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The Real Military Revolution

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> "The military implications of new organizational sciences that examine internetted, nonhierarchical versus hierarchical management models are yet to be fully understood." -- TRADOC Pam 525-5, *Force XXI Operations*[1]

Digitization of the battlefield is producing a revolution in military affairs, but not the one the architects of the military future have in mind. It is occurring because the American military, more than any other, has seized on the digital information revolution and is adapting it for combat as rapidly as possible. Using a carefully networked array of sensors, shooters, and automated information systems, the US armed forces expect to dominate 21st-century battlefields. Farther down the road, beyond 2010, the Army expects to marry these "knowledge-rich attributes" to new speed and agility, and to the increased range and lethality of new weapons.[2] These innovations are to become not merely part of, but the basis for, day-to-day military operations.

What is likely to happen, however, is more than just a new way to conduct old business. The work of complexity theorists (notably Andrew Ilachinski, Margaret Wheatley, and J. M. Epstein) suggests that something wholly new is going on.[3] In this case, "revolution" is not just a metaphor for rapid change. It really is a revolution in the basic sense, a new order of things that is sweeping away the old order whether we want it to or not. The implications of these new electronic networks for the structure of human institutions, including armies, are far more profound and far-reaching than most commentators seem to recognize.

Dr. Wheatley, a behavioral theorist, put it this way:

> They [the US Army] have the technology to move information down to the lowest level so that it is possible for the men inside tanks to have as much information as their commanders have. . . . But once you give that information to tank crews, and they start working for their own safety, their own victory, how are they going to respond to commands from above? And what happens to battle strategy? Is it in the head of the commander, or do you just train the crews and let them figure it out for themselves as the situation demands?[4]

Dr. Wheatley focuses on the decisionmaking questions posed by widespread use of automated information systems on the battlefield. This is a serious question, but it becomes urgent when the expected speed, agility, and lethality of the 21st-century Army is added to the equation. The urgency is generated not only by the ongoing "digitizing" of headquarters or large crewed vehicles such as tanks, but also by the effort to ensure that even individual soldiers are wired into the digital battlefield.[5]

One important outcome of this revolution may be the destruction of the long-standing, traditional military hierarchy. If so, one of the important instruments of this destruction could be the Land Warrior system, a set of personal information components designed to make individual soldiers an integral part of the digital battlefield by connecting them with Force XXI Battle Command Brigade and Below--the computer system and software at the heart of the Army's digitization effort.[6]

The Land Warrior system in its test and evaluation version includes a helmet eyepiece that folds down, presenting a computer screen or the display from a combination sighting system and video camera on the soldier's rifle. A personal computer and two radio systems are worn underneath the rucksack. On the chest strap of the soldier's ballistic protection vest is a folding handgrip that acts as a computer mouse, allowing him to operate the radios and manipulate his computer.

Land Warrior's capabilities are impressive, but they are directed toward traditional battlefield functions such as quicker response times, better reconnaissance, faster communications, more accurate artillery, and so forth.[7] All this will undoubtedly happen, but it won't happen in isolation. Integration into the wired battlefield forces us to come to grips with an inevitable but too often unrecognized consequence of the new information technology, the diffusion of power away from the highly centralized hierarchies that now make up most forms of human organization. This is only the first of some profoundly uncomfortable questions raised by the new digital systems, especially when those systems are extended to individual soldiers and small units. The phenomenon of self-organization also begins to emerge, as alluded to in the quote from Dr. Wheatley. This creates real difficulties for very large organizations like armies that depend on a strong, hierarchical control.

Armies are the very textbook models of bureaucratic structure--based on specialization of function, including decisionmaking, and an unambiguous chain of command. They are often referred to as "mechanistic," in the sense that a clock is mechanical, made up of many parts and subassemblies, each accomplishing strictly defined tasks to produce regular, reliable, and predictable outputs. It is probably no accident that the Army is often referred to as "the green machine." This mechanical model is responsible for the enormous success of traditional bureaucracies, including nation-states and their armies. They exist and prosper because they carry out very complex tasks (such as collecting taxes and fighting wars) with unrivaled effectiveness and efficiency.

