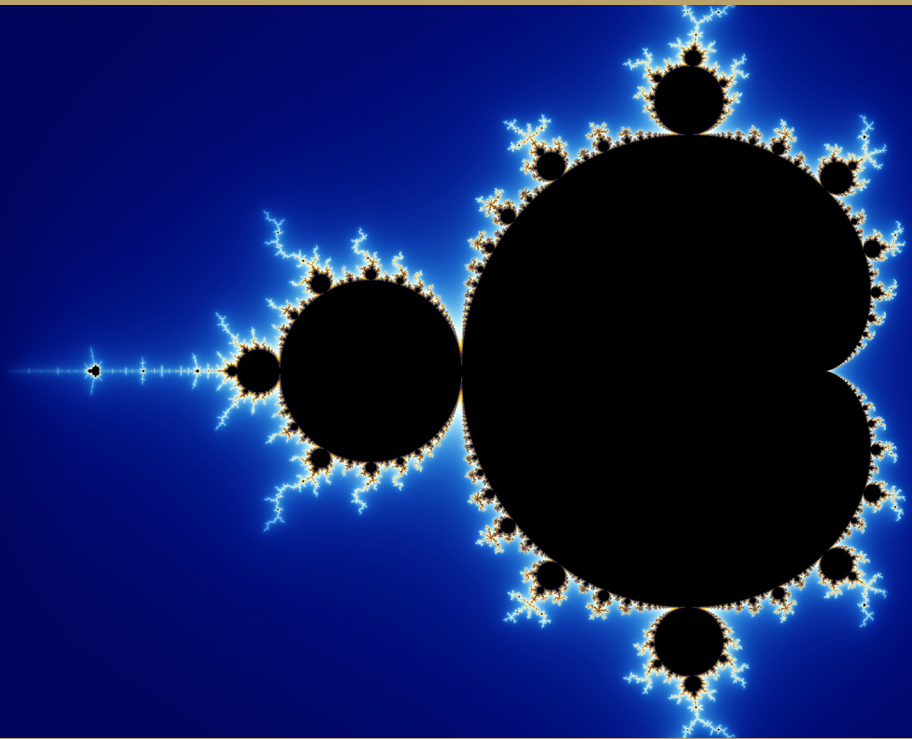


NUCLEAR DETERRENCE AS A **COMPLEX SYSTEM**

National Security Report



Edward Toton | James Scouras

Image from the Mandelbrot set, often used to represent complexity.
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Summary

The body of unclassified and declassified documents and eyewitness testimony from participants on both sides of the Cuban missile crisis has revealed numerous instances of potential escalation to nuclear war. Some of the potential escalations resulted from incomplete information, others from inappropriate subordinate action, and still others from actual missteps. It can be argued that these represent “close calls” that provide an evidentiary basis for inferring the risk of failure of nuclear deterrence. On the other hand, according to the declassified Defense Department assessment of military operations during the crisis, “The military establishment responded to a threat to our national security promptly, with imagination, vigor, and an exemplary degree of professional competence and skill.” This statement is consistent with the optimistic view that the US deterrence system in place during the crisis had such a degree of reliability that close calls were either manageable or of such low risk that they did not jeopardize the system’s overall performance.

There can be no dispute about the characterization of the nuclear deterrence system during the Cuban missile crisis and the current US system as complicated systems—these comprise a massive array of highly trained personnel, materiel, and sensor and communications systems. Researchers in the discipline of complex systems theory have cited five properties useful for identifying new problems as complex systems problems—high number of components/ interactions, significant interactions, nonlinearity, asymmetry, and nonholonomic constraints—any one of which is sufficient to characterize a system as a complex system. As an example, the property of nonlinearity means that a complex system can, on occasion, produce reactions entirely unexpected from the inputs made to it, while complicated systems do not produce such reactions. We show that the nuclear deterrence system in place during the Cuban missile crisis manifests all five of these properties based on the errors and incidents that occurred.

We establish that the US system for nuclear deterrence is a complex system in the formal sense, that nuclear deterrence must be regarded as a system-level function, and that the consequence of this is that there is the possibility of system-level failures not obviously connected to any component failures. These are emergent properties not predictable from an understanding of each of its components and interactions that may be candidates for Taleb’s black swan events.¹ To understand the potential risk of failure of the US nuclear deterrence system as it exists now and as it might exist in the larger context of multiple national actors and progressive disarmament, it is necessary to understand the potential interactions of components and command authority. For the analyst, this means constructing models that attempt to capture the nonlinearities of interactions, the existence of which is increasingly apparent.

¹ Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable*, 2nd ed. (New York: Random House, 2010).

“We came so close . . . The world came within a hair breadth of nuclear war.”¹ These were the words of Robert McNamara, secretary of defense during the Kennedy administration and the Cuban missile crisis, upon learning in the 1990s that the Soviet Union had succeeded in placing nuclear warheads in Cuba, including tactical warheads to repel any invasion. During that crisis, the United States did not know that the Soviets had any operational nuclear warheads in Cuba.² According to Secretary McNamara, “We had photographs of missile launchers but thought the warheads were yet to come.”³ And the possibility of tactical warheads that could be used to defeat an invasion was not considered. Relying on this incomplete intelligence, the Joint Chiefs of Staff recommended an invasion of Cuba, and at one point during the crisis, McNamara considered an invasion “almost inevitable.”⁴ Fortunately, as it almost certainly would have triggered nuclear war, the recommended invasion ultimately was not executed.

The body of unclassified and declassified documents and eyewitness testimony from participants on both sides of the Cuban missile crisis has revealed numerous instances of potential escalation to nuclear war. Like the unexecuted plan for invasion, some of these instances resulted from incomplete information, others resulted from inappropriate subordinate action, and still others from actual missteps. It can be argued that these instances were “close calls” that provide an evidentiary basis for inferring the risk of failure of nuclear deterrence. On the other hand, according to the declassified Defense Department assessment of military operations during the crisis, “The military establishment responded to a threat

to our national security promptly, with imagination, vigor, and an exemplary degree of professional competence and skill.”⁵ The US Air Force’s official study agreed that “the Air Force response to the Cuban crisis was outstanding.”⁶ These two statements are consistent with the optimistic view that the US deterrence system in place during the crisis had such a degree of reliability that close calls either could be managed or were of such low risk that they would not jeopardize the system’s overall performance.

The question of the reliability of the US deterrence system at the time of the Cuban missile crisis notwithstanding, the Soviet Union’s placement of ballistic missiles in Cuba created great instability in that system. Cuban-based ballistic missiles would have greatly increased the number and reduced the times of flight of nuclear weapons to major portions of the United States. In an era when the mutuality of assured destruction had not yet been accepted, the United States viewed this as an intolerable threat, particularly because it emanated from the Western Hemisphere, long a sphere of dominant US influence.

One of the lessons of the Cuban missile crisis was to avoid direct confrontation between the superpowers; heeding this lesson contributed to nuclear stability throughout the remainder of the Cold War. But is the geopolitical environment in the post-Cold War world prone to instabilities that could trigger nuclear war? According to the *Nuclear Posture Review* of 2018 “nuclear weapons have and will continue to play a critical role in deterring nuclear attack and in preventing large-scale conventional warfare between nuclear-armed states for the foreseeable future.”⁷

Today’s nuclear deterrence system is considerably improved over the system that existed in 1962. The nuclear triad has been completed, and new

¹ Robert McNamara, interviewed on CNN, June 18, 1998, as quoted in James Bamford, *Body of Secrets: Anatomy of the Ultra-Secret National Security Agency* (New York: Anchor Books, 2002), 124.

