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Findings on Mosaic Warfare from a Colonel Blotto Game

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Preface

As the U.S. Department of Defense continues to innovate, several approaches to conflict are under consideration to reduce cost and increase effectiveness and robustness. These approaches have emerged as complements or even alternatives to a more traditional focus on high-capability, high-cost platforms, such as the F-35 fighter, B-21 bomber, or *Ford*-class aircraft carrier.

One approach, championed primarily by the Defense Advanced Research Projects Agency (DARPA), is known as *Mosaic warfare*, after the analogy of creating a complex image from many small, simple pieces. This approach relies on fractionation of capabilities from large multicapability platforms onto multiple small ones, the ability to employ heterogenous mixes of capabilities throughout a battlespace, and, finally, the ability to rapidly compose a set of needed capabilities in a time and place to accomplish a mission. DARPA is exploring many Mosaic warfare challenges through a series of internal projects, such as Collaborative Operations in Denied Environments, OFFensive Swarm-Enabled Tactics, Adapting Cross-Domain Kill-Webs, Air Combat Evolution, System of Systems Integration Technology and Experimentation, Cross-Domain Maritime Surveillance and Targeting, and Assault Breaker II. However, these projects are primarily focused on solving implementation challenges without addressing a more fundamental question: Is Mosaic warfare better (i.e., more cost-effective and robust) than more-traditional approaches to conflict?

In 2019, DARPA asked the RAND Corporation's National Security Research Division (NSRD) to explore and validate the fundamental value propositions of the three key Mosaic warfare architectural attributes—fractionation, heterogeneity, and dynamic composition—

by means of reduced-order modeling and simulation. Another purpose of this study was to identify near-term Mosaic experimentation opportunities and experimental hypotheses through functional decomposition and recomposition of existing systems and architectures.

The results of the project are documented in this report and in the following RAND reports:

- Timothy R. Gulden, Jonathan Lamb, Jeff Hagen, and Nicholas A. O'Donoughue, *Modeling Rapidly Composable, Heterogeneous, and Fractionated Forces: Findings on Mosaic Warfare from an Agent-Based Model*, Santa Monica, Calif: RAND Corporation, RR-4396-OSD, 2021.
- Nicholas A. O'Donoughue, Samantha McBirney, and Brian Persons, *Distributed Kill Chains: Drawing Insights for Mosaic Warfare from the Immune System and from the Navy*, Santa Monica, Calif.: RAND Corporation, RR-A573-1, 2021.

This report is focused on a game theory–based modeling approach, one of the two modeling efforts undertaken for this project. This report focuses on Mosaic warfare's ability to more efficiently allocate resources when compared with a more *monolithic* strategy and shows the benefit of reduced-order modeling in drawing inferences on the mechanisms and value proposition of Mosaic warfare constructs. This report will be of interest to anyone studying Mosaic warfare constructs, particularly those who wish to understand or investigate the potential benefits and limitations in a resource allocation context.

This research was sponsored by DARPA and conducted within the Acquisition and Technology Policy Center of the RAND National Security Research Division (NSRD), which operates the National Defense Research Institute (NDRI), a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense intelligence enterprise.

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As the U.S. Department of Defense continues to innovate, several approaches to conflict are under consideration to reduce cost and increase effectiveness and robustness. These approaches have emerged as complements or even alternatives to high-capability, high-cost platforms, such as the F-35 fighter, B-21 bomber, or *Ford*-class aircraft carrier. One new approach, championed primarily by the Defense Advanced Research Projects Agency (DARPA), is known as *Mosaic warfare*, after the analogy of creating a complex image from many small, simple pieces. *Mosaic warfare* can be defined as the degree to which a player can quantize their resources, and it relies on fractionation of capabilities from large multicapability platforms onto multiple smaller ones, the ability to employ heterogeneous mixes of capabilities throughout a battlespace, and the ability to rapidly compose a set of needed capabilities in a time and place to accomplish a mission.

This report presents an intentionally abstract representation of a variably Mosaic architecture, focusing on this separation of capabilities, and asks the question, "Is Mosaic warfare better (i.e., more cost-effective and robust) than more-monolithic approaches to conflict?" We explore answers to this question via a competitive resource allocation game.

Competitive resource allocation problems are ubiquitous. The canonical example is the case of two military colonels who must each allocate a limited number of troops across different battlefields. The colonel who allocates more troops to a battlefield wins that battlefield, and the goal of each colonel is to win as many battlefields as possible. This now century-old abstraction of a competitive resource scenario is

known as the *Colonel Blotto game* (Roberson, 2006; Gross and Wagner, 1950).