Modern armies have succeeded wonderfully by following the mechanical, bureaucratic model: specialization, unambiguous lines of command, a rigid hierarchy, and enforcement of established routines. This same dedication to uniform, established, centralized procedures also makes them highly resistant to change. Bureaucracy is not intrinsically a bad idea; it is basic to the functioning not only of the modern state but also nearly every institution that makes up modern society. It is responsible for much of the success of these institutions and not to be discarded lightly. But the realization is growing that the new, highly interconnected, information-saturated organizations do not function like clocks; their functioning is more akin to living things.[8]

To understand this revolution and some of its early consequences for military organizations, it will first be necessary to take a brief detour into the basic concepts of system complexity.

Complex Systems

A system is a group of interacting parts functioning as a whole and distinguishable from its surroundings by recognizable boundaries. Ordinary observation tells us that the Army is a system. When we speak of something as "complex" we normally mean that it has a large number of parts that all work together in a consistent manner--despite having a vast number of interacting parts, a particular input will produce a predictable output. This is linear complexity. Our example of the clock is a good illustration of a complex linear system. It has hundreds of parts, but winding it up (input) always makes the hands start moving clockwise at a predetermined rate (output).[9] If it fails to do so, the system is defective. But an army is complex in less obvious ways.

Andrew Ilachinski, in his pioneering work on land warfare and complexity theory, demonstrates that the US Army (like all the military services) possesses dynamic complexity: the system's multitude of parts can and do interact in an inconsistent manner. This means that under certain circumstances, the elements interact in a constantly changing fashion with the result that a particular input can and often will yield an unpredictable output. The degree of dynamic complexity is a function of the number of parts in a system (such as an organization), and of the ability of those components (in this case headquarters, sub-units, and individual soldiers) to communicate with each other laterally as well as vertically and to act in an adaptive manner.[10]

The key concept is that the degree of dynamic complexity associated with the Army (or any military service) is increased by several orders of magnitude when widely distributed information systems enter the picture. Force XXI is important because it seeks to create a degree of interconnectivity never before attempted in an organization as large and diverse as an army. Land Warrior is very important because it carries this distribution to its ultimate degree by including individual soldiers.[11] When sub-elements of the system are given improved weapons plus great speed and agility in addition to information saturation, we enter a new realm of complexity. Knowledge and power are both diffused downward throughout the system. Not only do sub-elements down to the individual know more, but also their ability to act on that knowledge is greatly enhanced by the increase in their resources (more capable weapons, on-call fires) and radius of action (increased range and agility). When this happens under conditions of dynamic complexity, the sub-elements begin to adapt.

Not surprisingly, the combination of dynamic complexity and the ability to adapt is referred to as complex adaptivity. Now, in order to qualify as a complex adaptive system, an organization must display three specific characteristics in addition to complexity: spontaneous self-organization, adaptive behavior (learning and anticipation), and the ability to exist at the "edge of chaos," the point of balance between rigidity and chaos.[12]

Self-organizing means that as the system's components interact, they produce synergistic, emergent properties not displayed by the individual components. As used here, adaptive means the ability to learn from experience, the ability to change to apply what has been learned, and (most important) the ability to anticipate what is needed to be successful in the future.[13]

Finally, the system must function at the "edge of chaos," meaning it is able to avoid both disorganization and stasis. To do this, a system must strike a balance by taking risks to permit learning while maintaining enough control to prevent the organization from becoming anarchic.[14]

