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MULTISCALE REPRESENTATIONS PHASE II

New England Complex Systems Institute

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APPROVED: /s/
RAYMOND A. LIUZZI
Project Engineer

FOR THE DIRECTOR: /s/
JAMES A. COLLINS, Acting Chief
Information Technology Division
Information Directorate

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AFRL Project Engineer: Raymond A. Liuzzi/IFTB/(315) 330-3577 Raymond.Liuzzi@rl.af.mil

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13. ABSTRACT *(Maximum 200 Words)*

This report focuses on the assessment of military capabilities and military technology and the process of military modernization. Multiscale analysis provides an analytic tool that can be applied to evaluating force capabilities as well as the relevance of designs for technological innovations to support force structures and their modernization. Evolutionary engineering is a synthetic approach to complex systems development that is relevant to the creation of integrated and highly complex systems consisting of human and technology aspects. This effort has addressed: (1) the application of multiscale concepts to assess the Combined Relevant Operational Picture design concept, (2) the process of military modernization through evolutionary engineering that applies beyond the complexity limit of planning and decomposition, and (3) the application of multiscale analysis to functional capabilities of military force organization with specific application to littoral warfare.

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1. Overview

The study of complex systems is relevant to a wide range of priorities in the planning and execution of military conflict. Here we focus on the assessment of military capabilities and military technology and the process of military modernization. Multiscale analysis provides an analytic tool that can be applied to evaluating force capabilities as well as the relevance of designs for technological innovations to support force structures and their modernization. Evolutionary engineering is a synthetic approach to complex systems development that is relevant to the creation of integrated and highly complex systems consisting of human and technology aspects. In three reports we address: (1) the application of multiscale concepts to assess the Combined Relevant Operational Picture design concept, (2) the process of military modernization through evolutionary engineering that applies beyond the complexity limit of planning and decomposition (3) the application of multiscale analysis to functional capabilities of military force organization with specific application to littoral warfare. Executive summaries are provided in the following three sections. The complete reports follow.

2. Executive Summary: Multiscale Representations and the Combined Relevant Operational Picture

Many innovators have asserted that the US military must have networked forces to successfully conduct operations in the Information Age. Such visions generally include the Common Relevant Operational Picture (CROP) concept. The CROP concept suggests that all the militarily relevant information about a battlespace can be collected in a single repository and displayed in a single presentation architecture that is available for all military personnel. The motivation behind military network concepts may be traced to the dramatic growth of networks in non-military contexts. There are, however, key differences between the military concepts and civilian practice. Civilian networks, like the Internet, are often organically grown through distributed mechanisms and the information remains distributed and incoherent to unified presentation. In contrast, the military concept promotes a design that is centrally conceived and engineered. Similar attempts at central design in civilian contexts (such as the Microsoft Network), failed. Moreover, the CROP architecture does not actually correspond to the architecture of a networked system, it corresponds to a centralized data processing system. Accelerating the growth of military information networks requires a much more systematic and fundamental understanding of the relationship between network structure and function.

An understanding of complex systems requires a recognition of the complexity of components and complexity of the whole of a system. A finite complexity implies a limitation in the diversity of contexts that can be dealt with, and a limitation in the information flow that can be responded to. Of particular relevance to systems involving human beings, including military ones, is the finite complexity of a human being. In contrast to the CROP system as articulated, the central task of a sensor system is to provide **relevant** information. Increasing the availability of **potentially relevant** information must be carefully weighed against the damage due to distraction by irrelevant information. While this statement is natural and intuitive, even obvious, we emphasize this conclusion precisely because the CROP concept violates this concept. The imagined concept that somehow our attention will be drawn to precisely the piece of information that is relevant to our next action cannot be assumed. A more careful understanding of information in complex systems suggests that the most important task of an information processing system is discarding irrelevant information while retaining the relevant information.

Multiscale representations provide an analysis tool for identifying the relevant and irrelevant information. Of central importance is that it does not separate, but rather links information and action. Our analysis is guided by the recognition that an information system cannot be evaluated without an understanding of the structure and function of the system that uses this information. A multiscale analysis and the resulting evaluation framework must then focus on an examination of the decisions required at each important scale in Information Age command and control systems. These decisions must be matched to the information flows and command structure capabilities.

3. Executive Summary: Large Scale Engineering and Evolutionary Change: Useful Concepts for Implementation of FORCEnet

The traditional approach to large scale engineering projects, still often used today, follows the paradigm established by the Manhattan project and the Space program. According to this paradigm new technology, and a clear understanding and specification of what is needed will lead to a design that will be implemented and the mission will be accomplished. Studies of such projects over the past decade reveal that few such projects are successful. Many are impaired (over 50%) but are ultimately implemented in some form despite failing to achieve their functional specifications, being over budget, and over schedule. A remarkable fraction (30%) are completely abandoned.

A fundamental reason for the difficulties with modern large scale engineering projects is their inherent complexity. Multiscale analysis provides a formal understanding of the relationship between complexity and interdependence. Different parts of the system are interdependent so that changes in one part may have effects on other parts of the system. In highly complex engineering projects recursive decomposition and design is ineffective and ultimately must fail when component complexities are exceeded by interface complexities. Thus, the ability of designers—individuals or team of individuals—to coordinate the components is impractical. Interdependencies overwhelm the capabilities of planning and subsequent interface design and coordination.

The field of complex systems provides **two** answers to failures of large scale engineering projects. The **first** is to change objectives. Recognizing that complexity is a crucial property of engineering problems should lead planners to limit as much as possible the complexity of objectives. The **second** is to use an evolutionary process. This becomes essential when simplification will no longer work because the function required is intrinsically complex. This report focuses on the second, evolutionary engineering process because most modern large engineering projects are intrinsically complex and this complexity cannot be eliminated and the desired function retained.

A systematic approach to complex systems development requires an evolutionary strategy where the individuals and the technology (hardware and software) are all part of the evolutionary process. This evolutionary process must itself be designed to enable rapid change while ensuring the robustness of the system and safety. Evolutionary engineering strategies incorporate multiple parallel and diverse field testable components. These strategies require creating an environment that promotes ongoing dynamic improvement and adaptation in a functioning, reliable and safe real world context. Functional requirements, objectives and system architectures are defined in relation to performing actual tasks.

4. Executive Summary: Complexity of Military Conflict: Multiscale Complex Systems Analysis of Littoral Warfare

In recent years it has become widely recognized in the military that war is a complex encounter between complex systems in complex environments. Complex systems are formed of multiple interacting elements whose collective actions are difficult to infer from those of the individual parts. What is not as widely recognized is that multiscale complex systems analysis and the complexity profile can be used to characterize friendly and enemy forces as well as particular military conflicts, providing a means for anticipating outcomes of military conflicts and other missions.

The complexity profile distinguishes various forms of warfare and exposes the relationship between mission requirements in scale and complexity and organization capabilities. The simplest distinction is between large scale and complex military encounters. Large and uniform forces in deadly confrontation across a marked border in desert terrain that have a clear cut objective of inflicting massive damage on the enemy can be contrasted with loosely coordinated specialized forces in jungle, mountain or urban settings with minimal damage objectives or with peacekeeping functions. These examples begin to illustrate the distinction between conventional large scale but relatively simple conflicts, and complex military encounters. Complex warfare cannot be won by traditional war fighting strategies. This lesson was learned from Vietnam, and the Soviet experience in Afghanistan. To achieve mission objectives in high complexity environments with a dispersed enemy, the force organization, training, preparation and equipment should enable highly independent application of multiple forces. Compared to traditional war fighting, the key to success in such complex warfare contexts is the capability of small units to act independently. The emphasis must be on highly autonomous and independently capable forces with relatively weak coordination, rather than large scale coherence of forces. Small unit independence increases the number of actions that can be taken, i.e. complexity. This is manifest in the special force operations, especially in early stages of the recent war in Afghanistan.

While Vietnam and Afghanistan provide poster examples for complex warfare, traditional warfare also has various degrees of complexity. The organization, training and equipment of the US military illustrates the experience gained with conflicts of various degrees of complexity. We can recognize the complexity of different terrains and compare them with the structure of forces that are designed for them. Larger scale forces are designed to deal with larger scale conflicts, and more independent forces are designed to deal with high fine scale complexity conflicts. At the very largest scale (any moral issues aside), nuclear weapons are essentially unusable because their large scale impact in space and time implies they are ineffective for use in essentially any conflict. The largest scale conventional forces are ships found in the Navy designed for the simplest terrain, the open ocean. Tank divisions are well suited for deserts, and plains. Heavy and light infantry are suited for terrains with progressively greater fine scale complexity. The marines with small fighting units and high levels of training of individuals for independent action are suited for the interface of land and sea which is generally a terrain with high complexity at many scales. In a high fine scale complexity environment, e.g. near a shoreline, a few marines can defeat many ships. Similarly, in high fine scale complexity land environments, infantry can defeat tanks.

Hierarchical command systems are designed for the largest scale impacts and thus *relatively* simple warfare. Indeed, traditional military forces and related command control and planning, were designed for conventional large scale conflicts. Distributed control systems, when properly designed, can enhance the ability to meet complex challenges. The existing literature of military analysis and concept development, however, is missing basic guidance imperative for design, planning, execution and assessment of military systems and operations utilizing distributed control. How are such systems to be designed or even conceived? What are the basic principles that can guide commanders in selecting appropriate forces for complex encounters? How can the capabilities of enemy (or friendly) forces be evaluated? How can we estimate the likelihood of success of specific missions or the overall outcomes of military conflict? Multiscale analysis provides a basis for addressing these questions by analyzing the characteristic capabilities of organizational forms.

Modern military discussions have revolved around a network concept as a framing of organizational behavior. Indeed, the concept of a network as a model of social and technological organization is in widespread use in both military and non-military contexts. It often is used to suggest widespread availability of information and coordination. However, the capabilities of a network must be more carefully understood in relation to the desired function. A useful distinction is between a network of agents each of which has direct action capabilities, and a network of decision makers that determine collective actions. The two distinct coordination/action structures, by analogy with the immune system and the neuro-muscular system, suggest two different directions for improvements in current military functions. The first system is a distributed action system, the second is a distributed control but coherent action system. The first is effective at multiple localized and simultaneous tasks. The second is effective at determining a single but highly selected act at any one time. An effective military can utilize both types of organization but must recognize the quite different nature of the organization, training and technology that is needed for each.

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R1. Multiscale Representations and the Combined Relevant Operational Picture

Yaneer Bar-Yam
New England Complex Systems Institute

Reviewed by
Jeffrey R. Cares
Alidade Consulting

Reported to
John Q. Dickmann and William G. Glenney, IV
Chief of Naval Operations Strategic Studies Group

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Introduction

Many innovators have asserted that the US military must have networked forces to successfully conduct operations in the Information Age. This assertion is based on a general belief that traditional means of locating enemy forces, passing command and control information and amassing data for decisions will necessarily improve by the connection of dis-contiguous parts into a networked whole. There are now scores of networked concepts, including Network Centric Warfare (US Navy),[1] the Future Combat System (US Army),[2] the Dynamic Air Tasking Order (US Air Force), Sea Dragon (US Marine Corps) and Joint Vision 2020 (Joint Chiefs of Staff).[3] These concepts contain elements that are themselves networked subsystems (indeed, much of the recent spate of military innovation began with talk of a System of Systems).

The notion of a networked force does not specify, in and of itself, how distributed information is to be shared between networked parts. However, in various suggested strategies for implementation of network concepts it is assumed that information can be gathered and coherently presented by a single system. Although there are many competing visions, they all share the main characteristics of the Common Relevant Operational Picture (CROP) concept. The CROP concept suggests that all the militarily relevant information about a battlespace can be collected in a single repository and displayed in a single presentation architecture that is available for and can be tuned to the preferences and scope of authority of individual commanders at all levels as well as individual soldiers, airmen, marines and sailors.[4,5]

Since the purpose of the CROP is to collect sensory information and describe the military environment, whether or not it will successfully fulfill its promise is less a question of engineering design than it is a matter of system description. For most Information Age military contexts, the systems that must be described are complex systems. For the purpose of this discussion, a complex system is a system of interacting components whose collective behavior cannot be easily inferred from the behavior of the parts in isolation. Therefore, a scientific understanding of descriptions of complex systems is fundamental to successful development of concepts such as the CROP. Central to this scientific understanding is the notion of multiscale representations. Multiscale representations provide an analysis tool for the linkage of information and action. Multiscale representations treat information as an enabler of effective function and avoid the generic, universal information representation that, as will be discussed later, does not work in complex contexts.

The motivation behind military network concepts may be traced to the dramatic growth of networks in non-military contexts. There is, however, a difference between the military concepts and civilian practice. Civilian networks are often organically grown through distributed mechanisms and the information remains distributed and incoherent to unified presentation. Generally, the military concept of networks promotes a coherently and globally accessible system that is centrally conceived, centrally engineered, and centrally integrated.[6] Similar attempts at central design in civilian contexts (such as the Microsoft Network), failed to generate the success of the inherently distributed network systems. Accelerating the growth of military information networks requires a much more systematic and fundamental understanding of the relationship between network structure and function.

Two directions for future work based upon this first stage project include: (1) the development of multiscale representation analysis of military contexts and the implications for force structure and information management and (2) the development of an organic growth "enlightened evolutionary engineering" strategy for military networks based upon extensive "mental gaming" of actual military contexts.

Task 4.1.1 – Initial Investigation

The foundation for the use of multiscale representations involves specific development of methods for analysis of system capabilities. Among the essential concepts developed are:

There is a finite complexity of any entity at a particular scale. One must choose a scale at which to observe a system. Here scale refers to the level of detail, not the scope. For example, one can observe and describe an Army division at the fire team, squad, company, or battalion level. System detail above and below the selected scale is represented by more abstract descriptions than is available at the scale of observation. In other words, to detail the squads in a company means you have chosen the squad, not the company, scale of observation; similarly, to say that a battalion consists of one or more companies defines the battalion at the company, not the battalion scale. The complexity of an entity is a function of the scale of observation.[7]

This finite complexity implies a limitation in the diversity of contexts that can be dealt with by the system. It also implies a limitation in the information flow that can be responded to by the system. Continuing the previous example, observing an Army division at the division level means that squad level activities are abstracted in the detail. The Commanding General of the division, therefore, is ill suited to focus on squad level contexts, such as small units tactics, orders or movement. Likewise, a Squad Leader is ill- suited for command of the entire division. As a general principle, information flows and decisions in complex systems are extremely sensitive to scale. Decisions and information flows must match the scale of observation; otherwise, limitations in decisions and information flows confound the system. An effective analysis of military operations requires describing the impact that can be achieved by enemy and friendly forces at each scale of a potential or ongoing encounter. The ability of a system to deliver impacts at a particular scale depends both on force composition and on the Command Control Communications Computers Intelligence Surveillance Reconnaissance (C^4ISR) system that it employs. Any large scale force is composed of finer scale forces coordinated to achieve a large scale impact. In the simplest case, the scale of impact of a force involves the delivery of multiple shots in a coherent fashion. The ability to deliver coherent firepower can be achieved by simple coordination, but this is not the same as the ability to deliver measured amounts of firepower at specific targets. In complex military missions (examples include Vietnam and Kosovo), the finer scale forces cannot act in simple coherence and be effective. Complexity of operation involves delivery of diverse shots to diverse and distinct targets with multiple shots directed at targets which require multiple hits to satisfy mission objectives. The scale and complexity necessary to overcome a particular enemy force is dictated by the scale-dependent structure of the enemy force itself, and the scale-dependent structure of the battlespace (terrain, etc.), as well as the complexity of objective constraints (political, etc.). Thus, for example, centralized targeting may be effective in relatively simple large scale conflicts, but is not effective in highly complex encounters. The C^4ISR system should be designed to determine effective mission objective based firepower, and to coordinate its delivery, while the military structure must be designed to deliver this firepower.

Of particular relevance to systems involving human beings, including military ones, is the finite complexity of a human being at the scale of interaction between human beings. The limitation on the complexity of response of a human being is a key "human factor" that is relevant to the design of hybrid human/machine systems. Specific implications for the nature of effective design are to be discussed in various examples and below in progress reported toward task 4.1.2.

Task 4.1.2 – Concept Definition

In this project, specific attention has been made to the application of multiscale analysis to 21st Century Warfare and the comparison of traditional warfare with prospects for Network Centric Warfare. The focus, however, is on analysis of the CROP concept as a guiding principle for developing the information structure of networked forces.

The opportunities for communication in traditional military contexts have been limited. Experience with the effects of limited information, along with the explosion of information networks in society, has led to a general belief that creating networks that provide a ready access to information will lead to substantially improved effectiveness. Counter to this notion, the limitation of an individual human being's complexity suggests that information flow may not be helpful (and may even be dangerous) in a context where real-time response is necessary and action based upon relevant information can be impaired by spurious information, i.e. distraction. Even when relevant information can be extracted from an information rich source, substantial delay in response will result from the filtering process.

