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Clausewitzian Friction and Future War

REVISED EDITION

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Institute for National Strategic Studies
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Clausewitzian Friction and Future War

Revised Edition

Barry D. Watts

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Preface to the Revised Edition

Since this paper first appeared in 1996, I have had little reason to doubt my original hypothesis that Clausewitzian friction is a basic structural feature of combat interactions between opposing polities. As General Tommy Franks said of the fighting at Takur Ghar, Afghanistan, during Operation *Anaconda* in 2002, "that battle showed heroism, it showed fog, uncertainty, it showed friction—elements common to every war I think we've ever fought." He is right; friction has been a consistent, recurring feature of wars, not only in our own time but also as far back as the wars of Greek city states and the Persian empire. The further realization that every actor in war—from polities and nations to individual combatants and military forces—are complex adaptive systems only underscores my central argument: friction is unlikely to be eliminated from future war regardless of technological advances.

Widespread debate over the power of technology to eliminate friction from war confirms that military theory in the United States is immature. Not only is a broad theory of war and combat lacking, our voluminous literature on technologies in particular wars offers little in the way of a defensible schema to explain the general role of technology in combat interactions. My working hypothesis is that technological advantages, like frictional ones, increase the options of their possessor in possibility space, decrease those of the opponent, or some combination of the two. If this hypothesis continues to escape decisive falsification—as I believe it will—it would certainly imply that progress toward a mature, empirically based theory of war is possible.

I suggest in the afterword to this paper that tools such as genetic algorithms and other applications of agent- and rule-based mathematics along the lines pursued by Andrew Ilachinski at the Center for Naval Analyses could help in this endeavor. I am also strongly inclined to adopt evolutionary biology as a better model for military theory than physics, whether classical or quantum. Regardless of whether these suggestions bear fruit, if war is about what F.A. Hayek termed *essentially complex* *phenomena* in his Nobel lecture, then our theories of war will seldom, if ever, permit us to predict precise outcomes with any certainty. Instead, we will be limited to Hayek's *mere pattern predictions*—that is, "predictions of some of the general attributes" of war's emergent structures, but "not containing specific statements about the individual elements of which the structures will be made up." This is an important caveat that military theory should emulate and one that is wholly consistent with the view that friction cannot be eliminated.

With regard to achieving a mature and sophisticated theory of war as a whole, however, it is doubtful that we have reached even the end of the beginning. Again, one must decide whether general friction will persist in future war or can be overcome by technological advances. That genuine disagreement persists on such a basic point suggests how far military theory must advance to achieve a solid empirical grounding.

In 1990, Colin Gray observed, "The U.S. defense community is not the beneficiary of a mature and sophisticated theory of war as a whole." Worse, most involved in military affairs in the United States seem quite content with this situation. Few in the Armed Forces are exercised over the dearth of theory—even when it is focused on coping with real-world problems. American officers have generally seen themselves as doers rather than thinkers and have usually disdained even applied theory.

Since 1996, the U.S. military has mounted three major combat operations: *Allied Force* in 1999, which sought to stop ethnic cleansing in Kosovo; *Enduring Freedom* in 2001–2002, which aimed at eliminating both the Taliban and al Qaeda from Afghanistan in response to the terrorist attacks on the World Trade Center and the Pentagon on September 11; and *Iraqi Freedom* in 2003, whose immediate goal was removing Saddam Hussein and his entourage from power. On the one hand, the performance of the American military during the major combat phases of these conflicts was exemplary, as it had been in Operation *Desert Storm* in 1991. In contrast to mediocre-to-poor performance from the Battle of Long Island to Ia Drang Valley, the U.S. military displayed levels of first-battle competence largely without precedent in prior American history.

On the other hand, the Taliban, al Qaeda, and Iraqis were not exactly first-rate military opponents, particularly in comparison with the German military of World War II. Moreover, the most troubling manifestation of general friction in America's most recent conflicts has been achieving long-term political ends *after* the cessation of major combat operations. The end state for *Iraqi Freedom* is a comparatively stable—at least somewhat democratic—and economically prosperous Iraq. Yet more than a year after major combat ended, it is far from clear how successful the United States will be in achieving its ends. As Antulio Echevarria of the U.S. Army War College wrote in March 2004, the dominant "American way of war tends to shy away from thinking about the complicated process of turning military triumphs, whether on the scale of major campaigns or small-unit actions, into strategic successes." The problem that he highlights is fundamentally a manifestation of friction. It involves the recurring difficulties of connecting ends and means in war—difficulties that for Clausewitz were a basic source of friction. Looking ahead to the global war on terrorism that could last a generation, I would hazard the prediction that more attention will have to be given to this particular component of general friction.

This revised edition was made possible by the Institute for National Strategic Studies (INSS), which expressed interest in reissuing this paper for students of military strategy. The Publication Directorate of INSS—George Maerz, Lisa Yambrick, and Jeffrey Smotherman—brought this edition to completion under the supervision of Robert A. Silano, Director of Publications. I want to thank them all for their hard work in producing this paper anew.

Bethesda, Maryland
July 2004

Preface to the First Edition

The original version of this paper, completed in December 1995, was condensed by Williamson Murray, editor of *Brassey's Mershon American Defense Annual*, for the 1996–1997 edition. This condensation did not include three entire sections that are part of this present study (chapter 3 on Scharnhorst's influence, chapter 6 on strategic surprise, and chapter 9, which contained air combat data bearing on the role of friction in future war). Dr. Murray also cut significant parts of other sections, especially in chapter 10, and precipitated a fair amount of rewriting as he and I worked toward a version that met his length constraint but still reflected the essence of the original paper. While this process led to many textual improvements, it did not generate any substantive changes.

The impetus for substantive changes came from Alan Beyerchen, of the Ohio State University, in May 1996. Dr. Beyerchen, a formidable student of both Clausewitz and nonlinear dynamics, raised an important issue concerning possible measures of general friction that harked back to Andrew Marshall's query in late 1995 as to whether general friction had been declining in recent decades. After much discussion, I added several pages of new material in chapters 5 and 9 that introduced decision-cycle times and viable option sets in "possibility space" as candidate measures.

These additions prompted others, primarily in chapter 10. Besides expanding and improving the treatment of nonlinearity, the discussion of chance was thoroughly revised in light of Poincaré's 1908 essay on the same subject, again after much discussion with Beyerchen.

By the time these changes had been completed, the condensation of the original paper for *Brassey's Mershon American Defense Annual* was far enough along that the best I could do was make its text consistent with the post-Beyerchen version. There was no room to incorporate substantive changes. Thus, the present text restores most of the original and goes a step beyond it conceptually; this is one reason why the Director of NDU Press, Dr. Frederick Kiley, elected to go ahead with separate publication of the

complete paper. Dr. Kiley and I then decided to modify the title of this longer version to make it distinguishable from a reference standpoint.

Lastly, a special word of thanks is due Andrew Marshall, the Director of Net Assessment since 1973. He encouraged this project from the outset and, as always, provided probing questions and invaluable suggestions at every step of the way.

Bethesda, Maryland
September 1996

Chapter 1

The Once and Future Problem

Since the end of the U.S.-Soviet Cold War, there has been growing discussion of the possibility that technological advances in the means of combat will produce fundamental changes in how future wars will be fought. A number of observers have suggested that the nature of war itself will be transformed. Some proponents of this view have gone so far as to predict that these changes will include great reductions in, if not the outright elimination of, the various impediments to timely and effective action in war for which the Prussian theorist and soldier Carl von Clausewitz (1780–1831) introduced the term *friction*. Friction in war, of course, has a long historical lineage. It predates Clausewitz by centuries and has remained a stubbornly recurring factor in combat outcomes right down to the 1991 Persian Gulf War and subsequent conflicts. In looking to the future, a seminal question is whether Clausewitzian friction will succumb to the changes in leading-edge warfare that may lie ahead, or whether such impediments reflect more enduring aspects of war that technology can but marginally affect. It is this question that the present paper examines.

Clausewitz's earliest known use of the term *friction* to "describe the effect of reality on ideas and intentions in war" occurred in a September 29 letter written to his future wife, Marie von Brühl, less than 3 weeks before France defeated Prussia at the twin battles of Jena and Auerstädt on October 14, 1806.[1] By the time Clausewitz died in 1831, his original insight regarding friction's debilitating effects on the campaign of 1806 had grown into a central theme of the unfinished manuscript that his widow published as *On War* [*Vom Kriege*].[2]

American military officers today most often refer to Clausewitz's unified concept of a general friction *(Gesamtbegriff einer allgemeinen Friktion)* as the "fog and friction" of war.[3] The diverse difficulties and impediments to the effective use of military force that those possessing military experience instinctively associate with this phrase are generally acknowledged to have played significant roles in most, if not all, the wars that have taken place since Clausewitz's time. Even in a conflict as inundated with technically advanced weaponry as the 1991 Gulf War (Operation *Desert Storm*), there was no shortage of friction at any level—tactical, operational, strategic, or even political. Indeed, close examination of *Desert Storm* suggests that frictional impediments experienced by the winning side were not appreciably different in scope or magnitude than they were for the Germans during their lightning conquest of France and the Low Countries in May 1940.

The historical persistence of friction, despite vast changes in the means of war since Clausewitz's time, suggests that his concept may reflect far more than a transitory or contingent feature of land warfare during the Napoleonic era. Yet, as we try to think about how war may change over the next couple decades in response to technological advances, nothing precludes us from wondering whether the scope or overall magnitude of Clausewitzian friction may change. Some U.S. military officers who have grappled with how future wars may be fought have suggested that foreseeable advances in surveillance and information technologies will sufficiently lift the fog of war to enable future American commanders to "see and understand everything on a battlefield."[4] Nor are visionary military officers alone in this speculation. During a 6-month assessment conducted by a Washington policy center on the prospects for a "military technical revolution" (MTR), the participants concluded that "what the MTR promises, more than precision attacks or laser beams, is . . . to imbue the information loop with near-perfect clarity and accuracy, to reduce its operation to a matter of minutes or seconds, and—perhaps most important of all—to deny it in its entirety to the enemy."[5]

These forecasts concerning conflict in the information age raise at least three first-order questions about Clausewitz's unified concept of a general friction. First, is it likely, contrary to what he probably thought, that general friction is a transitory, nonstructural feature of the violent interaction between contending political entities we call war and amenable to technical solutions? Second, even if friction is, instead, an enduring, structural feature of combat processes, can technological advances appreciably reduce the aggregate quantities of friction experienced by one side or the other in future conflicts? Third, do wars since Clausewitz's time, or foreseeable advances in the means of waging future wars, demand major modifications of Clausewitz's original concept? Alternatively, how might his original concept change if interpreted in light of contemporary knowledge—particularly from the standpoint of disciplines such as evolutionary biology and nonlinear dynamics?

The first task is clarifying Clausewitz's mature notion of general friction. To establish a common baseline for discussion, we will review the evolution of friction in Clausewitz's thought (chapter 2), and its origins in the intellectual clarity of his mentor and second father, Gerhard Johann David von Scharnhorst (chapter 3). Using this baseline, the taxonomy of Clausewitz's mature concept will then be clarified and extended (chapter 4).

The second task is to subject our baseline understanding of general friction to the test of empirical evidence. What does the Persian Gulf War suggest about the persistence of Clausewitzian friction (chapter 5)? And does the role of friction in that conflict provide any grounds for concluding that its potential role or "magnitude" has appreciably diminished since World War II?

The third task is examining the prospective role of friction in *future* conflicts. This task presents special problems insofar as direct evidence about wars yet to be fought is not possible. Instead, arguments for friction's undiminished persistence in future war will have to be constructed on the basis of related structural limitations in other areas. The discussion will aim, therefore, at establishing three conclusions by various indirect arguments. First, the prospects for eliminating friction entirely appear quite dim because friction gives every evidence of being a built-in or structural feature of combat processes.[6] Second, whether friction's overall magnitude for one side or the other can be appreciably reduced by technological advances is less important than whether such advances facilitate being able to shift the relative balance of friction between opponents more in one's favor. Third, recasting Clausewitz's concept in contemporary terms is a useful step toward better understanding its likely role in future war regardless of what one may conclude about the possibility of either side largely eliminating its frictional impediments.

What sorts of arguments and evidence might build a case for these conclusions? Before military conflict even begins, there is the apparent intractability of the prospect of strategic surprise, which offers a "precombat" parallel to general friction (chapter 6). The inaccessibility to central economic planners of all the information needed to run a national economy more efficiently than market forces driven by a myriad of individual choices reveals an economic friction comparable to that built into military organizations (chapter 7). The propensities and constraints built into humankind by biological evolution provide a wellspring for general friction that seems likely to persist at some level as long as *Homo sapiens* does (chapter 8). Finally, air combat data and related experimental evidence can be used to quantify, within a single area of tactical interaction, the degree to which the presence of man himself "in the loop" dominates engagement outcomes (chapter 9).

With these indirect arguments for general friction's relatively undiminished persistence in future war in hand, the final task is to exploit the modern notion of nonlinearity as a basis for reconstructing Clausewitz's original concept in more contemporary terms (chapter 10). Among other things, the contemporary understanding of nonlinear dynamics reveals how nonlinearities built into combat processes can render the course and outcome of combat unpredictable in the long run by repeatedly magnifying the effects of differences between our constructs of unfolding military operations and their actuality.

Chapter 2

Development of the Unified Concept

This chapter and the next recapitulate current scholarship concerning Scharnhorst, Clausewitz, and their concept of general friction. While this recapitulation does not go appreciably beyond what can be found scattered throughout *Clausewitz and the State* by Peter Paret and related works pertaining to the origins, development, conceptualization, and theoretical aspects of general friction, it is important to pull the main threads of the story together in one place to provide a baseline understanding of Clausewitzian friction on which to build.

Once again, Clausewitz's earliest known use of the term *friction* occurred in a September 29, 1806, letter to his future wife. Written while in the field with the Prussian Prince August's grenadier battalion, Clausewitz invoked *Friktion* to voice his growing anxiety over the resistance Scharnhorst (1755–1813) was encountering to any all-out, bold, or well-conceived employment of Prussia's full military potential against the French under Napoleon Bonaparte.[7] As Clausewitz observed to Marie von Brühl, the Prussian army at that time had "three commanders-in-chief and two chiefs of staff," a situation that provoked him to lament: "How much must the effectiveness of a gifted man [Scharnhorst] be reduced when he is constantly confronted by obstacles of convenience and tradition, when he is paralyzed by constant friction with the opinions of others."[8]

In hindsight, Clausewitz's anxiety was warranted. Prussia's defeats at the twin battles of Jena and Auerstädt destroyed the Prussian army created by Frederick the Great (1712–1786), and, after the remnants were defeated at the battle of Friedland in June 1807, led to the reduction of the independent state that Frederick had managed to thrust into the first rank of European powers into a mere satellite of the French empire.[9]

When Clausewitz first used *Friktion* in the 1806 letter to Marie, he could only guess, despite his forebodings, how the campaign would actually turn out. Thus, to read this first known reference to friction in its actual historical context, the term was introduced to refer to the powerful resistance to sound decisions and effective action that had developed *within* the Prussian army itself before the outcome of the war was known.

Over the next 6 years Clausewitz expanded this original notion, incrementally identifying other sources of the vast differences that he and Scharnhorst saw between theory, plans, and intentions in war and war as it actually is (*eigentliche Krieg*).[10] By 1811, Clausewitz's summary lecture at the Berlin war college on the use of detachments mentioned two distinct sources of what he termed "the friction of the whole machinery": "the numerous chance events, which touch everything" and "the numerous difficulties that inhibit accurate execution of the precise plans that theory tends to formulate."[11] The second source of friction mentioned in this passage—internal resistance to precise plans—recalls the type of frictional impediment in Clausewitz's 1806 letter to Marie. The first—the play of chance—represents a significant expansion of the original notion through the addition of a second major category or source of friction.

By April of the following year, shortly before Clausewitz resigned his Prussian commission to switch sides and oppose both his king (Frederick William III) and the French in Napoleon's 1812 invasion of Russia, he had pushed the concept even further. In an essay Clausewitz sent to the Prussian crown prince (later Frederick William IV), whom he had been tutoring in addition to his duties on the war academy faculty, Clausewitz listed eight major sources of the "tremendous friction" that makes even the simplest plans and actions so difficult to execute in war:

- insufficient knowledge of the enemy
- rumors (information gained by remote observation or spies)
- uncertainty about one's own strength and position
- the uncertainties that cause friendly troops to tend to exaggerate their own difficulties
- differences between expectations and reality
- the fact that one's own army is never as strong as it appears on paper
- the difficulties in keeping an army supplied
- the tendency to change or abandon well-thought-out plans when confronted with the vivid physical images and perceptions of the battlefield.[12]

This taxonomy exhibits some overlap, if not redundancy. It also lacks the conceptual clarity exhibited by Clausewitz's discussion of the unified concept of a general friction (*Gesamtbegriff einer allgemeinen Friktion*) in the final chapters of *On War*'s first book. Nevertheless, this expanded formulation goes well beyond the letter of 1806 and, according to Peter Paret, constitutes Clausewitz's first systematic development of friction, including its positive as well as its negative aspects.[13]

Insofar as Clausewitz's efforts to reach a scientifically valid (or defensible) understanding of *eigentliche Krieg* (war as it actually is) are concerned, friction remained an enduring theoretical concern.[14] Undoubtedly the challenges and frictions he experienced both with the Russian army in 1812 and during the last 3 years of the Napoleonic wars (1813–1815) "strengthened his already pronounced realism," thereby reinforcing his intellectual propensity to find a comprehensive way to "distinguish real war from war on paper."[15] Still, to realize how central a concern friction became for Clausewitz, we need look no further than the unfinished manuscript that his widow published after his death as *Vom Kriege*—a work that "almost completely" occupied the last 12 years of his life and has since overshadowed everything else that Clausewitz wrote.[16] Not only is the unified concept treated at length in chapters 5 through 8 of *On War*'s first book but it also, as Paret has observed, "runs throughout the entire work."[17]

Paret's judgment of general friction's central role in *On War* can be readily confirmed by considering the overall argumentative thrust of the book's opening chapter—the only one of the manuscript's 125 chapters that Clausewitz considered finished at the time of his death.[18] The chapter's title poses the question: "What Is War?" In response, *Vom Kriege* begins by trying to abstract the essence of war from its pure concept by establishing the properties that war must have to be what it is.[19] Reflection on the essence of the concept leads immediately to the conclusion that war is the use of force to compel the enemy to do our will. From this *theoretical* conclusion, it is a short step to the equally theoretical implication that, since war is an act of force, "there is no logical limit to the application of that force."[20]

The sixth section of chapter 1 ("Modifications in Practice"), however, juxtaposes this implication of pure theory with the empirical fact that in the real world "the whole thing looks quite different."[21] A series of short sections, whose titles alone indicate the inadequacy of purely theoretical conclusions about war, then argue the validity of this empirical modification of war's abstract essence. As the section titles declare:

7. WAR IS NEVER AN ISOLATED ACT
8. WAR DOES NOT CONSIST OF A SINGLE SHORT BLOW
9. IN WAR THE RESULT IS NEVER FINAL

10. THE PROBABILITIES OF REAL LIFE REPLACE THE EXTREME AND THE ABSOLUTE REQUIRED BY THEORY
11. THE POLITICAL OBJECT NOW COMES TO THE FORE AGAIN
12. ANY INTERRUPTION OF MILITARY ACTIVITY IS NOT EXPLAINED BY ANYTHING YET SAID.

