Forged at the Edge of Chaos

Emergent Function Weapons

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A specific class of weapons is appropriately categorized under the moniker *emergent function weapons*. The devices in this category include not only swarming and flocking systems, but a host of system types that have in common the idea that they operate as complex adaptive systems whose battlefield functions manifest only from emergent behavior at scale. Emergence is the underlying phenomenon that enables flocking, swarming, clustering, patterned diffusion, and other self-organizing system behaviors. The concept of an emergent function weapon invites the military to establish a defense research program that moves beyond the endless quest for better sensors and more processing power and instead leverages contemporary advances in behavioral robotics.

A first-rate warship slowly drifts toward Okinawa and crosses into Japanese territorial waters. The Coast Guard tries to establish communications, but the ship does not respond to hails or interrogation. A patrol vessel approaches but finds no human activity visible on the ship. The engines appear active at a low idle, standard systems seem to be operating, and there is no evidence of external damage. Eventually, the patroller receives orders to send a boarding party to investigate and prevent the distressed vessel from running aground. A small, elite security team transfers to the distressed warship and finds the upper deck abandoned. Live audio and video from the tactical team's gear beamed back to the patrol vessel paint an increasingly confusing picture.

As the team members initially explore, they observe the normal hum of ship systems but no sign of human life. As they search deeper into the ship, the picture turns grim. The normal hum is still present, along with mutilated corpses. Body positions suggest the victims were running from something, but no obvious battle reconstruction makes sense. None of the wound patterns conform to conventional combat methods one would expect from projectiles or hand-to-hand fighting. Instead, the bodies look like they received innumerable slashes from fine razor blades. Now on high alert and with backup teams on

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standby, the tactical team executes a systematic search with orders to secure the ship and drop anchor.

The unexplainable carnage continues to materialize throughout the ship. As the team approaches the engine room, broken profanity underscores statements of incredulity—the density of casualties and heinousness of the conditions of the bodies increases markedly. Upon opening the hatch to the engine room, a team member reports that they see movement on a battery bank and hear intensifying buzzing and clicking sounds.

Leaders aboard the patrol vessel observe in horror as screams fill the audio channels, and the body cameras show frantic movements as the team runs from what looks like a large swarm of mosquitoes. Some team members open fire as they retreat, hitting nothing but bulkheads. One camera, either knocked to the ground in the chaos of retreat or still attached to a now-deceased team member, shows a swarm returning to the battery bank. The clicking stops. Only the quiet humming of the ship remains.

Complex Behaviors from Simple Machines

This gruesome vignette illustrates one potential outcome of militarizing a crossdisciplinary pool of knowledge that stretches from theories about complex systems to leading developments in behavioral robotics. It is far from the only potential outcome of such mastery, but it is a realistic use-case of a class of weapons practitioners might label as swarming devices. This article's position, however, is that a missing intermediate concept is needed to categorize a host of complex system behaviors, only one of which is swarming. For example, should swarming and flocking systems be regarded as fully distinct concepts? Intuitively, something relates them but what?

This article proposes partitioning the universe of weapons design into two general branches: (1) direct function weapons (DFWs), covering classical theories of operation for platforms, payloads, and munitions; and (2) emergent function weapons (EFWs). Further, the article argues that swarming, flocking, and related approaches to design belong to this superset of *emergent function* devices. This small ontological adjustment provides theorists, industry, and defense practitioners with a unifying framework to study these approaches to weapons design.

This article defines EFWs, distinguishing them from their more familiar direct function counterparts and highlighting the theoretical underpinnings of the emergent variety. It observes a disconnect between design philosophies at the leading edge of behavioral robotics versus those guiding the development and acquisition of advanced weapons systems. It identifies the desirable properties of EFWs and discusses the tradeoffs between direct and emergent designs. Finally, the article highlights how these weapons might extend existing approaches to dynamic targeting in highly contested combat environments, proposing a concept called hypervelocity targeting.

Defining Emergent Function Weapons

Concisely stated, an emergent function weapon is one with operational functions that rely on the emergent properties of complex systems. Such emergences generally appear at scale and are difficult to predict from an evaluation of raw components that comprise a system. Many "agents" (instances of the software program or physical device that follows some behavioral repertoire) operating as part of what scholars label a *complex adaptive system* compose an EFW ensemble.[1]

These ensembles feature high degrees of interaction between agents and, under the right conditions, generate emergent properties such as self-organization.[2] Operational performance is only apparent at runtime (simulated or actual) because designers seek aggregate behavior from the system's dynamics rather than from encoding explicit repertoires of behavior into a centralized hardware or software controller.