The military services are clearly complex adaptive systems. First, they all display dynamic complexity. They feature tens of thousands of autonomous "component parts" (units and individuals) that are constantly interacting. Because the "components" are autonomous in varying degrees, their interactions are variable and unpredictable. The services also have displayed the ability to spontaneously organize and reorganize themselves in response to changing environments through a combination of unifying doctrine, decentralized leadership, and institutionalized learning practices (e.g., after-action reviews). Finally, since they conduct business in the chaotic, high-risk arena of war, but strive to mitigate this environment with codified doctrine, standard operating procedures, and the like, the services are able to operate at the edge of chaos.[15]

War itself is a dynamic phenomenon. John F. Schmitt describes it as "an open system--continuously exchanging matter, energy, and information with other systems and the environment at large--war is in a continuous state of flux."[16] In fact, war is often the realm of chaos, lacking the sort of clockwork linear predictability so beloved of conventional analysts both inside and outside the military. Instead of an us vs. them duality--us against the enemy--military conflict is actually a set of complex, interdependent behaviors that are constantly in flux. The military as an institution adapts to changes in this environment, but it is a very slow, measured sort of adaptation, carefully controlled. The nature of the issues and systems involved--including their high costs (in lives, money, and consequences), slow development times, and the relatively rare occurrence of war--has made this an acceptable method at the strategic level. But it also leads in directions that are not always useful.

Things have been changing politically with the end of the Cold War, introducing more flux into the environment. Lesser military conflicts that manage to involve the major powers have become much more common. Much of what the military does is now characterized as "stability and support" operations rather than warfighting. The advent of the so-called information revolution and its application to this range of missions, married to increasingly capable units and individuals, have pushed the conflict environment even closer to the edge of chaos where complexity reigns and self-organization is most active.[17]

We have made it terribly difficult for our current military organizations to operate effectively on the edge of chaos. Instead, our endless quest for certainty is creating an "information pathology" (the term is borrowed from Martin van Creveld). Increasing complexity has led to increasing specialization that has led to increasing demands for information at all levels. This spawns new organizations and expands old ones to satisfy the demand for information, which in turn creates still more demand which in its turn creates more complexity and so on.[18] This cycle quickly becomes debilitating and, at best, leads to severe information congestion and overload.

To recap: although military organizations are complex and adaptive, traditionally their adaptation has been slow and restrained. Staying with the clock metaphor, the military approach to adaptation is based on what might be called the "conventional" model of the world. This sees the world as a clock-like mechanism, complicated in appearance, but essentially reducible to a fairly small number of basic principles that operate in ways that are simple, regular, and predictable. This view is not utterly wrong--much of the world does function on linear rules. But equally often it does not.

This is clear in military operations where the opponents interact continuously, shifting and adapting. The result is a complex interacting dynamic that complexity theorist William Arthur compares to a kaleidoscope.[19] The patterns produced are always made up of the same elements, but they are interlocking, non-linear, and non-repetitive. In this view there are no truly optimal solutions--the objective is to find workable ones that will maximize success in the face of uncertainty.

War is the extreme case of military operations, an environment characterized by lack of equilibrium, where there is a great deal of happenstance and residual conditions are very important. Warfighting produces a great deal of pressure for adaptation. It is an environment that tends to be on the edge of chaos because the elements are constantly adapting to each other and things are always in flux. It often produces results that are unpredictable and surprising (except in hindsight).

The problem is exacerbated because the world is not consistently organized. Parts really are wholly linear, that is, clock-like and mechanical. But other parts of it are chaotic. Other parts are truly random. Having said all the foregoing, how can complex systems on the level of an army overcome their own complexity in such a world? In other words, what can we do about it? Fortunately, nature provides some fairly direct examples of the way that complex adaptive systems work in the real world. As it happens, some of these phenomena, especially those made up of autonomous creatures (fish, birds, soldiers), turn out to be self-organizing. This ability to self-organize is the next key concept.[20]

