ASPJ

AIR & SPACE POWER JOURNAL

VOL. 35, ISSUE 2

SUMMER 2021

ASPJ
AIR & SPACE
POWER JOURNAL

Editorial Staff

Air & Space Power Journal
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The *Air & Space Power Journal* (ISSN 1554-2505), Air Force Recurring Publication 10-1, published quarterly in both online and printed editions, is the professional journal of the Department of the Air Force. It is designed to serve as an open forum for the presentation and stimulation of innovative thinking on military doctrine, strategy, force structure, readiness, and other matters of national defense. The views and opinions expressed or implied in the *Journal* are those of the authors and should not be construed as carrying the official sanction of the Department of Defense, the Department of the Air Force, Air Education and Training Command, Air University, or other agencies or departments of the US government.

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FEATURE

Thinking about Thinking

Training Aircrew to Make Decisions in Complex Situations

Lt Col E. Aaron Brady, USAF

Difficult Decisions

Recently, a flight of fighters in Syria saw evidence that a proregime aircraft struck friendly forces. A rigid command and control structure, coupled with strict rules of engagement that prevented aircrew from deciding to engage without higher-headquarters approval, led to extensive delays in targeting the threat to friendly forces. The aircrew, in this case, acted as most Air Force aircrew likely would—they felt they did not have the authority to make a decision and needed a high-level headquarters to provide guidance.

Several years before, a different fighter squadron deployed to Afghanistan to provide close air support. One day, a pilot participated in a strike controlled by a special task force. As the pilot's flight lead rolled in to attack after hours of preparation, the pilot noticed a collateral damage potential. Unsure of the ramifications of aborting the strike, the pilot quietly radioed "abort" a single time. The flight lead and attack controller missed the quiescent call in the heat of the moment. The flight lead fired, killing the target but also incurring unnecessary collateral damage.

In both stories, highly-trained and well-qualified aircrew faced ambiguous situations—situations in which the fog of war prevented the aircrew from clearly observing the variables or perceiving a single desired outcome. In the first case, the aircrew did not perceive that they were authorized to make a decision and instead were stuck in an interorganizational dilemma as component-level headquarters debated action. For this discussion, *aircrew* includes those officers at the air component headquarters coordinating with the aircrew in flight. These people were all products of the Air Force training model, although they came from several different communities within the Air Force. Of note, when the situation became more clear-cut, the headquarters rapidly approved action.

In the second case, the aircrew's decision was correct but poorly executed due to a lack of confidence. These aircrews went through the typical predeployment training regimen that squadrons usually conduct should time allow. Further, they were the products of perhaps the most robust and high-fidelity aircrew training programs in the world. So why did they perceive they either could not make a decision or not aggressively act when a decision was made? The common thread between these vignettes is a breakdown of normal Air Force decision-making processes in a complex, ambiguous environment.

This situation begs a simple question: why could well-trained Air Force aircrew not make or apply effective decision-making in these situations? The answer is also relatively simple. They did not perceive they could act, or they did not know how to act. This predicament, unfortunately, leads to a more challenging question: why did they not know after years of training? This article attempts to address this question by examining the theory behind Air Force tactical aircrew training.

The author posits that the Air Force excels at teaching aircrews to perform in unambiguous, large-scale tactical environments. However, the Air Force should place more emphasis on proactively developing aircrew judgment and improving the recognition of strategic context as a fundamental attribute of situational awareness. This argument rests on the logic that at its core, sound tactical decision-making rests on the ability to effectively orient. If training only develops judgment and familiarity within clear-cut environments, aircrews will continuously have difficulty making decisions in more complex environments. This difficulty will reinforce the notion that detailed guidance is required for any situation that falls outside clearly defined parameters (leading to repeats of the first vignette) or more simply or poorly made or executed decisions (resulting in undesirable tactical outcomes like in the second vignette). The Air Force needs to *think about how it teaches aircrews to think*.

The Theory of Air Force Training

Currently, Air Force training for tactical aircrews generally follows a decentralized building-block approach. This model relies mostly on squadron-level instructors teaching younger aircrews to solve tactical problems and upgrading those pilots to higher levels of responsibility. As aircrews grow more experienced, the problems they are expected to solve become commensurately more challenging. This methodology produces superbly trained aircrews in the world for solving *identifiable* tactical problems. This approach is insufficient for success in modern conflicts.

The Air Force Training Model

Most people have heard the phrase "crawl, walk, run," at some point in their lives. This phrase aptly summarizes the Air Force theory of training. Initial formal training programs produce basic aircrews and form the first part of the crawl phase.

The crawl phase is all about learning to fly or otherwise operating an aircraft as a junior part of a flight or combat team. The aircrew are taught to perform tactical tasks when directed and trained to be "thinking wingmen"; this means the ability to anticipate a flight lead's or aircraft commander's directions. Wingmen develop this skill through experience. This development forms the latter part of the crawl phase and blends into the first portion of the walk phase.

Walking entails becoming proficient at operating one's aircraft and transitioning from being a wingman to leading a small team—becoming a flight lead or aircraft commander. Squadron commanders design syllabi, framed by limits set in *Air Force Manual* 11-2MDS, to progress aircrew through the various upgrades. Squadron-level instructors conduct this training, guided by commanders and weapons officers. In the author's experience, over time, instructors often develop "pet problems"—somewhat complicated tactical problems they typically present to students.

As an example, an A-10 instructor might consistently present an upgrading flight lead with a convoy being attacked by enemy troops within 100 meters or a close air support strike without a qualified joint terminal attack controller. A common problem in the F-15E community is to have an SA-15 battery "pop up" during the mission. Bomber instructors often present problems such as last-minute target changes or weapons malfunctions.

Most aircrews spend the bulk of their flying careers performing continuation training—meaning aircrew training themselves. The flight leader designs a mission to accomplish specific objectives, usually focused on practicing a specific skill or set of skills. Air Combat Command's (ACC) Ready Aircrew Program provides guidance as to what aircrew must practice on an annual basis. Ideally, aircrews hone their combat capabilities during these flights.

Putting the crawl and walk phases together shows the ideas behind the bulk of aircrew training. During early training, aircrews learn to solve simple, technical problems such as delivering weapons, operating sensors, and so forth. As they perform continuation training, they improve these skills. Once they demonstrate an appropriate level of proficiency, commanders enroll aircrew in squadron-level programs to upgrade them to higher positions.[1] The problems then become more difficult—they are tactical as opposed to technical problems. In general, those aircrews learn to analyze tactical problems and solve them as quickly as possible. Once they have mastered this, aircrews are ready to move into the "run" phase.

A tactical Airman "runner" can plan and lead a package to accomplish a mission. These aircrew members are instructors and mission commanders. As mission commanders, they are expected to be able to compile a series of individual tactical problems into a broader, overarching tactical problem that the mission package must solve. As instructors, these same Airmen must understand how to design training scenarios to teach those skills and the more basic skills acquired during the crawl and walk phases to younger aircrew.

Most activity in Air Force training, therefore, focuses on instilling technical skill and tactical acumen. The Air Force model relies on its Airmen learning the art and science of identifying and solving tactical problems to provide combatant commanders with the right people to execute air warfare. The entirety of this discussion on the current training model leads to this point: tactical problems are the root of Air Force aircrew development.

What is a Tactical Problem?

There is no agreed-upon definition of a tactical problem, but instructors around the Air Force discuss them at length. Air Force doctrine asserts that tactics are "concerned with the unique employment of force" and the "specifics of how engagements are conducted."[2] *Air Force Tactics, Techniques, and Procedures* (*AFTTP*) 3-3.IPE defines *tactical problems* as "meeting the commander's intent within the threat environment."[3] Tactical problems begin with a phrase well-known to most operations Airmen: backward planning.

Tactical problems begin with an effect correlated to a point or set of points, in time and space. At its most simple level, this could be an air-tasking order-directed strike on a fixed target—like a bridge—with a tasked time-on-target for weapons impact. Depending on the scenario, there might be friendly ground forces or collateral damage concerns that complicate the situation. Often, there may be several ways of achieving the desired effect, although, the weapons one takes off with limit those choices. Which kinetic or nonkinetic munition the planner selects is based on several factors that revolve around risk.

While strategic risk can be much more complex, operational and tactical risk can generally be divided into two categories: risk to mission and risk to force. Within these categories, most Air Force tactical communities tend to emphasize certain issues during training to generate risk. Instructors simulate risk to mission through technical failures (like onboard system failures), communications failures (flawed information passed), or late changes (target changes). Instructors present risk to force via enemy threats, usually surface-to-air threats based on replication availability. Tactical problems, therefore, are situations in which aircrew must mitigate risks to deliver an effect at a prescribed point in time and space.

Solving Tactical Problems

Solving these problems entails combining resources with specific tactics. Tactics are specific formations, maneuvers, contracts, and any other techniques or procedures used to employ the resources. Resources are tangible assets allocated to a given mission, such as aircraft, weapons, nonkinetic/nonlethal capabilities, and so forth. Aircrews decide how best to distribute the available resources and what tactics to use to create the overall mandated effect while mitigating risk to the mission and the force.

Often, aircrews make these decisions on the ground during mission planning. The Air Force model emphasizes planning as the best time to resolve the myriad issues, making tactical problem-solving difficult. The purpose of mission planning, according to *AFTTP* 3-3.IPE, is to solve tactical problems.[4] Aircrews learn to determine artful combinations of resources and tactics to create tactical solutions. When progressing to higher levels, the problems become more complicated and expectations for solutions grow, leading to the preparation of multiple solutions in case the situation in flight invalidates the primary solution. The purpose of mission planning is to make decisions "at one g" to speed decision-making in flight. This model developed over decades based on hard lessons learned in the last 70 years. The model's strengths and weaknesses are rooted, wittingly or not, in accounting for how people think.

The OODA Loop and Heuristics

It is misleading to suggest that there is a single, articulated theory that underlies the described Air Force model. As argued previously, the bulk of aircrew development occurs within the operations groups and squadrons. This circumstance means that aircrew training and education are inherently decentralized. Each community develops its perspectives on what issues are important, and groups and squadrons further refine those perspectives. Nevertheless, common threads are observable across the tactical flying communities.

In military aviation, the ability to make accurate assessments and good decisions promptly is paramount. In one of the only codification examples of decision-making in Air Force guidance, most flying standardization and evaluation criteria include a category labeled as "Airmanship" or "Situational Awareness." This category is listed as "critical," and typically the first criterion listed is that the mission is executed in a "timely, efficient manner." The second criterion is along the lines of flying with "a sense of understanding and comprehension" of the situation, even as it changes in flight.[5]

Making sound decisions quickly based on an accurate understanding of the situation relates to John Boyd's famed Observe-Orient-Decide-Act (OODA) Loop. Boyd developed the OODA Loop initially as a model for understanding decision-making during dogfights. The pilot who could adapt to change faster would win the fight.[6] While Boyd adapted the OODA Loop dramatically throughout his lifetime to embrace strategic-operational problems, its original aerial tactical application remains a key part of many Air Force pilots' thinking. Instructors tend to focus on teaching their students to recognize situations and react as rapidly as possible. To do this, they present tactical problems to students with the goal of developing useful heuristics (mental models for solving problems). Two examples of basic heuristics taught to aviators from the beginning are "aviate-navigate-communicate" and "maintain aircraft control, analyze the situation and take the proper action, and land as soon as conditions permit." These simple phrases, drilled into their minds, provide a basic model for aircrew to understand prioritization and how to deal with emergencies, respectively.

In *Thinking, Fast and Slow*, Daniel Kahneman described the two systems that govern much of human thinking. System 1 functions automatically and quickly, while System 2 uses effortful thought to solve challenging problems.[7] When one intuitively knows the answer to two plus two, that is System 1 in action. However, years of experience as a child led to learning basic arithmetic skills, meaning that a developed mental model can be quickly applied when presented with a simple addition problem—a heuristic model. When thinking intensely about a chess move, that is an indication of using System 2 thinking. Unless already a chess master, a person does not have a model available to make rapid decisions, meaning they must consider the options before deciding and acting. Air Force training works under the presumption that a person can learn to *intuitively* know the right tactical "move" with the appropriate experiences, in the same way of intuitively knowing that two plus two is four.

This presumption is valid but only if the context is similar. Using the chess example, heuristics certainly help people play the game better. Psychologists and scientists conducted numerous studies of chess players in the past century. The general conclusion is that experienced players perceive chess positions as "chunks" or certain groupings of pieces. Having already learned the best move(s) for a given chunk, a player can quickly decide on an action. Masters may possess up to 100,000 chunks, while average players remember far fewer.[8] This example illustrates the idea behind Air Force training. Aircrews learn to recognize tactical problems and apply known solutions to solve them. This model only works, though, if both sides are playing chess and with the same ruleset. Aircrew judgment honed to function only with a narrow contextual frame will not benefit one's decision-making if the situation is outside that frame.

Kahneman's concept describes the cognitive process which occurs while working through the OODA Loop (see fig. 1). First, observe a situation. Observing, in the context of aircrew in a tactical environment, encompasses what Airmen refer to as situational awareness. This OODA Loop phase is defined as an aircrew's "continuous perception of self and aircraft concerning the dynamic environment of flight, threats, and mission, and the ability to forecast, then execute, tasks based on that perception."[9] The second portion of the definition shifts into orientation and decision.

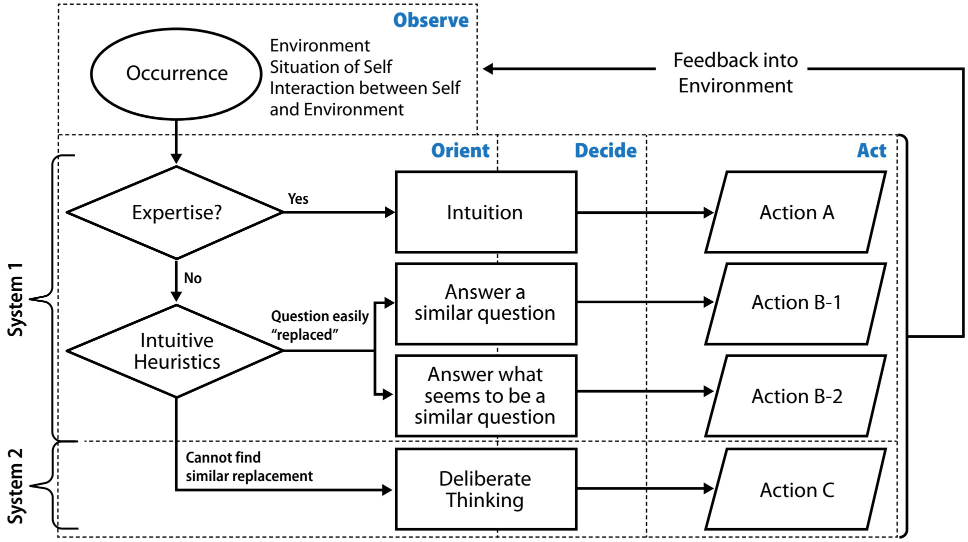

Figure 1. Kahneman's basic System 1/System 2 model overlaid with Boyd's OODA Loop

Boyd referred to orientation as "the big O," and it formed the center of his final iteration of the OODA Loop. He described *orientation* as an "amalgamation of genetic heritage, cultural traditions, previous experience, education, new information, and the analysis and synthesis that follows."[10] During tactical execution, orientation is the process of assessing the competing variables in an environment through a lens provided by years of Air Force training. Variables include physical properties like relative positions of objects, situational context like the intent of the current mission and rules of engagement, and cognitive context.

Cognitive context is the variable-set most applicable to this article. An Airman's mind is the place where aircrews interpret the observed physical and situational variables and assign meaning. This process allows the person to produce a set of possible decisions. The Air Force training model helps and hinders this process.

Earlier, this article explained System 1 thinking as an automatic, intuitive process. Kahneman argues that when people observe an occurrence, their minds seek a quick answer. People determine if the situation is precisely like one seen many times (and therefore already have a valid solution to the problem). If so, they apply the solution previously applied to the same problem. Humans rely upon an almost continuous stream of heuristics to navigate everyday life. Yet, despite their importance, they can, in some cases, have significant limitations and consequences. This tendency is particularly true for aircrew flying in a high-stakes, time-compressed environment.

Consider the difference between two pilots performing basic fighting maneuvers. If the flight lead has several thousand hours and thus has performed this skill potentially hundreds of times, this pilot will make any number of intuitive decisions during the engagements with minimal mental effort. Another pilot, fresh out of mission qualification training, may be unable to make those same decisions or take several seconds to enact a decision the experienced pilot performs in less than a second. This situation is intuition, or the lack thereof, at work. However, even highly experienced aircrew encounter less familiar situations.

If one cannot apply a known solution, the mind tends to transpose what it deems a similar situation to apply a solution perceived as valid. The mind finds a presumably acceptable existing model and unconsciously applies it to the current situation. This process can have serious consequences in solving novel problems.

Returning to basic fighter maneuvers, consider what often happens the first time a pilot fights another type of aircraft. Usually, even despite a briefing to the contrary, the pilot maneuvers in a way proper for fighting a similar aircraft but potentially inappropriate for a dissimilar aircraft with different weapons or flight characteristics. This tendency is an example of replacement. The pilot recognizes the situation: a dogfight against a dissimilar adversary. The pilot's mind, attempting to remain in System 1 thinking, orients on the situation by recalling heuristics useful for fighting a similar aircraft rather than go through the difficult process of determining new models for fighting the new aircraft. The mind presents a solution that appears valid but does not correspond to the true situation. Regardless, only if these two attempts to find an intuitive solution fail—or if one deliberately chooses—does the mind switch to System 2 thinking.

When one cannot intuit options, the mind resorts to deliberate thinking. This mode of thinking, while slower and more effortful, is best suited to resolving unfamiliar or complex problems. It is so effortful that using System 2 thinking can make one "effectively blind, even to stimuli that normally attract attention."[11] A characteristic of upgrading aircrew, especially in more difficult programs like instructor upgrades or the Weapons Instructor Course, is for students to stop communicating when the scenario becomes especially challenging. Most instructors can convey stories of students who either stopped acknowledging communications, stopped talking, or both. Likely, the student was in System 2 thinking. The student's mind was so focused on deliberately thinking through the problems that the student was unable to do other tasks, even critical ones, like communicating.

Air Force training aims to help aircrew remain in System 1 thinking—especially in flight—by building expertise or the ability to apply intuitive heuristics and thus orient, make decisions, and act quickly. Air Force training seeks to develop useful heuristics for an aircrew to make decisions earlier in the decision-making process, thereby speeding the OODA Loop cycle. Possessing a robust "toolkit" of models to resolve tactical problems with, aircrew should theoretically be able to make rapid decisions by operating mostly in System 1 with System 2 merely cross-checking the results of System 1. This conclusion brings the discussion back to the notion of tactical problems.

Previously, *tactical problems* were defined as comprising two key elements: effects and risks. Through years of training, aircrews learn to deliver effects at discrete locations and mitigate risks, including risks to the mission and force. Boyd's OODA Loop suggests that whoever can adjust to a continuously changing environment faster is more likely to succeed in a fight. Therefore, Air Force training strives to teach expertise for technical tasks and heuristic models for solving tactical problems so that aircrew can make quick decisions by remaining largely in fast System 1 thinking.

This system is quite effective at producing highly skilled aircrew for large-scale combat. When Air Force aircrew know exactly what the desired outcome is, they excel at determining solutions to problems. The Air Force training process produces aircrew with a mastery of dealing with clear tactical environments in which failure is only possible through poor execution.

What happens, though, when an aircrew does not know what the desired effect is? The very structure of the tactical problem breaks down because there *is no clearly defined desired effect*. The two stories in the introduction, as well as many others just like them, suggest that the current system does not prepare the aircrew well for the unclear situations that are becoming more commonplace in the various operating environments around the world.

Judgment

If tactical problem-solving revolves around combining situational awareness and judgment within a contextual frame to select a course of action, then failures in decision-making must stem from failures in one of those two broad categories. A brief examination of the ways instructors teach situational awareness and judgment suggests that any shortcomings with the current model stem from efforts to teach judgment.

Situational awareness is a key element in most aspects of the Air Force training model. Every aircraft standardization manual includes situational awareness as a critical criterion for evaluation, illustrating its perceived importance. This importance also plays out in training methodologies.

Debriefing techniques focus extensively on situational awareness. In the last two decades, the debrief focus point process took hold within the Combat Air Forces. After identifying the root cause of a problem, one should determine if the issue was an "input error" (the aircrew did not have correct situational awareness), "output error" (the pilot had situational awareness but did not execute as intended), or "decision error" (the pilot had situational awareness and executed as intended but made a bad decision).[12] While the specific terms vary in usage, this concept is embedded within ACC learning methodologies. Two of these errors are rooted in technical expertise and situational awareness. The third, decision errors, alludes to judgment.

Judgment, though, is a more elusive quality to both learn and teach. Sir Andrew Likierman, a former dean of the London Business School, asserts that *judgment* is "the ability to combine personal qualities with relevant knowledge and experience to form opinions and make decisions." The same author further argues that good judgment is essential to making decisions in ambiguous situations—the crux of this article.[13] Assuming that an Air Force flying training model is unable to meaningfully change someone's personal qualities (perhaps not a fair assumption, but necessary to limit the length of this discussion), this leaves the question of how the Air Force training model provides knowledge and experiences to inform decision-making.