Understanding how an EFW operates on the battlefield and how to design one requires oblique thinking. In an emergent function design, creators purposefully disaggregate the weapon's operational function. Typically, a single instance of the device would not be sufficient to perform a useful task on the battlefield. Instead, multiple devices aggregate into an ensemble (whether multiple copies of the same design or an array of heterogeneous devices) that adopts the formal properties of a complex adaptive system at scale.

Devices *appear to cooperate* to fulfill the weapon's overall function, but the devices have no concept of that overall function in their programming. Picture a terrarium with ants: four ants wander with little interaction, but past a certain threshold—perhaps 40 or 400 ants—they exhibit what scholars of complex systems call self-organizing behaviors.[3] Those behaviors are emergent properties that appear at scale; the object of EFW design is to exploit this phenomenon for tactical advantage.

By contrast, one might label traditional weapon designs as direct function weapons. These weapons explicitly do all the work of action without the weapon design itself leveraging emergent system behaviors. Operational users of direct function weapons certainly consider cascade effects, such as when seeking to cripple enemy logistical systems through efficient targeting behaviors. Still, nothing in the weapon's technical specifications requires an emergent property to appear for the weapon to function. The distinction between emergent and direct function weapons lies in where designers encode the governing logic of the weapon.

In a pure direct-function design, designers encode control logic into devices such as bombs or missiles or delivery vehicles such as aircraft. Practically, the work involves programming computers or fashioning electromechanical assemblies. When the job is com-

1. John H. Miller and Scott Page, *Complex Adaptive Systems: An Introduction to Computational Models of Social Life* (Princeton, NJ: Princeton University Press, 2009), 3.

2. Melanie Mitchell, *Complexity: A Guided Tour* (New York: Oxford University Press, 2011), 13.

3. Miller and Page, *Complex Adaptive Systems*, 214.

plete, the device contains all the logic necessary to perform operationally within published employment parameters.

Impressionistically, these devices reflect how mankind solves battlefield problems through step-by-step logical deduction. On the other hand, EFWs reflect how natural systems might solve that problem given time, space, opportunity, and pressure to adapt. The EFW design, which will likely require techniques ranging from genetic algorithms to reinforcement learning, will present at least as many technical and ethical challenges as opportunities.

Nevertheless, exploiting emergent properties in weapons design does not automatically correlate to vicious devices such as the vignette's robotic mosquitos. Emergence is a feature that regularly appears in complex systems from microscopic to cosmological and in natural and synthetic systems. In some cases, the elements of an EFW might not manifest as physical assets, such as flying robots, but rather ensembles of interacting software packages hosted on terrestrial, seaborne, airborne, and spaceborne computing environments. The ability to encode logic into the dynamics of a system and leverage emergent properties provides additional trade space in hardware and software for designers facing challenging operational requirements. Still, the approach is a departure from current practices in the defense industry, even where robotic and autonomous systems are concerned.

Advances in Robotics

Over the past 8 decades, the field of robotics underwent several iterations of what Thomas Kuhn called "normal science."[4] Academics and industry leaders pursued one avenue until finding intractable problems and pivoted to another avenue of research. Before the 1950s, society's grasp on the topic consisted of various fictional representations, prototypes, and industrial precursors. Only when key technologies existed simultaneously could experts in the field develop actual robotic systems. Enabling technologies included programmable multifunction processors based on the Von Neumann architecture, foundational artificial intelligence work of the kind Alan Turning accomplished, and the transistor (leading, in turn, to integrated circuits).[5]

In this milieu of robotics and computer science advances, initial progress enticed some early proponents to proclaim computers would solve any definable problem.[6] Some

4. Thomas S. Kuhn, *The Structure of Scientific Revolutions: 50th Anniversary Edition* (Chicago: Chicago University Press, 2012), 24.

5. J. von Neumann, "First Draft of a Report on the EDVAC," *IEEE Annals of the History of Computing* 15, no. 4 (1993), https://doi.org/; and A. M. Turing, "Computing Machinery and Intelligence," *Mind* 49 (1950), https://www.jstor.org/.