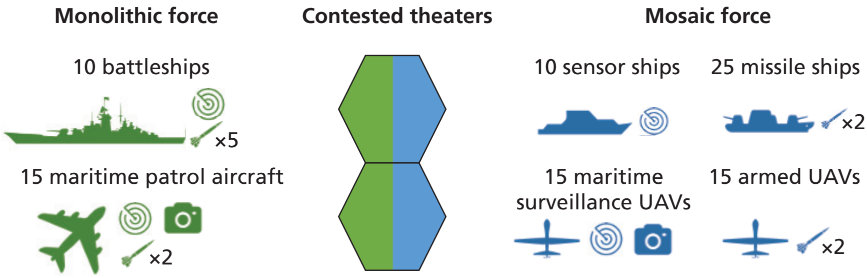
To leverage the Blotto game framework, we analyze what has been called a *multi-resource Blotto game* (Behnezhad et al., 2017). In the game, the players allocate platforms across a set of battlefields. Each platform has a set of capabilities. Generally, a platform may have more than one unit of each capability. Each unit of a capability carried by a platform is called a *resource*. Platforms can vary in both the quantity and type of capabilities.

Figure S.1 shows an illustrative example of a multi-resource Blotto game, in which one force has ten ships and 15 large aircraft, while the other has 35 small ships and 30 small aircraft. (This particular example shows a case that is *heterogeneous*, which means it has multiple capabilities.) Each colonel must allocate ships and aircraft between the two theaters. The winner of the theater is some function of the joint allocation of missiles, radars, and cameras.

Battlefields are won by the player who allocates more resources to them. *Overall utility* for each player is the number of battlefields won minus the number lost. (Battlefields that tie provide no utility to either player.) This is a zero-sum game, so the utility to one player is the negative of the utility to the other player.

The Mosaic force's expected utility is never less than zero, because the Mosaic force could always "mimic" a more aggregated force by cou-

Figure S.1
Illustration of a Heterogeneous Blotto Game



NOTE: UAV = unmanned aerial vehicle.

pling platforms together into a team. The expected utility in this case is zero, because the game would be a symmetric zero-sum game.[1]

The results presented in this report apply to the concepts of Mosaic warfare in general and should not be taken as an argument for or critique of any existing force posture. It is our intent to show that there are circumstances under which a fractionated force can be more efficient than an equivalently sized monolithic force and to investigate what those circumstances are.

Results

We showed that game theory, particularly the multi-resource Blotto game, is a useful tool for exploring the question of whether Mosaic warfare is better than more-monolithic approaches. Our results highlighted the potential of a Mosaic force to exploit asymmetries in the resource allocation of a more monolithic force. We explored the benefits of a Mosaic force in the context of resources (e.g., magazine size) and capabilities (e.g., platform specialization) and examined the mechanism for benefit in both cases.

We showed that in simple scenarios with only one capability, a Mosaic force can exploit asymmetries in the strategy employed by a monolithic force, but that this asymmetry decays as force size grows (for a given number of battlefields and a given level of aggregation). We studied the impact of random platform failure and showed that the dominant effect is a reduction in expected total force size, but that if total force size is small, the Mosaic force can tolerate higher failure rates.

We showed that when a Mosaic force is studied in reference to capabilities, and when battlefields are heterogeneous in what capa-

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1 We note here that this analysis is comparing a fully fractionated force with a force that has some level of concentration of capabilities. In other work, we set up the case differently. In Gulden, Lamb, Hagen, and O'Donoughue, 2021, an aggregated force (with six resources per platform) is compared with partially and fully fractionated forces (fewer than six resources per platform) with similar results; a fully fractionated force always matches or outperforms partially fractionated forces in efficiently allocating resources.

bilities are needed to win them, the Mosaic force does better when it focuses on battlefields that are won by a specific capability, while the monolithic force focuses on battlefields that are won by the total number of resources (regardless of which capability they represent).

Acknowledgments

The authors would like to express their sincere thanks to Timothy Grayson, Director of DARPA's Strategic Technology Office (STO), and Lt Col Daniel Javorsek, U.S. Air Force, a Program Manager in STO and our action officer, for their insight, direction, and support. We would also like to extend our appreciation to Ronald Hill and David Ott, support contractors for Dr. Grayson and Lt Col Javorsek, respectively, for their endless assistance coordinating the details of this project. We wish to thank Samuel Earp and John Kamp, who provide subject-matter expertise to STO and who were instrumental in strengthening our analysis.

During the review and quality assurance process, this report evolved greatly. The authors wish to thank Tom Hamilton, Amado Cordova, Jim Powers, and Joel Predd for their assistance reviewing the documents.