The last section title introduces the problem of the suspension of activity often observed in actual war. Explaining how it can occur seemingly contrary to war's abstract essence occupies sections 13 through 20. All that need be said for present purposes concerning their content is that imperfect knowledge and chance are introduced as part of the explanation. With this difficulty in hand, Clausewitz's argument concludes as follows:

> If we now consider briefly the *subjective nature* of war—the means by which war has to be fought—it will look more than ever like a gamble. . . .
>
> In short, absolute, so-called mathematical factors never find a firm basis in military calculations. From the very start there is an interplay of possibilities, probabilities, good luck and bad that weaves its way throughout the length and breadth of the tapestry. In the whole range of human activities, war most closely resembles a game of cards.[22]

The pattern of argument in the opening chapter of *On War*, then, is one of contrast between military theories, plans, or intentions and war as it actually is. The role of general friction in Clausewitz's theoretical writings must be understood in this context. To repeat the oft-cited definition given in chapter 7, book one, of *On War*: The unified concept of a general friction alone "more or less corresponds to the factors that distinguish real war from war on paper."[23] The diverse sources of general friction are the things that render action in war "like movement in a resistant element" and "span the gap between the pure concept of war and the concrete form that, as a general rule, war assumes."[24]

From Clausewitz's first use of the term *friction* in 1806 to his final revisions of *On War* between 1827 and 1830, friction was unquestionably among the conceptual tools he employed to understand the phenomena of war. Friction was not simply a notion that Clausewitz toyed with from time to time. Rather, the idea of 1806 grew over the course of more than two decades into a theoretical concept that lies at the very heart of his mature approach to the theory and conduct of war.

Chapter 3

Clarity about War as It Actually Is

Today Clausewitz is widely credited with having introduced the notion of *Friktion* to refer to the impediments encountered in war. It is probably fair to say that he was the first to explore both the positive and negative aspects of general friction as a theoretical device for mediating the differences between war in theory and war in practice. Nonetheless, the concept has roots in the thinking of Clausewitz's mentor Scharnhorst. As with *On War* as a whole, it was Scharnhorst who "first showed him the right course."[25] This chapter explores Scharnhorst's influence on the Clausewitzian notion of general friction.

Scharnhorst began his military career with the Hanoverian army. Early recognition of his potential as a teacher resulted in his first 15 years of service with Hanover being largely devoted to the teaching of officers and military scholarship.[26] By the early 1790s, he had "established a reputation throughout the armies of central Europe as a knowledgeable and prolific writer on military subjects, inventor of improvements in gunnery, and editor of several military periodicals."[27]

During the campaigns of 1793–1795, which were part of the War of the First Coalition against the First French Republic, he quickly proved his competence under fire while serving with the armies of the allied monarchies that opposed France's expansion into Flanders and Holland.[28] At the battle of Hondschoote, in September 1793, Scharnhorst took control of several weakened Hanoverian units fleeing the battlefield and turned the impending rout into an orderly rear-guard action that helped to preserve the entire corps.[29] The following year, when the Hanoverian general Rudolf von Hammerstein was ordered to occupy the town of Menin in southern Belgium, Scharnhorst served as his principal staff officer. At Menin, Scharnhorst improvised a system of ditches and barricades that enabled the garrison of 2,400 men to repel several French assaults following encirclement by 20,000 troops under Jean-Victor Moreau. After rejecting a French offer of honorable capitulation, Hammerstein decided to save his force by breaking through the siege. Scharnhorst took command of a part of the corps to make the attempt and, on the night of April 30, 1794, succeeded against strong French opposition. Though Menin was lost as expected, the deliverance of "the garrison was seen by the Allies as a moral victory and became a feat of arms famous in the military chronicle of those years" in which Scharnhorst's contributions were fully recognized.[30]

After the campaigns of 1793–1795, Scharnhorst returned to Hanover and began to use "his recent experience to clarify his ideas about the revolution in warfare that was obviously taking place in Europe."[31] The changes in warfare to which Scharnhorst now began to seek a response were well summarized by Clausewitz in the final book of *On War*. From the emergence of modern standing armies during the period 1560–1660[32] to the French Revolution in 1789, European wars had been fought mostly for the aims of the monarch by professional armies whose officers were drawn from the nobility while their ranks were filled with conscripted peasants, press-ganged "volunteers," or mercenaries.[33] In the "diplomatic type of warfare" that came to dominate the pre-1789 era, the aggressor's usual plan was to seize an enemy province or two during the summer campaign season while the defender tried to prevent him from doing so; no battle was ever sought, or fought, unless it served to further the moderate or limited ends of one side or the other within the European balance of power; and such wars, being primarily the concern of the government, were estranged from the interests of the people.[34] When battles were waged, the focus of prerevolutionary armies on delivering the greatest possible concentration of firepower "produced linear tactics—the deployment of troops in long, thin lines blazing away at each other at point-blank range—which turned pitched battles into murderous set-pieces that commanders of expensive regular forces avoided if they possibly could."[35] Beginning in 1793, though, this age of diplomatic wars waged by professional armies for limited ends came to an abrupt end with the emergence of the French nation-in-arms.[36] As Clausewitz wrote:

> Suddenly war again became the business of the people—a people of thirty millions [in the case of revolutionary France], all of whom considered themselves to be citizens. . . . The people therefore became a participant in war; instead of governments and armies as heretofore, the full weight of the nation was thrown into the balance. The resources and efforts now available for use surpassed all conventional limits; nothing

> now impeded the vigor with which war could be waged, and consequently the opponents of France faced the utmost peril.[37]

The great peril posed by revolutionary France from 1793 to 1815 did not lie fundamentally in advanced weaponry or military technique—although the French armies of the period were second to none in artillery and "made ingenious use of the new flexible and dispersed infantry formations" which had been in development even before 1789.[38] The issue that came to occupy Scharnhorst by 1795 was more fundamental:

> How was it that this rabble, untrained, undisciplined, under-officered, its generals as often as not jumped-up NCOs [noncommissioned officers], with no adequate supply system, let alone any serious administrative structure, how did it come about that these . . . forces could not only hold their own against the professional soldiers of the European powers but actually defeat them?[39]

In response, Scharnhorst took full note of the advantages in strategic position, numbers, unified political and military command, and incentive that France had enjoyed over the allies of the First Coalition; he also delineated with objectivity and precision the superior effectiveness of French organization and tactics.[40] But beyond these military considerations he discerned a deeper reason for French success: the greater strength possessed by a freer nation, a condition that was closely connected with the transformation of French society stemming from the revolution and the emergence of the idea of nationhood.[41] By revolutionizing society, the French state "set in motion new means and new forces" which enabled the energies of society to be exploited for war "as never before."[42] As Howard explains:

> For manpower they depended not on highly trained and expensive regular troops but on patriotic volunteers and, later, conscripts in apparently unlimited quantities whose services were virtually free. The French troops foraged for themselves, and if they deserted there were plenty more to take their place. Insufficiently trained for linear tactics in battle, they substituted a combination of free-firing skirmishers and dense columns of attack, first to wear down and then to overwhelm a defence that was in any case likely to be badly outnumbered. And to these hordes of self-sacrificing infantry Bonaparte was to add artillery in ever increasing proportions, and cavalry trained in merciless pursuit.[43]

The upshot of Scharnhorst's analysis of the deeper reasons for French success, first published in 1797, was clear recognition of a revolution in military affairs driven primarily by social and political changes. Granted, as Jean Colin argued in 1900, this revolution was not without *any* technological component: the latter half of the 18th century saw improvements in artillery, road building, and cartography that undoubtedly abetted the rise of a new kind of warfare after 1789.[44] Still, on the whole, modern scholars agree with Scharnhorst and Clausewitz that the primary changes were social-political. If so, then the military revolution of the 1793–1815 period is quite different from the contemporary *hypothesis* that, in coming decades, ongoing advances in microelectronics, information technologies and software, satellite communications, advanced sensors, and low-observable technologies will give rise to a *technologically driven* revolution in warfare akin to the development of mobile, armored warfare (blitzkrieg) or strategic bombing during 1918–1939.[45] It is the strong technological component of the emerging military revolution that has given rise to the further conjecture that American commanders will be liberated from the tyranny of Clausewitzian friction in future wars.

Armed with a clear understanding of the social-political basis of French military power after 1789, the next question for Scharnhorst became: How could monarchies like Hanover or Prussia deal with the challenge of the French nation-in-arms? If the wellspring of France's military prowess was the emergence of the French nation, went Scharnhorst's answer, then the monarchies, too, had to turn themselves into nations. But "was it possible to create a Nation except, as the French had done, by the overthrow of monarchical institutions and the creation of a plebiscitary dictatorship ruling by terror?"[46] Scharnhorst's solution was to propose the modernization of Hanover's military institutions. He advocated better education of commissioned and noncommissioned officers, promotion to lieutenant by examination, the abolition of nepotism and favoritism, more sensible application of military justice, expansion and reequipment of the artillery, transformation of infantry tactics along French lines, institution of a permanent general staff, reorganization of the army into all-arms divisions, and the introduction of conscription to diminish the mercenary character of the army.[47]

These reforms clearly entailed important political changes in Hanoverian society. In this sense, the revolution in military affairs that confronted Scharnhorst was a greater challenge than the technologically driven changes in how wars are fought that confronted militaries around the globe between 1918 and 1939. The requirement of monarchies like Prussia to reform their societies as well as their armies suggests that counters to the Napoleonic revolution demanded more fundamental adaptations than the technology-driven changes in warfare that the American military may face in the decades ahead. In fact, the challenge of military transformation that the German monarchies faced after 1789 was more akin to the challenges of American economic strength and such military technical innovations as Assault Breaker and the Strategic Defense Initiative that the Soviet General Staff faced in the 1980s. While those American military innovations remained immature through the final decade of the Cold War, senior Soviet military leaders recognized that, without fundamental restructuring of the flagging Soviet economy, they had little hope of being able to hold up their end of the long-term military competition with the West.

As compelling as Scharnhorst's analysis of the transformational challenge posed by revolutionary France may appear to us today, he found little support in Hanover. The Hanoverian military was not persuaded of the need for fundamental reform in the military sphere, and no one in the government of George III wanted to risk testing the willingness of the Hanoverian aristocracy to defend its longstanding privileges. Instead, "Scharnhorst was disregarded as a visionary or ambitious troublemaker, and vacancies in the higher ranks continued to be filled with men who were no match for him."[48]

It was this turn of events that brought Scharnhorst to Berlin in the late spring of 1801. Though he had turned down the original offer to enter Prussian service, he subsequently reopened negotiations, and, when Frederick William III met his terms, Scharnhorst resigned his Hanoverian commission and accepted appointment as a lieutenant colonel in the Prussian artillery. Stationed in Berlin, he set about trying to enact his reforms in the army created by Frederick the Great.

One of the duties Scharnhorst assumed in his new role was to recast the Berlin Institute for Young Officers into a national academy.[49] Since Scharnhorst himself lectured on strategy, tactics, and the duties of the general staff at the school during his initial years in Prussian service, he soon came into contact with Clausewitz. The young officer quickly attached himself to Scharnhorst as an admiring disciple, "his own ideas germinating and sprouting in the rays of that genial sun," and Scharnhorst reciprocated with an equal affection for the brilliant and receptive young man.[50] When, in the spring of 1804, Clausewitz completed the 3-year course at the head of his class, Scharnhorst had already reported to the king, Frederick William III, that Lieutenant von Clausewitz exhibited, among other qualities, "unusually good analysis of the whole."[51]

Scharnhorst, 46 years old when he arrived in Berlin, was at the height of his powers. Despite the fact that his initial lectures at the Berlin war college still presented the traditional argument that theory should eliminate accident and chance from war, in practice Scharnhorst, with his pronounced sense of realism, "had long given up this belief."[52]

The humane, rationalist hope of late 18th-century military writers such as Henry Lloyd (1720–1783) and Dietritch Adam Heinrich von Bülow (1757–1807) was to find a set of "rational principles based on hard, quantifiable data that might reduce the conduct of war to a branch of the natural sciences . . . from which the play of chance and uncertainty" could be entirely eliminated.[53] Lloyd, who held important field commands in the Austrian army during the Seven Years' War (1756–1763), became well known in Europe for his criticism of Frederick II (the Great) as a strategist based on his purported application of scientific principles to the historical events of that conflict.[54] Foreshadowing the mathematical approach that would later be pursued by the English automotive engineer Frederick W. Lanchester,[55] Lloyd's enthusiasm for achieving certainty in war led him to argue that whoever understands the relevant military data stemming from things like topological and geographical measurements, march tables, supply needs, and the geometrical relationship of supply lines to fighting fronts (or of armies to their bases) would be "in a position to initiate military operations with mathematical precision and to keep on waging war without ever being under the necessity of striking a blow."[56] Bülow, an army officer by training but without command experience, took an even more strongly quantitative position in *Reine und angewandete Strategie* [*Pure and Applied Strategy*]. Published in 1804, it claimed that the success of a military operation depended largely on the angle formed by two lines running from the extreme ends of the base of operations to the objective: If the base of the operation was suitably placed and sufficiently extended for the two lines to converge on the target at an angle of 90 degrees or more, "victory was as certain as could reasonably be expected."[57]

While Scharnhorst covered these viewpoints in lectures he gave while Lieutenant Clausewitz was a student in Berlin during 1801–1804, Scharnhorst's own views about the art of war were quite different than those of Lloyd and Bülow. Especially during the period 1802–1806, when Scharnhorst concentrated on teaching and building a "true military academy," his lectures began to address a part of the art of war that, as Clausewitz later wrote in Scharnhorst's obituary, had been virtually ignored in

Prussian "books and lecture halls: war as it actually is."[58] Perhaps the best account of what Clausewitz was seeking is contained in a summary by Peter Paret of Scharnhorst's theoretical views:

> No military theorist of the time was as conscious as Scharnhorst of the innate conflict between theory and reality. His elaboration of this fundamental issue, and his refusal to seek its solution in increasingly complex abstractions, constitute the most important lesson he taught Clausewitz. . . . Rather than emphasize that sound theory could eliminate accident, which was obviously sometimes the case, it might be pedagogically more productive, he [Scharnhorst] thought, and far more realistic, to stress the ability of theory to help men deal with surprise, to help them exploit the unforeseen. From there it was only a short step . . . to recognize the fortuitous not as a negative but as a positive force, an indispensable part of reality.[59]

Clausewitz took this short-but-difficult step with the development of his unified concept of a general friction. General friction became the concept that mediated between abstract theory based on the analysis of pure concepts and the realities of late 18th- and early 19th-century warfare.

The mature concept of general friction was not, therefore, Clausewitz's invention alone. Its origins also had roots in the realism and clarity of his teacher Scharnhorst about war as it actually is, the limits of pure theory, and the impossibility of eliminating chance—a powerful source of general friction—from military operations. The positive aspects of the solution that Clausewitz reached to the play of chance in war deserve special emphasis. Where theorists like Lloyd and Bülow saw in chance impediments that needed to be constrained, if not eliminated, Clausewitz came to see opportunities that able, alert commanders could exploit.[60]

Chapter 4

The Mature Clausewitzian Concept

With the foundation provided by chapters 2 and 3, we can now complete the initial task of clarifying Clausewitz's mature notion of general friction. The account of the concept in *On War* contains two interlocking difficulties: the absence of a reasonably exhaustive taxonomy of general friction's various components or sources and the confusing use of the term *Friktion* to refer both to the unified concept and to one of general friction's components or sources. The easiest way to clarify, much less extend, Clausewitz's original concept is to resolve these difficulties, and the place to begin is with what Clausewitz calls "the atmosphere of war."

The first book of *On War* lists various things that, for Clausewitz, coalesce to form the atmosphere of war (*der Atmosphäre des Kreiges*):

Chapter 3:	Chapter 8:
danger	danger
exertion	physical exertion
uncertainty	intelligence
chance[61]	friction[62]

What do these lists represent? Ignoring for the moment the discrepancies in the last two places of both lists and the perplexing occurrence of "friction" in the second, the answer is that these lists detail various elements or sources of general friction. This interpretation can be readily confirmed by observing that danger, physical exertion, intelligence, and chance (construed as the countless minor incidents that one can never foresee) are all unambiguously identified in *On War* as sources or components of friction in the inclusive sense of the unified concept that distinguishes real war from war on paper.[63]

Next, can the apparent discrepancies in the third and fourth items in the two lists be resolved? As a prelude to answering this question, it is useful to review the detailed meanings Clausewitz attached to danger and physical exertion as sources of general friction. A close reading of chapter 4 in book 1 of *On War*, titled "On Danger in War," reveals that the phenomenon at issue consists of the debilitating effects that the imminent threat of death or mutilation in battle has on the ability of combatants at every level to think clearly and act effectively. Physical exertion is much the same: the extraordinary physical demands that combat so often makes on participants can quickly begin to impede clear thought or effective action. For a sense of what danger and exertion have meant even on late 20th-century battlefields, the reader need look no further than Harold Moore and Joseph Galloway's searing account of the battles fought by two air-mobile infantry battalions of the 1st Cavalry Division in the Ia Drang Valley against three North Vietnamese regiments during November 1965; or, for an equally searing account of armored warfare, the reader might wish to examine Avigdor Kahalani's description of the defense mounted by the Israeli army on the Golan Heights in October 1973.[64]

Turning to *intelligence* versus *uncertainty, On War* initially describes the former in terms of "every sort of information about the enemy and his country—the basis, in short, of our own plans and operations."[65] Further discussion, however, turns quickly to the uncertainties and imperfections that pervade the information on which action in war is unavoidably based. Among other things, imperfect knowledge of a combat situation can not only lead to mistaken judgments as to what to do, but also undermine one's resolve to act at all.[66] The seeming discrepancy between the third items in the two lists is, therefore, more apparent than real. Perhaps all that need be added from a contemporary perspective is that in light of the fundamental role uncertainty plays in fields like quantum mechanics and information theory, uncertainty is the deeper, more pervasive concept of the two. For this reason *uncertainty* seems the preferable term.

