Probabilistic Reasoning Using Incomplete and Singular or Unique Evidence: *Complexity-Based Reasoning Innovation for Commanders*

Carl W. Hunt
Lieutenant Colonel
United States Army
Doctoral Student
School of Information Technology and Engineering
George Mason University
Fairfax, VA
chunt@gmu.edu
703-451-0604
fax: 703-440-3602

and

Dr. David A. Schum, Ph.D.
Professor
School of Information Technology and Engineering
George Mason University
Fairfax, VA
dschum@gmu.edu
703-993-1694
fax: 703-993-1521

Abstract

Military commanders face challenges that their counterparts in the business world would confront only in the rarest of circumstances. Commanders must make decisions that place their human and equipment resources in harm's way. When a commander or senior civilian military decision-maker must commit to an action that endangers the lives of his or her troops, their decisions and the information or evidence that supports their decisions take on a life of their own. The decision-making process becomes complex and adaptive by nature. Like trial lawyers, judges and juries, the commander and staff must weigh evidence about adversary and environments' capabilities and limitations. This evidence faces different tests for the commander than those of the legal community. The judge and jury can rigorously pursue the evidence to a final conclusion where the commander must often act quickly and precisely on totally incomplete evidence. The judge and jury make decisions on criminal matters that "only" require the proof of "beyond a reasonable doubt." Commanders must protect their assets and are held to the greatest of standards for success or failure—"beyond reasonable doubt" is not always sufficient. They must usually apply concepts such as probabilistic analysis. In this paper, we describe how probabilistic reasoning in cases of apparent unique or singular evidence provides useful insights and is the basis for mathematically sound inferences regarding hypotheses.

1. Introduction

"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[1]

In many military planning situations, hypothesis testing is conducted based on statistical evaluation of what has transpired before. While there are of course, multiple ways to test hypotheses, in this paper we discuss methods that involve quantitative measures of probability. The staff process often relies on the mathematics of probability to determine possible courses of actions and likely outcomes. Unfortunately, statistical analysis of events, based on previous outcomes, does not always apply. Sometimes, commanders and their staffs need to apply probabilistic reasoning on evidence that is unique or happens only rarely; there may be no accumulations of past outcomes to analyze. Does this mean that commanders cannot rely on probability as an important tool in hypothesis testing in instances of singular evidence? Not at all, and in fact, probabilistic analysis of such situations may be very useful if the right mix of methods is applied.

Equally important, we demonstrate ways this sort of reasoning technique can show how probabilistic inferencing finds mutual support with the emerging science of complexity theory and shores up the application of probabilistic reasoning to battlefield decision-making. It should be clear to see that while statistical reasoning may involve probability, not all probability involves statistics. We will see that there are advantages for commanders to consider their decision-making situations in light of complexity theory. There are keen insights probabilistic reasoning can bring to the surface in assessing the complex interrelationships of the evidence the commander must consider. We will also examine the very important role of modeling in understanding evidence.

We propose that probabilistic reasoning can be just as useful for hypothesis testing for commanders in cases of singular or unique evidence as it is in cases where rich statistical data exist. As a general observation, the enumerative methods required of statistical reasoning are not possible. The approach we describe mitigates this issue. These methods can be useful in assessing the complexity of the relationship of evidence to hypothesis and to the events that actually transpired or are likely to transpire. In many instances, as we will show, these same methods can apply to singular or unique evidence and the rich, complex interrelationships may be just as straightforward to determine.

Interestingly, the approach we describe in this paper is closely associated with the emerging sciences of complexity theory, an important area for commanders to begin to understand and apply in the face of asymmetric warfare. In fact, it is our belief that complexity theory may form the backbone of the next revolution in military affairs and particularly in military decision-making. The probabilistic methods we discuss in this paper may be useful in uncovering complex interrelationships of various items of evidence we may examine in the course of forming hypotheses. And, as useful as statistical distributions of past events may be, these

[1] Taken from Dr. Andrew Ilachinski's (Center for Naval Analysis) marvelous World Wide Web Site on Complexity Theory and its applications to the science and art of the military: please see http://www.cna.org/isaac/ for more information and WWW links about complexity theory.

distributions are not always necessary to ensure that the commander can access the tools of probability for hypothesis formulation and testing. Often, singular or unique evidence is not the best thing we have, but the only thing we have. The complex relationships that probabilistic reasoning can uncover will almost certainly provide better insight into decision-making.