CHAPTER ONE

Background

As the U.S. Department of Defense continues to innovate, several new approaches to conflict are under consideration to reduce cost and increase effectiveness and robustness. These have emerged as complements or even alternatives to high-capability, high-cost platforms, such as the F-35 fighter, B-21 bomber, or *Ford*-class aircraft carrier. One new approach, championed primarily by the Defense Advanced Research Projects Agency (DARPA), is known as *Mosaic warfare*, after the analogy of creating a complex image from many small, simple pieces. This approach relies on fractionation of capabilities from large multicapability platforms onto multiple smaller ones, the ability to employ heterogeneous mixes of capabilities throughout a battlespace, and the ability to rapidly compose a set of needed capabilities in a time and place to accomplish a mission.

The *Mosaic* approach to warfare is generally defined as replacing larger systems with dynamically composed collections of smaller, more-numerous systems (Deptula et al., 2019). The scope of the Mosaic warfare concept is potentially extremely broad, covering a range of land, sea, air, space, and cyber operations, and the effectiveness of the approach is likely to vary tremendously depending on the details of any given system and situation. This report presents an intentionally abstract representation of a variably Mosaic architecture, focusing on this separation of capabilities, and asks the question, "Is Mosaic warfare better (i.e., more cost-effective and robust) than more-monolithic approaches to conflict?"[1] We explore this question via a competitive resource allocation game.

Competitive resource allocation problems are ubiquitous. The canonical example is the case of two military colonels who must each allocate a limited number of troops across different battlefields. The colonel who allocates more troops to a battlefield wins the battlefield, and the goal of each colonel is to win as many battlefields as possible. This now century-old abstraction of a competitive resource scenario is known as the *Colonel Blotto game* (Roberson, 2006; Gross and Wagner, 1950).

Definitions

Throughout this report, we leverage terms that are not widely used. For clarity, we provide definitions of how they are used in this report:

- *Mosaic*, or *Mosaic-like*, refers to a force that is composed of units that are each small and simple. A simple example of a Mosaic force might be a fractionated force in which there is a separation of resources into distinct units that are individually tasked. In this report, we consider a Mosaic force taken to its limit, in which each unit possesses only a single capability.
- *Monolithic* refers to larger units that cannot be subdivided. An example of a monolithic force unit is an aircraft carrier, which is expected to achieve objectives as a unit that cannot be divided.

Modeling Mosaic Warfare with a Colonel Blotto Game

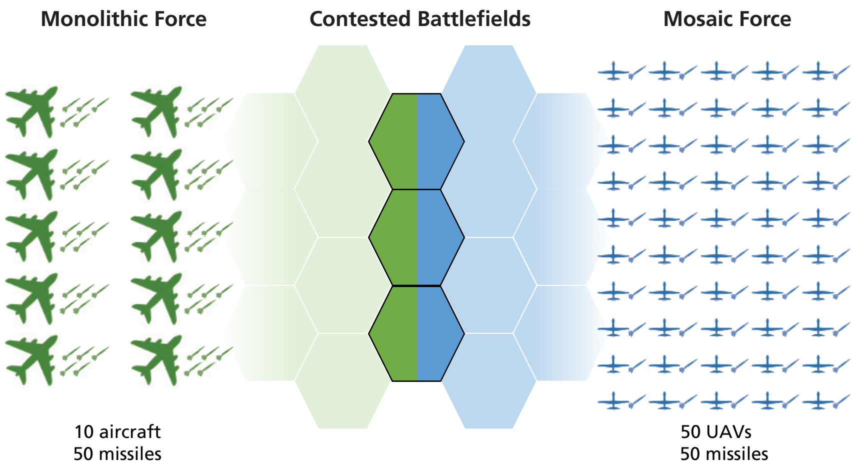
Because the Blotto game is intimately linked to military resource allocation problems, it provides an ideal framework for analyzing how a

[1] We are using the definition of *monolithic* that refers to a system or organization that is "large, powerful, and intractably indivisible and uniform" (Lexico.com, undated). This is admittedly problematic, in that the systems are not indivisible per se. However, they are indivisible insofar as they assign all capabilities together, whereas a Mosaic arrangement is free to assign the capabilities separately.

Mosaic force might perform against a monolithic force.[2] To leverage the Blotto game framework, we analyze what has been called a *multi-resource Blotto game* (Behnezhad et al., 2017). In the game, the players allocate platforms across a set of battlefields. Each platform has a set of capabilities. Generally, a platform may have one or more unit of each capability. We use the term *homogeneous* to describe cases in which there is only one type of capability, and we use *heterogeneous* to describe cases with multiple capabilities.