6. H. A. Simon and Allen Newell, "Heuristic Problem Solving: The Next Advance in Operations Research," *Operations Research* 6 (1958), https://www.jstor.org/; and Marvin Minsky, *Computation: Finite and Infinite Machines* (Hoboken, NJ: Prentice-Hall, 1967).

imagined robots would soon do any work that a human could.[7] After initial successes in applying robotics to factory-scale manufacturing processes and besting the vast majority of the population in relatively simple games such as checkers, the euphoria quickly died away.[8] It became clear that achieving the robotic vision of the day required significant research, material improvement, and processing capabilities that technology of the time simply could not deliver.

From the 1970s, the next wave of research sought to solve the key problems of robotics with a two-pronged approach. First, researchers leveraged increased computational power.[9] Second, they sought to create better sensors that presented more consistently accurate data to the computers (reducing the "noise" with which the computer would have to contend).[10]

But as this wave unfolded, researchers correctly deduced that some problems remained unsolvable even with near-perfect information. Simply put, the tasks for robots to solve still contained irreducible error factors, and the scale of even simple tasks proved computationally intractable.[11] The key insight this generation of roboticists deduced was that one could ask for near-infinite amounts of computing power and accurate data streams and yet still fail to solve the challenge. Something about the fundamental approach itself had to change.

The next epoch for robotics research appeared in the 1990s as the study of behavioral robotics. In this research program, roboticists pursued self-organizing systems to solve relevant problems.[12] Robots navigating physical environments is a classic example. In the 1970s, roboticists would have sought better information and processing power to try to preemptively calculate an optimal path through a crowded city square. On the other hand, behavioral robotics approached the task knowing that a predetermined perfect solution was unrealistic. Instead, a robot might move in a general direction and perform specific behaviors given small scenarios such as: avoid obstacles, wait for people or vehicles to clear out, look for open areas, and so forth.

In this line of thinking, researchers hoped that behavioral patterns would emerge to accomplish the overall task (i.e., cross the crowded square) by piecemeal actions without ever processing a completed, optimal answer. This approach enjoyed some success but proved insufficient to complete complex tasks. Particularly, it was difficult to tell which

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7. H. A. Simon, *The Shape of Automation for Men and Management* (New York: Harper & Row, 1965).

8. Paul Mickle, "1961: A Peep into the Automated Future," *The Trentonian*, 1961, http://www.capitalcentury.com/.

9. Hans Moravec, "The Role of Raw Power in Intelligence," unpublished manuscript, May 12, 1976, pdf, https://stacks.stanford.edu/.

10. Hans Moravec, *Mind Children* (Boston: Harvard University Press, 1990).

11. L. Stephen Coles et al., "Decision Analysis for an Experimental Robot with Unreliable Sensors" (paper presented at the 1975 International Joint Conferences on Artificial Intelligence, 1975), 749–57, https://citeseerx.ist.psu.edu/.

12. Ronald C. Arkin, *Behavior-Based Robotics* (Cambridge, MA: MIT Press, 1998).

behavior would emerge from the series of human-created rules and situations that might exist.[13]

Contemporary robotics research addresses shortcomings in the behavior-based approach by integrating reward-based machine-learning techniques. The novelty here is that the agent can modify its own behaviors given the initial stimuli, mimicking underlying processes that seem fundamental to how living organisms achieve complex behavioral repertoires.[14]

Behavioral Robotics and Defense Aerospace

Unfortunately, the transfer of learning from high-end robotics research to defense aerospace development has been exceptionally slow moving. The developmental activities of contractors working on advanced aircraft and autonomous systems today reflect activities roboticists pursued in the 1970s. Military services still pursue development of increasingly capable sensors to cover wider swaths of the electromagnetic spectrum with greater resolution. In parallel, they seek better processing capacity to push a higher volume and quality of data to classical algorithms for exploitation.[15]

Whatever automation exists in these projects still reflects an attempt to find optimal solutions by breaking the overall task into well-defined phases of execution and maximizing the volume of high-quality sensor inputs. Furthermore, the input to these few automated system functions generally involves a prerequisite step of human "wetware" manually interpreting and annotating sensor data.[16]

The gap between the leading edge of robotics research and the weight of effort within defense aerospace developmental activities leaves potential capability unexplored and unexploited. Today's applications of machine-learning algorithms are relatively piecemeal.[17] Even the literature within defense and security studies—the body of work reflecting the ideas by which scholars and practitioners evaluate potential futures—is mixed concerning ideas that behavioral robotics embraces. Some sources explicitly claim swarming

13. Maja J. Mataric, "Integration of Representation into Goal-Driven Behavior-Based Robot," *IEEE Transactions on Robotics and Automation* 8, no. 3 (June 1992), http://web.mit.edu/.