Self-organization

As noted above, complexity theory sees organizations as less like mechanisms and more like living things. "Complex, life-like behavior is the result of simple rules, unfolding from the bottom up." That is to say, the order in a complex, adaptive, self-organizing system arises from the interaction of the basic elements: fish, birds, ants, or, in this case, small units and individual soldiers. It is based on a small number of rules, but the results are far less regular and predictable. "It is more akin to the growth of a plant from a tiny seed or the unfolding of a computer program from a few lines of code, or the self-organizing behavior of a flock of birds."[21]

The self-organizing capacity of dynamically adaptive systems is amazing. They tend to eliminate redundancy, minimize connections, and establish priorities--all without outside direction. When something is organized, we tend to believe that someone organized it, some outside influence. But that's not necessarily so. Self-organization is a process in which the organization of a system occurs spontaneously based on the action of its members, without this process being controlled by an external system. The richness of possible behavior increases rapidly with the number of interconnections and the level of feedback.[22]

This is illustrated by the emergent structure of the Internet. A simple diagram of the major Internet companies with a line between them representing their relation (alliance, deal, agreement) immediately reveals an organization. For example, a cluster has formed around Microsoft, and another around Netscape (with a sub-cluster around Sun). The remaining nodes are attached, either directly or indirectly, to the emergent clusters. Some of these nodes form key bridges spanning the clusters.[23]

For most of us, a more familiar example is a flock of birds, all moving together as if under the direction of a leader or some central command. A swarm of hundreds at a time can speed up in one direction, then suddenly, in unison, decrease their velocity and turn to follow a different route. No matter how complicated their aerobatic path, the birds always stay close together but never collide. Obviously the birds lack published doctrine and are not receiving instructions from their flight leader, so how can they accomplish the kind of self-organization necessary for flocking?

Researcher Craig Reynolds found that he could replicate this behavior with computer-simulated birds that he called "boids."[24]

The basic flocking model needed only three simple behaviors:

1. Separation: Don't get too close to any object, including other boids.

2. Alignment: Try to match the speed and direction of nearby boids.

3. Cohesion: Head for the perceived center of mass of the boids in your immediate neighborhood.

The flocking that results is an example of emergent behavior. Each boid is autonomous; there are no overarching instructions for the entire population. Yet they stay in formation while flowing around objects and walls, just like a real-life school, flock, or herd. The simulation can start with the boids scattered around the screen randomly, and still they spontaneously collect themselves into a flock. The boids inevitably arrange themselves into cohesive flocks, even after flying around an obstacle.[25] What is so intriguing is that this simple system results in behaviors that are quite complex. There is no leader programmed into the system, nor is it a huge system of many complicated rules; rather, it is a system of only a few simple rules applied locally.[26]

Complexity theorists like to illustrate self-organization by pointing out that New York City never runs out of food. No one is in overall charge of feeding New York; no detailed movement plans are drawn up; no master schedule of shops and supermarkets is distributed. But, through the medium of the market, the city manages to feed itself anyway.[27]

In general terms, for self-organization to occur, a system must be neither too sparsely connected (leaving most units too independent) nor too intimately connected (allowing every unit to affect every other one too severely). The richness of possible behavior increases rapidly with the number of interconnections, the level of feedback, and the sophistication of the elements (birds or ants versus people). Battlefield digitization, especially with the addition of hundreds, eventually thousands of individual soldiers using Land Warrior systems, will be incredibly rich and complex, with a degree of potential adaptivity and innovation that is far beyond anything yet experienced. This is fortunate, because the system may prove very difficult to control. It is not hard to imagine commanders, even at the platoon and company level, flooded with data.

Imagine an environment of rapidly shifting battlefields, probably in urban areas. Fighters are moving and operating with lightning fluidity responding to changes in the situation at the individual and squad level. Deadly accurate fire support is on call by the basic soldier or marine. Response times are too short for bureaucratic channels and formulaic calls for fire. Instead, the digitized soldiers are able to take instant advantage of fleeting opportunities--a misstep by the enemy, a sudden break. Decisionmaking power is forced downward; there are too many individual situations and too many variations for commanders to control. Deciding how to prioritize resources in such a situation is a real problem. To blindly follow a pre-set operations order--"We will attack in *this* sector, preceded by a diversion *here*"--is to abandon most of the advantages gained by the panoply of sensors and information systems.