For a simple example, consider two aerial combat colonels who must allocate their platforms among three different battlefields (Figure 1.1). One colonel has a fleet of ten large aircraft, each with five missiles per aircraft, which, in this example, is the monolithic force. Another colonel has 50 small unmanned aerial vehicles (UAVs), or drones, each with one missile per drone, which is the Mosaic force. The winner of each battlefield is the colonel who allocates more total missiles to that battlefield.

Figure 1.1
Example of a Homogeneous Blotto Game



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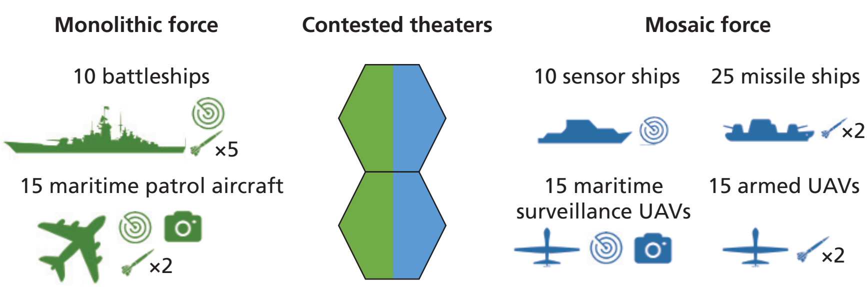
2 For the purposes of this report, we define *Mosaic force* as a force with one resource per platform.

For an example of a heterogeneous case, consider Figure 1.2. Each colonel must allocate ships and aircraft between the two theaters. The monolithic force has ten battleships, each equipped with five missiles and a radar, and 15 maritime patrol aircraft, each equipped with two missiles, a radar, and a camera. The Mosaic force in this example has ten sensor ships, each equipped with a radar; 25 missile ships, each equipped with two missiles; 15 maritime surveillance UAVs, each equipped with a radar and a camera; and 15 armed UAVs, each equipped with two missiles. The winner of the theater is some function of the joint allocation of missiles, radars, and cameras, such as "The player who allocates more missiles to a theater, provided they allocate at least two radars and one camera, is the winner."

As was previously mentioned, we define *Mosaic force* as a force with one resource per platform. The framework allows us to vary key parameters, such as the number and types of capabilities per platform in the opposing (monolithic) force, the nature of the battlefields, and the platform failure rates to draw a complete picture of the potential benefits of adopting a Mosaic force. We first consider the case in which there is only one capability, as described in the example shown in Figure 1.1, with large aircraft and drones, and determine how a force with one resource per platform performs against a force with several resources per platform. We augment the model to include the case in which platforms are imperfect and subject to error. We then analyze the potential benefits of a Mosaic force in scenarios with multiple capabilities, as described in the example shown in Figure 1.2, with aircraft

Figure 1.2
Example of a Heterogeneous Blotto Game



and battleships. That is, we examine whether it is better to have several different capabilities aggregated onto one platform or several platforms that each have one capability. A detailed discussion of heterogeneous Blotto games, including the formulation that we employed in this study, is provided in Grana, Lamb, and O'Donoughue, 2020.

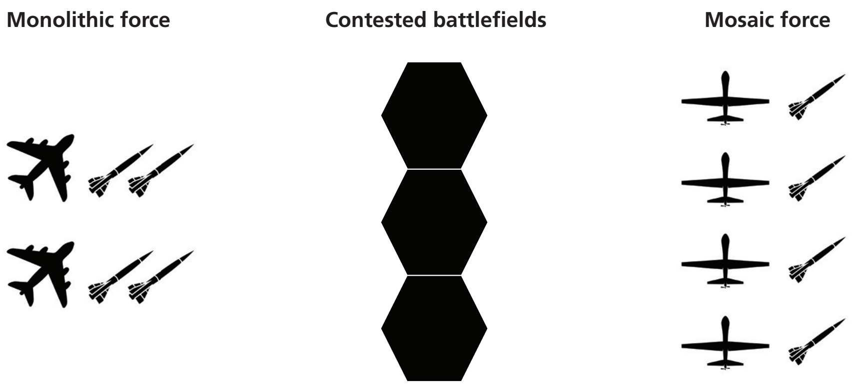
The solutions to our games employ a mixed strategy. In game theory, a *mixed strategy* is one in which players strategically randomize their specific actions to remain unpredictable.

CHAPTER TWO

Resource Fractionation Results

We begin by characterizing the benefits of a Mosaic force when there is only one capability. The difference between the Mosaic and monolithic forces is how many resources of that capability are carried on each platform. We consider cases wherein both players have the same number of total resources but where the resources might be concentrated differently across platforms. Figure 2.1 illustrates an example of a homogeneous Blotto game in which the Mosaic force has four platforms, each with one resource, while the monolithic force has two platforms, each with two resources.

