

On the Edge of Chaos: Battling Complexity with Complexity, an Examination of Swarm Logic

A Monograph

by

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Abstract

On the Edge of Chaos: Battling Complexity with Complexity, an Examination of Swarm Logic at the School of Advanced Military Studies, by MAJ Anthony E. Andrews, US Army, 59 pages.

The underlying premise for the US Army's newest operating concept published December 2017, *Multi-Domain Battle: Evolution of Combined Arms for the 21st Century*, is that growing complexity in warfare and increased adversarial capabilities necessitate a new approach to leveraging the US joint military force across all domains. This monograph explores the field of complexity science and concept that complex problems require complex solutions, namely swarming. While previous research has focused on the physical aspects of swarming and the ability to converge from a dispersed posture, this study looks to the core logic of this emergent phenomenon. By studying swarm logic through various levels of abstraction – natural case studies, simulations, and military case studies, this study demonstrates the effects of localized interactions and self-organization to power successful complex adaptive systems. These complex adaptive systems thrive in the very conditions that are supposed to challenge the future US military – highly degraded command and control with increased dispersion

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When inspired by some great purpose, some extraordinary project, all your thoughts break their bounds; your mind transcends limitations, your consciousness expands in every direction and you find yourself in a new, great and wonderful world. Dormant forces, faculties and talents become alive, and you discover yourself to be a greater person that you ever dreamed to be.

—Pantanjali, 150 A.D.

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Acronyms

C4	Command, Control, Communications, and Computers
IDF	Israel Defense Force
MDMP	Military Decision Making Process
OE	Operating Environment
OODA	Observe, Orient, Decide, and Act
RAND	Research and Development (Contraction formed the corporation's name)
SOD	Systemic Operational Design
TRADOC	Training and Doctrine Command

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Introduction

The phenomenon of swarming has captivated researchers and scientists as far back as Greek antiquity when intellectuals such as Socrates observed the complex social behavior of clustered animals.¹ With the inception of a formal field of study dedicated to complexity in the 1980s, it was not until the late 1990s and early 2000s that these concepts such as swarming and the associated evolving lexicon permeated military studies in the application of force. While the past 15 years have seen such study in the US military generally sidelined as it focused on low intensity conflict and stability operations, the renewed concern of a future conflict with a near-peer adversary in high intensity conflict has provided the impetus for resuming such study. However, after examining swarming as a theory of phenomena in complex adaptive systems, one finds that its value lies not simply in the physical manifestation of convergence that dominates most military research. Rather, the value of swarming lies in its robust logic to solve complex problems. By examining swarming in three levels of abstraction starting with its purest form – nature, followed by simulations of natural swarming, and concluded with military case studies of swarming, one can appreciate the potential value swarm logic offers to address a litany of future military problem sets.

In order to address complexity in warfare, one must first critically assess the study of warfare before transitioning to an interpretive lens shaped by the body of knowledge of complexity science and its associated language. Doing so validates the feasible examination of the relational characteristics between these two systems. As an initial point of reference, Bar-Yam, an acclaimed academic in the field of complex systems and founder of the New England Complex Systems Institute, describes the discipline of complex systems to be “field of science studying how parts of a system and their relationships give rise to the collective behaviors of the

¹ Jane Elliott and Derek Attridge, *Theory After “Theory”* (New York: Routledge, 2011), 183.

system, and how the system interrelates with its environment.”² While the identification of phenomena central to this field is not new, the formalization of the field and an evolving body of language associated with it have only been codified in the last forty years. This relatively new field of study acknowledges open systems design and constant adaptation as features that influence complex systems. As one reflects on war as a form of violent human interaction influenced by external factors such as the environment and social impetus, the various ways of war, or warfare, exercised by humans are diverse and highly contextual. It is therefore within reason to critically view warfare as part of an open system, where innumerable relationships give rise to a collective behavior of the system. Bar-Yam goes on to surmise that analytical approaches to complex systems, such as warfare, should include recognizing the importance of “patterns of behavior; the space of possibilities; and adaptive processes that select effective behaviors for a complex world.”³ Given this interpretation of warfare as an open system, one can then examine the study of warfare through three domains: military theorists, military doctrine, and future warfare concepts. It is critically important to acknowledge some pivotal observations on warfare by military theorists that both pre-date this field as well as those that developed their concepts concurrently. Such insight offers context for the actualization of military theory into doctrine, a contextual theory of action on how to prosecute war. Similarly, military theory and doctrine then influence the narrative of future warfare concepts that shape the organizational evolution of military force and its application.

² Yaneer Bar-Yam, “General Features of Complex Systems,” *Encyclopedia of Life Support Systems* (Online: United Nations Educational, Scientific and Cultural Organization (UNESCO), n.d.), accessed October 30, 2017, <http://www.eolss.net/sample-chapters/c15/E1-29-01-00.pdf>.

³ Ibid.

Articulating Complexity in Theories of Warfare

One of the preeminent military theorists influenced by the Romantic Period following the Scientific Revolution and subsequent Period of Enlightenment was Carl von Clausewitz. His writings on warfare differ from some of the more prescriptive approaches of earlier military theorists such as Antoine-Henri Jomini or Niccolò Machiavelli. Clausewitz acknowledged the human domain and factors of uncertainty that make timeless scientific approaches with linear causality an impossibility. Historian Alan Beyerchen elicits three considerations that enable such uncertainty based on Clausewitz's writings: interaction, friction, and chance.⁴ To address this uncertainty, Clausewitz theorized that one of the primary principles influencing the interactive nature of warfare is that one "must expect positive reactions, and the process of interaction that results."⁵ Warfare, therefore, is a complex adaptive system that cannot be fully modeled, or explained, given its open state and it will constantly react to influences on it.

Similarly, Field Marshal Helmuth von Moltke, the Chief of the Prussian and German General Staff, recognized the futility of binding rules in warfare given its diversity and rapid changes.⁶ This recognition of warfare's complexity shaped one of Moltke's most significant contributions to modern military theory with respect to decentralized military operations, *auftragstaktik*. As historian Gunther Rothenberg expounds, *auftragstaktik*, or mission tactics, emphasized individual initiative within an overall objective. Rothenberg posits that such an adaptive command and control philosophy has permeated modern day American military

⁴ Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," *International Security* 17, no. 3 (1992 1993): 72–73, accessed October 30, 2017, http://www.fd.unl.pt/docentes_docs/ma/aens_MA_20002.pdf.

⁵ Carl von Clausewitz, *On War*, ed. Michael Howard and Peter Paret, iBooks. (Princeton, NJ: Princeton University Press, 1976). Note: found digitally in Chapter Two under "Second Property: Positive Reaction".

⁶ Helmuth von Moltke, *On the Art of War*, ed. Daniel J. Hughes (Novato, CA: Presidio Press, 1995), 132.

thinking.⁷ This philosophy enables action and initiative in the constantly changing, open system of warfare.

Reflecting on the works of modern day military theorist, Antoine J. Bousquet, where he grapples to assess the roles of order and chaos on modern warfare, one finds that he embraces the term *chaoplexic* as the embodiment of these roles. Bousquet's chaoplexic warfare is significantly influenced by the works of John R. Boyd and his writings on adaptive systems to include his OODA Loop model as depicted in Figure 1. Such a decision model relies on continuous feedback loops to influence a process of Observing, Orienting, Deciding, and Acting. So as to erase any misinterpretation of the OODA Loop model as a potentially closed system, Bousquet highlights Boyd's application of the second law of thermodynamics to postulate that closed systems are unavoidably subject to rising entropy as time progresses and the mismatch between the changing environment and the model increases.⁸ Ultimately, Bousquet's purpose is to illustrate how complexity and open systems theory has permeated military thought as a means to describe and practice warfare.

⁷ Moltke, *On the Art of War*, x.

⁸ Antoine Bousquet, *The Scientific Way of Warfare: Order and Chaos on the Battlefields of Modernity* (New York: Columbia University Press, 2009), 189–190.

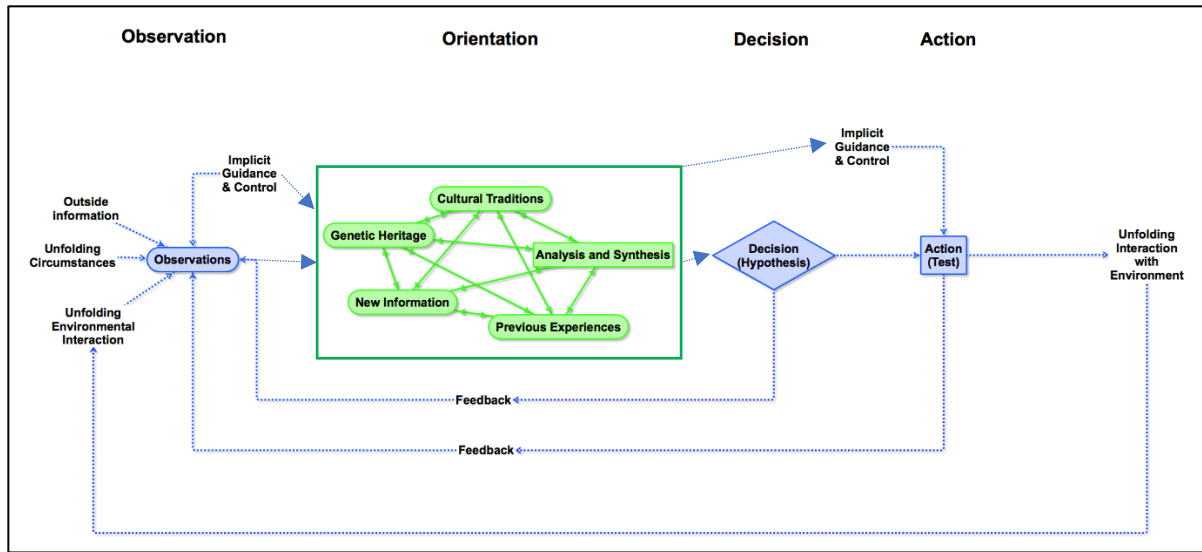


Figure 1. John Boyd’s OODA “loop”. Author’s own reproduction based on Boyd’s sketch in John Boyd, “The Essence of Winning and Losing” (Briefing, Jan. 1996).

Other modern theorists have gone so far as to make predictive assertions about the nature of future warfare. While the contextual assertions and assumptions by such theorists are not above reproach, the general phenomena of warfare described by their assessments supports the continued concept of complexity in warfare. American military theorist William S. Lind proposes the next generation of warfare, or Fourth Generation Warfare, will be characterized by highly decentralized forces.⁹ As such, the aperture for actors influencing the system continues to increase and be ill understood. Russian military theorist General-Major Vladimir Slipchenko proposes characteristics of his “sixth-generation” warfare as non-contact in nature. Aspects like information, economic, and political warfare permeate his description of future war.¹⁰ Such abstract concepts and the difficulty of measuring their affects only further affect the very nature of warfare as non-linear and impossible to completely understand.

⁹ William S. Lind et al., “The Changing Face of War - Into the Fourth Generation.Pdf,” *Marine Corps Gazette* 73, no. 10 (October 1989): 22–26, accessed October 31, 2017, <https://www.mca-marines.org/files/The%20Changing%20Face%20of%20War%20-%20Into%20the%20Fourth%20Generatio%20n.pdf>.

¹⁰ Makhmut Gareev and Vladimir Slipchenko, *Future War* (Fort Leavenworth, KS: Foreign Military Studies Office, 2007), vii–ix.

Combatting Complexity with Military Doctrine

Despite Clausewitz's assertion that a positive doctrine, or theory of action, is unattainable given the unpredictable nature of warfare as a complex, adaptive system, one must examine these attempts to address the contextual challenges of the period for which they were written. Such attempts are shaped by a framework, or operational concept, that guides the doctrinal approach. General David Perkins, the commander of the US Army Training and Doctrine Command (TRADOC), expounds the value of concept development as it "gives us [the military] the opportunity to define complex problems."¹¹ While the most recent US Army doctrine attempts to address the complexity of balancing traditional offensive and defensive operations with stability operations through such concepts as *Full Spectrum Operations* and its evolution, *Decisive Action*, the last significant evolution of force-on-force doctrine incorporates the concept of *Network Centric Warfare*. In one of the primary research papers establishing this operational concept, "Network Centric Warfare: Developing and Leveraging Information Superiority," researchers defined Network Centric Warfare as "the concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization."¹² This concept attempts to address the complexity of warfare by leveraging highly distributed and interconnected capabilities that can adapt their effects through a shared understanding of the evolving operational environment. As Admiral Arthur Cebrowski, the Director for C4 (Command, Control, Communications, Computers) Systems on the Joint Staff and John Garstka synthesized their findings on Network

¹¹ David G. Perkins, "Perkins Multi-Domain Battle," accessed October 31, 2017, <http://www.armyupress.army.mil/Journals/Military-Review/English-Edition-Archives/July-August-2017/Perkins-Multi-Domain-Battle/>.

¹² David S. Alberts, John J. Garstka, and Frederick P. Stein, "NETWORK CENTRIC WARFARE: Developing and Leveraging Information Superiority" (DOD C4ISR Cooperative Research Program, February 2000), 2, accessed October 31, 2017, http://dodccrp.org/files/Alberts_NCW.pdf.

Centric Warfare, “military operations are enormously complex, and complexity theory tells us that such enterprises organize best from the bottom-up.”¹³ As the US military returns its doctrinal focus to address concerns of near-peer adversaries and force-on-force high intensity conflict, it is prudent to acknowledge the last significant operational concept to address such threats from the military’s historical body of knowledge.