14. Leslie Pack Kaelbling, Michael L. Littman, and Andrew W. Moore, "Reinforcement Learning: A Survey," *Journal of Artificial Intelligence Research* 4 (1996), https://www.jair.org/.

15. Colville McFee, "Opening Doors to the Future 427th Reconnaissance Squadron Ribbon Cutting Ceremony," 9th Reconnaissance Wing Public Affairs, April 26, 2019, https://www.beale.af.mil/.

16. Ridge R. Flick, "Winning the Counterland Battle by Enabling Sensor-to-Shooter Automation," Air Land Sea Application (ALSA) Center (website), November 1, 2021, https://www.alsa.mil/.

17. Sydney J. Freedberg, "Culture, Not Tech, Is Obstacle to JADC2: JAIC," Breaking Defense, February 11, 2021, https://breakingdefense.com/.

weapons cannot replicate the self-organization found in nature's examples.[18] Others see no clear theoretical obstacle to doing exactly that.[19]

Leading minds and leading breakthroughs in the field of robotics continue to leverage behavior-based approaches as a framework for exploiting machine learning and related artificial intelligence techniques. This observation suggests further investigation of behavioral methods holds promise for the maturation of applied machine learning in military weapon systems. The emergent function weapon conceptual category is an ontological placeholder that invites importation of behavioral robotics into defense research and development programs. Implementing a behaviorally based project might invoke swarming, flocking, or another form of emergent behavior.

Leveraging Emergence Now

The Air Force is only now beginning to support ideas and demand new capabilities that make this discussion about EFWs institutionally relevant. For example, "digital engineering" is a process by which creators use computer-aided design software to create blueprints of weapon systems and build, test, model, simulate, and refine prototypes in virtual environments.[20]

This practice of high-fidelity digital modeling is an enabler for EFWs because finding desirable emergent properties requires either prescient creativity or extensive simulation support. Designing systems to exploit emergence requires shifts in thinking and practice but offers many potential benefits. In particular, four stand out: (1) extended capabilities for power- and compute-density-constrained devices; (2) the ability to invert employment -planning principles; (3) a design methodology inherently focused on scaling properties; and (4) disaggregation of the sensitive data that makes the weapon function in combat.

Though computing efficiency and power storage capabilities improve annually, an enduring lesson from the 1970s robotics research program is to be skeptical that these improvements will provide breakthroughs in capability.[21] The approach of an EFW is, therefore, to recast a computationally intensive task into one that a distributed aperture of potentially low-power, low-bandwidth, and low-processing power devices solve in the aggregate.

This approach leverages what scholars call "computation in the large," wherein no device in a complex adaptive system attempts to solve the overall problem.[22] Instead, the

18. John Arquilla and David Ronfeldt, *Swarming and the Future of Conflict*, Documented Briefing DB-311-OSD (Santa Monica, CA: RAND Corporation, 2000), https://www.rand.org/.

19. Paul Scharre, "How Swarming Will Change Warfare," *Bulletin of the Atomic Scientists* 74, no. 6 (2018), https://doi.org/.

20. Air Force Materiel Command (AFMC), "Digital Campaign: One Team . . . One Digital Lifecycle Enterprise," AFMC (website), n.d., accessed May 30, 2022, https://www.afmc.af.mil/.

21. John Shalf, "The Future of Computing beyond Moore's Law," *Philosophical Transactions of the Royal Society A* 378, no. 2166 (March 2020), https://doi.org/.

22. Mitchell, *Complexity*, 143–58.

microlevel actions of individual devices aggregate in such a way that the entire system produces the solution through emergence.

Complexity theorists regard systems such as economies as essentially giant distributed computers. Each buyer and seller in a market has neither the capability nor the information required to set global prices. Yet through the interactions of buyers and sellers, the economy continuously calculates the prices of commodities, stocks, and so forth.[23] Emergent function weapon design seeks to operationalize this phenomenon.