Figure 2.1
Illustration of a Homogeneous Blotto Game



NOTE: The number of resources per platform for the monolithic force is two in this example but varies between two and five in our study. The total number of resources for each force is four in this example but varies between four and 100 in our study.

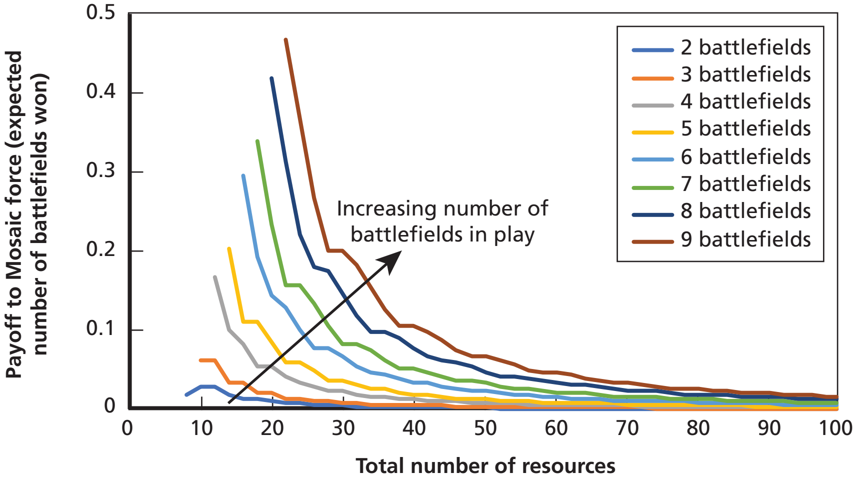
Battlefields are won by the player who allocates more resources to them. *Overall utility* for each player is the number of battlefields won minus the number lost. (Battlefields that tie provide no utility to either player.)

In this report, we assume that the Mosaic force has one resource of the capability per platform, and we vary the number of resources per platform for the monolithic force.

Our main results are given in Figure 2.2, which plots the Mosaic force's expected utility when faced with a monolithic force that has three resources per platform, as a function of the total force size (number of resources for each force) and number of battlefields. Detailed analysis of this test, including additional plots and discussion, are found in Grana, Lamb, and O'Donoughue, 2020.

The Mosaic force's expected utility is never less than zero, because the Mosaic force could always aggregate into a force identical to the monolithic case.

Figure 2.2
Mosaic Force Utility as a Function of Force Size

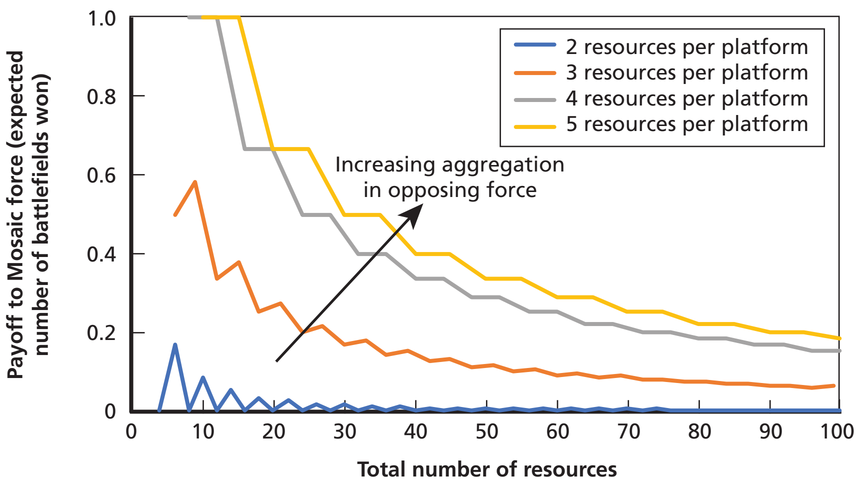


NOTE: The Mosaic force is fixed at one resource per platform, and the monolithic force is fixed at three resources per platform. The number of battlefields is varied from two to nine.

Additionally, the Mosaic force's expected utility advantage decreases as the total number of resources increases. The technical mechanism behind these results is discussed in Grana, Lamb, and O'Donoughue, 2020. From a high-level perspective, as the overall force becomes large compared with the number of resources per monolithic platform (which can be thought of as clumps of resources), the disadvantages of that clumping are mitigated for the monolithic force.

Finally, we examine the benefits of a Mosaic force as a function of the number of resources per monolithic platform. As Figure 2.3 shows, the benefits of a Mosaic force increase with the number of resources per platform in the opposing (monolithic) force. As one would expect, the disadvantages of clumping increase as the clumps are larger.