Exploiting Complexity in Future Warfare

As senior leaders in the US Army attempt to describe warfare conditions inherent to the future Operating Environment (OE), their descriptions are nothing short of dire, where the US military no longer enjoys such combat power overmatch as the previous two decades of conflict dating back to Operation Desert Storm. US Army General Mark Milley, the Chief of Staff of the US Army, in an address to the Association of The United States Army in October 2016 postulated that “the character of war, how wars are fought, where wars are fought, with what weapons and technologies, organizations and doctrines...is about to undergo fundamental, profound, and significant change.”¹⁴ General Milley goes on to describe various challenges of future war against a near-peer adversary such as increased battlefield lethality and limited or denied access to critical domains that a developing operational concept, Multi-Domain Battle, must address. Multi-Domain Battle, as a concept, seeks to exploit fleeting opportunities of emergent advantage in one domain to enable further exploitation in other domains.¹⁵ If the US military’s dire assumptions regarding the complexity and adaptiveness of future war are true, then the adversary best able to

¹³ Arthur K. Cebrowski and John H. Garstka, “Network-Centric Warfare - Its Origin and Future,” *Proceedings Magazine*, January 1998, accessed October 31, 2017, http://www.kinecton.com/ncoic/ncw_origin_future.pdf.

¹⁴ Mark A. Milley, “20161004 CSA AUSA Eisenhower Transcripts” (Speech presented at the AUSA Eisenhower Luncheon, AUSA Conference, October 4, 2016), accessed July 31, 2017, http://wpswps.org/wp-content/uploads/2016/11/20161004_CSA_AUSA_Eisenhower_Transcripts.pdf.

¹⁵ Sydney J. Freedberg, “A ‘Highly Lethal’ War Of ‘Fleeting’ Advantages: Multi-Domain Battle,” *Breaking Defense*, 14 November 2016, accessed October 31, 2017, <https://breakingdefense.com/2016/11/under-enemy-skies-armys-multi-domain-battle/>.

leverage emergence to mitigate factors contributing to uncertainty will dictate the conduct of war. Such a cognitive approach to problem solving, or operational approach in military parlance, transcends the levels of war.¹⁶ In doing so, victorious forces can shape emergent conditions conducive to positions of advantage while presenting increased levels of complexity, and therefore uncertainty and potential stagnation, to adversarial forces observing the complexity.

Foundation - Complexity Theories

Before exploiting complexity in warfare, one must first acknowledge the underpinning theory of complexity and then examine how students of complexity bridge conceptual theories of phenomena with theories of action. Given a common understanding of complexity theory and how the academic community has explored the associated emergent phenomena with multi-disciplinary approaches, one can critically examine a derivative theory of action originating in nature – swarming. Such analysis can inform complex, adaptive theories of action within the domain of warfare.

Complexity theory, in terms of a systems analysis framework, is characterized by a system with multiple agents dynamically interacting in multiple ways, following local rules and oblivious to any higher-level instructions.¹⁷ The dynamic interactions and relationships are not clearly understood or explicitly known by external observers. Neil Johnson, an acclaimed physicist known for his work with complex systems, proposes that complexity science is the “study of the phenomena which emerge from a collection of interacting objects.”¹⁸ Given this

¹⁶ US Joint doctrine articulates three levels of warfare – strategic, operational, tactical, to help commanders design and synchronize operations, allocate resources, and assign tasks to the appropriate command. Referenced in US Department of Defense, Joint Staff, Joint Publication (JP) 1, *Doctrine for the Armed Forces of the United States* (Washington, DC: Government Printing Office, March 25, 2011), I-7-I-8.

¹⁷ Steven Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (New York: Scribner, 2004), 19.

¹⁸ Neil F. Johnson, *Simply Complexity: A Clear Guide to Complexity Theory*. (Oxford, England: Oneworld Publications, 2011). Note as an ebook this was found under “1.1 a definition, of sorts” in “Chapter 1: Two's company, three is complexity.”

definition, it becomes evident that military theorists, such as Clausewitz, who analyzed the phenomena of warfare, were students of complexity science in retrospect. However, one finds that most military theorists, or complexity scientists through this modern understanding, were practitioners of the phenomena of which they were trying to make sense. The benefits are detailed understanding of certain relationships in the complex system of warfare, but the detractors are inherent biases and heuristics that limit the theorists' ability to identify and assess non-typical relationships. Periodically, a military theorist from another discipline or civilian background makes profound contributions to the evolving theory of warfare, but often their contributions are only recognized in hindsight as they tend to be shunned for a lack of military experience. Jean de Bloch, a Polish banker and railroad financier, used an economic framework to assess the potential of a war between the great powers of Europe prior to the end of the nineteenth century.¹⁹ Despite some of his revolutionary insight into the scales and impact of industrial warfare, his messages were widely ignored by the military community prior to World War I. Similarly, historian Julian Corbett, now recognized as one of the preeminent naval theorists, was poorly received early in his career by some in the British naval community due to his civilian background.²⁰ Arguably, Corbett and Bloch's diverse backgrounds widened their critical aperture to observe the phenomena of the complex system of warfare. The complexity of warfare that induces uncertainty is related to the degrees of imperfect understanding.

Multi-Disciplinary Approaches – Santa Fe Institute

The general consensus in academia and research as the field of complexity science coalesced into existence during the early 1980s was that multi-disciplinary approaches were the

¹⁹ Jean de Bloch, "Jean de Bloch: Selected Articles" (Combat Studies Institute, July 1993), accessed November 1, 2017, http://usacac.army.mil/cac2/CGSC/CARL/download/csipubs/SelectedArticles_Bloch.pdf.

²⁰ Jerker J. Widen, *Theorist of Maritime Strategy: Sir Julian Corbett and His Contribution to Military and Naval Thought* (London: Routledge, 2016), 42.

only feasible approach with a wide enough aperture to capture non-linear design features and improve relational understanding with reduced bias. Institutes devoted to the study of complexity theory such as the Santa Fe Institute grew in number during this time period. Since its foundation in 1984, the Santa Fe Institute has risen in prominence to the forefront of complexity science and is widely recognized as the leading institution devoted to exploring the concepts and phenomena behind complexity.²¹ Its strength since its inception is promoting cross-disciplinary approaches to observe and assess systems. Their diverse faculty has included Nobel Prize recipients from numerous fields such as chemistry, mathematics, physics and economics.²² In assessing this diverse approach to analyzing complex problems, particle physicist and writer, Mitch Waldrop asserts that the Santa Fe Institute “believes that they are forging the first rigorous alternative to the kind of linear, reductionist thinking that has dominated science since the time of Newton.”²³ Research at the Santa Fe Institute is characterized by two emergent themes: focusing on networks rather than entities to observe aggregated effects and focusing on aberrant results to provide further insight and understanding in non-linear causality.²⁴ These two themes have shaped much of the Santa Fe Institute’s attempt to explain the phenomena of certain complex systems. One of the significant domains of explanation explored between these two themes is the concept of emergence – “instances of some emergent high-order structure that may be explained by the

²¹ Santa Fe Institute, “About | Santa Fe Institute,” accessed November 1, 2017, <https://www.santafe.edu/about>.

²² Santa Fe Institute, “History | Santa Fe Institute,” accessed November 1, 2017, <https://santafe.edu/about/history>.

²³ M. Mitchell Waldrop, *Complexity: The Emerging Science at the Edge of Order and Chaos* (New York: Simon & Schuster Paperbacks, 2008), 13.

²⁴ Dan Dillon, *Review of the Santa Fe Institute: Institutional and Individual Qualities of Expert Interdisciplinary Work*, GoodWork Project Report Series (Cambridge, MA: Harvard Interdisciplinary Studies Project, October 15, 2001), 23.

lower-level dynamics generating the collective behavior or emergent property of the system in question.”²⁵

Emergence – Through the Looking Glass of Complexity

In his book, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, author Steven Johnson highlights the fact that complex systems do not necessarily display emergence until the local-interactions between the multiple agents that comprise the complex system result in some kind of discernible macro-behavior.²⁶ This macro-behavior is dependent on an observer, and as researchers Nils Baas and Claus Emmeche note in their research paper “On Emergence and Explanation” for the Santa Fe Institute, the observers must be considered part of the system and the potential for new observers may emerge from the system as it adapts.²⁷ Emergence, or the explanation of observed complex system behavior, is far from precise given the open nature of the system and its relative nature to the time of observation. However, the value of emergence is that it bridges the theoretical – complex systems, with the concrete – analytics. One of the particular instances of emergence explored by the Santa Fe Institute was the concept of swarms – “a collection of independent agents interacting via discrete events” and its derivative, swarm intelligence – “any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies.”²⁸

²⁵ Nils A. Baas and Claus Emmeche, *On Emergence and Explanation*, SFI Working Paper (Santa Fe, NM: Santa Fe Institute, 1997), accessed November 1, 2017, <https://sfi-edu.s3.amazonaws.com/sfi-edu/production/uploads/sfi-com/dev/uploads/filer/0e/2b/0e2bd954-67ca-415a-b0e6-ef3421ef2bcf/97-02-008.pdf>.

²⁶ Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software*, 19.

²⁷ Baas and Emmeche, *On Emergence and Explanation*.

²⁸ Nelson Minar et al., “The Swarm Simulation System: A Toolkit for Building Multi-Agent Simulations,” 3, accessed November 1, 2017, <http://cobweb.cs.uga.edu/~maria/pads/papers/swarm-MinarEtAl196.pdf>; Eric Bonabeau, Marco Dorigo, and Guy Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems*, vol. Santa Fe Institute Studies in the Sciences of Complexity (New York: Oxford University Press, 1999), 7, accessed November 1, 2017, <http://docshare04.docshare.tips/files/20663/206639475.pdf>.

Swarming as a distinct field of emergence within complexity theory provides significant insight into complex adaptive systems where the primary agents in the open system operate with limited knowledge and no centralized command and control to regulate their activity.

Swarming and the Potential of Simplicity

There exists an outward logical tension between simple agents in a swarm demonstrating complex adaptive behavior. This tension serves as the impetus for studying this emergent behavior and appreciating the potential of such systems. For the purpose of this study of swarms and their behavior, sometimes termed swarm logic or swarm intelligence, three categories will be observed. First, the purest form of a swarm, as recognized by Santa Fe Institute researchers Eric Bonabeau, Marco Dorigo, and Guy Theraulaz, is the naturally occurring, biological swarm.²⁹ Well-documented research examples in natural swarming that will be examined are bird flock behavior and ant colony behavior. Second, the derivative of natural swarm research pioneered by the Santa Fe Institute and subsequent academic institutions is swarm modeling through simulations. While the Swarm Multi-Agent System was the Santa Fe Institute's foray into modeling and simulations of swarms in the late 1990s, a newer simulation system called NetLogo will be used to examine the aforementioned swarm examples of bird flocks and ant colonies. NetLogo is widely used by academic and research institutions worldwide and provides a means to visualize aspects of the narrative discussed in natural swarming.³⁰ The last category, military case studies, will examine the swarming behavior of combatants in two case studies. The first case study, the Battle of Majuba Hill, during the First Boer War, demonstrated semi-autonomous behavior of individual and small units of Boers converging on massed British forces.³¹ The

²⁹ Bonabeau, Dorigo, and Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems*.

³⁰ Uri Wilensky, "NetLogo Home Page," accessed November 1, 2017, <http://ccl.northwestern.edu/netlogo/>.

³¹ Ian Castle, *Majuba 1881: The Hill of Destiny* (Oxford: Osprey Publishing Ltd., 2005), 67–83.

second case study will be the Battle of Balata during Operation Defensive Shield, when Israeli forces under Colonel Aviv Kochavi employed swarm tactics to overwhelm the Palestinian guerrilla forces entrenched in a refugee camp.³² These final military case studies will provide insight as to the viability of incorporating swarm logic in an operational approach. In concert, these case studies bound the ideal concepts of swarming found in nature with the pragmatic concepts required of military operations.

Observations of the emergent swarm behavior, or swarm intelligence, will fall into two primary categories based on the characterization of swarm behavior by prior researchers. The first category observed will be how the agents in a swarm communicate with one another through both direct and indirect means. Entomologist P.P. Grasse termed such indirect communication as *stigmergy* – “communication by altering the state of the environment in a way that will affect the behaviors of others for whom the environment is a stimulus.”³³ The second category will be how the swarm employs command and control techniques known as self-organization. The intent will be to observe localized behavior in natural and military swarms to assess their ability to address complex adaptive problem solving.

³² Gal Hirsch, *Defensive Shield: An Israeli Special Forces Commander on the Front Line of Counterterrorism* (Springfield, NJ: Gefen Publishing, 2016), 231.

³³ James F. Kennedy, Russell C. Eberhart, and Yuhui Shi, *Swarm Intelligence* (San Francisco, CA: Morgan Kaufmann Publishers, 2001), 104.

Natural Swarms

Go to the ant, thou sluggard; consider her ways, and be wise:
Which having no guide, overseer, or ruler,
Provideth her meat in the summer, and gathereth her food in the harvest.
—Proverbs 6:6-8, *King James Version of the Bible*

Simple agents in nature such as ants and birds have been battling complex, adaptive environments with non-linear, emergent methods for survival long before human scientists grappled with understanding and applying complex problem-solving methods. The following case studies in bird flock behavior and ant colony behavior will examine the emergent swarm behavior facilitated by the animals' limited and localized communication methods as well as self-organization capabilities. The study of these complex systems within the context of these two facets is not to reduce the observed indicators, but to appreciate the concept that "complexity in a system does not require complicated components or numerous complicated rules of interaction."³⁴ Rather, the simplicity of localized interaction with no centralized decision-making hierarchy enables complex adaptive group behavior. The authors of the book, *Self-Organization in Biological Systems*, many of whom were associated with the original study of swarming at the Santa Fe Institute, postulate that very little complexity must be built into the components of a self-organizing system to demonstrate the resultant complex adaptive behavior.³⁵ Bird flocking behavior will demonstrate the emergence of structures through self-organization, while Ant colony behavior will expand upon this self-organization to address complex adaptive learning. The intent is to understand how natural swarm logic may be leveraged in military operations and planning to address future complex challenges such as increased dispersion and degraded

³⁴ Scott Camazine et al., *Self Organization in Biological Systems*, Princeton Studies in Complexity (Princeton, NJ: Princeton University Press, 2001), 11.