The problem is complicated by the fact that a big part of the future force contains large numbers of robotic devices flying and crawling across the battlefield, feeding back not one set or a few sets of information, but dozens or perhaps hundreds. Instead of a single Predator UAV (unmanned aerial vehicle) working on behalf of a division or a brigade, a single squad of the 21st century may move its own robotic ground and air resources autonomously across the area of combat. Even at the platoon level it could prove disastrous to try to aggregate all this information in real time and coordinate responses. Instead, decisions have to be made at the squad and even the individual level. One obvious problem with all this adaptability, agility, and information saturation is that it makes centralized command and control someplace between difficult and impossible.

Given the degree of interconnection already described, emergent phenomena can be expected to occur in the chaos of combat. This is especially true in an intense situation like that of urban combat, where small units and individuals are likely to often be on their own with little useful contact or direction from higher headquarters.[28] The question is not "Will self-organization occur?" in these circumstances. It will happen whether we want it to or not. The proper question is "How do we guide the development of a self-organizing system, encouraging where necessary and constraining where appropriate?"[29]

Rules for a self-organizing force will arise spontaneously and might begin with something reminiscent of the guidance for the flock described earlier:

1. Stay in contact with the others.

2. Move as directly as possible toward the objective.

3. Avoid being killed.

The job of leadership in such a case is to provide clear goals and achievable objectives. Swarming behavior is the result of simple rules applied to local conditions. Information dominance may expand our working definition of "local," but it will never come to mean "universal." That means a priority for leaders will be to access remote conditions that will have an effect on the swarms under their supervision.[30]

The next issue becomes, What does a self-organizing system look like? How does it perform? There are a wide variety of these parallel-operating wholes--a swarm of bees, an anthill, a school of fish, a network of computers, an economy, or other collectives. The class of systems to which all of these belong is variously called networks, swarm systems, vivisystems, or collective systems, but the swarm seems an apt metaphor for a self-organizing military force.

Swarm Systems

Organizationally, a swarm is a collection of effectively autonomous members. "Autonomous" means that each member generally (but not exclusively) reacts as an individual according to internal rules and the state of its local environment (as opposed to obeying orders from a center, or reacting in lockstep to the overall environment). These autonomous members are highly connected to each other, but not to a central hub. Since there is no center of control, management is said to be decentrally distributed within the system.[31]

However, the swarms that constitute an army are very different from those of birds or social insects. Military swarms are not built on 10,000 nearly identical units such as a bee society. An army should be seen as a swarm of swarms--i.e., a huge swarm of more or less overlapping swarms of very different kinds. The minor swarms themselves are swarm-entities, so that we get a hierarchy of swarms. At all levels these swarms engage in distributed problem-solving based on an infinitely complicated web of interaction patterns.[32]

Thus, swarm systems are characterized by four distinct aspects:

- They are self-organizing.
- There is little or no imposed centralized control.
- The subunits are effectively autonomous.
- There is high connectivity between the subunits.

Much of the activity of swarm systems is based on peers influencing peers.

Self-organization is by no means perfect, it is just inevitable. When it occurs in a complex adaptive human system, such as a large organization, it can provide both benefits and difficulties. These emergent systems may often provide the best, most effective application of resources to accomplish goals, but long-range planners need to be alert to the advantages and disadvantages of self-organized systems.[33]

Benefits of Swarm Systems[34]

. *Adaptable*. Conventional armies devise doctrine and various standard operating procedures to react to predetermined stimuli. But swarms have better ability to adjust to new situations, or to change beyond a narrow range of options. There are countless novel possibilities in the exponential combinations of many interlinked individuals. As mentioned earlier, humans are much more ingenious than fish or birds, and thus a great deal of novelty can be expected.