This paper reflects a blending of thoughts on probabilistic reasoning as it applies to the military commander and to those who practice decision-making in other walks of life. We will focus on military decision-making and its relationship to complexity theory, however. Commanders must find ways to benefit from the new decision-enhancing technologies without being subdued by them. Our approach seeks to preserve the experiences, wisdom and imagination of the commander and staff as they deal with complex decision-making for which there may be little precedence.

It is probably the case that we will not fight our future wars in the same manner in which we have fought past wars. Precedence just does not always exist. The ideas we present attempt to capture some of the complex interactions of ideas that result in our effort to empower commanders with the clout of probabilistic reasoning in cases of singular or unique evidence. As David Schum has pointed out in previous papers, "probabilistic reasoning is far too rich an intellectual activity for us to suppose that we can capture all of this richness in any single formal system." [Schum, December, 1998]

Our paper discusses an approach to adapt features of both enumerative and non-enumerative methods of probabilistic reasoning. While we demonstrate primarily Bayesian techniques, we consider other formal systems such as those of Bacon, Laplace, Cohen and others. Schum has devoted much of his academic research in developing meaningful ways to apply probabilistic reasoning to large databases through what he labels evidence marshalling. In the course of his research, he has also discovered methods that support instances of singular or unique evidence, using similar proven techniques. The two primary components of this work include *discovery* and *induction*. Discovery has to do with the generation of the hypotheses commanders should consider, while induction in this situation deals with determining which hypothesis the commander should favor. This approach has potential to enhance decision-making for commanders in situations where evidence about enemy courses of action is unprecedented or obscured.

The application of complexity theory, relying on a more formalized process of discovery, will be a key component in building a mechanism to harness probabilistic reasoning in cases of unprecedented potential events. We will briefly explore the process of discovery, an often-overlooked element of the commander-staff relationship in decision-making, in our presentation of reasoning methods that support the commander's hypothesis testing schemes. Additionally, we must consider the role that modeling and simulation play in integrating probabilistic reasoning, complexity theory and the process of discovery. Models present windows through which the commander and staff may interface with the complex interrelationships that our probabilistic methods uncover. The underlying virtue of probabilistic analysis is that it assists us in understanding the complex richness of inference based on evidence. Models, useful for validating discovery, are an effective means of visualization for decision-making. We briefly examine work done in two models that have potential to enhance military decision-making.

2. **Courtrooms and Battlefields—Arenas for Conflict**

Regardless of the differences in the way commanders and the courts deal with evidence, there are interesting similarities between the way events unfold on the battlefield and the way a criminal case plays out in a court of law. The events that lead up to the battle or to the case on trial are often based on complex subtleties that would have been difficult to predict before they reached some point of no return and resulted in their respective actions. There may be innumerable interactions that took place to set the stage for a battle or for a criminal act that finds its way into a court. It is not difficult to imagine that the interactions that may precipitate these events are somewhat different every time. The settings for battle and courtroom cases are usually unique and the evidence that leads to the culmination of these events rarely combines or interacts the same way twice. There are patterns that we might recognize, to be sure, but each case is different, with potentially different outcomes for each event. Current efforts in pattern recognition technologies seek to uncover the similarities that a commander can assess to assist in decision-making, and breakthroughs in this area this will be important.

But consider how the outcomes of battles are rigorously studied for lessons learned. The patterns that observers uncover result in new ways to approach the next battle. Equally so, courtroom cases are rigorously studied and their outcomes often provide precedents for future applications of law, known as case law. Are there similarities in the way these two influential types of events are studied that can also interact and assist in our understanding of battlefield situations that require commanders to develop hypotheses based upon singular or unique evidence? Yes—we believe the joint study of these events can indeed improve our understanding of both events. The effective application of probabilistic techniques is the key to this greater mutual understanding. And, while there are differences in the way commanders and the courts must deal with evidence, it is worth noting the high standards on the relevance of evidence that our courts require. These same standards, at the least, should apply to the evidence the commander must weigh.