Some military innovators have suggested that the system must be designed like the "all-points-connected" networks of individuals in social systems (an example of which is the Internet). Such architectures may allow the development of more functionally oriented sub-networks of individuals through trial and experimentation over extended periods of time. When action is coordinated through such a network, limited sets of individuals and communications are involved. Whether a specific communication is built upon a network design through hardware or software is not essential, what is essential is that information relevant to specific acts is communicated effectively when rapid response is necessary.

The limitation in the complexity of response of an individual human being can be readily recognized in the context of information rich environments. Whether we consider the possibility of a person paying attention to multiple conversations at a party, or multiple channels of television simultaneously, limitations are well known scientifically (and fairly obvious to the lay person through everyday experience). While these examples show that an individual has an ability to focus attention on the relevant information in a "noisy" environment, this ability has limitations and any noise filtering accelerates exhaustion. Moreover, in hazardous or demanding environments distraction results in degraded attention.

The objective of this research is to provide a context for recognizing the role of information in action and response to environmental demands and challenges associated with specific tasks. *Our conclusions can be stated immediately: The CROP concept as articulated violates a basic principle of information distribution in complex systems. The central task of a sensor system is to provide* ***relevant*** *information Increasing the availability of* ***potentially relevant*** *information must be carefully weighed against the damage due to distraction by irrelevant information.* While this statement is natural and intuitive, even obvious, we emphasize this as the primary conclusion of our study precisely because the CROP concept, as articulated, fundamentally violates this concept.

Indeed, the CROP concept, while justified as the basis of the new networked military systems design, contrasts with other concepts of networked and distributed information systems (both real and imagined). *Instead, it corresponds to the concept of a centralized data processing system.* We note that the objective of multiscale representations is to determine the information relevant to a particular observer's scale. Therefore, the concept of a multiscale representation can provide substantial guidance about building more effective concepts of information distribution in a networked system. While such guidance is beyond the scope of the present project, we conclude this document with suggested research program to apply multiscale representations for the development of networked information systems that can replace the CROP concept.

Typically, information about the local environment is the most relevant, and information about remote locations is less relevant. In a command hierarchy, relevant information is information at the scale at which a commander must make decisions. At more senior levels of command, coarser scale information may require aggregation of finer scale information. As in the traditional saying, "can't see the forest for the trees," there is a great difficulty in recognizing the larger scale behavior from the details. Thus, the accessibility or exposure to such details does not necessarily enable effective action.

Consider the flood of e-mail messages that occupy substantial attention of each individual today. In the context of an interactive effort, the usefulness of e-mail is clear. However, in the context of time sensitive tasks with life and death consequences, such distractions are inappropriate. An open network, sometimes envisaged by planners, would be even worse, corresponding to having everybody see everybody else's email. At an even greater extreme, where mobile sensors are flooding a network with real-time video from many sources, attention to such an information flow is highly unrealistic.

A more careful understanding of information in complex systems suggests that the most important task of an information processing system is not collecting it (in fact, in many complex cases, this is the most trivial task). Discarding irrelevant information is the most important task, yet it is a task which is often most difficult. As an illustration, in the case of human perception we know that people do not have eyes in the back of their heads. This reflects the fundamental tradeoff that is being discussed: while information that is lost can, at times, be important, even life-saving, the importance of reserving attention for the information which is more likely to be important is essential and thus the tradeoff of ignoring substantial amounts of potentially useful information is being made by the biological system.

The availability of information can thus be seen to be detrimental in many cases. The imagined concept that somehow our attention will be drawn to precisely the piece of information that is relevant to our next action cannot be assumed. The process of design of a system to provide the relevant information must be carefully considered since *there is no generic network design that will provide a general solution to this problem.* This is the difficult task that is usually not recognized when conceptualizing information systems, or when recognized it is not adequately resourced when acquiring new sensor and information systems. Multiscale representations can provide the fundamental understanding necessary for examining strategies to identify the relevance of information in the context of specific tasks as well as the understanding necessary for effective development of future operational concepts that are centered on information intensive missions and functions. Application to specific tasks requires substantial "mental gaming" as well as direct testing of scenarios. Such scenario testing would involve teams of individuals performing specific tasks in challenging (complex) environments requiring coordinated behaviors.

Task 4.1.3 – Evaluation Framework

This section suggests a general framework for evaluating the CROP concept, to include the constraints of limited resources (humans, machines, bandwidth, collectors, knowledge, time) suitable for defining, in the abstract, solutions to the information dynamics problem. This framework can be used in further efforts (including Fleet Battle Experiments) to evaluate the CROP and similar or substantially distinct concepts.

The framework recognizes *scale* as the most fundamental characteristic of Information Age command and control. This is in stark contrast to other more tangible characteristics from Industrial Age command and control such as speed, reliability and security, all of which can trace their inception to modes of communication and models of the environment that depend on the delivery of physical messages rather than implicit meaning. A collection of messages (particularly messages containing positional information about an enemy) does not guarantee an understanding of the importance of the messages at scales coarser than the messages themselves. *Scales, then, are a set of perspectives from which the framework focuses attention on an Information Age command and control system.*

The evaluation framework requires identification of the particular scales from which the environment will be observed. For typical Industrial Age military contexts, these scales can be usefully defined using the existing levels of command. An area for future research is to identify what these scales will be in Information Age warfare processes.

Our analysis is guided by the recognition that an information system cannot be evaluated without an understanding of the function or task that it serves, and particularly the structure and function of the system that uses this information. A general framework for evaluation of the CROP concept can be based upon the principles of multiscale representation once the following key question is addressed: Is CROP and the related networked information system designed to serve the conventional command and control hierarchy, or is this system designed to replace the command structure with another? If it is to serve the existing command structure, then it must act to filter information by scale aggregation so as to allow effective functioning rather than to expose commanders to irrelevant information. If it is to change the command control system, then the evaluation framework requires joint analysis of command structure and the information structure in the context of expected mission objectives. In this project, we confine ourselves to describing the evaluation framework of the CROP concept as supporting structure to the existing command and control systems and organizations. We also discuss the context and reasons for extensions of this Phase I project that generalize this analysis to consider alternate command and control structures, organizations and technology architectures and their suitability for complex missions (see below).

The conventional command hierarchy assumes or demands aggregation of information as a natural outcome of the limited information flow between levels of command. Each commander is responsible for recognizing and reporting the limited information (such as enemy geo-location or own-force logistics data) that is essential for higher-level commanders to evaluate and respond to as aggregate information. Aggregation of information requires military specific understanding of both strategy and tactics in the context of military confrontation. Once orders are received, each commander is responsible for obtaining relevant environmental information that affects the manner of execution and interpreting the actions necessary for execution through orders to lower level commanders or soldiers in the field.

The CROP concept, as currently articulated, does not recognize the essential nature of the aggregation of information. At this time, computer based systems are not capable of the pattern recognition processes that are necessary for such information aggregation. More specifically, pattern recognition based abstraction is the product of military experience in the context of military operations. The translation of information to a coarser scale often entails identification of broad patterns and trends, creation of metaphors and symbols or re-interpretation of the information based on history, calculation or hunch. In short, in complex environments, translation from finer to coarser scales frequently requires fabrication of information that is not explicitly contained in the physical manifestation of the environment. Since computer systems are not, in themselves, capable of such aggregation at this time, human designed methods of information aggregation must be contained within (through electronic implementation) or in conjunction with (through human action) the CROP design. Development of the necessary filters of information and their representational abstractions in the form of auditory or visual displays should be considered a challenging task. This task is essential to the success of CROP.

The most basic framework for analysis of specific CROP implementations should be the analysis of the implementation of transparent aggregation of information. This aggregation should take the form of auditory or visual information flows that represent the necessary information at the scale needed for the commander response. Several levels of *focus* that limit distraction at the expense of potentially relevant information should be available. The information provided in such aggregated information displays must be guided by military intuition and experience, not just by technological feasibility.

While the gathering of and representation of information is the essential role of CROP, our evaluation framework points out the essential and complementary task of interpreting coarse scale information in the form of military goals, objectives and commands, in terms of actions in the context of specific environmental contexts. This corresponds to the detailing of coarser scale information into the fine scale. The translation of information to a finer scale often entails interpretation from broad patterns and trends to particular, singular events, deciphering of metaphors and symbols or relevance of collective determinations to individual histories, calculations or hunches. In short, in complex environments, translation from coarser to finer scales frequently requires interpretation of implications about the physical world in general to the details of physical things in particular.

Understanding multiscale representations is a fundamental prerequisite for building an effective fighting force dependent upon large quantities of information. This knowledge must be fully integrated into new concepts, technological design and acquisition decisions, experimentation, gaming and simulations of future combat. The guiding concepts for information systems and force design should capitalize on the multiscale nature of information, decisions and hierarchy in Information Age competition. This includes the analysis of strengths and weaknesses of friendly and enemy forces.

The CROP evaluation framework we have described adopts the CROP in the context of conventional military control. The challenge of applying this analysis to Information Age Warfare must not only recognize the importance of information aggregation, it must recognize the inherent complexity of Information Age Warfare contexts through the environmental, enemy and political components. Indeed, we might define Information Age Warfare as those contexts in which the demands of complex military operations exceed the information flow capacity of the conventional military structure. While this appears to be the key opportunity for CROP based concepts, the current CROP concept is not well suited for this task precisely because it does not recognize the need for information filtering and the limitations on human information flow in real time response.

If the warfare environment is complex enough, then

— collecting detail at fine scales does not guarantee a meaningful picture at coarser, composite scales.

— broad patterns from coarser scales do not guarantee a meaningful local picture at finer, distributed scales.

The CROP concept as defined does not solve these problems of information flow and representation. By not addressing these problems, the CROP fails to address the key role of information for networked forces engaged in Information Age Warfare. The information flow problems must be solved by changes in the command structure. The reason for this is an impossibility of abstraction in a complex context where individual actions do not aggregate to create collective behaviors in a simple way. Dis-contiguous distributed forces betray very little information in the physical location; deeper questions of intent and the dynamics of maneuver are contained in higher scale patterns. In this context, the relationship between scale and command level in the military hierarchy do not apply. The application of military force in this context requires new force structures in conjunction with radically different information systems to achieve the necessary aggregation of force behavior.

A multiscale analysis and the resulting evaluation framework must then focus on an examination of the decisions required at each important scale in Information Age command and control systems. These decisions must be matched to the command structure capabilities. For existing military contexts, these decisions often depend on physical attributes of the environment and the location of enemy and friendly forces.

An example is the archetypal Course of Action (COA) analysis. In many Industrial Age contexts, defensive decisions depended on which Avenue of Approach (AOA) an enemy might choose during an attack. A commander might consider the three most likely AOAs, and label each of these a COA. Then the commander would array forces to counter one or all of the COAs, leaving a reserve to commit once the enemy's particular COA was determined. A decision tree could be constructed from this analysis, with each decision in the tree depending on such physical considerations as AOA trafficability assessments, enemy location data or the state of friendly defensive positions. In the context of Information Age Warfare, where forces may be more mobile, more dispersed, more hidden by context or constraint and stealthier than previously, the variety of decisions and number of possibilities is many orders of magnitude greater and the standard COA analysis must be generalized for distributed decision-making and aggregation. An area for future research is to determine the types of Information Age decisions appropriate to each level in a command hierarchy.

Attendant to determining the appropriate scales and the useful decisions at those scales are measurements of the environment that will aid in making the decisions. By definition, an observer will search for information in the environment at the scale of observation. Insofar as there is physical evidence at that scale which helps with the decision, direct, explicit observation of the physical world is appropriate. Where the information is more implicit, observers (and, as a function of hierarchy, the entire chain of command) must find indirect physical evidence that translates into information that helps with a decision. An example of the former is determination of the center of mass as well as the speed and direction of an armored division on maneuvers in support of archetypal COA analysis. An area of future research is determination of the coarser scale patterns, structures and behaviors that translate physical measurement at a finer scale to decisions at a coarser scale. A mature evaluation framework would also allow for replication of finer scale instances from coarser scale patterns.

As a concluding note, since there is no generic network design that will provide a general solution to the problem of multiscale function, development of a framework to evaluate concepts such as the CROP is highly context dependent. In other words, while the concept of multiscale representations may be general, application of multiscale representations to a CROP concept within a specific network design is greatly impacted by the design of the network and the nature of the combat tasks. For this reason, development of the framework to any more than the general statements contained in this section will require *in situ* research during such events as Fleet Battle Experiments, war games or other high context activities.

Conclusions and Extensions of the Multiscale Analysis beyond the CROP

The focus of this report on the implications of multiscale representations for the CROP concept led to the centrality of the limitations of human complexity on the structure and function of an information network. In the context of more specific CROP designs, the framework of multiscale representations provides a mechanism for evaluating CROP concepts through the comparison of the system (human and machine) capability in aggregation of information, and commander capability in responding to this information.

The importance of this subject extends beyond the analysis of CROP to the analysis of the environmental complexity, the force structure, and the command and control of the force structure in view of specific mission objectives. Thus, a more systematic evaluation of multiscale representations in the context of military applications would discuss the effectiveness of military command and control structures in the context of complex mission objectives. Complex mission objectives are the context of difficult 21st century military challenges for which new information technologies are most relevant.

Thus, the application of multiscale representations to a second phase project should be pursued. In the context of pursuing this project, preliminary efforts have been made to consider both information aggregation, and multiscale complexity of military structure. The results of these investigations have been described in oral reports to the Chief of Naval Operations Strategic Studies Group and the Newport Center for Information Age Warfare Studies and would be the basis for extending this work in a second stage project. These reports are outlined below.

Additional Report topics:

First Oral Report:

1. Introduction to complex systems and patterns of collective behavior
2. Multiscale representations and force aggregation
3. Tradeoff between large scale and complex operations.
4. Control structure analysis for the coordination of complex response
5. Application of multiscale analysis to the 21st Century plans for littoral warfare
6. Multiscale representations and the 21st Century Warrior

Second Oral Report

1. Review of first oral report
2. Implications of multiscale analysis of control structures for large-scale engineering
3. Enlightened evolutionary engineering

References

1. D. S. Alberts, J. J. Garstka, F. P. Stein, Network Centric Warfare, DoD C4ISR Cooperative Research Program (1999)

2. Future Combat Systems: http://www.darpa.mil/fcs/

3. Joint Vision 2010: http://www.dtic.mil/jv2010/jv2010.pdf

4. U.S. Joint Forces Command (USJFCOM) definition---Common Relevant Operational Picture (CROP): CROP is a presentation of timely, fused, accurate, assured, and relevant information that can be tailored to meet the requirements of the joint force and is common to every organization and individual involved in joint operations. http://www.ijwa.org/J9/j9_main.htm

5. Ref. 3, p. 16: "the capability to collect, process, and disseminate an uninterrupted flow of information,…" p. 18: "Improved command and control, based on fused, all-source, real-time intelligence…".

6. Ref. 3, p.32: "The implementation process will integrate ongoing initiatives, such as the Joint Requirements Oversight Council, Joint Warfighting Capabilities Assessments, and Advanced Capabilities Technology Demonstrations (ACTD), to promote the integrated development of operational capabilities."