³⁵ *Ibid.*, 38.

command and control communicated in the emerging Army Operating Concept of Multi-Domain Battle.

Bird Flocks – Self-Organization Artistry

Birds in aerial flight demonstrate incredible feats of coordinated group movement often termed *flocking*. The emergent behavior of such aerial grouping has confounded researchers searching to explain how birds execute this coordinated flight. While researchers have hypothesized various behavior relationships to explain such movement, the ability to test these hypotheses has only made inroads in the past 20 years in conjunction with advances in technology to accurately observe bird behavior such as GPS tracking and stereovision cameras as well as advances in complexity theory and systems modeling. Before analyzing such emergent group behavior, it is critical to refine the discussion given a degree of etymological frustration with the term flocking as researchers Iztok Bajec and Frank Heppner highlight in their research paper “Organized Flight in Birds.”³⁶ To reduce ambiguity, Heppner’s taxonomy of bird flocks into “flight aggregations” and “flight flocks” provides a clear distinction between unorganized and organized groups, respectively, of flying birds.³⁷ Heppner expands upon his classification of organized groups or “flight flocks,” with a dichotomy of “line formations” and “cluster formations” to delineate between emergent flight formations.³⁸ These emergent formations will be examined with respect to communication between birds to facilitate coordinated movement as well as decision making as a function of command and control.

³⁶ Iztok L. Bajec and Frank H. Heppner, “Organized Flight in Birds,” *Animal Behaviour* 78, no. 4 (October 1, 2009): 778, accessed December 29, 2017, <http://www.sciencedirect.com/science/article/pii/S0003347209002966>.

³⁷ Frank H. Heppner, “Avian Flight Formations,” *Bird-Banding* 45, no. 2 (1974): 160, accessed December 30, 2017, <http://www.jstor.org/stable/4512025>.

³⁸ *Ibid.*, 160–164.

Heppner describes various geometric versions or combinations of line flight formations, however for the purposes of exploring the aspects that govern the self-organization of these flight formations, the formation shape will be reduced to the term *line* insofar as a clearly defined order of flight with a resultant line or queue.³⁹ Critical to line formations and their association with swarming, there exists no clear underlying social hierarchy governing the adaptive command and control of the flight formations aside from the positional authority of whichever bird has assumed the leading position for navigational purposes.⁴⁰ Research with respect to communication in formation flight flocks has generally centered upon visual and tactile cues. Heppner expands upon possible visual cues birds may use in line formation to explain their resultant spacing and formation shape. Continuous changes to trail distance, angle, and height seem to be influenced by visual cues to maintain an optimally reactive position for safe flight⁴¹. Tactile cues generally emanate from aerodynamic hypotheses to facilitate efficiency in flight.⁴² Trailing birds are able to sense various aerodynamic factors from lead birds and adjust their own flight to maximize their own aerodynamic efficiency.⁴³ Researchers at Lund University in Sweden determined that formation size directly correlated to flock speed as a function of collective aerodynamic improvement.⁴⁴ Regardless of the specific visual and tactile cues utilized to facilitate line

³⁹ Heppner, “Avian Flight Formations,” 160.

⁴⁰ Bernhard Voelkl et al., “Matching Times of Leading and Following Suggest Cooperation through Direct Reciprocity during V-Formation Flight in Ibis,” *Proceedings of the National Academy of Sciences* 112, no. 7 (February 17, 2015): 2117, accessed December 30, 2017, <http://www.pnas.org/content/112/7/2115>.

⁴¹ Bajec and Heppner, “Organized Flight in Birds,” 782.

⁴² *Ibid.*, 779-780.

⁴³ Steven J. Portugal et al., “Upwash Exploitation and Downwash Avoidance by Flap Phasing in Ibis Formation Flight,” *Nature* 505, no. 7483 (January 16, 2014): 399, accessed December 30, 2017, <https://search.proquest.com/docview/1493992077/abstract/5980B7C16B8649B6PQ/1>.

⁴⁴ Lund University, “Birds Fly Faster in Large Flocks,” *ScienceDaily*, August 16, 2016, accessed December 28, 2017, <https://www.sciencedaily.com/releases/2016/08/160816085035.htm>.

formation flight, the critical takeaway is that the formation is not centrally choreographed or organized. Sensory feedback loops remain at the individual level between birds in the line formation. The emergent efficiencies of line formations enable possible benefits to migration distance and speed with minimal chance of collisions.

The elaborate and highly dynamic movement of three-dimensional cluster formations of small bird flight flocks proves to be a much more complex and adaptive formation than the line formation. Heppner highlights the difficulties researchers have had to explain the collective management of such flight given the extreme reaction time of the entire cluster formation to make the collective formation appear to move in relative unison.⁴⁵ Given collective reaction times in the milliseconds, a hierarchical model based on reacting in series to a leading bird initiating the movement is negated, as it would result in exponential reaction times as the movement propagates throughout the cluster formation in a wavelike manner.⁴⁶ Research into Starling bird cluster formations demonstrated a constantly adapting formation with no leading edges as instantaneous turns resulted in leading edges constantly changing with positions within the cluster also continuously shifting.⁴⁷ This behavior was also noted amongst other bird types in cluster formations.⁴⁸ Such rapid and dynamic conditions negate a centralized command and control model for clustered formations. Similarly, communication methods to facilitate dynamic cluster formation seems mostly relegated to visual cues based on three-dimensional spatial relationships.⁴⁹ Such relative spatial synthesis is constrained by the birds' cognitive abilities to

⁴⁵ Bajec and Heppner, "Organized Flight in Birds," 783.

⁴⁶ Ibid.

⁴⁷ Michele Ballerini et al., "Empirical Investigation of Starling Flocks: A Benchmark Study in Collective Animal Behaviour," *Animal Behaviour* 76, no. 1 (July 1, 2008): 212, accessed December 30, 2017, <http://www.sciencedirect.com/science/article/pii/S0003347208001176>.

⁴⁸ Harold Pomeroy and Frank Heppner, "Structure of Turning in Airborne Rock Dove (*Columba Livia*) Flocks," *The Auk* 109, no. 2 (1992): 264, accessed December 31, 2017, <http://www.jstor.org/stable/4088194>.

⁴⁹ Bajec and Heppner, "Organized Flight in Birds," 784.

track multiple neighbors in flight. Pigeons, for example, can discriminate between approximately six objects at a time.⁵⁰ Critically, cluster formations demonstrate highly complex swarm logic with no significant influence of social hierarchies influencing flight characteristics. Rather, individual relationships affect the flight flock's emergent and adaptive shape as a function of self-organization.

Observing the swarm intelligence present in both line and cluster bird flock formations gives credence to the potential for highly dynamic self-organization. The speed of the localized feedback loops between individual birds in flight enables fluid collective adaptation. However, such dynamic behavior across three-dimensional space provides significant challenges to researchers to definitively assess collective problem solving aligned against a known purpose. To this end, researchers look towards more localized natural systems such as ant colonies where the scale and purpose of collective adaptation can be more easily observed for the purpose of refined understanding.

Ants Colonies – Operationalizing Self-Organization

The study of ant colony behavior in the field of swarming and swarm intelligence traces its roots back to E.O. Wilson's systematic study of their social behavior in 1953.⁵¹ Wilson's observations of the localized interactions of ants that contributed towards the larger colony's survival, adaptation, and expansion without a centralized command and control element made them an ideal case study for the groundbreaking swarm study conducted at the Santa Fe Institute by Bonabeau, Dorigo, and Theraulaz; so much so, that the cover artwork for the study is that of ants superimposed on a systems design.⁵² In analyzing ant swarm behavior, one finds that two

⁵⁰ Peter Friederici, "How a Flock of Birds Can Fly and Move Together," *Audubon*, 2009, accessed December 29, 2017, <http://www.audubon.org/magazine/march-april-2009/how-flock-birds-can-fly-and-move-together>.

⁵¹ Kennedy, Eberhart, and Shi, *Swarm Intelligence*, 99.

⁵² Bonabeau, Dorigo, and Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems*, cover page

factors influence their localized behavior and as such contribute to the larger behavior of their colonies – their communication and regulation methods operating at the local level that dictate roles in the colony.⁵³ These factors contribute to their emergent behavior, their demonstrated swarm intelligence.

In Bert Hölldobler and E.O. Wilson’s comprehensive treatise on ants, *The Ants*, various forms of known ant communication are explored in detail. Of the three categories: tactile, sound, and chemical, chemical proves to be the baseline form of communication through the medium of pheromones.⁵⁴ Through study and observation, researchers have found differences in pheromones contribute towards as many as twelve different responses ranging from alarm and simple attraction to caste determination.⁵⁵ Tactile communication such as antennation, or “antennal language,” seems to convey a greater sense of communication through nuances, but research has proven this an overestimation. Tactile communication only conveys a limited amount of information and mainly serves as a process to enable the chemical transmission process.⁵⁶ Certain ant species’ use of pheromones is sometimes supplemented by sounds produced by drumming or stridulation. Sometimes these are detected audibly and other times they are detected through vibration. However, current research reveals no evidence of modulation or “talking” through this medium that reinforces the concept that they are simple, unitary signals.⁵⁷ All the forms of communication illustrate that ants’ localized communication has varying degrees of robust meaning. To say that ant communication is simple, would be an oversimplification and

⁵³ Bert Hölldobler and Edward O. Wilson, *The Ants* (Cambridge, MA: Belknap Press of Harvard University Press, 1990), 355.

⁵⁴ *Ibid.*, 227.

⁵⁵ *Ibid.*

⁵⁶ *Ibid.*, 258.

⁵⁷ *Ibid.*, 257.

inaccurate. The synergism of various communication methods has yet to be studied in depth.⁵⁸ However, their communication is assumed void of complex detail to provide detailed information or context such as seen in other species with higher cognitive abilities and the resultant ability for individual learning. Holldobler and Wilson characterize this as *signal economy*, whereby the “small brain and short life span of ant workers limit the amount of information these insects can process and store.”⁵⁹ This localization and relatively simple cognition is crucial to reinforce the framework of swarm logic as a function of participating agents’ behavior driven by communicative capabilities to address complex conditions.

Despite this simple cognition and the constraints of limited communication, ant colonies are still able to adapt their collective behavior to changes in the environment without any centralized command and control. Paramount to understanding this concept of self-organization is to first acknowledge the social framework or roles for ants within the colony called castes. Wilson and Holldobler refer to this as the strategic design of the ant colony.⁶⁰ This design explores the dynamic roles within the context of these castes that dictate ants’ behavior. The roles are influenced by internal colony interactions as well as external interactions with the environment. As such, the choice of *strategic* is befitting given the constant evolution driven by feedback loops required of an effective strategy. Ant castes demonstrate such caste adaptation as polymorphism, where physical size and shape changes occur, as well as temporal castes, where roles adjust according to age.⁶¹ This framework for roles within the colony is shaped by competing internal colony demands as well as external environmental effects that influence a

⁵⁸ Hölldobler and Wilson, *The Ants*, 254.

⁵⁹ *Ibid.*, 252.

⁶⁰ *Ibid.*, 298.

⁶¹ *Ibid.*, 310–312.

colony's potential for work and energy, something that Wilson and Holldobler refer to as *ergonomic analysis*.⁶² The resultant emergent effect on the entire colony is self-organization.

This collective adaptation to facilitate self-organization is possible due to what Wilson and Holldobler term *dense heterarchy* in a journal article titled "Dense heterarchies and mass communication as the basis of organization in ant colonies."⁶³ The term *dense* refers to the frequency of individual interaction between ants and the term *heterarchy* refers to an organizational structure where the properties of the higher levels affect the lower levels to some degree, but induced activity by lower levels feeds back to influence the higher levels.⁶⁴ Critically, heterarchies do not demonstrate a central leadership role common to a hierarchy model. In heterarchies, the interaction, or feedback loops, driven by both individual ants as well as between castes to influence the larger colony's emergent behavior demonstrate a deference to both bottom-up feedback as well as lateral feedback as opposed to a top-down hierarchy. Additionally, such feedback is indicative of positive feedback loops that facilitate systemic change through reinforced effects.⁶⁵ Such organizational structure to address complexity shares similarities with Bar-Yam's hybrid hierarchy model that capitalizes on such lateral connections with a typical hierarchy model.⁶⁶ However, unlike Bar-Yam's hybrid model, Wilson and Holldobler capture the fact that ants are not limited by a single leader at the top of their structure. Rather, localized feedback loops facilitate group adaptation and prioritized work.

⁶² Hölldobler and Wilson, *The Ants*, 298.

⁶³ Edward O. Wilson and Bert Hölldobler, "Dense Heterarchies and Mass Communication as the Basis of Organization in Ant Colonies," *Trends in Ecology and Evolution* 3, no. 3 (March 1988): 65–68.

⁶⁴ *Ibid.*, 65.

⁶⁵ Complexity Labs, "Ecological Feedback Loops," *Complexity Labs*, January 7, 2016, accessed December 2, 2017, <http://complexitylabs.io/ecological-feedback-loops/>.