The mathematician Pierre Simon Laplace noted that even testimonies of witnesses could benefit from the application of probability. "The majority of our opinions being founded on the probability of proofs it is indeed important to submit it to calculus," he wrote in the late 18th century. Laplace claimed that it is preferable to make at least approximations of the likelihood of veracity of testimonies rather than engage in "specious reasonings," about these forms of testimony [Laplace, 1814, 1951].

We find testimony in many forms: intelligence reports, witness statements, staff briefings and almost any manner of non-tangible evidence are usually considered testimony in terms of making decisions about some situation. Generally, in order to link even physical evidence to a reasoning process, we need testimony to provide the glue between the actual physical evidence and its relevancy to the investigation at hand. Earlier we spoke of the differences between evidence and its applications in battlefield and courtroom. One of the troubles courts have had with statistical and probabilistic evidence is in the area of relevance. It is normally quite difficult in a court of law to introduce historical information such as statistical distributions and try to establish how such "evidence" is relevant to the case at hand. The same may be true in the commander's decision-making process. The commander faces the difficult challenge of applying history to the present situation—it just does not always fit. The courts seek evidence that is clearly relevant, and the commander must also. Even when evidence does seem relevant, the commander must decide its credibility and probative force. We will examine the concept of probative force shortly, but first let's examine Laplace's thoughts on credibility of testimonial evidence.

Laplace posited that there are four hypotheses regarding testimony that if we do not consider all of these possibilities, we run the risk of error in assessing testimony. These hypotheses include:

1) the witness does not deceive and is not mistaken

2) the witness does not deceive and is in fact mistaken

3) the witness does deceive and is not mistaken, and

4) the witness does deceive and is in fact mistaken. [Laplace]

What can we say about our assessment of testimony and evidence the commander encounters in light of Laplace's counsel? We noted earlier that even physical evidence requires testimonial evidence (such as briefings and intelligence summaries) to "glue" this evidence into the larger body of evidence. Laplace notes the four possible states of testimonial evidence. It is important for the commander to confidently assess the credible and objective nature of the evidence (and its source) and try to avoid complicating hypothesis generation. If this proves too difficult, however, we will see below how Bayes's rule might assist in this matter.

Finally, the commander can apply the legal system's technique of assessing the probative force of the evidence involved in military decision-making. Force, or weight, of evidence is the first place we clearly see the application of probabilistic reasoning applied to hypothesis formulation. This consideration of evidence requires grading the strength or weight in probabilistic terms. "We know that these gradings must be probabilistic in nature, given that the evidence we have is incomplete, inconclusive, and lacks credibility to some degree." [Schum, 1994] Corroboration from independent sources is an example of assessing the credibility of the source. Generally, evidence must have credibility and probative force, as noted above, and it must be relevant to the given situation. We will discuss the concept of force of evidence in greater detail below, in our presentation of a method to probabilistically reason with singular or unique evidence.

It seems apparent that commanders planning for a future action and investigators preparing for adjudication in courts of law face very similar situations. They both must deal with evidence that is incomplete and often inconclusive. Additionally, this evidence is usually dissonant, ambiguous, and imperfectly credible. This means that like it or not, we must apply some sort of probabilistic inference to assess the effect a particular piece of evidence will have on our decision-making. And compounding this situation, evidence often interacts in unpredictable ways that make it even more difficult to prepare rational plans for the future. For this reason, commanders need to understand the thinking behind complexity theory and the benefits complexity-based models can provide to their decision-making environment.

3. Complexity Theory and Modeling

Complexity theory represents a multi-disciplined approach to the study of relationships between elements of nature. It seeks understanding of the world through more realistic modeling of varied components. Complexity theory embraces many sciences including biology, physics, economics and sociology. Complexity-based models use "agents" as tools for discovery about their models. Agents in this sense are software objects that possess individual traits. If programmed with genetic algorithms, these agents can even improve their awareness, intelligence and performance.