7. Y. Bar-Yam, Dynamics of Complex Systems, especially Chapters 8 and 9.

8. P. J. Hiniker, 4th International Command and Control Research and Technology Symposium, 1998,http://www.dodccrp.org/Proceedings/DOCS/wcd00000/wcd0006f.htm

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Multiscale Representations Phase II:
Task 1: Implementation of Innovation in FORCEnet

September 2, 2002

R2. Large Scale Engineering and Evolutionary Change: Useful Concepts for Implementation of FORCEnet

Yaneer Bar-Yam
New England Complex Systems Institute

Reviewed by
Jeffrey R. Cares
Alidade Consulting

Reported to
John Q. Dickmann and William G. Glenney, IV
Chief of Naval Operations Strategic Studies Group

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Preface

The Chief of Naval Operations Strategic Studies Group XX (SSG XX) in its Final Report [1] designed a roadmap for rapid development and implementation of FORCEnet. A key aspect of this road map is recognition of the intrinsic limitations of conventional engineering approaches to large-scale complex engineering tasks and the imperative of using an evolutionary approach. The SSG XX assessment is consistent with and motivated in part by the perspective presented on March 30, 2001 by Yaneer Bar-Yam, Professor and President of the New England Complex Systems Institute. SSG XX stated:

As a highly complex system, FORCEnet cannot be designed in the traditional way. A significant part of its development must evolve through a robust experimentation process where new designs can be quickly and efficiently evaluated in an integrated environment with emphasis on human system interfaces. Supporting this evolution requires a fundamental redesign of Navy experimentation… [1, p. 4-11]

This evolutionary strategy, and suggested leadership organizational changes to enable it, forms the core of the implementation strategy described by SSG XX in Chapter 4 of its report. As stated by SSG XX the current mechanisms of the Navy are not effective for rapid acquisition of FORCEnet. Radical changes are required:

> Experimentation must become second-nature and an inherent part of the Navy's day-to-day activities. The notion of "build a little, test a little" must form the basis for identifying the capabilities and systems that will migrate into FORCEnet. The Navy should fundamentally rethink the way it does experimentation. The future paradigm must become one of focused iterative and affordable experimentation, with direct input and participation by the operational forces…If acted upon, SSG XX's recommendations will result in a complete redesign of Navy experimentation [1, p. 4-4]

The necessity to redesign Navy experimentation compelled SSG XX to conclude that a radical change to a process oriented "Organizational Model for Success" is necessary to overcome the serious barriers to FORCEnet implementation in the current Navy organization [1, p. xviii]. The evolutionary model for implementation and its enabling organizational structure lead to a "capability centric design and development process" [1, p. xix]

As an aid to further developments of the SSG efforts on implementation of FORCEnet some of the central concepts and background motivating these recommendations is described in the attached paper. In particular, this paper describes the basic motivation for and qualities of using evolutionary processes in large-scale engineering. As a case study it describes aspects of the Advanced Automation System, a project to modernize the Air Traffic Control system, because it is the largest engineering project to date whose failure has been adequately documented. Initiated in 1982, it was abandoned without success in 1994. Understanding why a 12 year project costing 3-6 billion dollars did not succeed to modernize one of the most antiquated systems still in use provides an important lesson for innovation through large scale engineering projects. The lecture on March 30, 2001 and this paper are part of a larger effort to apply multiscale complex systems analysis to military conflict. [2]

Enlightened Evolutionary Engineering

Large Scale Engineering

The traditional approach to large scale engineering projects follows the paradigm established by the Manhattan project and the Space program. There are several assumptions inherent to this paradigm. First, that substantially new technology will be used. Second, the new technology to be used is based upon a clear understanding of the basic principles or equations that govern the system (i.e. the relationship between energy and mass, $E=mc^2$, for the Manhattan project, or Newton's laws of mechanics and gravitation $F=-GMm/r^2$ for the space program). Third, that the goal of the project and its more specific objectives and specifications are clearly understood. Fourth, that based upon these specifications, a design will be created essentially from scratch and this design will be implemented and, consequently the mission will be accomplished.

Large scale engineering projects today generally continue to follow this paradigm. Projects are driven by a need to replace old "obsolete" systems with new systems, and particularly to use new technology. The time line of the project involves a sequence of stages: a planning stage at the beginning giving way to a specification stage, a design stage, and an implementation stage. The various stages of the process all assume that managers know what needs to be done and that this information can be included in a specification. Managers are deemed successful or unsuccessful depending on whether this specification is achieved. On the technical side, modern large scale engineering projects generally involve the integration of systems to create larger systems, their goals include adding multiple functions that have not been possible before, and they are expected to satisfy additional constraints, especially constraints of reliability, safety and security.

The images of success in the Manhattan and Space Projects remain with us. What really happens with large scale engineering projects is much less satisfactory. Many projects end up as failed and abandoned. This is true despite the tremendous investments that are made. A collection of such project failures is shown in Table 1 with costs ranging from around \$50 million to \$5 billion, and the final one, an automation project for dispatching of London Ambulances may have cost 20 lives before it was stopped after 48 hours. Each of these projects represents a substantial investment and would not have been abandoned without good reasons. The largest documented financial cost for a single project, the Federal Aviation Administration (FAA) Advanced Automation System was the government effort to improve air traffic control in the United States. Many of the major difficulties with air traffic delays and other limitations are blamed on the antiquated / obsolete air traffic control system. This system, originally built in the 1950s, used remarkably obsolete technology, including 1960s mainframe computers and equipment based upon vacuum tubes [3], with functional limitations that would compel any modern engineer into laughter. Still, an effort that cost 3-6 billion dollars between 1982 and 1994 was abandoned without improving the system.

Table I: List of Large Scale Engineering Project Failures*

System Function – Responsible Organization	**Years of Work (outcome)**	**Approximate Cost** M=Million, B=Billion
Vehicle Registration, Drivers license – California Dept. of Motor Vehicles [25-30]	1987-1994 (scrapped)	$44M
Automated reservations, ticketing, flight scheduling, fuel delivery, kitchens and general administration – United Air Lines [31]	Late 1960s–Early 1970s (scrapped)	$50M
State wide Automated Child Support System (SACSS) – California [32,33]	1991-1997 (scrapped)	$110M
Hotel reservations and flights – Hilton, Marriott, Budget, American Airlines [34]	1988-1992 (scrapped)	$125M
Advanced Logistics System – Air Force [35]	1968-1975 (scrapped)	$250M
Taurus Share trading system – British Stock Exchange [36]	1990-1993 (scrapped)	$100–$600M
IRS Tax Systems Modernization projects [37]	1989-1997 (scrapped)	$4B
FAA Advanced Automation System [5]	**1982-1994 (scrapped)**	**$3–$6B**
London Ambulance Service Computer Aided Dispatch System [38]	1991-1992 (scrapped)	$2.5M, 20 lives

*with thanks to J. Saltzer for providing some of the references.

When a large project like the redesign of the air traffic control system fails, participants and observers can often give reasons for the failure. Successful projects that are superficially similar (but do not involve the same level of complexity) seem to indicate that specific problems were responsible. In this case there are several good reasons for failure that appear unique. Specifically, the U.S. Government procurement process that involved both the FAA and Congress has been blamed. Other problems were that the specifications / requirements were not really known, that it was designed around a "Big Bang" change that would change the system from the old to the new over a very short time, that there was an emphasis on changing from manual to automated systems, and the “safety veto” exercised by air traffic controllers who could refuse the change because of their concerns about safety. The latter indeed appears to be a daunting challenge since the safety of airplanes full of people is a major concern that is not present in many other large scale engineering projects. While people have attributed the failure of the Advanced Automation System to these problems, the magnitude of failures of the large scale engineering projects in Table I, and the suggestion that each case involved its own unique reasons does not seem to strike at the core of the causes of failure.

A study of government Information Technology projects in 1994 [4] pointed to large scale waste throughout the Government, including a number of DoD projects. This led to the Information Technology Management Reform Act (ITMRA) part of the Clinger-Cohen Act in 1996. The objective of this Act was to bring strategies that were in use in the private sector into government acquisition processes. It is useful, therefore, to ask whether indeed the private sector had greater success in large scale engineering projects.

A general survey of large scale software engineering projects was performed in 1995 by the Standish Group International [5]. This study classified projects according to whether they met stated goals of the project, the time table, and cost estimates. They found that under 20% of the projects were on-time, on-budget and on-function (projects at large companies had a lower rate of under 10% success), over 50% of the projects were "challenged" which meant they were over budget typically by a factor of two, they were over schedule by a factor of two, and did not meet about two thirds of the original functional specifications. The remaining 30% of the projects were called "impaired" which meant that they were abandoned. When considering the major investments these projects represent of time and money, the numbers are staggering, easily reaching $100 Billion each year in direct costs. The high percentage of failures and the remarkable percentage of challenged projects suggest that there is a systematic reason for the difficulty involved in large scale engineering projects beyond the specific reasons for failure that one might identify in any one case.

Indeed despite ITMRA and related improvements, successors of the Advanced Automation System that are being worked on today, are finding the going slow and progress limited [6]. From 1995 until today, major achievements include replacing mainframe computers, replacing communications switching system, and the en-route controller radar stations. Still, the new equipment continues to be used in a manner that follows original protocols used for the old equipment, and the replacement of the Automated Radar Terminal System at Terminal Radar Facilities responsible for air traffic control near airports has not yet been achieved. The program to do so, the Standard Terminal Automation Replacement System (STARS), is facing many of the problems that affected the Advanced Automation System: cost overruns, delays, and safety vetoes of implementation.

A fundamental reason for the difficulties with modern large scale engineering projects is their inherent complexity. Complexity is generally a characteristic of large scale engineering projects today. Complexity implies that different parts of the system are interdependent so that changes in one part may have effects on other parts of the system. Complexity may cause unanticipated effects that lead to failures of the system. These “indirect” effects can be discussed in terms of multiple feedback loops among portions of the system, and in terms of emergent collective behaviors of the system as a whole. Such behaviors are generally difficult to anticipate and understand. Despite the superficial complexity of the Manhattan and Space Projects, the tasks that they were striving to achieve were relatively simple compared to the problem of air traffic control. To understand complexity of Air Traffic Control (ATC) it is necessary to consider the problem of 3-dimensional trajectory separation --- ensuring the paths of any two planes do not intersect at the same time; the many airplanes taking off and landing in a short period of time; and the remarkably low probability of failure that safety constraints impose. Failure in any one case may appear to have a specific cause, but the common inability to implement high cost systems can be attributed to their intrinsic complexity.

While the complexity of engineering projects has been increasing, it is important to recognize that complexity is not new. Indeed, engineers and managers are generally aware of the complexity of these projects and have developed systematic techniques to address them. There are several strategies that are commonly used including modularity, abstraction, hierarchy and layering. These methods are useful, but at some degree of interdependence they become ineffective. Modularity is a well recognized way to separate a large system into parts that can be individually designed and modified. However, modularity incorrectly assumes that a complex system behavior can be reduced to the sum of its parts. As systems become more complex the design of interfaces between parts occupies increasing attention and eventually the process breaks down. Abstraction simplifies the description or specification of the system. However abstraction assumes that the details to be provided to one part of the system (module) can be designed independently of details in other parts. Modularity and abstraction are generalized by various forms of hierarchical and layered specification, whether through the structure of the system, or through the attributes of parts of a system (e.g. in object oriented programming). Again, these two approaches either incorrectly portray performance or behavioral relationships between the system parts or assume details can be provided at a later stage. Similarly, management has developed ways to coordinate teams of people working on the same project through various carefully specified coordination mechanisms.

The question is why aren't these enough? An overly simple answer is that these mechanisms and techniques are hard to get right. A more useful answer addresses the basic issues in the behavior of complex systems, the effect of interdependence of parts and functional complexity of the parts and the whole system. Two theorems described in the appendix provide a basis for understanding the underlying problems of engineering complex systems. The first [7] relates the complexity of the engineered system to the complexity of the task it is required to perform. The second [8,9] proves that for all practical purposes adequate functional testing of complex engineered systems is impossible.

Once we recognize these fundamental problems of designing complex systems, how can we solve them? A partial answer can be found in the process of incremental change [5]. Incremental engineering is commonly used in engineering design through the creation of improved versions of existing hardware or software. The key to this suggestion is that when a new project is started, existing systems or rapid prototypes will serve as the foundation for iterative incremental changes. After many incremental changes the system can achieve substantial modification from its original form. This concept of incremental design is one step towards a more complex systems oriented approach. A complex systems perspective provides a larger conceptual framework —evolution—from which to understand how incremental change can enable rapid innovation. This evolutionary process is most commonly associated with the formation of complex biological organisms.

Complex Systems Approach to Innovation

The field of complex systems [8-11] provides **two** answers to failures of large scale engineering projects. The **first** is to change objectives. Recognizing that complexity is a crucial property of engineering problems should lead planners to limit as much as possible the complexity of objectives. This is key to structuring of successful projects. The **second** is to use an evolutionary process. This becomes essential when simplification will no longer work because the function required is intrinsically complex. In this case many alternative solutions can be tried in a systematic manner allowing construction of highly complex entities. This paper focuses on the second, evolutionary engineering process because most modern large scale engineering projects are intrinsically complex and this complexity cannot be eliminated and the desired function retained. A few remarks are made about the possibility of complexity limitation here for completeness.

Change objectives: Simplify when possible

The idea of limiting complexity seems obvious, but the real effort involved is to recognize what gives rise to complexity. The complexity of a task can be quantified as the number of possible wrong ways to perform it for every right way. The more likely a wrong choice, the more complex the task. In order for a system to perform a task it must be able to perform the right action. As a rule, this also means that the number of possible actions that the system can perform (and select between) must be at least this number. This is the “Law of requisite variety” (Appendix A.1) that relates the complexity of a task to the complexity of a system that can perform the task effectively.

Not surprisingly many of the key aspects of modern projects are precisely the ones that add complexity. Among the aspects of an engineering project that make it more complex are: integration of previously separate systems, multiplicity of functions, and constraints. Each of these has direct impact on the number of possibilities that the system must encounter.

Counting “the number of possibilities” may also be performed using the notion of description length. By Shannon’s information theory the length of a complete description is directly related to complexity. The length of a complete description of a system is the same as a fully detailed specification. A natural bound on the maximum length description that can be implemented by a team of human beings using conventional engineering, is the length that can be reasonably read by a single human being, i.e. a few books, but not much more than this. Within the range of possible complexities lower than this bound, there is an increase in the level of effort / cost of higher complexity projects. There is also an indirect cost associated with an increased difficulty in future innovation and adaptability.

In order to facilitate the choice of project objectives an estimate of complexity should be part of the initial process of evaluating an engineering project. This estimate can be related to the level of effort needed to complete a project based upon benchmarks. Thus by estimating the complexity we can limit it to a level that can be addressed by the resources available. When it is realized that there is a cost associated with complexity in terms of effort, maintenance and future innovation, then the initial scoping phase can be used to reduce the complexity as much as possible while still achieving essential function. This approach is directly counter to the common "wish list" approach to project scoping.

In some cases, it is possible to limit complexity without changing the overall desired system behavior and function. This is a superficial complexity which can, and should be, eliminated. However, as the Law of Requisite Variety states, when the complexity of the desired system function is intrinsically complex, then simplification is not possible unless a change in expectations occurs. This choice should be made in the initial part of the design process.

A useful analogy can be developed between engineering and changes in modern corporate behavior where there is a trend toward "outsourcing" and a focus on "core competencies" in the context of a "service economy". In essence, these are methods of simplifying the functioning of an organization. Similarly, effective strategies to simplify engineering projects include a focus on essential functions, avoiding integration, limiting the number of functions, relying on "ambient" resources, and relaxing constraints as much as possible. Determining what aspects of a system concept are really necessary for the functionality that is desired is crucial. When the desired functionality is intrinsically complex and we cannot simply choose to avoid it, then an evolutionary approach is necessary. This paper will focus on the case of highly complex engineering tasks rather than the application of complexity estimation and limitation.

Additional information about complexity estimation can be obtained from the references [8-12]. In these references a more detailed and formal approach is described that relates these concepts to the information theoretic notion of number of possibilities and considers the multiscale approach of determining at which scales system functions must be specified. The relationship of scale and complexity is linked to the dependencies between parts of the system. These dependencies are strongly influenced both by constraints and by imposition of multiple functions. Moreover, as discussed in the Appendix, the issues of functional complexity must be understood more carefully in order to determine the complexity of a task in an engineering context.

Evolve highly complex solutions

Simplifying the function of an engineered system is not always possible because the necessary or desired core function is itself highly complex. When the inherent nature of a complex task is too large to deal with using conventional large scale engineering processes, a better solution is to use an evolutionary process [13] to create an environment in which continuous innovation can occur.

Evolutionary processes, commonly understood to be analogous to free market competition, are based on incremental iterative change. However, there are basic differences between evolution and the notion of incremental engineering. Among these is that evolution assumes that many different systems exist at the same time, and that changes occur to these systems independently. The parallel testing of many different changes that can be combined later is distinctly different from conventional incremental engineering. It is more similar to the parallel and largely independent exploration of product improvements by different companies in a market economy, especially when there are many small companies. Another basic idea of evolution is that much testing is done "in the field"; the process of learning about effective solutions occurs through direct feedback from the environment. There are many more aspects of evolution that should be understood in order to make effective use of this process in complex large scale engineering projects. Even the conventional concepts of evolution as they are currently taught in basic biology courses are not sufficient to capture the richness of modern ideas about evolution [8 ch. 6,10,14-17]. In this paper we will provide a few basic concepts of evolution and discuss their significance in the context of implementation for large scale engineering projects.

Evolution

To introduce the concepts of evolution it is helpful to start from the conventional perspective then augment it with some of the modern modifications. Evolution is about the change in a population of organisms over time. This population changes not because the members of the population change directly, but because of a process of generational replacement by offspring that differ from their parents. The qualities of offspring are different from their parents, in part, because some parents have more offspring than others. The process by which the number of offspring are determined, termed selection, is considered a measure of organism effectiveness / fitness. Offspring tend to inherit traits of parents. Traits are modified by sexual reproduction and mutation that introduce novelty/variation. This novelty allows progressive changes over many generations. Thus, in the conventional perspective evolution is a process of replication with variation followed by selection based upon competition. In contrast with an engineering view where the process of innovation occurs through concept, design, specification, implementation and large scale manufacture, the evolutionary perspective would suggest that we consider the population of functioning products that are in use at a particular time as the changing population that will be replaced by new products over time. The change in this population occurs through the selection of which products increase their proportion in the population. This process of evolution involves the decisions of people as well as the changes that occur in the equipment itself.