² Bamford, *Body of Secrets*, 124.

³ Robert McNamara as quoted in Bamford, *Body of Secrets*, 124.

⁴ Bamford, *Body of Secrets*, 118.

⁵ Scott D. Sagan, *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons* (Princeton, NJ: Princeton University Press, 1993), 114.

⁶ Sagan, *The Limits of Safety*, 114.

⁷ *Nuclear Posture Review* (Washington, DC: US Department of Defense, February 2018), III.

technologies, capabilities, and procedures have been incorporated throughout its evolution. However, the bipolar world of the United States and the Soviet Union has dissolved. There are now eight acknowledged nuclear powers, at least one Middle Eastern state with ambitions of a nuclear capability, and at least one transnational terrorist group with expressed interest in acquiring and using nuclear weapons. It is a new multipolar nuclear world.⁸

How might an assessment of the risk of nuclear deterrence failure in this emerging multipolar world be useful? One example can be found in deliberations concerning the New Strategic Arms Reduction Treaty (START) Treaty, which reduces US and Russian nuclear arsenals. Adjustments of arsenals, changes in the political prominences of nuclear states, and evolution in the nuclear capabilities of participants have the potential not only to decrease but also to *increase* the risk of failure of nuclear deterrence. For the United States to make informed decisions about restructuring its nuclear posture and about the consequences of agreements such as the New START Treaty, it is prudent to consider the changes in this risk, arguing for a formal examination of the risk of failure of nuclear deterrence.

The search for ways to characterize the risk of failure of nuclear deterrence must be conducted in a data environment for which there has never been a nuclear exchange. The challenge of estimating the risk of failure of nuclear deterrence is formidable: fundamental questions on how to characterize the sociological behavior of human actors in the nuclear deterrence system, how to establish the existence of paths that could lead to failure, and how to quantify these elements remain unanswered.

The law of unintended consequences is sometimes referenced when unanticipated consequences occur as the result of some decision or action in a societal system. In fact, the failure to anticipate potential

unintended consequences results from what amounts to a piecemeal understanding of the system to be acted on. Complicated systems, such as a Swiss watch or a personal computer, have many often intricately interconnected components or parts, yet they follow a rigorous blueprint for behavior. As long as legitimate operations are exercised, complicated systems do not produce unanticipated consequences.

On the other hand, complex systems are complicated systems (including a variety of component types, a multiplicity of components, or both) with an added feature: the interactions of their components are not simple. As we will see in the subsequent discussion, systems that are complex in this technical sense have the property of nonlinearity (i.e., the response of a system to some selected input can be disproportionate to that input). More generally, nonlinear behavior may be observed as an unanticipated system response. As an example, we will see in the next section that a small navigational error made during a course correction over Alaska led a US strategic bomber carrying megaton-class nuclear weapons on a 1,300-mile flight that ultimately would have penetrated Soviet airspace; only a last-minute discovery of the error by a ground intercept radar in Alaska avoided this outcome. This small navigational error could have resulted in nuclear escalation—a consequence far greater in magnitude than the navigational error would suggest alone and an example of disproportionate or nonlinear response.

Identifying unintended consequences requires understanding the complex system of interest. In the case of a system of nuclear deterrence, unintended consequences could be catastrophic. The question then is whether the US nuclear deterrence system exhibits the behavior of a complex system in its technical sense. We posit that it does.

There is a consequence of identifying the nuclear deterrence system as a complex system. Complex systems exhibit the property of emergence: the appearance of behavior at the system level that cannot be predicted by the nature of the system components.

⁸ On terrorist nuclear aspirations, see *Joint Hearing of the House Armed Services Committee and the House Select Committee on Intelligence*, Washington, DC, July 25, 2007.

We infer that the concept of nuclear deterrence itself is an emergent property of the system of nuclear deterrence; a corollary is that the risk of failure must be an emergent property as well.

The consequence of this identification is significant: it is not possible a priori to rule out the existence of failure modes that lie entirely at the systems level without concomitant component-level failures. (It is tantalizing to identify potential system-level failures with black swan events—a term coined by Nicholas Taleb in his popular book, *The Black Swan*⁹). Therefore, the analysis of the risk of failure of nuclear deterrence is incomplete unless it is based on complex systems theory.

The discussion is organized as follows. The first section presents incidents in the Cuban missile crisis that potentially could have led to unintended nuclear war. These incidents serve as lessons for how complex systems can have components whose interactions could lead to unintended consequences. The deterrence system extant during the Cuban missile crisis behaved as a complex system; we infer that the current deterrence system is also complex.

The second section introduces concepts of complex systems theory, a research discipline that seeks to understand and predict systems' behavior through an understanding of how new properties and behaviors of a system emerge from component subsystems—the characterizations of which do not presage emergent system behavior. Complex systems theory provides insights for behaviors of many physical systems, living organisms, and colonies where classical physics and engineering principles fail. The present and future nuclear deterrence system is discussed within this understanding of complex systems.

Finally, the Conclusions and Recommendations section discusses what we have learned and what research may be necessary in the search for a complex systems theory of nuclear deterrence and its failure.

⁹ Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Improbable*, 2nd ed. (New York: Random House, 2010).

The Cuban Missile Crisis

It is often claimed that the nuclear deterrence system that existed between the United States and the Soviet Union was successful: after all, no nuclear weapons were launched, and no nuclear war broke out between these two nuclear superpowers. However, examination of declassified documents and eyewitness testimony revealed a number of incidents that can be categorized as near misses¹⁰—that is, it is conceivable that escalation to nuclear weapon exchanges could have occurred. The claim that nuclear deterrence worked might need to be replaced with the claim that we were lucky.

The successful orbiting of Sputnik on October 4, 1957, was a technological shock to the United States that demonstrated that the Soviets had the capability to deliver payloads over intercontinental distances with launch-to-impact times of approximately thirty minutes, making US nuclear bombers vulnerable to a surprise attack. In response, through an intense technology development program, the United States developed an intercontinental ballistic missile nuclear capability as well as a fleet of nuclear ballistic missile submarines—all in place by the time of the Cuban missile crisis in 1962. This nuclear defense system ensured a second-strike capability (the ability to launch a successful, devastating nuclear attack on the Soviet Union in response to a nuclear first strike on the United States), which is the basis of nuclear deterrence. As expressed by then secretary of defense Robert McNamara in the 1960s, such an assured second-strike capability possessed by both sides became enshrined in the doctrine of mutual assured destruction—a property that *emerged* from the Cold War race for nuclear armament supremacy.

There was a general sense in the United States that the country was very close to nuclear war during the Cuban missile crisis. The risk of nuclear war was perceived to hinge on the actions of the respective command centers of the two powers. In

¹⁰ Sagan, *The Limits of Safety*, 114.

the United States, the command center created by President Kennedy was the ExComm—the Executive Committee of the United States National Security Council. The nuclear deterrence system below the ExComm was composed of the vast infrastructure for weapons’ preparation, management, intelligence gathering, alert functions, and response to command updates. It was considered to function as designed—that is, flawlessly. If not, then errors could be managed promptly and without compromising the defense mission.