What about *chance* versus *friction* at the end of both lists? Here the discrepancy is more substantive. The opening paragraph of the relevant chapter in *On War* (book one, chapter 7, "Friction in War"), as well as the opening sentence of the third paragraph, seem to be about the unified concept of general friction, which Paret terms "the 'general concept' of friction"; by contrast, the second and fourth paragraphs—and all of the third save for the opening sentence—appear to focus on friction "in the narrow sense," which Paret interprets as "the impediments to smooth action produced by the thousands of individuals who make up an army."[67] Can one reconcile these apparently divergent aspects of general friction? In this case, they appear to be genuinely distinct. Friction in the narrow sense is certainly a robust source of resistance to effective action in war. It recalls the meaning Clausewitz originally attached to the term *Friktion* when he first used it in the 1806 letter written to Marie von Brühl before the battle of Auerstädt—a meaning that is reiterated toward the end of the third paragraph in chapter 7. However, it is not reasonable to equate this source of friction with chance in the sense of the unforeseeable accidents, the play of good luck and bad, that runs throughout the tapestry of war. Chance, understood as the countless accidents one can never foresee, is unquestionably a legitimate source of general friction, but seems quite distinct from friction in the narrow sense. This difference argues that chance (meaning fortuitous events rather than complete randomness) and friction (in the narrow sense) constitute distinct sources of general friction.

The analysis to this point suggests, therefore, replacing *On War*'s four-item lists with an expanded list containing five sources of general friction:

1. danger's impact on the ability to think clearly and act effectively in war
2. the effects on thought and action of combat's demands for exertion
3. uncertainties and imperfections in the information on which action in war is unavoidably based
4. friction in the narrow sense of the internal resistance to effective action stemming from the interactions between the many men and machines making up one's own forces
5. the play of chance, of good luck and bad, whose consequences combatants can never fully foresee.

Besides resolving the textual ambiguities about friction's various sources in *On War*, this list also tries to characterize each component in sufficient detail to make its role in war as clear as possible.

How complete is this taxonomy of general friction? If the general concept is construed as all the disparate things that distinguish real war from war on paper, it is not difficult to find other important and distinct sources of general friction in *On War*. Consider, once again, Clausewitz's argument from the first chapter as to why the actual conduct of war falls so far short of the maximum possible application of violence implicit in war's pure concept. One of the reasons Clausewitz gave concerns the spatial and temporal limitations to the employment of military force in the

Napoleonic era: "War does not consist of a single short blow." In an age of intercontinental, thermonuclear weapons, these *physical* limits may be considerably less than they were in Napoleon's day. Nonetheless, physical limits remain even with thermonuclear weapons, and to these physical limits must be added the *political* limitations of war's subordination to policy. In the final analysis, the political reason why nuclear weapons were not used during the Cold War was that American and Soviet policymakers alike came to realize that an all-out nuclear exchange between the two countries could serve no useful end.[68] Thus, physical and, above all, political limits to the unrestricted use of military force offer another source of general friction.

One can cull at least two more sources from the pages of *On War*. In book two, which discusses the theory of war, Clausewitz emphasizes the unpredictability of interaction with the enemy stemming from the opponent's independent will.[69] As will be suggested in chapter 10, unpredictability stemming from human decisions and interventions in the course of battle can be linked to chance in the sense of unforeseeable events. For now, though, it seems best to leave the unpredictability of interaction as a separate source of friction.

One further source of general friction can be found: Clausewitz's injunctions in book eight of *On War* that the *means* of war be suited to its *ends.*[70] Perhaps the most telling 20th-century case in point is the U.S. intervention in Vietnam. While the widely accepted view that the war was unwinnable entails a degree of determinism that is seldom warranted in human affairs, neither the firepower-intensive, "search-and-destroy" approach that the Army adopted under General William Westmoreland, with its misplaced focus on body counts, nor the incremental bombing of North Vietnam itself proved suitable means for building a viable South Vietnamese nation that would be capable of defending itself. As Scharnhorst said of the War of the First Coalition, "One side had everything to lose, the other little."[71] Given that Ho Chi Minh had calculated in the 1940s that he could beat the French if he lost only 10 of his own soldiers for every French soldier killed, much the same appears to have been true of America in Vietnam.[72]

With the three additional sources just sketched, one can give the following taxonomy for Clausewitz's "unified concept of a general friction [*Gesamtbegriff einer allgemeinen Friktion*]":

1. danger
2. physical exertion

3. uncertainties and imperfections in the information on which action in war is based
4. friction in the narrow sense of the resistance within one's own forces
5. chance events that cannot be readily foreseen
6. physical and political limits to the use of military force
7. unpredictability stemming from interaction with the enemy
8. disconnects between ends and means in war.[73]

This taxonomy clearly goes well beyond traditional and most contemporary readings of *Vom Kriege.*[74] Instead it suggests a view of general friction closer to what Clausewitz might have reached if he had lived long enough to revise *On War* to his satisfaction.

This paper began with three first-order questions about Clausewitzian friction:

1. Is it a structural feature of war or something more transitory?
2. Even if general friction cannot be eliminated altogether, can its magnitude for one adversary or the other be substantially reduced by technological advances such as those now anticipated in the information dimensions of future war?
3. What might Clausewitz's original notion look like if reformulated in the language and concepts of more contemporary disciplines like nonlinear dynamics?

The initial step toward answering these questions was to clarify Clausewitz's original concept, which we have now done. The next task, which will be the focus of chapter 5, is to present empirical evidence for general friction's persistence down to the present day.

Although we are not yet far enough along to offer full answers to the original questions about general friction, some preliminary insights can be drawn from the clarification of Clausewitz's general concept so far. Regarding the first question, Scharnhorst's and Clausewitz's staunch refusal to accept that any theories, systems, or principles of war could eliminate chance suggests that, in their view, friction was an inherent feature of violent conflict between nation-states. From the lowest-ranking soldier to generals and field marshals, friction was a force with which combatants on both sides had to cope.

Yet, turning to the second question, Clausewitz himself suggested various "lubricants" that could ease the "abrasion" or resistance that friction caused for one's own military operations. In *On War*, combat experience, maneuvers sufficiently realistic to train officers' judgment for coping with friction, and the genius of a leader like Napoleon are all mentioned as viable means of reducing general friction within one's own army.[75] The German general staff system's emphasis on individual initiative and judgment, for which Scharnhorst deserves considerable credit, constituted an institutional lubricant to general friction. And, as has been mentioned, there are at least hints in *On War* that elements like chance could provide opportunities to exploit friction's "equally pervasive force . . . on the enemy's side."[76] Thus, Scharnhorst and Clausewitz evidently believed that the relative balance of friction between two opponents could be manipulated to one's advantage, even if they were skeptical about driving up enemy friction as opposed to reducing one's own.

As for the third question, *Friktion*, like Clausewitz's notion of the opponent's center of gravity, was undoubtedly borrowed from Newtonian physics via Kantian concerns about how physics was possible as a body of knowledge. The first edition of Isaac Newton's *Philosophiæ Naturalis Principia Mathematica* [*Mathematical Principles of Natural Philosophy*], with which modern physics begins, appeared in 1687, and the core question of Immanuel Kant's *Critique of Pure Reason*, published in 1781, was *how* certain *a priori* synthetic judgments—like the equality of action and reaction in the exchange of motion,[77] which lay at the core of Newtonian physics—could be possible.[78] Clausewitz was familiar with these Newtonian and Kantian ideas and, even in *On War*, invoked the mechanistic image of the army as a machine whose internal friction "cannot, as in mechanics, be reduced to a few points."[79] Nonetheless, it is evident from the final list of general friction's sources developed in this section that, over time, his unified concept moved increasingly away from its mechanistic origins. Indeed, not one of the entries in the reconstructed taxonomy is inherently mechanical. Moreover, all of them, including chance, ultimately reduce to phenomena that affect the ability of human beings to think clearly and act effectively in war. Consequently, general friction may have more in common with 20th-century fields like nonlinear dynamics and the neo-Darwinian synthesis of evolution biology than first meets the eye.

Chapter 5

Friction and *Desert Storm*

Has general friction been a continuing feature of war since Clausewitz's time? If so, is there any evidence that the "magnitude" of its influence has changed appreciably in recent decades? A minimalist response would be simply to note that detailed campaign history since Napoleon has consistently and strongly confirmed general friction's persistence. In this regard, a colleague with many years of teaching experience at the National War College has observed that friction's persistence is the one Clausewitzian concept that most military officers—especially those from combat arms—instinctively embrace.[80] Indeed, friction is the one part of *On War* that uniformed students at American war colleges usually think they understand.

This minimal response, however, is unlikely to satisfy those lacking either firsthand experience with military operations or in-depth familiarity with the history of at least a few campaigns since Napoleon (particularly 20th-century military campaigns). Nor does it offer much insight into the possibility that the "magnitude" of general friction's influence on combat processes and outcomes may have changed over the years.

To furnish a more complete response to the questions about friction's role in recent times, therefore, this chapter will review evidence from the 1991 Persian Gulf War. Operation *Desert Storm* has been chosen for various reasons. First, when this paper was written, it was the most recent, large-scale conflict available. Second, coalition forces employed many of the most technologically advanced military systems in existence, including satellite communications and reconnaissance, direct-attack and standoff precision-guided weapons—for instance, Paveway III laser-guided bombs and the Tomahawk Land Attack Missile (TLAM)—and low-observable aircraft (the F–117). Third, having participated in the Gulf War Air Power Survey, the author is reasonably confident of having a solid grasp on what actually occurred during this 43-day campaign, particularly in the air.[81]

At the tactical level of the coalition air campaign, even the most cursory look at day-to-day operations suggests that there was no shortage of general friction. Aircrews had to cope with equipment malfunctions, inadequate mission-planning materials, lapses in intelligence on both targets and enemy defenses, coordination problems between strike and support aircraft (including a number of F–111F sorties aborted on the third day of the war because tankers for prestrike air refueling could not be found),[82] target and time-on-target changes after takeoff, unanticipated adjustments in prewar tactics, adverse weather, the traditional lack of timely bomb damage assessment, and, in many wings, minimal understanding of what higher headquarters was trying to accomplish from one day to the next. None of these problems was new under the sun in 1991. Indeed, the author personally experienced virtually all of them flying F–4s over North Vietnam during 1967–1968.

Elaboration of two examples from the preceding list should suffice to substantiate friction's seemingly undiminished pervasiveness at the tactical level of *Desert Storm*. After the initial 3 days of actual operations (January 17–19, 1991), coalition air commanders began to shift from low-altitude bombing operations to medium altitude in order to minimize further losses to Iraqi low-altitude air defenses, which consisted of large numbers of antiaircraft artillery (AAA) and infrared surface-to-air missiles (SAMs).[83] While this decision did not appreciably affect the accuracy of laser-guided bombs (LGBs) delivered from F–111Fs or F–117s already operating at medium altitude, it did degrade the visual-bombing accuracy of platforms like the F–16 and F/A–18 when pilots began releasing unguided bombs from altitudes well above 10,000 feet.[84] Since the F–16s and F/A–18s predominantly employed unguided munitions during *Desert Storm*, the persistence of this restriction until the coalition's ground offensive began on February 24 severely limited the ability of these aircraft to hit pinpoint targets such as bridges, fiber-optic cable junctions linking Baghdad to its forces in southern Iraq and Kuwait, or dug-in Iraqi armor.[85] Thus, in 1991, the combination of coalition sensitivity to losses, coupled with the impracticability of eliminating more than a fraction of Iraqi AAA and infrared SAMs, imposed an unexpected degradation in the visual bombing accuracy of coalition aircraft that persisted to the end of the campaign. During the Vietnam war, most air-to-ground bombing was done manually or with very early computerized bombing systems. As in 1991, staying high enough to avoid losses to low-altitude AAA systematically degraded bombing accuracies.

Adverse weather, which Clausewitz explicitly associated with friction in *On War*,[86] offers another unambiguous example of the frictional impediments to the execution of plans and intentions in *Desert Storm*. Adverse weather conditions substantially disrupted operations, especially during the early days of the air campaign and the coalition's ground offensive at the conflict's end. On the second and third nights of the war, more than half of the planned F–117 strikes were aborted or unsuccessful due to low clouds over Baghdad; on the second day of the ground campaign (February 25, 1991), all F–117 sorties were canceled due to weather.[87] So disruptive did the cumulative effects of adverse weather become to the air campaign that the coalition's head air planner, then-Brigadier General Buster C. Glosson, came to view it as his "number-one problem" and, by implication, as a greater impediment than the Iraqi Air Force.[88] Similar assessments of weather's disruptive effects on air operations can be found as far back as World War II. In reflecting on the Combined Bomber Offensive against Nazi Germany that he helped both to plan and execute, Major General Haywood Hansell observed in 1972 that "weather was actually a greater hazard and obstacle than the German Air Force" during 1942–1945.[89] In the case of adverse weather, therefore, it would probably be fair to say that it has consistently been a major frictional impediment to effective war in the air since the emergence of aircraft as a military weapon during World War I.[90]

Given the lopsided military outcome of *Desert Storm,* tactical-level friction was unquestionably far, far worse on the Iraqi side of the hill. If coalition air forces typically found themselves knee deep in various tactical frictions, the Iraqis drowned in it. In air-to-air combat, the Iraqi Air Force suffered 33 losses in exchange for a single coalition fighter believed to have been shot down by an Iraqi MiG–25 on the first night of the war.[91] So quickly did the Iraqis lose effective control of their own airspace that, over 43 days of fighting, they are known to have mounted only 2 air-to-surface attack sorties against coalition targets, and both of the Mirage F–1s involved were shot down prior to weapons release by an F–15 of the Royal Saudi Air Force.[92] The dominance of coalition air forces is, if anything, even more apparent in sortie comparisons between the opposing sides: by the end of *Desert Storm,* coalition fighter and bomber crews had flown over 68,000 shooter sorties—meaning sorties on which the aircraft involved carried air-to-air or air-to-ground munitions—to appreciably fewer than 1,000 by the Iraqis.[93]

In fairness, it should be said that the Iraqi Air Force was neither designed to deal with an adversary as large and capable as the coalition air forces it faced in 1991, nor did it seriously attempt to contest control of the air. Instead, the Iraqi Air Force seems to have hoped merely to impose some losses on its opponents' strike operations while riding out coalition airstrikes, if not the war, inside its hardened aircraft shelters.[94] Imagine, then, the shock—and friction—imposed on Iraqi squadrons when, on the night of January 22, 1991, coalition aircraft begin taking out individual shelters with LGBs.[95]

Coalition airpower imposed a similar shock on Iraqi ground forces. Saddam Hussein's strategy was not to rely on his air force for decisive results but, instead, to bank on his army being able to inflict enough casualties on coalition ground units that the allies would not be able to stand the pain; his model of future combat was the kind of bloody ground battles of attrition that had dominated the 1980–1988 Iran-Iraq war.[96] When, in late January 1991, Saddam Hussein ordered the probing attacks that precipitated the Battle of Khafji, he assumed that Iraqi ground forces could move at night despite the presence of coalition airpower. This assumption, however, proved disastrously wrong on the night of January 30. When an E–8 Joint Surveillance Target Attack Radar System (JSTARS) detected at least two Iraqi brigades on roads in eastern Kuwait trying to move south, coalition airpower proceeded to inflict such destruction that both units were stopped before they could even reach the Saudi border.[97] Further, while the inability of Iraqi ground forces to move even at night in the face of coalition airpower was a tactical issue, it had profound implications for Iraqi strategy. In retrospect, Saddam Hussein's only viable military option after *Desert Storm* began was to force an early start to a ground war of attrition, before his own ground forces were exhausted, in the hope that sending enough coalition soldiers home in body bags might shatter the coalition or turn American public opinion against the war. That this gambit failed in late January and was never attempted again not only shows how much coalition airpower dominated the military outcome of this conflict, but illustrates that unexpected frictional impediments can have operational and strategic consequences as well.

This last point suggests that Iraqi friction was far higher than the coalition's not only at the tactical level but at the operational and strategic levels of the campaign as well. In this sense, general friction's manifestations go far to explain both the failure of Iraqi strategy in the Gulf War as well as the lopsided military outcome. Understandably, these observations may tempt the reader to conclude that coalition forces encountered little, if any, friction at the operational and strategic levels. Although coalition friction was certainly less at these levels as well, it was by no means absent.

Consider coalition efforts during the Persian Gulf War to destroy the Iraqi nuclear program. The coalition's publicly stated goal of promoting the "security and the stability of the Persian Gulf" provided the political basis for trying to eliminate this program with military means.[98] By the eve of *Desert Storm,* destruction of Iraq's nuclear, chemical, and biological warfare capabilities, including research, production, and storage facilities, had become an explicit objective of the air campaign.[99] Indeed, these capabilities were identified by U.S. Central Command in the operations order for the campaign as one of Iraq's "three primary centers of gravity."[100]

In the case of Iraq's nuclear program, destruction was predominantly a postwar rather than a wartime objective since coalition commanders, air planners, and intelligence correctly believed that the Iraqis had not yet fielded even a crude nuclear device. Targeting of the program during *Desert Storm,* therefore, aimed at inflicting enough destruction on nuclear-related facilities that it would take many years for the Iraqis to reconstitute a viable development effort able to produce operational nuclear weapons.[101]

This seemingly straightforward targeting problem foundered not only on inadequate intelligence about individual targets but, more importantly, on coalition misunderstanding of the target system as a whole. The difficulties went much deeper than failing to identify even half of the geographic locations containing nuclear or nuclear-related facilities by the final days of the war.[102] The nature and operation of the Iraqi nuclear program were not understood.