Studies into critical thinking divide knowledge into three categories. *Declarative knowledge* is concepts, stories, principles, and so forth to make inferences. *Procedural knowledge* is knowing when to use declarative knowledge to act.[14] *Metacognition*, also called executive control, makes plans, sets goals, and observes the effects of one's actions.[15]

Analyzing this categorization of knowledge informs the type of knowledge one needs for good judgment is metacognition. Metacognition, typically described in an educational sense, focuses on the ability to assess one's thinking processes.[16] An aviation example of metacognition can be seen during emergency procedures. Part of the emergency heuristic described earlier and taught to all Air Force pilots is to "assess the situation." Metacognition is the part of the thought process that, after the aircrew has diagnosed the problem, pauses for a moment to verify that there are no other variables that might recommend a different course of action.

The Air Force model certainly provides both declarative and procedural knowledge. The training process supplies ample instruction in the technical aspects of performing aviation tasks. Additionally, the nature of aviation makes it difficult to perform tasks out of a suitable context. In an extreme example, one can see that performing a task normally associated with landing while cruising, like landing gear, would be "self-correcting." Since the training model provides these two forms of knowledge, instructors should ensure that they also deliberately teach metacognition. Figure 2 adds the forms of knowledge to the previous thinking model.

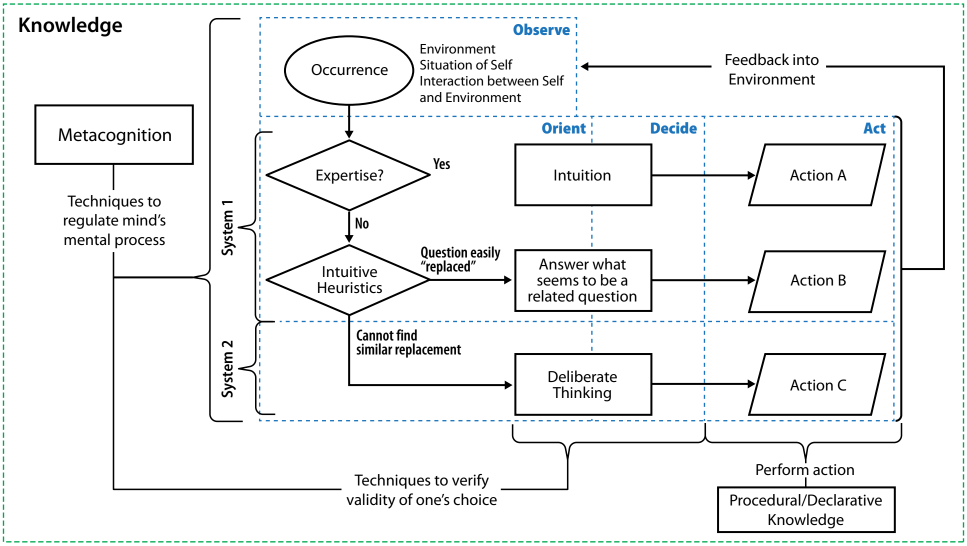

Figure 2. Kahneman's basic System 1/System 2 thinking model overlaid with Boyd's OODA Loop and forms of knowledge

One learns metacognition (and the other forms of knowledge) through the second aspect of judgment described by Sir Likierman: experience. The discrete events that comprise a typical training experience for an Airman teach that person technical expertise and a variety of heuristics to solve technical and tactical problems. Those experiences also coalesce into metacognitive processes that help an aircrew make choices about which expertise or model to apply to a given situation.

These observations lead to the conclusion that an aircrew's experiences and reflection on those experiences produce intuition, heuristics, and metacognitive processes. When a situation causes the aircrew to progress beyond the first stage of System 1 thinking (expertise), metacognitive processes guide the selection of heuristics or movement into deliberate thinking. Therefore, if experiences provided in training do not present ambiguous situations or operational context, it is significantly more difficult for an aircrew to develop the judgment to deal with complex situations. Worse, aircrew members might apply an irrelevant heuristic to the situation, make a poor decision, and not possess the metacognitive qualities necessary to validate their own decision. In short, the lack of ambiguity and context in training breeds the mental paralysis demonstrated at the beginning of this article.

Recommendations

Air Force training methods should more deliberately cultivate judgment to better prepare the aircrew for complex contemporary operational environments. This goal can be achieved by incorporating ambiguity and more complicated context into training environments. Instructors should present aircrew with situations in which there is no "right" or "winning" answer—situations that force the aircrew to make hard choices based on incomplete information. Given the decentralized methodology of Air Force training, these recommendations focus primarily on options for implementation at the squadron level.

Ambiguity

Ambiguity is the most important variable that should be introduced into training scenarios. By presenting aircrews with unfamiliar problems for which there is no clear answer, instructors will force them into System 2 thinking and provide opportunities for metacognitive development.

In most training tactical problems, the desired effect is clearly understood by the aircrew. The learning mostly occurs in using situational awareness and judgment to determine the best combination of resources and tactics to deliver that effect while mitigating risk. However, there is great value in sporadically presenting problems in which the answer is unknown. This tactic will force the aircrew to decide which resources they should use (or even if they should apply resources) and in what tactical manner given the situation.

One example, already becoming familiar given recent experiences in Syria, might be to include a third-party actor in an air interdiction scenario. A potential target could either belong to the intended enemy or the neutral third party, forcing the aircrew to decide whether to strike. Additionally, a third-party surface- or air-based platform might threaten trainees, forcing them to decide how to react.

Some challenges might even present moral dilemmas. For example, many Weapons School Integration phases include a noncombatant evacuation operation. The instructor of this mission could create a situation in which enemy forces break into the base perimeter during the loading process, or the assembly area begins to take artillery fire. Such a circumstance forces the mission commander to make an exceedingly difficult decision that has no clearly "correct" answer. Other opportunities exist to simultaneously force decision-making in ambiguous circumstances and enhance the concept of all-domain operations.

An instructor can generate a plan for a student that includes certain simulated effects created within or through other domains. At the appropriate time within the scenario, the instructor can either tell the student the desired effect was not achieved or provide no input whatsoever, forcing the aircrew to make a hard choice about further actions.

These options, among a myriad of other possibilities, intend to create situations in which there is no clear answer. The purpose is not to instruct the aircrew (whether in flight or the debrief) on what the *right* answer was; instead, the intent is to provide an opportunity to develop *judgment*. Ambiguity forces aircrew to apply System 2 deliberate thinking and use metacognitive skills to assess their thinking to ensure that their actions make sense in the given environment.

Operational Context

The above suggestions require that instructors put thought into the operational context of a given mission. Boyd emphasized context in a variety of forms as a key part of orienting. An Army research paper on tactical problem solving cited context as "the foundation for rational decision-making and purposeful activity."[17] Since most of the arguments in this article revolve around the process of orienting and deciding, the context within training is vital. Indeed, the *Integrated Planning and Employment* manual (*AFTTP* 3-3.IPE), asserts that "tactical experts need to be aware of the multi-domain context in which their missions are conducted and strive to understand how their tactical operations both rely on and bolster other domains."[18] Without context, situational awareness is incomplete since contextless awareness would only include the physical aspects of the situation and ignore countless other variables which should inform judgment.

This lack of awareness does not mean that each training scenario requires an intricate backstory or a highly developed plot. Instead, instructors should deliberately provide information before the mission that should color the upgrading aircrew's perspective. Then, the instructor should strive to present a situation in which the aircrew must make a decision, taking the information into account.

An example that applies to any counterland mission might be to lay out a situation in which the aircrew must disrupt or prevent enemy movement through a certain area to enable friendly action in another domain. Then, the instructor might present easy targets in different areas of the battlespace to see if the aircrew loses sight of the intended purpose. Another related example is to place a scenario within a more constrained operational environment. Consider the difference in decision-making that might result from presenting the same target, such as a convoy of light armored vehicles traveling through a town, in a large-scale combat context versus a more constrained context like that present over Kosovo in 1999. In a large-scale combat environment, it is likely appropriate to attack immediately. In a more limited environment, a better decision might be to wait until the convoy is in the open, although there is a risk associated with potentially losing track of the target. These sorts of decisions and risk-mitigation discussions are precisely the point of introducing tactical problems within different contexts.

When to Introduce These Concepts

In a recent discussion about this subject, an instructor asked this author at what training level such concepts could be realistically introduced. While there is no clear answer to this important question, it seems logical that these ideas do not apply to early training ("crawl" phase) when aircrews are still learning basic skills. Instructors should introduce minor contextual problems or small amounts of ambiguity to aircrews in the intermediate ("walk") phase of training. Aircrews in the advanced ("run") phase should receive more complex context and ambiguous situations to further develop judgment. This approach rests on the idea that there is a distinct separation between technical skill and tactical problem solving.

During early training, aircrews learn technical skills—how to operate systems, how to perform maneuvers, and the like. They do not need to learn why to use those skills. The expectation is that a flight leader or aircraft commander will inform them when it is time to employ a known skill. Ambiguity or complicated context would merely confuse the learning objectives.

However, the latter phases of training teach aircrews to solve tactical problems. Aircrews should learn from the beginning that selecting the appropriate resources and tactics for a given problem does not rest solely on the tactical situation. There are broader considerations that should inform their judgment. Further, the situation may not always be clear, and context should help inform their decision-making in those times.

The need to learn good judgment should be balanced, though, with the understanding that aircrews in an upgrade are usually performing a role for the first time. Most of the tactical problems that aircrews face should be clear and the context relatively easy to understand, allowing them to develop a baseline for judgment. As the aircrew progresses through the given upgrade, they should be presented with more complicated context and ambiguous situations commensurate with their experience and performance. Only by presenting these situations will aircrews develop better judgment tools.

Continuation training is another opportunity to present ambiguity and context. This form of training is where aircrews spend most of their flying careers and, ipso facto, where they develop most of their perspectives on decision-making. This approach may not always be effective because it is challenging for flight leaders or aircraft commanders to give themselves a problem to which they do not have an answer. Further, there is some risk in this approach. Overzealous aircrews may give themselves or their wingmen problems that put them into unsafe situations. Additionally, each time someone resolves a problem, they create a new heuristic for themselves.

These considerations lead to three conclusions. First, ambiguity and context should be presented during upgrade training because instructors are the best people in a squadron capable of managing safety, and the upgrading aircrew will not know the answer ahead of time. Second, commanders should consider having instructors fly on continuation training missions with the express intent of presenting such situations to the other aircrew. Finally, the point is not for an aircrew to conclude in a debrief that "when faced with X, I should do Y." The goal is to look at a successfully resolved problem and ask, "how did I approach thinking about this novel problem that worked out so well?" Instructors should not repeatedly present the same problems to an aircrew. Such a practice reduces the likelihood of aircrew-building heuristics, instead encouraging increased emphasis on *thinking processes*.

Opportunity Cost

Such an approach should improve the overall quality of an aircrew's thinking. As a result, an aircrew would be more capable of effectively orienting during future missions. This, in turn, would make the aircrew more capable tactical problem solvers. Leaders should not, therefore, view adding ambiguity into training scenarios as an additional burden to already overtaxed squadron training schedules.

Ideally, the Air Force should fund additional flight hours to give commanders more sorties to provide this sort of training. However, fiscal realities, steadily increasing costs per flying hour for large portions of the CAF's fleet, and squadrons already flying their aircraft at or near maximum sustainable utilization rates make increasing sorties unlikely. Additional spending due to COVID-19 in excess of $4 trillion makes any increase in sorties virtually impossible in the near future since defense budgets will probably reduce.

If live flying resources will not increase, commanders should consider reducing or even dropping training time spent on familiarization-only recruiter assistance program events. The added time could then be used to add the training described in this article. The improved aircrew judgment that would result would presumably improve their ability to make better decisions in missions they are unfamiliar with, potentially offsetting the negative aspect of cutting familiarization training.

Another option is to leverage simulators. Simulator missions generally require minimal effort to produce and have the advantage of being able to present entities and situations not easily created in typical live training. However, simulators often suffer from technical issues that sometimes detract from the desired tactical focus (nonfunctional systems, improper displays, etc.). Additionally, commanders will need to devote instructors' time to simulator missions. In this author's experience, most simulator mission debriefs last for 10 minutes or less absent significant errors. To get the full desired effect, a simulator debrief should incorporate a full analysis of the student aircrew's decision-making and performance, using debrief focus points or learning points just like a live flight.

Time spent on ambiguous tactical problems invariably means that one or two more traditional tactical problems are not presented. However, aircrews will still spend most of their training time solving traditional tactical problems (those with clear-cut desired outcomes and sufficient information available to accurately orient to the situation with few unknown variables). Thus, they will still achieve a similar level of skill at general tactical problem solving. Introducing ambiguous problems should only improve an aircrew's overall problem-solving ability, not detract from the skillset development the current model instills in the aircrew.

Conclusion

The Air Force training model is a sound concept that has delivered exceptional results over decades. However, the operational environments aircrews may face in the next decade are unlikely to be characterized by relatively unrestricted, large-scale combat against peer adversaries.[19] While Air Force aircrews should prepare for that possibility, they must also be able to make decisions in more ambiguous and confusing environments like those found in Afghanistan, Syria, or the next potential combat zone.

Air Force commanders and instructors should emphasize developing nuanced judgment within the aircrew. Aircrews should enhance their situational awareness with deeper understandings of operational context. Introducing operational context and ambiguous situations into training regularly should improve and develop aircrews' judgment throughout their flying careers. They should then apply that judgment to complex situations and make reasonable decisions that advance the joint force, through tactical action, toward achieving operational and strategic objectives. ✪

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Notes

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FEATURE

Game-Theoretic System Design in the Development of Space Power

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John M. Colombi, PhD

Introduction

The US space enterprise plays an integral role in maintaining the peace and prosperity of the nation. In times of conflict, the country depends on American space power. Leaders within the US space community advance space power through the evaluation and execution of strategically interdependent decisions. These decisions pertain to the technology development, acquisition, and operation of space systems and are analogous to moves, strategies, and payoffs in multiplayer games. Using game-theoretic models, decision-makers possess the valuable opportunity to partially manipulate game structure before stepping into the role of a player. To bolster this hypothesis, this article presents several game-theoretic system design concepts. First, this article contextualizes the spectrum of agent strategic interactions, from collaboration through competitive to more antagonistic outcomes. Second, a new taxonomy for the classification of game-theoretic models is proposed. Third, we expound on the proposed taxonomy using eight atomic game structures and exemplify their use with pertinent space applications.

Game Theory

Game theory dates back to work by John Von Neumann in 1928. With wide applications in political science, economics, biology and genetics, sociology, linguistics, and even system design, game theory is a tool to solve decision-making problems. A game involves a set number of players, strategies (decisions, possible moves, or actions), and a payoff or value that captures the outcome of each play per player.[1] The strategy or strategies for each player can be simple and small, or complicated. Consider chess, where the number of possible moves and strategies are massive. But even for atomic games with two players and two possible moves each, one can observe interesting and counterintuitive scenarios and equilibria. Three important aspects of game theory include agent utility balance, Nash equilibrium, and the Pareto front.

Agent utility balance states that an outcome holds approximately the same utility for all agents.

Nash equilibrium relies on the conventional use of the term in the field of game theory—a set of strategies, one for each player, such that no player has an incentive to unilaterally change their current decision or move.[2] A player achieves a pure-strategy Nash equilibrium (where such equilibrium exists) by playing a single strategy. A player can achieve indifference in the other player(s) through a mixed-strategy Nash equilibrium wherein a set of pure strategies are played with some probability.[3]

Generally, **Pareto optimality** exists when no single criterion can be improved without diminishing at least one other criterion. In the case of a two-player game, the two-dimensional Pareto front considers each agent utility as a positive asset for maximization. The Pareto front is formed using nondominated outcomes within the game-theoretic model.[4]

The Atomic Competitive Element Taxonomy

The Atomic Competitive Element (ACE) taxonomy presents an abstract and descriptive decision space that illustrates contextually desirable attributes. Therefore, an understanding of the ACE taxonomy encompasses comprehension of that context, specifically, agent goals and the resultant behavior. While the user may frame any game-theoretic model with the ACE taxonomy, situations containing self-interested players (who nonetheless display a willingness to cooperate to achieve a mutually beneficial outcome) provide the most natural fit. Close allies with a shared goal, working toward a collaborative outcome, often diverge from the ACE taxonomy construct. Similarly, hostiles committed to self-deleterious min-max strategies frequently eschew such a framework. The span between these extremes—including self-interested cooperators, competitors, and belligerents—fit naturally into the ACE taxonomy construct.

Collaborative outcomes maximize the collective utility of the agents within the game. Close allies with a shared vision, generally common values, and a shared goal, often work toward such outcomes; each agent sees the team success as personal success. Under certain circumstances, such an approach can maximize both coalition and individual utility over the long term. By maximizing team utility, collaborative outcomes always exist on the Pareto front. Collaborative outcomes do not fit as naturally within the ACE taxonomy framework.

Cooperative, competitive, and antagonistic outcomes always use Nash equilibria as the baseline solution. Agents working toward a cooperative outcome are willing to move from a Nash equilibrium to a mutually beneficial outcome with a higher utility for both players. In a cooperative context, agents treat each other benevolently and work for the betterment of other agents as long as the respective individual agent garners a positive or neutral result. Cooperative outcomes generally fall on a Nash equilibrium or a Pareto front outcome with adequate utility balance and mutual utility improvement. They also generally maximize individual utility within a specific game. Allies with shared interests work together toward the same outcome. Importantly, agents within such a context need not demonstrate altruism (i.e., agents act in self-interest), but the agents must trust each other and act in good faith.

Naturally, competitors pursue competitive outcomes and seek to maximize individual utility through individual effort. Competitive outcomes land on Nash equilibria. Agents within such a context display indifference toward other agents—seeking neither good nor harm for fellow players.

Antagonistic outcomes display the same characteristics as competitive outcomes except that, in such a context, agents choose to harm each other when there is no cost to do so. For example, an agent given two options with the same personal utility would follow a min-max strategy to minimize the other agent's utility. Cooperative, competitive, and antagonistic outcomes, as well as the associated agent behavior, naturally fit into the ACE taxonomy framework.

In a hostile context, adversarial players engage in a pure min-max strategy wherein every choice minimizes the other agent's maximum possible utility.[5] When seeking a hostile outcome, agents pursue this min-max approach even when such a strategy presents self-detrimental consequences. Interestingly, these hostile agents are not self-interested and can be trusted to always commit the most harmful action. Hostile outcomes and belligerents do not fit into the ACE taxonomy construct. Reference figure 1 for the spectrum of interaction among agents in a game.

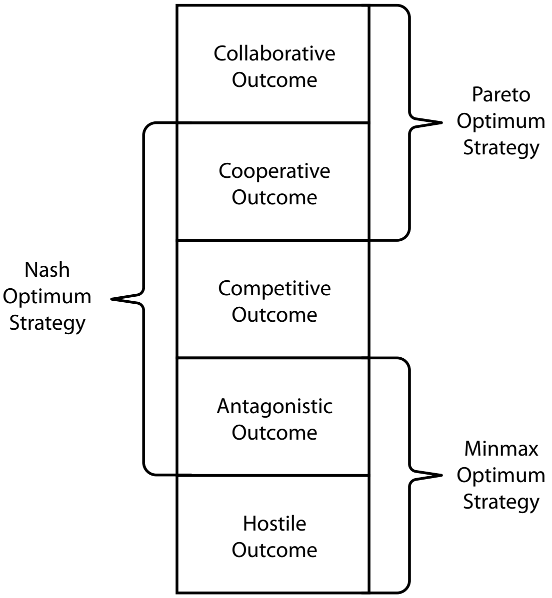


Figure 1. Spectrum of interaction

The ACE taxonomy illustrates and classifies game-theoretic models according to three contextually desirable attributes (for the stability of an outcome), which may exist in a particular outcome: agent utility balance, Nash equilibrium, and the Pareto front.

The ACE taxonomy represents these three attributes with primary colors, their combinations with secondary colors, the presence of all three attributes with white, and the absence of all three attributes with gray. Reference figure 2 for the Venn diagram illustrating the ACE taxonomy.

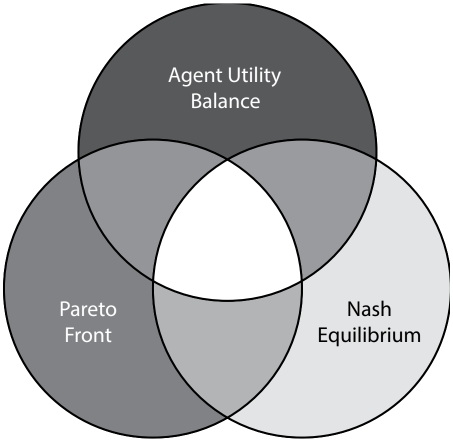


Figure 2. Factors of stability in multiagent games

Characterization of Atomic Competitive Elements

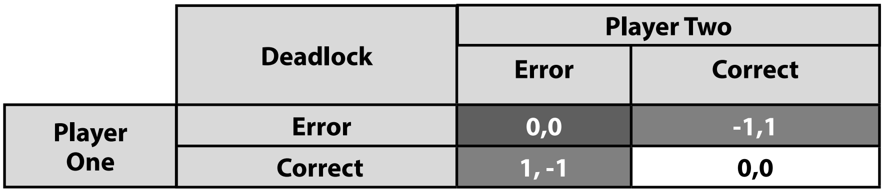
This section introduces and characterizes eight fundamental building blocks of ACE that are significant in the formation of many higher-complexity game-theoretic models. The user of this taxonomy may recognize each kind of ACE by its unique color scheme based on the three properties (agent utility balance, Nash equilibrium, and the Pareto front) present or not within each of the four outcome cells of the respective two-by-two matrix. This taxonomy does not consider game-theoretic models as unique ACE wherein the game designer may trivially rearrange the choices of the respective game to achieve a repeated color scheme. Systematically categorizing game-theoretic models at a fundamental level empowers the user to identify the scenario at hand, understand the scenario's dynamics, and draw upon heuristic solutions to maximize the utility for one or more agents within the game. Specifically, this article uses this taxonomy to address challenges and opportunities in the development of space power.

