits the search to preconceived expectations of what a good solution should look like. Biological evolution has solved this problem, but in an extremely inefficient way: random mutation to explore adjacent reachable potential solutions. But evolution is opportunistic only because it is does not (and cannot) look ahead to future states. Human intelligence is constrained by the individual's experience and knowledge, but evolution is constrained by what can be achieved locally. There is some evidence that hybrid techniques can yield better results more efficiently by drawing on multiple perspectives of a situation. A hybrid technique is one that uses humans and computers jointly to search the space of potential solutions, using the strengths of each.

Computer scientists, inspired by the seeming ingenuity of evolution to produce novel adaptations, have developed a variety of techniques that apply the principles of biological

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[11] Murray Williamson, *et. al.*, *An Historical Perspective on Effects-Based Operations* IDA Paper P-3606 (Alexandria, VA: Institute for Defense Analyses, October 2001), 37–46.

evolution to the search for improved solutions or designs. Using these evolutionary techniques, the scientist develops a way to *encode* or translate potential solutions into a sequence of ones and zeros inside of agents running in a computer program. These encodings are analogous to a set of genes in an organism and are evaluated by the computer against a function, called a fitness function, to determine how well they solve the problem. The multi-dimensional *surface* representing this fitness function is called a *fitness landscape*. Stanford University computer scientist John Koza produced an example of this technique when he developed a machine that used genetic programming to produce the first patent by a nonhuman designer.[12] Answers from this kind of system tend to be easily accepted, because one knows when one has something that works.

The *search space* is determined by all the combinations of actions (decisions) the agent can conceivably take to improve its situation (solve the problem). If there are only two variables the agent can alter, and the number of variables is limited, the search space will look like a 3-D, topographic map with the higher points on the map representing those more probable to improve agent survivability. Generally, finding better solutions (higher ground) means having to travel through a valley (passing through a less desirable state) first. Most humans can easily find the optimal solution by inspection on a simple map like this, particularly if they are provided with a view of the search space (also known as a fitness landscape). But unlike toy problems that might be represented by a few variables, real problems, like those that businesses, governments, militaries, and organisms encounter yield search spaces that are multi-dimensional, usually massively so, and the optimum cannot be found by visual inspection. Humans faced with decisions in this kind of landscape can generally use their experience as a guide, but this limits exploring the possibilities, and doing so can lead to disadvantage relative to others with better options. Therefore, mapping this fitness landscape becomes the challenge in developing better search methods and ways of identifying key information.

Because there are so many conceivable solutions that they cannot all be examined, an adaptive search strategy emphasizing, for example, "freedom of action" is essential to finding solutions that open up a spectrum of opportunities or are less costly to execute. While military analysts would prefer to optimal solutions, most of the time we will settle for a solution that is at least better than what we can guess at. In some cases, evolutionary techniques have yielded excellent results—they are reasonably good at exploring the search space for solutions. For example, the National Aeronautic and Space Administration

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[12] John Koza, "John Koza has Built an Invention Machine," *Popular Science* (19 April 2006) <www.popsci.com/scitech/article/2006-04/john-koza-has-built-invention-machine> accessed 10 Aug 2010.

(NASA) used genetic methods to develop an antenna for a spacecraft.[13] Genetic methods mimic biological evolution by using a population of potential solutions, each represented by a sequence of bits that specify parameters for that solution. The solutions replicate by combining and mutating—the better solutions having a much better chance of replicating and surviving, and the lesser solutions eventually being eliminated from the population.

D. Summary

Complex adaptive systems are composed of agents, interacting through rules to produce non-linear, emergent behavior. The field of complex adaptive systems provides tools that can help military analysis in some cases. It provides insight into the nature of adaptation that suggests how to improve adaptability. Further, it provides a way of recognizing and capitalizing on latent structure in data. Finally, complex adaptive systems are implicit search engines or systems that attempt to improve survival in a landscape of potential solutions.