It may be helpful to point out that this approach (the treatment of the population of engineered products as evolving) is quite different than the approach previously used to introduce evolution in an engineering context through genetic algorithms or evolutionary algorithms (GA/EA) [18,19]. The GA/EA approach has considered automating the process of design by transferring the entire problem into a computer. According to this strategy, we develop a representation of possible systems, specify the utility function, implement selection and replication and subsequently create the entire system design in the computer. While the GA/EA approach can help in specific cases, it is well known that evolution from scratch is slow. Thus it is helpful to take advantage of the capability of human beings to contribute to the design of systems. The objective of the use of evolutionary process described here is to avoid relying upon an individual human being to design systems that can perform complex tasks. As shown in the Appendix, a computer by itself cannot solve such problems either. Our objective here is to embed the process of design into that of many human beings (using computers) coordinated through an evolutionary process.

A modern view of evolution recognizes that the process of evolution involves ecosystems of interdependent organisms. Such networks of dependency are generally characteristic of complex systems and are present at every level: inside the organism in genomic networks and neural networks, and outside of them in food webs and ecosystems [20,21]. The existence of networks reflects the importance of thinking about patterns of behavior in addition to the behavior of individual components. Still, for the purpose of simplicity we can start by using the concepts of evolution as a process of reproduction with variation and selection with competition to guide our understanding of key aspects of how processes inside and between organisms take place in such networks.

Since one of the basic concepts of evolution is competition, one question that has been of concern is the origins of cooperation. This is particularly relevant to understanding the nature of networks, which include various dependencies including cooperation as well as competition. Fundamentally, it should be recognized that cooperation and competition are not counter to each other if they exist at different levels of organization [10]. Indeed, they are essential complements; cooperation at one level of organization is necessary for competition at a higher level of organization, and vice versa. This becomes apparent when we consider team sports where cooperation between players is necessary for competition between teams, and the competition between teams gives rise to cooperation between players. This multilevel perspective is different than conventional perspectives and is an essential part of the modern understanding of the evolution and development of complex systems

Another important aspect of evolution arises from considering the continued existence of bacteria at the same time as human beings. Why should bacteria, that existed long before human beings, and therefore presumably are more primitive, continue to exist? Or if they exist, why should human beings exist as well? This question points to the remarkable diversity of life that exists as a counterpoint to the centrality of selection in the evolutionary process. A simple interpretation of selection (survival of the fittest) would seem to suggest that there should be only one type of organism. The reason this is not the case ultimately resides in the existence of diverse resources. Diverse resources account for diverse organisms because a single organism type is not well suited to consume all of the different types of resources. Even though under some circumstances bacteria and human beings can compete for the same resources, there are many times when, due to the scale of the resources or their composition, there is no direct competition. Indeed, it is hard to determine whether it is more important to consider the cooperation or competition between human beings and bacteria in the context of the many different interactions between them (including symbiotic, parasitic and pathogenic). Thus the question of whether human beings or bacteria are more evolved is not really the central question, the key question has to do with which is better at consuming which kind of resources. Again, the diversity of entities and components must be considered in developing complex systems.

A third aspect of evolution is recognizing that in complex organisms like the human being, the process of adaptation through learning can itself be considered a kind of evolutionary process. This kind of evolution is often called "mimetic" evolution. The internal process that occurs in trial and error learning involves multiple possible concepts and processes. Through this process the more effective ones are selected within the specific context or environment in which people exist. The learning that occurs through communication between people corresponds to replication of patterns of thought. The rapid pace of human social evolution can be compared with the rapid pace of bacterial biological evolution. This comparison suggests that even when large complex structures exist, the evolutionary process of change continues to be rapid through the ongoing change of internal parts.

While the development of system-wide evolutionary process is not the standard use of evolution in engineering, it can be considered an extension of how innovation actually takes place in a market place. The larger process in this case is one in which many different companies are competing and independently innovating with tests of the effectiveness of their products being seen through their adoption by people who choose which products to buy and use. In a military context, the adoption of technology is a more centrally controlled process, still there is a process of testing that goes on that is more akin to trial and error learning than is recognized by the conventional specification-design-implementation pipeline paradigm. Moreover, at times there are decisions that are made by various parts of the military that reflect a non-uniform adoption and the possibility of progressive adoption of more effective products.

Enlightened evolutionary engineering

The development of evolutionary processes in engineering requires a basic rethinking of how conventional engineering steps are to be accomplished. Also, since evolution is not a simple process, effective evolutionary strategies must be carefully considered, and, even when many aspects of the process are understood, they must be developed through trial and error.

The basic concept of designing an evolutionary process is to create an environment in which a process of innovation and change (i.e. creative change or innovation) takes place. To do this we develop the perspective that tasks to be performed are analogous to resources in biology. Individual parts of the system, whether they are hardware, software or people involved in executing the tasks are analogous to various organisms that are involved in an evolutionary process. Changes in the individual parts take place through introducing alternate components (equipment, software, training or by moving people to different tasks). All of these changes are part of the dynamics of the system. Within this environment it is possible for conventional engineering of equipment or software components to occur. The focus of such engineering efforts is on change to small parts of the system rather than on change to the system as a whole. This concept of incremental replacement of components (equipment, software, training, tasks) involves changes in one part of the system, not in every part of the system. Even when the same component exists in many parts of the system, changes are not imposed on all of these parts at the same time. Multiple small teams are involved in design and implementation of these changes. It is important to note that this is the opposite of standardization—the explicit imposition of variety. The development environment should be constructed so that exploration of possibilities can be accomplished in a rapid (efficient) manner. Wider adoption of a particular change, corresponding to reproduction in biology, occurs when experience with a component indicates improved performance. Wider adoption occurs through informed selection by individuals involved. This process of "selection" explicitly entails feedback about aggregate system performance in the context of real world tasks.

Thus the process of innovation in the context of large scale systems engineering involves multiple variants of equipment, software, training or human roles that perform similar tasks in parallel. The appearance of redundancy and parallelism is counter to the conventional engineering approach which assumes specific function assignments rather than parallel ones. This is the primary difference between evolutionary processes and incremental approaches to engineering. The process of overall change consisting of an innovation that, for example, replaces one version of a particular type of equipment with another, occurs in several stages. In the first stage a new variant of the equipment (or other component) is introduced. Locally, this variant may perform better or worse than others. However, overall, the first introduction of the equipment does not significantly affect the performance of the entire system because other equipment is operating in parallel. The second stage occurs if the new variant is more effective: others may adopt it in other parts of the system. As adoption occurs there is a load transfer from older versions to the new version in the context of competition, both in the local context and in the larger context of the entire system. The third stage involves keeping older systems around for longer than they are needed, using them for a smaller and smaller part of the load until eventually they are discarded 'naturally'. Following a single process of innovation, is, however, not really the point of the evolutionary engineering process. Instead, the key is recognizing the variety of possibilities and subsystems that exist at any one time and how they act together in the process of innovation.

The conventional development process currently used in large scale engineering projects is not entirely abandoned in the evolutionary context. Instead, it is placed within a larger scale context of an evolutionary process. This means that individuals or teams that are developing parts of the system can still use well known and tested strategies for planning, specification, design, implementation and testing. The important caveat to be made here is that these tools are limited to parts of the system whose complexity is appropriate to the tool in use. Also, the time scale of the conventional development process is matched to the time scale of the larger evolutionary process so that field testing can provide direct feedback on effectiveness. This is similar to various proposals suggested for incremental iterative engineering. What is different, is the importance of parallel execution of components in a context designed for redundancy and robustness so that the implementation of alternatives can be done in parallel and effective improvements can be combined. At the same time, the ongoing variety provides robustness to changes in the function of the system. Specifically, if the function of the system is changed because of external changes, the system can adapt rapidly because there are various possible variants of subsystems that can be employed.

The process of generational variation in biology includes sexual reproduction. This is analogous to the formation of composite structures or systems when a modular architecture is used [8]. In this context, “composite” refers to making new combinations of system modules as a method of introducing new variants. Indeed, the use of modular composite patterns is a basis for creativity in any context [8, ch 2]. The importance and attention that should be devoted to establishing module boundaries reflects the non-universal nature of the functional performance of different modular architectures and their adaptiveness. Modular boundaries and encapsulation methods should be used so that interdependence between modules is simpler than dependence within modules.

The conventional division between human beings and machines should be modified in the context of thinking about evolutionary engineering processes. Human beings and the technology (computers, communication devices, electronic networks, etc.) should all be understood to be part of the system. Moreover, the process of creating system components (training, design, engineering, construction) also becomes part of the system itself. In particular, human beings are interactive agents in the process of creation (design, development) and the process of implementation, as well as in the process of system function. Similarly, computers are also interactive agents involved in the processes of design, development and function.

Evolution is a process of cyclical feedback and the role of the dynamics of this feedback often leads to a need to balance different performance aspects that are mutually contradictory. Understanding the balance needed is a current area of research and simple guidelines are not yet known. The best that can be done is to alert the manager of the evolutionary engineering process to the symptoms of effective evolutionary change so that they can be recognized and modifications “on the fly” can be made in the evolutionary environment with the objective of improving the balance. Since the evolutionary engineering process will be designed in such a way that iterative refinement of the process itself is possible, this is not a critical limitation. Indeed, this is consistent with the idea that comprehensive advance planning (as currently understood) is often not possible and that the system is designed to be effective in an adaptive process.

The central contradiction here is that the process of selection and competition after some time generally gives rise to a single dominant type that inhibits innovation. This is known as the "founder effect" in biology and sociology and as monopolization in economics. To avoid internal inhibition of change, the process must be designed to promote change and destabilize uniform solutions to problems, when it is appropriate (i.e., dictated by system performance in the context of interaction and feedback with the external environment). Such promotions of change might on the surface appear counter to the process of selection itself, since over the short term, promoting alternatives to established solutions appears to be counter to selection of the most effective system known at that time.

Another balance that must be reached is between promoting the propagation and adoption of improved systems and inhibiting propagation in order to allow sufficient time for testing. If adoption is too rapid, a solution that appears effective over the short term may come to dominate before it is tested in circumstances that are rare but important, leading to large scale failure when these circumstances arise. [22] If adoption is too slow, the system cannot effectively evolve, giving rise to an inhibition of change as previously noted.

Application to air traffic control

How can we apply evolutionary processes to implement change in a context where risk of large scale catastrophe is high? Our primary example will be the air traffic control system. Similar problems exist in other contexts including the nuclear power industry, and in various military contexts such as with nuclear weapons.

The problem with innovation in the air traffic control system does not appear to have been solved because we still have the "safety veto": How can we introduce changes in what an air traffic controller is doing without introducing grave risks to people in airplanes? This was the problem that eventually derailed the Advanced Automation System. Still today, the process of innovation in the air traffic control system is very slow because of a need to extensively test any proposed change. The key to solving this problem is recognizing that there already exists a process of innovation in the air traffic control system — the training of new air traffic controllers. Air traffic controllers undergo extensive, multi-stage on the job training [23]. A key one for our purposes is the stage in which the air traffic controller in training is acting as Controller, but a second Controller (supervisor) is present with override capability over the trainee. Thus, when a person is being trained, he or she performs the task under supervision with override to prevent accidents from happening. This same mechanism can be used for air traffic control innovation in hardware and software as well as in other processes. The key is to have two different stations that can perform the same functions, where one of them has an innovation in hardware or software, and the other with the more conventional system has override capability over the first.1 In this

1 A similar phenomenon was observed, though at least partly not intended, in the Navy's Fleet Battle Experiment Delta (FBE-D), October 1998. This experiment was conducted in conjunction with FOAL EAGLE '98 a military exercise of the Combined Forces Command Korea. While this was not actual combat, the joint exercise provided a realistic environment for testing of the Automated Deep Operations Coordination System (ADOCS) and Land Attack Warfare System (LAWS) software systems for joint mission management as compared to conventional procedures (specifically Counter Special Operations Forces (CSOF) procedures). In contrast to the evolutionary approach recommended in this paper, the original intention was to run the new system in parallel with the conventional one without using the new one in actual operations, but comparing their effectiveness. However, Operators decided the parallel system was better and they gravitated toward the experimental system to accomplish their tasks. As stated in a report on the experiment [39]: "The original measure of effectiveness to compare current procedures with the LAWS-ADOCS network could not be fully evaluated because operators adopted the experiment architecture in support of exercise events. This unintended use of LAWS in support of Foal Eagle operations clearly demonstrated the LAWS value added to CSOF." Indeed, the evolutionary approach is even clearer in the

case both of the air traffic controllers would be experienced controllers, not trainees. This dual system can be used to test new options for air traffic control stations while providing the same standard of safety. (Note that this dual system is not the same as the current dual system of Radar Controller and Radar Associate Controller, but is either in addition to, or possibly as a substantial modification of, this system).

There are many possible innovations that could be tested. For example, the traditional air traffic control stations consist of monochrome screens with visual sweeps of the air space. Any change in this system could introduce problems. For example, the sweeping of the screen appears obsolete compared to modern screen technology and only a residue of the limited technology that existed in the 1950s. However, a process of sweeping may be useful to keep a person alert in the context of continuous monitoring. In this case, an unchanging screen may lead to failures rather than improvements. How can this be tested safely? By introducing a version of new screens that involves continuous presentation, color displays or other changes in a trainer context. Allowing sufficient time for an air traffic controller to become used to the new system, the override capability can be retained for an extended period of time to test the system under many contexts: day, night, low and high traffic, extreme weather, etc. Such redundant execution of tasks is needed as well as maintaining older solutions that are more extensively tested. Indeed, we can expect that many variations on displays would be distracting or ineffective at bringing the key information to the attention of the air traffic controllers. Without such extensive field testing mistakes would surely be made.

The idea of using a double "trainer" has a biological justification through analogy with the double set of chromosomes that exist in humans and animals generally. The double set of chromosomes acts at least in part as a security system to buffer the effects of changes in the genome. In this case either of the chromosomes may be changed so that there are two different parallel systems that are both undergoing change. The probability of failure would be high, except that they both exist and failure of one does not generally lead to failure of function of the organism.

The overall picture of the use of such trainers is that most if not all air traffic controllers would work in pairs, where one has override capability. It is also possible to set up a double override capability to allow mutual oversight. It may be argued that the cost of having double the number of air traffic controllers is prohibitive. However, the alternative has already been demonstrated to be ineffective at the level of $3-6B in direct wasted expenses for modernization [6], while the ongoing losses to the industry on an annual basis are easily billions of dollars per year due to canceled and delayed flights caused by ineffectiveness of the air traffic control system.

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following observation demonstrating the importance of real-time coexistence of innovative and conventional systems so that a new system can be tested in actual operations and the original system can be used as necessary or desirable: “As FOAL EAGLE 98 and FBE-D Delta progressed, the LAWS based FBE-D events transitioned to full support of FOAL EAGLE. Operators used the best communication path available from the FOAL EAGLE and FBE-D capabilities.”

A broader perspective on the role of trainers can be obtained through the concept of redundancy. Redundancy is the most general mechanism for achieving reliability and security in function. The level of redundancy required increases as the demand level for safety does. Redundancy can also be related to the scale of operation as discussed in the context of multiscale complexity [8-12].

The importance of redundant execution of tasks can be understood in the context of the air traffic control system. The air traffic control system exists at the maximum level of functionality. In this context safety violations are highly probable when any change is introduced in the system. By introducing redundancy, an additional level of safety is introduced. Once there is additional safety in the system through redundancy, there can be a possibility of change in the system. Even though each change that is introduced is small, rapid change can result because of the parallel testing of small changes at many different locations.

It may be helpful to note that in this process the people who are making the decisions about what changes to make through the process of wider adoption are the people who are closest to the process itself, in this case the air traffic controllers. This is counter to the conventional engineering change process where the people making most of the decisions are far away from the execution process and often do not have direct experience with it (or at least, *recent* direct experience). At the same time, the people who are introducing the innovations in technology remain the people who are most familiar with it, the engineers and designers of systems that are then tested and adopted by real world evaluation.

In current engineering context, once the overall concept, objectives or functionality of the system desired is determined, the role of engineering management is to provide a sequence of progressively more detailed specifications of the system (i.e. the waterfall method). In the context of evolutionary engineering, the role of management becomes more indirect. Rather than specifying the system, management specifies a process and context for the development of the system. Goals of the system (as specified the desired functionality) are embedded in the context of the tasks involved in this process. For example, the process could involve the operation of double Air Traffic Control stations, while the functional goals are implicitly embodied through the direct evaluation of functional capabilities. This kind of indirect management may seem to be almost superfluous. Ultimately, however, the most important role of management in this approach is to establish mechanisms by which hidden consequences of changes are made more visible. They may be hidden because the consequences are longer term or larger scale or cumulative. For example, in the case of the air traffic control system, one key to effective imposition of safety is the availability of direct measures of proximity to failure, measures of “near misses”. When changes are implemented in the system direct measures of near misses provide feedback about the effectiveness of the change in the context of the system. This feedback can then be used to determine when a particular innovation should be more widely adopted.