. *Evolvable*. Evolution is the result of adaptation. Conventional bureaucratic systems can shift the locus of adaptation (slowly) from one part of the system to another. Force XXI, the Army After Next, and the Army Transformation programs are attempts to do this at a very high level. Future conflict is unlikely to allow the luxury of evolution at a deliberate pace. Swarms have the potential for rapid evolution. In swarm systems, individual variation and imperfection lead to perpetual novelty; in sum, this leads to evolution.

. *Resilient*. Because a swarm is a collective system made up of multitudes in parallel, there is enormous redundancy. Because the swarm is highly adaptable and evolves quickly, failures tend to be minimal. This also means that a digital army cannot fall below some minimum size. To the extent that future US Army leaders attempt to eliminate this redundancy, they are probably mistaken.

Disadvantages of Swarm Systems

. *Nonoptimal*. Because swarm systems are highly redundant and have no central control, they are inefficient. Resources are not efficiently allotted and duplication of effort is always rampant, but this is typical of armies in any case. Swarms can dampen inefficiency, but never to the degree that a linear system can.

. *Noncontrollable*. It is very difficult to exercise control over a swarm. Swarm systems must be guided the way a shepherd drives a herd: by applying force at crucial leverage points.

. *Nonpredictable*. The complexity of a swarm system leads to unforeseeable results. Emergent novelty is a primary characteristic of self-organization by adaptive systems. Not all novelty is desirable.

. *Nonunderstandable*. Sequential systems are understandable; complex adaptive systems are a swamp of intersecting logic. Instead of A causing B, which in turn causes C, A indirectly causes everything else and everything else indirectly causes A. If we regard Land Warrior as a very large computational collective (a swarm), we don't strictly need to know exactly how the system works in the non-technological sense. We can still build it, use it, and make it better. But whether we understand a system or not, we are responsible for it, so understanding would help.[35]

. *Nonimmediate*. This is a major challenge for an army made up of military swarms. Linear systems tend to be very direct--flip a switch and the light comes on. Simple collective systems tend to operate simply. But complex swarm systems with rich hierarchies take time. The more complex the swarm, the longer it takes. Each hierarchical layer has to settle down; lateral causes have to slosh around and come to rest; a multitude of autonomous agents need to become acquainted with each other. However, time is relative. The current US Army is dynamically complex but far from a linear system or even a simple collective; its ability to react and adapt on any scale is already severely compromised. Swarm systems would almost certainly improve this ability at the tactical level and perhaps even at levels above that.

Adapting to the Future

The idea of swarm behavior may seem strange because we are used to our more-or-less linear bureaucratic models. In fact, this is the kind of behavior that characterizes natural systems ranging from flocks of birds to schools of fish. But because we have grown up with these biological systems, we have always accepted them. Because humans are a lot more complex than ants or fish and have lots more capacity for novel behavior, some very unexpected results should be expected.

TRADOC's pamphlet on Force XXI acknowledges the possibility of changes like these when it states, "Future technology will require the Army to reassess time-honored means of battle command. . . . It must recognize where bold change is necessary and where little or no change is needed."[36] The US military has already embraced the information revolution, but in doing so, we have taken a tiger by the tail and it is already too late to let it go. In the words of William Arthur, we are left to "observe carefully, act courageously, and pick our timing extremely well."[37]

NOTES

1. US Army Training and Doctrine Command (TRADOC), Pam 525-5, *Force XXI Operations*, 1 August 1994, p. 4, Internet, http://www.tradoc.army.mil/tpubs/pams/p525-5toc.htm, accessed 23 February 2000.

2. US Army War College, "America's Army: Preparing for Tomorrow's Security Challenges," Army Issue Paper No. 2, November 1998, Carlisle Barracks, Pa., esp. pp. 1, 8. These initiatives will continue under the current Army Transformation program, as confirmed by Major Thomas W. Collins, Office of the Chief of Public Affairs, Department of the Army.