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[13] Jason D. Lohn, *et. al.*, "An Evolved Antenna for Deployment on NASA's Space Technology 5 Mission," *Genetic Programming* 8 (2005): 301–15, <www.springerlink.com/content/j83kp71803664377/ full-text.pdf> accessed 13Sept 2010.

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2. Example Applications of Complex Adaptive Systems

This section will comment on a small sample of the many applications of complex adaptive systems techniques that have been developed.

A. Reconstruction in Afghanistan

The first example of complex adaptive systems making a unique contribution to military analysis is the case of Adaptive Campaigning, developed by the Australians, Dr. Anne-Marie Grisogono and Dr. Alex Ryan, and implemented by LTC Mick Ryan in reconstruction efforts in Afghanistan. This example is salient, because the science of complex adaptive systems provides the conceptual framework for Adaptive Campaigning.[14]

Adaptive Campaigning grew out of Action Group 14: Complex Adaptive Systems, which was established with a three-year mandate in 2006 by The Technical Cooperation Program, a confederation of the five Anglophone nations: the United States, Great Britain, Canada, New Zealand, and Australia. Their objective was, among other things, to "develop [a] fundamental theory of complex systems and processes" and "methodologies, tools, and techniques for applying complex systems science insights and concepts to real world problems in defence and security."[15]

The Australians began studying adaptation in natural systems in an attempt to develop general principles of adaptation. They looked to Nature for inspiration and education, because Nature has "solved" innumerable complex problems in innumerable complex adaptive systems. The model developed is "*[change—evaluate—select—implement] repeat.*"[16] This is easily recognized as a variant of the standard description of the evolutionary process of natural selection—replication with mutation and selection based on implicit fitness evaluation in the context of the population's environment. We can also see another natural system in this model—learning in humans.

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[14] Anne-Marie Grisogono and Alex Ryan, "Operationalizing Adaptive Campaigning," 2007 CCRTS: Adapting C2 to the 21st Century, 1, <www.dodccrp.org/events/12th_ICCRTS/CD/html/papers/198.pdf> accessed 28 Aug 2010.

[15] Anne-Marie Grisogono, "AG14—Complex Adaptive Systems for Defence," brief to Joint Systems & Analysis Group Meeting, 11 June 2008, 4.

[16] Anne-Marie Grisogono, *et. al.*, "TTCP Technical Report, Joint Systems & Analysis Action Group 14 Complex Adaptive Systems for Defence: Synthesis Report, Conceptual Framework for Adaptation," May 2010, 5.

Among other things, the Australians suggested replacing the OODA-loop with an ASDA-loop. OODA standing for Observe, Orient, Decide, Act—a generalized plan for military action developed by American military strategist Col John Boyd. ASDA stands for Act, Sense, Decide, Adapt. While the Australians were attempting to couch their ideas in terms recognizable to soldier-implementers, the shift, while subtle, is important. *Act* can be repetitive. *Adapt* explicitly recognizes the need to change. This approach assumes that the commander will not know what the perfect course of action is and must do something to acquire information so that he can adapt his actions to correspond more directly with the continuously revealed nature of his mission in context. Furthermore, it's an attempt to circumvent or counteract cognitive biases that invariably sneak into the decision-making process by forcing the commander to continually test his assumptions and knowledge of his environment. This idea runs counter to the natural human desire to "set it and forget it." Humans want to make decisions and then move on to the next problem. This can work well in a complicated environment, but not so well in a complex one. The nonlinearity and inherent unpredictability of complex environments ensures that many necessary assumptions are found to be false and many corroborated essential facts can change with little warning. Unfortunately for commanders (and the rest of us), many facts are time-dependent.

A few pages cannot do justice to the depth and breadth of Dr. Grisogono's work, but one more facet of the work needs to be mentioned. Anyone who studies ecology or genetic algorithms understands the importance of having fitness functions that correspond to survivability. Consider this simple question: *Which is better adapted, a lion or a penguin?* No organism has infinite strength, speed, intelligence, size, or resistance from disease and predation. There is no such thing as a perfect organism. When environments change, what was once an advantage can quickly become a liability. This is a crucial insight. It's not just what an organism (or agent) is, what it has, or what it can do that improves survivability, but its ability to adapt to changes.