Figure 2.3
Increasing Aggregation in the Opposing Force Increases the Utility of Fractionation



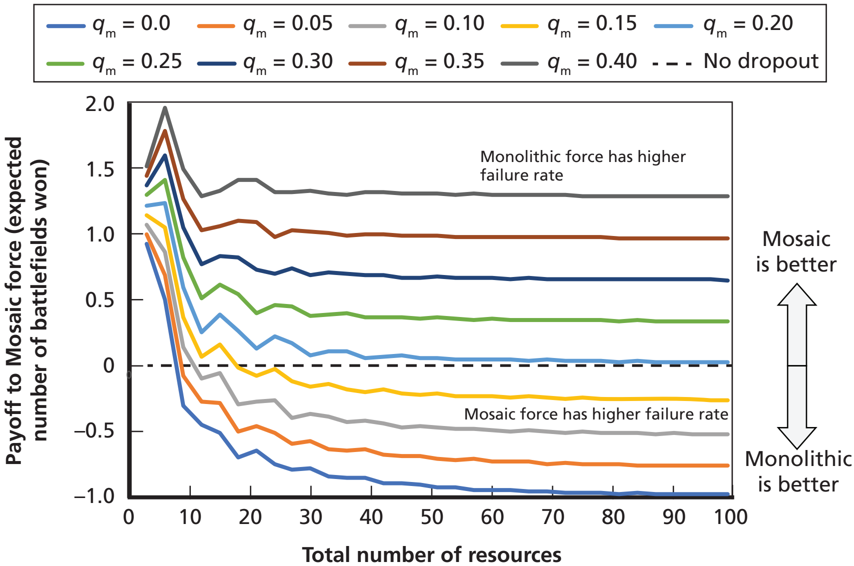
NOTE: The monolithic force has between two and five resources per platform. There are four battlefields, and the total resource size is varied from ten to 100 resources. The total number of resources is always a multiple of the number of resources per platform, so the blue curve (three resources per monolithic platform) terminates at 99 total resources instead of 100.

Random Failure of Platforms

We now consider the case when platforms are subject to random and independent failure. Dropouts may represent any number of phenomena in a system of interest.[1]

Figure 2.4 plots the Mosaic force's expected utility as a function of force size when its failure probability is $q = 0.20$, the monolithic force has three resources per platform, and there are five battlefields. Each

Figure 2.4
Impact of Failure on the Utility of Fractionation



NOTE: The Mosaic force's expected utility is plotted against a monolithic force with three resources per platform and five battlefields, as a function of force size, when failure probability is 0.20 for the Mosaic force and is between 0.00 and 0.40 for the monolithic force. The solid black line represents the Mosaic force's expected utility when neither side is subject to dropout, and the dashed line represents the point of equilibrium between the two forces.

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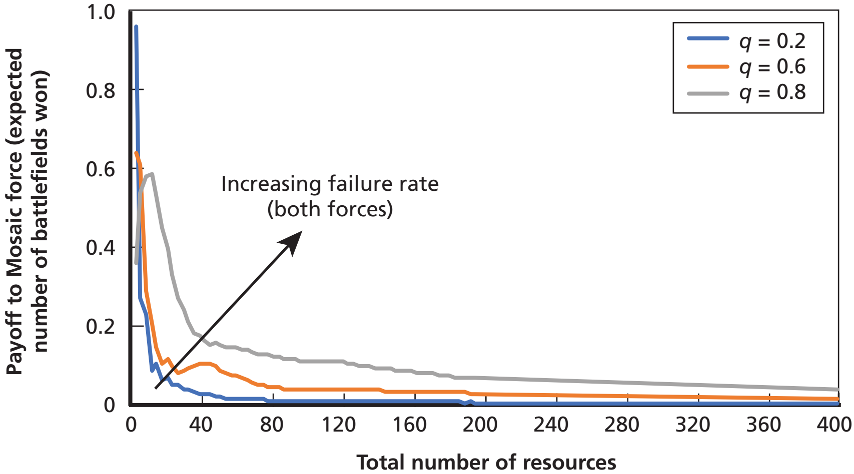
[1] *Dropouts* are platforms that, for some unspecified reason, fail to deliver their capabilities to the battlefield in question. This could be a result of navigation or payload failures, or even attrition. The mechanisms are less important than the fact that the failures occur after the colonel has allocated his or her forces.

line represents a different platform failure probability for the monolithic force. (q_m is the monolithic force's failure probability.) The solid black line is included for comparison and represents the Mosaic force's expected utility when neither platform is subject to failure. The black dashed line indicates zero utility, the point at which the monolithic and Mosaic forces are evenly matched. All points below the dashed line indicate situations where the monolithic force is preferred.