⁶⁶ Yaneer Bar-Yam, *Making Things Work: Solving Complex Problems in a Complex World* (Cambridge, MA: NECSI, Knowledge Press, 2004), 66.

Assessment of Natural Swarm Logic

The natural case studies of bird flocking and ant colonies provide insight to the role of swarm logic in governing their collective complex adaptive behavior. Contextually driven by evolutionary benefits such as the ants efficiently exploiting food sources or in the case of the birds, efficiently migrating or warding off predators with large, dense formations, natural swarm logic enables the collective to thrive in a complex world. Studies such as “From Compromise to Leadership in Pigeon Homing” reinforce the concept that collective intelligence or swarm intelligence in nature provides advantages over individual intelligence in solving complex problems.⁶⁷ Critically, the explored elements in nature of command and control for self-organization and the means of localized communication to inform individual action amongst these animals are externally imposed by nature and evolution. These simple agents do not forgo advanced cognitive recognition to operate in this manner; it is merely the best these animals can collectively muster to ensure survival and propagation. Humans, with their much greater potential for cognition, can choose to leverage both social enablers such as swarm intelligence and individual capabilities to facilitate survival or degrees of independence. However, in the context of the challenges prescribed in future military conflict, the US military assumes adversaries will target the US military’s current critical requirements and vulnerabilities such as its reliance on networks to facilitate hierarchal command and control structures. The hyper-connected, lethal combat conditions the US military currently employs through a hierarchical model will be sufficiently denied; individual units’ operational understanding will mirror that of the individual ant or individual starling - prone to piecemeal destruction by a hostile environment. Only through swarm logic will such individual agents be able to coalesce and overcome such complexity.

⁶⁷ Dora Biro et al., “From Compromise to Leadership in Pigeon Homing,” *Current Biology* 16, no. 21 (November 7, 2006): 2125, accessed December 30, 2017, <http://www.sciencedirect.com/science/article/pii/S0960982206021555>.

Swarm Logic Simulations

If the previous natural case studies on bird flocks and ant colonies are interpreted as a narrative description for swarming behavior, simulations provide a means to manipulate and visualize the emergent behavior in a manner conducive to analytical study. Such a combination of narrative and visualization provides increased understanding of the emergent phenomena attributed to swarm logic. While many commercial and publically available simulation systems have been created to model natural swarm behavior, *NetLogo* was chosen given its wide adoption by researchers and universities programs to teach complex systems modeling.⁶⁸ NetLogo is a programmable modeling system developed by Uri Wilensky for simulating complex systems such as natural and social phenomena based upon individual agent interactions.⁶⁹ The independent behavior between agents executed in parallel give rise to emergent behavior of the larger system displayed through NetLogo's graphical interface.⁷⁰ In order to better understand the natural case studies in swarm logic for bird flocks and ant colonies, the following aligned simulations will provide additional insight into adaptive problem solving through the emergent behavior of swarms.

Bird Flocking Simulation

The “Flocking” simulation model, provided by NetLogo, attempts to model bird flocking void of any form of leadership.⁷¹ The simulation traces its individual bird behavior algorithm back to bird simulation work by Craig Reynolds.⁷² Reynold's simulation, titled “the boid flock

⁶⁸ Maciej Komosinski, *Artificial Life Models in Software* (London: Springer, 2014), 192.

⁶⁹ “NetLogo 6.0.2 User Manual,” accessed November 1, 2017, <http://ccl.northwestern.edu/netlogo/docs/whatis.html>.

⁷⁰ Ibid.

⁷¹ Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

⁷² Wilensky, *NetLogo Flocking Model*.

model” demonstrated a simplified version of flocking behavior as seen in birds and schools of fish with individual agents he termed *boids* as a word construct derived from the bird-like objects, or bird-oids.⁷³ In NetLogo’s Flocking simulation, individual bird behavior defined by three rules enables individual birds to converge into flight flocks as they travel through the open simulation environment. By leveraging swarm logic, individual birds in the simulation flight flock are able to mimic natural bird flight flocking phenomena and self-organize into adaptive flight formations.

Bird flocks – constrained behavior and environmental context

The three rules governing the individual birds behavior in the simulation are as follows: first, the alignment rule dictates that a bird will attempt to turn in the direction similar to that traveled by nearby birds; second, the separation rule dictates that a bird will avoid another bird that gets too close to avoid collisions given this two-dimensional simulation environment; third, the cohesion rule dictates that a bird will move towards other nearby birds.⁷⁴ The simulation environment is not bounded by borders. As such, birds travel paths wrap around the world – a bird that exits the environment out of the bottom left will reappear from the top right as if the environment was boundless such as a sphere. Variables to determine the initial start criteria employed when the setup button is chosen such as population of total birds, individual bird’s vision to detect other birds, separation criteria to avoid collisions, and various turning criteria can be seen in the left portion of the simulation as seen in Figure 2. The birds are randomly distributed across the environment with randomized initial headings. Once the go button is selected, the individual birds operate according to the predefined rules and these constraints. Elapsed time is measured in ticks as seen in the top of Figure 2 under the normal speed heading.

⁷³ Craig W. Reynolds, “Flocks, Herds, and Schools: A Distributed Behavioral Model,” in *Computer Graphics*, ed. Maureen C. Stone, 1987, 25–34, accessed December 31, 2017, <http://www.red3d.com/cwr/papers/1987/boids.html>.

⁷⁴ Wilensky, *NetLogo Flocking Model*.

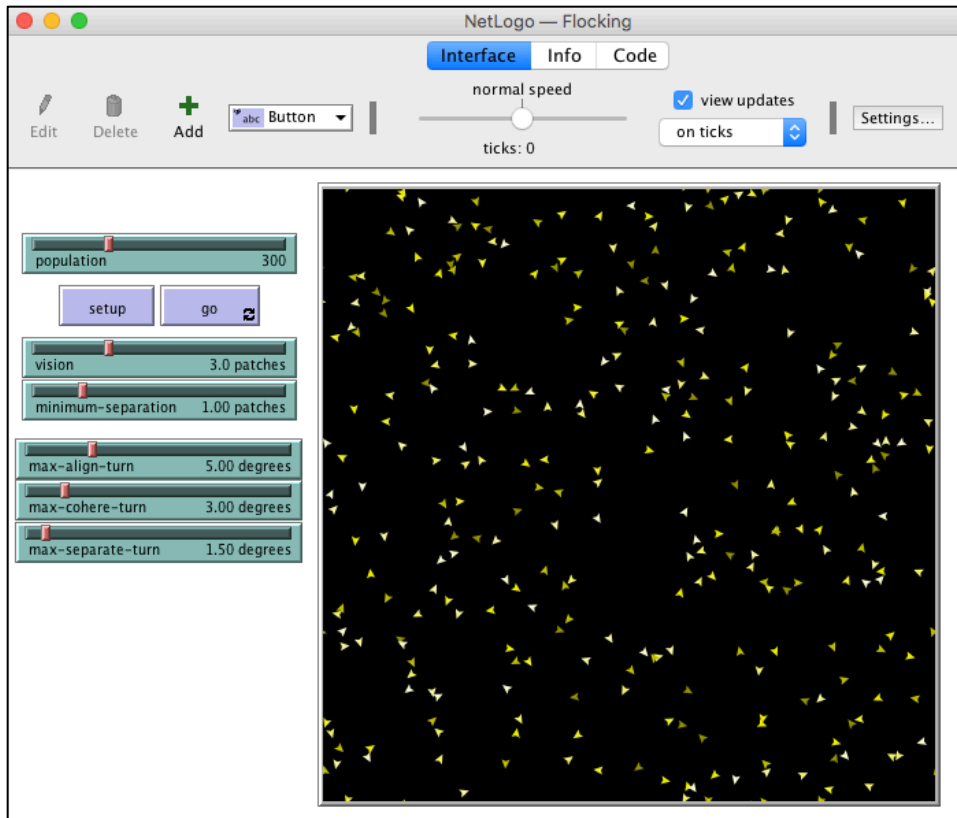


Figure 2. Birds, initial conditions for the flocking simulation. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

Emergent behavior

In order to detect the collective flight flocking emergent behavior of the individual birds, snapshots of the simulation are taken at different timed intervals. First, they are taken at approximately 50 tick intervals, followed by approximately 100 tick intervals, and finally by 1000 tick intervals. Figure 3 demonstrates the contrasting levels of convergence between birds at time reference 57 ticks on the left and time reference 104 ticks on the right. Noticeably, the birds have begun converging into distinct flocks when compared to their randomized distribution in Figure 2. Each flight flock begins to demonstrate a distinct direction. However, there is no primacy of direction between all flight flocks.

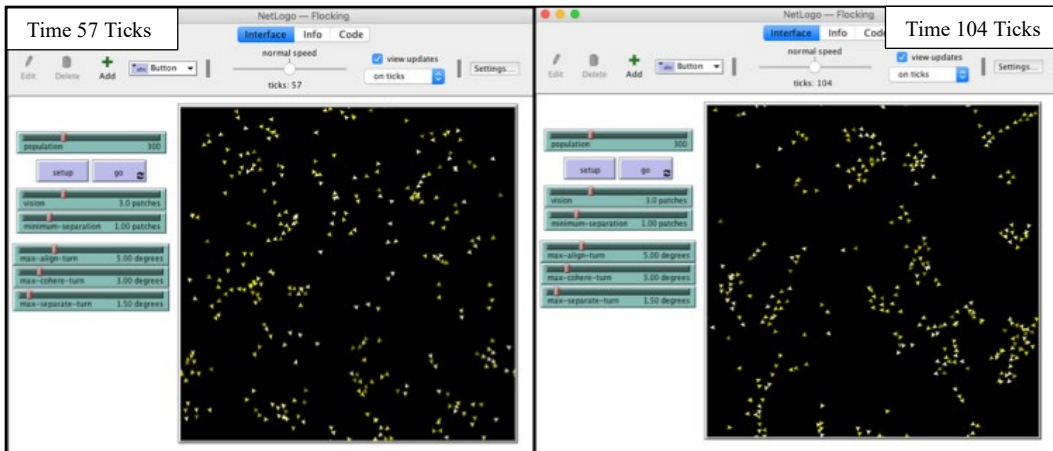


Figure 3. Birds, initial emergent flocking at time reference 57 and 104 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

By the time of the snapshots in Figure 4 and their respective 202 and 302 tick times, the individual bird flight rules have resulted in larger flight flock size as well as an emergent flight direction of generally top right to bottom left for all flocks as annotated by the superimposed arrow.

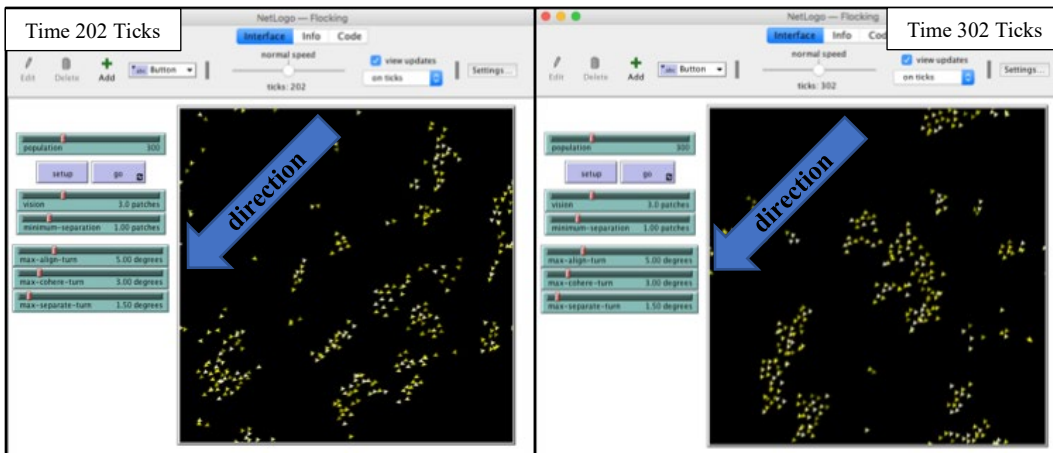


Figure 4. Birds, emergent flocking at time reference 202 and 302 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

By the time of snapshots in Figure 5 and their respective 1000 and 2001 tick times, the longer time period for observation has reduced isolated bird activity. The emergent grouping demonstrates minimal further changes to flight flock density in the second snapshot.