A recent work on complexity theory and nonlinearity, published by the National Defense University, highlights several key factors that commanders must consider in considering the evidence before them and how it all interacts to present an assessment of the current situation. Some of these factors may seem disconcerting to the commander who is engaged in forming hypotheses about future courses of action, but these factors appear to be very meaningful. Tom Cwerwinski, author of this work [Cwerwinski, 1998], notes the following about nonlinearity:

a) Nonlinearity[2] does not conform to those qualities found in linearity

b) It is not proportional, additive or replicable; inputs and outputs are not proportional

c) The demonstration of cause and effects are ambiguous

d) The whole is not quantitatively equal to its parts, or even quantitatively recognizable in its constituent components

e) Results cannot be assumed to be repeatable—the same experiment may not come out the same way in successive attempts[3]

Nonlinear, agent-based modeling may represent entities that are as finely grained as a single individual or an entire collection of individuals, such as an economy or culture. The agents in these models exhibit behaviors based on the notion of few rules and many, often unprogrammed, interactions between their fellow agents and the environment. Complexity modelers look for emergent behaviors of agents that exhibit self-organization. Determining emergent behavior is not necessarily a deductive matter. In fact, complexity theory defines emergence as the rise of higher-level properties and behaviors that are not typically deducible from lower-level properties with which an agent may have started. Emergence plays a very important role in discovering the interrelationships between items of evidence the commander must examine in hypothesis formulation.[4]

Self-organization represents significant importance for complexity-based modeling and simulation. Per Bak, professor at the Niels Bohr Institute of the University of Copenhagen, Denmark, notes that self-organized criticality is the basic engine for producing complexity in the real world. Self-organized criticality can occur when a complex system discovers an area within its environment that facilitates evolution [Bak, 1996]. Some complexity theorists call this area the *edge of chaos*, a site for innovation or adaptation. Recognition and analysis of adaptation and

---

[2] Nonlinearity in this case is simply defined as the opposite of linearity—in a linear world, 2+2 always equals 4; a certain cause always produces a certain effect; the sum of the parts equals the whole. This is not always the case in the nonlinear world.

[3] The notion of sensitivity to initial conditions, taken from Chaos Theory, applies in nonlinear systems.

[4] Ilachinski's WWW site has excellent references and links to the thinking behind complexity theory.

innovation will be important tools for the commander and staff in forming hypotheses on singular or unique evidence.

Adaptation is indeed an important feature of complexity theory. Complexity scientists identify a complex adaptive system as one that coevolves with its environment and other agents within the environment [Kauffman, 1995]. In the behaviors of these agents, we find global order from their localized interactions with each other and the environment in which they exist. Coevolution suggests that change in one entity influences the actions of other entities (or even the environment). Again, the commander who can recognize and understand the effects and results of coevolution within the evidence he or she must assess will have an edge in decision-making.

4. **The Process of Discovery**

What is the process of discovery and how might we understand its role in probabilistic reasoning with singular or unique evidence? Perhaps we may define discovery with metaphor in our search for definitions that are more formal. "When asked how he came to discover the theory of relativity, Einstein replied that he imagined how the world would look if he were riding on a beam of light" [Casti, 1997]. In a sense, Einstein not only saw the light, as it were, he became the light—he saw the world differently. If there is a way to introduce some formality into discovery-based thinking, it might be to provide a mechanism to think outside oneself. Arthur Koestler writes that discovery "often means simply the uncovering of something that has always been there but was hidden from the eye by the blinkers of habit" [Koestler, 1964].

Discovery clearly involves seeing the world differently—perhaps even seeing things in a way that no one has seen them before. Surely curiosity is at the root of this approach to thinking [Schum, 1999]. Therefore, it seems prudent to stimulate curiosity in assessing evidence the commander must shape into a hypothesis about some current situation or future action. Another formal method of reasoning that has recently found favor in the artificial intelligence community is what is known as abduction. Of the three major forms of inference—deduction, induction and abduction—it is abduction that seems to involve curiosity and discovery.