Designing Rules of the Game

In order to promote effective adoption of the evolutionary engineering model it is important to anchor it in common experience. Without developing the analogy here extensively, it is useful to note that the most common experience we have with evolutionary analogues is in games and sports. The framework of the game in this case is that the immediate goal is successful completion of tasks, just like the goal in biology is successful consumption of resources. The agents of the system comprising human beings, hardware and software, are competing to perform tasks. We can also think about this as an economy or market in which performing the tasks is the objective. In sports and economics there are often extrinsic rewards for effective execution (financial bonuses, honors). While this is not ruled out, the evolutionary process suggests that success be rewarded by replication, which in this context is wider adoption of innovations. Indeed, the competitive spirit of human beings leads to a preference that the innovations that they contribute to or are using will be more widely adopted. Thus, the possibility of wider adoption should be sufficient to create a dynamic of mutual influence and constructive competition. Management can constructively foster competitive sportsmanship between individuals and especially between teams, a useful lesson that can be gained from the sports analogy.

In keeping with the sports analogy, it is intuitive to think about creating the evolutionary engineering context as setting up the "rules of the game". In the context of designing highly complex systems, the complexity of tasks to be performed is the source of functional complexity of demands on the system. Thus the objective of designing the rules of the game should be to avoid additional complexity due to the rules themselves. Only the rules that are truly necessary should be established, these rules should be as simple as possible.

Special care should be taken to avoid having rules of the game specify the mechanism or structure of the engineering solutions of the problem. Instead, a perspective of diversity of possible solutions of parts or aspects of the problem should be adopted. Unlike some sports where the structure and size of teams and the role of players is carefully specified, in an evolutionary process limitations on the diversity of possibilities should be avoided. Diversity can then be realized in the ecosystem allowing the ecology to consist of multiple types of parts, some larger some smaller. How strongly integrated or weakly coordinated are the parts is determined by the needs of the tasks as determined through the evolutionary engineering process. What is essential is that the parts are field usable. Indeed, integration of the parts into collectives is not the objective and the more closely coupled parts are, the more difficult change is. Thus, in the competition between evolving parts, the rate at which innovation can take place, the "evolvability" of the system, is higher when there are smaller parts. As a matter of guidance, larger scale integrated systems should only be used when smaller more loosely coordinated parts cannot perform the necessary functions.

Safety

The rules that are necessary are generally the ones that impose safety constraints. Safety in task performance is established by ensuring task redundancy and exclusion. One example of imposing redundancy in the air traffic control system through “trainers” was discussed above.

The importance of exclusivity of tasks can also be illustrated in air traffic control. One example of exclusivity that exists in the current system is the responsibility of air traffic controllers for distinct geographical areas. When considering the implementation of new systems this constraint might or might not be necessary. This must be carefully considered in the context of establishing rules of the game.

An example where a new exclusivity of action is likely to be necessary is in the communication between air traffic controllers and pilots, so that pilots do not receive conflicting instructions. In the context of paired air traffic controllers, it is necessary to impose the constraint of exclusivity of action. Primary communication and override protocols must be clearly established. Such rules of safety arise naturally in the context of developing the process by which the environment for innovation is established.

The existence of a competitive context for the process of adoption of technology, just as in sports, leads to the possibility of violations of safety rules to achieve objectives. Since the motivation for rule violations can be mitigated in many ways but not eliminated, it should be expected that there would be a need to impose safety constraints that protect the integrity of the game. Such rules that protect the performing system, not just the safety of task performance, will require monitoring and refereeing. Establishing such refereeing mechanisms is a critical role of management that becomes more important in evolutionary engineering than in traditional large scale engineering processes.

Promoting innovation through generational change

As discussed above, there is a need to overcome the founder effect of entrenched systems. To do so, rules that promote innovation should be established. An example which has a direct biological analog, the generation time / life time of the organism, is analogous to *requiring* a certain rate at which new innovations are introduced. This is not a requirement or specification of which innovation should be adopted, it is a requirement that some innovation will be adopted among alternatives that are available at that time.

Artificial Evolution Beyond the Natural Evolutionary Model

Enlightened evolutionary engineering provides an important paradigm for improving the effectiveness of large scale engineering projects. While a discussion of lessons from natural evolution provides a basis for this discussion, there are at least two contexts where we can find examples of “artificial’ evolutionary processes that are specifically designed to accelerate the evolutionary process in order to achieve adaptation at a rapid rate. These are found in the immune system and in the process of learning discussed previously.

The process of immune system “maturation” by which the immune system improves its ability to fight alien substances (antigens) involves a process of replication of molecules “antibodies” that are selected through their effectiveness in binding (affinity) to these antigens. In human beings, as well as other mammals, the process of replication and selection is accelerated in special places called germinal centers. In these centers, fragments of antigens are stored and used to test the affinity of antigens produced by an accelerated process of evolutionary change involving high replication rates, a shortened generation time and rapid mutation. These changes and other aspects of the design of germinal centers have shown to be highly effective at accelerating adaptation. [24] The analogy to an engineering context would be the use of a simulation center where accelerated testing and exploration of prototypes can be performed. The use of some level of simulated context is common for testing engineering projects. The biological analogy suggests incorporation of a multiple iterative parallel evolutionary strategy in simulated and real contexts, with a highly accelerated evolutionary process in the simulated environment.

The process of learning that occurs to train the modular architecture of the brain includes the off-line time of sleeping [8, ch. 3] Sleep has been proposed to have a key psychofunctional role in the testing and refinement of separated modular components of a modular architecture. This role allows simplification of individual parts, allowing the entire system to learn new functions while avoiding overload of the components. The analogy in an engineering context is exercise, testing and redesign of individual components in a context where the individual component functional role is evaluated while at least partially dissociated from the rest of the system.

Taken together, the functional roles of germinal centers and of sleep imply the importance of off-line experimentation (place and time) in conjunction with actual field experimentation so that the evolutionary engineering process can accelerate adoption of effective strategies and components of strategies. While it is not known whether natural evolution creates such off-line opportunities, quasi-artificial evolutionary processes use them as an integral part of the process.

Finally, there is an additional responsibility of management not captured in the natural evolutionary process—goal setting. Goal directed behavior corresponds to a directed learning process, which can be found in models of cognitive functioning [8, sect. 3.1.12].

Assumptions

The evolutionary process for engineering design has its own set of assumptions that are relevant to considering when it is applicable. It assumes:

- tasks can be divided into interdependent parts (even if we don't know how)
- there are small tasks and large tasks.
- integration has a cost in adaptability that should only be paid if/when necessary.
- the coordination between parts can be strong or weak.
- central control is only effective for not too complex systems.
- detailed planning is only effective for not too complex systems.
- one should build on what works.
- diversity enables adaptive response

- parallelism / redundancy provides functional security and enables learning

Conclusions

The complexity of large scale engineering projects has led to the abandonment of many expensive projects and led to highly impaired implementations in other cases. The cause of such failures is the complexity of the projects themselves. A systematic approach to complex systems development requires an evolutionary strategy where the individuals and the technology (hardware and software) are all part of the evolutionary process. This evolutionary process must itself be designed to enable rapid changes while ensuring the robustness of the system and safety. The systematic application of evolutionary process in this context is an essential aspect of innovation when complex systems with complex functions and tasks are to be created.

This paper has proposed that large scale engineering projects should be managed as evolutionary processes that undergo continuous rapid improvement through adaptive innovation. This innovation occurs through iterative incremental changes performed in parallel and thus is linked to diverse small subsystems of various sizes and relationships. Constraints and dependencies increase complexity and should be imposed only when necessary. This context must establish necessary security for task performance and for the system that is performing the tasks. In the evolutionary context, people and technology are agents that are involved in design, implementation and function. Management's basic oversight (meta) tasks are to create a context and design the process of innovation, and to shorten the natural feedback loops through extended measures of performance. The prime directive in the context of the large scale engineering projects is to simplify whenever possible, avoiding strategies that unnecessarily introduce complexity and impede adaptability.

Key points:

Simplify whenever possible.
Tasks are performed by competing parts
Parallel diverse iterative incremental change
Local adoption of more effective solutions
People and equipment are part of evolutionary process.

Appendix A: Two Theorems of Complex Systems

A.1 Requisite variety

The Law of Requisite Variety states: The larger the variety of actions available to a control system, the larger the variety of perturbations it is able to compensate [7]. Quantitatively, it specifies that the probability of success of a well adapted system in the context of its environment can be bounded:

$$-\mathrm{Log}_2(P) < C(e) - C(a)$$

Qualitatively, this theorem specifies the conditions in which success is possible: a matching between the environmental complexity and the system complexity, where success implies regulation of the impact of the environment on the system.

The implications of this theorem are widespread in relating the complexity of desired function to the complexity of the system that can succeed in the desired function. This is relevant to discussions of the limitations of specific engineered control system structures, to the limitations of human beings and of human organizational structures.

Note that this theorem, as formulated, does not take into account the possibility of avoidance (actions that compensate for multiple perturbations because they anticipate and thus avoid the direct impact of the perturbations), or the relative measure of the space of success to that of the space of possibilities. These limitations can be compensated for.

A.2 Functional complexity

Given a system whose function we want to specify, for which the environmental (input) variables have a complexity of $C(e)$, and the actions of the system have a complexity of $C(a)$, then the complexity of specification of the function of the system is:

$$C(f) = C(a)\, 2^{C(e)}$$

Where complexity is defined as the logarithm (base 2) of the number of possibilities or, equivalently, the length of a description in bits. The proof follows from recognizing that a complete specification of the function is given by a table whose rows are the actions (C (a) bits) for each possible input, of which there are $2^{C(e)}$. Since no restriction has been assumed on the actions, all actions are possible and this is the minimal length description of the function. Note that this theorem applies to the complexity of description as defined by the observer, so that each of the quantities can be defined by the desires of the observer for descriptive accuracy. This theorem is known in the study of Boolean functions (binary functions of binary variables) but is not widely understood as a basic theorem in complex systems [8,9].

The implications of this theorem are widespread and significant to science and engineering. The exponential relationship between the complexity of function and the complexity of environmental variables implies that systems that have environmental variables (inputs) with more than a few bits (i.e. 100 bits or more of relevant input) have functional complexities that are greater than the number of atoms in a human being, and thus cannot be reasonably specified. Since this is true about most systems that we characterize as "complex" the limitation is quite general. The implications are that fully phenomenological approaches to describing complex systems, such as the behaviorist approach to human psychology, cannot be successful. Similarly, the testing of response or behavioral descriptions of complex systems cannot be performed. This is relevant to various contexts from the testing of computer chips, today with over 100 bits of input, to testing of the effects of medical drugs in double blind population studies, today used in various combinations with various quantities for synergistic effects, with a need to avoid harmful drug interactions. In each case the number of environmental variables (inputs) is large enough that all cases cannot be tested. This theorem describes generally the problem of testing the functional behavior of any complex engineered system.

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Multiscale Representations Phase II:
Task 2: Multiscale Analysis of Littoral Warfare

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R3. Complexity of Military Conflict: Multiscale Complex Systems Analysis of Littoral Warfare

Yaneer Bar-Yam
New England Complex Systems Institute

Reported to
John Q. Dickmann and William G. Glenney IV
Chief of Naval Operations Strategic Studies Group.

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Preface

In 1998 the Chief of Naval Operations Strategic Studies Group (SSG) XVII articulated a post Cold War need to focus on asymmetric warfare, specifically including information warfare, weapons of mass destruction and terrorism[1, p. 10]. Their central challenge was to develop the theme "Naval Campaign: Littorial Air/Land Challenges for the 21st Century." In response, SSG XVII-XX have developed the concepts of Network Centric Warfare, Sea Power, Sea Strike, Naval Power Forward, and FORCEnet [1-4].

A recognition of the relevance of complex systems concepts to the challenges of 21st Century warfare led to the invitation of Yaneer Bar-Yam, president of the New England Complex Systems Institute, to lecture periodically at the SSG beginning in January 2000 and specifically to address the topic of littoral warfare. The following paper by Professor Bar-Yam discusses the relevance of Multiscale Complex Systems Analysis to a characterization of the differences between conventional and complex warfare challenges, with particular application to littoral warfare.

The conclusions suggest that littoral warfare cannot be readily incorporated into Navy operations without considering the specific organizational and technological requirements needed to perform effectively in this high complexity environment. The significance of organizational structure to meeting complex challenges is already apparent from the difference between the organization and training of the Navy and Marines. Beyond the organizational structure, there is a broad relevance of complexity to the selection of appropriate technology and of identifying military objectives in the context of littoral warfare.

This paper is presented as an aid both to conceiving of littoral warfare concepts, and more generally as an introduction to the use of the conceptual tools provided by multiscale analysis. Experience with complex warfare in Vietnam and Afghanistan illustrates the importance of these concepts. A more formal and quantitative application of multiscale methods, not undertaken here, is possible to extend its usefulness. This paper is part of a larger effort to apply multiscale complex systems analysis to military conflict.[5,6]

Multiscale Approach to Complex Warfare Analysis

Introduction

Overview

In recent years it has become widely recognized in the military that war is a complex encounter between complex systems in complex environments[7-11]. Complex systems are formed of multiple interacting elements whose collective actions are difficult to infer from those of the individual parts, predictability is severely limited, and response to external forces does not scale linearly with the applied force. It is reasonable to postulate that warfare can be better executed by those who understand complex systems than those who focus on simple linear, transparent, classically logical, Newtonian constructs. What is not as widely recognized is that complexity can be used to characterize friendly and enemy forces as well as particular military conflicts. In a very important sense, that we will make clear in this paper, a direct military encounter between the U.S. and the Soviet Union would have been less complex than the current War on Terrorism. The recent recognition of the complex nature of war arises first because of an increasing need to engage in complex conflicts, second because of the availability of new technology that enables a greater number of military options and thus a higher complexity of action and finally because of new scientific developments that provide an increasingly robust theoretical framework and conceptual lens through which to analyze and assess warfare and combat.

Large and uniform forces in deadly confrontation across a marked border in desert terrain that have a clear cut objective of inflicting massive damage on the enemy can be contrasted with loosely coordinated specialized forces in jungle, mountain or urban settings with minimal damage objectives or with peacekeeping functions. These examples begin to illustrate the distinction between conventional large scale but relatively simple conflicts, and complex military encounters. Hierarchical command systems are designed for the largest scale impacts and thus *relatively* simple warfare. Indeed, traditional military forces and related command control and planning, were designed for conventional large scale conflicts. Distributed control systems, when properly designed, can enhance the ability to meet complex challenges. The existing literature of military analysis and concept development, however, is missing basic guidance imperative for design, planning, execution and assessment of military systems and operations utilizing distributed control. How are such systems to be designed or even conceived? What are the basic principles that can guide commanders in selecting appropriate forces for complex encounters? How can the capabilities of enemy (or friendly) forces be evaluated? How can we estimate the likelihood of success of specific missions or the overall outcomes of military conflict?

A conventional analysis of aggregate force size and firepower and incapacitation of the enemy via attrition provides little if any guidance for the conduct of complex warfare. Instead of scale alone (e.g. manpower or firepower), complexity (e.g. the variety of possible actions that can be taken, see below) should be used as a measure of force capability in the context of complex military scenarios. In a high complexity environment, high complexity forces are more capable than low complexity ones. Thus, an effective analysis of warfighting capability must include both scale and complexity of the forces and the environment where the conflict occurs. Scale and complexity are not, however, independently controllable—they are interrelated. Similarly, analyzing the mechanism of incapacitation of a force in a complex encounter must consider the complexity of the force. Force incapacitation can take place through reduction in complexity rather than casualties or firepower reduction. Specifically, incapacitation of a force can take place through damage to coordination mechanisms, relocation of forces, restrictions on possible actions, alteration of the psychosocial context, or reliable interception of communications.

Analysis of the capabilities of an existing force is important. However, for military planning, we also would like to understand the related question: How can one increase the capability of a force? Since complexity is desirable, how can the complexity of a force be increased? The complexity of a military force is directly linked to its ability to conduct multiple partially independent and coordinated actions of military units. It is thus related to command and control structures, its information sensing, processing, decision and communication capabilities as well as its sociocultural background. Substantial improvement in the complexity of a military force requires profound redesign of force organization and related training and culture.

Multiscale complex systems analysis (MCSA) provides a formal framework for understanding the interplay of scale and complexity in complex systems and their capabilities in the face of challenges. For military forces, MCSA can provide an understanding of appropriate measures of effectiveness for both conventional and information age military forces. It can also provide guidance about what aspects of conventional military experience remain relevant and which should be changed in the context of complex conflict. Many of these issues revolve around the problem of distributed command, control and coordination of forces. The basic paradigms and concepts of distributed control are often counterintuitive to commanders and planners whose training focuses on hierarchical systems designed for operation of large scale forces. When used to study specific examples, MCSA provides a way of demystifying the functioning of distributed control systems.

This document is organized to provide basic guidance in the use of MCSA for insights into information age warfare. After introducing the basic concept of complexity as it relates to functional capability we discuss the "complexity profile" which characterizes the dependence of complexity on scale. These fundamental concepts are then applied to littoral conflict and its implications for organizational structure. The design of complex organizations suitable for different complex functions is discussed. A key distinction is made between distributed networked action agents, and networked control agents commanding large scale actions. This leads to a more general discussion of complex military conflict and the role of force organization, training and contextual information.