Paleontologists and geologists recognize five mass extinction events from the ancient past of life on Earth. In each episode, 25 percent to more than 75 percent of families of organisms died off. There were many other mass extinctions annihilating a lesser, but nevertheless large, percentage of families and genera. An analogous thing happens for companies and industries unprepared for change. Few milkmen or elevator attendants remain. Companies that rent VHS tapes in specialized shops are struggling as newer technologies make their products obsolete.

Considering these facts, it is understandable why the Australians advocate what they call an *adaptive stance* where commanders are constantly looking for ways to test their knowledge about the world.[17] Adaptability requires more than just saying the words, "I'll adapt to change." It requires developing specific personal skills necessary to enhance

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[17] Grisogono, *et. al.*, "TTCP Technical Report," 34.

adaptive performance, and it requires having in place attitudes and social structures that enable and foster adaptive performance.

Moreover, the Australian analysts have established a way to think about levels of learning in systems.[18] Each level implemented adds powerful new capability to adapt within a system. The third level and above, for example, provide a generalized method of not just how to become better adapted, but how to become more adaptable.

B.   Collective Intelligence

The second example is another of how complexity thinking in itself can provide unique insight into analysis for militarily relevant problems. Dr. David Bray, formerly of IDA, has applied the notion of *wisdom of the crowds*[19] or *crowdsourcing* to analyze the functioning of the US Intelligence Community. Bray's analysis is prescriptive. The world is a complex place and the kinds of threats the United States faces are numerous and varied. The quality of analysis that can be produced by a *diverse*, *connected, interacting* intelligence community is better than what we could expect from the BOGSAT[20] where there is far less diversity. Moreover, typical hierarchical management structures severely limit communication. Bray writes "Diversity trumps ability."[21] It is not just a matter of putting a random group of people in a room or connecting them on the Internet to achieve the best results. Dr. Bray explains how this system, comprising people with diverse experiences, can produce better results than a group of experts, and he lists the preconditions necessary for them to do so.

The mechanism described in the previous paragraph works for much the same reason that an evolutionary search works. The problem with admonishing people to "think outside the box" is that when they claw their way out, they are just in a bigger box. The search space for any individual is constrained by the box he lives in—this is as true for experts as for non-experts. Moreover, the experts' boxes have a high degree of overlap. Having diverse experience and knowledge provides ideas and insights that expand the search space. However, the members of the diversified team have to all share the same goal and their values cannot be so divergent that the group splinters.[22]

Finally, Bray offers a number of examples to show how crowdsourcing has worked outside the federal government and provides some insight into how to pick the particular

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[18] Grisogono, *et. al.*, "TTCP Technical Report," 19–22.

[19] James Surowiecki, *The Wisdom of Crowds: Why the Many are Smarter than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations*, Doubleday, 2004.

[20] Bunch of Old Guys Sitting Around a Table.

[21] David A. Bray, *Collective Intelligence and Knowledge Ecosystems: The Future of the U.S. Intelligence Community* (15 Aug 2008), available at SSRN: http://ssrn.com/abstract=1303211.

[22] Bray, *Collective Intelligence and Knowledge Ecosystems,* 22.

"crowd." The challenge is to pick the right crowd and provide them the means and incentives to work together towards the solution of common problems.