Published in 1993, Scott Sagan’s book *The Limits of Safety*¹¹ (on which this section is largely based) explores Cuban missile crisis events that bring into question the belief that a nuclear arsenal can provide a flawless nuclear deterrent. Uncovered from unclassified materials in the public domain, materials obtained through the Freedom of Information Act, and eyewitness accounts, these events were within the strategic defense infrastructure on which the command center relied, were close calls in that there were plausible alternatives that could have led to war, and were unanticipated. These features have important implications for how to characterize such complicated systems.

We next discuss two examples selected from the large number of cases Sagan examined. While these examples can be regarded as close calls, there has been no assessment of the likelihoods that they might have led to nuclear escalation. The examples demonstrate the difficulty in anticipating such events and the importance of understanding human action in a complex system.

The Lost Bomber Incident

As described by Sagan, at the moment of President Kennedy’s television address on October 22, the US Strategic Air Command increased its B-52 airborne alert system (code-named Chrome Dome) to sixty-six sorties a day from the peacetime level of

twelve sorties a day.¹² During the crisis, these sorties were distributed over three basic routes: the southern route crossed the Atlantic Ocean and established orbital loitering over the Mediterranean Sea; a second route extended over Ontario to the Hudson Bay and established orbital loitering near Thule, Greenland; and the third route essentially circumnavigated North America—to and across Greenland, over the Arctic Ocean north of Canada, across Alaska, and down the Pacific coast of the United States to return to their bases. Each of the B-52s carried three or four thermonuclear (i.e., megaton-class) weapons.

The airborne alert routes used by the US Strategic Air Command Chrome Dome bombers were supposed to be safe, and direct orders from the secretary of defense specified that no aircraft would approach the territories of the Soviet Union or China.¹³ However, on August 23, 1962, the crew of one of these flights made a navigational error during a course correction over Alaska and assumed a course that would lead the bomber eventually to penetrate Soviet territory if not corrected. The crew was unaware of this navigational error, flew a distance of approximately 1,300 miles, and came within 300 miles of Soviet airspace when a ground control intercept from Alaska detected the location error and radioed an immediate course change.

It was known that the Soviet Union had invested heavily in the development of air defense interceptors in the 1950s and 1960s. By 1962, the Soviet Union had hundreds of MIG-19s, with a combat range of four hundred miles, and MIG-21s, with a combat range of two hundred miles. Although the basing of these was not known, the projection of the lost bomber route strongly suggests that at the time that the bomber was alerted, it was already well within interceptor combat range.

It is not known whether the Soviet Union was aware of the lost bomber’s potential intrusion into its airspace.

¹¹ Sagan, *The Limits of Safety*.

¹² Sagan, *The Limits of Safety*, 63.

¹³ Sagan, *The Limits of Safety*, 74.

However, the potential intrusion by a B-52 armed with at least three thermonuclear weapons must be regarded as an event that could have resulted in a serious confrontation between the Soviet Union and the United States. We see from this that a relatively small failure in the system—as easily attributable to equipment error as human error—could have had catastrophic consequences.

The Vandenberg Missile Launch

The second incident of concern to us involved Vandenberg Air Force Base in Southern California.¹⁴ Vandenberg housed both the US Strategic Air Command operational test and evaluation facilities and intercontinental ballistic missile test facilities. Test missiles were flown into the Pacific Kwajalein test range. On October 22, 1962, when alert status was raised to DEFCON 3, test silos and missiles were in various states of repair or test preparation. Air Force Systems Command began preparations to ready the sites for combat capability. By October 30, nine missiles at Vandenberg had been outfitted with nuclear warheads and were prepared for launch.

One Atlas intercontinental ballistic missile had been standing ready for a test flight in the week after October 22 when DEFCON 3 was announced. While other missiles surrounding this intercontinental ballistic missile were being reconfigured for nuclear combat capability, this missile was held in reserve as a test missile. On the night of October 26, at 4:00 a.m., this missile was launched toward the Kwajalein test range. This launch was executed without the knowledge of Washington, which focused its attention on actions, and possible launches, in Cuba.

It is difficult to estimate the risk involved in this launch. It is not known, for example, whether the Soviets were aware of it. There was no satellite coverage at this time, but it would be unreasonable to assume that the Soviet Union would have had no observers in the vicinity of Vandenberg during

the missile crisis. Certainly there would have been opportunity to observe the heightened activity at the launch sites between October 22 and 26, and there would have been opportunity for visual detection of an early morning launch from a presumptive nuclear-configured launch facility.

What we have here is an event that resulted from decision-making (to proceed with the scheduled test) at the local command level without the knowledge of the highest command level in Washington and failure of the highest command level to rescind local decision-making authority in this crisis. For a time, this local command functioned autonomously without realizing the potential impact of its action. It is difficult to argue that there was no great risk in this action: if the Soviet command had received intelligence of a nighttime launch from a presumed nuclear-capable facility, for which the time from launch to impact would be considerably less than that of an intruding bomber, it would have undoubtedly fostered a high-risk decision-making environment for that command. This event must be regarded as a high-risk close-call event.

Observations

It is evident from these two examples that human behavior is an important factor in the reliability of systems for nuclear deterrence. This is well known to the designers of the current US nuclear deterrence system: a culture of safety is established through functional design and extensive training. Functional design uses cooperative decision-making to mitigate individual errors; extensive training of operational personnel emphasizes the importance of safety and training in appropriate responses to anticipated problems and ingrains safe operational procedures during heightened threat levels and potential crises. In other words, the risk of failure resulting from human error is thought to be made acceptably low through rigorous training and redundancy of responsibility. On the other hand, this thought must be tempered by the reality of cultural complacency,

¹⁴ Sagan, *The Limits of Safety*, 78.

as was exhibited in the cross-US flight of a B-52 bomber loaded with six nuclear cruise missiles in September 2007.¹⁵

The Vandenberg missile launch occurred as a result of component-level decision-making independent of national command; the lost bomber incident occurred because of navigation error. The latter could be attributed to a mechanical or physical error in which the navigator believed the instrument read-outs, or there could have been actual human error in the interpretation of indicators. In any case, this form of error (now extremely unlikely with modern navigation tools) is quite analogous to a simple hardware component error. Human management of navigational systems remains paramount, however, and the sustained flight of the lost bomber shows that its crew did not discover this error for an extended period of time. It is therefore appropriate to attribute this failure to human error as well.

These failures are just two examples of human component-level system errors that could have led to an escalated confrontation during the Cuban missile crisis and to nuclear war. The command-level belief that there were no Soviet nuclear warheads on Cuban soil during the crisis, as discussed in the introduction, reveals the risk of failure of nuclear deterrence attributable to command-level assumptions in decision-making. We conclude from this that human decisions in a nuclear deterrence system have the potential for catastrophic consequence when the decisions themselves may not at the time be perceived as having this import. That is, the deterrence system can have responses that are disproportionately greater than the human actions may first suggest. We will see later that this nonlinear behavior is consistent with behavior of a complex system.

Nuclear Deterrence as a Complex System

Sagan points out that both the hawkish and the dovish positions on the Cuban missile crisis reflected the belief that nuclear weapons had an intense inhibiting effect on the likelihood that John Kennedy or Nikita Khrushchev would make a premeditated decision to authorize a nuclear strike.¹⁶ On the other hand, neither position acknowledged the possibility of an accidental escalation to nuclear war.