Deadlock

In Deadlock, each player knows both the correct and incorrect answer and must simply choose the correct answer. If both players choose the same answer, they earn a neutral utility value. If one player makes an unforced error, the winning player achieves positive utility at the expense of the losing player. Importantly, this game, as well as the other games, are presented in a strategic form where both players must act simultaneously; players do not know what the other player will do, and prior communication or coordination is not guaranteed.

Perhaps the most stable and simple game-theoretic model, Deadlock contains a single balanced pure-strategy Nash equilibrium on the Pareto front. Deadlock presents a straightforward, intuitive scenario wherein agents converge to the Nash equilibrium with no opportunity to improve utility through cooperation.[6] Other outcomes within Deadlock represent unforced errors by one or more agents. Reference table 1 for the game of Deadlock using the ACE taxonomy.

Table 1. Deadlock



	Deadlock	**Player Two**	
		Error	**Correct**
Player One	**Error**	**0,0**	**-1,1**
	Correct	**1, -1**	**0,0**

Pure Coordination

In Pure Coordination, players must decide to stay or go. If both players choose the same answer, both players achieve a positive utility. If players differ in their choices, neither benefits.

The self-explanatory Pure Coordination game-theoretic model presents an extremely stable game in the presence of effective communication with two balanced pure-strategy Nash equilibria on the Pareto front and one mixed-strategy Nash equilibrium.[7] Since the payoffs for both pure strategies hold the same utility for each agent, players of the game display indifference in the pursuit of a particular pure strategy and act amiably in the respective coordination. Reference table 2 for the game of Pure Coordination, using the ACE taxonomy.

Table 2. Pure Coordination

	Pure Coordination	**Player Two**	
		Stay	**Go**
Player One	**Stay**	**1, 1**	**0, 0**
	Go	**0, 0**	**1, 1**

Stag Hunt

In Stag Hunt, each player must decide to hunt the stag or hunt the two hares. Hares can be caught by one player, but the stag requires both players working together to catch it. If each player hunts for hares, each will catch one hare and achieve a utility of one. If both players hunt for the stag, each will achieve a utility of three, since the stag is worth six total utility. However, if one player hunts for hares, that player will catch both hares and achieve a utility of two, while the other player will earn nothing since they will be unable to singlehandedly catch the stag.

Stag Hunt generally represents the synergistic effect of cooperative resource harvesting with one pure-strategy Nash equilibrium on the three-cell Pareto front, one pure-strategy Nash equilibrium off the Pareto front, and one mixed-strategy Nash equilibrium.[8] The Pareto front pure strategy presents high stability in the presence of effective communication and the absence of adversarial intentions. In a similar fashion to other ACE, such as Stoplight and Chicken, this game presents the opportunity for game-theoretic system design to expand the scope of the scenario to achieve a higher utility for both players. The game designer may translate the strategic form of the game to an extensive form and introduce a new branch on the first node with outcome utility less than the utility of synergistic harvesting but greater than individualistic harvesting. Given logical, sophisticated agents capable of forward induction, the players will not use the new branch and will instead converge to synergistic resource harvesting.[9] Reference table 3 for the game of Stag Hunt using the ACE taxonomy.

Table 3. Stag Hunt

	Stag Hunt	Player Two	
		Stag	Hare
Player One	Stag	3, 3	0, 2
	Hare	2, 0	1, 1

Matching Pennies

In Matching Pennies, each player decides whether to play their coin heads-up or tails-up. One player wins if both coins match while the other player wins if the coins do not match.

Matching Pennies represents arguably the most unstable simple game-theoretic model with no balance, one mixed-strategy Nash equilibrium and a four-cell Pareto front that spans the entire decision space. In Matching Pennies, one agent attempts to match the metaphorical penny while the other agent works to prevent the match.[10] Reference table 4 for the game of Matching Pennies using the ACE taxonomy.

Table 4. Matching Pennies

	Matching Pennies	Player Two	
		Heads	Tails
Player One	Heads	1, -1	-1, 1
	Tails	-1, 1	1, -1

Stoplight

In Stoplight, two drivers arrive at an intersection simultaneously and must decide whether to continue or stop. If one continues, that driver will gain a utility of one while the other driver will be indifferent. If both players stop, both players will be mildly annoyed and lose one utility value. If both players continue, they will cause an accident greatly detrimental to their utility values.

Stoplight represents the quintessential game-theoretic model for the application of correlated equilibrium with two unbalanced pure-strategy Nash equilibria on the Pareto front, one mixed-strategy Nash equilibrium, and two balanced, mutually deleterious outcomes off the Pareto front.[11] In the Stoplight model, logical agents use a correlated equilibrium mechanism (perceived as fair by all agents) whenever possible to maximize overall and individual utility. Reference table 5 for the game of Stoplight using the ACE taxonomy.

Table 5. Stoplight

	Stoplight	**Player Two**	
		Continue	**Stop**
Player One	**Continue**	-5, -5	1, 0
	Stop	0, 1	-1, -1

Fundamentally, Stoplight represents the same ACE as both the Battle of the Sexes and Volunteer's Dilemma game-theoretic models. Stoplight addresses safe traffic flow, Battle of the Sexes addresses coordination (or lack thereof) for an entertainment venue, and the Volunteer's Dilemma addresses costly intervention to help a crime victim.[12] Effectively, since each of these game-theoretic models represents the same kind of ACE, game agents, or the game designer may use a fair correlated equilibrium mechanism to achieve a higher utility.

Prisoner's Dilemma

In the Prisoner's Dilemma, an interrogator can convict two players of minor crimes without a confession such that each player will spend one month in jail. The interrogator offers a plea bargain to both suspects where they can sell out the other player for personal leniency—if only one player takes the deal, that player will receive no time in jail while the other player will spend 12 months in jail having been successfully convicted of the more serious crime with the help of the defector's confession. However, if both players confess, their confessions are worthless, and each will receive eight months in jail on the charges of the more serious crime.

The Prisoner's Dilemma represents arguably the most famous game-theoretic model with a single pure-strategy Nash equilibrium off the Pareto front. The game demonstrates the difficulty among self-interested, untrustworthy agents in moving from the Nash equilibrium to a balanced, mutually beneficial outcome. The difficulty in establishing the mutually beneficial outcome lies in the opportunity for profitable deviation by an untrustworthy agent.[13] Reference table 6 for the game of Prisoner's Dilemma using the ACE taxonomy.

Table 6. Prisoner's Dilemma

	Prisoner's Dilemma	Player Two	
		Silence	Defect
Player One	Silence	-1, -1	-12, 0
	Defect	0, -12	-8, -8

The Prisoner's Dilemma forms an important conduit to understanding other game-theoretic models such as the Optional Prisoner's Dilemma, repeated Prisoner's Dilemma games, the Tragedy of the Commons, the Hawk-Dove game, and duopolistic competition.

The Optional Prisoner's Dilemma represents an exogenous manipulation of the traditional game and enables an agent to abstain when playing with a perceived defector to achieve a higher utility. Repeated Prisoner Dilemma games allow for higher levels of cooperation and more sophisticated strategies such as tit for tat; an unknown or infinite number of Prisoner Dilemma games aids the strategic enhancement for improved utility. Scenarios that permit proactive self-determined agent mixing (players may choose which agent to play with from the available pool) especially increase the utility value for cooperative agents. Robert Axelrod explored the concept of the Prisoner's Dilemma in his developing notion of cooperation as an evolutionarily stable strategy.[14] In his work with the Prisoner's Dilemma, Ahmed Ibrahim contended that "evolutionary mechanisms have nothing to do with conflict between the causes of the tragedy and their solutions for it, whether the solution is that of outcompeting the tragedy or its contrary." In considering the existence of cooperation among organisms, Ibrahim asserted the presence of a conscious intervener.[15]

The Tragedy of the Commons represents a more unwieldy N-player version of the Prisoner's Dilemma where at least one agent exploits a common resource for personal gain to the detriment of the common resource and the community. Garrett Hardin suggested privatization and top-down regulation (mutual coercion) as remedies, implicitly assuming the existence of a strong, efficient central authority.[16] Elinor Ostrom focused on bottom-up institutions and articulated conditions that fostered such cooperation: easy-to-monitor resources, moderate rates of change, robust social networks, the ability to exclude outsiders, and a strong push for self-enforcement among community members.[17] The pseudonymous Satoshi Nakamoto utilized cryptography to protect a common in the form of a public ledger.[18]

The Hawk-Dove game exists as a superset of three simpler games wherein the Prisoner's Dilemma fundamentally represents the manifestation of relatively low-cost conflict. The game designer, by exogenous manipulation, may significantly increase the relative cost of conflict with respect to the value of the prize to transform the Prisoner's Dilemma into a game of Chicken. Such a transformation creates a new set of strategies as well as new pathways for game-theoretic system design.

The dynamics of the Prisoner's Dilemma, to some degree, check the spread of collusion in duopolistic competition and preserve the health of a limited marketplace.

Take or Share

In Take or Share, each player must decide whether to take the pot of money or share the pot of money worth eight dollars. If both players share, they will split the pot. If both players take, each will receive no money. If one player takes, that player will receive all the money while the other player receives nothing.

In the Hawk-Dove superset, Take or Share represents the knife-edge transition from Prisoner's Dilemma to Chicken as the relative cost of conflict increases. Outside of artificial or discretized environments, such knife-edge equilibria do not exist. Take or Share encompasses three pure-strategy Nash equilibria and infinitely many partially mixed strategy Nash equilibria.[19] Reference table 7 for the game of Take or Share using the ACE taxonomy.

Table 7. Take or Share

	Take or Share	Player Two	
		Share	Take
Player One	Share	4, 4	0, 8
	Take	8, 0	0, 0

Chicken

In Chicken, two drivers drive toward each other at high speeds in a show of bravado. If both drivers swerve, nothing will happen. If both continue, each will be engulfed in a devastating accident. If one swerves, that player will be embarrassed for having lost the intimidation game, while the player who continued will gain positive utility in the form of a fearless reputation. Incidentally, the authors recommend against playing the game of Chicken.

Chicken represents arguably the most fascinating simple game-theoretic model with two unbalanced pure-strategy Nash equilibria along a three-cell Pareto front as well as one mixed-strategy Nash equilibrium. Generally, Chicken exists as an intimidation game with high-value assets at stake and represents relatively high-cost conflict in the Hawk-Dove superset. The mixed-strategy Nash equilibrium enables the use of comparative statics that demonstrate a dramatic decrease in the probability of conflict for any incremental, mutual increase in the cost of conflict. Political scientists use such results to explain the role nuclear weapons play in peacekeeping under the construct of mutually assured destruction.[20] Reference table 8 for the game of Chicken using the ACE taxonomy.

Table 8. Chicken

	Chicken	**Player Two**	
		Continue	**Swerve**
Player One	**Continue**	**-10, -10**	**2, -2**
	Swerve	**-2, 2**	**0, 0**

Counterintuitively, increasing the cost of conflict improves the overall payoff for an agent within the Chicken game when playing the mixed strategy. However, throwing the cost of conflict disproportionately out of balance significantly increases the chance the agents play the pure-strategy Nash equilibrium deleterious to the respective agent.

Exogenous control accounts for the cost of conflict in the game of Chicken (high-cost Hawk-Dove) where each agent makes a binary choice between conflict and peace. In a game where agents may choose a private commitment of resources to some conflict (i.e., a cost known only to the respective agent), Maynard Smith discovered the evolutionarily stable strategy of generating an exponential distribution using the value of the prize of the conflict as the beta parameter and randomly drawing from that distribution to determine the acceptable value of the cost of the commitment to conflict. Given that the expected value of the cost of the conflict equals the value of the prize of the conflict, the expected overall utility for such a stable approach equals zero. Therefore, Smith suggested the use of some credible mechanism for correlated equilibrium to improve the utility for both agents; he later learned certain animals use the ownership principle as that mechanism.[21]

Space Power Applications

Space Debris and the Prisoner's Dilemma

The development of space power offers each nation the opportunity to bolster its technical acumen, national prestige, and instruments of war. Among the many facets of space power, direct ascent antisatellite (DA-ASAT) weapons offer an instructive case study on the generation of space debris. Perhaps the four most pertinent events related to DA-ASAT weapons and space debris include the 1985 destruction of the US P78-1 Solwind satellite, using an air-launched ASM-135 (during the era of the Strategic Defense Initiative), the 2007 destruction of the Chinese FY-1C (Fengyun, "Wind and Cloud") satellite using a ground-launched SC-19, the 2008 destruction of the US USA-193 satellite using a sea-launched Standard Missile-3 (Operation Burnt Frost), and the 2019 destruction of the Indian Microsat-R satellite using a ground-launched Prithvi Defense Vehicle Mark-II (Mission Shakti, "Power").[22] All four of these satellites experienced destruction at the hands of their owners, and each event caused significant orbital debris. Notably, however, the US and India conducted their tests in such a manner as to deorbit all the debris within several years and much of the debris within the first several weeks and months. In contrast, China's demonstration contributed to the formation of a perpetual low-earth orbit Kessler field.

Beyond DA-ASAT weapons, many other space activities and events contributed to the debris cloud in space. Spacefaring nations often leave spent rocket bodies and nonfunctional spacecraft in orbit, finding such an approach more economical than returning the artificial satellites to Earth. Many of these objects undergo physical explosions (e.g., explosions caused by the pressure buildup in the fuel lines) or chemical explosions (e.g., a hypergolic ignition of residual propellants, an explosion caused by severely decayed batteries, or the purposeful self-destruction of Soviet Union satellites) that further contribute to space debris pollution. Satellites often face the threat of conjunction (i.e., accidental, hypervelocity, destructive collision); the 2009 Cosmos 2251 and Iridium 33 collision provides the most destructive, polluting example. The Soviet Union contributed to the space debris field with spacecraft that leaked sodium-potassium droplets (meant to cool the nuclear reactor onboard the respective satellite) into orbit.[23]

In each of the aforementioned scenarios, the agents involved chose an action to maximize individual utility to the detriment (directly or indirectly) of the space community as a whole. During the era of the US and Soviet Union bipolar dichotomization of power, such events functioned within the context of a Prisoner's Dilemma. With a larger and growing community of modern spacefaring entities (to include the US, Russia, China, the European Space Agency, Japan, India, South Korea, North Korea, Iran, and Israel), the current space debris events occur in the framework of a Tragedy of the Commons.[24] While nations utilize the more egregious events as political weapons within the international community, no mechanism exists to definitively prevent the creation of space debris. The 1967 Outer Space Treaty prohibits the privatization of space, and no top-down organization currently wields the power necessary to impose and enforce space debris regulations on the collective group of spacefaring nations.[25] The factors that would contribute to the effective formation of bottom-up institutions capable of addressing the space debris issue simply do not exist. The innovation of technologies capable of addressing the space debris problem (e.g., reusable rocket bodies, mechanical space debris collection devices, or lasers used to deorbit space debris) afford a worthwhile goal. The political efforts to prevent the proliferation of harmful space debris also provide an avenue for potential progress. However, the core characteristics of the Prisoner's Dilemma ACE and the associated game-theoretic models suggest the inevitability of an increasingly polluted space. Therefore, the main thrust of the US efforts in this field should be in the development of spacecraft capable of surviving and operating in such an environment—not in the attempt to prevent the formation of such an environment. Increasing the resiliency of spacecraft to hypervelocity impacts, using simpler, cost-effective replaceable spacecraft, disaggregating satellite constellation architectures, or transitioning to less-polluted orbital regimes all provide potential avenues for such an undertaking. In a polluted yet still usable space environment, spacecraft maneuver also provides a mechanism for survivability. However, the finite fuel onboard a satellite mandates the prudent use of any such maneuver. To ensure spacecraft maneuvers are conducted judiciously and effectively, the US requires a robust array of space domain awareness capabilities, including both ground-based and space-based sensors and processors.

Department of Defense Policy and Deadlock

Deadlock illustrates the self-imposed damage of unforced errors by one or more agents. A plethora of policies, some worthy of several research papers, guide the personnel and technological development of the Department of Defense, including the US Space Force. Any of these policies that inadvertently cause a substantive number of talented people to exit the US military might be considered an unforced error. Furthermore, policies that neglect the development of critical technologies (e.g., cyber) might be considered unforced errors. When agents do not understand the implications of their actions or hold some other goal as a higher priority, they may fail to reach the stable equilibrium within the Deadlock ACE.

Conjunction, Collision, or Rendezvous and Proximity Operations

The Pure Coordination ACE covers mutually desirable rendezvous and proximity operations in space, such as the docking of a supply vessel to the International Space Station. While the orbital dynamics and control theory of such an endeavor present a technological hurdle, the game-theoretic considerations are quite simple and require only sound communication. The Matching Pennies ACE addresses situations in which one agent desires the proximate interaction and the other agent desires the opposite. In a pertinent situation concerning the optimal pursuit of a spacecraft by a piece of space debris, David Spendel relied on the field of Differential Game Theory—specifically, the Homicidal Chauffer game-theoretic model.[26]

Space Resource Harvesting as the Stag Hunt

The nascent field of space resource harvesting holds tremendous potential. Lunar extraction may yield nuclear fusion fuel and rare earth metals with important technological and industrial uses on Earth. Near-earth object chondrites and achondrites may yield valuable resources for *in situ* utilization by manned missions or high-value precious metals.[27] Given the Stag Hunt ACE framework, synergistic cooperation in the harvesting of these resources may occur naturally. In cases where there are barriers to such cooperation, an agent (acting as a game designer) may use game-theoretic system design to exogenously change the structure of the game. The agent translates the strategic form game to an extensive form information set and adds a new branch on the previous node. This new course of action strikes a balance in individual utility between synergistic cooperation and the preexisting choice to not cooperate. The respective agent will never use this new branch so long as the other agent demonstrates forward induction through the *a priori* commitment to synergistic cooperation. Perhaps counterintuitively, the more developed an entity's capacity for previous space resource harvesting, the greater trust other agents will place in that entity's commitment to cooperation. Therefore, early US investment in space resource harvesting may incur a beneficial positive feedback cycle.

Stoplight and Correlated Equilibrium

The Stoplight ACE encompasses the Stoplight, Volunteer's Dilemma, and Battle of the Sexes game-theoretic models. The respective space analogs of these models are cooperative maneuvering to avoid a collision, international policing in space, and harvesting space resources in one of two locations where the utility payoff for each agent is different based on the location. Correlated equilibrium provides a natural and beneficial heuristic solution for the challenges posed in this ACE. The type of mechanism used for correlated equilibrium (e.g., memorandum of understanding alternating decision power or an international third party) is immaterial as long as all players view the mechanism as fair and effective.

Chicken as High-Cost Conflict or Intimidation

The Chicken ACE manifests itself as a high-cost Hawk-Dove game-theoretic model. The space analog presents itself in one of two ways: two spacefaring entities with spacecraft on a collision course where neither will maneuver or the impending large-scale conflict between two nations encompassing the space domain. There are several game-theoretic system design approaches capable of addressing the Chicken ACE. Similar to the Stag Hunt, a game designer may exogenously translate the game into extensive form and add a branch to the previous node. This new branch acts as a commitment mechanism that turns an incredible threat into a credible threat (much like the concept of burning bridges). The commitment mechanism may exist in a technological form (a doomsday device serves as a sensational example) or in a diplomatic-political form (such as the use of a "red line"). The strength of this approach rests in the strength of the commitment mechanism; for example, if other agents do not believe in the credibility of a player's red line, the approach will falter. To preserve credibility, red lines must be enforced even when doing so seems impractical since a failed red-line strategy will impact an agent's credibility in any future game against a player with knowledge of the unenforced red line. If a player is unwilling to follow through with the red-line threat, the player should consider not making the red-line threat in the first place.

Another game-theoretic system design approach drives the hypothetical mutual cost of conflict so high that the comparative statics indicate that the two agents would never enter into such a conflict. Quintessentially, the space-contextual application for such an approach would be the commitment by two or more nations to disregard the Outer Space Treaty and commit to the use of nuclear weapons in space should a conflict ever occur.

A final game-theoretic system design approach encompasses an agent that reduces the individual cost of conflict or collision. If the two agents play the mixed-strategy Nash equilibrium, this approach will work to the detriment of the agent using this method. However, this approach improves the probability that the two agents will transition to the pure-strategy Nash equilibrium favorable to the player that used this taxonomy. In the space domain, a nation might enact this approach by developing lower-cost, less reliable, and less exquisite spacecraft, which the nation can affordably replenish in the event of a collision or malfunction.