Abduction, according to American philosopher Charles Saunders Peirce, is an instinct for guessing right. "I perform an abduction when I so much as express in a sentence anything I see. The truth is that the whole fabric of our knowledge is one matted felt of pure hypothesis confirmed and refined by induction," Peirce wrote about his thoughts on the ubiquity of abduction in human reasoning [Sebeok, et. al., 1983,]. Abduction is an inference, writes Bonfantini and Proni, and is no more original and inventive than induction or deduction. According to Peirce, they note, "it is just as mechanical or automatic to derive the *rule* from the case and the result (induction) as it is to derive the *result* from the rule and the case (deduction) or the *case* from the rule and the result (abduction)" [Bonfantini, Proni, 1983]. In a clarifying essay on what he calls the three types of abduction and their accompanying properties, Umberto Eco describes four distinct grades of abduction [Eco, 1983]. In this sense, then we have somewhat formalized the way discovery and abduction work in our inference models.

Schum notes that if Peirce is correct, "new ideas emerge as we combine, marshal or organize thoughts and evidence in different ways." [Schum, Nov., 1998] The French mathematician Jacques Hadamard [1954, 29] adds to these thoughts: "Indeed, it is obvious that invention or discovery, be it in mathematics or anywhere else, takes place by combining ideas." We find then that combining ideas and information, in ways that others before us have not, forms the core of the process of discovery. Peirce, Eco, and Bonfantini all help us to see how abduction, induction and deduction work together in this process, with abduction being the stimulus for us to introduce our own thoughts and intuition into the process to ensure that our hypotheses rise above mere deductive recantations. This is crucial to the process of infusing the commander's experiences into hypothesis formulation without reducing the process to merely planning by standard operating procedures.

5. **Marshaling Singular or Unique Evidence into Hypotheses**

We have shown how the three methods of inference (abduction, deduction and induction) can interact to introduce the process of discovery into the formulation of hypotheses for military decision-making. When backed up with the tools that complexity theory-based modeling can provide, we see that the commander can have a visual interface to evidence and the interrelationships between the evidence and his or her hypothesis. What of the "black box" process that occurs to build and test these complex interrelationships? Now we come to the power of probabilistic reasoning and its support to military decision-making, even in cases of singular or unique evidence.

The power that brings together probabilistic reasoning and complexity theory is two-fold. The first component is a feature of Bayesian analysis known as conditional nonindependence. Recall that Bayes Rule (or Theorem) is a form of conditional probability that accommodates a more accurate assessment of the introduction of new evidence. In essence Bayes Rule helps us calculate the probability of hypothesis *H*, given event *A* has occurred, set against the probability of event *A*, given that hypothesis *H* has occurred, and the probability of event *A*, given that hypothesis *H* has not occurred. In a generalized formula, this looks as follows:

$$p(H \mid A) = \frac{p(A \mid H)\,p(H)}{p(A \mid H)\,p(H) + p(A \mid H')\,p(H')}$$

This is of course a simple example and explanation of Bayes Rule, but it does demonstrate the importance of considering both the occurrence and non-occurrence of a given event in assessing the overall effect of one event upon another [Porkess, 1991]. Also, note how an analysis of evidence in this light can depict the sensitivity to initial conditions in this formula in terms of the relationships between the occurrences and lack of occurrences of a given event.

Consider that *A*, above, is an item of unique evidence (e.g., has not been previously accounted for in any sort of statistical distribution maintained in a military table or standard operating procedure). Each item of evidence may have its own influence on the commander's existing hypothesis, but when considered together, indicate an influence that the commander has never seen before. In such a situation, these two items of evidence are thus said to be possibly nonindependent, conditional upon the occurrence or lack of occurrence of the given hypothesis. The determination of the sensitivity of these items of evidence in relation to the hypothesis is measured by a concept known as an odds-likelihood ratio. This ratio is a measure of the odds Ω of the occurrence of hypothesis *H* and the odds of the occurrence of *not H* (H'), all subject to the influence of the items of evidence [Kadane and Schum, 1996, 125-129]. In the case of the likelihood ratio L_A of H and H', conditioned upon evidence A, consider the following formula:

$$L_A = \frac{\Omega(H : H' | A)}{\Omega(H : H')}$$

The idea of conditional nonindependence is one of the most important features of Bayes Rule and a center of gravity for capturing subtle interactions between items of evidence. We observe this conditional nonindependence in the following way (where Ω_1 is the posterior odds, Ω_0 is the prior odds, and Ω_2 is the new posterior odds, after consideration of the likelihood of new evidence *B*, given existing evidence *A*, or $L_{B|A}$:

$$\Omega_1 = \Omega_0 L_A$$
$$\Omega_2 = \Omega_1 L_{B\,|\,A}$$
$$\Omega_2 = \Omega_{L_A L_{B\,|\,A}}$$

We then ask if $L_{B|A} = L_B$. If not, then *A* and *B* are conditionally nonindependent, given *H* or *H'*.