In 1976 the Iraqis had struck a deal with the French to supply 2 nuclear reactors, the larger being a 70-megawatt (thermal) reactor that the French dubbed Osirak and Saddam Hussein named *Tammuz* to honor the month in the Arabic calendar during which his Ba'th party came to power in 1968.[103] When oil-rich Iraq began subsequently acquiring large amounts of uranium ore concentrate (yellowcake) neither subject to international safeguards nor directly usable as fuel, the possibility arose that once Osirak came on line it would be used to irradiate yellowcake, which, if reprocessed, would begin yielding weapons-grade plutonium.[104] This alarming prospect provoked the Israelis to plan a preemptive strike against the Osirak reactor at Al Tuwaitha, about 25 miles southeast of Baghdad, before it became operational.[105] The attack was carried out by Israeli fighters on Sunday, June 7, 1981, and Osirak was not subsequently rebuilt.

While it was generally believed in the West that Iraqi efforts to acquire nuclear weapons went mostly dormant for at least the next 5 or 6 years, the truth of the matter was quite different. The picture eventually pieced together by international inspectors in the months after *Desert Storm* ended was that the Iraqi response to the Israeli raid had been to redesign the program to minimize its vulnerability to accurate bombing. Realizing that the reactors necessary to produce plutonium in the quantities needed for nuclear weapons presented large, fixed targets that were as vulnerable to destruction as Osirak had been, the Iraqis altered the nature of their nuclear program; instead of pursuing plutonium weapons, they shifted to enriched uranium.[106] In short order the Iraqis embarked on a clandestine, lavishly funded, and highly redundant program that included three parallel tracks for uranium enrichment: electromagnetic-isotope separation using calutrons; chemical enrichment; and gaseous-centrifuge enrichment.[107] At the same time, they instituted a range of measures to hide what they were doing from the outside world. These measures included orchestrated deception of International Atomic Energy Agency inspectors, extensive concealment and dispersal, compartmentalization, and the use of middlemen and front companies to import needed elements from foreign sources; even the construction of decoy facilities became part and parcel of this national-level program.[108] In retrospect, this redesign of Iraqi efforts to acquire nuclear weapons succeeded. Through the final days of *Desert Storm,* the nature, scope, and detailed operation of Baghdad's nuclear program were never understood by coalition commanders and military planners.

As a result, coalition air forces were unable to target the Iraqi nuclear program effectively during *Desert Storm,* much less destroy it. Even with laser-guided bombs, aircrew still have to know where to aim and at what they are aiming. To compound further the frictional impediments coalition airmen encountered with this target system, the Iraqis displayed a surprising capacity to evacuate, further disperse, and hide program elements, including nuclear material, once the campaign began.[109] The upshot was that while Iraqi work on nuclear weapons was halted by *Desert Storm* and many program elements were damaged or dispersed, the coalition failed to achieve its operational objective of eliminating Iraq's nuclear program. The crux of this failure, moreover, lay in textbook manifestations of Clausewitzian friction: coalition failure to grasp the nature of the target system reinforced by prodigious Iraqi efforts to conceal its nuclear ambitions from the outside world.[110] Admittedly, the magnitude of the coalition's military success by February 28, 1991, created a postwar situation in which the political goal of limiting Iraq's threat to its regional neighbors was later achieved by perhaps the most intrusive compliance regimes imposed on a sovereign nation since the occupations of Nazi Germany and imperial Japan following World War II. But what one cannot deny is that general friction prevented coalition forces from achieving their stated operational and political goals regarding Iraq's nuclear-weapons program during *Desert Storm*.[111]

One can draw much the same conclusion regarding the coalition's operational goal of "destroying" Iraq's Republican Guard forces, which were also identified by the theater commander, General H. Norman Schwarzkopf, as a primary center of gravity. Despite U.S. Army doctrinal emphasis on synchronization, the planned timing between the Marine-led holding attack in the east, whose objective was to reach Kuwait City, and the multi-corps "left hook" from the west, which aimed at destroying the Republican Guard, was substantially out of "synch." Third Army's VII and XVIII Airborne Corps were to take "seven to ten days" to execute the left hook and destroy the Republican Guard, whereas the Marines, informed by what they learned of actual Iraqi capabilities from the fighting around Al Khafji in late January 1991, replanned their attack to reach Kuwait City within 3 days and, in the event, made that timeline.[112] To make matters worse, when the coalition's ground offensive kicked off around 0400 hours on February 24, 1991, Third Army initially stuck with its original plan of delaying the advance of the heavy units in XVIII Airborne and VII Corps for 24 hours.[113]

As early as 0840, however, Schwarzkopf received reports of Iraqi demolitions in Kuwait City indicative of withdrawal preparations and called Lieutenant General John Yesock, the Third Army commander, to obtain his views on scrapping the original timetable and attacking early with the heavy forces.[114] The attacks of the heavy units in XVIII Airborne and VII Corps were then moved up to 1500 hours on the 24th. Nonetheless, the time lost soon became impossible to make up, especially in the case of VII Corps. As darkness approached on February 24, the VII Corps commander, Lieutenant General Frederick Franks, after consulting with his three division commanders about the wisdom of pressing ahead through the night, elected to stop his advance until daybreak the following morning.[115] Regardless of the reasons for this decision, it did not reflect the theater commander's intent. As the Third Army historian later wrote: "A gap had begun to open between the tactical operations Franks was fighting in the field and the operation Schwarzkopf envisioned in the basement of the Ministry of Defense [in Riyadh]."[116]

This frictional gap continued to widen as the ground offensive unfolded. Indeed, by the fourth day of the campaign "Schwarzkopf did not know where his leading forces actually were."[117] It would be going too far to argue that this single gap between intentions and actuality in the Gulf War explains why Iraq's armored forces and Republican Guard were not completely destroyed despite the immense tactical success of the coalition's 100-hour ground offensive.[118] Another important source of friction bearing on this outcome was the gap between the belief of key coalition ground commanders that the Iraqis would stand and fight and what the Iraqis actually did: begin a wholesale withdrawal from the Kuwait theater of operations on the night of February 25.[119]

These two frictions, in turn, were compounded by a number of others. The coalition's 100-hour ground offensive occurred in some of the worst weather of the campaign. Because none of the Iraqi armored and mechanized units in the theater ended up fighting from the positions they had occupied prior to February 24,[120] considerable uncertainty developed within XVIII Airborne and VII Corps as to their locations by February 26. Further, there was no time in an operation that ended in 100 hours to calibrate the accuracy of reporting up the chain of command by those doing the fighting. More crucially, coordination problems between soldiers and airmen, especially on February 27, undermined the effective use of fixed-wing aviation to prevent the escape of Iraqi armored forces that, in October 1994, would again require deployment of American forces to the Persian Gulf. On top of these impediments, Army commanders basically stuck with their original plan of trying to destroy the Republican Guard forces by smashing headlong into them with a multidivision phalanx of armored and mechanized units rather than first encircling the Iraqi forces and then reducing them at the coalition's leisure.[121] This operational concept, which emphasized synchronization between units aimed at presenting no flanks, was a doctrinally driven preference very different from the practices of leading armored commanders in World War II such as Heinz Guderian, Hermann Balck, and John Wood.[122] In Clausewitzian terms, this preference for synchronization focused above all else on minimizing the internal friction of one's own military "machine." As such, it exemplifies friction in the narrow sense and harks back to Clausewitz's first-known use of the term *Friktion* in 1806.

The picture that emerges regarding friction in the 100-hour coalition ground offensive, then, is one of multiple frictions overlaid on top of one another, with several growing worse as the offensive unfolded. From this perspective, the *cumulative* weight of friction appears more than adequate to explain how and why coalition commanders failed to achieve their operational objective of destroying the Republican Guard. General Schwarzkopf implied in his postwar book that his intention had been to inflict sufficient destruction on Republican Guard units that they would no longer be "a threat to any other nation."[123] The return of additional U.S. forces to the Gulf when T–72-equipped Republican Guard forces that had escaped destruction in 1991 again menaced Kuwait in October 1994 demonstrates that this goal was not achieved during *Desert Storm*.[124] Thus, despite the coalition's enormous military success, it is evident that general friction had operational, if not strategic, effects even on the coalition's side of the hill.

In sum, scrutiny of Operation *Desert Storm* reveals that Clausewitzian friction persisted at every level of the campaign. Even for the coalition, general friction had operational and strategic consequences, not merely tactical effects. Moreover, none of the specific frictional impediments documented—from adverse weather and faulty intelligence to the Army's doctrinal infatuation with synchronization—would be unfamiliar to Clausewitz or Scharnhorst. Every impediment discussed in this section can be understood in terms of the list of general friction's sources at the end of chapter 4.

What about the overall magnitude of general friction in 1991 compared to earlier conflicts in this century? The most relevant quantity for comparison would be the differential between coalition friction and Iraqi friction. How might this frictional imbalance between opponents compare with imbalances during campaigns from the Vietnam period, the Korean War, or earlier?

The immediate problem, of course, is finding some way of gauging or measuring the required differential on a scale that is comparable over periods of decades, if not longer. Unfortunately, especially at the operational and strategic levels, no such metric readily springs to mind. Indeed, setting aside recurring claims from at least some operations researchers and military modelers to have captured everything important about combat in their equations, the author is not aware that such an overarching metric has ever been seriously proposed, and for obvious reasons. The considerable difficulties of constructing such a metric are apparent in the final taxonomy of general friction's various sources or components presented in chapter 4. What single metric could quantify the frictional imbalance between two sides stemming from things as diverse as danger, uncertainties in the information on which action in war is based, chance, physical and political limits to the use of military force, and disconnects between ends and means in war? Further, given the enormous advances in the means of combat during the 20th century, would the frictional imbalance between coalition and Iraqi forces during the initial 2 days of *Desert Storm* be comparable with that evident during the battles of Jena and Auerstädt on October 14, 1806? One suspects that merely describing such a metric—even if just in qualitative terms—would be hard given the likelihood that frictional imbalances could fluctuate considerably over the course of any actual campaign. Precisely measuring such imbalances in specific historical cases on a scale applicable to earlier or later conflicts would, almost certainly, be even harder.[125]

Do these difficulties mean that nothing can be said about the relative magnitude of general friction over the course of recent decades? Intuitively at least, detailed examination of the relevant campaign history suggests that the frictional differential between victor and vanquished in 1991 was not appreciably different from what it was during the German blitzkrieg across the Low Countries and France in May 1940. These two campaigns, separated in time by just over a half century, are perhaps as comparable in scale and duration as most that could be selected from the 20th century. Both produced lopsided blowouts in which the winning side's friction was palpably less than the loser's.[126] Yet, in each case, friction at the operational and strategic levels also caused the winning side to fall short of all it might have achieved in ways that had long-term consequences: in 1940 some 338,000 Allied troops, mostly British, escaped from Dunkirk harbor and the surrounding beaches to fight another day, much as happened with elements of Iraq's Republican Guard in 1991.[127] Thus, from 1940 to 1991 it seems initially plausible not only to suggest that friction persisted, but also to speculate that it persisted relatively undiminished in "magnitude."

Can we put some substance behind this speculation? Logically, it presumes that these well-matched historical cases contain features or dimensions that do, in fact, provide rough measures of the relative balance of friction between the opposing sides.[128] Can any such measures be suggested, even if they elude precise quantification? The details of these campaigns offer two candidates: "decision-cycle times" and what will be termed "option sets in possibility space." To be stressed is that these candidate metrics do not purport to be universally applicable or to capture more than aspects of general friction. Instead, they are intended to indicate the direction in which such metrics might be sought.

In the case of the blitzkrieg in May 1940, a feature that gives some insight into the frictional imbalance between opponents is the degree to which Germans quickly achieved a temporal advantage of days between their pace of offensive execution and the Allied responses. By pushing the main attack, including the bulk of German armored forces, through the "impassable" Ardennes where the Allies least expected it, the Germans got an early temporal advantage. French intelligence was unable to identify the main German attack, and as late as the morning of May 13—the third day of the campaign and only hours before XIX Panzer Corps under Heinz Guderian crossed the Meuse River around Sedan—French commanders and analysts continued to believe that the main attack would be to the north through central Belgium.[129] Once across the Meuse, Guderian in particular elected to "press forward with less than two-thirds of his forces and without regard for enemy actions against his flanks."[130] Hence, the armored breakthroughs were exploited at a pace that only widened the temporal gap between German actions and Allied responses. Consequently, the "cycle times" of successive German decisions began to fall further and further inside those of the French and British. By the time the leading German spearheads began pivoting to the west and the Channel coast on May 15, this temporal gap in decision-cycle times between the two sides had grown to the point of being comparable to a chess game in which one side is allowed two moves for every one taken by the opponent.

Many of the same patterns are evident in *Desert Storm*. As was true of the Allies in 1940, the Iraqis were surprised about the direction of the main coalition ground offensive. During the preceding 39 days of unrelenting air attack, the Iraqis evidently developed no inkling that the coalition was moving two entire corps hundreds of miles to the west to form the main attack. And, once the coalition's ground offensive started, Iraqi ground forces were, at best, only able to move in slow motion compared to the pace of coalition units—much as happened to French and British ground units in May 1940 compared to the speed with which panzer units advanced. In the chess analogy, the Iraqis' situation during

February 24–28, 1991, is perhaps best compared to a game in which coalition ground forces were allotted two, or possibly even more, moves for every Iraqi one and the Iraqis were only able to "see" the location of coalition "pieces" when they actually attacked Iraqi units. Thus, in terms of decision-cycle times, the frictional imbalance between opponents in 1991 appears, if anything, to have been slightly larger than in May 1940.

Decision-cycle times, though, address only a slice of general friction. A somewhat broader, but by no means comprehensive, indicator of the relative balances of general friction in 1940 and 1991 is the notion of options (or option sets) in possibility space, meaning the aggregate of viable moves available to each side over the course of these two campaigns. In both instances, the set of viable options available to the eventual victor was probably larger than that available to the eventual loser at the outset of offensive operations. Further, over the course of the two campaigns, viable options for the Allies in 1940 and the Iraqis in 1991 contracted rapidly and substantially compared, respectively, to those of the Germans and the U.S.-led coalition.[131] In a matter of days from the beginning of large-scale combat, the losing side's best remaining option had been reduced to salvaging as many soldiers and as much military equipment from the theater as possible, strategic defeat having become unavoidable. Indeed, since the Iraqis had more initial latitude to negotiate their way (and their forces) out of the theater of operations without surrendering national sovereignty than did the French, Dutch, and Belgians in May 1940, the differential in viable option sets may have been *less* during the first 3 weeks of *Desert Storm* than it was at any stage of the 1940 campaign.

Decision-cycle times and options in possibility space, then, do seem to furnish conceptual metrics that enable one to compare, if but roughly or incompletely, the magnitude of frictional imbalances between opponents in May 1940 and January-February 1991. In the case of decision-cycle times, one could even envision quantifying the imbalance at specific stages of these conflicts in hours or days. What about option sets in possibility space? Might they be similarly quantifiable? On the one hand, viable options in possibility space appear to be the more general of the two "measures." On the other, the notion of viable options in a multidimensional "possibility space" is probably not amenable to being captured by a single number. Instead, estimates of attractive options over time would almost surely require a more complex mathematical object. As Alan Beyerchen has speculated, the frictional imbalance between adversaries at any point may be better envisioned as a dynamic shape in a multidimensional "phase space"[132] rather than as any single number or value.[133] That said, it is not at all obvious that the differential in option sets was greater in 1940 than in 1991.

Again, the two metrics just discussed do not purport to be universally applicable or to encompass all imaginable manifestations of general friction. They were drawn from two very similar campaigns. They were not intended to solve the problem of quantifying the relative frictional imbalance between opposing sides, but to indicate the direction in which progress might be possible, thereby giving some substance to the intuition that the magnitude of such imbalances has not changed greatly over the half century.

To recapitulate the argument so far, two of four tasks have been completed: clarifying Clausewitz's concept of general friction, and confirming its persistence as a factor in combat outcomes as recently as 1991. The exposition will now turn to the third and most daunting task: to build a case for general friction's relatively undiminished persistence in *future* war.

Chapter 6

The Intractability of Strategic Surprise

Granting that Clausewitzian friction prevented coalition forces from achieving important operational-strategic goals despite the lopsided outcome of *Desert Storm*, why should one take the next step and infer that technological advances in the future will be unable to find any enduring solution to the historical problems of friction? The direct evidence just presented of general friction's evidently undiminished persistence as recently as 1991 is of little avail regarding friction's *future* role under the premise of technological progress. Direct, empirical evidence from wars still to be fought, after all, is unobtainable. Nonetheless, reasons can be found in fields as diverse as economics, evolutionary biology, and nonlinear dynamics for suspecting that many real-world processes, including physical ones, can exhibit structural unpredictability.[134] Since this sort of inherent unpredictability seems to be part and parcel of what Clausewitz subsumed under his *Gesamtbegriff einer allgemeinen Friktion*, confirmation of similar, if not related, unpredictabilities in fields far from war would begin to build a case for the conclusion that Clausewitzian friction will persist regardless of technological progress. The case built on the ubiquity of unpredictable processes will not, of course, be a direct one. Like evolutionary biologists, who cannot directly observe the workings of natural selection, we shall have to rely on *indirect* arguments.[135] The first of these indirect arguments arises from considering the prewar problem of avoiding strategic surprise.

The attack on Pearl Harbor transformed the problem of strategic surprise into a deeply personal experience for an entire generation of Americans.[136] The horrific consequences of a surprise Soviet nuclear attack on the United States, which was a constant feature of the four-decade Cold War between the United States and the Soviet Union, reinforced the primacy of this problem for another generation. Yet, notwithstanding all the efforts that American leaders, defense analysts, intelligence experts, and military planners have put into "solving" the problem of strategic surprise, the literature on the subject, as well as history since 1941, suggests that the problem is intractable.