We have seen that the Defense Department and Air Force assessments of performance during the Cuban missile crisis reflected an optimistic view of the reliability of the system of nuclear deterrence. But the nature of the events discussed in the previous section, and of others discussed by Sagan, suggests that it is appropriate to label these as close calls (i.e., these events had some nonnegligible probabilities of leading to nuclear escalation). The optimism of the Defense Department and the Air Force carries within it that *every* future close call will be caught in a timely manner and corrected—optimism not warranted when even one miss invites the risk of nuclear escalation.

The question arises as to whether there is a meaningful, objective expression for the risk of failure of nuclear deterrence, an expression that reduces the large gap between those who believe that the risk is slight and those who believe that the risk is significant. We will shortly see how the system architecture of a nuclear deterrence system raises issues that must be addressed, if such an expression is sought. We will see that the few examples of close calls already discussed clearly establish that the nuclear deterrence system in place during the Cuban missile crisis was, in fact, a complex system in the technical sense of this term. It is therefore necessary that we address properties of complex systems in general.

¹⁵ Agence France-Presse (AFP), “B-52 Carried Nuclear Missiles Over US by Mistake: Military,” September 5, 2007.

¹⁶ Sagan, *The Limits of Safety*, 55.

The Nature of Complex Systems

Weaver, in his paper “Science and Complexity,”¹⁷ was perhaps the first scientist to set down a categorization of the types of problems that science has resolved or needs to resolve. The first of these he called problems of simplicity. Problems of simplicity are characterized by variables. A manageable set of variables could be used to predict future behavior from current observation, and this approach was successful in physics and engineering in the seventeenth through nineteenth centuries. A simple example is the modeling of the solar system, for which variables of location, rotation, and velocity could reliably be predicted from careful initial observation.

The second category he named problems of disorganized complexity. These were problems that implied fantastically large numbers of variables for which it would be impossible to predict future behavior from present observation, even granting that a comprehensive observation could be accomplished. Here, the discipline of statistical mechanics was dramatically successful in characterizing a system with a very large number of identical components (such as molecules in a gas) even if the details of the interactions of individual molecules were unknown; it was only necessary to assume that there was randomness of behavior from one component to another.

Weaver’s third and final category is one that he called problems of organized complexity. Here problems are characterized by the presence of qualitatively different components (in contrast to molecules in a gas, for example), and the number of variables implied for description may be large but not as large as in problems of disorganized complexity. In addition, the interactions of the components may be much more complicated than would be assumed for problems of disorganized complexity. Weaver offered examples such as employee unions, political organizations,

and even nations. He expressed the point of view that problems of organized complexity were the next great challenge, and the next great opportunity, for science in the second half of the twentieth century.

Even in problems of disorganized complexity, we see behaviors that are not evident or anticipated in the components composing these complex systems. For example, the thermodynamics of a bulk collection of gas molecules is developed with powerful statistical mechanics theorems. The resulting thermodynamic laws—the second law of thermodynamics, in particular—are clearly behaviors not possibly implied in the simple collision mechanisms of individual molecules. Behavior that appears in a system as a whole but is not implied in the components and their individual interactions is called emergent behavior.

Vertebrates provide a more compelling example. There is a great deal of structure in any vertebrate: there is differentiation of cells among those that support specific function or organ composition, and there is considerable functional differentiation to provide subsystem support to the system (individual organism). We also see purposeful action on the part of the individual to forage for food and to reproduce, for example. On the human level, we see highly intellectual activity as well. These system-level functions are not presaged in the makeup of the constituent cells of the body. These are dramatic manifestations of emergence.

Emergent properties may be indiscernible, rudimentary, or sophisticated, depending on the sophistication of the system components and the degree of complexity of the interactions among components. For example, on first look, harvester ant colonies appear to be fairly disorganized collectives. However, on closer inspection, these colonies exhibit structural differences in their components (the breeding queen, foragers, and soldier ants, for example). There is purposeful behavior to pressures of famine or attack by another colony. And, most interesting, there is a life span of a colony—from adolescence to adulthood to senescence and eventual

¹⁷ Warren Weaver, “Science and Complexity,” *American Scientist* 36 (1948): 536–544.

death over a period of approximately fifteen years. This collective life span is far greater than the life span of any one ant. We conclude that the colony's behavior cannot be presaged in the behaviors of individual ants.

It is useful to discuss another example of colony behavior, which was ultimately understood through mathematical representation of the interactions of single organisms. Slime molds are commonly found in forests in areas that are rich in nutrients. They are composed of single-cell organisms that typically have dimensions measured in micrometers and are therefore seen individually only through microscopes. However, when the number of these organisms is in the millions or greater, the characteristic mold carpet is clearly identifiable by the naked eye.

Because the slime mold is so simple in structure, it exhibits behavior that has long been mysterious. Whenever a colony becomes environmentally distressed (e.g., because of nutrient depletion in its neighborhood), it begins to exhibit collective behavior; the colony functions as a single organism with macroscopically visual structural movement.¹⁸ In the case of nutrient depletion, this coordinated movement leads the macroscopic organism to crawl in search for a more nutritionally rich location; once the organism finds such a location, it reverts to individual single-cell behavior.

Microbiologists have long known that each slime mold cell could produce a common substance called acrasin (also known as cyclic adenosine monophosphate, or cAMP). They also knew that the individual organisms would respond to concentrations of cAMP and migrate according to the gradient of the concentration of this substance. The microbiology community generally believed that there were special cells (pacemaker cells) that directed the motion of the colony through a process of chemical communication with cAMP. However,

continued research failed to find any cells that were morphologically and functionally different from the majority of the colony.

Keller and Segel took a different approach to describing this collective behavior. They postulated a mathematical representation of a slime mold colony for which only two parameters were needed—the number of individual cells per unit volume of water (the number density) and the local concentration of a chemical substrate.¹⁹ It is useful here to use a more simplified version of the Keller–Segel model, as described by Blanchet et al., in which there are just two coupled equations representing the number density (n) of the single-cell organisms and the concentration of cAMP (c):²⁰

$$\frac{\partial n}{\partial t} = \nabla^2 n - \chi \nabla \cdot (n \nabla c) \quad (1)$$

$$\nabla^2 c = -n. \quad (2)$$

Here, the extent of the water pond may be no larger than one's hand—far larger in scale than the single-cell organisms themselves. When the number of cells is very large, the number density can be considered a continuous quantity, varying smoothly from point to point and in time within the pond. The first equation relates the time rate of change of the number density anywhere in the pond (the left-hand side) to various spatial derivatives of the number density itself and the concentration of cAMP. The second equation is a relationship between spatial derivatives of this concentration (on the left-hand side) and the number density at any particular point in the pond. The quantity χ is a number that represents the sensitivity of the individual organisms to the concentration of cAMP; its value is derived from experimental observation.

¹⁸ Steven Johnson, *Emergence: The Connected Lives of Ants, Brains, Cities, and Software* (New York: Simon & Schuster, 2001), 13ff.

¹⁹ Evelyn F. Keller and Lee A. Segel, "A Model for Chemotaxis," *Journal of Theoretical Biology* 30, no. 2 (1971): 225–234.