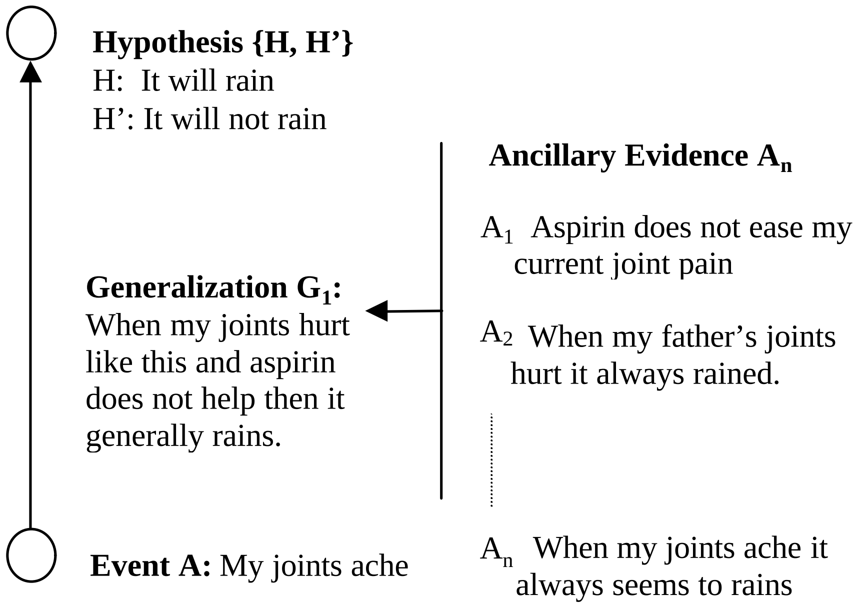
We showed how this approach generally applies to unique items of evidence and uncovering interrelationships between them in hypothesis formulation and testing. Now let us consider how this concept allows us to weigh singular items of evidence. The key concepts behind this method include the effective use of generalizations and ancillary evidence (or meta-evidence). As Schum notes, "no statistics, even if available, are relevant to these assessments, nor would any canvassing of our of our past experiences involving other people and situations be relevant" [Schum, Dec., 1998]. Recall that evidence must be relevant, credible and possess some probative force to be useful and reliable, although experience and intuition do temper this process, as noted above.

We must avoid the trap of trying to introduce statistical but irrelevant evidence to a situation. We should instead rely on broader generalizations about certain events, backed up by ancillary evidence that helps make general applications more specific and useful. A generalization as used in this context is simply some action or item that normally or usually happens when something else happens. For example, when there are dark, thunderous clouds overhead, it normally rains (but not always; there is some uncertainty). We can generalize from the evidence of the clouds that rain is likely, but it would be helpful to have some sort of ancillary evidence to help us better prepare for the likely event of the rain. At this point we apply Baconian reasoning and pay as close attention to what we do not consider as to what we do consider in assessing our evidence. The Baconian method can help us eliminate evidence or hypotheses that do not pass the tests we set for them [Cohen, 1989]. In this way we are better able to build "helping", or ancillary inferences to make generalizations more applicable to the singular or unique evidence in view.

Ancillary evidence focuses on aspects of credibility of evidence. It examines such attributes as veracity, objectivity and observational sensitivity of the source of evidence.[5] Note the example below, using our weather situation. While weather is not a singular or unique evidence

[5] See Schum, 1994, for an in-depth look at the issues surrounding ancillary evidence and its role in building the strength of generalizations.

phenomena, it does demonstrate how ancillary evidence can be applied to a generalization to increase the potential for building more effective hypotheses. Thus, ancillary evidence can help to increase (or decrease) the utility of a generalization to build support for H or H'.[6]



The important point here is that we have a stronger basis for assessing the two probabilities $p(H|A)$ and $p(H'|A)$. It is more effective to grade the probative force of G_1 based on the supply of ancillary evidence depicted than it would be relying on a singular generalization that assumes "when my joints ache it usually rains" or a singular observation that "my joints ache." This ancillary evidence provides more probative force that can strengthen or refute our generalizations.