When the total number of resources is small, the Mosaic force has an advantage over the monolithic force, even when its probability of failure is higher than that of the monolithic force. This is represented by the bottom four lines (blue, orange, green, and red), which show positive expected utility for small force sizes (fewer than nine to 18 total resources per force). However, as the force size (i.e., number of resources) increases, the benefits to a Mosaic force disappear. Only when the failure probability is equal for the Mosaic and monolithic forces are the expected force sizes the same. For large enough force sizes, the monolithic force's advantage from having a larger expected force size outweighs the disadvantage it faces from allocating its resources in larger clumps. This result generalizes to other parameterizations of the model.

Figure 2.5 shows that when the failure rate q is equal between the monolithic and Mosaic forces, the Mosaic force's expected utility still converges to 0 as force size increases, as was originally shown in Figures 2.2–2.4. As the failure rate increases from 0.20 to 0.80, the expected utility converges more slowly. This is because increasing the error rate slows the growth in the expected force size, which effectively increases the scarcity of resources that do not fail. When failure is modeled as a random event with uniform distribution across a force after units have been allocated to battlefields, the effects are more pronounced for a monolithic force than for a Mosaic force. This is because each individual platform failure will represent a larger percentage of the monolithic force's total resources, and the result will be a concentration of the effects, increasing the uneven distribution of forces relative to a Mosaic force.

Figure 2.5
Increased Failure Rate Increases Utility of Mosaic Force



NOTE: The graph shows the Mosaic force's equilibrium expected utility against a monolithic force with four resources per platform as a function of force size (total number of resources) when forces are subject to the same random failure *q*. There are four battlefields.

CHAPTER THREE

Capability Fractionation Results

In this chapter, we investigate cases in which the principal difference between the two forces is how many capabilities are carried on each platform. We consider a game with two different capabilities, "blue" and "green." We assume that the monolithic force has two resources per platform (one of each capability), while the Mosaic force has only one capability per platform (half of its platforms carry the first capability, and half carry the second). Figure 3.1 sketches an example of the

Figure 3.1
Illustration of a Heterogeneous Blotto Game

NOTE: In this pictorial representation, each player has two resources of each capability, indicated by the green missiles and blue bombs. However, the Mosaic force has four platforms, while the monolithic force has only two. The player who allocates more of the blue bombs to the upper battlefield wins the battlefield. The player who allocates more of the green missiles to the bottom battlefield wins the battlefield. Finally, the player who allocates more total resources (blue bombs plus green missiles) wins the battlefield in the middle.

scenario using aircraft, with the two capabilities represented as different kinds of weapons, but this scenario can be conceptualized with sensors, communications, electronic warfare, or any other capability.

We consider three types of battlefields, each defined by an associated function that determines the winner. For the first type of battlefield, the player who allocates more "blue" resources wins the battlefield. For the second type of battlefield, the player who allocates more "green" resources wins the battlefield. For the third type of battlefield, the player who allocates more of both resources (the sum of blue and green resources) wins the battlefield.

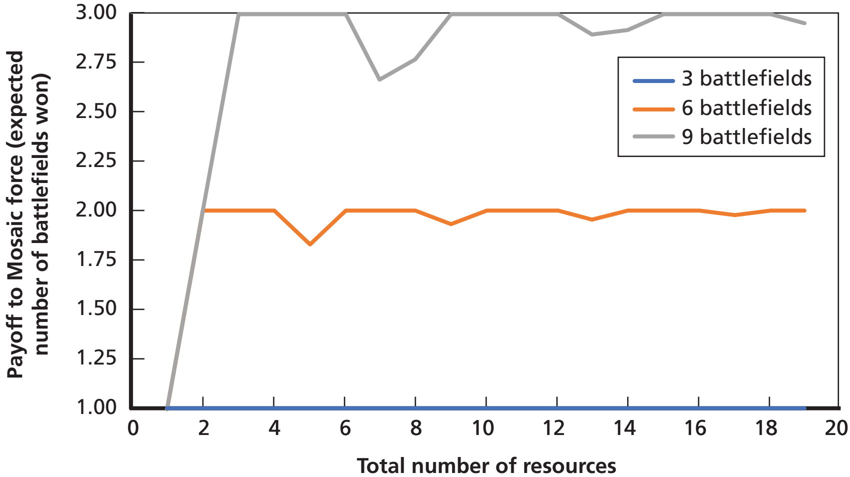
To determine the effect of the number of battlefields, we computed the Mosaic force's expected utility when there are three, six, and nine battlefields. In each case, one-third of the battlefields have a winner decided by the joint allocation of blue resources only, one-third of the battlefields have a winner decided by the joint allocation of green resources only, and one-third of the battlefields have a winner determined by the total of blue and green resources allocated to them.