²⁰ Adrien Blanchet, Jean Dolbeault, and Benoît Perthame, "Two-Dimensional Keller-Segel Model: Optical Critical Mass and Qualitative Properties of the Solutions," *Electronic Journal of Differential Equations* 44 (2006): 1–33.

It is easy to see that there is an inherent nonlinearity in these equations. The second equation is itself linear in the sense that a doubling of the number density is consistent with a doubling of the concentration. But in the first equation, a doubling of these quantities does not work: the second term grows by a factor of four under this operation, whereas the other terms in the equation are only doubled. This means that the behavior of concentration and number density must depend critically on the actual values of these parameters.

In the life of a slime mold colony, there are times when the second, nonlinear term is small enough to be ignored and there are times when it is not; when the nonlinear term is negligible, there is no collective behavior. The behavior of the general solution of these equations reveals the periods for which the colony will function as a collective entity. This collective behavior arises from the overall structure of the two-component system (cells and chemical). Throughout this process, each individual cell responds only to its local environment, propelling itself according to the local gradient of chemical concentration (∇c) (chemotaxis).

We see that the collective behavior of a slime mold colony is an emergent property of the system; this property is not presaged in the behavior of individual cells. More important, however, is the fact that the understanding of the origin of collective behavior is achieved through a mathematical representation of the slime mold colony as an example of Weaver's systems of organized complexity. Furthermore, this mathematical representation allows us to determine quantitative behaviors through integration of these equations (whether exactly or through numerical analysis)—a level of insight that is not achievable through discourse alone.

These examples show how we can gain insights into the behavior of systems in nature by using the principles of complex systems theory when the conventional principles of physics and engineering have proven inadequate. Furthermore, it is easy

to understand how the assumption of linear, proportionate interactions for a system must fundamentally overlook the richness of behavior of these systems and potential emergent behavior, and how behavior expected under such an assumption can be prone to error.

Complex systems theory can be applied to artificial systems as well as living organisms, the principles being essentially the same. Many systems of the technological age, such as nuclear reactor power plants and airline transport aircraft, imply nonlinear interactions. It is even possible to consider the human brain in the context of complex systems theory when behavioral features are considered. In fact, human thought is likely an emergent property of the brain, because behavioral responses (such as emotional behaviors) can be nonlinear and thought is not presaged in the behaviors of individual neurons.

Researchers in complex systems theory since the time of Weaver have identified properties of complex systems that are useful for classifying new problems as complex systems problems. For example, Yates²¹ has identified these properties of complex systems:

- **High number of components/interactions.** Large numbers of components and interactions make it difficult for anyone to apprehend the system and understand the significance of interactions.
- **Significant interactions.** Significant interactions can be those perceived and those hidden interactions that essentially determine the relationships of outputs to inputs.
- **Nonlinearity.** Nonlinearity describes the disproportionate scale of an output in comparison to an input to a complex system—small changes in interactions can produce dramatically different systems behavior and sometimes counterintuitive responses.

²¹ F. Eugene Yates, "Complexity and the Limits to Knowledge," *American Journal of Physiology* 4, no. 3 (1978): R201–R204.

- **Asymmetry.** Components of complex systems are disparate in nature and complexity, increasing the difficulty of understanding.
- **Nonholonomic constraints.** Subsystems can be isolated from the system command structure; independent subsystems responses are possible. For example, ballistic missile submarines may on occasion operate in conditions where they cannot communicate with command. During these periods, the submarines are independent and autonomous, although they are still guided by strict regulations.

Generally, several of these features will be discernible in complex systems, and it is not necessary that all be present for a system to be identified as a complex system.

As we will shortly see, these characteristics can be used to determine to what degree the nuclear deterrence system during the Cuban missile crisis can be considered a complex system and, by inference, to what degree the current nuclear deterrence system can be considered a complex system.

The Nuclear Deterrence System Is a Complex System

We discussed the Cuban missile crisis and introduced two examples of close calls—events that conceivably could have led to escalation to a nuclear war. We remarked that the United States had developed an intercontinental ballistic missile nuclear capability as well as a fleet of eight nuclear ballistic missile submarines, thereby providing an assured second-strike capability—the ability to launch a successful, devastating nuclear retaliatory attack on the Soviet Union in response to its nuclear first-strike attack on the United States.

The deterrence system at the time of the Cuban missile crisis was highly complicated, and its components varied greatly in their composition (e.g., land, air, and sea equipment). Not only was

there a multiplicity of disparate hardware essential to the system, but there was also a hierarchy of human components with the knowledge and training necessary to fulfill the deterrence mission as well as retaliatory strikes, if necessary. This great assembly of hardware and communications needed to support the missions confirms the presence of many components and interactions—one of the hallmarks of complex systems. The disparate nature of the components of the system, including hardware and human components, satisfies the attribute of asymmetry of a complex system.

The lost bomber incident was likely the result of human error, although a technical malfunction might have been a causative agent. Whatever the cause, the crew did not discover the navigational error during a flight of more than 1,300 miles. If the Soviet Union had decided to attack this nuclear-armed bomber, escalation to nuclear war could not be ruled out. Here, a relatively small error could have resulted in a catastrophic outcome. This conforms to the attribute of nonlinearity.

The Vandenberg launch incident was the launch of a test missile in the direction of the Sino-Soviet bloc territory. This launch was executed during the height of the Cuban missile crisis without the knowledge of national command authority. This is an example of nonholonomic constraints, another attribute of complex systems.

If we acknowledge that any system of nuclear deterrence must essentially incorporate significant interactions, then we see that the consideration of just two close-call events is sufficient to satisfy the attribution of all five of Yates's attributes of complex systems. We can conclude with confidence that the US nuclear deterrence system in existence at the time of the Cuban missile crisis can be fully characterized as a complex system.

The US nuclear deterrence system of today has considerably improved since the time of the Cuban missile crisis. For example, now sophisticated satellite-based sensors provide more timely and

accurate intelligence. Equipment and training improvements have been implemented over the years to reduce the risk of failures such as those that occurred during the Cuban missile crisis. Nonetheless, most of the attributes of complex systems remain attributes of the modern nuclear deterrence system. We can conclude that the current US nuclear deterrence system should be discussed in the context of complex systems and their behaviors.

Nuclear Deterrence Is an Emergent Property

The doctrine of mutual assured destruction did not exist at the dawn of the atomic age. As each side raced to achieve a nuclear “advantage,” or at least prevent the other side from developing an advantage, both sides reacted to the other side’s growing capabilities in a vicious cycle. Eventually, both the United States and the Soviet Union developed reliable second-strike capabilities. The recognition that the assurance of an effective second-strike capability meant that no first strike by an opponent could avoid certain nuclear annihilation led ultimately to the perception of nuclear stability between the two superpowers. In the 1960s, then secretary of defense Robert McNamara finally recognized and expressed the concept of assured destruction as a property that emerged from the Cold War race for nuclear armament supremacy. The Soviet Union’s development of a second-strike capability meant that a concept of mutual assured destruction was in place and that a more stable status had been achieved between the two superpowers.