The second component in our "black box" is not as well known as conditional nonindependence. This aspect of our method for probabilistic reasoning to singular or unique evidence is manifested in a research project of Schum's and Peter Tillers, known as the MarshalPlan [Schum, Nov., 1998]. It is in the MarshalPlan that we begin to see the potential effects of self-organization within an information space that we can consider a complex adaptive system.

The MarshalPlan attempts to accomplish several objectives, the most important of which is to accommodate recombination of ideas, thoughts and evidence. It does this using what is known as an attractor (borrowed from complexity theory) that we metaphorically describe as a *magnet*. This magnet, metaphorically speaking, may also be considered the basis of attraction for what Sherlock Holmes called *trifles*. A study of Sherlock Holmes "methods" in fact helps us form a basis for discovery among a complex pool of data. Sherlock Holmes commented to Dr. Watson in the *Bascombe Valley Mystery* "You know my method. It is founded on the observation of trifles" [Seebeok, et. al., 1983, 23]. It appears that Holmes avoided trying to fit hypotheses to a few outstanding facts, as he accused the "imbecile" Inspector Lastrade, and attempted to use these facts as attractors for the trifles he observed. It is our belief that sometimes the trifles do

[6] Evidence charting conventions are adapted from Schum, 1996.

not fit the major facts and can self-organize into a basis for attraction of their own. This is the powerful linkage of complexity theory and the probabilistic assessment of various types of evidence.

As Schum points out, "…new hypotheses are generated from *combinations* of trifles. We might observe there to be something significant about the *joint* consideration of certain trifles that goes well beyond the significance of these same trifles when they are considered separately" [Schum, 1999]. Note the use of the words "combination" and "joint"—these are key components of emergence and complex systems. The MarshalPlan is thus a visual interface to examine emergent behavior between "objects" (items) of evidence and the way these objects might interact with our hypotheses.

The MarshalPlan project was designed to help decision-makers avoid combinatorial explosions of interrelationships of trifles and key facts, and to help us avoid the mindless strategy of looking through everything in the hopes of finding something. Here magnets play a vital role as attractors for self-organization. Trifle combinations must depend on how the magnets are tuned, and the tuning of the magnets is based on the questions we pose of our information space. Our job is to examine the self-organizing, emergent behaviors of a combination of trifles, noting nonindependent "formations" and testing hypotheses against these new possibilities. This process may also lead to machine-assisted abductively formed new hypotheses. This is clearly a nonlinear development, deeply rooted in complexity theory, and can be of great assistance in assessing the impact of ancillary evidence to the generalizations we need to make in generating probabilistic inferences with singular or unique evidence.

Not all of the parts of the MarshalPlan are in place such that we can roll out a prototype model to begin testing yet, but there are tangible pieces of it in existence. Schum and Tillers have built a basic working prototype using Claris Corporation's Hypercard™. This model uses some 15 marshaling operations to act as magnets for trifles, but has not fully harnessed the power of emergence and complex adaptive systems approaches. Hunt has recently begun discussions with Andy Ilachinski, of the Center for Naval Analysis, and creator of the EINSTein[7] emergent behavior modeling system, to determine the feasibility of building MarshalPlan within the EINSTein environment. EINSTein would provide a highly visual interface for observing the complex interactions between trifles and probanda and could lead to new "emergent" developments in MarshalPlan itself. MarshalPlan and EINSTein could conceivably team to provide the visual interface between the commander and the information going into the decision-making process, and support discovery-based complex adaptive modeling of evidence for hypothesis formulation and testing.

6. **Summary**

Throughout this paper we have attempted to provide concrete examples of how we can harness both changes in technology and continuity of thought about reasoning techniques that reflect centuries of philosophy concerning decision-making in the face of singular or unique evidence. Our objective was to demonstrate ways to enhance the future of hypothesis testing for command and control. We applied the sciences of complexity and probabilistic reasoning to the hard

[7] See Ilachinski's World Wide Web site at http://www.cna.org/isaac/ for more details about EINSTein.

problems commanders face in making decisions based on incomplete and singular or unique evidence. We briefly demonstrated how different forms of evidence could be assessed together, in modified Bayesian methods, to improve decision-making for commanders.