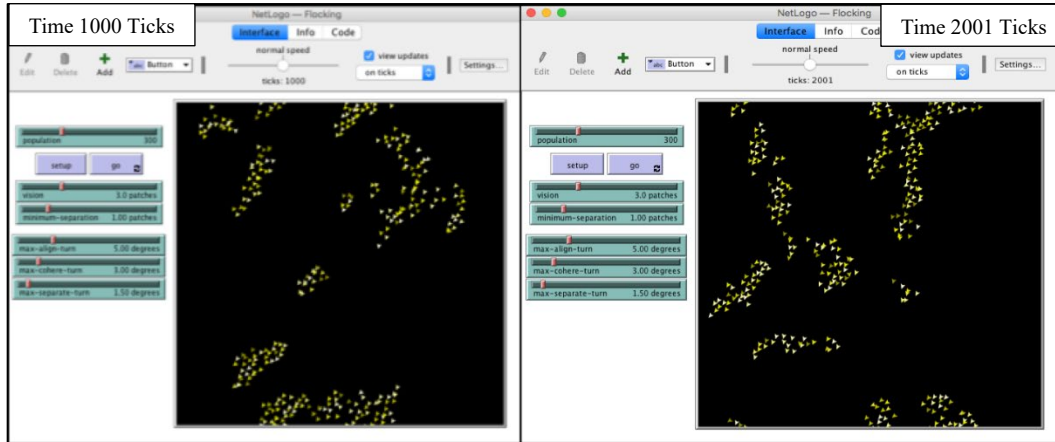


Figure 5. Birds, emergent flocking at time reference 1000 and 2001 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

Assessment of bird flock behavior

The emergent flight flocking and the fluid nature of the flocking shapes are best appreciated when the simulation is in motion. Nevertheless, the evolution of these still frame snapshots from the simulation capture the dynamic collective behavior of the flight flock despite only single bird behavior rules governing the system. There exists a stark contrast to the starting conditions of individual birds seen in Figure 2 with the final time snapshot at 2001 ticks shown enlarged in Figure 6 for better visual acuity. The swarm logic that enables such emergent grouping is limited to individual bird visual sensory feedback as a communication medium. The primacy of this localized visual feedback is derivative from the preceding natural case study. In the absence of centralized command and control, the flight flocks are able to coalesce and mimic the self-organization found in natural bird flight flocking. The complex adaptive flight patterns constantly shift and adapt throughout the simulation. The simplicity of the two-dimensional

simulation does little justice for the hyper-adaptive three-dimensional flight flocks of starlings seen in nature, but the underlying possibility of complex adaptation through self-organization remains despite the simple rules governing individual behavior.

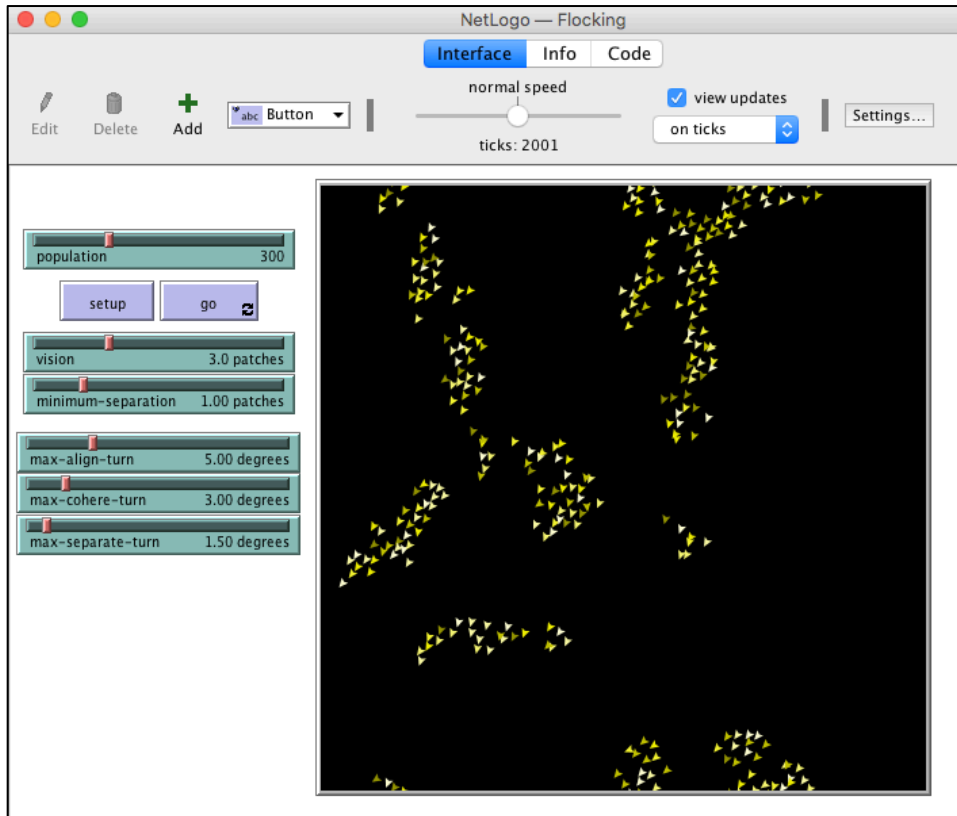


Figure 6. Birds, final reference at 2001 ticks, large view. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Flocking Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1998), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Flocking>.

Ant Colony Simulation

The “Ants” simulation model, provided by NetLogo, attempts to model limited food gathering techniques by worker ants emanating from a singular nest, or colony.⁷⁵ Through individual behavior defined by simple cognitive abilities and constrained communication methods to support the objective of food collection, the ants are able to explore their environment and

⁷⁵ Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

exploit three food sources of varying distance and direction from the colony. This ill-defined task of food gathering, void of specific locations details, is accomplished with no cognitive ability to remember past success as well as no robust communication ability to broadcast discovered details of food sources throughout the population of workers in the colony. Having such advantage would enable individual efficiencies through learning and detailed directives, and yet the collective behavior of the colony is able to achieve the object of complete food source exploitation without the capacity to individually learn or have action coordinated by a centralized command and control structure. By leveraging swarm logic, the ant colony is able to not only self-organize as seen in the bird flocking simulation, but also purposefully adapt to its environment. As such, the ant colony is able to optimize food collection through emergent phenomena between its individual ant interactions.

Ant colony – constrained behavior and environmental context

Before observing the emergent behavior of the ant colony, one must acknowledge the environment's defining conditions and the modeling system's definition of ant behavior as they constrain the natural system meant to modeled through scale and scope. The simulation window depicted in Figure 7 contains the environment window on the right, elapsed time measured in ticks under the normal speed heading, slider bars on the left to manipulate the starting number of ants as well as the behavior of their deployed scent, and lastly a food source tracking graph. The food source tracker on the left side of the interface illustrates trend analysis in food quantity relative to time. This can be used as a general measure of the effectiveness of emergent behavior in food collection.

What is important to note for the environmental frame, is that the boundary forms a backstop for the ants wandering and will cause them to turn around. The nest from which the ants all emanate is a fixed position depicted in purple and the three food sources, colored varying shades of blue, are located at different distances and locations on the map to make each distinct with respect to its relationship to the nest. Once the go button is selected, the ants originate from

the central nest and behave under two distinct categories, searching for food - as depicted in red, and returning food to the nest – as depicted in orange. If they are searching for food, they seek out any scent trail from an ant returning with food. The behavior of this scent dropped by returning ants is controlled by two slider bars seen in the left side of Figure 7 that control the diffusion rate – how far the scent extends from the point of placement, as well as the evaporation rate – how quickly the scent disappears. If no scent trail is detected, they assume a randomized search pattern until they encounter a food source or a scent trail to follow. Once they find a food source and pick up a unit of food, they turn orange and head directly back to the nest with their food. When they deposit the food, they turn red again and resume their food search behavior previously described.

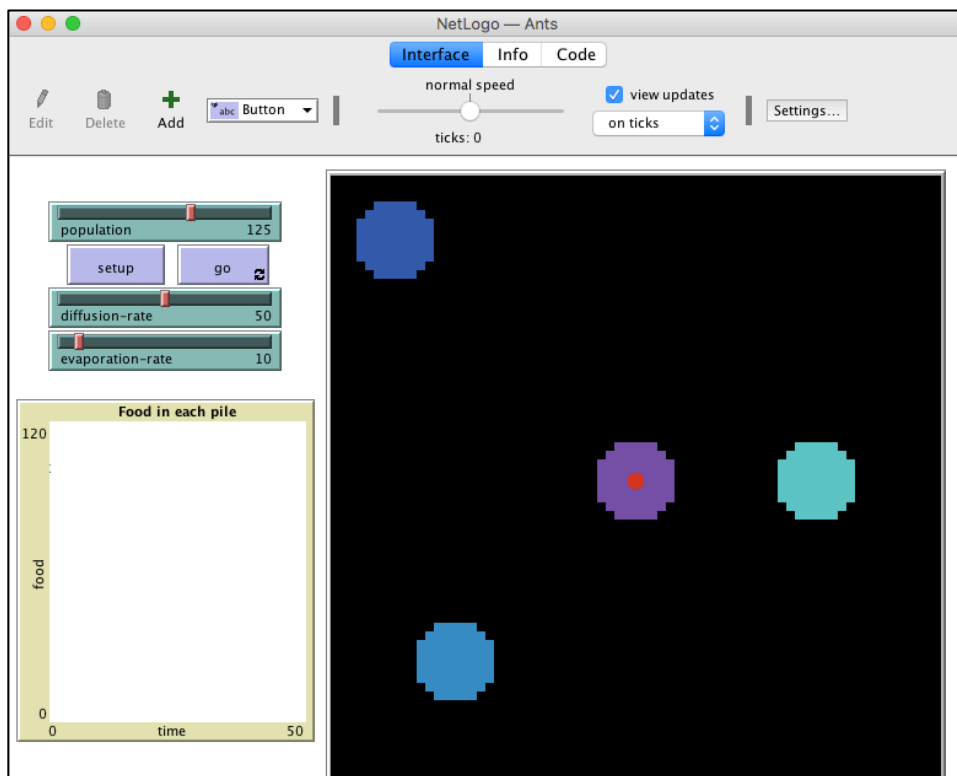


Figure 7. Ants, initial conditions for the ant simulation. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

Emergent behavior

The following sequence of figures depicts the ants' emergent behavior to optimize food collection based on simple, localized movement rules and scent-based communication. Figures often pair subsequent snapshots of the emergent behavior to help appreciate the collective and emergent adaptation. Once the simulation is activated, the randomized search pattern is begun by all ants given the absence of a detected food source as seen in left image of Figure 8 at time reference 25 ticks. Of note, the very first ant has encountered the nearest food source to the east of the nest.

As time progresses, the eastern food source is increasingly exploited as more ants encounter the scent trail between it and the nest as seen by the glowing scent trail in the right image of Figure 8 at time reference 58 ticks. As such, more and more ants target the closest food source. The second closest food source to the southwest of the nest begins to be exploited but the density of returning ants does not allow a sufficient scent trail to last. Therefore, the scent trail and the density of ants exploiting the food source are sub-optimal.

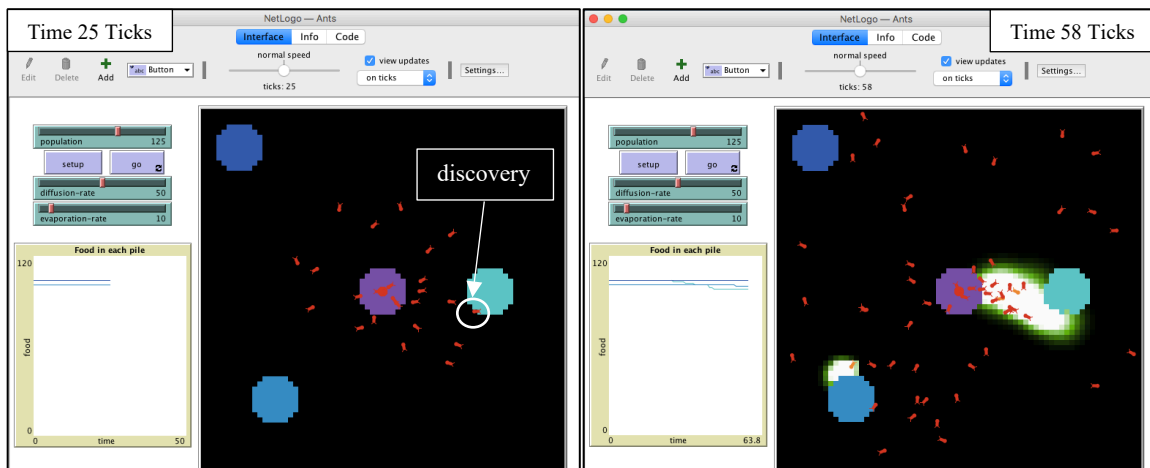


Figure 8. Ants, initial foraging optimization at time reference 25 and 58 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

By the next snapshot in time as illustrated by Figure 9, one notices the closest food source to the east is almost extinguished. The figure remains a large, single image given the complexity of concurrent food exploitation between all three food sources. The scent trail and search optimization illustrates the preponderance of ants exploiting the eastern source with its greatly diminished food count. Interestingly, all three food sources have been sufficiently discovered to warrant scent trails with varying degrees of persistence. However, the second closest food source to the southwest still commands a greater number of ants than the furthest food source to the northwest. Also of note, given the closed environment, very few ants remain in a randomized search pattern void of scent influence.