The classic 20th-century account of how strategic surprise can occur despite a wealth of intelligence on enemy actions and intentions remains Roberta Wohlstetter's 1962 study of the surprise attack on the American fleet at Pearl Harbor on December 7, 1941. "Never before," she concluded after sifting through the sources available to the American Government during the months preceding the attack, "have we had so complete an intelligence picture of the enemy."[137] The available "signals"—meaning clues, signs, or other pieces of evidence about Japanese moves or intentions[138]—were abundant. An American cryptanalyst had broken the top-priority Japanese diplomatic code (known as MAGIC), allowing the U.S. Government to listen to a large portion of the privileged communications between Tokyo and major Japanese embassies such as Berlin, Rome, and Washington; cryptanalysts had also achieved some success in reading the codes used by Japanese agents in major American cities and ports; American naval leaders possessed traffic analysis on Japanese naval and military codes; extremely competent on-the-spot political and economic analysis was furnished by the U.S. Embassy in Tokyo; additional classified information was provided by British intelligence (although there was a tendency at this stage among both the British and Americans to distrust each other's privileged information); and there were various unclassified sources of information, including very accurate reporting and predictions on the Japanese political scene by the overseas correspondents of several major American newspapers.[139] "All that we lacked was the date of December 8 [Tokyo time], a precise list of targets, and—most important—an ability to estimate correctly Japanese desperation and daring."[140] Yet, despite this plethora of information, the Japanese attack on Pearl Harbor "was in fact a complete surprise to the United States."[141]

How could so complete a surprise occur in the presence of such a rich array of signals? Wohlstetter responded that both the relevant signals, as well as the meaning that came to be attached to them *after* the Japanese attack, were embedded in an atmosphere of "buzzing and blooming confusion" or "noise" that made their identification and interpretation extremely difficult and uncertain given "the very human tendency to pay attention to the signals that support current expectations about the enemy."[142] In 1941, this phenomenon of background noise went far beyond the "natural clatter of useless information and competing signals." The attack on Pearl Harbor was preceded by previous alerts that turned out to be false alarms that numbed subsequent reactions to further signals of potential danger; American attention in Hawaii focused more on sabotage than attack due to the prevailing hypothesis of a probable Japanese attack on Siberia; and the Japanese were successful in concealing certain key signals while introducing misleading ones into American collection systems.[143] As for the issue of understanding the meaning of the signals that were (in retrospect) relevant, American assessments of the Japanese ability and willingness to accept the risks of an attack on the U.S. fleet at Pearl Harbor were quite different from those that the Japanese in fact embraced in their war planning and decisionmaking.[144] Thus, even if the right signals could have been identified amid the surrounding noise, it is far from obvious that they would have been correctly understood at the time.

The most telling example of the collective difficulties was the arrival in Manila, some 9 to 10 hours before Japanese aircraft struck there, of the message that Pearl Harbor had been attacked. Although the significance of this signal seems crystal clear in retrospect, at the time it failed to provide "an unambiguous signal of an attack on the Philippines."[145] Among other reasons, American commanders in the Philippines did not respond with alacrity to the signal on the presumption that the Japanese did not have the means for an immediate air attack. The Japanese Zero fighter was believed by American intelligence—mistakenly it turned out—to lack the range to reach U.S. airfields in the Philippines from land bases on Formosa; and the alternative, using carriers, was ruled out because all six of Japan's large carriers were presumed—correctly in this case—to have been committed to the attack on Pearl Harbor.[146] "There is a difference, then, between having a signal available somewhere in the heap of irrelevancies, and perceiving it as a warning; and there is also a difference between perceiving it as a warning, and acting or getting action on it."[147]

From such discouraging evidence and observations, Wohlstetter concluded that the problem of avoiding strategic surprise was essentially intractable:

> [W]e have found the roots of . . . surprise in circumstances that affected honest, dedicated, and intelligent men. The possibility of such surprise at any time lies in the conditions of human perception and stems from uncertainties so basic that they are not likely to be eliminated, though they

might be reduced. . . . The precautions of secrecy, which are necessary even in a democracy to keep open privileged sources of information, may hamper those who have the power of decision. Moreover, human attention is directed by beliefs as to what is likely to occur, and one cannot always listen to the right signals.[148]

Has subsequent experience with strategic surprise revealed credible reasons for questioning Wohlstetter's implication that the problem may be intractable? From an evidentiary standpoint, the historical record is clear: strategic surprise, like general friction, has continued to recur despite prodigious efforts by governments and intelligence services to avoid it. In 1973, for instance, the Israeli government was as surprised by timing, place, and method of the coordinated Egyptian-Syrian attack on the morning of October 6 as the Russians had been by the Nazi invasion of June 22, 1941 (Operation *Barbarossa*).[149] Worse, U.S. intelligence, though aided by such technical advances as satellite reconnaissance, was every bit as surprised by the Arab attack in 1973 as the Israelis were.[150] Much as in 1941, a number of relevant signals were received, but the "buzzing and blooming" noise, reinforced by active and successful Arab deception, obscured their significance while various explanatory hypotheses for the Arab force build-ups being observed so complicated interpretation that, as late as October 5,"no [Israeli] national-level leader thought that war was imminent."[151] A similar picture of the problems of warning and decision emerges from a careful review of the noise, wishful thinking, ingrained hypotheses, and ambiguities of meaning that obscured Saddam Hussein's true intentions in the months preceding Iraq's seizure of oil-rich Kuwait in August 1990. Particularly striking in this case is the fact that the day before the invasion, the Kuwaiti emir and top officials of Kuwait's foreign ministry remained firmly convinced, despite the receipt of top-secret U.S. photographs that plainly showed the massing of Iraqi forces on Kuwait's borders, that Saddam Hussein was bluffing and could, once again, be bought off as he had been in prior crises as far back as July 1961.[152]

It should not be surprising, then, that later students of strategic surprise, including Richard Betts, Avi Shlaim, and Ephraim Kam, have agreed with Wohlstetter's original conclusion that the problem is intractable.[153] This consensus not only reflects history, but general agreement on the degree to which the root sources of the intractability lie in uncertainties and aspects of human perception and judgment too fundamental to eliminate once and for all. Direct evidence of enemy intentions is usually lacking and warning indicators are ambiguous; conceptions affecting the meaning attached to the signals that are received often persist stubbornly in the face of contradictory evidence; and the strong interdependency among many aspects of surprise attack means that one wrong hypothesis can quickly lead both intelligence collection and interpretation down the wrong path.[154] Among other reasons, the attackers can always change their minds at the last moment, as the Arabs are now thought to have done in May 1973, thereby making surprise far harder for the potential victim to avoid at a later date.[155]

How does this appreciation of the likely impossibility of eliminating any and all prospects of falling victim to a future surprise attack help one argue that general friction, too, is unlikely to be eliminated from or greatly diminished in future conflict? The first point to be made is one of consistency. Despite the persuasive historical evidence that strategic surprise has been a recurring problem *in the past,* it remains conceivable that it might be eliminated by technological advances we cannot yet clearly foresee or, perhaps, even imagine. What would be logically untenable, however, is to hold that either surprise or friction is tractable but not the other. If there is no ironclad, bulletproof guarantee against being the victim of a surprise attack in the future, then manifestations of Clausewitzian friction will also undoubtedly continue to form the atmosphere of war, even if their severity can be reduced.

The force of this argument springs from recognizing the causal similarities underlying both surprise attack and certain aspects of general friction. More than a few 20th-century wars have begun with surprise attacks, and their avoidance at the grand-strategic level tends, not unreasonably, to be categorized as a preconflict problem. Still, at the levels of operational art and tactics, surprise attacks also occur *within* ongoing conflicts. Setting aside the unique threshold associated with war initiation, uncertainties in the information on which action is based, danger, chance, and the unpredictability of two-sided interaction appear to be as much sources or causes of the prewar surprise-attack problem as they are of general friction during subsequent military operations. The possibility of being subjected to a surprise attack that initiates conflict can be viewed, therefore, as a prewar manifestation of general friction. And because the underlying cognitive challenges of avoiding surprise are fundamentally the same on either side of the arbitrary threshold separating peace from war, the future tractability of surprise attack at the outset, as well as the related aspects of general friction during wartime, can be viewed as opposite sides of one and the same problem. If either problem is intractable, then so is the other, and all evidence to date strongly suggests that eliminating all possibility of surprise is, for practical purposes, as intractable as the class of computing problems epitomized by the task of calculating the shortest route connecting each of some finite number of cities.[156]

Does the intractability of strategic surprise shed any light on the prospective magnitude of friction in future war? Certainly in the 20th century, the potentially catastrophic consequences of being surprised do not appear to have lessened. The Soviet Union eventually recovered from the surprise of Operation *Barbarossa* and went on to play a major role in the eventual Allied defeat of Nazi Germany, but at a horrific cost in human and societal damage, especially during the initial German offensives. The Israelis, too, were able to recover from the surprise of the combined Egyptian-Syrian attack on October 6, 1973, but, again, at considerable cost. Both the Soviet Union in 1941 and Israel in 1973 stood for a time on the brink of catastrophic defeat as a result of being surprised. The likely adverse consequences of an all-out Soviet strategic-nuclear attack on the United States at any time during the Cold War would have undoubtedly surpassed those that flowed from either the surprise German attack of June 22, 1941, or the surprise Arab attack of October 6, 1973. Hence the frictional potential of surprise either at the outset of, or during, war does not appear to have abated discernibly over the last six decades.

As for the foreseeable future, precision-guided weapons offer the potential for surprise attacks or operations to be more damaging than even in the recent past. More to the heart of the matter, if the roots of surprise lie in aspects of human perception and uncertainties too basic for technological advances to affect, much less eliminate, then it is difficult to see why this source of friction would diminish in the magnitude of its prospective effects on future war.

Chapter 7

Dispersed Information

Not only did chapter 6 provide an indirect argument for general friction's relatively undiminished persistence in future war—as opposed to merely documenting its recurrence in past conflicts—but it shed new light on several traditional sources of Clausewitzian friction (danger and informational uncertainties, for example). A second indirect argument for general friction's robust persistence arises from the distribution of information within very complex systems such as market economies or the Earth's biosphere. In both market economics and evolutionary biology, even quite fundamental information involved in the underlying adaptive processes (or adaptations) is, for all practical purposes, inaccessible at particular places and times.[157] The claim of this chapter is that comparably fundamental information involved in the orchestration of combat within any reasonably large volume of battlespace exhibits precisely the same inaccessibility due to its distribution in space and, especially, time. Even granting the enormous advances in information systems and related technologies now widely expected in the decades ahead, the temporal distribution of critical information bearing on the conduct and effectiveness of military operations alone seems sufficient to ensure not only the future persistence of general friction, but to raise doubts about the possibility of greatly reducing its overall magnitude.

One place to begin building a case for this conclusion is the work of the economist Friedrich von Hayek (1900–1992). He was perhaps the 20th century's greatest champion of the extended, spontaneous order of human cooperation that constitutes market or capitalist economies. Over a career that spanned more than six decades, especially during 20 fruitful years spent at the London School of Economics and Political Science after 1931, he also became the foremost critic of socialist economics, arguing ultimately that the aims and programs associated with centrally directed economies were "factually impossible to achieve or execute . . . [and] logically impossible."[158]

At the core of Hayek's mature economic philosophy lies the notion of the market as an evolutionary process of discovery (or adaptation) whose primary function is the gathering and processing of dispersed, unsurveyable information. As *The Economist* explained in its 1992 obituary of Hayek:

> Modern economies are vastly complicated. Somehow they must process immense quantities of information—concerning the tastes and incomes of consumers, the outputs and costs of producers, future products and methods of production, and the myriad of interdependences of all of the above. The task of gathering this information, let alone making sense of it, is beyond any designing intelligence. But it is not beyond the market, which yields "spontaneous order" out of chaos.[159]

Or, in Hayek's own words: "Modern economics explains how such an extended order can come into being, and how it itself constitutes an information-gathering process, able to call up, and to put to use, widely dispersed information that no central planning agency, let alone any individual, could know as a whole, possess, or control."[160] Indeed, for Hayek, the principal task of the social sciences in general and of economics in particular is to show "how the intentional actions of many humans lead to unintended social formations" or spontaneous orders.[161]

How could the exquisite order of the market have arisen spontaneously without being designed and consciously directed by human reason? In Hayek's view, the first step in this evolutionary process was the development of "several property, which is H.S. Maine's more precise term for what is usually described as private property."[162] The emergence of "several property" in primitive human groups, the details of which are now lost in prehistory, was "indispensable for the development of trading, and thereby for the formation of larger coherent and cooperating structures, and for the appearance of those signals we call prices."[163] In turn, the development of trade, which Hayek identified as a precondition for the emergence of Egyptian, Greek, and other ancient civilizations, depended on the freedom or liberty of traders to be able to profit from the use of privileged "information for purposes known only to themselves."[164]

Given this "reconstruction" of how today's extended market order most likely emerged, how could such a structure gather and process information that is inaccessible to any single individual or group?

> Much of the particular information which any individual possesses can be used only to the extent to which he himself can use it in his own decisions. Nobody can communicate to another all he knows, because much of the information he can make use of he himself will elicit only

> in the process of making plans for action. Such information will be evoked as he works upon the particular task he has undertaken in the conditions in which he finds himself. . . . Only thus can the individual find out what to look for, and what helps him to do this in the market is the responses others make to what they find in their own environments . . . . The market is the only known method of providing information enabling individuals to judge comparative advantages of different uses of resources of which they have immediate knowledge and through whose use, whether they so intend or not, they serve the needs of distant unknown individuals. This dispersed knowledge is *essentially* dispersed, and cannot possibly be gathered together and conveyed to an authority charged with the task of deliberately creating order.[165]

This "*essentially* dispersed" economic information emphasized is distributed in time as well as in space. Economic actions will be adapted through the extended order "not only to others distant in space but also to events beyond the life expectancies of acting individuals."[166] Some of the information that the extended order gathers and processes comes into existence only when individuals are confronted with particular economic choices in particular circumstances. Other elements, especially those having to do with long-term consequences, can be known only later in time because of the subsequent contingent choices open to other individuals. Just as a planned surprise attack can be aborted at the last moment, individuals can react in more than one way to perceived economic signals and effects at times of their own choosing. In the marketplace, therefore, "unintended consequences are paramount: a distribution of resources is effected by an impersonal process in which individuals, acting for their own ends (themselves also often rather vague), literally do not and cannot know what will be the net result of their interactions."[167]

Hayek's outlook reflects a keen appreciation of the fact that there are "limits to our knowledge or reason in certain areas."[168] He points to the marginal-utility theory developed by W.S. Jevons, Carl Menger, and others, with its stress on the "subjective" nature of economic values, as having produced a "new paradigm" for explaining how structures can, and do, arise "without design from human interaction."[169] This new paradigm, in turn, rested on "the discovery" that economic events could not be entirely explained "by preceding events acting as determining causes" due to the role of later interactions.[170] The upshot is not to suspend causality. However, the temporal inaccessibility of key economic information means that detailed predictability is lost.

This same pattern of "*essentially* dispersed" information also plays a crucial role in evolutionary biology. Consider speciation events, meaning the earliest point in lineage of a group of living organisms united by descent at which the emergence of a new species can be discerned. An example would be searching for the female who is the most recent direct ancestor, in the female line, of every human being alive today. Scientists have christened her the "Mitochondrial Eve" in light of the fact that, since the mitochondria in our cells are passed exclusively through the maternal line, all the mitochondria in all the people alive today are direct descendants of the mitochondria in her cells.[171] However, because her offspring could, whether by accident or a lack of evolutionary fitness, have all died off, Mitochondrial Eve "can only be *retrospectively* crowned."[172] Her status as the closest direct female ancestor of every human alive today depends not only on contingencies in her own time, but on those in later times as well. For this reason her status, like all events associated with demarcation or emergence of species, was "invisible at the time" it occurred.[173]

In both economics and evolutionary biology, then, the distribution or dispersal of critical information in both space and time suggests definite limits to what can be known by any individual, or group of individuals, at any given point in time. From an evidentiary standpoint, the consistent failure throughout the present century of centrally directed economies to achieve economic performance comparable to that of the extended market order argues that these limits ought to be taken seriously.[174] Sufficiently complete and unimpeachable information to eliminate major uncertainties about the future course of events does not appear to be possible in economics and, almost certainly, the same is true of biological adaptation through natural selection.[175] Granted, these parallels to the frictional uncertainties that confront combatants in wartime cannot, in and of themselves, establish the existence of similar limits to combat processes; arguments by analogy alone are never decisive, however insightful they may be. Nonetheless, awareness of the existence of such limits in other highly contingent processes certainly opens the door to the *possibility* that the same could be true of war, even of future war.

Is there any empirical evidence that might support this conclusion? Consider, once again, the profound uncertainties that coalition planners faced *during Desert Storm* in trying to eliminate the Iraqi nuclear program. Only the intrusive inspections conducted under United Nations auspices *after* the war revealed how much of Iraq's nuclear program had escaped destruction during *Desert Storm*. In this same vein, revelations in August 1995 concerning Iraqi preparations in December 1990 to employ biological agents against coalition forces show that there were fundamental facts about that campaign that were neither known nor knowable outside Saddam Hussein's inner circle and selected military units for some years after *Desert Storm* ended.[176] To see the essential contingency of such matters, consider the following possibility. If all physical evidence (including documents) regarding Iraqi biological-warfare capabilities had been destroyed, and if everyone involved had gone to their graves without telling, the information that surfaced in 1995 following the defection of some of Saddam Hussein's closest associates would, one day, have become unrecoverable.

For those unpersuaded by the preceding pair of examples, consider a third: the temporal contingency of determining whether enough destruction had been imposed on the Republican Guard heavy forces by February 28, 1991, to preclude their being used at some later date to threaten Iraq's neighbors. By mid-1993, more than 2 years after *Desert Storm* ended, this question had become a subject of heated debate.[177] Yet, as we saw in chapter 5, it was not unambiguously decidable by Western observers until October 1994, when Republican Guard heavy units, equipped with T–72s that had escaped destruction in 1991, again deployed to threaten Kuwait. Because resolution of the uncertainty depended on subsequent Iraqi actions, it exemplifies the essential temporal dispersion of fundamental knowledge about military effectiveness.[178] Just as the problem of strategic surprise appears intractable, there can be no guarantees that such temporal dispersion of equally elementary knowledge about the efficacy of particular military actions will not recur in the future. Indeed, based on history, the most plausible conclusion to draw is that such dispersion will continue to be a feature of future war. If it does, then so will Clausewitzian friction.

The distinction between explicit and tacit knowledge offers additional support for this viewpoint. In this context, *explicit* knowledge refers to meaningful information that is available for entry into databases and information systems. *Tacit* knowledge, by contrast, encompasses the implicit information and processing capabilities that humans carry around inside them by virtue of their genetic endowment and biological development, cultural background and upbringing, and cumulative individual experiences.[179] Such knowledge is, in an important sense, not directly accessible, although it can be drawn upon implicitly in appropriate contexts. Michael Polanyi used "tacit knowledge" to refer to human capabilities to know or sense more than can be explicitly told or specified, and offered the ability to recognize the face of a friend or relative based on subsidiary awareness of particulars as an example of such knowledge.[180] A military example would be the tacit understanding of how fellow aircrew or flight members are likely to react to unexpected combat situations that is accumulated by regularly flying and training together with the same individuals. Military organizations such as squadrons, wings, and air divisions contain large amounts of such information, although it is widely dispersed among individuals, difficult (if not impossible) to enumerate in detail, and generally only called into use by concrete circumstances or instances of organizational activity. The right kinds of tacit knowledge can give military organizations a tremendous, long-term advantage over prospective adversaries, as Israeli dominance over Arab air forces from 1967 through 1982 documents.[181] Dysfunctional tacit knowledge, on the other hand, can have quite the opposite effect, as Scharnhorst discovered in the final weeks preceding the twin battles of Jena and Auerstädt. These points not only illuminate the roots of friction in the narrow sense that originally led Clausewitz to coin the term, but suggest a fairly deep argument for general friction's future persistence at some nontrivial level. Unless tacit knowledge can be wholly eliminated as a component of the combat capabilities of military units, friction in the narrow sense will remain a feature of future combat.