Central to this discussion is the realization that complexity is not only a property of information age warfare. While modern complex confrontations can be demanding, all military encounters are complex. A detailed understanding of complexity thus sheds light on conventional as well as modern conflict. The existing experience of traditional and modern conflicts has already led to substantial incorporation of complexity related insights into military structure, doctrine and culture. Nevertheless, specific analysis of the interplay of scale and complexity can dramatically influence force design in conjunction with technology (specifically, Command Control Communications Computers Intelligence Surveillance Reconnaissance Targeting (C^4ISRT)) for meeting specific military challenges.

Complexity and Scale

The complexity of a task can be quantified as the number of possible wrong ways to perform it for every right way. The more likely a wrong choice, the higher the complexity of the task. In order for a system to perform a task successfully it must be able to perform the right action. As a rule, this also means that the number of possible actions that the system can perform (and select between) must be at least this number (the number of wrong ways that a task can be performed for every right way). This is the "Law of requisite variety" (Appendix A[18]) that relates the complexity of a task to the complexity of a system that can perform the task effectively. This law is the basis of the need for high complexity systems to exist, namely, to perform high complexity tasks. High complexity biological organisms exist because simpler organisms are less likely to survive. While human designed systems, such as military ones, might sometimes be built with unnecessary complexity, still, when a high complexity task exists, only a high complexity system can perform it.

Complexity increases in military conflict as the application of effective force must be more carefully selected or more accurately targeted, and where the implications of errors in these choices become more severe. Thus, hidden enemies in high complexity terrains and particularly enemies co-mingled with bystanders or friendly forces present high complexity challenges. In addition to the targeting itself, the transport of forces increases in complexity as the selection of method or route becomes more constrained in higher complexity terrains.[2]

Evaluating complexity by counting "the number of possibilities" can be more readily applied in many cases using the notion of description length. Specifically, we evaluate the length of description of the task, for task complexity, and the length of the description of the system, for system complexity. In each case, a complete description is necessary. By Shannon's information theory, there is a correspondence between the length of the description and the number of possibilities. This is a useful approach because it is often possible to imagine the amount of text needed to describe a system without actually writing the description.

In the context of warfare, and with other complex tasks, there is an additional need to consider the scale of action necessary for successful completion. Scale refers to the number of parts of a system that act together in a strictly coordinated way. We also consider that an observer, due to observational limitations, can only see down to a certain level of detail (scale) corresponding to the number of coordinated parts that can be noticed by that observer. A calculation of aggregate force that can be applied by a system is a characterization of the largest scale of potential action. When multiple partly independent actions are necessary to achieve success in a mission, they are characterized by level of force (scale) of each action. The simplest case involves delivery of

[2] Logistics presents an additional set of tasks that in conventional warfare was often the limiting aspect of a force's ability to sustain and prevail in encounters due to its inherent complexity.

multiple shots in a coherent fashion. This is not the same as the ability to direct the same quantity of firepower at a set of separately specified targets. In complex military conflicts, finer scale forces selectively deliver diverse but specific shots to diverse and distinct targets with multiple shots directed at some of the targets as a necessity for mission success. The scale and complexity necessary to overcome a particular enemy force is dictated by the scale dependent structure of the enemy force itself (the degree to which its forces are aggregated), and the scale dependent structure of constraints in the battle space (terrain, etc.), as well as the scale dependent structure of objectives, including objective constraints (political, etc.).

Multiscale complex systems analysis (MCSA) is based upon the "complexity profile" which asks, given a particular cutoff in scale, what is the complexity (number of possible actions) of the system larger than this scale, and how does this complexity depend on the cutoff scale. For a military system, complexity above a particular scale includes all possible force actions at or above this scale. Smaller force actions are not included. This dependence of complexity as a function of scale reveals the capabilities of the force at each scale of a potential encounter, from the smallest to the largest.

When forces are organized hierarchically, the number of possible actions at a small scale increases as the number of small units (e.g. fire teams) increases. The number of possible actions at a large scale increases as the number of larger units (e.g. battalions) increases. Thus, the complexity profile roughly corresponds to the number of units at each level of command (individual, fire team, squad, company, or battalion). However, it also depends on how independent the individuals are within fire teams, how independent fire teams are within squads, how independent squads are within companies and how independent companies are within battalions. When the units at a particular level of organization are more independent the complexity is larger at that scale, however, the possibility (complexity) of larger scale action is smaller. It is important to emphasize that for the complexity profile of a particular military force we consider *all* of the units at each level. For example, we count the number of fire teams in the entire military force, rather than the number of fire teams in a particular squad. The dependence of the complexity on the scale, i.e. the complexity at the individual, fire team, squad, company, and battalion levels of organization is the complexity profile of the entire military force. This is particularly important when attempting to understand operational concepts and organizational structures that use non-hierarchical organizations enabling direct coordination between fire teams in different battalions.

A force that is organized, trained and otherwise prepared to apply large scale force is not well suited to high complexity conflicts. Similarly, a force that is designed for high complexity conflicts is not well suited to large scale conflicts. More generally, the complexity of a force's capabilities at each scale of a possible encounter is a key property that describes the abilities of that force. This, then, is the central basis for evaluating the effectiveness of force design in the face of a specific complex military mission or conflict.

When considering the capabilities of forces in information age warfare, military technology should not be evaluated separately from force organization. In a well designed force, technology and force organization are inseparable. Indeed, the C^4ISR system should be designed in conjunction with military organization. The role of information and information processing is tightly linked to functional capabilities since the specific information needed (and not too much more) must be present in the right place at the right time to enable effective system functioning. While today we often think about information and action as being distinct, they are linked to each other when we consider the description of the action, the information in a command that causes the action, and the information that leads to the command. Thus, in complex systems, the distinction between physical and informational aspects of the system is blurred.

Complexity Profile

We will present a conceptual analysis of warfare based upon its complexity profile. Additional discussion of the complexity profile can be found in the references. From the point of view of describing the action of a military force, the complexity profile specifies the dependence of the complexity (amount of information necessary to describe a system) on scale (resolution / level-of-detail in the description). At finer levels of detail there is more to describe, at coarser levels of detail there is less to describe. When we consider the amount of information as a function of scale, we obtain the complexity profile. The complexity profile shows how the complexity changes with the scale of observation. Again, it is important to note that at each scale the entire system is being described, not just a part of it.

The often anecdotal or ad-hoc discussions of the tradeoff between forces that are designed for large scale and complex conflict can be formalized. Figure 1 illustrates schematically three types of organizational structure. If the parts of the system are independent (blue in the figure), then there is a lot to describe at a fine scale, but at larger scales there is little to describe. This corresponds to having independent fire teams with no coordination at higher levels of command. If the system parts are all coordinated to act together (green in the figure), then the behavior is visible at a large scale and there is not much more to describe at fine scales. This corresponds to having a battalion with no separation into finer scale units. If different groups of parts are variously coordinated (red in the figure) then as we increase the level of detail (decrease the scale) there is a more gradual increase in the complexity. For the same set of components organized in a different way the complexity profile can be shown to have the same area under the curve [12,13]. This allows us to compare different organizational structures. Such comparisons are particularly important for modern information age warfare where hierarchical force organization need not apply, and the complexity profile allows comparison of different types of force organization and their capabilities and limitations. A similar analysis can be applied to discuss other types of systems important in military contexts including, for example, different types of terrain.

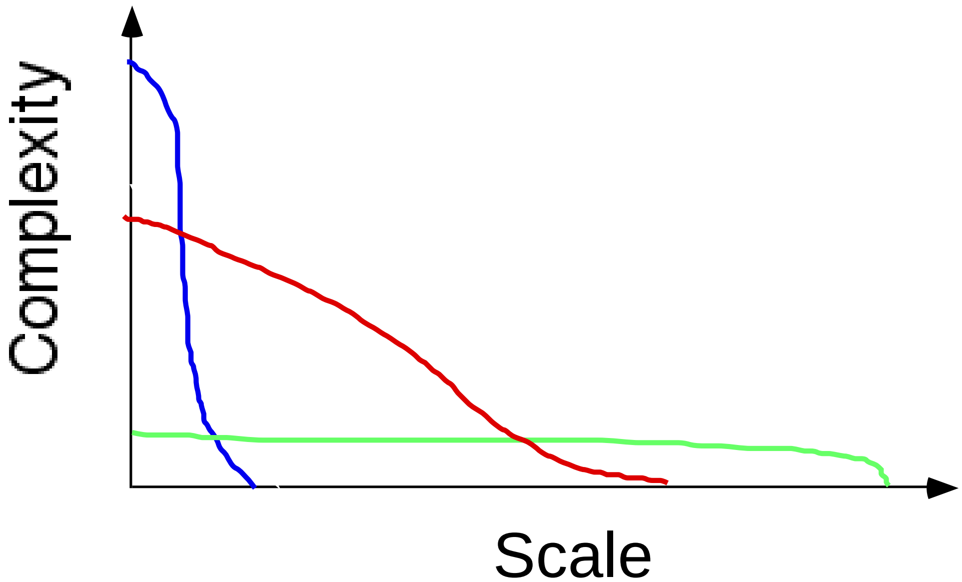

Figure 1: Illustration of the complexity profile for three different types of organization. Blue: independent agents, Green: coherent, Red: various degrees of coordination.

Why is complexity and the complexity profile important? Complexity is a measure of the number (variety) of possible ways a system can act. If the number of ways a task might have to be performed to be done correctly is larger than the number of ways the system can act, then that system is not likely to be successful at that task. For an otherwise ideally performing system, the probability of success is given quantitatively by the difference between the task complexity and the system complexity. This is a statement of the Law of Requisite Variety (Appendix A). We generalize this law by recognizing that the each task requires a certain scale of effort as measured, for example, by the number of people needed to perform it. Thus, success of an organization requires sufficient complexity at each scale of action. High complexity, by itself, does not guarantee a system is well designed for its task. However, without sufficient complexity even good designs will fail.

When we combine the requirement of a sufficient complexity at each scale of a task, with the theorem which states that the area under the complexity profile is the same for different organizational structures formed of the same components we obtain a fundamental result: Any choice of organizational structure implies a particular tradeoff of capabilities of the system at different scales. The simplest statement of this result was given earlier, but can now be more precisely stated: a system designed for large scale force is not capable of fine scale high complexity tasks. Similarly, a system designed for fine scale high complexity tasks is not capable of tasks requiring large scale forces. More generally, each type of system organization has a particular trade off in terms of capabilities at particular scales of behavior. These capabilities are embodied in the complexity profile of the system.

The tradeoff between large scale and fine scale complexity in functional capability can also be seen from a comparison of animal and human locomotion and limb utilization (figure 2). Four legged animals use all four limbs to exert large scale force to achieve motion of the largest object that an animal generally has to move --- itself. Human beings use only two limbs (legs) for locomotion. For the same mass of animal, human beings do not run as fast. However, the other two limbs are adapted as hands and fingers to enable the manipulation of smaller objects. The sacrifice of larger scale motion for finer scale manipulation illustrates the general tradeoff that occurs in the scale dependence of behaviors. When parts are independent there are a larger number of possible motions they can perform. When parts are dependent they form larger scale behaviors.

Figure 2: Comparison of the use of four limbs for faster---larger scale---locomotion (left) as opposed to two limbs for locomotion along with finer scale manipulations using the other two limbs (right). This illustrates the tradeoffs of capability at different scales for different types of organization.

Another example is the use of various forms of “wheels” for human locomotion: bicycles, roller blades, scooters, etc. While wheels enable higher speed, the degree of control over this motion is limited. Thus they require a simpler environment for safe operation--- smoother and/or flatter roads. The faster the speed, the simpler the environment required.

These tradeoffs illustrate a fundamental principle of complex systems, the importance of what we call Form For Function (or “Structure Serves Function”). More specifically, that the scale of the challenge (function) to be met (performed) determines the scale of the response needed. Whenever a new design is suggested or a solution of an existing problem is offered, it is important to ask what are the circumstances / environments in which this system will be effective, as contrasted with the original system. Since there is no universally effective system, it is often a matter of choosing the right system for the task or challenge that is anticipated.

It is important to emphasize: When asking about the effectiveness of various control structures such as hierarchical control, distributed control networks, and other structures, one should recognize that they are not good or bad in their own right. The only way to evaluate them is by asking “What are the functional requirements?” In particular, an understanding of why and when hierarchical command structures are effective is a necessary prerequisite for determining when they should and should not be used. An analysis using the complexity profile, summarized in the next section, indicates that hierarchical structures are ineffective at tasks with high complexity involving coordination between disparate parts of the organization. Recently military doctrine has attempted to separate hierarchical command from distributed control[7]. The same analysis implies that this separation is insufficient for effective high complexity in function at a particular time. However, we later discuss how this concept may be useful when relatively low complexity of large scale action occurs at a particular time, but high complexity over time is needed.

Hierarchical and Distributed Command and Control

One application of the complexity profile concept is to understand the limitations of hierarchical command[12-15] (see Fig. 3). The key to this understanding is that each individual has a limited complexity. In particular, an individual is limited in ability to process information and to communicate with others (bandwidth) [12-15]. In an idealized hierarchy, only the single leader of the organization can coordinate the largest organizational units whose commanders are directly under his/her command. The coordination between these units cannot be of greater complexity than the leader. More generally, we can state that to the extent that any single human being is responsible for coordinating parts of an organization, the coordinated behaviors of the organization will be limited to the complexity of a single individual. Since coordinated behaviors are relatively large scale behaviors, this implies that there is a limit to the complexity of larger scale behaviors of the organization. Thus, using a command hierarchy is effective at amplifying the scale of behavior, but not its complexity. By contrast, a network structure (like the human brain) can have a complexity greater than that of an individual element (neuron). While an arbitrary network is not guaranteed to have a complexity higher than that of an individual component, it is possible for such a network to exist. For high complexity tasks, we therefore consider hierarchical systems inadequate and look to networked systems for effective performance.

Indeed, the fundamental limitation on the complexity of hierarchical organizations implies that hierarchies are not effective at performing high complexity tasks. The recent tendency toward distributed control in corporate management suggests that the complexity of our socio-economic system is so high that hierarchical control is ineffective in the modern world. This is also the case for complex modern warfare. The emphasis on network warfare concepts in current military thinking reflects a recognition of the limitations of hierarchical control in this context.

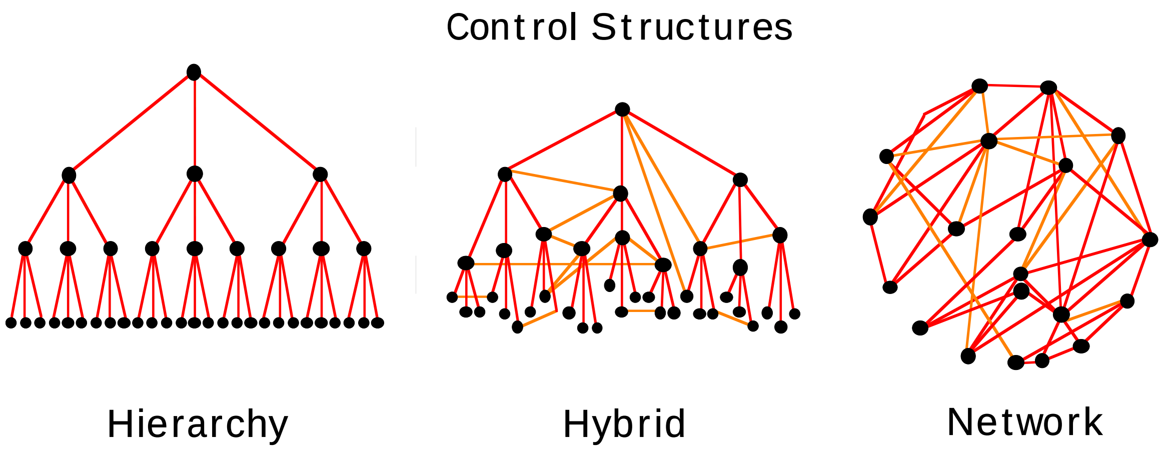

Fig. 3: An ideal hierarchy (left) relies upon a single individual to coordinate the large scale behaviors of the system. The complexity of these behaviors is therefore limited in to no more than the complexity of a single individual and his/her ability to communicate (bandwidth limitation). A network structure (right) is not limited this way and, indeed, the brain is a network which has a higher complexity of its collective behavior than the behavior of any individual neuron. In considering hybrid control structures (center) we should recognize that any such structure will be limited in the complexity of its large scale behavior to the extent that a single individual controls these activities.

Distributed control is often discussed today as a panacea for problems of hierarchical control. While distributed control can help, it must be recognized that the concept of "distributed control" does not correspond to a specific control structure. Distributing control in and of itself does not lead to effective systems or solve problems with hierarchical control. It is the design[3] of specific distributed control structures that are effective in specific types of tasks that provides a functional advantage. Still, we now recognize that there are many ways to achieve effectively functioning systems where functional behavior and control is distributed and can be said to arise by self-organization, and that the traditional perspective that the only alternative to hierarchical control is anarchy is not correct. As a prelude to discussion of littoral combat, the following discussion will focus on two types of systems which have distinct forms of distributed control.