Consequently, EFWs invert some portion of operational employment planning principles, favoring self-organizing system behaviors instead of a top-down operational direction. For example, missions such as reconnaissance or search and rescue generally involve allocating sensors to search large areas for objects of interest. Coordinating such an activity requires logical plans for sensor distribution and information reporting. Using a direct function methodology, humans think through the problem of where to point which sensors and when, create a primary plan, and then develop a series of contingency plans.

An emergent function methodology features little preplanning and requires no centralized control to achieve the mission objective. Instead, the search path is an artifact of the emergent behaviors of the EFW interacting with the operating environment.

Emergent function weapons only achieve these interesting outcomes by operating as complex adaptive systems at some level of scale. Estimating the specific scale required for each application likely varies significantly enough to require dynamics simulations. Scaling is a requirement, but the consistent presence of that requirement forces the entire design methodology to optimize for scaling from the outset.

The distribution of costs for the development of an EFW is likely front-loaded: a large effort to find a design that will produce the right emergent behaviors at runtime; a significant effort to produce factory tooling to create the devices of the complex adaptive system; and a lower intensity but longer-running optimization, tuning, and testing effort throughout the lifecycle of the system. That distribution suggests building additional devices in production would be relatively inexpensive, contrasted with other program budget elements. Thus, when researchers find one of those rare, winning combinations of parameters that creates a desirable emergent system behavior, program managers can exploit the finding and build larger inventories of devices.

Lastly, the peculiar development lifecycle disaggregates the weapon from the shared knowledge of why the weapon works as it does in any configuration. The data loaded in the robotic device would consist of some low-level control logic (e.g., to actuate flight control surfaces) but mostly parameterized data that, to a third-party observer, lacks context.

The rationale behind the settings for dozens to thousands of unlabeled parameters on the device exists only in the laboratory. Even if an adversary recovered copies of the device, they would have no obvious means of ascertaining why these parameters were effective in one context but not others. Reverse engineering EFWs might be inherently

23. Mitchell, 9–10.

difficult, depending on the depth of parameterization. Their true lethality resides in the simulation and testing environments that discover unique combinations of parameter values that create particular emergent behaviors.

Maintaining Healthy Skepticism

If a research and development program in EFWs does gain traction, the first risk to success will be institutional misunderstanding, misuse, or misrepresentation of the concept. Labels for concepts become popular, then, as leaders wrestle with the ideas or early pilot projects fail to produce results worth the hype of the new buzz-phrase, the labels fall out of fashion, and the ideas become altered and repackaged with new acronyms.

For example, attrition-tolerant aircraft and command-and-control methodologies linking manned and unmanned systems have both undergone such fashion trend upheavals. The term low cost attrittable aircraft technology (LCAAT) peaked in popularity between 2017 and 2020, but as prototype vehicle losses mounted and the reaction from the combatant commands was less than enthusiastic, its vocabulary waned in popularity. Similar vocabulary shift patterns occurred where the term manned-unmanned teaming (MUM-T) fell out use in favor of collaborative combat aircraft (CCA).[24]

In one sense, this cycle is simply an artifact of the social system of the Pentagon engaging in collective thinking and creativity. In another sense, the cycle becomes connected to notions such as social status associated with so-called "staying on trend." A socially motivated pursuit of intellectually fashionable vocabulary detracts from rather than adds to the organization's ability to think collaboratively and collegially. Instead of applying effort to rigorous ontological designs of future fighting concepts, a corrosive, pathological trend of pseudointellectualism tempts the Pentagon to mill through buzz-phrases. The concept of emergent function weapons might easily be lost in the noise of such an environment.

Humility is part of the price of admission for something as ambitious as a defense research program on weapons that harness emergence from complexity. That requirement runs in two directions. First, scholars, researchers, and industry leaders who must secure resources in order to work on exploiting emergence must avoid the trap of overselling the idea.