As a product of the buildup of a nuclear deterrence system that included a second-strike capability, we see on the one hand that the concept of nuclear deterrence itself is a system-level attribute and, on the other hand, that no component itself presages this attribute. One might argue that the human components will be aware of this attribute, but this knowledge does not determine the task performance of the human components. If anything, knowledge

of this attribute in times of escalated tensions might interfere with the proper functioning of human components because of compelling cultural or familial concerns. We can conclude that nuclear deterrence is an emergent property of the system.

The Risk of Failure of Nuclear Deterrence Is an Emergent Property

It is at least possible to conceptualize the process of evaluating performance of nuclear deterrence over the full spectrum of conflict scenarios, hardware and human component failures, and all command-level choices. Some fraction of these factors would terminate in the use of a nuclear weapon, whereas others would not. In each and every possibility, the outcome is entirely dependent on the evaluation of the system performance. The set of failures and the entire set of possibilities are each system-level entities that depend fundamentally on the emergent property of deterrence. It is incontrovertible: the probability of failure is itself an emergent property of the deterrence system, leading us to infer that the risk of failure as well is an emergent property of the deterrence system.

This conclusion has profound consequences. We have already shown that there are fundamental nonlinearities inherent in the system, some of which originate from human components within the system below command level or at command level. Of course, we expect that the deterrence system might be susceptible to physical accidents (even an accidental nuclear detonation) or component-level human error, as displayed in the lost bomber incident during the Cuban missile crisis. These are what we might call single-point or single-cause failures. However, when nonlinear interactions exist in the system, it is possible that the simple reduction of response of a component rather than an outright failure could lead to unexpected responses elsewhere in the system leading to failure. And finally, nonlinearities in the system that can cause failure of nuclear deterrence must also, in principle, allow for a system failure when no individual component in the system has failed.

We need only refer to the history of airline transport accidents to see that many catastrophic failures were attributable to “pilot error” when human error in decision-making on the occasion of some relatively minor mechanical problem led to loss of the aircraft. The system-level failure that we speak of here is analogous to a series of pilot decisions that appear rational in and of themselves but lead to the loss of the aircraft nonetheless. These are the kinds of system failures that cannot be ruled out a priori; only careful analysis can establish the absence or existence of such potential failures in any particular complex system.

Implications

There are two schools of thought about the reliability of complex systems that could be advanced for systems such as nuclear power plants, oceanic tankers, airline transport aircraft, and, in our case, the system of nuclear deterrence.²² The first is the high-reliability point of view that attempts to reduce the risk of failure by training, inculcation of a culture of safety, and redundancy. This point of view primarily addresses the human component’s contribution to the reliability of complex systems. It is an optimistic point of view because it holds that, if sufficient emphasis is placed on these human components, any catastrophic error could essentially be rendered impossible. The second school of thought is the normal accidents point of view and is based on Perrow’s research presented in his book *Normal Accidents*.²³ Perrow argues that complex systems will always exhibit catastrophic failures that remain essentially unpredictable. He also argues that failure-specific remedies or fixes to existing complex systems likely introduce unforeseen interactions so that other failures may then be possible. This point of view is the more pessimistic view of complex systems in that it expects catastrophic failures to be inherent in these complex systems.

²² Sagan, *The Limits of Safety*.

²³ Charles Perrow, *Normal Accidents: Living with High-Risk Technologies* (Princeton, NJ: Princeton University Press, 1999).

It could be argued that the human component has the potential to enhance system reliability as well as to be the source of system failures. Of course, this is implied in the high-reliability point of view that emphasizes training under failure simulations to cope with surprise failure events. Where human intervention is eschewed is in unplanned improvisation; the risk of unintended consequences is so great for the failure in nuclear deterrence that improvisation cannot be relied on as a safe mitigation of developing unplanned failure events.

On the other hand, command-level decision-making is essentially improvisational. Although studies historical conflicts may be studied and human character may be judged, there is no formal declaration of the conditions under which one decision might be preferred over another when conflict arises among nuclear powers. This underscores the essential difference between human involvement at the command level and the component level in a nuclear deterrence system for which training, safety, and redundancy are intended to ensure a high-reliability system for the command level.

The existence of failures arising through the complexity of the deterrence system would give substance to the belief in black swan events that would be tied essentially to system-level interactions. The potential existence of system-level failures would cast doubt on the belief in the high-reliability point of view and validate the normal accidents point of view. The question before us is whether we can develop any rational means to establish the extent of potential catastrophic failures in the nuclear deterrence system and whether we can estimate any measure of the probabilities of their occurrence.

Nuclear Deterrence Modeling Requirements

We have presented a series of arguments that establishes the following three things: (1) the US system for

nuclear deterrence is a complex system in the formal sense; (2) nuclear deterrence must be regarded as a system-level function; and (3) as a consequence of this recognition, the failure of nuclear deterrence can arise through hardware failures, human component failures, and command-level missteps, and there is even the possibility of system-level failures not obviously connected to any component failures. To understand the potential risk of failure of the US nuclear deterrence system as it exists now and as it might exist in the larger context of multiple national actors and progressive disarmament, it is necessary to understand the potential interactions of components and command authority. For the analyst, this means constructing models that attempt to capture the nonlinearities of interaction, the existence of which is increasingly apparent.

Morton Kaplan, in his book *System and Process in International Politics*,²⁴ sought to develop a systems methodology to analyze international political systems. He posited six systems that he considered representative (but not necessarily exhaustive) of potential international systems. Of these (balance of power, loose bipolar, tight bipolar, universal, hierarchical, and unit veto), two are of interest to our problem:

- **Loose bipolar.** Here, two supranational actors decomposed into national actors—the Communist bloc and NATO participants. In addition, the United Nations exists as a supranational system.
- **Unit veto.** The unit veto system is something of an anomaly in the listing of potential political systems. It arises through its members' possession of a weapon that is assured of destroying an opponent member even if the owner of the weapon cannot guarantee its own survival. As such, there can be no political system, and the status of the system is frozen once all members possess this weapon.

Kaplan's international political systems are theoretical constructs, with the exception of balance of power (composed of the pre-World War I states) and loose bipolar (composed of the United States and the Soviet Union, together with their allies). The bipolar system during the Cold War dissolved with the Soviet Union, and only the US–NATO supranational actor remains. On the other hand, the emergence of nuclear nations has elements of the unit veto system, and the consequences of this system must be taken into account when considering the evolution of the multipolar nuclear power system.

Kaplan's approach to international political systems allows him to assess characteristics such as stability or evolutionary development alternatives for these systems. Our discussion of the US system of nuclear deterrence up to this point has taken the viewpoint of this system bounded by an external environment of other actors and the nuclear systems they have. Alternatively, Kaplan's approach leads us to consider the point of view that the US system of nuclear deterrence should be treated as a subsystem in the larger context of a multipolar nuclear power system. We conclude that the modeling requirements must include specification of the nuclear deterrence system's domain: on the one hand, we can treat the deterrence system as confined to US interests and assets; on the other hand, we can consider these as a subsystem within the larger context of a multipolar nuclear power system.

We have now identified most of the factors that need to be considered for modeling. However, it is also necessary to consider information flow within the complex system.

The assembly of all the equipment and human component assets in the US nuclear deterrence system is not random but is instead a well-coordinated network of these components. There is a well-defined structure of information exchange and flow that is clearly designed to obtain the maximum useful information that flows across the system boundary from its external environment

²⁴ Morton A. Kaplan, *System and Process in International Politics* (New York: John Wiley & Sons, 1957).

