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

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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.[1]

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.

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[1] 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.

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 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^4ISRT 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.

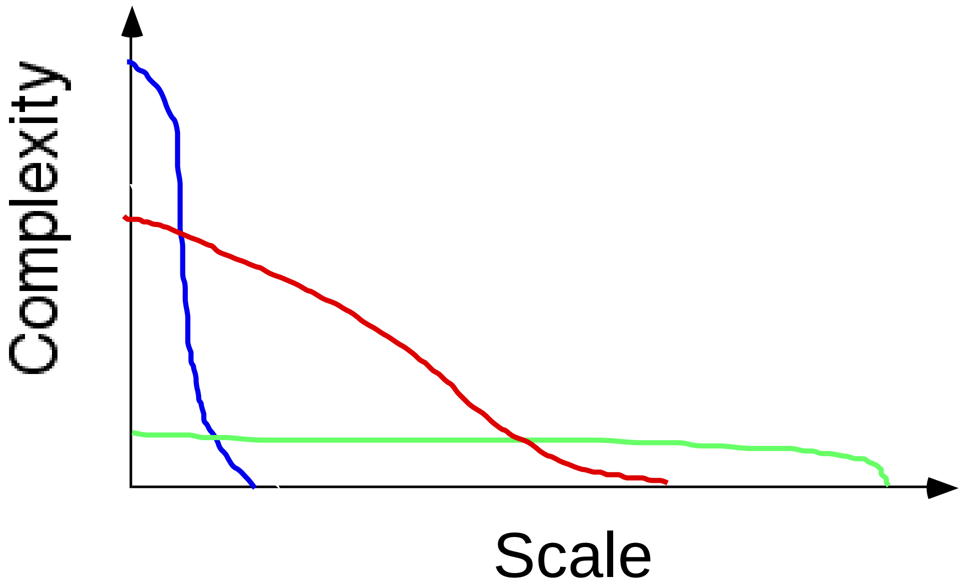

Figure 1: Illustration of the complexity profile for three different types of organization. Blue: independent agents, Green: coherent, Red: various degrees of coordination.

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.

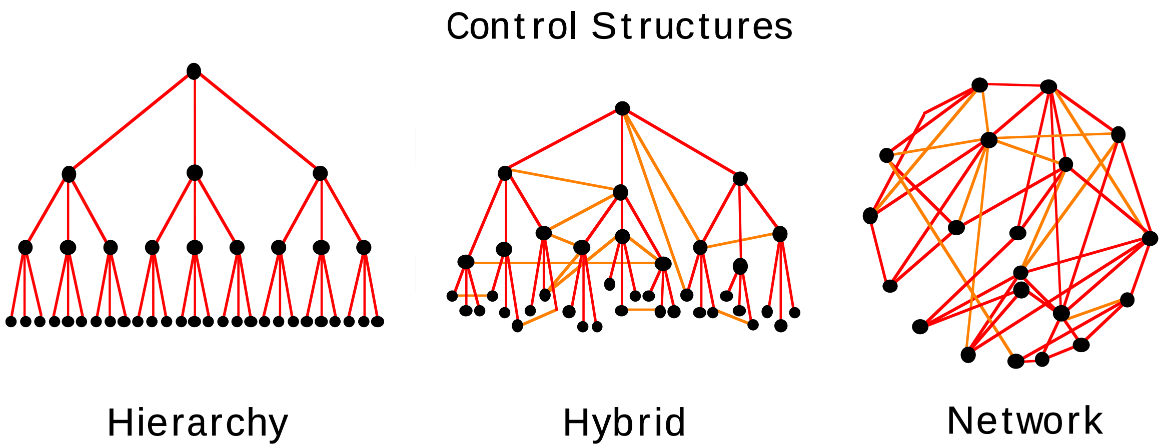

Fig. 3: An ideal hierarchy (left) relies upon a single individual to coordinate the large scale behaviors of the system. The complexity of these behaviors is therefore limited in to no more than the complexity of a single individual and his/her ability to communicate (bandwidth limitation). A network 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[2] 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.