Second, while moving from the familiar toward the unfamiliar is natural, senior leaders and headquarters staff challenged to think about future force design must resist the temptation to interpret EFWs entirely through familiar lenses of yesterday's doctrines. Furthermore, they must avoid the collective social pathology that will tempt them to think about EFWs and the idea of emergent system behaviors as though they were fodder for just another short-lived round of buzz-phrases. Emergence, like many fascinating properties of the physical universe, operates whether or not humans choose to study it or harness it for advantage. But if they do pursue it, they should not expect quick results or

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24. Thomas Hamilton and David A. Ochmanek, *Operating Low-Cost, Reusable Unmanned Aerial Vehicles in Contested Environments: Preliminary Evaluation of Operational Concepts*, RAND Report 4407 (Santa Monica, CA: RAND Corporation, 2020), https://www.rand.org/.

for the encounter to leave their original patterns of thinking—or their warfighting doctrines—undisturbed.

Instead, those exploring EFWs should be clear about the scope of utility and the limitations of the concept. As with any design effort in any engineering discipline, the theoretical basis for EFWs represents an adjustment of tradeoffs, not a panacea. A good research and development program will achieve favorable trades that expand a designer's toolkit in helpful ways. Understanding this trade-space requires a fair appraisal of the costs of the EFW approach. The tradeoffs between direct and emergent functional design extend from the practical to the social and ethical.

Tradeoffs

First, the preponderance of weapons designs will likely remain direct function, owing to the eminent practicality of such approaches and the inherent difficulty in designing for elusive emergent functions. There is little motive to replace proven air-delivered precision munitions with an alternative based on a complex system, for example, when the added complexity might not result in any corresponding gain in battlefield performance.

Emergent function weapons are likely to appear first as special-use tools for focused operational scenarios. When further matured, they will probably maximize return on investment as enablers that tackle difficult tactical and operational tasks when integrated with existing fleets of classically designed weapon systems. But building EFWs to counter specific adversary systems on their own (such as the ship in the vignette) may require extensive intelligence on details of the foreign weapon system.

Second, until someone designs sufficiently advanced software development packages that support rapid scripting of interactive behavioral repertoires and embedded systems dynamics simulations, the practical act of EFW design will likely be taxing, manual labor. Designing EFWs from scratch may require significant research support. Constructing a complex adaptive system that will meet specific war-fighting requirements through an emergent behavior may even drive live combat test, evaluation, and optimization work across the lifecycle of the weapon. Emergent function weapons would likely occupy a point on the spectrum of generalizability halfway between conventional weapons and tailored cyber exploits.

Third, the concept of an EFW originates from subject matter in a crossdisciplinary field that few if any educational programs through the undergraduate level tend to cover as a core curriculum. While by no means too difficult for students or professionals to grasp, the notion of emergence from complexity may be unfamiliar to many audiences and evoke wild ideas that exceed the true scope of the subject.

Mass unfamiliarity with the conceptual basis of a proposed weapon design is a significant messaging challenge for a public institution that is accountable to citizens who fund it. It is likely, even more than the military experienced with remotely piloted aircraft programs, society's collective mental processing of EFWs may generate a host of critiques about "killer robots" and "playing God with robotics."[25] If the Pentagon must spend significant political capital managing the domestic narrative, it may be less patient with fledgling EFW projects.

Supporting Dynamic Targeting

With a balanced view of the opportunities, costs, and tradeoffs associated with EFWs, it is reasonable to ask what application of this concept would yield a significant return on investment and thereby drive a productive defense research program. In one sense, the history of the Air Force is a history of targeting theories.

From the earliest days of industrial webs to Operation Desert Storm to modern targeting constructs, two simple but important ideas predominate: prioritizing *what* to target and ascertaining *how much* one can successfully target simultaneously.[26] The modern concept for satisfying these properties is to focus on the performance of the dynamic targeting cycle, sometimes called a kill chain, the steps of which are: find, fix, track, target, engage, and assess (F2T2EA).[27] But the US military did not arrive at this elegant formulation overnight, nor did it arrive at the idea independently.

In the 1970s and 1980s, the United States pursued development programs in precision-guided munitions and digitization of command and control, including airborne data networking.[28] Beyond improving tactical performance on the battlefield, these projects aided the Western powers in offsetting Soviet numerical advantages and battle strategies in Europe.