C. Drug Trafficking as a Complex Adaptive System

On 26 October 2006, Dr. Robert Anthony spoke to IDA's informal Complex Adaptive Systems Group, his presentation titled "Drug Trafficking as a Complex Adaptive System." Dr. Anthony was able to describe "empirical regularities and patterns" in the drug trafficking trade and "identify adaptive principles."[23] For example, cocaine passes through five steps from drug laboratories in Colombia to street buyers in the United States. Each step represents a unique part of the process of developing and distributing the drug; however, on average, the smugglers at each step use the same mark-up, serve the same number of customers, and suffer the same percent of losses. The smugglers at each step share the risks and benefits equally with those at the other steps.[24] During extreme shortages and price shocks, the same mark-ups are again passed along to each level, magnifying the street cost. The main value of Dr. Anthony's research was a list of implications of the results. For example, "*lack of trust, competition and law enforcement*" encapsulate scaling laws that "*constrain the business plans for traffickers.*" He then speculated on potential commonality between drug networks and terrorist networks and provided a mapping of common characteristics in each area.[25] Risk reduces trust, which limits the size of groups and affects network configuration. While he did not discuss the issue in his talk on drug trafficking, Dr. Anthony's subsequent research revealed similar scaling relations in an analysis of casualties in Iraq.[26] After examining the distribution of engagements by the number of casualties in the engagement, Dr. Anthony determined that with the exception of a few outliers, the data formed a particular kind of mathematical distribution (called an inverse power law), which suggests there might be some underlying cause.[27]

1. Recruiting and the artificial labor market

The previous two examples were from presentations by scientists sharing their work and ideas at IDA's complex adaptive systems meetings, but the following example turned up in a literature survey.

In this example, an agent-based model was applied to an analysis significant to the military, namely an Artificial Labor Market (ALM), developed by Chaturvedi, *et. al.* for

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[23] Robert Anthony, "Drug Trafficking as a Complex Adaptive System: Lessons for Counter-Terrorism?" brief presented to IDA's informal Complex Adaptive Systems Group, Alexandria, Vir., 26 Oct 2006.

[24] Robert Anthony, explanation of his own work during brief presented to IDA's informal Complex Adaptive Systems Group, Alexandria, Virginia, 26 Oct 2006.

[25] Anthony, "Drug Trafficking as a Complex Adaptive System," slide 26.

[26] Robert Anthony, conversation with the author, 26 Oct 2006.

[27] Robert Anthony, email to the author, 9 Feb 2011.

the United States Army Recruiting Command. The authors state, "*Currently, there is no single model or set of models that are accepted as being able to credibly support decision-making…*"[28] The agent-based model they constructed allowed them to test the effects of policy decisions on recruitment results by defining individual, heterogeneous behaviors. The model was implemented in an agent-based simulation environment called Synthetic Environment for Analysis and Simulation. Agent behavior was calibrated using recent historical data.[29]

The developers used the model to support a two-day Strategic Simulation Leadership Exercise. The model allowed recruiting commanders to experiment with different strategies and policies to determine their potential effects on recruiting. The simulation was not intended to be predictive, but the results were considered believable by the subject matter experts. The value of this ALM is not its predictions, but rather its ability to enable recruiters to perform multiple runs, explore alternatives such as redistributing recruiters, and gain insight into the possibilities. This led the recruiters to consider using mobile recruiting stations.

An interesting aspect of this system is that it consists of "two worlds." One is a record of real-world data while the other maintains the ALM. The system is always running and the developers refer to it as continuous computational experimentation. But the stored data could be used for validation of emergent behavior as well as for keeping the ALM synchronized with reality.[30]

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[28] Alok Chaturvedi, *et. al.*, "Agent-based simulation for computational experimentation: Developing an artificial labor market," *European Journal of Operational Research* 166 (2005): 694–716.

[29] Chaturvedi, *et. al.*, "Agent-based simulation," 694–716.

[30] Chaturvedi, *et. al.*, "Agent-based simulation," 694–716.

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3.   Conclusions and Recommendations

The concept of complex adaptive systems provides a valuable new tool kit for understanding and addressing a broad range of phenomena relevant to military problems. Complexity has always permeated the military problem space. Technological developments have not in general decreased that complexity, and in many cases have increased it. Ubiquitous computing power and networking, for example, have allowed unprecedented access to and sharing of information, but have also created new vulnerabilities—new niches for attacks. Efforts to guard against those vulnerabilities have produced their own niche requiring human-, computing-, networking-, and other resources.

Complex adaptive systems provide a framework for understanding how complexity arises and how adaptation occurs. Using a CAS approach suggests ways of improving adaptive response, as well as ways of potentially reducing complexity. The fundamental research associated with CAS needs to be thoughtfully critiqued. By means of hypotheses generated from it, current CAS theory can be tested, revised, and perhaps replaced by improved theories. What do one have to do to be more adaptable? Just saying the words or issuing fiats doesn't make it happen.