There are two paradigmatic types of biological organization that are convenient to consider when we think about distributed control. These are the immune system[19-22] and the neuro-muscular system [12 chs 2,3, 23-25]. The immune system is a system of largely independently acting agents that achieve some degree of coordination of activities and functional specialization through communication. The neuro-muscular system has two segregated components, the nervous system which generally may be thought of as a distributed network, and the individual muscles that consist of highly synchronously (coherently) behaving muscle cells.

[3] Or the selection by an evolutionary design process of a system [6].

Using the complexity profile we can see that the immune system can be understood to act with high complexity at a very fine scale with many independent agents whose individual actions do not aggregate to high complexity large scale behaviors. By contrast, the neuro-muscular system achieves high complexity behaviors over time due to the complexity of distributed control of the nervous system, but at any one time it performs individual large scale actions---the large scale behavior of the muscles. Thus there is a difference between high complexity behavior at a particular time and high complexity behavior over time as captured by the immune and neuro-muscular system. These differences arise as a result of differences in control structures and the relation of the control structures to scale and complexity

The context in which the immune system operates---internal to the human body it is striving to protect---can be contrasted with the context in which the neuro-muscular system operates---in response to external forces or conditions that are separated from the human body by a margin of space that is typically of a size larger than that of the human body itself. This illustrates the distinct environments and tasks in which distinct organizational structures are effective. It also illustrates the importance of functional segregation since both the immune system and the neuro-muscular system are parts of the same organism viewed as a collective. By specialization of subsystems, different types of functional tasks for protecting internal components and responding to the external environment are possible.

The example of the neuro-muscular system and the immune system also shows how organizational structure reflects a tradeoff between scale and complexity. A system designed for large scale behavior is not the same as a system designed for high complexity behavior at a fine scale.

We now apply these concepts to the contexts and functions of military efforts and the specific issues associated with Navy planning associated with littoral conflict.

Complex Warfare

Littoral Conflict

The analysis of warfare using MCSA might be compared to the analysis of ballistic projectiles using laws of mechanics. Newton developed laws to describe properties of the world around him that helped us describe them more universally and more precisely. His laws were not necessary to the invention and use of ballistic projectiles, but they help us understand them. Further, Newton's laws are helpful in designing many systems that are much more difficult to understand than simple projectiles. Similarly, the study of complex systems has begun to provide us with formal tools for understanding the behavior of complex military encounters. MCSA can relate the organizational structure of a system to its functional capabilities, and compare them to a similar analysis of the tasks or objectives that we might call upon the system to perform. Such analysis can be performed for friendly or enemy forces to reveal strengths and weaknesses in terms of the challenges to which they are well and ill suited. The simplest statement of functional capability is that the scale of a system should match the scale of the challenge to be met. MCSA generalizes this by recognizing that a single challenge often involves multiple tasks. Each task has a particular scale of action. At each scale the complexity of the system (given by the number of actions that can be made by the system) must be equal to the complexity of the task. Just as with ballistic projectiles, the first step in applying these concepts is recognizing how they are already used in the military and the relationship of this use to its effectiveness.

Military organizations and their related equipment are designed around the experience of historical military conflicts and thus the experience of the complexity of conflicts can be found within them. Specifically, the organization of military forces and hardware follows the demands of terrain and of enemy forces. Based upon our understanding of the complexity profile we can categorize different terrains and forces according to their scale dependent complexity. Such an analysis is directly relevant to the consideration of Navy plans for engaging in littoral warfare.

Above the human scale, the ocean environment is by its uniformity the simplest / largest scale environment on earth (figure 4). The large scale uniformity allows the existence of large scale entities and large scale military conflicts. Indeed the largest scale military structures are air craft carriers and the related aircraft carrier battle group.

Figure 4: Example of ocean environment

While military conflicts in the ocean can be large scale direct confrontations, open ocean warfare is not without fine scale complexity. The major fine scale problem that exists is one of detection of small enemy vessels, especially those that are underwater (mines or submarines). Even without fine scale structures in the terrain to hide within, the small enemy vessels increase the complexity of conflict through the large number of possible locations they can be in. The complexity of detecting and responding to small enemy forces is not unique to the open ocean. Indeed, in land based warfare hiding is typically easier. Small enemy forces are particularly problematic in open ocean warfare because other aspects of ocean warfare are "simple". This simplicity leads to large scale ocean vessels which are vulnerable / less capable in the context of a finer scale high complexity challenges, i.e. small enemy vessels.. To overcome this difficulty the largest vessel is accompanied by several smaller vessels that are more capable at detecting and eliminating smaller scale threats.

Figure 5: Examples of littoral environment

The simplicity of the large scale ocean terrain is to be contrasted with the complexity at many scales of the littoral region (figure 5). Complexity of the land-water interface arises both because of the natural features of this interface and because of the human aspects of population centers in the littoral region. A complex systems analysis considers the information needed to describe the littoral region including the properties of land and water variations at the interface: coastline, cliffs, marshes, swamps, mud, brush, sand, reefs, rocks, and their specific shapes. The physical shape and structure of the littoral as an interface of two different domains also requires equipment and human capabilities that are able to operate effectively in both regions, or to be subject to the constraint of confinement to one or the other. Thus the design of amphibious craft is itself a high complexity task and otherwise, various aspects of equipment and training are effective in one or the other domains. To this physical aspect of the demands of the environment must be added the human aspects, including cities, ports, land vehicles and boats that are often located in the littoral region.

The difficulties of large scale vessels in addressing small scale enemy vessels in the open ocean are greatly multiplied in the context of the littoral, where enemy vessels or units can be even smaller and hiding is much easier. The problem of detection which is important in the context of ocean warfare, here becomes much more severe, not easier. A relevant example is the case of the attack on the USS Cole on October 12, 2000.

The complexity of the littoral region implies that there are many obstacles that prevent mobility of large objects, such as ships designed for the open ocean. In contrast, small objects such as little boats, pedestrians, swimmers or divers, can maneuver and remain hidden. The attack on the USS Cole was successful because a maneuverable dingy was able to approach a large ship. The ability of the ship to defend itself was inhibited by the possible confusion of enemy and friend, and by the likelihood that fires will inflict damage to non-enemy structures. Such problems are particularly difficult when the state of conflict is not well recognized, suggesting surprise is likely. However, even when conflict is apparent, there are many ways to attack a large ship and few defensive and offensive actions that the ship can take in the littoral when confronted with many or even a few small enemies that are hidden in areas where collateral damage should be avoided.

The specific implications of the complexity of the littoral region can be readily recognized in the Marines whose organizational structure and training is designed to deal with this terrain. These implications include the need for small independently acting groups and more distributed control. The Marines are known to be highly reliant on individual training and the diverse, resourceful and specialized nature of its individual and group forces. There is also a recognized need for the intensive use of technology that enables functionality in this complex environment. When considering the complexity of the physical environment it is essential to realize that this environment is not in and of itself the complexity of the military challenge, it only serves as the context in which the challenge is found. Thus the complexity of the physical terrain can be used by enemy forces to limit the effectiveness of, or attack, forces that are not appropriately structured. As the USS Cole case demonstrated, a small, even low technology enemy can effectively attack a much larger vessel in the littoral region. This is also the strength of the Marines since a few individuals could destroy a fleet located in a port or otherwise located in the littoral region.

A systematic analysis of littoral warfare should thus be based upon a recognition that large scale confrontations that can be pictured on large scale maps as arrows representing force movement do not necessarily capture the essential properties of littoral warfare. Littoral warfare must be represented at a fine scale in terms of small unit or even individual actions. The friendly and enemy forces are likely to be mixed spatially, so that it would be very difficult to use a large scale view to describe the conflict. Even if the location of all forces could be known, instead of distinct red and blue areas, there would be red and blue dots in overlapping areas, potentially moving in any direction in local conflicts. Enemy forces (and even friendly forces) are likely to be hidden, and civilians are likely to be present. This implies that the force organization that would be effective in such contexts must allow individuals or individual teams to function effectively in the local context with limited (though important) coordination between units. Key areas of investigation of the force organization design and force operation include access, penetration and movement of forces as well as the problems of detection and engagement of small hidden forces and of friendly fire due to the lack of clear separation of enemy and friendly forces.

There is an important exception to the complexity of littoral terrain which is the possibility of reaching over the littoral to large scale enemy ground forces that are inland from the littoral. Long range bombardment or air attack of large scale ground forces bypasses the complexity of the littoral using the large scale context of the atmosphere. Such force projection considered as part of Navy sea strike capabilities is an example of a context where conventional large scale naval forces have particular advantages in attacking large scale enemy forces.[4]

When we consider the network centric warfare model and map it onto this analysis, we see that the two examples of neuromuscular and immune systems may be effective in two distinct contexts. Specifically, the fine scale complexity of the littoral may be the domain for networked loosely coupled forces analogous to an immune system. By contrast, when a large enemy force is present, the possibility of effective sensors and actions to attack the large scale force can be realized by force projection across the littoral region. Both of these concepts have played a role in SSG reports, however a clearer understanding of the different contexts in which they are effective is important. The much higher fine scale complexity of the littoral region than the open ocean is already manifest in the radical differences in organizational structure, training and equipment for the Marines as opposed to the Navy. The need to enhance the Navy and Marine capabilities in littoral warfare must take such organizational issues into consideration, the general concept of networks is insufficient since there are several quite different kinds of networks that are effective in different contexts.

Networks in Warfare

The concept of a network as a model of social and technological organization is now in widespread use. It often is used to suggest widespread availability of information and coordination. However, the capabilities of a network must be more carefully understood in

[4] Projecting force across the littoral assumes that enemy forces in the (complex) littoral are not able to oppose this crossing.

relation to the desired function. A useful distinction is the one previously mentioned, between a network of agents each of which has direct action capabilities, and a network of decision makers that determine collective actions. The first system is a distributed action system, the second is a distributed control but coherent action system. The first is effective at multiple localized and simultaneous tasks. The second is effective at determining a single but highly selected act at any one time. An effective military can utilize both types of organization but must recognize the quite different nature of the organization, training and technology that is needed for each. The two distinct coordination/action structures, by analogy with the immune system and the neuro-muscular system, suggest two different directions for improvements in current military functions. These two types of networks are discussed in the following two sections.

Networked action agents

The immune system consists of a variety of types of agents (cells) many of which are capable of movement, have sensory receptors, communicate with each other, and are individually capable of attacking harmful agents (antigens) as part of the immune response. This system is a useful analogy for a system of agents where sensor-decision-effectors are tightly coupled within each agent and distributed control, coordination and networking is present in the connections between them. Other frequently used analogies for networked action agents include swarming insects.[26] Insect swarms are a useful model but may have less information about effective military forces than the immune system because of the elaborate interactions between immune system agents.

For the military context, to be concrete, we can consider an individual agent (warfighter) to be a warrior or a small watercraft. In this scenario, each individual warfighter has substantially independent sensor, decision, effector capability. The high capability of the individual warfighter then receives a substantial augmentation from local force coordination. Understanding this local coordination requires specific task and mission objectives since complex conflicts tend to have distinct local conditions. Still, because the high complexity of function resides in the individual activity, the key to understanding such coordination resides in simple pattern formation. It is important to distinguish simple pattern forming coordination from more intricate tactical planning of carefully timed actions of specific force units. Instead, pattern formation reflects the possibility of local coordination of sensors and local coordination of fires to achieve larger scale effect than is possible with a single warfighter. The coordination can use relatively simple communication protocols that allow local adaptation for swarming, flocking, or related simple collective patterns.

In addition to considering a warrior or a watercraft as an agent, a single agent may itself be a team of individuals. Moreover, the team can be homogeneous or heterogeneous. A homogenous team consists of a few individuals who are similarly trained or a group of similar ships. A heterogeneous team would consist of warriors with diverse training or equipment, a combination of ships with distinct functional capabilities, a combination of ships and warriors, or warriors, ships and aircraft. On a large scale, the aircraft battle group could be considered a single agent, however we would more typically think about smaller sized agents, and larger numbers of them. The key to identifying a single agent is the independence of function and action, an “encapsulation” of the agent, allowing independent action.

Once we have identified the agent, we can consider the network of these agents. Often when networks of agents are conceived, the network itself is assumed to be formed of a set of similar agents (a homogeneous network). A homogenous network can be a network of similarly trained and equipped warriors, or a network of small and similar ships. This can be generalized slightly by considering an agent to be a team that acts together as a unit. As discussed above the team can be a homogenous or heterogeneous team formed out of warriors, ships, aircraft or combinations of them. As long as all of the teams are similar to each other in their composition (whether or not they are homogenous or heterogeneous teams) it is a homogenous network because each team acts as a unit. Considering only homogeneous networks is limiting in terms of considering strategies for effective function. Instead, we can consider the agents that form the network to be functionally diverse, possibly of a few but potentially of many types. This is the case in the immune system which consists of several different types of cells. Some of these types of cells are themselves highly diverse through specialized molecular "equipment." Thus there are different levels of differentiated function and the different types coordinate with each other for collective behavior.

It may be useful to contrast the difference between a heterogeneous team and a heterogeneous network. A heterogeneous team might consist of several warriors with a particular combination of skills and equipment (for example, the Green Berets 12 person teams with specialties in weapons, engineering, medical care, communications, operations and intelligence). Each team would be an independently functioning group that generally remained together throughout a mission. The internal coordination within the team would be highly developed and the loss of one or two members could significantly reduce the capability of the team. In the heterogeneous network, there are several different types of individuals, these may be the same as the ones in the heterogeneous team. However, the cooperation between these different types of individuals would be created on an ad-hoc basis according to the need for different numbers of different types of skills as required by different types of conditions. The coordination between individuals and teamwork would be, of necessity, less well developed, and the group would be more robust to loss or addition of other members. In some cases this might be expected to involve a wider range of skills. In this case teams are not well defined because the number of individuals of a particular specialization is not well defined except in the context of local conditions. Thus the system must allow for the relative density of different specialties to vary from place to place and the communication system must allow for the needed coordination of their separate motion and aggregation into ad hoc teams. This coordination can be quite simple locally transmitted calls for certain types of assistance depending on the local situation without central coordination. As stated before, the distinction between the heterogeneous network and the heterogeneous team is not designed to advocate one or the other. Each is more or less effective depending on the environment and mission. Also a heterogeneous network may itself be formed out of various types of teams including heterogeneous and homogenous teams.

Distributed action agents interact with each other primarily through local communication to achieve coordination of their individual actions for effective attack, defense, search or other tasks. The primary role of such coordination is to achieve the right level of local capability, for example, the number of agents to achieve the right amount of firepower. When one or a few individuals are necessary for a particular task, others should not congregate there. When more are necessary they should. Local coordination replaces the role of command and control coordination of a hierarchical force. Thus, when a network of agents acts, the pattern of spatial density, the spatial pattern of movement, and the spatial patterns of fires and other local characteristics, manifests the emergence of collective behavior from the local interactions. The emergent collective behaviors are not directly specified. Indeed, the specific pattern that arises should not be controlled because the pattern is determined by the response of the agents to the local challenges they face in the environment as well as interactions with each other. Efforts to globally control the overall pattern would inhibit the local adaptation to challenges. The way such emergent pattern formation occurs from local rules of interaction is generally considered mysterious. It is essential to demystify such patterns in order to develop an understanding of both their mechanism and their effectiveness. In this regard, the self-organization that occurs through local interaction is often considered to be more capable than it really is.

To understand the pattern formation process [12,14], it is instructive to consider the role of interaction rules such as “local activation long-range inhibition” in achieving coordinated local behaviors and their extension to swarming, flocking and other coordinated animal behaviors. This rule implies that agents that are near each other have a tendency to perform the same acts, while agents that are farther away are inhibited from the same act. This rule in effect controls the scale of cooperation of the agents so that the necessary scale of action is performed, but it is limited to this scale. The key mechanism for achieving such behavior is through local communication rules that coordinate movement or coordinate acts (e.g. fires) by largely independent agents. In comparison with uncoordinated agents the process and patterns that occur may seem fantastic and mysterious. Once understood, both the opportunities and limitations of such coordination can be recognized. When higher levels of coordination/patterns are necessary, then the agents involved must have a higher level of practiced coordination and exercised teamwork just as in conventional military training for team effectiveness. This is not achieved by simple self-organization but rather by evolutionary trial and error selection that can later be learned / trained as effective patterns of collective behavior.