The inaccessibility of critical information involved in combat processes, arising from the essential dispersion of that information in space and time, argues that at least two sources of general friction listed at the end of chapter 4—uncertainties in the information on which action in war is based and friction in the narrow sense of resistance to effective action within one's own forces—will persist in the future. It is conceivable that advances in information technologies may reduce the spatial dispersion of explicit knowledge. Perhaps related advances can even render some portions of tacit knowledge explicit, although one suspects, given how much of the brain's information processing is both dispersed and inaccessible to consciousness in any direct or real-time manner, that much tacit knowledge will remain so.[182] However, temporally dispersed information and irreducibly tacit knowledge appear to present clear limits to how much of all that combatants might like to know can actually be gathered together and explicitly grasped. Hence the prospects for one opponent or the other to reduce substantially, much less drive near the vanishing point, the frictions arising from the dispersed information and tacit knowledge embedded in human organizations seem dim. These conclusions can be supported without appealing directly to the occurrence of similar phenomena in Hayek's extended market order and evolutionary biology. Yet the family resemblance across all three areas does not seem to be merely accidental.

Chapter 8

Evolutionary Biology as an Exemplar

The previous chapter utilized evolutionary biology to open the door to the possibility that the spatial-temporal inaccessibility of certain information argues that human beings and their institutions can neither eliminate all uncertainty about the higher-level effects of future combat interactions, nor substantially reduce the magnitude of such uncertainties beyond the limits set by dispersed information and tacit knowledge. This chapter has two aims: first, to consider evolutionary biology as a source of general friction in its own right; and, second, to explore whether evolutionary biology may offer a better model for a "scientific" theory of war than quantitative sciences like physics.

On the current reading of fragmentary evidence from diverse fields, the human family, genus *Homo*, emerged some 2 to 3 million years ago in Africa, east of the Rift Valley in response, initially, to geographic isolation and, spurred by subsequent climatic pressures, evolved rapidly toward modern man, *Homo sapiens*.[183] Since the mid-1980s, when consensus finally emerged concerning the evidence of the molecular and fossil records, the last great step in human evolution from "archaic" *Homo sapiens* to "early modern" man is estimated to have occurred between 45,000 and 90,000 years ago.[184]

These observations presume that Charles Darwin (1809–1882) was on to something fundamental when he published *The Origin of the Species* in 1859. His core evolutionary thesis was that the rich diversity of living species making up the Earth's biosphere had come about

> chiefly through the natural selection of numerous successive, slight, favorable variations; aided in an important manner by the inherited effects of the use and disuse of parts; and in an unimportant manner, that is in relation to adaptive structures, whether past or present, by the direct action of external conditions, and by variations which seem to us in our ignorance to arise spontaneously.[185]

This idea will not be defended here beyond two observations. First, *The Origin of the Species* contained large gaps "that have only recently begun to be properly filled in," the most fundamental being the absence of the concept of the gene as a discrete unit of particulate inheritance.[186] Though the basic idea had been put forth by the monk Gregor Mendel in an obscure Austrian journal in 1865, Darwin himself never hit upon the concept of a gene or any adequate theory of inheritance. This most serious gap in his original theory was not filled in until the early 1930s when the statistician and biologist R.A. Fisher and his colleagues worked out modern population genetics.[187] There were, of course, other weaknesses in Darwin's formulation of descent by natural selection. While most of these were made secure during the 1940s through the work of Theodosius Dobzhansky, Julian Huxley, Ernst Mayr, and others, it has "taken another half-century to iron out most of the wrinkles" in the fabric of the modern synthesis, neo-Darwinism.[188]

Second, notwithstanding much sentiment and strong opinion to the contrary, neo-Darwinism is about as secure as any scientific theory ever has been or could be. True, vigorous controversies remain in evolutionary theory, not the least of which is how self-replicating molecules could have initially emerged. Nonetheless, these controversies are matters of "just science," meaning that no matter how they turn out they "will not undo the basic Darwinian idea."[189] As the paleontologist Stephen Jay Gould observed: "Natural selection is an immensely powerful yet beautifully simple theory that has held up remarkably well, under intense and unrelenting scrutiny and testing, for 135 years."[190] An indication of just how secure core Darwinism (the minimal theory that biological evolution is guided in adaptively nonrandom directions by the nonrandom survival of random hereditary changes) is can be gleaned from Richard Dawkins' argument that it is the only known empirical theory capable, even in principle, "of solving that most difficult of problems posed by life anywhere in the universe, namely, the problem of the existence of adaptive complexity."[191]

Given this understanding of evolutionary theory, how might it support general friction's relatively undiminished persistence in future war? Consider the various lists of friction's sources in chapter 4, both Clausewitz's and the author's more inclusive list of eight. Occupying the first two places in all of them are danger and war's demands for physical exertion. These are straightforward and remarkably uncontroversial sources of friction, especially at the tactical level of individual combatants and small units. Nevertheless, there is evidence that their combined effects on human beings in ground combat establish a temporal limit on how long continuous operations can be sustained without risking precipitous declines in effectiveness. Further, because this limit—about 4 days—has not changed over at least the last 130 years, it appears to be rooted in human cognitive and physical limits built in by evolution.

The most recent evidence bearing on these claims surfaced during the Persian Gulf War in 1991. Particularly during the final 15 hours of the coalition's ground offensive, incidents occurred that in the view of Richard Swain, the U.S. Third Army historian, "were indicative of the larger problem of friction in war."[192] These events included the VII Corps failure to capture the road junction near Safwan in accordance with General Schwarzkopf's desires, as well as the fact that the VII Corps effectively stopped in place at 0130 hours on the morning of February 28, 1991, rather than continuing to advance until 0800, the official time for the cessation of offensive operations. One can easily identify the immediate or proximate causes of these lapses. Key individuals in the chain of command had had little sleep since the ground campaign started, and many were approaching physical and mental exhaustion; gaps had begun to open up between where friendly units actually were on the ground and where higher echelons thought they were; and the clarity of communications, up as well as down the chain of command, had begun to deteriorate in the press of events. However, one can push the analysis deeper, and that is precisely what Richard Swain did in reflecting on what had occurred:

> Douglas Southall Freeman notes that, during the American Civil War, "in the Army of Northern Virginia the men could stand almost anything for four days, but the fifth day in almost every instance they would crack." When judging the apparent unraveling of tight control on the night of 27–28 February [1991] by men who had had little rest for four days of movement and combat, one may well remember Freeman's warning: "Beware of the fifth day. . . ." Interestingly enough, Major General Rupert Smith of the lst U.K. Armored Division began issuing written, rather than oral, orders to avoid confusion due to fatigue on the part of the sender and the receiver.[193]

Swain attributes the loss of tight control to fatigue. Fatigue directly recalls war's demands for physical exertion, one of Clausewitz's sources of general friction. When such exertions occur in time of war, though, the companion friction stemming from human lives being at stake—including one's own—is probably impossible to separate. For participants in combat units during sustained operations, the risk of death or mutilation is constant and compelling. Yet, even for high-level commanders like General Schwarzkopf, danger makes itself felt in terms of their personal responsibility for the men under their command. Bad decisions on their parts can get people killed unnecessarily, and this all-too-visceral danger can, and does, impose its own kind of friction.

The fact that coalition forces appear to have run up against the same 4-day limit on sustained operations in 1991 experienced by the Confederate Army of Northern Virginia during 1862–1865 suggests that enduring human limitations are involved.[194] These psychological and physical limitations are not as constant and precise across diverse individuals and groups as the temperature at which water freezes or the position of the moon in its orbit at some future time. And coherent operations can and have been sustained over longer periods than 4 days by ensuring that combatants get sufficient sleep whenever the opportunity arises.[195] Nevertheless, the underlying psychological and physical limitations not only appear to be every bit as real as the regularities in sciences like physics, but to be grounded, ultimately, in the environmental circumstances of the late (or upper) Pliocene, some 2 to 3 million years ago, that gave rise to the emergence of the genus *Homo*. It is also worth noting that, as Lionel Tiger emphasized, human cortical tissue developed in these evolutionary conditions "to facilitate action," particularly with respect to courtship and reproduction, not abstract thought.[196]

There are, then, finite limits, grounded in biology and evolution, to the capabilities of humans to receive sensory data, orient themselves by integrating that input with prior experience and information, reach plausible decisions about what to do next, and act upon those decisions.[197] Any time the demands of combat begin to push participants toward those limits, much less up against them, various frictions begin to impede more and more effective observation, orientation, decisions, and actions. As many fighter pilots can attest from firsthand experience, the stresses of combat can quickly constrain sensory input, with auditory inputs from other crew and flight-members being the first to go. Danger and physical exertion can also degrade orientation in a combat situation, precipitate poor decisions, and produce slow, ragged, or even flawed execution. In the extreme case of pilots realizing that they are about to lose an air-to-air encounter, individuals have been known to freeze to their sticks, straighten out, and run "right into their graves like men stricken blind who run, screaming, off a cliff."[198] The consequences of such effects seem as potentially severe in future combat as they have often been in the past conflicts. Indeed, short of "reengineering" *Homo sapiens* at the genetic level, it is difficult to see how the *potential* adverse effects of exceeding these inherent biological limitations can be reliably reduced, much less eliminated, so long as humans and their purposes remain an integral part of war.

Biology, therefore, confers relative permanence on at least some sources of friction in war. The *potential* of danger and exertion to impede effective military operations is always there, just beneath the surface. Realistic training and actual combat experience can, as Clausewitz recognized, do much to keep these prospective impediments at bay, beneath the surface. However, like interrelated human potentials for sex and aggression that evolution has programmed in for at least 99 percent of the time *Homo* has been a distinct genus, the potential for a determined, capable adversary to push human combatants beyond their biological capacities for effective observation, orientation, decisionmaking, and action seems an inherent, deeply programmed limitation.[199] From this evolutionary perspective, technological solutions per se are almost certainly not possible so long as we remain human.

The theory of biological evolution has another implication for our thinking about Clausewitzian friction. The evidence and arguments presented so far suggest that the following sorts of propositions could form the basis of a reasonably comprehensive theory of war and conflict.

> *Proposition I*: War is a violent, two-sided contest of opposing wills dominated by Clausewitzian friction.
>
> *Proposition II*: Outcomes are highly contingent, and the various indirect effects or second-order consequences arising from a campaign or war may not be knowable until some time after the conflict has ended.
>
> *Proposition III*: In combat, from moment to moment, it is the differential between the levels of general friction experienced by the two sides that matters most.[200]
>
> *Proposition IV*: So long as human purposes, frailties, proclivities, and limitations remain an integral part of war, Clausewitzian friction will retain the potential to make the difference between success and failure.

The salient observation about these four propositions for present purposes is that they are neither readily nor obviously amenable to the kind of quantification that enables tides or the positions of the planets to be precisely predicted indefinitely into the future. Only proposition III offers any hint of a quantifiable, predictive relationship. But even in this instance some overarching metric for measuring the absolute level of friction experienced at a given moment by each side would be needed, and no such universal metric exists. In fact, it seems open to doubt whether such a metric is possible other than in a qualitative or conceptual sense.

True, indicators like decision-cycle times and option sets in possibility spaces provide ways of gaining insight into the rough balance of general friction over the course of particular historical episodes. And the notion of options in a possibility space relative to politico-military objectives might even provide the basis for a fairly comprehensive indicator of general friction. Still, we do not appear to have anything comparable to measurable physical quantities like temperature or velocity.

To push this last point a bit further, Isaac Newton originally formulated his famous second law of motion as: "*The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.*"[201] In the mathematical notation of the calculus, the scalar version of this law is expressed by the equation:

$$F = \frac{d(mv)}{dt} = \frac{dm}{dt}v + m\frac{dv}{dt} = \frac{dm}{dt}v + ma,$$

where F is the impressed force, m is the mass of the object subjected to the force, v the object's velocity, t is time, and a is the object's acceleration (the time rate of change of v). When v is small compared to the speed of light, dm/dt approaches zero and we get the most familiar form of Newton's second law, $F = ma$. Moreover, force, mass, velocity, time, and acceleration—F, m, v, t, and a—are all physically measurable quantities. As Ernst Mayr has emphasized, physicists since Newton have been strongly (and arrogantly) inclined to see these sorts of quantitative, predictive laws as "co-extensive with science."[202] By implication, this attitude has led many in the so-called hard sciences to the prejudice that evolutionary biology is somehow not a full-fledged empirical science on a par with the Newtonian synthesis, or else is at best a proto-science still awaiting its own Newton. The reason is that the principles of evolutionary biology established by Darwin and his successors are more like the four qualitative hypotheses just proposed about war than quantitative laws like $F = ma$.[203]

Is the identification of science with quantitative, predictive laws defensible? To reiterate the fundamental point made early in the opening paragraphs of this chapter, evolution by means of natural selection is arguably the best confirmed theory in the history of science. Newtonian mechanics is not an exception since, strictly speaking, the Newtonian synthesis was supplanted by the relativistic mechanics of Albert Einstein early in this century, and both Newtonian and relativistic mechanics were then upstaged at the microscopic level of electrons and protons by the emergence of quantum mechanics during the 1920s. As a result, a major implication of Darwinian theory is to show that one cannot regard explanations as unscientific and "unsatisfactory" when they do not contain quantitative laws, "or when they are not such as to enable the event in question to have been predicted."[204] Moreover, even that most quantitative of empirical sciences, physics, is not thoroughly quantitative down to its roots. As the mathematician and physicist Jules Henri Poincaré rightly argued, the scientist's selection of which facts to pay attention to out of the practically infinite number of knowable facts, while by no means capricious or random, is ultimately based on qualitative judgments such as simplicity, repeatability, and beauty—judgments that defy quantification.[205] Last but not least, Poincaré's most far-reaching contribution to mathematical physics was probably the creation of topology, a branch of mathematics that permits the *qualitative* analysis of dynamical systems.[206] Topological methods enable one to obtain information about the global behavior of a dynamical system by constructing a geometric picture that is "totally inaccessible from the classical bash-out-a-formula viewpoint."[207]

Two points follow from these observations. First, despite its heavily nonquantitative and nonpredictive character, evolutionary biology is as legitimate an empirical science as anything in physics. Indeed, its lack of quantification arises from the contingency and diversity of the phenomena with which it deals. Second, for this very reason, evolutionary biology would appear to be a better paradigm for an overarching theory of war than, say, quantum physics. Regardless of how one feels about the detailed content of any of the four hypotheses offered above, they do illustrate the kinds of qualitative, but empirically refutable, propositions that an adequate science of war would require.

Chapter 9

Situation Awareness in Air-to-Air Combat

The three previous chapters sought to build indirect arguments supporting the proposition that the potential for, if not the actuality of, general friction is likely to persist more or less undiminished in future wars despite technological advances. This conclusion should not, however, be construed as implying that friction is impervious to technological manipulation. Weapons influence how friction will manifest itself, and superior weapons can broaden the potential for manipulating the relative balance of friction between opposing sides in one's favor.

To demonstrate technology's ability to manipulate Clausewitzian friction, it will be necessary to focus on tactical interactions. Tactical interactions and effects, unlike those at the operational and strategic levels of war, *are* amenable to quantification and statistical analysis—at least up to a point. The reason for separating the aspects of war that are quantifiable from those that are not along the imprecise boundary dividing tactical interactions from the operational level of war lies in the degree of penetration by political-strategic objectives. In the author's experience, the concrete, specific political-strategic objectives that pervade the conduct of actual conflicts so influence strategy and operational art as to render both inputs and outputs at those levels irredeemably qualitative in character. Only at the level of tactical interactions do political-strategic aims become sufficiently remote to allow a fair degree of quantification of overall results.[208]

The choice of what type of tactical interactions to examine is not, presumably, of critical importance beyond the fact that interactions involving relatively small numbers of participants may be easier to analyze for present purposes than those involving large numbers of active shooters and decisionmakers. In ground engagements involving hundreds or thousands of combatants, for example, it may be considerably more difficult to ascertain friction's role—or the lack thereof—than in air-to-air engagements involving a handful of aircraft.[209] Air-to-air combat has been selected in part for this reason. However, it seems a prudent choice for a few other reasons. Not only has an extensive body of air-to-air combat experience been accumulated since 1914, but a number of test evaluations have been flown on instrumented ranges and in simulators for the express purpose of providing statistically relevant data. In addition, air-to-air combat is as dependent on and pervaded by advanced technology as any area of late 20th-century warfare. Land and naval warfare reach back to the beginnings of recorded history. Powered flight, by comparison, was achieved only in 1903 as a result of aeronautical and engineering advances achieved by Orville and Wilbur Wright, and the heavier-than-air fighter is a phenomenon that dates only from World War I. Without the airplane, there would have been neither airmen nor air forces, and so strong has been the psychological attachment of American airmen to the planes they happened to fly that, to this day, many pilots identify themselves first and foremost as the "drivers" of specific aircraft types, often down to the model.[210]

What factors have tended to drive engagement outcomes in air-to-air combat? Surprise was linked to general friction in chapter 6. Air combat experience going at least back to World War II suggests that surprise in the form of the unseen attacker has been pivotal in three-quarters or more of the kills. In writing about his experiences flying long-range escort missions over northern Europe with the U.S. Eighth Air Force, P–38 pilot Mark Hubbard stressed that "90 percent of all fighters shot down never saw the guy who hit them."[211] Hubbard was by no means alone in observing that friction in the form of the unseen attacker from six o'clock played a dominant role in engagement outcomes. The American P–47 pilot Hubert Zemke (17.75 air-to-air kills in World War II) stressed that "few pilots are shot down by enemies they see."[212] Similarly, the German Me-109 pilot Erich Hartmann, whose 352 kills during World War II made him the top scorer of all time, later stated that he was "sure that 80 percent of kills never knew he was there before he opened fire."[213]

Subsequent technological developments in the means of air-to-air combat did not change the basic pattern observed by Hubbard, Zemke, and Hartmann during World War II. These developments include the shift to jet fighters for air superiority during the Korean War, the advent of infrared air-to-air missiles by the mid-1950s, and the appearance of radar-guided air-to-air missiles in time for American use in the Vietnam War. The best combat data are from the American involvement in Southeast Asia. From April 1965 to January 1973, American aircrews experienced more than 280 "decisive" air-to-air engagements, meaning encounters in which at least one U.S. or North Vietnamese aircraft was destroyed.[214] These engagements produced some 190 aerial kills of North Vietnamese fighters against 92 American losses. Detailed reconstructions of the 112 decisive engagements from December 18, 1971, to January 12, 1973, revealed that 81 percent of all aircrews downed on both sides either were unaware of the attack, or else did not become aware in time to take effective defensive action.[215] In the jargon of contemporary American aircrews, such failures to be sufficiently cognizant of what is taking place in the combat area around one to avoid being shot by an unseen or unnoticed adversary have come to be described as a breakdown of situation (or situational) awareness. In an air-to-air context, *situation awareness* (or SA) can be understood as the ability of opposing aircrews to develop and sustain accurate representations of where all the participants in or near the air combat arena are, what they are doing, and where they are likely to be in the immediate future. This understanding of situation awareness is, of course, crucial to appreciating that the driver in 81 percent of the decisive air-to-air engagements in Southeast Asia from December 1971 to January 1973 involved more than just the "element of surprise," although this was the interpretation at the time.[216] Surprise can certainly affect combatant situation awareness on either side. However, situation awareness as defined here is, like general friction, a considerably broader concept.