(when the focus is on the US deterrence system viewed as a system in an environment of external nuclear power actors) and efficient and reliable information flowdown through the network to convey command instructions.

Shannon and Weaver²⁵ described the general problem of communications in terms of three levels:

- **Level A.** “How accurately can the symbols of communication be transmitted?”
- **Level B.** “How precisely do the transmitted symbols convey the desired meaning?”
- **Level C.** “How effectively does the received meaning affect conduct in the desired way?”

For the US system of nuclear deterrence, we can be confident that there is continuing improvement in the technical capability addressed in level A. However, level B precisely addresses the semantics problem. During heightened alert, as was the case during the Cuban missile crisis, it is evident that there was uncertainty in intentions and meaning of content in communications from the Soviet Union command level, and it can be presumed that the Soviet Union’s perception of the United States’ intentions suffered similarly. In the current multipolar nuclear power system, factors such as cultural differences, religious affiliation, sensitivity to perceived slights by neighbors, and interpretations of foreign influences represent semantic challenges that constitute a contextual problem for meaningful interpretation. We see that context is an important factor through its influence on how information is to be used to determine whether a nuclear alert is warranted, whether a negotiation strategy is in need of changing, or which strategies are likely to be successful in designing an arms reduction procedure, for example.

Because human motivation and intent are so vital to the description and prediction of the nuclear deterrence system, sociological behavior must be sufficiently understood so that it can be represented in a form useful to system modeling. Sociological behavior includes those factors that qualify intent and meaning in communication and therefore assist in providing context.

Conclusions and Recommendations

As was said earlier, whether one argued from a high level of confidence in prevailing through the Cuban missile crisis or from a state of great concern that unintended, catastrophic consequences could result, nuclear weapons had an intense effect inhibiting both Kennedy and Khrushchev from making a premeditated decision to authorize a nuclear strike. That is, both positions held that a deliberate breakout of nuclear war in the Cuban missile crisis was unlikely. The multipolarity of today’s world suggests, however, that the risk of nuclear war could be much greater now than during the Cuban missile crisis. Is this really the case? Is there a way to arrive at an objective, or at least less subjective, assessment of the risk of failure of nuclear deterrence by considering the question from the perspective of complex systems theory?

The identification of the US system of nuclear deterrence as a complex system forces us to recognize that ignoring features such as nonlinear interactions amounts to piecemeal thinking: judgments about the risk of events are likely to be in error, but, at minimum, there can be no confidence in such judgments without an appreciation of the impact of complex systems’ behavior in nuclear deterrence.

Having come this far in the analysis, we are nonetheless confronted with considerable uncertainty. If, for example, we succeed in constructing a mathematical model for a system of nuclear deterrence, how do we determine the objective validity of its predictions? Any constructed models are bound to entail approximations; we may restrict choices for

²⁵ Claude E. Shannon and Warren Weaver, *The Mathematical Theory of Communication* (Chicago: University of Illinois Press, 1963), 24.

command levels or discretize what would normally be a range of potential options in order to make the analysis manageable. On what basis could we decide that improvements in detail would lead to a convergence of predictions to some true value? Is it not possible that high detail could lead to large changes in predictions? These are some of the questions that arise and that only future research can address.

Nuclear Deterrence as a Complex System

The insights developed from the conclusion that a nuclear deterrence system is a complex system include the realization that the risk of failure of nuclear deterrence is an emergent property of the system and that the existence of failures that are wholly dependent on system properties for which there is no component failure cannot be ruled out a priori (i.e., without formal assessment).

Norbert Wiener described cybernetics as the control and communication in the animal and machine and developed mathematical analyses of complex systems such as the cell in the human body.²⁶ The flow of information from the environment in which the system finds itself as well as information about the status of the system itself are similarly described for the human cell and for a system of nuclear deterrence. In the case of deterrence, the flow of information to and from the command level is of paramount importance, and corruption by noise or ambiguity of meaning is an important factor for the successful operation of this complex system. That is, information conveyed by transmission over a network must be calibrated against the context of origination (such as cultural beliefs and biases of the originator) and by other factors such as the system's state of alert.

The human cell may be a complex system, but it is almost always surrounded by other human cells in the body. That is, the human body is a complex system composed of complex subsystems: the interaction of a human cell with its environment is not that of interaction with a passive environment, such as with heat, light, or water, but instead the interaction with neighboring cells that can respond to the behavior of the given cell. So far in this discussion, we have regarded the US nuclear deterrence system as a complex system in interaction with an environment, much like the single individual human cell. In the case of nuclear deterrence of the last century, we have discussed nuclear deterrence as if the Soviet system were an essentially independent system. However, if we regard the US–Soviet standoff as a complex system in and of itself, we see that there can be interactions among the two subsystems that may support emergent behavior not realizable by studying the US deterrence subsystem as an independent system. It is therefore important that we remain aware of this level of complexity in the current political state of the world.

Nuclear Deterrence in the Multipolar World

In the 1960s, Kaplan sought definitions of system variables and formal rules that govern the political relationships among actors—the national and international groups that can decide and order implementations of these decisions. His intent was to build a predictive methodology that could project future changes in international politics. Kaplan studied six categories of political systems; by extension, we can discuss the multipolar nuclear power world.

The new multipolar nuclear world is composed of not only nuclear states but also transnational terrorist groups that are interested in acquiring and using nuclear weapons. Each of these can be regarded as a complex subsystem in the complex multipolar nuclear world. Kaplan stressed the need

²⁶ Norbert Wiener, *Cybernetics, or Control and Communication in the Animal and the Machine*, 2nd ed. (Cambridge, MA: MIT Press, 1961).

for identifying the conditions for political stability and the consequences of changes in stability, such as the change of a democratic government into a dictatorship, to name one example. For us, the definition of stability in nuclear deterrence has great importance; nuclear stability in a future of arms reduction has even greater importance.

Kaplan said,

The crux of the matter is whether regularities can be discovered which permit the organisation of the materials of international politics within a simple framework of reasonable explanatory or predictive power.

If such an endeavour is to succeed, analytical tools are required in order to abstract systematically the materials of international behaviour from their biographical or historical setting and to organise them into a coherent body of timeless propositions.²⁷

This remains true for the system of nuclear deterrence.

Recommendations

It is clear that any attempt to model a system of nuclear deterrence with the intent to quantify its risk of failure must overcome a number of obstacles. Perhaps the most formidable obstacle is the construction of algorithms that can represent human response to a multitude of requirements as well as political, cultural, and religious beliefs. Studies in the domain of social sciences need to be coordinated with mathematical modelers who can express the needs of formal representation in systematic complex systems models.

The architecture of a nuclear deterrence system is the structure on which a complex systems model can be built. This structure forms the basis of a network interpretation of the command and control function as described by Wiener; this provides the framework

on which the essentially nonlinear functional responses operate.