Conclusion

This article asserted that decision-makers could use game-theoretic system design to understand space power challenges and opportunities better, as well as achieve better outcomes for the US space enterprise. In support of this thesis, we contextualized the spectrum of agent strategic interactions, proposed a new taxonomy for the classification of game-theoretic models, and expounded the proposed taxonomy, using eight atomic game structures with pertinent space applications. In this effort, we strive for the advancement of strategic thinking in the space domain for the enhancement of the US space security posture. ✪

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FEATURE

Coming to a Theater near You

Evolving Air Combat to Counter Anti-Access and Area-Denial

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With a measure of suspense in 2015, the UK completed its Strategic Defense and Security Review (SDSR) and began to signal a broad defense policy shift among Western nations. SDSR was one of the first policies to note a general decline of international cooperation. Coupled with increasingly capable state-based threats, SDSR raised concern for the future of the existing rules-based international order.[1] This signal reverberated within the defense communities of Western nations. Australia published similar conclusions in its 2016 Defense White Paper. Being geographically isolated, Australia fundamentally relies on the international order for its continued security and prosperity.[2] "Strong, Secure, Engaged (SSE)," Canada's Defence Policy, speaks to Canada being a beneficiary of the international rules-based order and acknowledges that such an environment underpins the country's strategic interests. SSE also speaks to the re-emergence of major-power competition and the need to balance the interests of our alliances with the emergence of China.[3] The latest US *National Defense Strategy* prioritizes building the US's military advantage over its explicitly stated rivals of Russia and China.[4] New Zealand has echoed similar conclusions, and the North Atlantic Treaty Organization (NATO) has fallen in step as well, intending to adapt the alliance to address challenges to the rules-based international order and geopolitical competition while monitoring the shift in the global balance of power as a result of China's rise.[5]

China's defense policy, "National Defense in the New Era," denounces the growing threat to global stability. China, however, sees US hegemony as the source of increased competition among states and reproaches NATO for the alliance's increased deployments to Eastern Europe.[6] Lastly, Russia's defense policy warily noted what it saw as the West's destabilization efforts in the Eurasian region and NATO's growing global military capability with its positioning of forces to Russia's near-abroad.[7]

One need not look further for a better example of diplomatic posturing on the international stage. The message communicated is that lines are being drawn, and the stage is being set. As policy guides from above, so commanders below make fast their preparations. The fundamental change in underlying assumptions is that operations are no longer conducted from a position of advantage and may instead be from one of disadvantage. As such, this article will show that for the Royal Canadian Air Force (RCAF) and Western air forces to succeed in a contested operating environment, they must shift to an operational command and control (C2) model that is more resilient, flexible, and capitalizes on emerging technologies. This article focuses on how and why the distribution of control of forces in theater is necessary, and the current and future shifts occurring as autonomous vehicles begin to augment existing force structures.

The Modern Operating Environment

The general trend of economic advancement and diffusion of military technology will increase Western nations' power projection costs and erode the tactical advantage of forces in the field. As some countries acquire advanced military capabilities and the means to control access to their regions, other nations face the dilemma of continual defense investments versus assuring access to the global commons for all.[8]

The major adversaries to the Western powers are both capable and credible within their sphere of influence and in more domains than those occupied by traditional military forces. Encapsulating this idea is the current concept of anti-access/area denial (A2/AD).[9] Simply put, A2/AD means that the act of entry into a theater will be contested, and if successful, the adversary will challenge a friendly force's freedom of movement within. A concept like this should not seem new because it is not. The term does have utility as a rallying point and is a reminder to academics and officers of how war with a major power could appear. After 20 years of low-intensity conflict, a reminder may be sorely needed.

Nontraditional and traditional means of power will be enhanced by real-time, multispectral surveillance. Space-based, cyber, and enhanced conventional weapon systems will challenge the freedom of movement. Machine learning and artificial intelligence will simultaneously stress legacy decision-making structures and empower those with the requisite agility to harness the coming speed of action. Overcoming these challenges in the past required more capable equipment, leading to higher levels of defense spending. For most Western nations, this higher cost has traditionally been offset by a shrinking force structure. This offset has resulted in small, capable, but irreplaceable forces that increased the implicit risk to operations.[10] Additionally, A2/AD increases these risks. In this environment, a further challenge may be to prepare future commanders capable of conducting high-intensity combat operations from a corps that has been accustomed to everything but.[11]

A2/AD signifies an environment where the adversary can employ advanced capabilities on a sufficient scale across the physical and virtual domains and the resiliency to maintain operational effectiveness while suffering attrition. Examples of antiaccess capabilities are cruise and ballistic missiles, surveillance systems (satellites, aircraft, and surface or ship-based radar), antisatellite weapons, submarines, and cyber-attack methods. Examples of area denial capabilities include integrated air defense systems (air and surface-based systems, both fixed and mobile), cruise and ballistic missiles, antiship missiles, antiarmor systems, longer-range man-portable air defense systems, precision-guided munitions, autonomous weapon systems, unmanned aircraft and underwater vehicles, and swarm tactics.[12]

In the Eastern European theater, Russian surface-based weapon systems represent a significant layer of their A2/AD posture. This layer consists primarily of the S-300/400 surface-to-air missiles (SAM), Iskander-M ballistic missiles, and K300P Bastion antiship missiles.[13] Additionally, frontline fighters mainly consisting of Sukhoi Flanker variants present a complementary layer of air defense.

China's A2/AD layers are equally complex. Its air defense is anchored on a network of early warning radars along its coast, complemented with Russian SA-20 and domestically produced CSA-9 surface-to-air missile systems. Further augmenting these SAM systems will be the Russian SA-21 and indigenous HQ-19 systems. The People's Liberation Army Air Force employs a mix of fourth and fifth-generation aircraft and continues to develop longer-range air-to-air missiles.[14] The ability to forward-base these forces on outposts in the South China Sea will further extend China's A2/AD umbrella.[15]

The People's Liberation Army Navy (PLAN) continues to be fundamental to China's A2/AD ambitions. Its efforts to develop a multicarrier navy with modern nuclear-powered submarines and escorts like the Type 055 stealth-guided missile destroyer will allow it to credibly intervene in the South China Sea and project its power beyond the first island chain.[16] Equipped with modern cruise missiles and SAM systems and an increasing ability to sustain operations beyond the first island chain, the PLAN is effectively expanding China's A2/AD eastward while consolidating its strength closer to home.[17]

China fields a wide range of conventional and nuclear-capable ballistic missiles capable of precision strikes versus land targets and surface vessels. Counterspace capabilities include ground-based lasers, orbiting space robots, and antisatellite missiles.[18] The People's Liberation Army cyberwarfare strategy advocates targeting C2 and logistics networks to dissuade military responses to crisis situations and hinder effectiveness from the outset of hostilities.[19]

These developments do not go unnoticed. The Future Air Operating Concept acknowledged the challenge that A2/AD brought to RCAF operations and described the imperative to be able to operate in contested and degraded environments. This challenge means achieving freedom of maneuver in the air domain and across the electromagnetic (EM) spectrum. To meet operational objectives, the RCAF sees low-observability and stand-off weapons and sensors as advantageous qualities to possess.[20]

Countering A2/AD Conceptually: Evolving Doctrine

One concept proposed to address the A2/AD challenge was cross-domain synergy.[21] The idea was not only of fighting jointly but integrating advantageous service-specific capabilities to create windows of superiority in supporting domains and enabling freedom of force movement in another domain. This concept also envisions the integration of capabilities at lower levels to maintain an operational tempo in the face of denied communications and a degraded EM spectrum.[22] An example of this type of integration would be to utilize cyber capabilities to degrade an adversary's air defense systems sufficiently to allow strike and suppression of enemy air defense (SEAD) assets to ingress, destroy their targets, and egress. One challenge of any integration-based concept is having the relevant expertise at the tactical and operational level to plan operations and execute missions. Special capabilities and the reluctance to share technical information between services and nations are not new operational problems and may be aggravated under this concept. These problems are partially mitigated by the participation in recurring multinational air exercises at different tiers of classification and allied information sharing agreements. These agreements cannot be taken for granted though and continued organizational security modernization should be done concurrently.[23]

Another concept to counter A2/AD is the distributed control of operations. Its hypothesis is that the tenet of centralized control and decentralized execution is itself incomplete if applied to a modern A2/AD environment. Recent conflicts that Western nations have been party to have not challenged the resiliency of the information network that underpins much of the C2 capability of its forces. In a major power conflict, offensive cyber and antisatellite attacks may be the primary means of accomplishing this.[24] The threat to forward-deployed air assets from air and missile attacks cannot be discounted either.[25] Therefore, believing that a capable adversary will deny our information sharing networks, control can no longer be rigidly centralized if air forces are to be effective. Authorities and control must at times devolve to ensure continued integration of combat capability and maintain operational tempo. As a result, an isolated combined forces air component commander (CFACC) cannot inhibit lower operations centers and C2 units from assuming control authority to organize, task, and manage combat missions without imperiling operational objectives.[26]

One major difficulty, however, is that forces and combat capabilities tend to be geographically dispersed within a theater to mitigate the risk of loss to forward bases already within an A2/AD environment.[27] Distributed control must be able to join dispersed forces, and the "key to this process is establishing and practicing detailed protocols for when and how to assume control authorities as well as clear guidance as to commander's intent." Cross-domain synergy reiterates the obvious in that advantageous capabilities that reside in other domains must be integrated into the force package where and when they are needed. Cross-domain synergy does not provide the how, which is where the concept of distributed control should fill the gap.

Unfortunately, academic literature on distributed control hesitates to bridge that gap in detail. For example, Larry Broadwell Jr. and Gilmary Hostage III correctly suggest that distributed control could be exercised in degrees. The CFACC or the combined air operations center (CAOC) could reallocate resources from a relatively inactive portion of the theater to more intense areas and delegate authorities for a set period, or subordinate C2 elements could assume additional control activities after a period of lost communications.[28] Generally, these control authorities are already delegated, and the authors only tangentially address the heart of the matter (what they refer to as self-organization). What so few who write on distributed control acknowledge bluntly is its central idea of the transfer of operational control (OPCON) from the CAOC to a lower level. It is the idea that under specific circumstances, the tactical level will assume OPCON over itself and plan and execute on the last-known intent and orders to maintain operational tempo. In other words, keep fighting.

A blend consisting of cross-domain synergy as the solute and distributed control as the solvent may be the conceptual solution to countering A2/AD. United States Air Force (USAF) doctrine seems to be trending in this direction.

> During these operations, forward based airpower can conduct air operations based on a standing "integrated tasking order" (ITO). In this air equivalent of mission command, forward based air expeditionary wings or task forces receive conditions-based authorities with standing orders and commander's intent on the ITO. This empowers subordinate commanders with the flexibility to provide coverage of key defensive counterair combat air patrols (CAPs); air interdiction kill boxes; suppression of enemy air defense CAPs; close air support; or intelligence, surveillance, and reconnaissance in support of surface forces. This decentralized execution model enables local commanders to maintain pressure on the enemy even when disconnected from communications with higher headquarters due to a contested environment against a peer or near-peer adversary.[29]

A new candidate for that solution may be joint all-domain operations (JADO)—an operational statement that discards freedoms and assumptions previously taken for granted. It positions the USAF and willing allies to reimagine C2 to allow for conditions-based authorities supported by broad access to information; converge fires from all domains to achieve mass; emphasize cooperative information sharing on resilient, dispersed networks; automatically synthesize and share intelligence; and to disaggregate and disperse supply to enable resiliency and maintain operational tempo through limited self-sustainment. Given the trends in international relations, the refinement of JADO should proceed with vigor.[30]

Influencing Operations

Several operational factors should be considered when designing a system that would allow the distribution of control (delegation of authority) within an air campaign. Broadly speaking, a survivable C2 network must be established through distribution of tasks, information, and responsibilities. Geographically dividing the joint operating area (JOA) into regions with tactical commanders dual-hatting as regional air component commanders (RACC) may be one method. If so, RACCs must have organic subject-matter expertise and support, limited it may be, to integrate capabilities from other domains to achieve those windows of advantage where they are needed.[31] As a further contingency, control should be distributed to individual squadrons in the event they become isolated from the RACC. By establishing a preplanned system of marshal points and combat air patrol locations with coordination timings throughout the JOA, what emerges may be a crudely effective method of allowing forces to self-organize into strike packages or counterair formations. Lastly, the commander's intent must be drafted in a manner that can be used as a stand-alone by tactical commanders and subordinate units all the way down to individual formations to organize, plan, and execute missions to achieve operational objectives.

The CFACC must clearly define what the transition events to and from distributed control are if C2 systems are denied or become unreliable. This definition includes the loss of satellite communications, cut fiber optic cables, or a cyberattack on communications infrastructure. It could also arise from the retrograde of personnel due to the risk of a strike on the CAOC or its complete loss due to enemy action. An event may also be triggered by allied forces adopting a passive employment/emissions control (EMCON) posture for a predetermined period.[32] Further, a description of the control authority to be delegated, and to whom, should be clear. Consideration should be given to delegating control of missions to airborne early warning assets (preferably fifth-generation platforms such as E-7 Wedgetail), control and reporting centers, or mission commander-qualified aircrew in fifth-generation fighters for *ad hoc* airborne packages.[33]

The CFACC, or the designated airspace control authority should publish a contingency airspace control plan that supports the required operational tempo in a communications-denied environment. A plan of this nature should rely heavily on procedural control and permit the unhindered flow of passive/EMCON assets into, within, and from the JOA.[34]

The CFACC, or the designated area air defense commander, should publish a contingency area air defense plan that supports the identification and engagement requirements in a communications-denied environment with friendly assets operating passively/EMCON. Additionally, the plan should include considerations for additional defensive air patrols if forward deployed assets are destroyed. Complicating this will be the multinational nature of operations, specifically establishing friendly identification criteria that can be met by different aircraft from different countries.[35] Despite the universal recognition of the importance of interoperability, this is an area where willing nations may be denied participation because identification (ID) capabilities have not been modernized.[36]

Rules of engagement (ROE) should always be drafted in such a manner to permit the targeting of adversary forces and infrastructure regardless of the functional status of theater C2. What enables the application of ROE are ID criteria that are practical and balance the risk of fratricide and collateral damage with mission objectives and tactical game plans. ID criteria must be coordinated at all levels to ensure that safe-passage transit corridors, altitudes, and electronic indications of friendly and enemy aircraft used to fulfill the ID matrix are achievable and operationally effective. Exacerbating this issue is the probability of coalition air forces operating passively from time to time.[37] As described previously, what will challenge the coalition force's ability to establish positive ID are participating nations' combat identification system capabilities. Fighter aircraft that do not employ modern cooperative and noncooperative methods of determining positive ID of adversary air, land, and surface weapon systems may be relegated to support rear areas of the JOA.

Effective positive ID criteria will also enable the continuity of dynamic targeting. Such criteria must account for semi and autonomous air vehicle operations, as will be discussed later. To account for periods where reach-back and intratheater support are lacking, target engagement authority should be delegated to the cockpit to the maximum extent practicable, along with acceptable noncombatant casualty values for time-sensitive and high-payoff targets. To ensure the continuity of deliberate targeting, preapproved target folders drawn from the joint integrated prioritized target list should be allocated to different RACCs or squadrons and updated regularly. Achievable intelligence, surveillance, and reconnaissance (ISR) requirements should be articulated to support joint targeting coordination boards at the tactical level. An unhindered target approval mechanism is needed to maintain the required flexibility and tempo for air interdiction and strategic attack missions.

The maintenance of operational tempo, or that of an effective counterpunch, is key. To permit this, a flexible air tasking cycle is required. If operations transition to distributed control, a series of preplanned air tasking orders that cover a set time period could be used. Coupled with last-known mission orders and commander's intent, the isolated force commander can begin to plan, assign, and execute tasks in furtherance of the CFACC's objectives. This method must recognize that the destruction of friendly forces, integral or peripheral to the isolated commander, is a possibility and may impact what is achievable. Isolated regions or forces may find that the day-to-day capabilities for offensive or defensive missions may only be known once assets are airborne and the force package and weapon loads can be determined. Mission commanders should be prepared to rely on the intraflight datalink and standard procedural flow of aircraft within the JOA to coordinate while utilizing standardized tactics, techniques, and procedures to execute missions.[38]

As logistical chains represent high-value targets for the adversary, *in situ* weapon inventory levels at each operating location should be described in terms of operational effects to be achieved.[39] Tactical commanders and logistic officers should maintain war stocks at sufficient levels to achieve their primary mission for a predetermined time period should a reversion to distributed control occur as a result of enemy action. Disaggregating supply, sharing sustainment information, and empowering lower-echelon logistics officers in the same regard as operations officers to adapt and support operational tempo is fundamental to mission success.[40]

Addressing the human element, tactical commanders must be psychologically prepared to rule in favor of military necessity when confronted by concerns of proportionality or collateral damage. Likewise, legal advisors must be professionally prepared to support actions that favor military necessity. Mandatory adherence to a goal of zero civilian casualties is an unacceptable risk to mission success.

Finally, multinational air exercises must continue to evolve and present degraded operating environments to aircrew such as: denied or degraded space-based capabilities such as ISR, satellite communication, global positioning satellite (GPS), and launch detection and tracking; denial of key portions of the EM spectrum; effects resulting from cyberspace attacks; and passive/EMCON employment. Decision-support mechanisms should be degraded to a level where "imperfect knowledge including missing or degraded information, intelligence, and communications capabilities" challenge commanders' decision-making abilities.[41] These air exercises are the only arena where the RCAF Fighter Force can holistically test their combat capability. The RCAF Air Warfare Centre and the Fighter Standards and Evaluation Team, in partnership with the USAF's 561st Weapons Squadron, should further develop and refine tactics, techniques, and procedures for such environments.

Cross-domain synergy and other similarly sounding concepts may be rightly criticized as simply jointness on steroids. Distributed control could be criticized as a modern regurgitation of the concept of tasking by exception,[42] or something that harkens back to the day when the business of war fighting did not have access to the luxury of communications at the speed of light. Some ideas are ahead of their time, such as Gen Merrill A. McPeak's vision of a composite air wing, now practical (ironically requiring fewer types of fighters) with truly multimission aircraft such as the F-22 and F-35.[43] Actually, what lies before us are concepts that have been slowly forged over time. All we must do is decide when to stop folding steel and quench the blade.

Moving from the Conceptual to the Concrete

The targeting of C2 and communications infrastructure of a forward deployed force will isolate and expose it to attack and reduce its operational effectiveness. A2/AD will invite the attrition of friendly weapon systems—systems that cannot be regenerated in a manner achieved in previous major conflicts. While this last point was raised in the discussion of the future operating environment, it should be acknowledged that this implication will be negatively weighted toward the forward deployed force. The solution to these problems for air forces will lie in adopting the conceptual shift described previously, coupled with the fielding of "attritable,"[44] autonomous, combat vehicles. The technology emerging includes unmanned combat air vehicles (UCAV) with advanced communications and information technology, and software algorithms to enable autonomous operations. Complementary to and controlled by manned fighters initially, UCAV usage will mature to fully autonomous operations utilizing swarming-type tactics. In addition to nature, history has shown many examples of swarm tactics employed in the land domain,[45] and thanks to advanced technologies, the exigencies of defense budgets, and supportive policy, its potential in the air domain may be showcased in the next major war.[46]

While the path forward may be classified, the one leading to our present location is unobscured. BAE's Taranis UCAV demonstrator, coupled with Defense Secretary Gavin Williamson's recent announcement in favor of "swarm squadrons of network-enabled drones capable of confusing and overwhelming enemy air defenses,"[47] indicates the British intent. These drones will form a squadron meant to complement and enhance existing F-35 and Typhoon capabilities.[48] After Northrup Grumman developed the X-47B demonstrator for the US Navy (USN), Boeing was awarded a contract under the carrier-based aerial refueling system project to build the MQ-25 Stingray that will give the USN an autonomous, unmanned refueler with an option to develop an ISR capability.[49] The USAF's science and technology strategy includes Skyborg, a recently announced Vanguard research program that will develop an "autonomy-focused. . . low-cost teamed aircraft that can thwart adversaries with quick, decisive actions in contested environments."[50] Under the Air Force Research Laboratory's Low-Cost Attritable Aircraft Technology portfolio, the XQ-58 Valkyrie is in development to meet Skyborg's requirements.[51] The Royal Australian Air Force (RAAF) and Boeing announced in early 2019 the Airpower Teaming system, affectionately referred to as the "loyal wingman" project, to equip the RAAF with low-cost, unmanned fighters.[52]

In the near term, semiautonomous UCAVs will present several benefits and challenges. The political level will be challenged to continue investment in national military capabilities fulfilled with legacy technology. At the strategic level, low-cost, attritable, and easily repairable drones will lower the risk calculus. Previously considered high-risk operations will become tenable, at least for as long as the edge is maintained. Lowering the risk and cost of military operations for Western nations may cause an adversary to lower their estimation of the threshold of war, resulting in a measure of deterrence. Operationally, with UCAVs supplementing the mass of fighter assets in theater, manned fighters could be increasingly dispersed to increase their survivability in the event of hostile action. The replenishment of UCAVs lost in combat could arrive by airlift, thereby quickly regenerating a location's combat capability. Tactically, operations with UCAVs will upend concepts such as an acceptable level of risk, force ratio, and fighter mutual support. Passive, or a blend of active and passive, target engagement offers new shooter-sensor support employment methods. Lastly, combining observable and low-observable platforms into formations will offer new tactical options to flow forces in relation to the threat, sowing doubt and confusion along the way.

Semiautonomy represents only a precursor. Achieving full autonomy will enhance both the benefits and risks. Instead of loyal wingmen, one has loyal swarms. With autonomous, low-observable UCAVs conducting aerial refueling from autonomous, low-observable aerial refuelers, a given theater could be infested with friendly swarms. Initial contested entry operations could task UCAV-only missions to achieve control of the air until the airspace is sanitized of threats. The swarm could then transition to a direct support role, enmeshed with manned fighter operations. An infestation could be easily sequenced, staggering arrivals of UCAVs into theater such that relief sorties could be scheduled in a predictable manner. Unpredictability arising from losses in combat and expended weapon states could be discounted by maintaining a reserve force on ground alert at forward air bases to replenish the swarm where needed. As such, the word infest may find a suitable home in the lexicon of air forces as a tactical condition of the air domain, a task to achieve, and a situation to leverage in the planning and execution of strike, SEAD, close air support, counterair, or countersea missions.