While it seems plausible to those experienced in the air combat arena that situation awareness provides at least an indicator or marker of frictional imbalances at the tactical level, the two concepts are not coextensive. Generally speaking, *high* situation awareness for a given side implies low friction for that side and vice versa. However, the better than 20 percent of fighter crews shot down by enemy fighters in Southeast Asia during 1971–1973 who became aware of the attacker just before ordnance impacted their aircraft—but too late to take effective defensive action—arguably had high situation awareness during the final seconds before being hit. Yet it is equally clear that they also confronted high friction in those last seconds. After all, their options in possibility space had abruptly been reduced to the point where few, if any, desirable courses of action remained. True, aircrews in these dire circumstances could still choose among such possibilities as initiating futile last-ditch maneuvers, reaching for the ejection-seat handles, or simply waiting to see how much damage their aircraft ultimately sustained from the opponent's bullets or missiles. But since none of these possibilities is very desirable, their real options were few to none.

With this distinction between situation awareness and general friction in mind, how is the ebb and flow of the former related to the waxing and waning of the latter? Does the imbalance of situation awareness between adversaries over the course of an engagement provide a sense of the persistence or magnitude of frictional imbalances? Building on the notion of option sets in possibility space, the answer involves two interwoven but opposing threads or tendencies. The first concerns the disappearance of options over time, the second the creation or emergence of new ones. One is dissipative, the other is creative.

In air-to-air combat, the unexercised options that may disappear or recede over the course of a tactical evolution are more concrete than the high-level or "strategic" options affecting whole campaigns such as the German blitzkrieg of May 1940. If, for example, the pilots on one side elect to enter the fight in a formation so tight that their opponents are easily able to acquire all of them at the outset, then a host of more dispersed, difficult-to-deal-with options are quickly foregone by the side embracing the tight formation. The potential for that side to generate ambiguity, confusion, or surprise later in the engagement is, of course, by no means closed. Still, some options have been lost at the outset with consequences that may or may not eventually prove fatal, and others will fall by the wayside with each successive move or action.

At most, however, the falling aside of options at successive branch points in an air-to-air engagement represents only the negative or dissipative aspect of how option sets can wax and wane during an aerial encounter. The positive or creative aspect is the generation of new possibilities by dint of one's own initiative, creativity, quickness, and, above all, interaction with the opposing side. For instance, at long ranges an abrupt maneuver by one pilot to move his aircraft outside the effective envelope of an enemy's air-to-air missiles introduces a rapid transient that the opponent is unlikely to grasp and assimilate instantaneously. If the move is successful, then the defender's options widen while the attacker's narrow, at least momentarily. Or, equivalently, the defender's *friction* lessens while the attacker's does not, thus producing a shift in the relative balance of friction in favor of the defender. Although changes in each opponent's situation awareness may sometimes briefly diverge from changes in the balance of friction, the evolution just described can be understood in terms of a quantitative shift in SA in favor of the defender. Hence, with brief exceptions, there appears to be some linkage between the two sides' friction levels and their SA levels.[217]

Even without the evidence from subsequent tests like Air Combat Evaluation (ACEVAL) in the late 1970s and the Advanced Medium Range Air-to-Air Missile (AMRAAM) Operational Utility Evaluation (OUE) in the early 1980s , combat data from Europe in World War II and Southeast Asia during 1965–1973 not only confirm the contention in chapter 8 (proposition I) that general friction can *dominate* combat outcomes, but indirectly quantify what the term "dominate" has meant in historical air-to-air combat. If some 80 percent of the losses have resulted from aircrews being *unaware* that they were under attack until they either were hit or did not have time to react effectively, then a *relative deficit* of situation awareness[218] has been the root cause of the majority of losses in actual air-to-air combat. A deficit in situation awareness accounts for four out of five losses. While this statistic may not measure frictional imbalances directly, it does reflect the influence friction has had on outcomes over the course of large numbers of air-to-air engagements.

After the Vietnam War, SA dominance of fighter-versus-fighter combat was extensively confirmed by large-scale simulations of air-to-air engagements. In the late 1970s, two major air-to-air tests were flown on an instrumented air combat maneuvering range north of Nellis Air Force Base, Nevada: the Air Intercept Missile Evaluation (AIMVAL) and ACEVAL. These tests pitted "Blue Force" F–15s and F–14s against "Red Force" F–5Es, chosen to simulate the Soviet-built MiG–21; Cubic Corporation's air combat maneuvering instrumentation system provided a combat area some 40 nautical miles in diameter as well as real-time data on the engagements.[219] The Blue fighters were "armed" with guns, short-range infrared (IR) missiles, and the medium-range, radar-guided AIM–7F Sparrow; Red ordnance was limited to guns and IR missiles.

AIMVAL sought to assess the operational utility of five existing and proposed infrared missile concepts.[220] ACEVAL explored the factors affecting engagement outcomes when multiple aircraft are involved, with force size, force ratio, and initial ground controlled intercept (GCI) condition (Red advantage, neutral, or Blue advantage) as the primary test variables.[221] AIMVAL's test matrix included Blue-versus-Red force ratios of 1-v-1 (one F–15 or F–14 versus one F–5E), 1-v-2, 2-v-2, and 2-v-4, and called for 540 valid engagements involving 1,800 sorties.[222] The ACEVAL test matrix added 2-v-1, 4-v-2, and 4-v-4 trials to the four force ratios used in AIMVAL and required a total of 360 valid engagements involving 1,488 sorties.[223] Needless to say, many additional engagements and sorties were flown preparing for the actual trials. In fact, perhaps the most famous single engagement of both tests—the ACEVAL "Towering Inferno" 4-v-4 in which all 8 participants were shot down after 1 minute and 52 seconds—was not a valid trial.[224]

By the end of 1977, there was growing debate over the implications of these tests. ACEVAL, for example, was originally designed on the premise that when Blue fighters employed radar-guided missiles to shoot from beyond visual range (BVR), engagement outcomes would depend "primarily upon the performance characteristics of the avionics and weapons systems employed" and, with proper testing, could be predicted on that basis.[225] If this premise had been borne out, it would have represented a sharp departure from historical combat experience in which human factors such as inferior situation awareness had consistently proven to be the dominant factor in engagement outcomes. At the time, there were a number of observers who viewed AIMVAL and ACEVAL first and foremost as a basis for choosing between hardware alternatives. Even some seasoned fighter pilots insisted on reading the tests as showing that hardware factors like long-range identification and missile performance would drive engagement outcomes in the future.[226] On the other hand, there were also interpretations that fit much better with historical combat experience. In particular, Lieutenant Colonel "Shad" Dvorchak, who was directly involved with analyzing AIMVAL/ACEVAL data at Nellis Air Force Base, noted that in AIMVAL, incremental hardware advantages had tended to wash out in the long run as opponents adapted, and that in ACEVAL, human interactions had been five times as influential on outcomes as test variables like force ratio or the initial GCI condition.[227] Suffice it to say, however, that by 1979 there was a wide range of opinion on the potential of technological advances to preempt the frictional factors that had dominated historical air combat.

In retrospect, the AMRAAM OUE, conducted in McDonnell Douglas flight simulators starting in 1981, resolved the issue in favor of Clausewitz. The AMRAAM OUE test matrix called for over 1,200 engagements involving around 10,000 simulator sorties.[228] Instead of a small cadre of specially selected aircrew, AMRAAM OUE participants were drawn from operational units in the United States. Scenarios included fighter-sweep situations (2-v-2 and 2-v-4) as well as trials in which the Blue fighters faced

Red fighters escorting strike aircraft (2-v-4 + 4, 2-v-2 + 6, and 4-v-4 + 4). About half the trials were excursions from the standard sweep and combat air patrol scenarios.

Throughout AIMVAL and ACEVAL, visual identification prior to weapon employment had been a mandatory rule of engagement and the only radar missile allowed had been the AIM–7F Sparrow.[229] Inevitably these constraints biased both tests against effective BVR employment. In the AMRAAM OUE, by comparison, the Blue force was given the medium-range, radar-guided AMRAAM and half the non-excursion trials were run with BVR rules of engagement. The natural expectation was that in the BVR trials at least, Blue hardware advantages would drive engagement outcomes. The bottom line from the test, however, turned out to be otherwise. Situation awareness proved to be "the single most important factor affecting engagement outcomes."[230] For both sides, being aware of adversary weapons envelopes and keeping outside them to avoid being "shot," while trying to maneuver adversaries into their own weapons envelopes, proved as important and dominant as it had been in ACEVAL. Especially for Red fighters facing the AMRAAM, the role of situation awareness in scoring kills and avoiding being shot down tended to hang on even smaller differences than before.

To preempt misinterpretation, the *statistical* dominance of AMRAAM OUE engagement outcomes by situation awareness should not be construed as implying that hardware—including aircraft performance, avionics, and missile capabilities—counted for nothing. To the contrary, superior Blue hardware conferred building blocks or baseline elements of advantage that the Red side had to work hard to overcome and, in the aggregate, Blue hardware advantages were reflected in superior Blue exchange ratios. Statistically, though, the outcome of any particular engagement most often hinged on very small differences here or there across a large set of interrelated human and hardware factors, and the dominant of these factors was situation awareness.

This test result reinforces historical air-to-air combat data rather than contradicting them. It also supports the Clausewitzian hypothesis that friction is a structural feature of combat interactions with humans "in the loop." Finally, it lends concrete empirical support—at least at the tactical level—for the proposition that eradicating friction in some permanent way through hardware improvements is, at best, unlikely.

Does the bottom line from the AMRAAM OUE further imply that technological manipulation of friction is difficult or impossible? Not at all *if* the technology is focused on the root problems. Since the earliest days of air-to-air combat in World War I, sorting in the sense of the timely and effective targeting of opponents has been a sine qua non of positive results (downing enemy aircraft as opposed to merely avoiding being shot down oneself). While sorting is a trivial problem in isolated 1-v-1 engagements—and manageable with voice communication in 2-v-2s—it becomes vastly more difficult in 4-v-4s or more complex engagements. Obviously sorting in complex engagements requires situation awareness, and this awareness has to be maintained while maneuvering one's own aircraft, manipulating its sensors, and making the critical targeting decisions that produce kills. Since top performing fighters can sustain G-loadings as high as nine times the Earth's gravity, as well as high pitch and roll rates, the environment inside the cockpit is both physically and mentally demanding. All-aspect, high-G missiles, including some able to be fired from well beyond visual range, further complicate the problems of developing and maintaining high situation awareness because the missile envelopes themselves are highly dynamic. Last but not least, the time spans participants have for observing what is going on, orienting themselves, deciding what to do (including sorting or targeting), and trying to execute split-second decisions are highly compressed. Thus, even the slightest misstep in sorting during 4-v-4 or more complex engagements can quickly lead to disaster, as the Blue side's failure to target two of the Red fighters at the outset of the 1-minute-and-52-second "Towering Inferno" trial from ACEVAL illustrates.[231]

Small wonder, then, that sorting efficiencies in complex engagements have been quite low. By 1984, Billy R. Sparks, a former F–105 "Wild Weasel" pilot with combat experience over North Vietnam, had been involved in analyzing or running three major humans-in-the-loop tests: AIMVAL/ACEVAL, the AMRAAM OUE, and the Multi-Source Integration test (also conducted in simulators). Yet, in reflecting on all that experience, Sparks felt that he had not once witnessed perfect sorting in 4-v-4 and more complex engagements.[232] "You're only about one-third as efficient as you think you are [at sorting in complex engagements], which is why you go out with a sexy missile and lose your ass anyway."[233] As Clausewitz wrote, in war "the simplest thing is difficult," and it is hard for normal efforts to achieve even moderate results.[234] Such observations go far to explain why even small SA deficits relative to the opposition have been statistically more dominant in engagement outcomes than differences in aircraft, weapons, force ratios, or other conditions such as having help from GCI. It also strongly suggests that friction's influence on outcomes in air combat during World War II was not noticeably different in Korea's "MiG Alley," the Vietnam War, the Middle East in 1967, 1973, and 1982, or even in *Desert Storm*. In this sense, general friction's "magnitude" does not appear to have diminished noticeably over the course of all the technological advances separating the P–51 from the F–15.

Could information technology be used to mitigate this longstanding pattern of very low sorting efficiencies in complex engagements arising from seemingly small lapses in situation awareness? Early experience in 4-v-4 and more complex engagements with the recently fielded Joint Tactical Information Distribution System (JTIDS) indicates that the answer is "yes." JTIDS not only provides integrated, all-aspect identification of friendlies and hostiles based on available information, but even displays targeting decisions by others in one's flight. The aggregate gains in air-to-air effectiveness resulting from these improvements in situation awareness and sorting have been nothing less than spectacular. During *Desert Storm,* F–15Cs, aided in most cases by E–3A Airborne Warning and Control Systems (AWACS) aircraft, downed 28 Iraqi fighters without a single loss, including 15 kills from engagements that began with BVR shots.[235] When JTIDS–equipped F–15s flew against basically the same fighter/AWACS combination that had done so well in the Gulf War, the JTIDS "information advantage" enabled them to dominate their opponents by exchange ratios of four-to-one or better.[236] Hence technology, properly applied, can certainly manipulate the differential in friction between opposing sides to one's advantage at the tactical level.

This conclusion suggests a corollary concerning nontechnological stratagems for gaining tactical advantage that, while deserving mention, will not be argued at length. If advances in information technologies alone, when focused on root problems such as situation awareness, can provide a four- or fivefold advantage in air-to-air exchange ratios, then it seems plausible to expect that superior tactics, training, employment concepts, or even organizational arrangements would also provide substantial margins of advantage at the tactical level as well. Perhaps improvements in tactics or training could even provide margins of superiority comparable in magnitude to the initial experience with JTIDS–equipped F–15s, although this extension of the hypothesis would have to be confirmed empirically.

The implication that *cannot* be drawn from JTIDS experience, however, is that friction has been permanently eliminated. If adversary forces fielded a system comparable to JTIDS, then the burden of achieving superior situation awareness and sorting in air-to-air would fall back on the "manual" abilities of human brains to absorb, interpret, and act upon automated information about who is where and doing what more quickly or more effectively than the opponents (or both). Exactly how frictional imbalances might ultimately manifest themselves in this technologically altered set of conditions is hard to anticipate. What can be said with confidence, though, is that by reducing the aspects of friction we have been discussing with improved information systems, friction will probably manifest itself in other ways or in areas that we may not even be able to predict. There are two reasons for this conclusion. First, new technology amounts to introducing novelty into the combat area, and the indirect and second-order consequences of novelty within the context of human interactions are seldom, if ever, fully predictable. Second, if both sides have access to the novelty or innovation—in this case JTIDS—then transforming the resulting SA and targeting data into knowledge and action better or quicker than the opponents will still ultimately be taking place in the same sort of gray matter that members of our species have been carrying around in their skulls for the last 45,000 to 90,000 years. Both sides will have improved compared to where they were without JTIDS, but the relative margin of advantage will fall back to differences between the men in the machines.

Chapter 10

Nonlinearity and a Modern Taxonomy

All but one of the historical and conceptual elements necessary for the fourth and final task of this paper—recasting general friction in modern terms—have now been introduced. The sole outstanding item is the concept of nonlinearity as it has come to be understood in fields like mathematics and physics since the early 1960s. By revealing how small differences in inputs can make large differences in outcomes, nonlinear dynamics will not only complete the task begun in chapter 6 of building a case for friction's undiminished persistence in future war, but also furnish the last conceptual elements needed to update and extend Clausewitz's original concept.

Nonlinear science has been deferred until now mostly to avoid burdening the exposition any earlier than necessary with a subject that some readers may find unfamiliar, difficult to grasp, or simply alien to the subject at hand. As mentioned in chapter 4, Clausewitz himself was not the least shy about appropriating concepts like friction and center of gravity from the physics of his day to illuminate the phenomena of war. Furthermore, Alan Beyerchen argued convincingly not only that Clausewitz himself perceived war "as a profoundly nonlinear phenomenon . . . consistent with our current understanding of nonlinear dynamics," but also that the prevalence of a *linear* approach to war by most students of the subject "has made it difficult to assimilate and appreciate the intent and contribution of *On War*."[237] This author's experience has also confirmed that attempts to apply the ideas of nonlinear science to the study of war continue to be met with resistance, if not incomprehension, for precisely the reason Beyerchen cited: the widespread predominance of linear modes of thought. Hence, it seemed wise to defer nonlinearity until all the other evidence and arguments suggestive of its relevance had been deployed.