3. See, for example, Andrew Ilachinski, *Land Warfare and Complexity, Part II: An Assessment of the Applicability of Nonlinear Dynamics and Complex Systems Theory to the Study of Land Warfare*, CRM 96-68 (Alexandria, Va.: Center for Naval Analysis, 1996); and J. M. Epstein, "The Adaptive Dynamic Model of Combat," in *1991 Lectures on Complex Systems*,ed. L. Nadel and D. Stein (Redwood City, Calif.: Addison-Wesley, 1992), pp. 437-59.

4. Quoted in Leigh Buchanan, "Organic Restructuring," *CIO*, 1 September 1994, pp. 66-76.

5. See, for example, Glenn W. Goodman, Jr., "Wireless Tactical Internet," *Armed Forces Journal*, February 2000, pp. 40-45.

6. Brian Palmer, "The Army and Partner Raytheon Reinvent the Foot Soldier," *Fortune*, 21 December 1998.

7. For example, US Army, Office of the Chief of Staff, *Force XXI:America's Army of the 21st Century* (Ft. Monroe, Va.: Louisiana Maneuvers Task Force, 15 January 1995); William M. Luoma, "NetWar: The Other Side of Information Warfare," Defense Technical Information Center (DTIC) 94520064, 8 February 1994; Stefan Eisen, Jr., "NetWar, It's Not Just for Hackers Anymore," DTIC ADA297897, 22 June 1995.

8. For example, Michael Rothschild, "Bionomics," May 1992, Internet, http://www.bionomics.org/text/resource/articles/ar_101.html, accessed 20 January 2000. See also Kevin Kelly, *Out of Control: The Rise of Neo-Biological Civilization* (Redwood City, Calif.: Addison-Wesley, 1994).

9. Peter M. Senge, *The Fifth Discipline: The Art and Practice of the Learning Organization* (New York: Currency/Doubleday, 1994), p. 71.

10. Ilachinski, *Land Warfare and Complexity, Part II*; see also Andrew Ilachinski, *Land Warfare and Complexity, Part I: Mathematical Background and Technical Sourcebook*, CIM 461-68 (Alexandria, Va.: Center for Naval Analysis, 1996).

11. Definitions are taken from "Self-Organizing Systems (SOS)," November 1998, Internet, USENET Newsgroup comp.theory.self-org-sys., http://www.calresco.force9.co.uk/sos/sosfaq.htm, accessed 5 May 1999.

12. Notions of complexity in the sense it is used here date back as far as Heraclitians, an Ionian Greek philosopher. In the 5th century B.C., he held that all things were constantly in a state of flux. (Anthony Flew, *A Dictionary of Philosophy* [New York: St. Martin's Press, 1979], p. 145.) The same notions were applied to economics in the 1930s by the economist Joseph Schumpater, but neither of these thinkers was able to break the dominance of linear logic.

13. Emergent behaviors are those behaviors exhibited by a group that are not exhibited or even implied in the behavior of individuals. A single brain cell doesn't think or perform any behavior that suggests the property of thought, but the interactions among the large mass of cells in our brains exhibit the emergent property of thought. Linda P. Beckerman, "The Non-Linear Dynamics of War," Science Applications International Corporation, 1999.

14. M. Mitchell Waldrop, *The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster, 1993), p. 11.

15. This insight was first provided to the author by the members of Seminar 4, School of Advanced Military Studies (SAMS), Ft. Leavenworth, Kans., 1998.

16. John F. Schmitt, "Command and (Out of Control): The Military Implications of Complexity Theory," in *Complexity, Global Politics and National Security*, ed. David S. Alberts and Thomas J. Czerwinski (Washington: National Defense Univ., 1997), p. 230.