UCAV swarms sharing multispectral sensor information will employ network-enabled weapons capable of being retargeted midflight. Efforts to employ networked weapons collaboratively is another USAF Vanguard project, aptly named Golden Horde. Planned initial demonstrators are the Collaborative Small Diameter Bomb 1 and the Collaborative Miniature Air-Launched Decoy, both modified versions of what is currently in US inventory.[53] With networks able self-organize, converge, act, and disperse as required to achieve their objectives, the doctrine of the BattleSwarm, proposed by John Arquilla and David Ronfeldt, may be coming to a theater near you.[54]

The controlling function of an autonomous swarm would most certainly be given to an advanced algorithm or AI. Vehicle and weapon type, task, target, and threat could be the determining factors in deciding swarm behavior, just as they are determining factors in planning large-force employments of traditional air forces.[55] In the face of A2/AD, overcoming adversary defenses may suggest the use of stand-off weapons and vehicles, ideally networked in such a way as to produce cooperative actions. Arquilla and Ronfeldt refer to this practice as "swarming by fire." In this case, a hive-type mentality, where the swarm is treated as one amorphous body working in concert, may be an appropriate organizational method. An analogy can be drawn from bees, whose omni-directional approach culminates with a singular sting, consuming the life of the bee. This type of approach might be more suitable for expendable, or single-use vehicles. For example, future air-launched decoys could be programmed and employed in a cooperative, responsive manner to confuse, divert, or deceive adversary defenses. The Golden Horde, at least initially, will rely on collaborative behavior or a set of predetermined "plays" decided upon during the mission planning process. A "playbook" will be loaded into the weapons before flight. Once airborne, the optimal play will be selected and executed, as determined by the task and the conditions of the operating environment. "Golden Horde does not use artificial intelligence or machine learning to make determinations independently regarding which targets to strike. The system only selects from set plays and cannot violate defined Rules of Engagement."[56] Even lacking a sophisticated swarm behavior model, a simple linear approach of weapons flying to the target area could achieve the effect of saturating adversary air defenses with the necessary quantity of weapons at their desired points of impact. Where the encirclement of a target or target area may be more appropriate, smaller, microdrones may be the answer. Recently divulged tests with the Perdix system in 2017 saw 103 microdrones launched from pylon-mounted canisters carried by two USN Super Hornets. These microdrones were externally controlled to accomplish basic formations and maneuvers relative to different points on the ground. Target vulnerability analysis, coupled with live destructive testing, computer modeling, and simulation, may offer the capability of using microdrones carrying small quantities of explosives to attack specific adversary systems and their vulnerable points precisely and efficiently.[57]

The long-endurance and low-observable properties of UCAVs make the comparison to the tactical employment of German U-boats a natural one. Instead of a hive approach to organization, the swarm operates under a wolfpack mentality. The pack hunts while dispersed, and the detection of an enemy target triggers the convergence of the pack, or massing of the forces, at the desired target. Here, the low-probability of intercept/low-probability of detection radios, antennae, and waveforms would be of critical importance to incorporate offboard sensor information from other UCAVs and aerospace assets discreetly.[58] Coupled with onboard sensors, the assembly and distribution of battlespace information to network participants would result in offboard targeting information that could support passive weapon employment and passive weapon support. Ideally, the target under attack remains unaware that it is being employed against or from which direction the attack is coming. After the engagement is complete, the pack disperses or reorients itself for follow-on action. Adversary aircraft challenging friendly forces organized in such a manner would be inviting ambush.

Although swarms of UCAVs employing hordes of weapons is a tantalizing, if not dystopian vision, of the future of air combat, the challenges of achieving this capability and its vulnerabilities cannot be discounted. In addition to the possibility of an adversary counterswarm, disrupting the flow of information should be considered the Achilles' heel, whether by an offensive cyber attack, electronic jamming, or deception.[59] The challenges of sharing sensitive information and technology among allies participating in coalition operations is ever-present and may only be compounded by this technology. Allies are not all equal, and this may be yet another fault line. Lastly, ROE may in fact be the most difficult hurdle to overcome. Logical arguments tend to fall flat in the face of collective fear and mistrust toward the idea of autonomous weapons, and only the foolhardy would blindly ignore the risks. Can the current laws of armed conflict support autonomous target identification, classification, and engagement, or do they need to be updated to reflect modern technological capabilities? If they can be applied, are there situations where the state might elect to relax a UCAV's programmed compliance measures in extremis to stave off defeat, or aggressively press a window of opportunity to achieve victory? To what extent must there be man-in-the-loop redundancy? These and other questions must be addressed in such a manner as to not reveal technical capabilities, if possible. Finally, are these technologies yet another case of over-promising and under-delivering, as air forces have often been criticized of? Time, certainly, will tell.

If the efforts to develop autonomous capabilities represent anything, it is the drive to maximize the economies and efficiencies of warfare. Complementing these future trends should be efforts to digitally twin the battlespace. Models that forecast terrestrial and space weather, EM propagation, and GPS accuracy should be integrated with enemy orders of battle, threat libraries complete with technical information, target capabilities, and vulnerabilities. Advanced surface, subsurface, air, and space sensors that can detect, localize, and classify electronic and infrared emissions can be integrated. Layered with blue force systems and capabilities, as well as logistic, supply chain, and force-generation models, the operational level can run AI-powered wargames. We may already be there, and if so, the next question is how to twin the battlespace in real-time such that operational-level commanders can make decisions supported by advice from an AI. Control, it turns out, may be distributed to the machines in the end. If, through our diligence and persistence, we completely digitize the environment of war, the last vestiges of an analog business may be the race to see who activates their system first.

Conclusion

Confronting and prevailing in the face of A2/AD systems requires advancements in doctrine and technology. Officers and politicians must become reacquainted with the probability of effective adversary attacks and the subsequent need of a resilient fighting force. These notions should inform discussions regarding the reorientation of our force structure. Centralized C2, highlighted by the last 20 years of counterinsurgency operations, may be ill-suited against a capable adversary. Distributing control to dispersed forces will cushion any blows, allow for effective responses, and enable the force to employ enhanced survivability tactics. Advanced fighters and UCAVs with advanced communication networks, sensors, and special capabilities will exercise greater lethality concomitant with a greater conditional latitude.

Networked-enabled weapons are here. Semiautonomous UCAVs will arrive shortly and eventually transition to fully autonomous modes of operation. The benefits of this type of weapon will fundamentally alter the risk calculus at all levels of conflict and help to maintain the edge that defends the international rules-based order. The challenges will be protecting the information tethers, overcoming organizational inertia, and gaining legal and social acceptance.

One of the 10 corporate risks identified in the *National Defense Strategic Planning Directive 2020–21* is that the "[Department of National Defense (DND)/ Canadian Armed Forces (CAF)] long term strategy doesn't accurately predict future capability requirements and concepts of operations to posture the CAF to provide required responses."[60] Canada's defense policy has reiterated its continued engagement in international affairs and its support for the international rules-based order. The level of airpower Canada wants to provide to that support is yet to be determined. The trajectory of air combat evidenced by our allies' initiatives may be unpalatable, deemed unaffordable, or assessed unachievable given Canada's byzantine defense procurement process. In any military acquisition, capability signals intent, and with strategic acquisitions such as the Canadian Surface Combatant and the Future Fighter Capability Project yet to be implemented, we would be well-advised to carefully consider the signals we are sending both to our adversaries and our allies. ✪

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32. "The selective and controlled use of electromagnetic, acoustic, or other emitters to optimize command and control capabilities while minimizing, for operations security: a. detection by enemy sensors; b. mutual interference among friendly systems; and/or c. enemy interference with the ability to execute a military deception plan." CJCS, *DOD Dictionary*.

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other component operations. . ." CJCS, Joint Publication (JP), *Joint Air Operations* (Washington, DC: CJCS, 25 July 2019), II-3.

34. CJCS, JP 3-30, II-6.

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36. "Weapons control procedures and airspace control procedures for all air defense weapon systems and forces must be established. . . . Area Air Defense Plan should also be integrated with the Airspace Control Plan to ensure airspace control areas/sectors are synchronized with air defense regions/sectors." CJCS, JP 3-30, II-7.

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43. James W. Canan, "McPeak's Plan," *Air Force Magazine*, 1 February 1991, https://www.airforcemag.com/.

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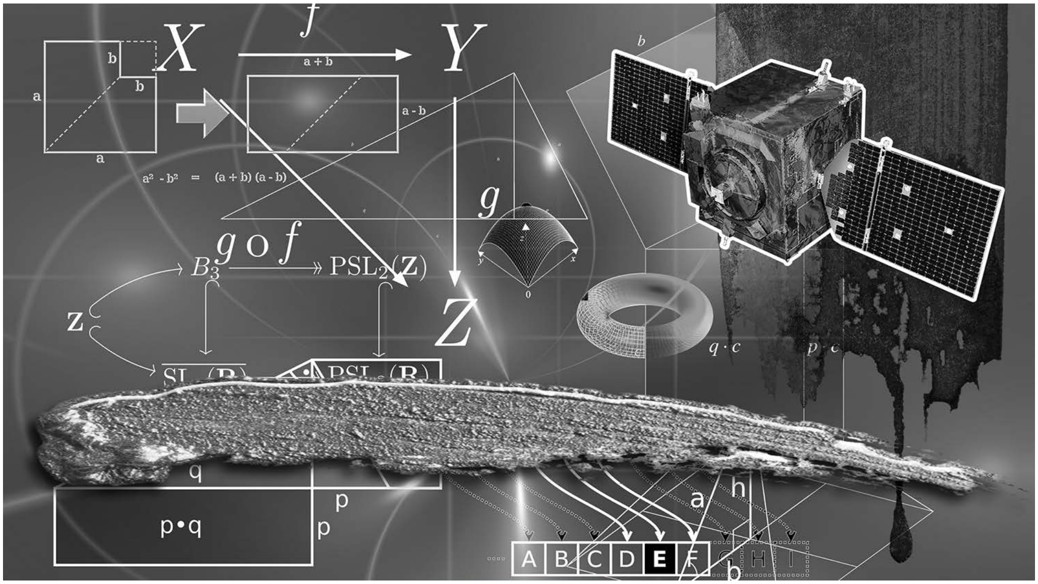
FEATURE

OverSTEMulated

The Science and Art of Space Power Leadership

Maj Brian Stewart, USSF
Col Raj Agrawal, USSF

> *No one can select from the bottom those who will be the leaders at the top because unmeasured and unknown factors enter into scientific, or any, leadership. There are brains and character, strength and health, happiness and spiritual vitality, interest and motivation, and no one knows what else, that must need enter into this supra-mathematical calculus. We think it much the best plan, in this constitutional Republic, that opportunity be held out to all kinds of conditions of men whereby they can better themselves.*
>
> Vannevar Bush,
> *Science, The Endless Frontier: A Report to the President on a Program for Postwar Scientific Research*, 141



Introduction

In this article, we examine the US Air Force (USAF) and United States Space Force's (USSF) decision to require science, technology, engineering, and math (STEM) degrees for the space operations officer career field, as well as whether STEM-degreed space officers historically rise to the top of their respective peer group, evidenced by being selected for squadron command. A decision to place educational quotas on officer accessions excludes a large and diverse group of potential officers, so it is imperative that the requirements align with a desired outcome. To evaluate STEM requirements empirically, we examine two multiyear studies conducted by *Google*, the RAND Corporation's findings on Air Force STEM requirements, and our own cursory analysis of space operations officer performance data. We find that STEM degrees are not useful predictors of competitive selection for space operations command positions, nor are they useful for predicting performance within peer groups.[1] Aside from not predicting success in the space operations career field, two significant risks emerge as a result of overemphasis on STEM:

1. Diversity (Demographic and Cognitive). Demographically, women and some minorities (primarily Black and Hispanic populations) are underrepresented in STEM fields; STEM requirements also preclude a greater diversity of thought and experience. Diversity enhances the formulation of soft skills, leads to greater innovation, and enhances overall team performance.

2. Supply. Initial analysis suggests that the space operations career field is not meeting target accession numbers specified in the *Air Force Officer Classification Directory*, and the available pool of eligible officers will continue to shrink as the Air Force's cyber career field has now instituted STEM requirements as well.[2]

Background

During the last 20 years, the US has been barraged by reports that American students are falling behind global competitors in education, specifically in the production of STEM graduates. US students have also performed poorly in the last several decades on administered standardized tests that measure STEM skills compared to students around the world.[3] With the emergence of China, India, and others as global powers, the disparity in STEM education can appear to be a significant weakness for the US, compared to its potential competitors. The Department of Education has allocated tens of millions of dollars toward STEM education in the last 20 years and maintains that "if we want a nation where our future leaders, neighbors, and workers have the ability to understand and solve some of the complex challenges of today and tomorrow, and to meet the demands of the dynamic and evolving workforce, building students' skills, content knowledge, and fluency in STEM fields is essential."[4] As a result, STEM education has captured the attention of national security decision-makers and has fostered a sense of urgency for corrective action; however, research suggests that United States' obsession with STEM might have gone too far and potentially sacrifices qualities that have been integral to the US' growth as a global superpower in the last 100 years.[5] The USAF has similarly prioritized STEM—and several officer career fields, including space operations—and have implemented STEM requirements for their new accessions.[6] The USSF has inherited these STEM requirements and, as a result, could be in danger of losing its greatest strength—diverse and agile leadership. All of these efforts and expenditures appear to be in the best interest of national defense and the continued prosperity of the US, yet the far-reaching and long-lasting implications of these decisions deserve to further scrutiny.

At face value, STEM requirements seem entirely logical, particularly when considering the highly technical nature of space operations. It is reasonable to assume that technically minded college graduates would not only excel but be necessary to lead the growing number of complex space mission sets. In fact, the 2001 Space Commission made this recommendation explicitly, citing similar requirements in the Navy nuclear officer career field.[7] At least part of this logic is based on an Air Force artifact where officers, not enlisted, are the primary operators of military systems (i.e., airplanes). Shortly after the Air Force's creation, enlisted pilots were converted to officers and warrant officer ranks were removed from the service entirely. In the space operations community, however, it is common practice for officers and enlisted members to perform the same or similar crew functions, despite STEM requirements only applying to officer operators. If the USSF intends to carry this practice forward into its new service, where officers will continue to be both technical and tactical experts, the advancing nature of emerging space technology may necessitate a technical education. Currently, it is unclear whether baccalaureate degree programs are the best source of that education, nor does this address the enlisted crew members who have no such accession requirement. The Air Force space operations career field management team did not put mechanisms in place to assess past and present performance of non-STEM graduates in the career field, nor were assessments made on the most critical factors that determine optimal utility, so there are no existing data to indicate whether a STEM education is indeed fundamental to effective space operations leadership. For reference, other highly technical operations career fields within the Air Force specifically chose not to impose STEM requirements as their analyses showed STEM education was not causal or even positively related to performance in those career fields.[8]

Before 2012, the Air Force's space operations officer career field, usually referred to by its specialty code of "13S," accepted officers with any undergraduate degree specialization. However, with the emergence of competition between nation states—particularly in the space domain—along with increasing complexity of systems and threats, many senior leaders believed that 13S officers of the future would need to be far more technically competent than their mostly non-STEM educated predecessors. To address this perceived gap, the 13S career field management team added STEM constraints for officers entering their field in 2012. The restrictions mandated that new accessions would need to meet STEM prerequisites through their baccalaureate or graduate degree programs to access into the 13S career specialty. Specifically, the guidance mandated that greater than or equal to 80 percent of new accessions *should* be sourced from a selection of particularly useful STEM degrees (identified as Tier 1 and 2), and less than or equal to 20 percent *could* come from any bachelor or master of science degree (Tier 3).[9] Any officer candidates outside these STEM thresholds would be placed elsewhere in the service. If similar constraints apply to the USSF, candidates falling outside these thresholds would not be considered for employment.

Significant Risk, Questionable Return

At this point, it is important to revisit the risks incurred by continuing to focus on STEM at the exclusion of other degrees: diversity and supply. The value of diversity is now widely acknowledged in the military and society. Diversity fuels innovation, enhances performance, empowers the collective, and raises our moral standard, enabling organizations to avoid common pitfalls like groupthink and overconfidence.[10] While commonly assessed against demographic data, it is also relevant to consider diversity of thought, beliefs, and experience. Unfortunately, STEM requirements cull diversity in all of its many forms. Women, as well as Black and Hispanic students, are underrepresented in the STEM fields, while Asian/Pacific Islanders are overrepresented from a demographic standpoint.[11] As a result, any restrictions on hiring STEM graduates inherently limits diversity simply as a result of participation. A valid argument against STEM restrictions could be made on that fact alone. While many efforts are underway to increase minority interest and participation in STEM fields, ultimately, the numbers still reflect that certain demographic groups are more likely to pursue STEM education. Instead of the USSF hoping that this trend will change, recognition of the current environment is crucial to efforts of recruiting and retaining a more diverse service. In addition to demographic constraints, STEM policies also inhibit the diversity of thought, experience, and beliefs that candidates outside of STEM have to offer. This type of diversity can be enhanced by selecting officers from a variety of different majors, regions, schools, commissioning sources, and so forth.

Another factor to consider is whether the supply actually exists to continue enforcing STEM requirements for new accessions. Figure 1 (below) compares actual accessions by tier to Air Force target accession percentages. Over the three years of available data, actual accessions were substantially behind target. Moving forward, the Air Force's cyber operations career field now requires STEM degrees for 90 percent of their accessions, and that will eat into the available pool for 13S in the future. Additionally, other science and engineering career fields in the USAF and USSF (developmental engineers, scientists, statisticians, etc.) require

STEM degrees. Combined with the already low number of STEM graduates in America (thinking back to the original crisis), the ability to meet target accession numbers for STEM in the 13S career field is tenuous at best.

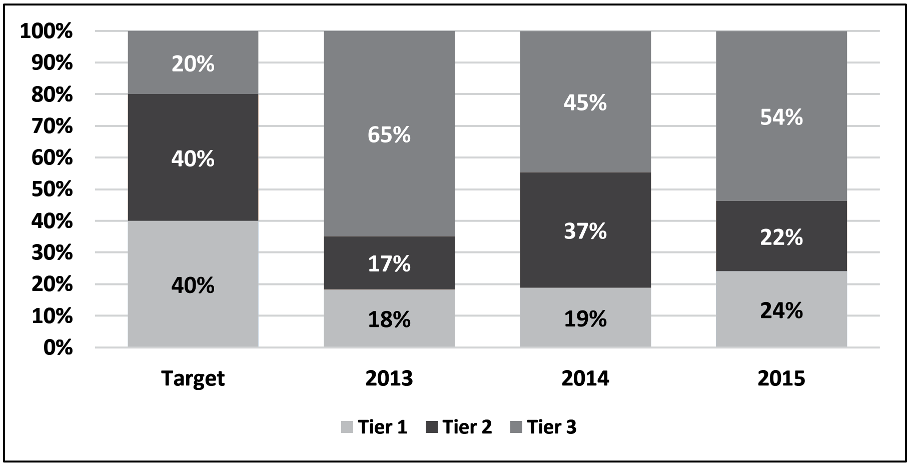


Figure 1. Accession goals versus actual accessions for 2013–15 year groups

There are certainly mechanisms that could be put in place to meet accession numbers, if required, such as diverting STEM graduates exclusively to career fields with STEM requirements or mandating higher numbers of STEM majors for college scholarship recipients or US Air Force Academy students. However, the real question is whether the data supports such a requirement to begin with, and the answer is no. It is also unlikely that the future will change that fact. On the contrary, future conflicts will add pressure on kill chains to operate at machine speed and many of the tasks performed by human space operators today will be automated.[12] Machine learning and artificial intelligence are already changing the way we collect, interpret, and act upon data. In addition to reducing cognitive load and human error, this will be a requirement due to the evolution in the speed and conduct of warfare. In an increasingly computerized and automated environment, the importance of leadership and other nontechnical skills will be magnified. The ability to perform calculations on the fly without computer aid is not only improbable, but a terrible use of a human operator's limited cognitive processing ability. Instead, the humans that occupy operations floors of the future must be strong communicators, they must be calm under pressure, creative, empathetic, and decisive. These are not skills intrinsically linked to STEM education.

The recent Congressional *Future of Defense Task Force Report 2020* identified both the issues with diversity in STEM education and the limits on STEM supply and applied the findings to the US security apparatus' ability to develop a twenty-first century workforce. The task force ultimately concluded that "when gaming out the future of defense, the US must seek to leverage the capabilities of all of its citizens," which is a clear call to action to recognize strengths from a variety of demographic and educational backgrounds.[13]

Research Data on STEM Requirements

The RAND Corporation conducted a study in 2014 that focused on STEM requirements across Air Force career fields. The report states that career field managers generally "value officers with STEM degrees," and this preference is based upon a belief that these officers excel in critical thinking and problem-solving. However, the report goes on to say that "this preference may be unfounded since the evidence of a difference in critical thinking and problem-solving skills between science graduates and graduates in the social sciences/humanities is not conclusive (see, e.g., Arum and Roska, 2011)."[14] Additionally, RAND did not find a preference for STEM in other operations career fields. For example, the rated community (flyers) that includes pilots, combat systems operators, and air battle managers, from which the vast majority of the Air Force's senior leaders have ascended, "observed that a STEM degree is not necessary for effective performance as a rated officer." Instead, they found that "while a STEM degree may provide some advantage in the academic portions of initial training, problem-solving, multitasking, and stress-management skills are more important for performance and progression."[15] The RAND STEM report concluded with a recommendation that the Air Force "develop evidence-based methods to assist Career Field Managers in refining academic degree requirements for their functional areas" and "develop a more precise and visible framework. . . to know more precisely whom it needs to recruit, access, and classify."[16] It is unclear if this was ever accomplished for the 13S career field, but this article could be the first step toward rectifying that issue.