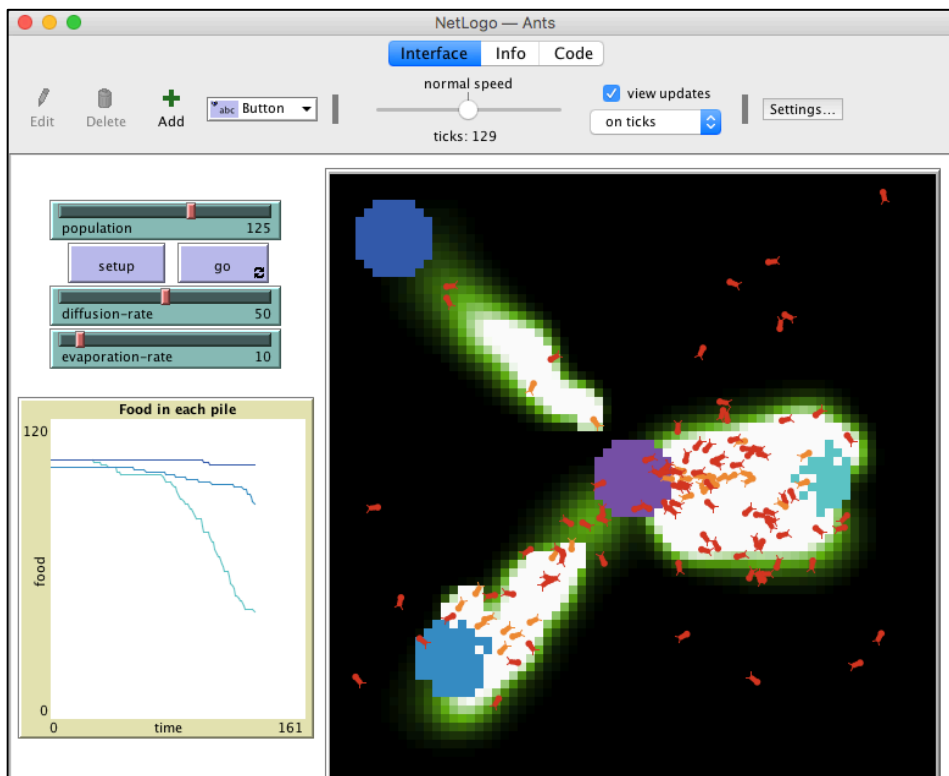


Figure 9. Ants, mature foraging optimization at time reference 129 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

In the left image of Figure 10 at time reference 243 ticks, one finds that the eastern food source is depleted and the scent trail has fully evaporated given the lack of reinforcing scent. The scent trail to the southwest has increased given less ants focused on the east. The remaining mass of ants to the east are about to naturally redistribute themselves in search of additional food by way of randomized searching or scent as seen in the right image in Figure 10 at time reference 422 ticks. This emergent collective reframing is still driven by localized communication with no greater awareness nor centralized control to drive efficiency.

One can note in the food graphs on the left side of the ant environments in Figure 10, the depletion of the second furthest food pile occurred at a generalized rate commensurate with its further location than the first food source depleted. The furthest location remains relatively undisturbed given its distance, the small number of ants able to exploit it, and the natural evaporation of the scent trail before it can be reinforced sufficiently by other ants. Given the depletion of the southwest food source in the right image of Figure 10 at time reference 422 ticks, the weighted density of mass to that side is about to be redistributed as seen in Figure 11.

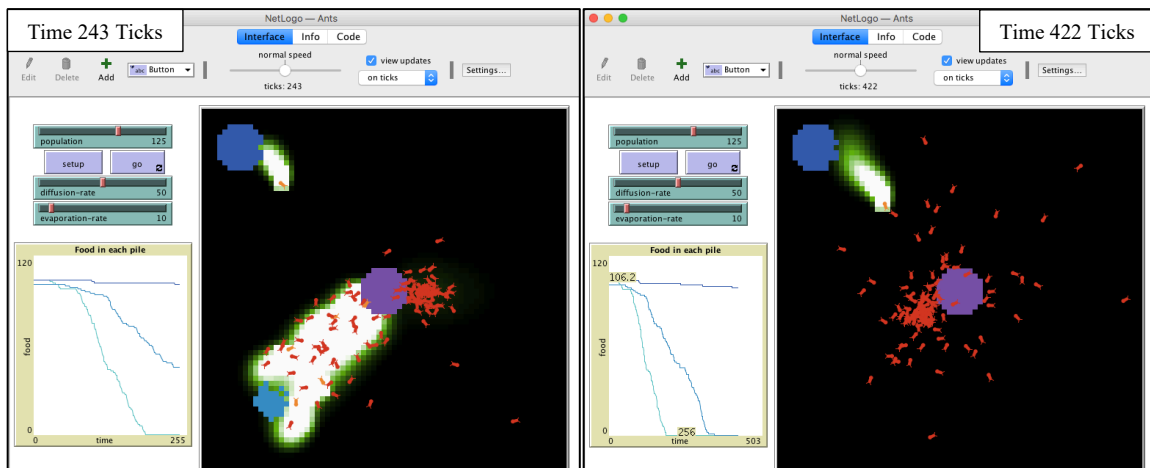


Figure 10. Ants, reframing foraging optimization at time reference 243 and 422 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

In the left image of Figure 11 at time reference 1023 ticks, a stronger scent trail has begun to emerge between the final food source in the northwest and the nest. However, many ants have randomly dispersed themselves across the environment given the lower probability of encountering a scent necessitating a randomized search pattern. Such emergent dispersion contrasts with the dense optimization seen in Figure 9.

Nevertheless, the ants are able to optimize the exploitation of the farthest food source given enough time as seen in the right image of Figure 11 at time reference 1247 ticks. The effects of time to enable this optimization can be seen in the left food chart with the exponential food exploitation once sufficient scent and ant density occurs. Fewer ants remain in randomized search patterns as most have been driven by their simple behavior rules to exploit the last food source.

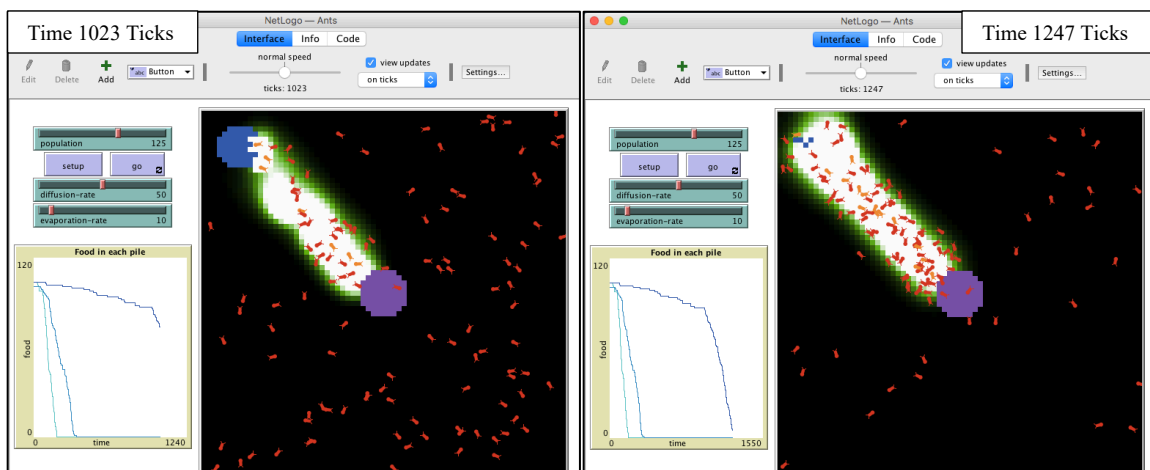


Figure 11. Ants, challenging spatial conditions at time reference 1023 and 1247 ticks. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

Once all food sources have been depleted as seen in Figure 12, the ants return to their randomized search behavior given the lack of possible food sources to facilitate scent optimization techniques.

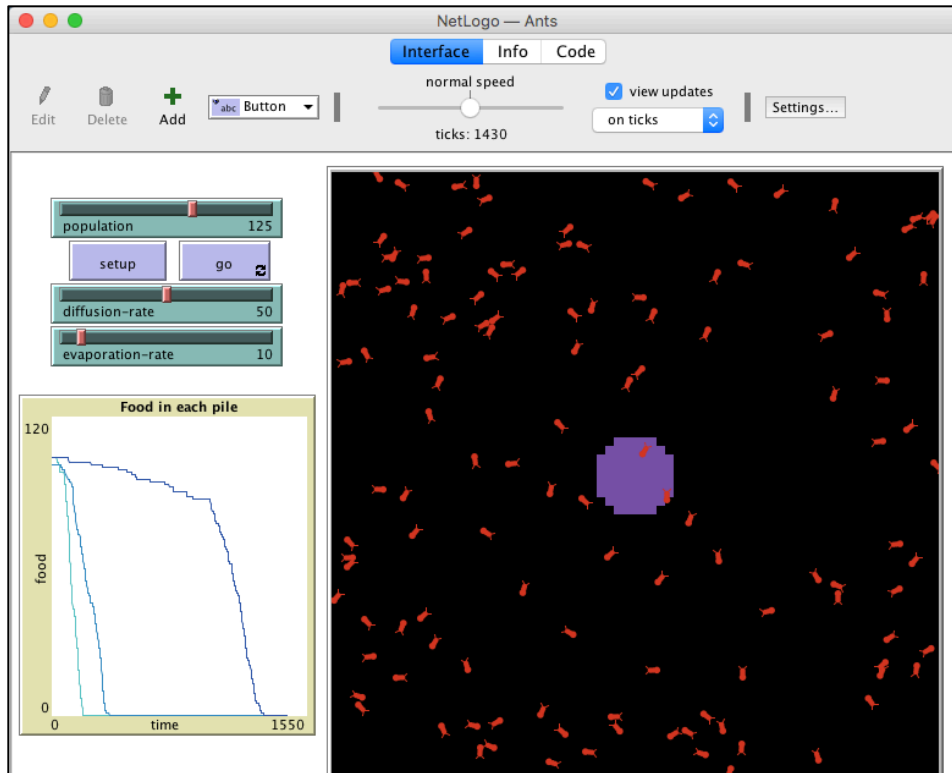


Figure 12. Ants, returning to randomized foraging. Image source is a screen shot derived from the following simulation software: Uri Wilensky, *NetLogo Ants Model* (Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University, 1997), accessed November 18, 2017, <http://ccl.northwestern.edu/netlogo/models/Ants>.

Assessment of ant swarm behavior

While the exploitation of these food sources seems like a trivial objective for simple agents like ants in a closed environment, it is important to highlight the emergent optimization when observing the behavior of the larger collective colony. Without centralized command and control to exploit detected food sources, the ants were able to optimize their exploitation based on proximity and time. Differences in context will demonstrate varying rates of efficiency influenced by the communication medium – diffusion and evaporation of scent in this scenario. However, with limited direction and simple cognitive abilities, the colony was able to maximize emergent behavior through localized communication to gather food. One should not focus on such contextual details as specific density rates or exploitation rates to optimize the model as this insight will be constrained to the model. Rather, observing the general phenomena provides

valuable insight into the power of swarm logic to achieve an objective or directive in a complex environment without centralized command and control.

Swarming in Military Operations

Natural case studies in swarming and their derivative simulations provide insight as to the value of the underlying swarm logic from which one may develop an interpretive lens to assess historical military action. While the Battles of Majuba Hill during the First Boer War and Balata during the Second Intifada demonstrate the typical convergence that swarming is characterized by, it is the underpinning logic of self-organization enabled by localized communication that must be assessed. Doing so provides insight for employing military operational approaches on the edge of chaos – “the region of greatest interconnected activity and experimentation, it is where the greatest potential for emergent behavior is found.”⁷⁶

First Boer War – Battle of Majuba Hill

The Battle of Majuba Hill on 27 February 1881, while relatively insignificant in scale compared to European continental warfare of the 19th century, proved strategically significant as the humiliating decisive defeat of British forces in South Africa by Boers – farmers of Dutch ancestry assumed to be inferior in all senses of the word, caused the British government to reframe the growing unrest in South Africa and sue for peace. Initially, British policy in the region had been bellicose and aggressive as it looked to expand its territorial holdings to claim interior lands occupied by the Boer settlers recently discovered in 1867 to be rich in diamonds.⁷⁷ By November 1880, the Boers’ growing discontent boiled over with armed conflict sparking the onset of the First Boer War. Nevertheless, the imposing British governor of the region, Sir Owen

⁷⁶ Everett C. Dolman, *Pure Strategy: Power and Principle in the Space and Information Age* (New York: Routledge, 2005), 111.

⁷⁷ Oliver Ransford, *The Battle of Majuba Hill - the First Boer War* (New York: Thomas Y. Crowell Company, 1968), 9.

Lanyon, summed up the British inability to understand and assess the situation when he reported to London that he doubted any serious trouble would arise from the situation.⁷⁸ Less than a year later, the most dominant global empire would accept terms of peace dictated by these ragtag farmers.

British military forces in the region under the command of Major-General Sir George Pomeroy-Colley mobilized for the Majuba Campaign represented a small, but professional force of varying experience. Numbered at approximately 1,200 troops, Colley's force comprised of 12 infantry companies, 120 sailors to constitute a naval land force, four to six artillery pieces depending on the historical reference, and an ad-hoc cavalry force numbered between 120-150 mounted troops.⁷⁹ Many had experienced combat in the region during the latter stages of the Zulu War in 1879. Colley spent much of his career between India and South Africa with combat experience in China. His rise to prominence in the British military is partially attributable to his exceptional academic performance at the Staff College at Sandhurst.⁸⁰ Critically, Colley never had a command prior to his assumption of forces in the region and as such relied upon positional power enabled by the institutional hierarchy heavily ingrained in the British military culture.⁸¹ Compounded this lack of command experience by the officer in charge of the campaign was the fact that most British staff officers and subordinate commanders in the region had few, if any time working together and establishing integral working relationships to be stressed during times

⁷⁸ Castle, *Majuba 1881: The Hill of Destiny*, 10.

⁷⁹ Ransford, *The Battle of Majuba Hill - the First Boer War*, 39. Also see Castle, *Majuba 1881: The Hill of Destiny*, 14–15.

⁸⁰ Castle, *Majuba 1881: The Hill of Destiny*, 11.