17. For a further discussion of this and related issues, see Alan D. Beyerchen, "Clausewitz, Nonlinearity and the Unpredictability of War," *International Security*, 17 (Winter 1992/93), 59-90.

18. Martin van Creveld, *Command in War* (Boston: Harvard Univ. Press, 1987), pp. 247, 258.

19. Quoted in Waldrop, p. 12.

20. Pak Bak and Khan Chen, "Self-Organized Criticality," *Scientific American*, January 1991, pp. 46-53. See also Jonathan Rosenhead, "Complexity Theory and Management Practice," *Science as Culture*, 19 October 1998, Internet, http://www.human-nature.com/science-as-culture/rosenhead.html, accessed 6 January 2000.

21. Waldrop, p. 329.

22. "Complexity, Complex Systems & Chaos Theory: Organizations as Self-Adaptive Complex Systems," Internet, http://www.brint.com/systems.htm, accessed 2 June 2000.

23. See "Self-organizing Internet Industry," Internet, http://www.orgnet.com/netindustry.html, accessed 15 February 2000. Also David Byrne, "Complexity Theory and Social Research," *Social Research Update*, Autumn 1997, pp. 12-13.

24. The basic paper on this topic is Craig W. Reynolds, "Flocks, Herds, and Schools: A Distributed Behavioral Model," *Computer Graphics*, 21 (No. 4, 1987), 25-34. See also, Craig W. Reynolds, "An Evolved, Vision-Based Model of Obstacle Avoidance Behavior," *Santa Fe Institute Studies in the Sciences of Complexity, Proceedings, Volume XVI*, ed. C. Langton (Redwood City, Calif.: Addison-Wesley, 1994), pp. 327-46.

25. Discovery Online. A demonstration of the "Boids" program is available at this website: http://www.discovery.com/area/science/life/life1.3.html, accessed 7 February 2000.

26. Jason Hagney, "Flocking Birds and Schooling Fish," Susquehanna University, Internet, http://www.susqu.edu/facstaff/b/brakke/complexity/hagey/flock.htm, accessed 10 February 2000.

27. David Berreby, "Complexity Theory: Fact-free Science or Business Tool?" *Strategy and Business* (First Quarter, 1998), Internet, http://www.strategy-business.com/strategy/98104/page1.html, accessed 4 May 1999.

28. In the worst cases, the priority for subordinates becomes to stay in touch with their higher headquarters, forcing them away from the point of contact. In these cases even the lowest commander has poor situational awareness. For an extended discussion of this point, see van Creveld, pp. 228-30.

29. J. T. Dockery and A. E. R. Woodcock examine historical data for possible examples of self-organization under dynamic complexity in *The Military Landscape: Mathematical Models of Combat* (Cambridge, Eng.: Woodhead Publishing, 1993).

30. For a discussion of swarm behavior, see Eric Bonabeau and Guy Théraulaz, "Swarm Smarts," *Scientific American*, March 2000, pp. 112-16.

31. Kevin Kelly, Internet, http://panushka.absolutvodka.com/kelly/ch2-f.html, accessed 27 May 1999.

32. "Swarm-semiotics," Internet, http://www.molbio.ku.dk/MolBioPages/abk/PersonalPages/Jesper/Swarm.html,

accessed 8 February 2000.

33. For examples of self-organizing systems at work in business and industry, see John Bartholdi and Donald Eisenstein, "Why Bucket Brigades?" Research Report, 1 December 1998, Internet, http://www.isye.gatech.edu/people/faculty/John_Bartholdi/bucket-brigades.html, accessed 3 May 1999.

34. The terms "adaptable," "evolvable," and so forth as used in the discussion of advantages and disadvantages are taken from Kelly's use of the terms. Kelly, however, makes no military application of these concepts. Kevin Kelly, *Out Of Control*, pp. 261-66.

35. Ibid.

36. TRADOC Pam 525-5, *Force XXI Operations*, p. 5.

37. Waldrop, p. 331.

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