The findings of the rated community are also supported by several studies from the private sector, academia, and prior experiments with this type of narrow focus. The studies demonstrate that STEM requirements alone are not useful for predicting future success, even in technical career fields or organizations. Instead, these studies show that STEM requirements limit diversity, tamper innovation, and can hinder overall performance. In his recent book *Range: Why Generalists Triumph in a Specialized World*, David Epstein demonstrates how our obsession with specialization is unfounded, and that diversity of thought, experience, and beliefs allow generalists to "triumph in a specialized world."[17]

These challenges are not new for military leadership, nor are they specific to the United States. The Royal Navy made a push toward "technocrat" leaders before World War I and one admiral "almost lost the war through his obdurate quest for technical solutions to the U-boat problem."[18] The technocrat leaders of the Royal

Navy proved incapable of decisive leadership in battle and instead grasped for technical safety nets, which are what they knew best. Critics for this period of misguided naval force management warned the late twentieth century Royal Air Force against committing the same errors by conflating the technical nature of their work with the importance of broader leadership ability and perspective.[19] Now it's time for the USSF to appreciate and heed this warning.

The private sector has experienced similar challenges with too narrow a focus on STEM requirements, including one of the most tech savvy organizations on the planet, Google. Since its inception, Google has placed a premium on hiring the best possible candidates and selecting individuals capable not just of evolution, but revolution. Fittingly, Google initially used algorithms to identify and hire the best computer science graduates in the world, but as the company grew, cooperation and communication proved to be as valuable to success as coding. In a robust analysis of more than 15 years' worth of hiring and performance data, Google's Project Oxygen showed that out of the top eight traits that led to success at Google, STEM skills came in last. The skills that were most important were actually "communicating and listening well; possessing insights into others; being a good critical thinker and problem solver; and being able to make connections across complex ideas." The most important factor to success will not come as a surprise, being a good coach or leader.[20] As a result of the findings, Google expanded their hiring to include more liberal arts, humanities, and business graduates.

A skeptical reader might say that it is obvious that in a company full of STEM graduates, the defining characteristics for success must be soft skills as they would be most differentiated. However, that line of thinking still concedes that tech savvy alone is not sufficient to effectively lead large and complex technical organizations, nor optimally effective teams. Additionally, Google did not stop with the results of Project Oxygen and instead sought greater insight into the characteristics of their highest performing teams. Project Aristotle examined Google's most innovative and successful teams, as well as decades worth of academic literature on team performance. The results showed that teams filled with the top-performing individuals who excelled in STEM actually performed worse than "B-teams" filled with a mixed bag of performers that also tended to be more soft-skill dominant. The researchers cited numerous reasons for this outcome, but, in general, A-teams were filled with individuals that sought to optimize efficiency and output while continuing to operate as individuals even when working as a collective. As a result, the net intelligence of the group was no higher than the individual members. On the B-teams, though, information exchange and empathy were key tenets, which contributed to improved performance overall.[21]

The aforementioned studies enabled Google to adjust hiring practices, leadership selection, and team composition, but that is not to say that Google suffered nothing during their STEM-blinded period. One of Google's most elite teams, Product Management, had a firm requirement that all employees needed a computer science degree. Three notable employees tried to join the team to bring forward good ideas while working for Google but were barred admittance due to not meeting the hard-coded computer science requirement. Frustrated by the erroneous prohibition, these employees chose to leave Google to pursue their good ideas elsewhere; Biz Stone went on to cofound Twitter, Ben Silbermann founded Pinterest, and Kevin Systrom cofounded Instagram.[22] Who has the 13S community turned away in the last eight years? Who will be turned away in the future?

To assess the performance of space operations officers by degree, we were given access to personnel rankings for the 2013–15 year groups. These groups fall after the STEM requirements were implemented, so our analysis has limitations. However, the data allowed us to examine personnel by specific degrees, which could be bucketed into the tiers established by the Air Force Officer Classification Directory for the 13S career field. The Tier 3 degrees serve as a sort of proxy for non-STEM in this analysis, despite the fact that all tiers have to meet basic STEM coursework requirements, even if their degrees were not STEM. To evaluate performance of graduates with no STEM requirements, we also looked at command selection in the space operations career field for 2017, as all of these officers entered the career field many years before STEM requirements were implemented. Unfortunately, the data is flawed for a different reason, as we do not have a sense of the total inventory of STEM vs. non-STEM for the year groups eligible for command in this selection. Regardless, we believe the data is convincing enough to overcome some of these limitations, and at the very least demand further analysis with more complete databases.

The board scores for space operations officers in the 2013–15 year are roughly distributed equally across year groups and across degree tier and major (see fig. 2). Additionally, all year groups have non-STEM graduates in the top third of performers and STEM graduates in the bottom third and vice-versa (see fig. 3). No significant advantage or performance improvement exists for any tier, which at the very least demonstrates that the tiered accession targets are not meaningful in the space operations career field.

When digging deeper into individual performance, the success of non-STEM majors is evident across all year groups. All year groups have non-STEM graduates in the top 10 officers and also Tier 1 graduates in the bottom 10 officers by ranking.[23] The key takeaway from all of the performance data is that people can be successful (or not) regardless of what they studied in college. What many have failed to consider is that majoring in non-STEM fields is not necessarily indicative of any lack of ability in learning and understanding STEM.

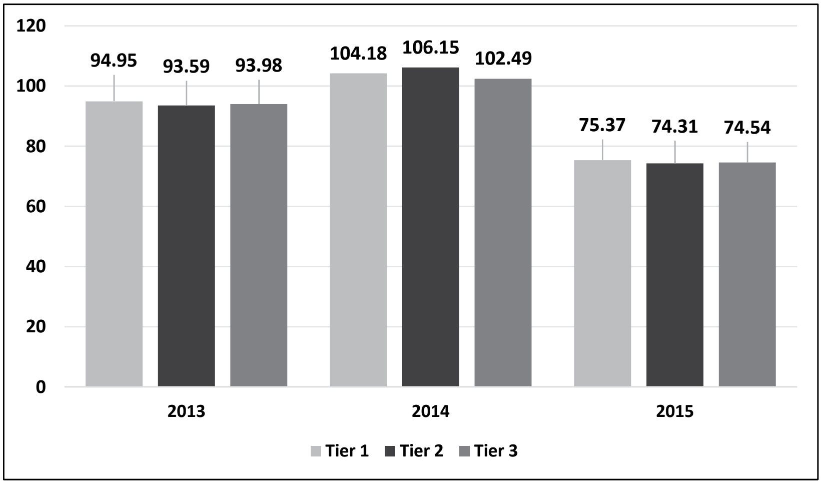


Figure 2. Average board score by degree tier and year group

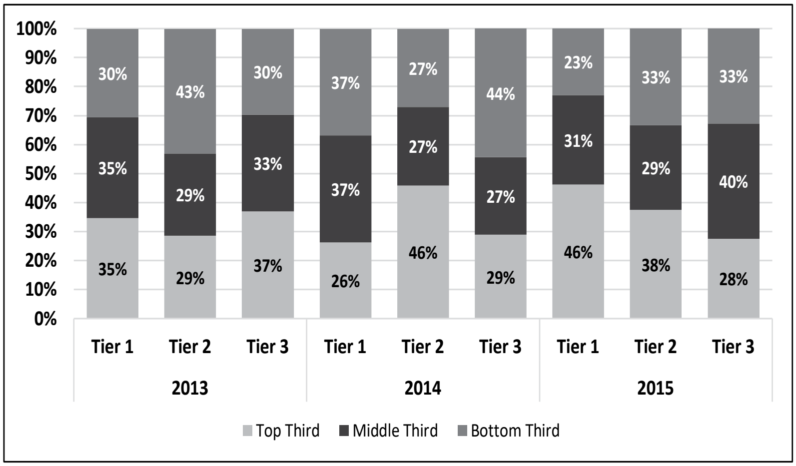


Figure 3. Percentage of education tier in each ranking third, by year group

The Vigilant Eagle board is the process used by the space community to select its squadron commanders, which is arguably the most pivotal leadership position in the USAF and USSF. If ever there was an indicator of success in a given career field, and the community's confidence in the competence, potential, and effectiveness of an individual, squadron command is that litmus test. The 2017 Vigilant Eagle board selected 24 people for command; only four out of the 24 commanders selected had STEM degrees, and only one of the four STEM majors started their career as a 13S. Said differently, one officer out of 21 who entered the service as a 13S and was selected for command had a STEM degree. The other three selected for command began their careers as engineers and/or program managers in the acquisition career field. These officers and their peers are the ones who are currently on the frontlines of space operations. They are leading the transformation that we believe is so demanding of STEM education, yet they are doing it without STEM degrees. Either the supply of STEM in the 13S career field for these year groups was so low that there simply were not STEM graduates to select for command, or there is more to leadership in space operations than a STEM degree.

The argument being made here is not that non-STEM grads are more effective leaders, because that claim is equally erroneous. Rather, the data show that non-STEM officers can not only survive but thrive as 13S leaders, as well as in virtually any other USAF or USSF career field. Artificially limiting the potential diversity, innovation, and performance of future space operations units based on assumptions about the inferiority or incapability of non-STEM graduates not only limits the potential to include more diversity of thought and experience, but it also potentially weakens joint power projection. It is incumbent upon all leaders to be willing to continuously evaluate assumptions and adjust fires if needed.[24]

Conclusion

Leadership is both an art and science, and the future USSF officer corps would be most effective as a diverse and balanced team trained and educated to lead across all areas. Ten years from now, the people making these decisions will be retired and counting on the rest of us to continue to lead and succeed. To do so, we need to recruit and retain the best possible people, who embody not only the science of leadership but the art as well. Leadership is essential to continued military power projection and its relationship to deterring conflict. The USSF needs a diverse team of leaders who are motivated and willing to work hard but, even more so, are skilled at leading diverse teams to address dynamic challenges at a pace that outmatches the competition. To ensure success across this diverse team, we should focus on rigorous initial training and continuous education. There are no data that support an argument that a STEM major will be more successful in military technical training programs than a non-STEM major. Even if that were the case, leadership ability is mostly linked to the successful employment of soft skills that are frequently a focus of non-STEM education. ✪

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Notes

1. The transition of space operations officers from the Air Force to the newly established Space Force is currently in progress, but the Space Force will likely continue the STEM requirements for new space operations officer accessions.

2. The military already competes with commercial and other entities for STEM graduates in the US. This competition affects the supply of STEM officers to all services. Our assessment is based on the number of STEM graduates who are entering the Air and Space Forces.

3. National Center for Education Statistics, *International Data Explorer* (Washington, DC: Department of Education, accessed 20 July 2020), https://nces.ed.gov/.

4. US Department of Education, *Science, Technology, Engineering, and Math, Including Computer Science* (Washington, DC: Department of Education, accessed 29 June 2020), https://www.ed.gov/.

5. Alexandra Ossola, "Is the U.S. Focusing Too Much on STEM?" *Atlantic,* 3 December 2014, https://www.theatlantic.com/; Fareed Zakaria, "Why America's Obsession with STEM Education is Dangerous," *Washington Post,* 26 March 2015, https://www.washingtonpost.com/; Laura McInerney, "A Misguided Obsession with STEM Subjects Is to Blame for the Decline in English A-Levels," *Guardian,* 16 July 2019, https://www.theguardian.com/; and Colin Seale, "A Perfect Time To End Our STEM Obsession: 3 Ideas for Teaching Critical Thinking at Home During (and after) The Coronavirus Pandemic," *Forbes,* 15 March 2020, https://www.forbes.com/.

6. National Research Council, *Examination of the U.S. Air Force's Science, Technology, Engineering, and Mathematics (STEM) Workforce Needs in the Future and Its Strategy to Meet Those Needs* (Washington, DC: National Academies Press, 2010); and Lisa M. Harrington et al., *Air Force-Wide Needs for Science, Technology, Engineering, and Mathematics (STEM) Academic Degrees* (Santa Monica, CA: RAND Corporation, 2014), 113.

7. Commission to Assess United States National Security Space Management and Organization, *Report of the Commission to Assess United States National Security Space Management and Organization* (Washington DC: US Government Printing Office, 2001), 45.

8. There are no STEM requirements for pilots, combat systems operators, air battle managers, special operations officers, or intelligence officers. The intelligence community actually prioritizes liberal arts (45 percent) over STEM (30 percent), though they still allow any degree to join the career field. Cyber operations have recently added STEM requirements with 90 percent supposed to be sourced from STEM, while 10 percent can come from any degree. Air Force Personnel

Center (AFPC), *Air Force Officer Classification Directory (AFOCD)* (Randolph AFB, TX: United States Air Force, 2017), 244–49.

9. AFPC, *AFOCD,* 246–47.

10. Toyah Miller and Maria Del Carmen Triana, "Demographic Diversity in the Boardroom: Mediators of the Board Diversity–Firm Performance Relationship," *Journal of Management Studies* 46, no. 5 (July 2009): 755–86; Christian R. Østergaard, Bram Timmermans, and Kari Kristinsson, "Does a Different View Create Something New? The Effect of Employee Diversity on Innovation," *Research Policy,* April 2011, 500–09; and Irving L. Janis, *Victims of Groupthink: A Psychological Study of Foreign-Policy Decisions and Fiascoes* (Boston: Houghton Mifflin, 1972).

11. Amanda L. Griffith, "Persistence of Women and Minorities in STEM Field Majors: Is It the School That Matters?" *Economics of Education Review* 29, no. 6 (December 2010): 911-22; and Eugene Anderson and Dongbin Kim, *Increasing the Success of Minority Students in Science and Technology* (Washington, DC: American Council on Education, March 2006).

12. Mady Mayfield, "Air Force Envisions AI Automating Satellite Operations," *National Defense Magazine,* 4 December 2019, https://www.nationaldefensemagazine.org/; and US Small Business Administration (SBA), *Autonomous Satellite Ground Operations* (Washington, DC: SBA, 2016), https://www.sbir.gov/.

13. US House of Representatives, House Armed Services Committee, *Future of Defense Task Force 2020* (Washington, DC: US House of Representatives, 23 September 2020), 55.

14. Harrington et al., *Air Force-Wide Needs,* xiii.

15. Harrington et al., *Air Force-Wide Needs,* xiii.

16. Harrington et al., *Air Force-Wide Needs,* xiv.

17. David Epstein, *Range: Why Generalists Triumph in a Specialized World* (New York: Penguin, 28 May 2019).

18. Andrew Gordon, *Military Transformation in Long Periods of Peace: The Victorian Royal Navy* (Cambridge, UK: Cambridge University Press, 2006), 161.

19. Gordon, *Military Transformation,* 161.

20. Valerie Strauss, "The Surprising Thing Google Learned about Its Employees—and What It Means for Today's Students," *Washington Post,* 20 December 2017, https://www.washingtonpost.com/.

21. Charles Duhigg, "What Google Learned From Its Quest to Build the Perfect Team," *New York Times,* 25 February 2016, https://www.nytimes.com/.

22. Kim Scott, *Radical Candor: Be a Kick-Ass Boss without Losing Your Humanity* (New York: St. Martin's Press, 2017).

23. For example, three of the top 10 officers in the 2013 year group have business management (non-STEM) degrees, while two of the bottom five have aerospace engineering (Tier-1 STEM) degrees.

24. Academic literature is filled with examples of seemingly valid indicators of success that do not withstand the gauntlet of real-world application. Famously, Kahneman and Tversky's work on predicting the success of officer candidates in Israeli Defense Force training programs and repeatedly failing led them to identify, publish, and popularize the bias of the "illusion of validity" (Kahneman [2016]; Lewis [2013]; etc.). From a US perspective, Angela Duckworth's best-selling book *Grit: The Power of Passion and Perseverance* details her analysis of indicators of success for candidates of the United States Military Academy. She, too, found that measures that might seem relevant at face-value often do not play out as expected (Duckworth [2016]). These examples

highlight the fact that decisions are often made by well-meaning and entirely capable leaders based on logical assumptions that ultimately do not pan out in reality. Daniel Kahneman, *Thinking, Fast and Slow* (New York: Farrar, Straus, and Giroux, 2013); Michael Lewis, *The Undoing Project: A Friendship That Changed Our Minds* (New York: W. W. Norton and Company, 2016); and Angela Duckworth, *Grit: The Power of Passion and Perseverance* (New York: Scribner, 2016).

VIEW

A Concept for Next-Generation Combat Search and Rescue

Col James R. Ayers, USAF, Retired
Alec Wahlman, PhD

Introduction

The return of great-power competition means near-peer adversaries are challenging United States military superiority across many domains and missions. One of these missions is the ability to rescue aircrew shot down over hostile territory, a mission the US military calls combat search and rescue (CSAR). Currently, there is a gap as US military CSAR aircraft packages cannot follow advanced stealthy aircraft deep into areas with advanced air defenses. The gap has implications for the costs of air campaigns, aircrew morale, and even coalition operations as the US military has often provided CSAR support to allies. However, there are options to upgrade US CSAR capabilities. A combination of new equipment and a new concept for CSAR may give rescue packages the survivability and lethality needed to generate a reasonable chance of success, even against air defenses that could down a fifth-generation fighter. In this article, we will describe this new concept as well as how it might be tested.

The Problem

Today, the sophisticated air defenses of adversaries like China and Russia would make traditional rescue operations infeasible. The participants of a 2017 National Academies of Sciences conference on CSAR concluded that against near-peer adversaries, conventional CSAR was "highly unlikely to be viable."[1] Modern surface-to-air missiles can engage nonstealthy aircraft out to several hundred kilometers. The HH-60G—the current generation rescue helicopter—would not survive long against these threats, nor would the likely escorts of the fourth-generation nonstealthy fighters, such as the F-16, F-15E, or A-10. The net result of such a mission could be losing additional aircrew and their aircraft, producing a vicious cycle of more personnel to be rescued. Stealthy fifth-generation fighters (i.e., F-35, F-22) are more survivable in such an environment, but they are not invincible. Should any one of those advanced platforms be shot down deep inside the threat rings of an advanced air defense system, the aircrew could be on their own because the US military has no fifth-generation CSAR to go with its fifth-generation fighters. If fifth-generation aircraft could be spared from the larger air campaign as CSAR escorts, the vulnerability of the rescue helicopter itself would still jeopardize the mission.

History and Importance of CSAR

The US military's CSAR capability first took shape in World War II but in a limited form. Most successful rescues were via submarine or seaplane, of aircrew on the water or at the shoreline. US forces alone rescued few personnel inland.[2] Aircrews shot down over German-occupied Europe could still be rescued but only with the assistance of third parties (e.g., the French resistance) over much longer timelines than with conventional CSAR missions and at a relatively low rate of success. A preview of CSAR's future on land was provided in April 1944 in Burma, when the US Army conducted the first helicopter rescue of an American pilot, using an early prototype Sikorsky YR-4.[3]

In the Korean War, CSAR expanded its geographic scope with US forces able to regularly rescue personnel inland. The helicopters were crude by today's standards and available in small numbers, but they gave commanders a new inland rescue capability. Even at this early stage, helicopters brought home 60 percent of United States Air Force personnel rescued during the war.[4] The US military developed many of the CSAR basic principles and functions during this period. During the Vietnam War, CSAR evolved further into what many are familiar with today. That CSAR capability carried the US military into the twenty-first century, including the long counterinsurgency campaigns in Afghanistan and Iraq.

But for a few notable exceptions since the Korean War (e.g., Hanoi, 1972; Baghdad, 1991), US military commanders have had viable options for recovering their downed aircrew. Knowing that recovery assets were in place increased US and partner nation commanders' willingness to send aircrews on higher risk missions while also benefiting aircrew morale. A CSAR system without the ability to penetrate advanced air defenses could strain coalition coordination with some partners opting out from risking the enemy parading their pilots as trophies. Moreover, the expensive and time-consuming process of developing aircrew capable of operating America's best aircraft make those personnel important and difficult to replace. High-tempo operations, absent a robust CSAR capability, could result in substantial personnel losses that could take years to replace. During a prolonged conflict, the impact on operations from pilot shortages (from all causes) could be profound; this happened when both Germany and Japan could not maintain their supply of trained and experienced aircrew late in World War II.[5] This is not to say pressing on with an aggressive air campaign would be impossible despite the lack of a viable CSAR capability, but it would raise the costs.

A New Concept

The US Air Force launched *Agility Prime* in April 2020 to accelerate the era of electric vertical takeoff and landing (eVTOL) aircraft for military and commercial use, and CSAR could be one possible military use of these vehicles.[6] The program could accelerate fielding platforms important for advanced CSAR, but the Air Force still needed a concept for employing them. The authors have an initial framework for such a concept built upon three central pillars:

- Risk no additional personnel during a rescue.
- Do not pause the larger ongoing air campaign, nor draw significant resources away from it.
- Conduct the rescue rapidly, within a few hours if possible.

For context, a conventional rescue package could include several helicopters and approximately half a dozen fighter aircraft to deal with air defenses and other threats to the downed aircrew (e.g., enemy vehicles and infantry). The exact composition of any package would vary, customized by commanders to address each mission's needs, along with the assets available at that time. CSAR missions would sometimes include aircraft for protection against opposing aircraft, depending on enemy capabilities. However, our concept will not discuss this element as it would likely not differ from how fighter cover is provided for current CSAR missions and use the same existing platforms (i.e., F-22, F-35).

In contrast, we envision a much larger rescue formation, composed solely of unmanned systems, at least until any recovered personnel are aboard the recovery vehicle(s). The formation includes many more aircraft than a conventional package (63 aircraft total, 60 escorts plus three recovery vehicles), to dramatically increase the formation's ability to take losses while maintaining the ability to accomplish the mission, putting no additional personnel at risk.

None of the aircraft in the formation need a runway, which allows for the rescue formation's aircraft to remain dispersed because they no longer need to concentrate around a few airfields, which tend to be high on an enemy's targeting list. This independence from runways also aids response time because these aircraft can be based close to the front line.