⁸¹ Ransford, *The Battle of Majuba Hill - the First Boer War*, 35.

of battle.⁸² Nevertheless, Colley assessed his British force as more than adequate to address the Boer threat in the region.⁸³

In contrast, the Boer forces seemed the antithesis of the highly organized and professional British forces under Colley's command. While Petrus Jacobus Joubert was elected the overall military commander of the Boer forces as its Commandant-General, the military decision-making process for his militia force was highly collaborative through war councils.⁸⁴ This decentralized approach to warfare manifested itself in the tactical conduct of Boer forces as they saw themselves as "intelligent individuals who were free to move to any part of the battlefield where they would be considered most useful."⁸⁵ The capabilities of the Boer forces can best be synthesized by addressing the cultural complexities that governed this volunteer militia insofar as their decentralized command and control as well as their technical and tactical competencies honed through an unforgiving life in a harsh frontier environment. The rights of the individual reinforced by a steadfast Puritan background defined the Boer settlers' worldview. Their preference to live "out of sight of their neighbors' smoke' in physical and mental isolation" resulted in remote farmsteads free of overarching governance.⁸⁶ This livelihood was supported through the judicious use of long-range weapons for hunting wild game and the mastery of

⁸² Mike Snook, *Into the Jaws of Death, British Military Blunders, 1879-1900* (Annapolis, MD: Naval Institute Press, 2008), 67.

⁸³ Castle, *Majuba 1881: The Hill of Destiny*, 17.

⁸⁴ Ibid.

⁸⁵ Ransford, *The Battle of Majuba Hill - the First Boer War*, 40.

⁸⁶ Ibid., 9.

horseback riding for travel across the rough terrain.⁸⁷ The resultant was a highly mobile, lethal fighting force that operated in a loose formation that gave rise to the term, *commando*.⁸⁸

Operational approach – bridging the current environment with the desired environment

Major-General Colley conceived the Majuba Campaign to march on the Boer's newly established capital of Heidelberg in order to entice the Boer forces into a decisive battle that would quell their insurrection in the pursuit of independence. Two primary constraints directly influenced this campaign. First, Colley had limited available forces that he hoped to supplement during his advance with both reinforcements from abroad as well as relieved garrison forces currently besieged by Boers. Boer numbers, while difficult to definitely assess given their fluid formation of volunteers numbered approximately 2,000 in comparison to Colley's force of 1,200.⁸⁹ Second, Colley knew that time was against him as popular support for the insurrection grew with each passing day. As such, Colley chose the most direct route despite significant, canalizing terrain along the Drakensberg Mountains that favored defensive positions. The Boer forces under Joubert similarly grasped the strategic situation impacted by restrictive terrain and subsequently deployed their forces in defensive positions along the avenue of approach chosen by Colley.

Over the course of the three-month campaign leading up to the culminating Battle of Majuba, British forces were proportionally decimated on three separate occasions, necessitating a British operational pause prior to the Battle of Majuba to reinforce its formation with troops brought from India.⁹⁰ With the British overland route blocked by Boer forces at natural choke

⁸⁷ Ransford, *The Battle of Majuba Hill - the First Boer War*, 9.

⁸⁸ Ibid. The etymology of the word *commando* and its African roots is further explored in a journal article by Elliott V. K. Dobbie, titled "The Word 'Commando'" in *American Speech*, Volume 19, Number 2, April 1944.

⁸⁹ Ibid., 38,42.

⁹⁰ Castle, *Majuba 1881: The Hill of Destiny*, 57.

points in the vicinity of Laing's Nek, Colley decided his force should secure the large, unoccupied mountain of Majuba. From these heights, Colley could observe the Boer forces in their blocking positions around Laing's Nek. However, to Colley's detriment, the heights placed the British forces beyond any effective weapons range by which to influence the Boers. Once the Boer forces ascertained their relatively safety despite their lower position, they convened via a war council and decided to transition from their defensive blocking positions to an offensive posture and assault the enemy forces now occupying the mountain with an ad-hoc volunteer force.⁹¹ The subsequent swarming attack witnessed Boer forces advance up considerably steep and challenging terrain to decisively route the British forces. The ad-hoc manner in which Boer forces advanced up the challenging terrain individually maneuvering from cover to cover is seen depicted in a Boer artist's rendering following the battle in Figure 13. Of the approximate 400 British forces to occupy the mountaintop to include Colley, 240 or approximately 59 percent were lost in comparison to the two Boers killed and six wounded of the estimated Boer force of 450.⁹² Such statistics seem significantly skewed given the established British defensive position on high terrain with equitable numbers and both sides only employing rifle and pistol fire. Colley's death on the mountaintop and the defeat of his forces brought an effective end to the First Boer War as British diplomats sought out peace negotiations and quelled the British Army's desire to reclaim their lost honor.

⁹¹ Castle, *Majuba 1881: The Hill of Destiny*, 70.

⁹² *Ibid.*, 82–83.



Figure 13. Battle of Majuba Hill, a Boer artist's rendering of the battle. Source: Oliver Ransford, *The Battle of Majuba Hill - the First Boer War* (New York, NY: Thomas Y. Crowell Company, 1968), 102.

Observations on swarming phenomena – the outcomes of action

To study the command and control of military forces in the Battle of Majuba is to contrast ineffective centralized leadership with effective, highly decentralized leadership. As noted above, the British forces under Colley demonstrated a strict adherence to the ingrained military hierarchy common to European armies of the time. While this hierarchal model may work to successfully orchestrate battle with a commander and staff who can understand and synthesize the complexity unfolding before them, this model becomes a significant detriment when those key nodes in the decision-making structure become either indecisive or ineffective through poor decision-making. At the onset of the Boer advance in the morning, the commander of the attached naval forces and close friend of Colley, Commander Stewart, was mortally wounded by long range Boer fire while standing next to Colley. This significantly influenced Colley's demeanor and perhaps this cognitive shock contributed to future indecision as the attack

developed.⁹³ Even when subordinate British commanders recognized the potential severity of the emergent Boer attack, they were unable to effectively communicate this to Colley to induce a corrective action from this top-down leadership model.⁹⁴ Boer forces on the other hand utilized localized communication between individual fighters and ad hoc command elements to coordinate covering fire and maneuver to advance on the entrenched British forces. One must be careful not to attribute classical hierarchical leadership models on these ad-hoc elements. The underlying emphasis of individual autonomy in the decentralized militia of the Boer forces can best be characterized from a preceding battle in the campaign on 8 February when the Boer field commander, Nicholas Smit, tried to press his men to attack and achieve decisive results before the day ended. The Boer forces promptly refused with documented refusals such as, “what the hell!”⁹⁵ Nevertheless, after three hours Boer forces managed to crest the slope to the flat high ground at the top of the mountain and subsequently overwhelm British fighting positions. When a subordinate British officer attempted a final plea to take initiative and conduct a bayonet charge, his request was frustratingly tempered by Colley who commanded him to delay such an action.⁹⁶ The results were decisive as the Boer’s emergent actions overwhelmed the decision cycle and responsiveness of the British. This reinforces the assertion by complexity scientist, Bar-Yam that “centrally controlled or hierarchical organizations are not capable of highly complex tasks.”⁹⁷ A commander’s ability to process and understand the developing complexity to spawn successful decisions in this cascading decision model creates a cognitive bottleneck. As such, the commander’s ability to address complexity limits the entire organization.⁹⁸

⁹³ Castle, *Majuba 1881: The Hill of Destiny*, 72.

⁹⁴ *Ibid.*, 72–73.

⁹⁵ *Ibid.*, 51.

⁹⁶ *Ibid.*, 78.

⁹⁷ Bar-Yam, *Making Things Work: Solving Complex Problems in a Complex World*, 19.

⁹⁸ *Ibid.*, 66.

Operation Defensive Shield – Battle of Balata

The enemy interprets space in a traditional, classical manner, and I do not want to obey this interpretation and fall into his traps. Not only do I not want to fall into his traps, I want to surprise him! This is the essence of war. I need to win. I need to emerge from an unexpected place.

—Aviv Kochavi, IDF Commander in charge of clearing the Balata refugee camp

In Gal Hirsch's book, *Defensive Shield*, the necessity of significant organizational adaptation to address complex new environments and threats is embodied by Hirsch's reference to a business management book, *Crazy Times Call for Crazy Organizations*.⁹⁹ Quite simply, these new environments and threats may require the complete abandonment of previous organizational paradigms. This simple concept to revolutionize force design proves monumental when overlaid against US military directives such as enabling national security and addressing evolving future threats. Steven Metz of the Army War College's Strategic Studies Institute highlights this underlying tension in force design between evolutionary approaches and revolutionary approaches to the application of land power. Metz argues that far futures wargames "should provide the players with a complex opponent or challenge and then task them to design a force (specifically an interagency force) to deal with it" as opposed to the current model of "working with an extrapolation of the current force and current capabilities."¹⁰⁰ The organizational concepts and operational approach championed by Gal Hirsch to address the complex threat environment during the Second Intifada illustrates successful adaptation to employ swarm logic.

The evolution of Israel Defense Force (IDF) operational planning provides context for the swarming tactics later utilized by Gal Hirsch during the Second Intifada. Between 1995 and 2005, Systemic Operational Design (SOD) was promoted at length to IDF leadership by Shimon Naveh

⁹⁹ Hirsch, *Defensive Shield: An Israeli Special Forces Commander on the Front Line of Counterterrorism*, 137.

¹⁰⁰ Steven Metz, "Five Questions with Steven Metz on U.S. Landpower," January 13, 2014, accessed December 11, 2017, <https://warontherocks.com/2014/01/five-questions-with-steven-metz-on-u-s-landpower/>.

following his critical analysis of Russian and Western operational approaches to warfare during his doctoral research and subsequent PhD from King's College, London.¹⁰¹ SOD promotes a systemic form of operations that employs advanced maneuver and fire compositions enabled by a systemic form of knowledge creation.¹⁰² As such, SOD represents the antithesis of linear design so prevalent in modern US military doctrine such as the Military Decision Making Process (MDMP). As a student of Naveh and SOD at the Operational Theory Research Institute, Hirsch aggressively approached reframing possible approaches for IDF assets to address future complex problems.¹⁰³ Hirsch transformed his understanding of the operational art from "old-school attack to nuances of pouncing, developing the cloud of wasps, and refinement of the concept of swarms."¹⁰⁴ Such an emergent and overwhelming philosophy would shape the ensuing IDF operations during Operation Defensive Shield, an operation charged with the "systematic dismantling of terror infrastructure through the region."¹⁰⁵

Operational approach – bridging the current environment with the desired environment

Gal Hirsch assumed the position of the J3 for the IDF Central Command when it was charged with planning an incursion into Lebanon to counter Palestinian terror organizations sponsoring the Second Intifada.¹⁰⁶ As such, Hirsch was responsible for the joint operational planning executed in the named operation, Defensive Shield, from March until May of 2002.

¹⁰¹ Ofra Graicer, "Self Disruption: Seizing the High Ground of Systemic Operational Design (SOD)," *Journal of Military and Strategic Studies* 17, no. 4 (March 1, 2017): 24.

¹⁰² *Ibid.*, 25.

¹⁰³ Hirsch, *Defensive Shield: An Israeli Special Forces Commander on the Front Line of Counterterrorism*, 127–130.

¹⁰⁴ *Ibid.*, 130.

¹⁰⁵ *Ibid.*, 165.

¹⁰⁶ Joint military staff positions often use abbreviated alpha-numeric titles to denote what staff section they are aligned with or in charge of as a principle staff officer. In this case, Hirsch was the J3 which indicates he was the primary joint staff officer in charge of operations for the IDF Central Command.

Within the context of the Second Intifada, Operation Defensive Shield represented a counterstrike to disrupt the enemy's decision cycle and ability to project power.¹⁰⁷ Hirsch critically understood that as a counterstrike force, he could not present the adversary with predictable responses. Instead, Hirsch had to create multiple dilemmas for the enemy and deny the enemy the ability to unduly influence his friendly force decision cycle. He sought out a "multidirectional, multidimensional 'buzz,' an unending, irritating and bothersome 'noise'" which made enemy adaption stagnant and ineffective.¹⁰⁸ Hirsch coined the tactics he promoted to achieve such effects "decentralized swarm maneuver," which created multiple friction points with the enemy to overwhelm their ability to operate successfully.¹⁰⁹ Such non-linear, adaptive tactics sought to exploit emergent success.

Hirsch's vision of non-linear operations was actualized by Brigadier General Aviv Kochavi, commander the IDF 35th Paratroopers Brigade. When Kochavi and his military planners visualized the complex tactical problem presented by clearing the refugee camp of Balata, they recognized the constraints of urban environment and how the adversary would most likely leverage this space to facilitate a tactical advantage.¹¹⁰ This spatial problem as a function of the urban density can truly be appreciated from an overhead satellite image as seen in Figure 14. Kochavi's forces charged with clearing Balata challenged the spatial constraints by executing a tactical strategy of "walking through walls" and creating non-traditional avenues of approach through the urban environment.¹¹¹

¹⁰⁷ Hirsch, *Defensive Shield: An Israeli Special Forces Commander on the Front Line of Counterterrorism*, 159.

¹⁰⁸ *Ibid.*, 231.

¹⁰⁹ *Ibid.*, 274.

¹¹⁰ Shimon Naveh, "Between the Striated and the Smooth," *Cabinet*, 2006, accessed December 31, 2017, <http://www.cabinetmagazine.org/issues/22/naveh.php>.

¹¹¹ Eyal Weizman, "Walking Through Walls: Soldiers as Architects in the Israeli-Palestinian Conflict," *Radical Philosophy* 136 (March 2006): 9.



Figure 14. Balata, a Palestinian refugee camp near Nablus. Source Shimon Naveh, “Between the Striated and the Smooth. Urban Enclaves and Fractal Maneuver” (Archipelago of Exceptions. Sovereignities of Extraterritoriality, November 2005), 4. Text from presentation also available online: accessed December 13, 2017, <http://www.publicspace.org/en/text-library/eng/b023-between-the-striated-and-the-smooth-urban-enclaves-and-fractal-maneuvers>.