In summary, we noted at the beginning that all statistical reasoning involves probability, but not all probabilistic reasoning involves statistics. Commanders are faced with situations where the evidence upon which they need to formulate and test hypotheses is incomplete, singular or unique. There may be no statistical distribution of past events from which to draw conclusions about likely enemy courses of action. In such cases, probabilistic reasoning is still a powerful tool for the commander and staff, given that they understand the right blend of techniques to apply. Commanders may also leverage complexity theory and the process of discovery to enhance their reasoning capabilities in light of unprecedented situations of unique and singular evidence. Even in the case of maximum uncertainty, the commander and staff can make better informed decisions about the future, using proven probabilistic techniques that are tailored to deal with complex situations that reflect little or no precedence. New modeling techniques such as MarshalPlan and EINSTein may serve to assist commanders in marshaling evidence in a visual manner to help build and test emergent hypotheses that capture the complex interactions of a dynamic battlefield.

7. **References**

[Bak, 1996] Bak, P. *How Nature Works: The Science of Self-Organized Criticality*, Springer-Verlag, NY, 1996.

[Bonfantini, Proni, 1983] Bonfantini, M., and Proni, G., To Guess or Not to Guess, from *The Sign of Three*, edited by U. Eco and T. Sebeok, Indiana University Press, 1983, p. 131.

[Casti, 1997] Casti, J., *Would Be Worlds: How Simulation is Changing the Frontiers of Science*, Wiley, NY, 1997.

[Cohen, 1989] Cohen, L. J., The Introduction to the Philosophy of Induction and Probability, Oxford University Press, NY, 1989, p. 14.

[Cwerwinski, 1998] Czerwinski, T., *Coping with the Bounds: Speculations on Nonlinearity in Military Affairs*, National Defense University, Washington, DC, 1998, p. 10.

[Eco, 1983] Eco, U., Horns, Hooves, Insteps, from *The Sign of Three*, edited by U. Eco and T. Sebeok, Indiana University Press, 1983, p. 198.

[Hadamard, 1954] Hadamard, J., *The Psychology of Invention in the Mathematical Field*, Princeton University Press, NY, 1945, p. 29.

[Kadane and Schum, 1996, 125-129] Kadane, J., and Schum, D., *A Probabilistic Analysis of the Sacco and Vanzetti Evidence*, Wiley, NY, 1996, pp. 125-129.

[Kauffman, 1995] Kauffman, S., At Home in the Universe, Oxford University Press, New York, 1995.

[Koestler, 1964] Koestler, A., *The Act of Creation*, Penguin Books, NY, 1964.

[Laplace, 1814, 1951] De Laplace, P., *A Philosophical Essay on Probabilities*, Dover Publications, Mineola, NY, 1951, p. 109.

[Porkess, 1991] Porkess, R., *The Harper Collins Dictionary of Statistics*, Harper Collins, NY, 1991.

[Schum, Dec., 1998] Schum, D., Singular Evidence and Probabilistic Reasoning in Judicial Proof, a chapter for *Harmonization in Forensic Expertise*, Seminarium for the Law of Evidence, Leiden University, the Netherlands, December, 1998.

[Schum, Nov., 1998] Schum, D., Marshaling Thoughts and Evidence During Fact Investigation, presented at the 75th Anniversary Symposium Series, South Texas College of Law, Houston, TX, November, 1998.

[Schum, 1999] Schum, D., Probabilistic Reasoning and the Science of Complexity, a chapter for *Decision Science and Technology: Reflections on the Contributions of Ward Edwards*, Kluwer Academic Publishers, 1999.

[Schum, 1994] Schum, D., *Evidential Foundations of Probabilistic Reasoning*, Wiley, NY, 1994.

[Sebeok, Umiker-Sebeok, 1983] Sebeok, T., and Umiker-Sebeok, J., "You Know My Method", from *The Sign of Three*, edited by U. Eco and T. Sebeok, Indiana University Press, 1983, p. 16.