Note: the platforms we describe illustrate the needed platform characteristics but should not be considered the only possible solutions.

As our focus is on the challenges of CSAR in high-threat environments, the rescue formation described is optimized for that environment. In the future, the US military would certainly conduct CSAR in a range of environments, so our described formation is intended as a compliment to existing CSAR capabilities.

New Rescue Package Characteristics

A key technology behind the concept we propose is a repurposed all-electric urban air taxi aircraft—a type of aircraft that the aviation industry has matured rapidly in recent years. During the last few years, the capital markets have been investing hundreds of millions of dollars into a number of commercial research and development efforts on flying electric urban taxis.[7] Advances in electric propulsion, battery technology, and autonomous flying has spurred a broad push across the aviation industry to be the first to market. Battery prices have fallen 87 percent from 2010–19, reducing platform cost.[8]

Perhaps an even stronger motivation has been the potential for dramatic reductions in operating costs. Data from 2018 for the New York City government's fleet of vehicles showed annual maintenance costs alone (not counting fuel) were approximately 80 percent less when comparing similar-sized all-electric vehicles to vehicles with internal combustion engines.[9] Most developers of flying taxi designs envision the pilot being replaced by autonomous flight capability at some point, further reducing costs.

Most flying taxi designs in development are ill-suited to a rescue mission inside hostile airspace; they are generally slow, short-range quadcopters, optimized for short hops around a city. But some commercial technologies show promise in potential military applications. For example, a German company, Lilium, envisions a taxi capable of flying between cities. In flight testing, now with an estimate in-service date of 2025, the Lilium Jet (fig. 1) is designed to fly 300 km at 300 kph.[10] It achieves this higher speed and long-range by dispensing with the usual large, exposed rotors and instead using 36 small basketball-sized electric fans, each nested in its own nacelle and arrayed in rows along the front and rear wings. The rear wing is fixed; only the row of engines along the trailing edge rotates for vertical flight. The entire front wing rotates for vertical or horizontal flight. This design allows the wings to provide the lift in horizontal flight, freeing the engines to provide forward thrust. The Lilium Jet is designed for four passengers plus one pilot, with the long-term goal to replace the pilot with an autonomous flight capability.

Figure 1. Lilium Jet

Table 1. Electric air taxis—comparison of desirable characteristics

Characteristic	*Commercial Mission*	*CSAR Mission*
Low noise	Valuable	Valuable
Low operating cost	Valuable	Secondary
Speed and range	Valuable for city-to-city	Valuable
Low heat signature	Irrelevant	Valuable
Lower radar cross section	Irrelevant	Valuable
Autonomy	Valuable	Valuable

There are no indications the Lilium's designers envision any military applications, but the commercial urban taxi mission has several requirements that overlap with CSAR. For example, the Lilium is designed for quiet operations over urban areas, which also happens to be valuable for CSAR. In some cases, the needs of the commercial mission produce accidental benefits for CSAR. An example would be the electric propulsion system that the commercial users want for its low operating cost, while CSAR operators value the low heat signature that comes with that engine type. See table 1 for a summary of mission characteristic comparison.

The escorting platforms for the rescue package could be several models of in-service long-endurance loitering munitions. The Harop is a long-range loitering munition built in Israel, designed to target air defense systems, capable of flying up to 400 kph and 1000 km.[11] The Harop includes a sensor for detecting radar emissions along with an optical sensor to confirm targets, but a human operator commands any attack. The small 40 lb. warhead in the fuselage does not detach, so to destroy a target, the Harop must dive into it. Though not necessarily expendable, if no targets are found it can return to its launch point for recapture and refueling. The Harop launches from a truck with its wings folding out to their full 3 m span after launch. For the rescue package, the Harops would be focused on suppressing enemy air defenses.

The Hero 900 is another Israeli-made, long-range loitering munition but slower, smaller, and with a maximum range of 250 km. Also, truck-launched, it carries an optical sensor and small 20 kg warhead, can be recovered after launch, and has a human operator controlling any attacks.[12] The Heroes in the rescue package would deal with both air defenses and threats like ground vehicles or patrols that threaten the recovery vehicle or downed pilot.

Both loitering munitions depend on communication links back to human operators for executing attacks. Were those links lost for extended periods of time, this would sharply reduce the effectiveness of these munitions. The viability of US communications to support the use of these escorting munitions is a key question for this concept and should be explored further.

One possible solution would be equipping these munitions with an autonomous attack capability, something they currently do not possess, at least per open sources. Adding such a capability would involve two challenges: technical and policy. We suspect that the policy challenge is the greater of the two, considering the impressive capabilities of the current generation of smart munitions. US policy does not specifically prohibit lethal autonomous munitions. Department of Defense (DOD) Directive 3000.09 requires that autonomous and semi-autonomous systems "shall be designed to allow commander and operators to exercise appropriate levels of human judgement over the use of force."[13] With the DOD's historical sensitivity to civilian casualties, defining that a lethal autonomous system meet that standard of "appropriate levels" standard would be difficult.

The rescue package's design would resemble a conventional rescue package in function but differ in platforms. For comparison, consider a notional rescue package composed of two HH-60 helicopter recovery vehicles, four A-10s to deal with various ground targets, and four F-16s focused on enemy air defenses. Every CSAR mission is different, but this gives a baseline for comparison. If one were to design an unmanned package that was roughly equivalent, using the previously mentioned platforms, that package could include three Lilium recovery vehicles, 12 Harops, and 48 Heroes. In this composition, we are aiming to roughly replicate the functions of the manned package. The large number of munitions on the escorting manned fighters requires a large number of escorting drones since they carry only one warhead each. See table 2 for a summary of the two rescue package designs.

Table 2. Comparison of rescue packages

Package Type	*Platform*	*Role*
Conventional, Manned	2x HH 60	Personnel recovery
	4x F-16	Suppress air defenses
	4x A-10	Protect pilot and recovery vehicle
	Total: 10	
Unmanned	3x Lilium Jet	Personnel recovery
	12x Harop	Suppress air defenses
	48x Hero	Protect pilot and recovery vehicle
	Total: 63	

The key advantage of the unmanned package is its ability to absorb substantial losses and still retain its core functions; we assumed such losses during its fight to the pickup point. Escorting drones attacking threats that could not be bypassed would suffer some losses, others would be to undiscovered pop-up threats. We also assumed two parameters for each rescue mission: 1) that the larger air campaign would have revealed some enemy threats, and 2) that additional threats were certain to exist. Thus, the rescue package was designed to feel its way forward, paying for information with lost platforms. That dynamic is key; the unmanned package can afford that cost where the smaller manned package cannot.

Because the 60 escorting drones carry both sensors and warheads, although both of modest capability, this creates a dilemma for the enemy: accept the risk of an approaching drone discovering and destroying a valuable asset needed for the larger conflict or engage and risk revealing the asset's location. In the context of the larger conflict, enemy forces will be dealing with other threats, such as a wave of F-35s, that may follow shortly after a rescue package, so they will have some difficult choices. Is a package of relatively low-cost recovery vehicles and escorting drones worth risking detection by firing or depleting precious surface-to-air missile inventories? In terms of the larger conflict, losing an inexpensive drone to a top-of-the-line Russian S400 missile would be a win for the Blue team.

Testing the Concept

This concept is immature and needs testing against the spectrum of threats a near-peer can present. Portions of the concept may be flawed, or the entire concept may be found wanting, but we see the combination of need and promise as making such an effort worthwhile. Below is a list of questions we see as key to better understanding the concept's viability, which could be explored via war games and experiments.

- What is the interplay between Red electronic warfare capabilities, drone autonomy, and US policy on lethal autonomous systems?
- What are the communications and navigation challenges (e.g., bandwidth, personnel) for coordinating the many platforms in the rescue package in a hostile electromagnetic environment?
- What is the cost trade-space between advance air defense munitions and the platforms in the rescue package?
- How effective would less-advanced air defenses (e.g., man-portable surface-to-air missiles, radar-guided artillery) be against the unmanned rescue package?
- How would this CSAR capability impact the larger Blue air campaign, and vice versa?
- What is the relative value of various performance characteristics (e.g., speed, stealth, lethality, sensors, range, cost) for the platforms in the rescue package?

- How sensitive is the overall rescue package performance to changing mission variables (e.g., number of personnel down, terrain, distance into enemy territory, weather)?
- What is the utility of decoys in the rescue package?
- Where are the most effective Red counters to such a rescue package?

Conclusion

While the nation's best aircraft offer impressive capabilities against advanced air defenses, one cannot forget the crews that operate them. To preserve that critical human capital for whatever conflicts the future holds, the US military's CSAR capabilities should evolve for the new threats. This evolution is possible if existing capabilities are augmented with specialized rescue packages that are unmanned, larger, and can sustain much higher losses while retaining effectiveness. Loitering drones for escorts, plus eVTOL recovery aircraft, could provide the needed hardware. The concept described in this article, combined with that hardware, could give future CSAR missions a fighting chance in even the highest threat environments. ✪

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VIEW

Every Airman and Guardian a Technologist

Reinvigorating a Disruptive Technology Culture

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The US Air Force (USAF) and Space Force (USSF) face an era of fierce technological competition against rapidly modernizing great-power competitors. Sustaining war-fighting advantages in the twenty-first century will require a dramatic increase in technological innovation at all levels. As articulated by Gen Charles Q. Brown Jr., Air Force chief of staff, the mandate is clear: accelerate change or lose.[1]

Recent reforms led by Dr. Will Roper, the assistant secretary for acquisition, technology, and logistics, and other senior Air Force leaders helped the Department of the Air Force accelerate acquisition processes and bring more commercial technologies into the acquisition pipeline. These processes include embracing digital engineering to shorten product development times, expanding agile non-Federal Acquisition Regulation procurement mechanisms, and creating new innovation cells that connect commercial innovators with Air Force needs. The USSF has moved early to embrace rapid acquisition practices as its standard for future space systems.

Accelerating acquisition processes is only part of what is needed. Many other processes and functions should be aligned to create military services that are optimized to prevail in an environment of disruptive technological change. True disruption is painful, and imposing it voluntarily on one's organization is hard. Past disruptive changes in military technology were controversial and required difficult changes to military traditions and institutions. Those disruptive changes were pivotal to maintaining a technological advantage in earlier eras, and future victories may depend on reinvigorating the USAF and USSF's ability to foster, embrace, and institutionalize disruptive technology faster and more effectively than our competitors.

Fortunately, the shared heritage of the USAF and USSF was built on disruptive technological change. In this article, we briefly review the successful practices of earlier eras to illuminate how they supported the efficient advancement of disruptive change during those periods. We then reconsider those enabling practices in the current context and make recommendations for reinvigorating institutional service cultures that are postured to accelerate a new era of technological warfighting dominance.

A Heritage of Disruption and Reinvention

Air and space forces have experienced an unusual period of relative technological stability since the end of the Cold War and during the Global War on Terror. Many frontline systems today are upgraded versions of those that fought during the Gulf War 30 years ago. As a result, today's servicemembers and organizations have not experienced the dramatic level of change experienced by previous generations of Airmen.

The USAF had its origins in the desire to use an emerging technology—the airplane—to conduct warfare in a new and decisive way. The new technology enabled military operations against the enemy that were very different from the established ways of conducting war in the early twentieth century. The pro-innovation practices of the era enabled a rapid cycle of disruptive technological innovation, followed by the substantial reinvention of equipment, doctrine, and organization that made transformational change almost routine.

For example, the first military flight demonstrations in the US were performed by the Wright Brothers at Fort Myer near Washington, DC in 1909.[2] Within less than 10 years, the Army Air Service was conducting large-scale operations in World War I as a scout (reconnaissance) and pursuit (air-to-air fighter) force with all the required training, maintenance, and supporting functions in place. Comprehensive doctrinal changes were developed after the war, leading to the rise of strategic bombing theory and the demand for long-range heavy bombers. As a result, the Army Air Forces went to World War II primarily as a bomber force, with other operations such as pursuit working in support to thousands of heavy bombers. Ten years after World War II, the USAF had converted its frontline bomber and fighter units to jets, with all the changes that entailed. Within another 10 years, intercontinental ballistic missiles had become a core weapon system. By 1965, the first generation of nuclear missiles, Atlas, was already being phased out in favor of the newer Titan II, and the USAF was operating its first orbiting satellites.

This pace and breadth of technological change seem almost inconceivable today. This process didn't happen only with the engagement of a few innovators. The ability of the service to reinvent itself continuously as technology advanced relied upon the service culture—the way we collectively perceive ourselves. Doctrine preceded and anticipated technology in many cases. Logisticians, maintainers, personnelists, and trainers rapidly accepted change and adapted their methods as new technologies replaced old, sometimes in just a few years. Senior service leaders and budget specialists planned for the next generation of technology, often while the current generation was just reaching the field.

Certainly, the competitive pressures of the world wars and the Cold War provided a strong demand and sense of urgency. However, strong demand alone didn't account for the service's repeated success in meeting that demand. Several core cultural practices helped account for the early Air Force's ability to develop and adopt disruptive innovations and reinvent itself quickly.

Technologists and Operators as a Team

Civilian inventors such as the Wright Brothers, Glenn Curtiss, and their peers in Europe worked to design better airplanes, but they were not primary drivers for the adoption of airpower by the militaries of the great powers. Technology-minded military thinkers and operators were central in adopting the airplane, which had no existing role in military operations. Junior and midgrade officers in the US Army's Signal Corps were instrumental in bringing the Wright Brothers to demonstrate their aircraft at Fort Myer.[3] Many early combat pilots had learned to fly in the prewar days when pilots built their planes from kits and served as their own mechanics. They saw themselves as tinkerers and were active participants in developing new methods of air combat, sometimes designing and building equipment themselves. Innovative military scout pilots first used firearms to attack enemy aircraft during their patrols and carried grenades and specially made bombs to drop on the advancing enemy and supply areas as they passed overhead.[4]

Military innovators routinely moved back and forth between technical and operational roles in the junior and middle grades. For instance, the future Gen Henry "Hap" Arnold spent his early years in the cockpit helping to test early air-to-ground radio communications and, in addition to leading flying units, served as a major and colonel in the Aeronautical Division overseeing new aircraft and weapon development. His personal experiences with emerging technology were important to his later work to build the Army Air Forces and the early Air Force. Gen Jimmy Doolittle started his career as an engineering officer and test pilot and was sent by the military to get master's and doctorate degrees in aeronautical engineering at the Massachusetts Institute of Technology. He credited this kind of technical training with solidifying the relationship between flyers and technologists. Later in World War II, as the commander of the Eighth Air Force, Doolittle established an Operational Engineering Division in Europe to keep engineers close to his combat squadrons.

The close relationship between technologists and operations endured in the Vietnam era. For example, Col Joe Davis, a former F-84 attack pilot, served as the vice commander of the Armament Development and Test Center at Eglin AFB, Florida, in 1965. He developed the idea of using newly invented lasers to guide bombs to ground targets.[5] Davis sponsored laser engineers at Texas Instruments to design and build the first prototype laser-guided bombs and personally flew the live-fire test missions with the weapon in Southeast Asia.

In short, science and technology (S&T) was close to operations; and operators, if not technically trained themselves, were familiar with research and development (R&D) and understood what was in development and technically feasible. The relatively small size of the early Air Force R&D enterprise helped to naturally create the melding of operational and technical competencies, sometimes in the same individual. Such close working relationships at the junior and field grades are cited as a key factor in modern Israel's small but highly efficient defense R&D establishment.[6]

Technologists as Leaders in Doctrine and Future Force Design

After World War I, technically astute aviators codified new theories about employing airplanes in warfare. The early airpower theorists such as Gen Giulio Douhet in Italy, Air Marshal Hugh Trenchard and B. H. Liddell Hart in the United Kingdom, and Gen William "Billy" Mitchell in the United States focused their arguments on how the inherent capabilities of aircraft could impact future warfare. Because the aircraft of the 1920s only offered a foreshadowing of what the theorists envisioned, they focused on the potential of future systems.

For example, in 1925, Liddell Hart wrote:

> The air has introduced a third dimension into warfare. . . Aircraft enable us to jump over the army which shields the enemy government, industry, and people, and so strike direct and immediately at the seat of the opposing will and policy. A nation's nerve system, no longer covered by the flesh of its troops, is now laid bare to attack.[7]

In the US, technically trained military theorists at the Air Corps Tactical School further refined the idea of striking at the heart of the enemy through the third dimension, yielding precision bombing theory. This doctrinal refinement furthered the argument that bombing vital enemy targets from the air could be strategically decisive. This refinement was a dramatic departure from previously accepted concepts of victory. As many Airmen know, this eagerness to pursue heretical doctrinal concepts got some of the advocates of precision bombing theory, including General Mitchell and the young Colonel Arnold, into trouble with their superiors.

The buildup of US airpower before World War II was guided by the doctrine developed in the interwar period. Technologists and theorists drove the vision for future force design. For instance, theorists as early as Douhet had envisioned the "battle plane," a long-range aircraft capable of carrying a heavy bomb load into an enemy's heartland and bristling with defensive armament to protect itself.[8] Fleets of battle planes would form the core of offensive airpower. The four-engine B-17 Flying Fortress was conceived and championed as the US's battle plane and was a faithful incarnation of the doctrinal concept.[9]

The emergence of ballistic missiles precipitated another doctrinal revolution. Military innovators such as Gen Bernard Schriever saw the potential for ballistic missiles to provide a potentially superior means to carry nuclear warheads into the vital centers of the enemy, and the improvement of Soviet surface-to-air missiles threatened the credibility of existing bombers as a strategic deterrent.[10] Just as the long-range bomber had provided the means to bypass enemy ground forces, the ballistic missile provided a way to bypass the enemy's improving air defenses. General Schriever drove the development of the Air Force's ballistic missile and space forces during the 1950s and 1960s. Holding an advanced degree in aerospace engineering and experienced in R&D leadership, General Schriever aligned the new technology of ballistic missiles with future force design and the concurrent development of strategic deterrence theory.

Leadership and Training Support for Technological Preeminence

After World War II, an assessment of the role of military scientists and engineers in the war predicted that "any future war will require within the services a large group of technically trained officers of high skill to function in research, planning, and operations."[11] General Arnold sponsored Dr. Theodore von Kármán to produce the landmark report *Toward New Horizons*, assessing the future of the Air Force. The summary volume stated that "the first essential of air power is preeminence in research."[12] This short but powerful observation established that S&T would provide the foundation of USAF combat effectiveness and help solidify a culture of technical skill and innovation readiness for the newly independent Air Force.

The men in charge of the future Air Forces should always remember that problems never have final or universal solutions, and only a constant inquisitive attitude toward science and a ceaseless and swift adaptation to new developments can maintain the security of this nation.[13]

This principle was matched with initiatives to embed technological excellence further into institutional DNA. High levels of investment in S&T were typical for the young USAF. The Air Corps Engineering School was expanded to create the Air Force Institute of Technology, offering advanced technical degrees to officers. At the base level, initiatives encouraged technical competence for all ranks.

For example, Gen Curtis E. LeMay, Strategic Air Command commander, encouraged mechanical and electrical skills among Airmen by establishing auto hobby shops at air bases.[14]

Getting Off Track

If the Air Force had continued the disruption-embracing practices of its earlier decades, it would be well positioned for today's new era of technological competition. However, toward the end of the Cold War, the cycle of technology-driven reinvention slowed dramatically.

As the US military absorbed the experience of Vietnam, the concept of airpower solidified around a single primary technological implementation, the high-performance jet fighter. The "fighter generals" assumed predominance in the Air Force's top leadership.[15] As Carl Builder observed in his influential 1994 book *The Icarus Syndrome: The Role of Air Power Theory in the Evolution and Fate of the U.S. Air Force*, the centrality of the jet fighter remained essentially unchanged during the 20 years post-Vietnam, and indeed it has remained largely intact through the almost 30 years since he wrote. The rise of the jet fighter made sense because it is a versatile and capable weapon system. Technologically, new fourth-generation multirole fighters provided much of the striking power that had previously required dedicated bombers. Precision guided weapons, such as laser-guided bombs, provided greater potency with smaller bomb loads, and the growing use of aerial refueling provided jet fighters with intercontinental range.

Unfortunately, Builder argued, this initiated a period of doctrinal stasis as new airpower theory lost its central role in driving the future direction of the USAF to be replaced by a focus on incremental improvements in the tactical and operational art of flying jet aircraft.

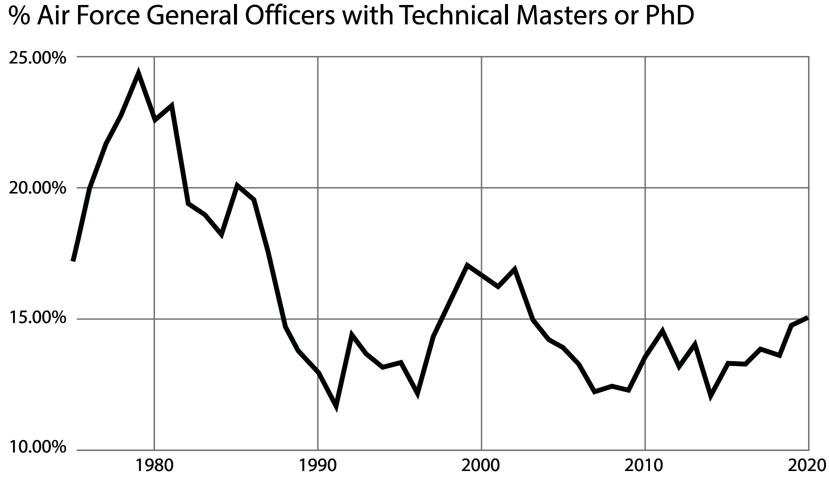
Instead of advocating new war-fighting doctrines, Air Force leaders devoted their energies to pushing for the next incremental airplane development program.[16] As Builder put it, "Somewhere during this time, the institutional Air Force was shifting its compass from a guiding theory of air power to a devotion to the symbols or means of air power—to the airplanes themselves."[17]

This shift might have been a temporary state of affairs, but the fall of the Soviet Union removed the main source of competition for the US military. Then, starting in 2001, the US military spent two decades engaged in conflicts against difficult but relatively low-tech terrorist and insurgent forces over whom US technological supremacy was never in question.