Thus, the generic pattern forming behaviors are relatively simple. They are quite different from the kinds of coordination that are possible by central control, and do not have the richness of structure and function of individual biological organisms that evolved over many generations. Such evolutionary systems that have been selected for specific complex function result from an overlap of many layers of patterns. We should not expect simple self-organization by local interactions to give rise to such complex behaviors. On the other hand, the simple coordination that is possible through local interactions is a powerful mechanism for effective action in a high fine scale complexity terrain where independence is essential but some coordination is also necessary to deal with local variations in the functional requirements. It is essential when the simultaneous local functional needs varies from place to place in a way that would overwhelm the possibility of central control. Developing simple local communication protocols for such pattern forming processes and the related appropriate technology is important. Many such local coordination mechanism are likely to exist already. Augmenting and enhancing the existing (natural) patterns of local behavior should be the immediate objective, as suggested by an evolutionary approach to innovation.[6]

A simple example of local coordination can be found in the penetration of forces through a barrier of rough terrain when the objective is to reach the other side rapidly (e.g. passing through a littoral access). When visibility is limited, as it is generally in high complexity terrains, a simple but efficient means of communicating the location of passages ("it's easier over here") that can allow easier movement should help. This communication should be local because moving to the location of an access route is only helpful if it is nearby. It should also be clandestine. Centrally coordinated or long range movement of forces is less important in this case.

In any discussion of the complex warfare between networks of largely independent agents, an essential issue is friendly fire. The problem of friendly fire arises because there are generally no clear (large scale) boundaries between friendly forces, enemy forces and bystanders. The need to differentiate between different classes of agents in a rapid response context places high demands on the complexity of function of individual agents, as well as on coordination. Because of the possibility of a shared coherent technology among friendly forces, this is a context where "appropriate" technology which can serve to facilitate senses, improve local situational awareness or inhibit weapon fire against friendly forces can be key to effective distributed networked operations. Because of the opportunity for innovation this is an ideal context for application of evolutionary processes to the engineering of novel technological, organizational and/or procedural solutions [6].

Networked decision coherent targeted acts

The neuro-muscular system can be understood to be composed of a sensory system, a decision system, and an effector system. The decision system is designed as a distributed control network. The network enables high complexity decisions based upon disparate information sources, while the effector system is designed for large scale impacts. Because of the networked decision system the choice of when and which large scale impact to perform can be made highly selectively. The complexity appears because each act at a particular time can be precise and carefully selected. Different acts can be selected at subsequent times.

In a military context, a similar sensory, decision and effector system has been actively discussed as integral to network centric warfare. To understand the role of such a system, it is useful to realize the forces involved may be similar to large scale conventional forces, however, they are coupled to the highly distributed decision making process that enables many factors about the current situation to be considered in the selected act. The availability of large scale forces does not always necessitate their full use, just as the availability of muscles that can kick or punch does not imply that they will always be used in this maximum capacity. A delicate nudge can be highly effective under some circumstances. The force to be used is selected carefully from many options to achieve desired objectives. This strategy is a natural extension of centralized military planning processes, where centralized does not also mean hierarchical. It is consistent with the concept of centralized command with distributed control [7]. The objective is, however, not solely to deliver many fires to many different targets at the same time, instead it is to deliver the right force to the right target at the right time through a remarkable understanding of the specifics of the situation as it changes in time.

Using the neuro-muscular system analogy, the central decision making system (brain) as the decision network resides between the sensors (e.g. eyes, ears and nose), as a collective, and the weapons (muscles) as a collective. While sensor fusion and weapon coordination have been key concepts in recent military research, development gaming and experimentation, it is useful to note that aside from limited pattern finding processes that can be effectively performed by computers, the ultimate nature of sensor fusion and weapon coordination is the essential role of the decision network itself that heavily relies upon human beings. This does not mean that technology cannot assist in sensor fusion, but that one should anticipate the response systems to involve technology as well as human beings actively in “sensor fusion” and “weapon coordination” systems.

In order to achieve both high complexity and time sensitive actions by a decision network, and the possibility of learning by this network, an analogy to models of the functioning of the brain may be useful [12, chs 2,3]. In particular, the brain has various stages of reactive systems that operate on short time scales. Reactions at progressively longer time scales involve increasingly elaborate decision making mechanisms. These mechanisms integrate multiple distributed cognitive processes. Moreover, the longer time scale actions may serve to correct actions that are initiated by the shorter time scale reactions rather than to initiate them directly. Such recall or redirect corrective decision making processes are already part of the military system, but their integral relevance to network decision making may not be fully understood and should be the subject of further study.

Summary of Complex Warfare: Terrain and force organization

Traditional warfare is a large scale conflict of forces where the largest scale force wins. Such considerations are relevant to frontal confrontation in simple terrains. Complex warfare is characterized by small-scale hidden enemy forces. The Gulf War represents a modern example of a traditional warfare scenario. While there exist earlier examples, the first major US experience with complex warfare was Vietnam. There are many arguments for why the US did not win. The main problem, however, was the complexity of the warfare: the high complexity terrain, the inability to distinguish friend and enemy—the inability to locate and target the many nearly independent parts of the enemy. Lessons learned in Vietnam were central in military effectiveness in the war in Afghanistan.

Complex warfare cannot be won by traditional war fighting strategies. This lesson was learned from Vietnam, and the Soviet experience in Afghanistan. To achieve mission objectives in high complexity environments with a dispersed enemy, the force organization, training, preparation and equipment should enable highly independent application of multiple forces whose offensive and defensive scale sufficiently exceeds the scale of the individual challenges to be met. Compared to traditional war fighting, the key to success in such complex warfare contexts is the capability of small units to act independently. The emphasis must be on highly autonomous and independently capable forces with relatively weak coordination, rather than large scale coherence of forces. Small unit independence increases the number of actions that can be taken, i.e. complexity. This is manifest in the special force operations, especially in early stages of the war in Afghanistan.

In addition to the overall force organization, the effectiveness of forces relies upon its overall adaptive capability to meeting the specific nature of individual challenges. The specific environment of Vietnam is quite different than that in Afghanistan. The overall organization of special forces is well suited to both. Still, the characteristics of each context, including climate and terrain, as well as psycho-socio-cultural context of the enemy and civilian population, must be adapted to by specific preparation and equipment suited to that situation. Experience gained with similar environments and training for the context is essential.

The war on terrorists, whether it is against the terrorist cells distributed around the world or against those holed up in mountainous terrain in Afghanistan, has all the characteristics of complex warfare. Forces with high fine scale complexity, such as special operations, the integration of diplomatic, intelligence, law enforcement agencies and agents into military conflict, and the extensive use of non-lethal force and psychological warfare reflects the natural extension of the fine scale actions and forces that are needed in achieving local and global objectives of complex warfare.

While Vietnam and Afghanistan provide poster examples for complex warfare, traditional warfare also has various degrees of complexity. The organization, training and equipment of the US military illustrates the experience gained with conflicts of various degrees of complexity. We can recognize the complexity of different terrains (Figure 6) and compare them with the structure of forces that are designed to deal with them. Larger scale forces are designed to deal with larger scale conflicts, and more independent forces are designed to deal with high fine scale complexity conflicts. At the very largest scale (any moral issues aside), nuclear weapons are essentially unusable because their large scale impact in space and time implies they are ineffective for use in essentially any conflict. The largest scale conventional forces are ships found in the Navy designed for the simplest terrain, the open ocean. Tank divisions are well suited for deserts, and plains. Heavy and light infantry are suited for terrains with progressively greater fine scale complexity. The marines with small fighting units and high levels of training of individuals for independent action are suited for the interface of land and sea which is generally a terrain with high complexity at many scales. In a high fine scale complexity environment, e.g. near a shoreline, a few marines can defeat many ships. Similarly, in high fine scale complexity land environments, infantry can defeat tanks.

It is helpful to have an earlier example of effective management of complex warfare that illustrates this point. The 10th Mountain Division was established in 1941 as a result of an awareness of the experience of Finnish soldiers on skis that annihilated two invading Soviet tank divisions in 1939.[27] Trained on Mount Rainier, or in Colorado, this light infantry division was central to the defeat of German troops occupying ridge positions on the North Apennine Mountains of Italy.

These examples illustrate that it is impossible to have a single organizational structure that is effective for diverse military conflicts. In particular, forces cannot be well designed for success in both large scale and complex encounters. Instead, tradeoffs must be chosen. To be successful in a range of possible conflicts, the military should be partitioned into parts to provide capability for addressing conflicts with varying scales and complexities. More generally, if we consider a conflict as having a complexity profile that specifies the number of actions needed at each scale, the forces can be well adapted to the conflict by having a similar complexity profile.

Figure 6: Pictures illustrating different terrains. From top left running left to right: ocean, desert, plain, hills and villages, littoral, Vietnam and Afghanistan.

Summary and Extensions

Multiscale complex systems analysis provides a formal approach to understanding warfare in complex environments and against opponents well adapted to such environments. Many of the existing military structures incorporate the results of experience with complex conflict and therefore embody a multiscale understanding. A multiscale analysis enables us to recognize explicitly the capabilities of these military structures, and to extend this understanding to considering networked organizations with more distributed control structures. It provides guidance about the potential role of useful technological innovation that enhances force capabilities without sacrificing the benefits of historical experience with military conflict. Just as significant is the possibility of evaluating enemy and friendly force strengths and weaknesses through recognizing the challenges that they can and cannot meet effectively in complex warfare conditions. This provides an opportunity to replace conventional attrition analysis of force capability based on collective firepower to an approach that can directly consider the organization of enemy and friendly forces and the conditions of conflict between them.

An effective analysis of military operations requires describing the impact that can be achieved by enemy and friendly forces at each scale of a potential or ongoing encounter. The ability of a system to deliver impacts at a particular scale depends both on force composition and on the C^4ISRT system that it employs. Any large scale force is composed of finer scale forces coordinated to achieve a large scale impact. In the simplest case, the scale of impact of a force involves the delivery of multiple shots in a coherent fashion. Coherent firepower can be achieved by simple coordination mechanisms. In a traditional hierarchical organization of military operations, the firepower that can be coordinated is dictated by the nature of the command structure. Individuals are coordinated into a fire team, fire teams are coordinated into a squad, then a company, a battalion and so on to the entire military force. Coordination between fire teams in different battalions, or between Army, Air Force and Navy units is limited. Such coordination has been found inadequate in modern warfare leading to the introduction of a diversity of coordination mechanisms between individuals even in widely different parts of the military as measured by the conventional hierarchical structure. This change reflects the need for radically different coordination mechanisms in high complexity environments. High complexity environments require an ability to deliver specific types of firepower at specific targets in an adaptive fashion based upon details of local conditions. The scale and complexity of operations necessary to overcome a particular enemy force is dictated by the scale dependent structure of the enemy force, the scale dependent structure of the battle space (terrain, etc.), as well as the complexity of objectives and related constraints (political, etc.).

The need for radical changes in coordination in the military has led to a widespread recognition of the relevance of networks as the basis for effective action and more specifically for innovative forms of command, control and communication. In this paper, an essential distinction has been made between two paradigms that illustrate fundamentally different approaches to networked operations. The first involves networked action agents capable of individual action but coordinated for effective collective function through self-organized patterns. Analogous behaviors can be identified in swarming insects and the immune system. The second involves networked decision makers receiving information from a set of sensors and controlling coherent large scale effectors. Analogous organizational structures can be identified in the physiological neuro-muscular system. Each of these important models of networks deserves consideration for the development of networked military forces. The two paradigms are also not restrictive in the sense that there are many intermediate cases that can be considered. For example, we might consider a small number of large sensor-decision-effector systems, like human arms, that can act in parallel and possibly be coordinated.

Rather than considering military success to be a result of larger scale forces, it is better to consider the key to success as a higher complexity at every scale of the encounter at which confrontation occurs. A higher complexity corresponds to the ability to act in more possible ways. In a conflict between two otherwise matched forces, when one force is systematically capable of more possible actions, its offensive actions cannot be met by defensive actions of the other force, and it can respond effectively to the offensive actions of the other force. This method of assessment includes, as a special case, the existence of larger scale forces than the enemy, since at that scale the complexity of the enemy is zero while that of friendly forces is not zero. It also includes the case of a high complexity at a fine scale where the advantage is more intuitively that of higher complexity as manifest in more possible options of action. The conventional perspective of large scale forces is a specific but highly restrictive example of this strategy, as can be seen from the effectiveness of small forces in the context of high fine scale complexity encounters.

Examples of the role of force complexity include the more conventional importance of tactical agility of large scale forces, and the modern emphasis on diverse capabilities of Special Forces. The significance of complexity is most readily apparent, however, when we consider the capabilities of small scale forces against large scale conventional forces in a high complexity terrain. Heavy military equipment (ships and tanks) that provide an advantage in simple terrains (ocean, desert and plains) are often a liability in mountainous, jungle, littoral or urban terrains. Massing forces for offensive and defensive advantage in simple conflicts is counter indicated in complex conflicts where dispersal provides an advantage. These observations are apparent when considering the capabilities of guerrillas against massed forces in a jungle, tanks in the mountains and ships in a port. The conventional military organization that provided large ships for the open ocean, tank divisions for desert and plains, heavy and light infantry for progressively more difficult terrain and Marines for littoral conflict manifests this understanding of the relevance of force organization and training for various degrees of complexity in conflict. The modern reliance on Special Forces reflects and ongoing recognition of the need for ever higher complexity forces for ever higher complexity military conflicts.

Using the complexity profile, a multiscale complex systems analysis characterizes the degree of complexity at each scale of action. Effective forces have complexity profiles that correspond to that of the terrain---high complexity in a high complexity terrain, low complexity in a low complexity terrain. Since complexity increases rapidly as the independence of units at the desired scale of action increases, but larger scale actions are possible only as the coordination between such units increases, there is an inherent tradeoff between the complexity of action at one scale and the possibility (complexity) of larger scale actions. Simple coordination to achieve the very large scale action characteristic of conventional warfare is different from the coordination needed to achieve a wide range of scales of possible action as is necessary in complex warfare.

A systematic discussion of warfare in high complexity terrains suggests the following central statement: A complex terrain has general characteristics and special properties. The general characteristics are the statistical properties of the terrain and of the enemy forces. The specific properties include the overall climate and socio-cultural context as well as the location of features of the terrain and of the enemy forces. The general characteristics give advantage to forces that are designed for these characteristics as discussed above. The special features give advantage to forces that know these particular features. While general principles can provide guidance, nothing can replace experience in learning the effective design of forces and the special features of the terrain.

There are a number of important extensions of this work which should be pursued. Among these are:

1) Implications of Multiscale Complex Systems Analysis for training of the 21st Century Warrior.
2) A description of distributed action agents that achieve collective behavior through pattern formation.
3) A description of distributed control and lessons from the analogy to the neuro-muscular system.
4) Quantitative analysis of the complexity profile of specific terrains, military forces or military conflicts, conventional and modern.
5) Addressing enemy force adaptability and the effect of our actions on enemy force organization.

We end this paper with a brief introduction to the problem of enemy force adaptability because of its direct relevance to the ongoing military activities in Afghanistan and the War on Terrorism.

In a multiscale conflict, where there are large and small scale forces, destroying the large scale forces does not necessarily incapacitate the fine scale forces. It is even possible for the destruction of the large scale forces to be counter productive in promoting the development of finer scale forces that are harder to deal with. Since fine scale forces are generally highly adaptable and evolve rapidly, the possibility of dangerous enemy adaptations that are able to take advantage of unknown weaknesses in friendly forces is high. In such cases, by eliminating the large scale component of enemy forces, we may actually contribute to their effectiveness. In complex warfare the adaptation of enemy forces to our strengths and weaknesses is the greatest long term challenge.

This is a case where our actions today shape our enemy of tomorrow. Thus, it is our ability to field our own rapidly evolving fine scale forces that is the key to complex warfare and represents the main challenge to conventional force structures. The existence of high fine scale complexity forces, such as special operations, and integration of diplomatic, intelligence, law enforcement agencies and agents into military conflict, and the extensive use of non-lethal force and psychological warfare reflects the natural extension of the fine scale actions and forces that are needed in achieving local and global objectives of complex warfare.

The ongoing development of unique military forces, extending the notion of special forces and their technological capabilities (as individuals and as groups), is needed to increase the effectiveness at addressing high complexity challenges. The development of effective individual and team strategies should take advantage of evolutionary processes [6], which should be particularly effective because the teams are engaged in local actions. Moreover, because new circumstances require rapid adaptation, extensive development and planning of such innovations is not effective. A system which is intrinsically built around rapid innovation will be much more effective.

Appendix A: Law of Requisite Variety

The Law of Requisite Variety provides a quantitative expression relating the complexity of the environment, the complexity of the system and the likelihood of success of the system in performing a particular function for which it is designed. It states: The larger the variety of actions available to a control system, the larger the variety of perturbations it is able to compensate[18]. Quantitatively, it specifies that the probability of success, P, of a well adapted system in the context of its environment is decreased by the complexity of the environment $C(e)$ and increased by the complexity of its actions $C(a)$ according to the expression:

$$-\mathrm{Log}_2(P) < C(e) - C(a)$$

Qualitatively, this theorem specifies the conditions in which success is possible: a matching between the environmental complexity and the system complexity, where success implies regulation of the impact of the environment on the system.

The implications of this theorem are widespread in relating the complexity of desired function to the complexity of the system that can succeed in the desired function. This is relevant to discussions of the limitations of specific engineered control system structures, to the limitations of human beings and of human organizational structures.

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