At the time, however, Americans tended to view each project analytically and independently. They paid less attention to the holistic implications of how the projects, when brought together, would radically alter major combat operations.[29] Soviet Marshal Nikolai Ogarkov saw the convergence of trends and sounded the alarm among his colleagues. He and other Soviet thought leaders claimed that the Americans were building Рекогносцировочно-ударный комплекс (Рук, or RUK in the Latin alphabet), a

25. Amie Haven, "Killer Robots in the US Military: Ethics as an Afterthought," Towards Data Science, October 25, 2019, https://towardsdatascience.com/; and Joseph O. Chapa, *Is Remote Warfare Moral? Weighing Issues of Life and Death from 7000 Miles* (New York: PublicAffairs, 2022).

26. Scott D. West, *Warden and the Air Corps Tactical School: Déjà Vu?* (Maxwell AFB, AL: Air University, October 1999), https://media.defense.gov/.

27. ALSA Center, Air Force Techniques, Tactics, and Procedures 3-2.72, *Multi-Service Tactics, Techniques, and Procedures for Strike Coordination and Reconnaissance* (Hampton, VA: ALSA Center, January 2022), 43–54, https://www.alsa.mil/.

28. Dima Adamsky, *The Culture of Military Innovation: The Impact of Cultural Factors on the Revolution in Military Affairs in Russia, the US, and Israel* (Stanford, CA: Stanford University Press, 2010), 1–5, 33–34.

29. Adamsky, *Military Innovation,* 28–55.

"reconnaissance-strike complex" linking long-range precision fires with long-range reconnaissance.[30]

The massive air campaign of Operation Desert Storm, with its air operations center closing the loop between intelligence findings and sortie generation via an air tasking order cycle, essentially embodied the RUK. The exceptional performance of that air campaign seemed to validate Soviet concerns about American capabilities. The early 1990s marked a stepwise change in the velocity of prioritized targeting cycles. But air tasking order-based deliberate targeting operates on a time horizon marked in days. If applied as the sole targeting construct, it would perform exceptionally well against predictably located targets such as infrastructure and less spectacularly against elusive and highly mobile targets.

The complementary construct became dynamic targeting. Then, in the early twenty-first century, a doctrine called strike coordination and reconnaissance (SCAR) extended dynamic targeting.[31] In this model, the air tasking order designates an aircraft or formation to assume SCAR leadership over a specified geographic area. The aircrew utilizes the theater commander's prioritized target list to sift the sensor data they collect from the battlefield. As other strike aircraft arrive, the SCAR crew simultaneously directs those aircraft to attack discovered targets in prioritized order, destroying as many targets as quickly as possible.

In essence, SCAR represents another stepwise change in the velocity of prioritized targeting capability. Subdividing the battlespace and appointing a SCAR lead for each section permits highly parallel operations and impressive rates of target destruction. Much to the chagrin of senior Air Force leaders who want to liquidate the asset, the MQ-9 Reaper, with its remote cockpit that permits access to multiple intelligence sources while remaining connected to the battlespace, is a top-performing asset for SCAR leadership duties.[32]

But consider a complex and highly contested battlespace like the Donbas region of eastern Ukraine. Even an asset such as the MQ-9, which can accept more risk than a human-inhabited vehicle, might not attain a favorable ratio of enemy targets destroyed per aircraft lost. Direct-function thinking might pursue either of two methods to restore a functioning reconnaissance-strike complex in such an environment.

With their deep investments in low-observable aircraft, Americans might put a stealthier remotely piloted aircraft over the battlefield and resume the same model they used with the MQ-9. With more modest means but impressive creativity and resolve, as

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30. Barry D. Watts, *The Maturing Revolution in Military Affairs*, Center for Strategic and Budgetary Assessment (CSBA) Report (Washington DC: CSBA, 2011), 1–4, https://csbaonline.org/.

31. ALSA Center, *Multi-Service Tactics*, 1–13.

32. Rachel S. Karas, "As Contested Battlespace Grows, MQ-9 Explores New Roles," *Inside the Air Force* 28, no. 26 (June 30, 2017), https://www.jstor.org/; and Lawrence A. Stutzriem, "Reimagining the MQ-9 Reaper," Mitchell Institute Policy Paper, vol. 30 (Arlington, VA: The Mitchell Institute, November 18, 2021), https://mitchellaerospacepower.org/.

their Аеророзвідка (Aerorozvidka) team exemplifies, Ukrainians employ small unmanned systems to find-fix-track while artillery or aircraft target-engage-assess to close the kill chain.[33] Emergent-function thinking, however, would pursue a completely different path.