Consequently, S&T became a more isolated subfield within the acquisition function, less connected to operations and to strategic decision-making within the Air Force. It also became more civilian in nature, with uniformed military presence reduced to a minimum and more focused on administration. Instead of shaping the future, the priority for S&T shifted to addressing "technology gaps" within existing operational constructs as communicated by operational commands. This incremental focus was strengthened further by grading Air Force S&T, using metrics like technology transition percentages and quantifiable return-on-investment. In short, instead of helping drive the strategic agenda regarding the character of the future USAF, S&T became a specialized support function tasked with maturing technology for desired but optional improvements to current capabilities.

To be sure, there were some dramatic advances by USAF S&T during the past few decades. However, the most visible of them, stealth technology and unmanned air vehicles, had to overcome significant skepticism from the institutional USAF of their time because the status quo doctrine did not call for them. Early development programs in those new areas, such as the F-117 Nighthawk and the MQ-1 Predator, had champions within the USAF but faced reluctance from institutional leaders who perceived that they competed for resources against more conventional aircraft programs.[18]

This relative decline in the perceived importance of S&T was reflected in a decline in the percentage of general officers holding advanced degrees in technical fields. As shown in figure 1, since the late 1970s the percentage decreased from almost 25 percent to a current value of less than 15 percent. Only a single USAF general officer billet currently requires an advanced STEM (science, technology, engineering, and math) degree as a qualification.



Source: Air Force Personnel Center

Figure 1. Relative decline of Air Force general officers holding advanced technical degrees, 1970–present

The decline in emphasis on technological change and reinvention was also reflected in a relative decline in resources for S&T. As shown in figure 2, S&T resources fell from an average of 2.5 to 3.0 percent of the USAF's total budget during the Cold War period of the 1960s and 1970s to less than 1.9 percent today, a relative decline of about a third.[19]

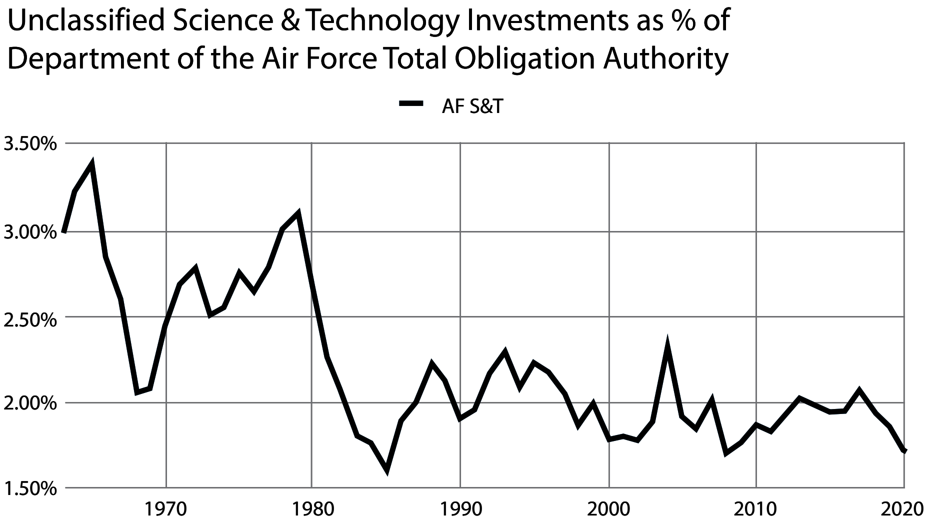


Figure 2. Data from President's Budget submission 1963–2021 by fiscal year, includes civilian pay and Space Force funding

New Competitive Challenges

The level of military technological competition today may be greater than at any time in the past 100 years, not only because of the re-emergence of peer competitors but because the US military has largely lost the budgetary advantage it historically enjoyed over its rivals. During World War II, the US gross domestic product (GDP) easily surpassed that of all the Axis powers combined.[20] During the Cold War, the Soviet Union's GDP reached only about 26 percent that of the US.[21] Today, China's GDP alone is two-thirds that of the US, and in terms of local currency purchasing power, may exceed the US GDP.[22] On a purchasing power basis, Chinese military spending in 2017 may have reached 87 percent that of the US.[23]

In particular, the US defense sector no longer dominates the investment landscape for S&T. In 1960, the US accounted for 69 percent of global R&D expenditures. US federal defense R&D alone accounted for 36 percent of global R&D.[24] In 2016, by contrast, US federal defense R&D spending accounted for less than 4 percent of global R&D. Approximately 93 percent of global R&D was funded by either commercial or foreign sources.[25]

Foreign and commercial investment is especially pronounced in many areas of emerging technology that will be critical to future military advantage, such as artificial intelligence, microelectronics, and robotics. As the unclassified *Summary of the 2018 National Defense Strategy* says:

> New commercial technology will change society and, ultimately, the character of war. The fact that many technological developments will come from the commercial sector means that state competitors and non-state actors will also have access to them, a fact that risks eroding the conventional overmatch to which our Nation has grown accustomed.[26]

The US military can no longer outspend its rivals or rely on uniquely US sources of technology. American advantage will depend on superior efficiency in developing disruptive military technologies and translating them into revolutionary war-fighting capabilities and quickly seizing their benefits through institutional reinvention.

Recommendations for Reinvigorating a Disruptive Innovation Culture

Fortunately, there are abundant signs that the posture toward S&T and doctrinal evolution in the Air Force is starting to change. For instance, the secretary of the Air Force and the Air Force chief of staff published a new *Air Force Science and Technology Strategy* in 2019 that explicitly calls for shifting a substantial portion of Air Force S&T investment toward "transformational" innovations that can deliver sustainable technological advantages over fast-moving adversaries.[27]

Innovation cells like AFWERX have made progress in promoting "innovation" across the USAF and USSF, helping generate excitement about technological change. Their activities are generally associated with activities like "Spark Tanks" and interactions with startup companies. However, bringing innovation from the margins back to the core war-fighting practices of the services requires reinventing the practices that enabled rapid technological change in earlier eras. This reinvention includes restoring a close relationship between technological innovation and operations, reestablishing a strong role for technologists in future force planning and building new training and leadership practices to help reinvigorate a culture where "every Airman and Guardian is a technologist."

Reconnect technologists and operators. In earlier eras, military technologists and operators had shared experience at the "tactical edge" and a close relationship that gave them a personal understanding of each other's specialties. This relationship was built by cross-training and working together at the junior and midgrades. In today's more specialized world, it may be more challenging for individual service members to be fully cross-qualified, but they can be brought back into closer rapport. For example, the Air Force's Advanced Battle Management System field exercises and the Army's Project Convergence have shown the future combat necessity to do software coding at the tactical edge to respond to technical challenges in real time.[28] The work can't be delegated to civilians or contractors in rear areas—it requires uniformed technologists who can work "under fire." New initiatives could place military technologists in, or in close cooperation with, operational units with the mission of engineering technical solutions in peacetime and times of conflict. One option would be to establish operationally integrated engineering cells at the wing, delta, or other unit levels. They would provide operational connection to the service's larger technological community, identifying and solving technical challenges in real time, and mentoring units through the process of adopting and integrating disruptive new technologies. Also, wargames and exercises should include unanticipated technological moves by potential adversaries that impose "technological surprise" on friendly forces. This tactic can build the ability of operators and technologists to work together to quickly develop and deploy solutions at the tactical edge.

Restore technologists as leaders in future force design. Earlier eras utilized military technologists, including technically educated operators, to help create new theory and doctrine and cocreate the vision for the shape of the future force. The establishment of the Air Force Warfighting Integration Capability, now known as AF Futures, and the Space Warfighting Analysis Center has created strong new centers for future force planning. These offices should embrace the role of the old Air Corps Tactical School to foster and develop future war-fighting theory and doctrine that can guide emerging technology development and target capabilities that go beyond what current systems and forces can deliver. These organizations have welcomed the early involvement of technologists by inviting detailees from the S&T community. This good start should be expanded to emphasize technological expertise and vision as a core competency in future force design. This expansion will also require military technologists to rebuild competencies in doctrine development and future force design, areas where they have not been substantially involved for decades. Collaborative planning activities like those in the new Warfighter-Technologist (WARTECH) process coled by AF Futures and the Air Force Research Laboratory are a good first step.

Establish foundational training. Air, space, and cyber systems are increasingly based on digital microelectronics, software, and robotics. Competence in these areas will be an almost universal requirement, whether in a maintenance facility, the cockpit, or a space operations center. Also, effective innovation must arise from a foundation of technical competence. "Innovative" ideas that are not anchored in physics, and a solid technical understanding can be impractical. The danger of disconnected "innovators" has been lampooned via characters such as Michael Keaton's eccentric brainstorming "idea man" in the movie *Night Shift*, who suggests providing mayonnaise right in the can with tuna fish before proposing the even "better idea" of feeding live tuna fish mayonnaise.[29] Every servicemember needs some level of foundational technical competence to be effective. This level of competence includes an informed understanding of emerging technical possibilities and a mentality of constantly looking ahead for new technological means that can change the ways we go to war. To make this point, former Air Force Secretary Heather Wilson said in many of her speeches to Airmen, "We're all bicycle mechanics at heart."[30] All Marines receive two weeks of marksmanship training whether they will serve as infantry or not. In the same way, Airmen and space professionals should receive initial skills training in technical concepts that enable war-fighting effectiveness. The USSF's move to establish Space Warfighting Discipline training for all incoming members is a good model. This practice should be followed up by providing additional training in technical subjects, using modern mechanisms such as online training portals. For instance, the National Security Commission on Artificial Intelligence has recommended establishing emerging technology certifications that are similar to today's joint qualification certification, to qualify military members for service in positions that will demand competence in emerging technologies.[31] General LeMay's initiative for encouraging technical hobbies should be modernized to provide base facilities for members to pursue projects in software, robotics, and similar fields.

Develop military science and engineering leaders. To out-innovate fast-moving adversaries, the services must restore a stronger community of empowered uniformed science and engineering leaders. This restoration involves better using the technical competence of science and engineering officers entering the USAF and USSF and providing more opportunities for them to develop their technical and leadership talents. Early career experiences for military scientists and engineers should go beyond the current focus on administering standard DOD acquisition contracts to include training in integrating with operations and deploying solutions in real time. More opportunities to lead other military members, such as within operationally integrated engineering cells, can provide these officers with development opportunities that also use their technical skills. Military scientists and engineers should have access to resources to apply their skills to inventing solutions. For instance, competitive grants could be made available to fund inventions with operational impact and develop the intellectual property themselves instead of relying on contractors. The Air Force Research Laboratory-managed Edison Grant pilot is a promising start. The pilot could be connected with the current Squadron Innovation Fund, which has provided $64 million in funding for hundreds of projects to "kick start squadron-level innovation at the tactical edge."[32] Lastly, more general officer positions should favor candidates with advanced degrees and experience in science and engineering, in keeping with the technological nature of future war fighting.

Provide senior leader messaging and example. Changing culture requires a strong example from leadership. As part of his campaign to reform Marine Corps culture, esprit de corps, and doctrine after the Vietnam War, Marine Corps Commandant Gen Alfred M. Gray established the dictum "every Marine a rifleman" and insisted that every incoming Marine receives marksmanship training regardless of what operational specialty they enter.[33] His phrase articulated the core cultural value instilled within the Corps that every Marine is, at heart, a disciplined warrior ready to take up a rifle and engage in close combat if called upon to do so. Similar messaging from USAF and USSF leaders is important for focusing their service members on the technical nature of future war fighting in their domains, placing priority on the need for every Airman and space professional to be a technologist, regardless of their specific role. Senior leadership roles themselves are important indicators of an organization's priorities. The USSF has established the chief technology and innovation officer (CTIO) as a key military position at the service headquarters, much as the chief technology officer is a key strategic role at large tech companies. This move clearly broadcasts the strategic importance of technology to the USSF's war-fighting mission. It also provides the CTIO with the breadth and authority to take action in accordance with that reality. Similar top positions dedicated to Air Force technology could send a similar message. Lastly, there is no doubt that resource allocation is a strong indicator of organizational priorities. To compete effectively, the USAF and USSF should strive to restore S&T funding to at least the fraction of the overall service budgets that was commonplace during the Cold War.

Conclusion

To prevail in the current era of fierce competition for military technological advantage and future conflicts with innovative adversaries, the USAF and USSF must revive the readiness to embrace disruptive new technologies and reinvent themselves. For more than a century, Airmen have identified, matured, and employed the latest technology to bring bold visions to reality and change the rules of warfare. Technological innovation must once again be part of the core cultural "DNA" of both services, present not only within specialized acquisition functions and innovation programs but in operations, doctrine development, training, and elsewhere. The recommendations outlined here create a framework for reinvigorating such a disruptive innovation culture. At their core is restoring the role of military scientists and engineers as the essential link between S&T, operations, and future force design. They aim to reaffirm an institutional principle that technology is the key to combat advantage in our war-fighting domains, and therefore all USAF and USSF members must be, to some degree, technologists. ✪

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COMMENTARY

Harvesting the Rewards of Multinational Cooperation

The Royal Air Force's Project Seedcorn

Steven Paget, PhD

The introduction of the first P-8 Poseidon aircraft into service as part of a £3 billion program marked a major milestone for the defense of the United Kingdom (UK), but the move has been underpinned by multinational cooperation.[1] The Royal Air Force (RAF) announced that the fourth RAF P-8 Poseidon maritime patrol aircraft, which arrived at RAF Lossiemouth in late 2020, has been named the "Spirit of Reykjavik" in recognition of "the role played by the Icelandic capital and its people in enabling the Allied victory during the Battle of the Atlantic."[2] The acknowledgment of the importance of Iceland during the Second World War is a poignant tribute, but the wider significance of other nations supporting the RAF's maritime airpower should not be underestimated.

The Seedcorn initiative, which saw personnel embedded with multinational partners, was designed to underpin the preservation of the UK's maritime patrol aircraft skills and has helped to enable the effective integration of the P-8 Poseidon—a multirole aircraft that addresses a gap in the RAF's maritime patrol capability.[3] The P-8 Poseidon will undertake various roles, including patrolling the seas, antisubmarine warfare, helping to protect the nuclear deterrent, and search and rescue missions.[4] The eventual nine P-8s have been deemed a "political and operational necessity" for the UK, given the "resurgent Russian submarine threat in the Atlantic and North Sea."[5] The aircraft are already demonstrating their worth with an RAF P-8 completing its first operational mission on 3 August 2020, when it tracked a Russian warship in the North Sea.[6] The mission was momentous, but it should be noted that the RAF received significant support from multinational partners in reaching initial operating capability.

Exchanges with the United States have been especially noteworthy and have been described as a "staple of the relationship" between the RAF and US Air Force (USAF).[7] The RAF and USAF approved reciprocal exchanges under the military personnel exchange program in 1971 and the initiative was eventually expanded to enable UK personnel to serve with the US Army, Coast Guard, Marine Corps, and Navy.[8] Perhaps most notably, RAF and Royal Navy pilots underwent training with the US Marine Corps in preparation for the introduction of the F-35, with 120 personnel undergoing instruction in the US in 2017.[9] RAF aircrews have also been reported to have flown a range of "high-sensitivity" USAF aircraft, including the F-22, F-117, RC-135, and the B-2.[10] The RAF has also had both student and instructor pilots participate in the USAF's Pilot Training Next 2.0 initiative.[11] Seedcorn represents, therefore, just one element of the broadening of personnel exchange arrangements between the UK and the US.

Personnel exchanges have been considered an essential means to develop partner capability and improve interoperability. It has been reasoned, "To ensure the interconnected multinational force works cohesively, service members and leaders from each nation must learn to communicate and understand the perspectives of their international partners."[12] Exchanges between high-end allies have been considered particularly important.[13] MSgt Douglas Braden (USAF) has described personnel exchanges as the "bilateral sharing of best practices."[14] Flt Lt Ian Hart (RAF), who flew the B-2 on exchange with the USAF, highlighted the mutual benefits of exchanges involving UK and US personnel:

> We do have different ways of looking at things. We're a smaller air force so the way we approach a problem is different to the way the USAF will approach it. So, I like to think my different tactical background enables me to bring an alternate viewpoint on the tactical procedures used. Ultimately, we're looking at developing the way we work together.[15]

The importance of personnel exchanges has prompted air forces around the world to expand and enhance their programs.[16] Their significance prompted Gary Roughead, a former US Navy chief of naval operations, to contend, "As in all endeavours, people are key. There must be more flexibility in how we embed military personnel into each other's forces."[17] The requirement for that flexibility was emphasized by the RAF's training requirement in maritime patrol aircraft.

The retirement of the Nimrod MR2 and the cancellation of the Nimrod MRA4 in 2010 resulted in the RAF not having a specialist maritime patrol aircraft for "the first time in its history."[18] In advance of the acquisition and receipt of the P-8s, and to "re-grow" maritime patrol aircraft capability, RAF personnel were embedded in the Royal Australian Air Force, Royal Canadian Air Force, Royal New Zealand Air Force, and the US Navy under the "Seedcorn" initiative.[19] Lord Astor of Hever declared:

> The Seedcorn initiative will sustain the UK's ability to operate high-end fixed-wing maritime patrol aviation in a range of complex operating environments by maintaining highly perishable skills, particularly in anti-submarine warfare, anti-surface unit warfare, search and rescue, and maritime intelligence, target acquisition and reconnaissance.[20]

It was estimated that the Seedcorn program would cost up to £2.4 million per year when it was initiated.[21] It was announced in June 2016, however, that the program had already cost "some £14.1 million" since its commencement in 2012.[22] While the expenditure may seem extravagant, the benefits can be considered to outweigh the costs. Some RAF crews have, for example, accumulated more than 1,000 flying hours on US P-8s.[23] That experience has been critical in helping to prevent the diminishment of expertise. Air Vice-Marshal Gerry Mayhew proclaimed in 2016:

> The Seedcorn initiative has been vital in ensuring that our future MPA [maritime patrol aircraft] aircrew are prepared to regenerate the UK's MPA capability. By retaining those essential skills, our aircrew are already on the front foot when it comes to operating these new aircraft.[24]

The success of British personnel during competitions such as the US Navy's antisubmarine rodeos was viewed as evidence that the RAF would operate the P-8s with "high efficiency" from the outset.[25]

Then Air Commodore Ian Gale has contended that "Seedcorn" is a mutually beneficial initiative:

> The US Navy is being incredibly helpful with bringing in our P-8 fleet. They're assisting with processes, skills and knowledge and we're already working very closely operationally with them. We're deepening that, and all the time we're adding knowledge to our force and it's de-risking our programme. In return, the Seedcorn personnel are providing useful input into the US Navy. It's an equal relationship in that they're helping us grow our force and by doing so, of course, we're contributing to the global requirement to conduct maritime patrol operations.[26]

In addition to the individuals seconded under Seedcorn, 38 members of the 120th Squadron commenced operational conversion training at NAS Jacksonville, Florida, in January 2019, marking the first complete crew to undertake US-based training.[27]

Although there will be a transition to training all RAF P-8 personnel in the UK, the importance of overseas support in preserving perishable skills and kick-starting the regeneration of the RAF's maritime patrol aircraft capability deserves recognition as an example of the importance of defense engagement.[28] The training of personnel to operate the P-8s is not unique. In 2013, for example, Chief Petty Officer Stacy Gager became the first Royal Navy sailor to qualify as an aircraft director on a US Navy aircraft carrier as part of the long-lead specialist skills program, following a training period onboard the USS *Dwight D. Eisenhower*.[29] The program was initiated with the intention of training at least 300 personnel in preparation for the introduction of the Queen Elizabeth Class aircraft carriers. Bruce Lemkin prudently observed, "The most advanced system needs trained operators who understand both the systems and the operating procedures. Interoperability is not just 'things,' it is people."[30]

Building and strengthening partner capacity is often viewed through the lens of supporting developing nations. That is frequently but not exclusively, the case as demonstrated by historical and contemporary experience. The support provided by France, Italy, and the UK in developing and sustaining the American Expeditionary Forces Air Service in World War I was an early example of airpower capacity building.[31] Project "Seedcorn" is merely one of the latest iterations of partner capacity being enhanced to support a common and collective effort; in this case, maritime patrol operations.

The Seedcorn initiative demonstrated the importance of international exchanges in maintaining skills as a necessary bridge in the event of a capability gap and provides a model for emulation in the future. In reference to the US-UK relationship, Maj Jeff Olsen (USAF) declared that the "special relationship" in the realm of airpower was "alive and well" in 2010, an idea reinforced by the "Seedcorn" initiative.[32] The "special relationship" can be extended to the wider Five Eyes network as cooperation with Australia, Canada, and New Zealand also proved to be significant. Not only are there direct benefits for the personnel and the wider RAF, but there is significant potential for improvements in interoperability as Australia, New Zealand, and the US will also be operating P-8s. In name and practice, the P-8s—as well as the Seedcorn initiative that has helped to preserve the necessary skills—represent the spirit of multinational cooperation and emphasize the significance of military personnel exchanges. ✪

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