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[2] 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.

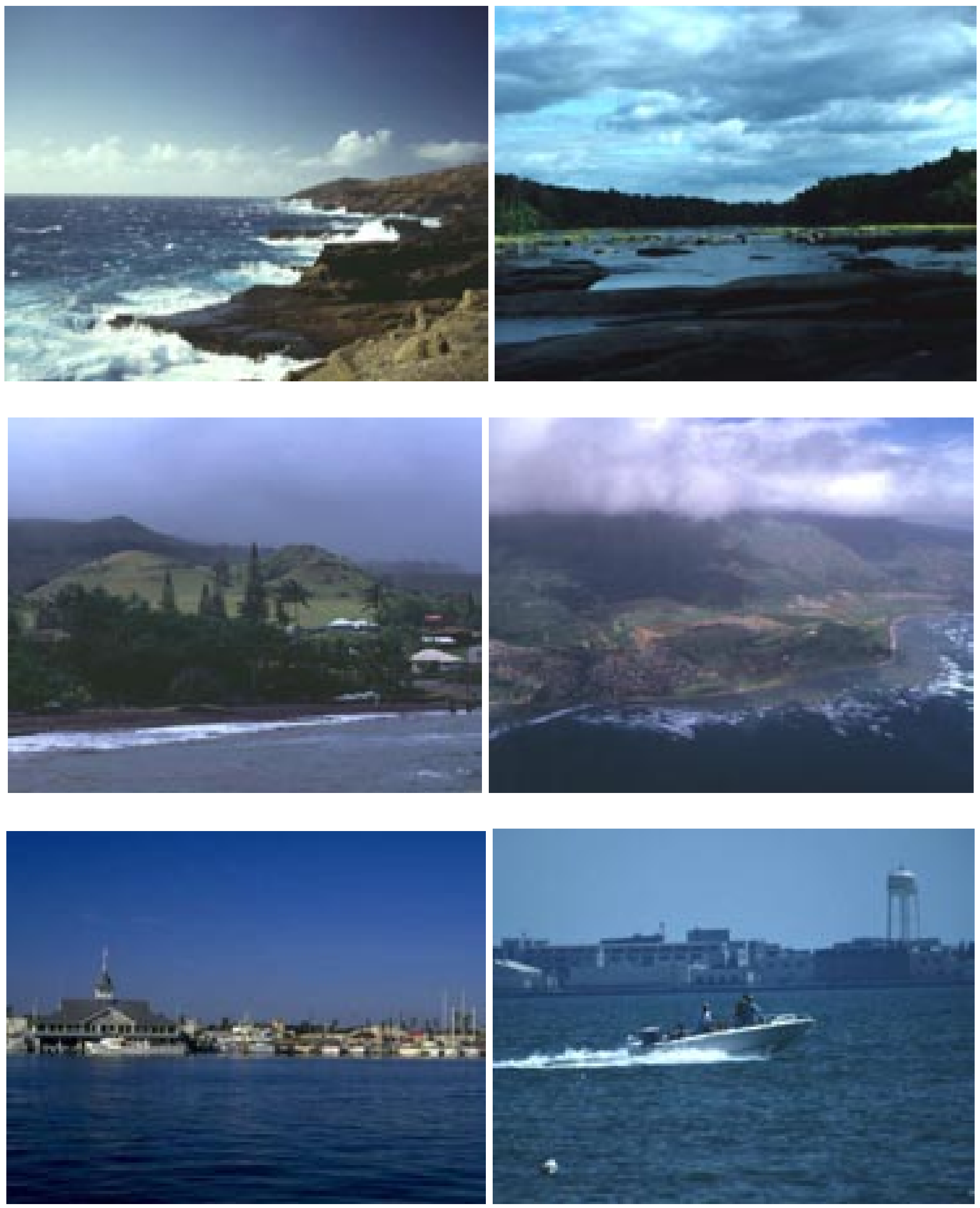

Figure 5: Examples of littoral environment

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.[3]

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.

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

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 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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