Figure 3.2 shows that, unlike in the case of a single capability, the benefits of a Mosaic force remain roughly unaffected by the force size. As the graph demonstrates, the Mosaic force's expected utility is roughly one-third of the total number of battlefields.

This result suggests that it is generally wise for the monolithic player to allocate platforms preferentially to battlefields where both of their resources are used and for the Mosaic player to allocate platforms to battlefields that require only one capability. A more detailed discussion and mathematical proof of this result can be found in Grana, Lamb, and O'Donoughue, 2020.

This heterogeneity of battlefields breaks the dependence of prior results on force size, because the ability of the monolithic force to efficiently allocate its resources is no longer improved with larger force sizes. This is effectively a handicap on the monolithic force, which must concentrate on battlefields that require all of the capabilities or else risk wasting some capabilities on battlefields that do not value them, while the Mosaic force is capable of allocating capabilities only to battlefields where they will have a positive impact.

Figure 3.2
Expected Utility of Mosaic Force with Heterogeneous Capabilities



NOTE: The figure shows the Mosaic force's expected utility against a monolithic force as a function of force size (total number of resources) with three, six, and nine battlefields. The monolithic force has two resources, one of each type, per platform. The plot shows that as the force size grows, the benefits of adopting a Mosaic force are relatively constant.

We note that the scenario, as drawn in Figure 3.1, depicts a monolithic force that does not represent a modern multi-role fighter, such as the F-35, which can alter its loadout to match its mission. A commander could load only bombs onto some aircraft in a strike role and only missiles onto other aircraft in an air superiority role and perhaps maintain some aircraft as general-purpose aircraft with a mixed loadout. In that example, however, the multi-role fighters are exhibiting Mosaic-like traits, specifically *heterogeneity* (in that not all aircraft are given the same loadout) and *rapid composability* (in that the mission commander can alter the loadout of each aircraft with relative ease). Extension of this flexibility to include not only weapons but also sensors, electronic warfare payloads, and perhaps even communications or command-and-control functions (as envisioned in the Mosaic warfare concept) serves to increase the flexibility available to mission commanders.

CHAPTER FOUR

Discussion

The goal of this exercise was to develop a reduced-order model that can begin to illuminate some of the key trade-offs in adopting a Mosaic force. We showed that game theory, particularly the multi-resource Blotto game, is a useful tool for exploring the question of whether a Mosaic approach is better (i.e., more cost-effective and robust) than more-monolithic approaches to conflict. Our results highlight the potential of a Mosaic force to exploit limitations in the resource allocation of a more monolithic force. We explored the benefits of a Mosaic force in the context of resources (e.g., magazine size) and capabilities (e.g., platform specialization) and examined the mechanism for benefit in both cases.

We showed that a Mosaic force has an advantage over a monolithic force in simple scenarios with only one capability, but this advantage decays as force size grows (for a given number of battlefields and for a given level of aggregation in the monolithic force). We studied the impact of random platform failure and showed that for small forces, a Mosaic force can tolerate higher failure rates.

We showed that when a Mosaic force is studied in reference to capabilities, and when battlefields are heterogeneous in what capabilities are needed to win them, the Mosaic force does better when it focuses on battlefields that are won by a specific capability, while the monolithic force does better when it focuses on battlefields that are won by the total number of resources.

These findings point to the value of multi-resource Blotto games to illustrate the mechanisms of underlying situations where a Mosaic force is preferable. We recommend additional studies to add complexity to these games. These enhancements could include battlefield payoff functions informed by real-world kill chains and targets, complex force structures with a mix of fractionated and aggregated platforms of varying degrees, and more-realistic models of capabilities, including some with reusability (e.g., sensors) and some with a limited magazine (e.g., missiles and bombs).

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As the U.S. Department of Defense continues to innovate, several approaches to conflict are under consideration to reduce cost and increase effectiveness and robustness. The Defense Advanced Research Projects Agency is investigating a warfighting construct known as *Mosaic warfare*, after the analogy of creating a complex image from many small, simple pieces. This approach relies on fractionation of capabilities from large platforms onto multiple smaller ones, the ability to employ heterogeneous mixes of capabilities throughout a battlespace, and, finally, the ability to rapidly compose a set of needed capabilities in a time and place to accomplish a mission.

The main focus of this research is on the potential benefits and trade-offs of *Mosaic warfare*, which can be defined as the degree to which a player can quantize their resources. Researchers studied the benefits of a Mosaic force using a competitive resource allocation problem known as a *Colonel Blotto game*. The canonical example of such a game involves two military colonels who must each allocate a limited number of troops across different battlefields. The colonel who allocates more troops to a battlefield wins that battlefield, and the goal of each colonel is to win as many battlefields as possible.

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