Kochavi’s strategy of “walking through walls” gave rise to a form of tactical swarming maneuver he coined, *Fractal Maneuver*. Kochavi predicted such maneuver would “disguise our form from them, impose chaotic conditions on their cognitive process, and deconstruct or destructure their operational form.”¹¹² Thus, Kochavi would meet Hirsch’s intent of decentralized swarm maneuver. Naveh surmises Kochavi’s concept of Fractal Maneuver was influenced by French philosophers Gilles Deleuze and Felix Guattari whose theories were promoted to Israeli officers at the Operational Theory Research Institute.¹¹³ A visual depiction of Fractal Maneuver

¹¹² Naveh, “Between the Striated and the Smooth.”

¹¹³ Yotam Feldman, “Dr. Naveh, or, How I Learned to Stop Worrying and Walk through Walls - Haaretz.Com,” *Haaretz*, October 25, 2007, sec. Israel News, accessed January 1, 2018, <https://www.haaretz.com/israel-news/dr-naveh-or-how-i-learned-to-stop-worrying-and-walk-through-walls-1.231912>.

from Naveh's presentation on combat operations in Balata can be seen in Figure 15 where one can appreciate the effects of such maneuver to converge unpredictably on the enemy from all directions.

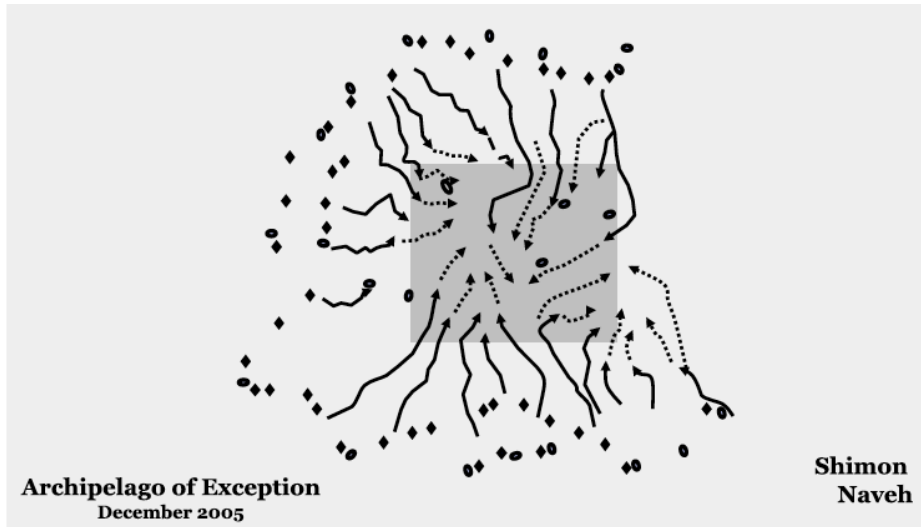


Figure 15. Fractal Maneuver visualized. Source Shimon Naveh, “Between the Striated and the Smooth. Urban Enclaves and Fractal Maneuver” (Archipelago of Exceptions. Sovereignties of Extraterritoriality, November 2005), 1. Text from presentation also available online: accessed December 13, 2017, <http://www.publicspace.org/en/text-library/eng/b023-between-the-striated-and-the-smooth-urban-enclaves-and-fractal-maneuvers>.

Observations on swarming phenomena – the outcomes of action

Despite some concerns by Kochavi's subordinate commanders regarding coordinating their movement and de-conflicting their movement with adjacent converging units, the resultant emergent paths through the dense urban setting of Balata can be seen in Figure 16.¹¹⁴ These paths are unconstrained by the urban features of Balata such as alleyways and roads that would have normally canalized movement.

¹¹⁴ Naveh, “Between the Striated and the Smooth.”



Figure 16. The resultant swarm from Fractal Maneuver. Source Shimon Naveh, “Between the Striated and the Smooth. Urban Enclaves and Fractal Maneuver” (Archipelago of Exceptions. Sovereignities of Extraterritoriality, November 2005), 11. Text from presentation also available online: accessed December 13, 2017, <http://www.publicspace.org/en/text-library/eng/b023-between-the-striated-and-the-smooth-urban-enclaves-and-fractal-maneuvers>.

The decisive action by small IDF teams to maneuver through the urban environment was driven by a general directive but not constrained by dictating which specific walls to pass through as the IDF forces made their way to their assigned objectives.¹¹⁵ Such small unit action to move through rather than around urban obstacles can best be appreciated by the IDF soldiers urban movement in Balata depicted in Figure 17. Local, organic elements from the assaulting IDF forces were used for command and control per Kochavi’s mission orders: “each unit will combine three components in its operation—observation teams, sniper teams, and teams that are supposed to attract the attention of the insurgent fighters.”¹¹⁶ There was no overhead element coordinating

¹¹⁵ Naveh, “Between the Striated and the Smooth.”

¹¹⁶ Ibid.

each advancing unit once the mission commenced, just localized communication between elements. The specific casualty totals are still contested by Palestinians, but Kochavi claimed 74 armed terrorists killed, 155 civilians injured and 480 taken prisoner, as opposed to two Israelis killed and 19 injured.¹¹⁷ Such effects from physically and cognitively overwhelming an adversary validate the successful application of swarm logic through the contextual application of Fractal Maneuver in the Battle of Balata.



Figure 17. IDF forces actualizing swarm logic through the urban terrain. Source Shimon Naveh, “Between the Striated and the Smooth. Urban Enclaves and Fractal Maneuver” (Archipelago of Exceptions. Sovereignities of Extraterritoriality, November 2005), 9. Text from presentation also available online: accessed December 13, 2017, <http://www.publicspace.org/en/text-library/eng/b023-between-the-striated-and-the-smooth-urban-enclaves-and-fractal-maneuvers>.

¹¹⁷ Barbara Opall-Rome, “Marines to Train at New Israeli Combat Center,” *DeepJournal*, June 26, 2007, accessed January 1, 2018, <http://www.deepjournal.com/p/2/a/en/807.html>.

Future Potential of Swarm Logic

Intelligence is the complexity that arises from the communication and coordination of simple units.

—Adam Brate, *Technomanifestos: Visions from the Information Revolutionaries*

As US military leaders assess future battle and the inherent complexity, it would be remiss to discard or underappreciate swarming. Given swarming as nature's operational approach to complexity, one must be cautious not to devolve the examination to the tactical effects, or convergence, of swarms. Doing so fixates one on the actualization of the emergent phenomena rather than the conditions that enabled it; it provides the pretext for linear approaches to replicate this convergence. The non-linearity of swarm logic facilitates real-time, adaptive intelligence and subsequent action. Employing swarm logic as a broader operational approach not only empowers emergent problem solving, but it induces complex problem making for adversaries attempting to make sense of friendly actions. The challenges for application in the US military such as organizational structure, service and support methods, and leadership culture deserve significant study. The solutions will continue to necessitate multi-disciplinary approaches as advances in other fields facilitate improved understanding in complexity science writ large.

Limited Past Interpretations

Previous studies in the military application of swarm logic have demonstrated unfortunate biases that negate the very benefits of such an emergent approach to address complex problems. These biases have constrained the interpretation of swarm logic through command and control mechanisms evolved from prior military operating concepts. This facade of complex problem solving, then exhibits a limited approach of linear problem solving to address increasing complex problems. Such misplaced analysis results in exploitable dependencies that can paralyze responsiveness as opposed to the robust and adaptive nature of the swarm logic exhibited by natural swarms.

A study in the military application of swarming by RAND titled *Swarming and the Future of Conflict*, exhibits fundamental flaws in the interpretation of swarm logic grounded in linear problem solving. The study opens by stating that swarming is a “deliberately structured, coordinated, strategic way to strike from all directions.”¹¹⁸ While the surmised resultant action from small units is relatively accurate, the command and control description elicits the authors’ bias of evolved understanding grounded in the operating concept of Network Centric Warfare. The authors themselves preface their work as a continuation of their analysis on *netwar*, a highly networked form of warfare that appears to profess non-linear problem-solving techniques through decentralized approaches. However, both *netwar* and swarming in the RAND constructs exhibit increased dependencies on these networked approaches to coordinate the convergence of effects. The fallacy to this approach is these networked solutions still rely upon critical decision nodes and a general top-down hierarchical decision-making model. Understanding and pursuant action must still transverse a linear design structure regardless of force dispersion and as such these approaches do not leverage complex adaptive problem-solving present in natural swarming.

The strength of swarming does not simply lie in the physicality of its convergent nature as the various case studies in the RAND study promote. This would be to reduce this complex behavior to various conditional endstates rather than assess the logic that underpins the phenomena. The true strength of swarming is the underlying logic that enables its adaptive nature. When Arquilla and Ronfeldt’s RAND study acknowledges natural swarms and social swarms, it does so by focusing on the swarm’s resultant physical convergence that they term sustainable *pulsing*.¹¹⁹ By observing such an endstate without examining the ways in which nature accomplishes this emergent behavior, the study arrives at flawed conclusions from their military

¹¹⁸ John Arquilla and David Ronfeldt, *Swarming and the Future of Conflict* (Santa Monica, CA: RAND, 2000), vii.

¹¹⁹ *Ibid*, 26.

case studies influenced by dependencies on command and control techniques promoted by Network Centric Warfare. By stating, “swarming clearly depends – far more than traditional approaches to battle – upon robust information flows,” they do so under the guise of coordinating the convergence based on bottom-up understanding, but top-down decision making.

Once swarming is viewed as a viable complex operational approach to future military problems, the dialogue can expand from the physicality of swarming to the conceptual. The dense heterarchies proposed by Wilson as a means to understand propensity of interactions in ant colony swarming was inherently physical. However, if one interprets the density of interactions as not constrained to purely physical interaction but also non-physical interaction where the exchanges are localized in a common medium, the richness of interaction can become more abstract. Swarm logic can therefore permeate both concrete and abstract problems. Swarm logic can transcend problems from the tactical space to the strategic space.

While the natural and military case studies used to examine swarming in this monograph provide insight to its potential value to influence an operational approach in an increasingly complex world, the scale of study was purposefully limited. Additional research in two domains should continue to inform this topic. First, future military case studies should examine larger scales of combat that exhibit facets of swarm logic through decentralized military operations to achieving positions of relative advantage. Potential areas include, but are not limited to, military operations in the Franco-Prussian War in 1870 and the Burma Campaign in 1942. Second, the continued study of addressing and leveraging complexity in other fields such as economics, artificial intelligence, psychology, and organizational leadership models will enrich the multi-disciplinary approach required to improve understanding for the applicability of swarm logic. Continued research within these two domains will challenge the breadth and depth of swarm logic and its potential role to influence operational approaches.

Operational Art – Problem Solving and Problem Making

If it is accurate to assume that complexity in warfare permeates strategic to tactical interpretations of an open system, it follows that the current paradigm of linear problem solving cannot adequately address warfare. The pace of system adaptation and evolution will outpace the capacity and capability of linear models in-so-far as effective decision making to maintain spatial, temporal, and cognitive positions of advantage over adversaries. Operational artists, those who attempt to achieve desired strategic outcomes with arranged tactical actions, must recognize the shortfalls of current design paradigms in complex problem solving. Bar-Yam highlights the symbiotic relationship between problems and effective solutions when he observes the necessity to “relat[e] the nature of the problem to the nature of the solution, a kind of yin-yang complementary.”¹²⁰ As such, operational artists must inculcate the concept that only complex adaptive solutions can adequately address complex problems.

Given the same duality of problem solving, complex adaptive solutions present adversaries with multiple ambiguous dilemmas. Such simultaneity denies clear targeting criteria for adversaries to counter friendly actions and denies adversaries the ability to effectively influence a friendly forces decision-making cycle given its decentralized and adaptive nature. Such an approach diametrically opposes linear operational design constructs such as the very common concept of *center of gravity*. When joint US military doctrine postulates that a center of gravity – “a source of power that provides moral and physical strength, freedom of action, or will to act,”¹²¹ can be sufficiently identified and targeted, the doctrine reveals its linear bias and reductionist tendencies for operational design in a complex operational environment. If the US military is truly opposed by a near-peer adversary who can establish such complex operational

¹²⁰ Bar-Yam, *Making Things Work: Solving Complex Problems in a Complex World*, 15.

¹²¹ US Department of Defense, Joint Staff, Joint Publication (JP) 5-0, *Joint Planning* (Washington, DC: Government Printing Office, June 2017), GL-6.

challenges as effective Anti-Access/Area Denial (A2/AD) measures such as those described in the operating concept of Multi-Domain Battle, then the US military needs to present the adversary with complex approaches that exploit seams through emergence.¹²² The Multi-Domain Battle Operating Concept stresses creating multiple dilemmas for an adversary when it should be stressing creating complex dilemmas.¹²³ The necessity of adaptation for modern and future militaries is captured by Gal Hirsch in his article *On Dinosaurs and Hornets* when he states, “a key task of a modern army should be not only to break its own form, but compel the enemy to assume a form, to have an image.”¹²⁴ This was written in the context of asymmetric warfare from a counter-insurgency perspective, but the concept of rapid flexibility remains valid as the US military assesses future conflict with a near-peer adversary. Swarm logic provides operational artists a broad framework to facilitate the complex adaptive solutions required of complex problems.

¹²² “Multi-Domain Battle: Evolution of Combined Arms for the 21st Century 2025-2040” (US Army Training and Doctrine Command, December 2017), 6.

¹²³ *Ibid.*, 39.

¹²⁴ Gal Hirsch, “On Dinosaurs and Hornets - a Critical View on Operational Moulds in Asymmetric Conflicts,” *The RUSI Journal* 148, no. 4 (August 2003): 62.

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