Attempts to quantify the probability of catastrophic events in complex systems when no such events have yet occurred are analogous to the dropping of a blind man on a plateau. How does he decide whether the rise under his feet is from a local hillock or the base of foothills of a mountain ridge? The JASON report takes the following position:

It is simply not possible to validate (evaluate) predictive models of rare events that have not occurred, and un-validated models cannot be relied upon. An additional difficulty is that rare event assessment is largely a question of human behavior, in the domain of the social sciences, and predictive social sciences models pose even greater challenges than predictive models in the physical sciences. Reliable models for ameliorating rare events will need to address smaller, well-defined, testable pieces of the larger problem.²⁸

We concur and recommend the construction of complex systems models that are simple in design yet capture selected features of a nuclear deterrence system. From these, we can develop strategies that could facilitate descriptions of stability, how to return to stability when disturbances occur, and how it might be possible to characterize the risk of classes of improbable events, if not specific events themselves.

The elements we have identified that are relevant to the modeling of nuclear deterrence apply to the US system in an external environment or as a subsystem in the larger context of multiple state actors and are summarized here:

- **Composition.** This identifies the components within the system (“hardware”). Components may be actual hardware and human operators below the command level.

²⁷ Kaplan, *System and Process*, 19.

²⁸ *Rare Events*, JASON Report JSR-09-108 (McLean, VA: MITRE Corporation, October 2009).

- **Command.** This is composed of those individuals and organizations with hierarchical authority over the deterrence system and who actively participate in the decision-making with respect to nuclear deterrence in peacetime and in periods of alert.
- **Network architecture.** This is the blueprint by which the components are integrated with one another and with the command level. In the case of the multipolar system, there is no system command level; the integration is predominantly within each subsystem, and interaction channels are established among the subsystems' command levels.
- **Sociological representation.** This is the body of information that characterizes command-level actors in their respective subsystems: the breadth of choices in decision-making, the factors that may introduce cultural biases, and other factors.
- **Context.** This encompasses the cultural factors that influence inference of meaning in the semantics biases due to cultural and other factors. This also includes factors such as geographical advantages or difficulties for the movement and positioning of forces, economic ramifications, and non-nuclear-state neighbors.
- **Algorithmic representation.** This refers to the actual construction of mathematical rules for behavior, functioning, and communications among the nodes of the nuclear deterrence network.

These elements provide the basis for embarking on the search for a formal model of nuclear deterrence by which the quantified risk of failure of nuclear deterrence could be assessed.

Formal model development is the next step toward a goal of characterizing the risk of failure of nuclear deterrence. This must be considered as an exploratory process that could yield much insight into the problems of sociological response modeling and methods for establishing the existence of potential failure modes in a complex system. Because the feasibility of useful prediction of the risk of failure of nuclear deterrence is not yet established, it should prove useful first to investigate relatively simple system models. After the development of confidence in modeling capability, the resulting tools should return to the US nuclear deterrence system extant during the Cuban missile crisis and ask the question, What was the risk of failure of nuclear deterrence from the known close calls? The credibility of the answer will reflect on the credibility of the analysis.

Finally, we reiterate the importance of the relationship between the granularity or resolution of a model and the stability of predictions. It has not been established, nor is it obvious, that adding technical detail inevitably leads to a more accurate (i.e., less uncertain) result. If, in fact, predictions become more uncertain with increased fidelity, then the quantification of the risk of failure of nuclear deterrence will prove elusive, even with the insights developed here.

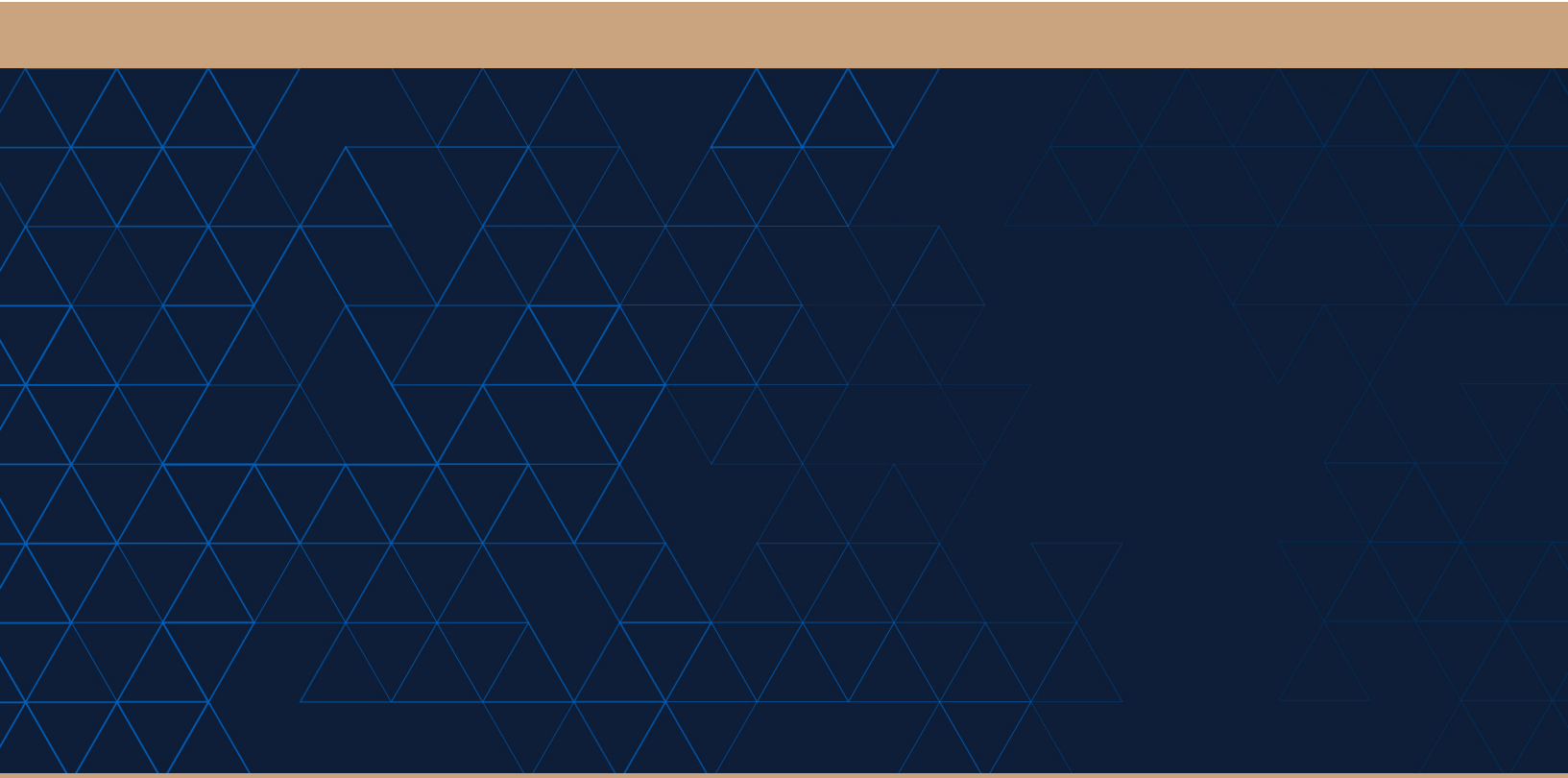
Acknowledgments

Appreciation and thanks are given to Michael Frankel, whose imagination spurred critical thinking about the formalism of the risk of failure of nuclear deterrence; to Andrew Bennett and Jane Booker, who facilitated early discussions of this project; to Max Crownover and Martin Hellman for constructive thoughts and reviews of previous drafts of this paper; and to David Lyle for his insightful commentary.

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