Complex adaptive systems tools also provide methods for discerning and explaining structure in some complex environments. Underlying relationships and interdependencies revealed through these latent structures may point to vulnerabilities or other opportunities for addressing problems faced by US military forces. Is there structure in these data? If there is structure, can the military use it to advantage?

Complex adaptive systems tools enable exploring relationships in complex environments—notably in economic situations. They may not, at this point, provide answers as simple and clear as, "Turn left for best results." But they can in some cases allow one to roughly map the solution space. An answer like "Go left, straight or back, but whatever you do, don't turn right," may not be desirable, but it might be a useful rule under some conditions that only the agent-based model of the systemic implications could reveal. More generally, one could ask: What are the potential unexpected consequences? What is the spectrum of possibilities? Is there anything I need to absolutely avoid?

Complex adaptive systems tools provide a mechanism for searching for simple adaptive rule sets that lead to systemic consequences in various complex, massively multidimensional search spaces. This mechanism addresses viability more than optimality.

These techniques, tools, and ways of thinking do not replace traditional tools or human judgment. Rather, they augment them. Complex adaptive systems methods can be used to target potential solutions for more detailed analysis through traditional means. The IDA research staff should be aware of the potential for complex adaptive systems techniques to address military problems, as well as of the strengths and weaknesses of each of these techniques. IDA should not attempt to apply the techniques to every problem, but it should develop an understanding of where they might be useful.

War in all of its manifestations and in many of its particulars is a complex activity, requiring adaptive responses for effective performance. Military analysts should not ignore that complexity, and should recognize they run the risk, like Tolstoy's Napoleon, that decisions—after they are made, while they are being made, and even before they are made — may become irrelevant in the changing environment.

IDA should stay involved in complex adaptive systems and should continue bringing in recognized experts—academics, soldiers, businessmen, policy-makers—to speak about this developing topic. These experts can provide insights into current complex adaptive systems methodologies—the successes as well as the failures, the problems encountered, the lessons learned, and the value garnered from applying those methods. We should continue to learn from and nurture in-house expertise.

While IDA should continue to bring in speakers to give the research staff topical overviews, it should also consider a parallel seminar series for interested staff on the details of certain methods. IDA research staff can learn about specific tools such as agent-based model toolkits, neural networking kits, social networking kits, genetic algorithms, and genetic programming. In some cases, IDA might invite guests from sister institutions or academia to demonstrate or perhaps teach tools they have developed or are using.

We could also encourage collaborative mutual assistance by identifying connections to and among active IDA projects. Results of the individual projects are informative in their own right, but the results can also offer pointers to new ideas and to potential experts who can speak to IDA as a whole. It is good if there are people on specific projects who understand how to use these techniques; it is much better if IDA can cross-pollinate projects and divisions. It could be that those projects could benefit from presenting their complexity-related issues to a wider IDA audience.

IDA could engage academia to learn the details of these techniques—taking online or traditional courses, and attending demonstrations, seminars, colloquia and conferences. We could likewise compile an electronic annotated bibliography—or, better, locate and access one already built.

Finally, IDA could periodically organize and assess the company's existing knowledge base in this discipline. This would capture the lessons learned and make this information accessible to all of IDA. Who knows how to do what? What current tasks embody

problems that could benefit from complexity methods and what tasks are already using those techniques? Is there anything IDA researchers can learn at the higher level about comparative value and added value of the traditional methods versus the complexity methods? What do the IDA staff collectively know and what do they need to know and where should they be looking in the future?

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14. ABSTRACT
Since 2006, the Institute for Defense Analyses (IDA) has hosted an informal series of lectures to familiarize the research staff with Complex Adaptive Systems. These lectures were generally well-attended and every SAC research division, as well as STPI was represented. Speakers were from IDA, academia, industry, Department of Defense and government. This paper distills some of the knowledge acquired as a permanent record for the Institute.

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