Consider a change from the "killer mosquito" vignette. Instead of developing a swarm of robots that conduct the entire kill chain autonomously, imagine designing a distributed aperture, emergent function sensing system and deploying it over vast areas of the battlespace. The devices, perhaps numbering in the thousands or tens of thousands, make no attempt to engage enemies.

Instead, they remain largely out of sight, preferring to perch in treetops when possible. If the targeting objective were enemy equipment, designers might equip the devices with low-power detectors tuned to "sniff" compounds from engine exhaust. If the targeting objective were adversary troops, the detectors might instead target ketones associated with human perspiration.[34] The emergent behavior required, in this case, is for the devices to change their spatial concentration, marking clusters of interest by being collectively attracted to targets of interest.

The concentration would not be a frenzy, either. Instead, the change in the field density of devices nearest the enemy would look unremarkable from the ground yet be high enough to correspond to a reporting threshold. Once reaching the threshold, the devices might collectively emit signals that a persistent air asset, such as an MQ-9 orbiting farther from enemy air defenses, would collect. The simple but detailed data in the signals (phase angles, modulation patterns, etc.), combined with the collecting aircraft's known position and time at receipt, would create a heat map of enemy target activity. The specificity of that data would depend on the cleverness of the designers in choosing detectors and communication schemes.

At a minimum, a heat map would provide cueing information for other sensors to identify enemy targets positively. At its best, the map might differentiate targets consistently and accurately, enabling US forces to find, fix, and track massive arrays of targets in parallel, without manual sensor allocation planning, thus accelerating the SCAR model. In some future iteration, the ambient field of detector devices might also recognize inbound friendly munitions and provide terminal guidance to targets. In this kind of *hypervelocity targeting*, the SCAR would direct all attacking aircraft to send munitions into tracked hotspots, allowing the devices to take control of the weapons during the terminal phase of flight.

33. Alia Shoaib, "Inside the Elite Ukrainian Drone Unit Founded by Volunteer IT Experts: 'We Are All Soldiers Now,'" *Business Insider*, April 9, 2022, https://www.businessinsider.com/.

34. Sara Nilsson et al., "Behavioral Responses to Mammalian Blood Odor and a Blood Odor Component in Four Species of Large Carnivores," *PLoS ONE* 9, no. 11 (October 2014), https://doi.org/.

Conclusions

This example of a hyperscale reconnaissance-strike complex illustrates why a conceptual holding category for emergent function weapons is helpful and appropriate. The devices envisioned are not exactly swarming or precisely flocking, yet they operate together as a complex adaptive system with battlefield functions that manifest only from emergent behavior at scale. Emergence is the underlying phenomenon that enables flocking, swarming, clustering, patterned diffusion, and other self-organizing system behaviors. The need to complete targeting cycles successfully in increasingly dynamic and dangerous battlespaces, and the as-yet untapped potential of emergence, provide compelling reasons to investigate these approaches.

The concept of an EFW invites the military to establish a defense research program that moves beyond the endless quest for better sensors and more processing power and instead leverages contemporary advances in behavioral robotics. Supporting constructs such as digital engineering are becoming part of the Air Force's institutional vocabulary. The combination of battlefield necessity, a clear research opportunity, and the presence of enabling mechanisms suggest now is an appropriate time to explore this design concept.

Researchers and defense leaders should approach EFW design with conservative expectations, however, because the task of shaping complex adaptive systems to force particular patterns of emergent behavior is intensely difficult. Even successful attempts are likely to have severe scope limits with the design working in some environments but not others, requiring continual adjustment during the lifecycle of the weapon system. The toolsets needed to craft weapons that follow this theory of operation might partially exist in piecemeal software packages today.

Still, designers need time to build an integrated development environment, symbolic languages, and an understanding of principles for achieving various desirable emergences from ensembles of devices operating in a complex adaptive system. Emergent function weapons are unlikely to become the singularly defining weapons of the future, but they are probably part of a wild future of advanced military capabilities.

More importantly, the conceptual category of an emergent function weapon provides a unifying construct for scholars, researchers, war fighters, and defense leaders to effectively categorize swarming, flocking, clustering, patterned diffusion, and many other complex system behaviors whose underlying commonality is leveraging emergent effects.