What is nonlinear science all about? The core ideas are not hard to describe. Nonlinear dynamics arise from repeated iteration or feedback. A system, whether physical or mathematical, starts in some initial state. That initial state provides the input to a feedback mechanism which determines the new state of the system. The new state then provides the input through which the feedback mechanism determines the system's next state, and so on. Each successive state is causally dependent on its predecessor, but what happens to the system over the course of many iterations can be more complex and less predictable than one might suppose. If the nonlinear system exhibits *sensitive* dependence on initial or later states, then at least three long-term outcomes are possible: (1) the system eventually settles down in some single state and remains there despite further iterations (long-term stability); (2) the system settles on a series of states which it thereafter cycles through endlessly (periodic behavior); or (3) the system wanders aimlessly or unpredictably (so-called chaotic behavior). In the third case, detailed predictability of the actual state of the system can be lost over the course of a large enough number of iterations.[238] Chaotic behavior, however, should not be confused with randomness. Successive tosses of a coin remain the exemplar of a random process; if the coin is not biased, then the probability of either "heads" or "tails" on one's next toss is 50 percent. The paradigmatic example of a chaotic process, by contrast, is a "flipperless" pinball machine of infinite length. Edward Lorenz has characterized its behavior as being sensitively dependent on a single "interior" initial condition, namely the speed imparted to the pinball by the plunger that players use to put each ball into play.[239] On this view, *chaos* may be described as "behavior that is deterministic, or is nearly so if it occurs in a tangible system that possesses a slight amount of randomness, but does not *look* deterministic."[240]

The "mathematics of chaos" that has been used since the early 1960s to explain the sort of nonlinear dynamics exemplified by Lorenz's infinite pinball machine can be easily demonstrated using a personal computer or a programmable calculator to explore a simple nonlinear equation such as the "logistic mapping," $x_{n+1} = kx_n(1 - x_n)$ (where the variable x is a real number in the interval [0, 1], and the "tunable" constant k can be set between 1 and 4).[241] Depending on the choice of k, the logistic mapping exhibits all three of the long-term outcomes just described: stable, periodic, and chaotic behavior. Unfortunately, those uncomfortable with mathematics and programming languages (however "user friendly") are easily deterred from such "experiments" even though, for the very simplest nonlinear functions, the requisite calculations do not require more than the arithmetic of real numbers. Yes, as a practical matter the amount of repetitive number crunching involved in any serious exploration demands machine assistance, and one does have to be meticulous about the number of places to the right of the decimal point to which calculations are carried.[242] Still, the mathematics of elementary nonlinear functions like the logistic mapping are readily accessible to anyone willing to invest a modest amount of time and effort.[243]

The mathematics aside, nonlinearity has a crucial contribution to make toward completing the case for the view that general friction will persist more or less undiminished in future war regardless of technological developments. Specifically, the role nonlinearity plays is to close the door once and for all to the sort of fully predictable (at least in principle), clockwork universe advocated most persuasively during Clausewitz's lifetime by Pierre Simon de Laplace, a mathematical physicist.

The idea that the subsequent motions and effects of physical phenomena could be completely predicted on the basis of their earlier states was first argued at length in the 1750s by the Jesuit priest Roger Boscovich.[244] However, it was Laplace who, more than anyone else, seemed to make good on this heady promise. At an early age, he set himself the task of tying up the loose ends of the Newtonian enterprise. Using the improved calculus developed by various colleagues, particularly Joseph-Louis Lagrange, Laplace was widely perceived to have "removed all the known errors from, and explained all known anomalies in, the Newtonian cosmology and physics."[245] Whereas Isaac Newton had never been fully convinced of the stability of the solar system, suggesting that it might require some divine correction now and again,[246] Laplace eventually claimed to have proven "that every known secular variation, such as the changing speeds of Saturn and Jupiter, was cyclic and that the system was indeed entirely stable and required no divine maintenance."[247] Laplace also completed the theory of tides and solved another of Newton's famous problems, the deduction from first principles of the velocity of sound in air.[248] This unbroken string of triumphs in removing all the known anomalies in Newtonian mechanics led Laplace to conclude that the universe was rigidly deterministic in the spirit of Boscovich.

Laplace's clearest expression of this wholesale mechanization of the world picture can be found in *Essai philosophique sur les probabilitiés* [*Philosophical Essay on Probabilities*], which is a lucid nontechnical introduction to his principal work on the laws of chance, the *Théorie analytique des probabilitiés.*[249] "Given for one instant," he wrote:

> an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who compose it—an intelligence sufficiently vast to submit these data to analysis—it would embrace in the same formula the movements of the greatest bodies of the universe and those of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes. . . . The curve described by a simple molecule of air or vapor is regulated in a manner just as certain as the planetary orbits; the only difference between them is that due to our ignorance.[250]

On Laplace's understanding of reality, the operation of the universe, down to the most minute details and the smallest particles, is strictly determined by quantitative, predictive, mathematical laws. The world is quite literally a giant clockwork. To Laplace's so-called demon—meaning a sufficiently vast intelligence with sufficiently accurate and complete data about the universe at any point in time—all past and future states are calculable. Regardless of human ignorance or shortcomings in such matters, the mathematical laws of nature leave nothing to chance, not even combat outcomes or the emergence and evolution of biological life on Earth.[251]

The difficulty with this Laplacian outlook is not, of course, its plausibility or enduring appeal. By the beginning of the 20th century the vast majority of working physicists accepted "Laplacian determinism"—meaning causality plus long-term predictability—as a well-established scientific fact, and many people still do so today. The problem is that the universe we happen to inhabit is not broadly deterministic in the full sense Laplace meant—not even quantitative domains like physics and pure mathematics. There are processes like the Earth's tides and solar eclipses that can, barring unforeseen perturbations, be highly periodic and, hence, precisely predictable and precisely retrodictable across the majority of their dynamic range. However, there are also processes such as the evolution of the precise weather conditions at a given location on the Earth (temperature, winds, humidity, cloud conditions, the presence or absence of precipitation, etc.) that are so sensitive to the slightest disturbances or differences in initial conditions that detailed predictability is generally lost over time spans as short as 2 weeks.[252] While strongly nonlinear processes like long-term weather prediction are "deterministic" in the restricted or narrow sense of being causally determined, they predominantly exhibit long-term unpredictability that is inconsistent with full-blown Laplacian determinism. At best, these sorts of highly nonlinear processes harbor occasional islands of predictable behavior within a sea of unpredictability.[253]

This untidy situation reared its head early in the development of Newtonian physics. During the drafting of the first edition of *Principia Mathematica,* which appeared in 1687, Newton ran into difficulties moving from the problem of two bodies mutually attracted to one another by gravitation, which he easily solved, to the problem of describing the dynamics of many such bodies (the many-body problem).[254] In the summer of 1694 he returned to this problem in the form of the dynamics of the moon moving about the Earth, which was in turn orbiting the sun (the three-body problem).[255] Once again, though, Newton's achievements fell short of his aspirations. In retrospect, his difficulties with the irregularities of lunar motion are wholly understandable. As we now know, the three-body problem "does not admit a general analytic solution."[256] So his renewed efforts in 1694–1695 to find such a solution to the "inequalities" in the moon's orbit were doomed to failure, just as they had been in 1685–1686 when he was laboring to complete the first edition of *Principia Mathematica.* The problem he labored to solve was literally an impossible one in the sense in which Newton aspired to solve it.[257]

Again, Laplace thought he had proved that the observed perturbations of the planets were periodic rather than cumulative: They would "repeat themselves at regular intervals, and never exceed a certain moderate amount," thus substituting dynamic stability for divine intervention.[258] Unfortunately, physicists no longer consider Laplace's proof of the stability of the solar system rigorous, and "all attempts to make it so have failed."[259] Indeed, in recent years evidence has been accumulating to show that the orbit of Pluto, and the solar system as a whole, appear to be unstable or chaotic on time scales of 4 million to 20 million years.[260]

The first individual to recognize that the three-body problem included unstable or nonperiodic behavior was Poincaré. In an 1890 essay he showed that a gravitational system involving only three bodies would not always give rise to predictable or periodic motion. Specifically, in the case of an idealized form of the three-body problem in which the third body is vastly smaller than the other two, Poincaré discovered motion so complex and irregular—*homoclinic tangles,* to use the technical term—that he did not even attempt to draw the corresponding figure.[261] This "chaotic" behavior is "fundamental" or built in; neither "gathering more information," nor processing it better, will eliminate the unpredictability.[262] As

Poincaré wrote in 1903 of chance in the sense of causes too small to be discernible giving rise to large, noticeable effects:

> A very small cause which escapes our notice determines a considerable effect that we cannot fail to see, and then we say that the effect is due to chance. If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. But even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation *approximately.* If that enabled us to predict the situation with *the same approximation,* that is all we require, and we should say that the phenomenon had been predicted, that is governed by laws. But it is not always so; it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon.[263]

The seminal experiment that first showed chaos had physical as well as mathematical reality was carried out on superfluid helium by Albert Libchaber and Jean Maurer at the École Normale Supérieure in the mid-1970s. As Mitchell Feigenbaum declared when he saw Libchaber's jagged graph of a period-doubling cascade in the waves traveling up and down the vortices which heating created in Libchaber and Maurer's tiny experimental device: "The moment Albert did his experiment, and chaos showed up in a real thing, not to mention in a fluid, it completely changed the reaction of the [physics] world [to chaos]."[264] Since then, scientists have confirmed the kind of chaotic[265] or unpredictable behavior that is the essence of contemporary nonlinear dynamics in a wide range of physical phenomena, including electronic circuits, mechanical and electromechanical systems, hydrodynamics, acoustics, optics, solid-state physics, biology, and even ecology.[266] Chaotic behavior, which lies between order and disorder, is quite widespread in the real world, if not fairly ubiquitous. Granted, stable and periodic dynamics, as exemplified by the Earth's tides, are also widespread. Even a "nonlinear" system like the logistic mapping exhibits stable or periodic behavior over most values of the tunable parameter *k;* only for *k* greater than 3.57 or so[267] (depending on the computer and program being used) does truly unpredictable, chaotic behavior ensue. That said, pockets or areas of chaos infect a wide range of physical phenomena, and within those "chaotic regions" detailed predictability is lost. In this sense, chance abounds there.

What bearing has the discovery of nonlinearity's physical reality on friction in future war? Clausewitz wrote of war that no other human activity "is so continuously or universally bound up with chance" and suggested that war most resembles a game of cards in its sensitivity to chance.[268] He and Scharnhorst believed that chance (*Zufall*)[269] could not be eliminated from military affairs. Clausewitz identified chance events as an explicit source of general friction, although he did not (and could not) explain how small differences from what is expected or predicted could potentially turn success into failure and vice versa. What the empirical fact of nonlinear dynamics does is to explain how such small differences or "chance" occurrences of "the kind you can never really foresee" can give rise to long-term unpredictability.[270] Laplace believed that human judgments about chance and probability were simply the result of ignorance. In many cases, including games of chance like cards, he felt that we simply do not know enough, or have enough calculation time, to predict the outcomes. Expressed in the language of nonlinear dynamics, Laplace's presumption is that human ignorance prevents us from completely eliminating tiny differences between our representations of phenomena and their actuality. If, however, these small differences cannot be eliminated, then nonlinear dynamics explain how global or macroscopic unpredictability can arise from the structural dynamics of iterated feedback when the feedback function exhibits, in at least some part of its domain, extreme sensitivity to initial or later conditions. Since there is increasingly persuasive evidence from a number of fields, especially mathematical logic and physics, that any coherent or formal system we develop "to represent or deal with large portions of reality will at best represent or deal with that reality incompletely or imperfectly," it appears that these differences and mismatches cannot be eliminated.[271] Consequently, the existence of nonlinear systems confirms some of the deepest insights Clausewitz and Scharnhorst had into the nature of combat processes and the fundamental role of chance in those processes. It also suggests that unforeseen and unforeseeable differences in initial or later conditions—which, on present evidence, cannot be wholly eliminated even by Laplace's demon—allow us to subsume chance within the framework of nonlinearity.

How might these insights into the connections between nonlinearity and at least two components of general friction help us recast the concept in more modern terms? Perhaps the most thought-provoking piece of research bearing on this question was carried out by James Dewar, James Gillogly, and Mario Juncosa of The Rand Corporation. Their aim was to see if nonlinear effects arising from "mathematical chaos" could be demonstrated in a simple computer model of land

Table 1: Exemplar of a Simple Combat Model

Parameter	**Blue**	**Red**
Initial troop strength	B_o	R_o
Combat attrition calculation	$B_{n+1} = B_n - R_n/2048$	$R_{n+1} = R_n - B_n/512$
Reinforcement threshold	$R_n/B_n \geq 4$ *or* $B_n < 0.8\ B_o$	$R_n/B_n \leq 2.5$ *or* $R_n < 0.8\ R_o$
Reinforcement block size	300	300
Maximum allowable reinforcement blocks	5	5
Reinforcement delay (time steps)	70	70
Withdrawal threshold	$R_n/B_n \geq 10$ *or* $B_n < 0.7\ B_o$	$R_n/B_n \leq 1.5$ *or* $R_n < 0.7\ R_o$

Source: James A. Dewar, James J. Gillogly, and Mario L. Juncosa, "Non-Monotonicity, Chaos, and Combat Models," The Rand Corporation, R–3995–RC, 1991.

combat.[272] Their point of departure was the fact that computer models of combat often produce "nonintuitive" results, by which they meant "non-monotonicities in which a capability added to the side of one combatant leads to a less-favorable result for that side."[273] Since such puzzling behavior in computer models can arise from other numerous sources than nonlinearity—including round-off error, the wrong step size (timestep granularity), or delayed feedback—Dewar, Gillogly, and Juncosa chose a class of very elementary "Lanchester square law," attrition models that were designed to facilitate the elimination of such alternative sources of nonlinear behavior.[274] As the exemplar in table 1 indicates, this class of combat models also included reinforcement criteria based on the state of the battle at the end of a given step. This feature was a mathematical surrogate for human decisionmaking (or intervention) in the battle in response to the attrition suffered by both sides.

What would constitute intuitive and unintuitive, or monotonic and nonmonotonic, behavior in such a model? Dewar, Gillogly, and Juncosa offered the following characterization. As an example of monotonic behavior, fix Blue's initial strength at 830 troops and allow Red's initial strength to vary from 1,500 to 3,500 troops. Each value of R_o represents a separate "battle" from which a winner is determined when one side or the other withdraws at the end of some step. In this particular case, the behavior is exactly what one would intuitively expect and desire. Blue wins from R_o = 1,500 until R_o = 2,696; thereafter, Red wins all the battles; the situation appears to be entirely linear. However, with B_o = 500 and R_o varying from 700 to 1,800, seriously nonmonotonic behavior ensues: "Red wins when starting with as few as 884 troops, loses when starting with as many as 1,623 troops, and suffers a surprising number of reversals of fortune in between."[275] This unpredictable flip-flopping of which side wins as R_o varies from 884 to 1,623 troops is what constitutes unintuitive or nonmonotonic behavior.

What did Dewar, Gillogly, and Juncosa conclude about mathematical chaos in this type of model? After eliminating computational and input sources of nonintuitive behavior such as roundoff error and time-step granularity, they were able to demonstrate nonmonotonicity in a version of the underlying model they termed the "force-ratio-only mapping":

> Specifically, in a simple model with unlimited reinforcements, we have shown for a specific decision (when to call in battle reinforcements) based on the state of the battle (specifically, on the ratio of the opposing forces numerical strengths) that the underlying dynamics of the model satisfy four mathematical conditions characteristic of chaotic systems. . . . The "misbehavior" of this model is structural rather than computational, it is in the nature of the phenomenon being modeled—decisions based on the state of the battle.[276]

They further noted that if the reinforcement decisions are "scripted" so that they are no longer a function of the state of the battle, then "the nonlinearities, the chaos, and the nonmonotonicities generally disappear."[277] What implications, if any, can we draw from this research concerning friction in future war? Dewar, Gillogly, and Juncosa were reluctant to make any inferences about real war as opposed to war on paper based on the mathematical features of the force-ratio-only mapping:

> Historic battles have been known to hinge on very subtle effects of decisionmaking and have been described as "chaotic." This research holds out the promise that mathematical chaos and the chaos of war might be related. As a strong caveat here, it is too easy to presume that they are necessarily connected. Whether or not the behavior in our simple model is akin to behavior in a real battle is an interesting question but one that requires serious thought and research.[278]

This paper seeks to furnish precisely the serious thinking and historical research that Dewar, Gillogly, and Juncosa recommended prior to linking mathematical chaos in their simple combat model to something like the general friction manifested by real war. Given the complexities of actual combat, this sort of linkage need not insist that decisionmaking in the force-ratio-only mapping faithfully models any concrete instances of decisionmaking in actual combat. Nevertheless, nonlinear behavior has been confirmed in a wide range of physical processes. Thus, the demonstration of nonmonotonicity in a mathematical model of combat, however simplified, is certainly suggestive as to how effectiveness, results, and overall outcomes in war might be unpredictable.

One can go further. As first noted in chapter 4, Clausewitz insisted in book two that the very nature of dual interaction between opposing sides was bound to make interaction unpredictable.[279] Nonlinear dynamics in general, and Dewar, Gillogly, and Juncosa's results with their force-ratio-only mapping in particular, reveal how inspired Clausewitz's observation was. It is no longer a mystery to explain how unpredictability in war can arise from human purposes and decisions without any suspension of causality. In nonlinear systems that are sensitively dependent on initial or later conditions, the interaction of iterative feedback can so magnify the smallest of differences, including those stemming from human decisions, as to render combat outcomes *structurally* unpredictable. In other words, while technological advances might temporarily mitigate general friction, they could neither eliminate it nor substantially reduce its potential magnitude.

With these insights added to those of earlier sections, general friction can now be reconstructed in modern terms. The presumption underlying this specific reconstruction is that general friction ultimately arises from three elementary sources: (1) human beings and their purposes, (2) the spatial-temporal inaccessibility of key information in military affairs, and (3) the unpredictability of chaotic processes and interactions, especially of interactions with the enemy. This hypothesis suggests the following list of general friction's sources as a late 20th-century alternative to the eight "Clausewitzian" sources listed at the end of chapter 4:

- constraints imposed by human physical and cognitive limits, whose magnitude and effects are inevitably magnified by the intense stresses, pressures, and responsibilities of actual combat
- informational uncertainties and unforeseeable differences between perceived and actual reality[280] stemming, ultimately, from the spatial-temporal dispersion of information in the external

environment, in friendly and enemy military organizations, and in the mental constructs of individual participants on both sides

- the structural nonlinearity of combat processes which can give rise to the long-term unpredictability of results and emergent phenomena by magnifying the effects of unknowable small differences and unforeseen events (or, conversely, producing negligible results from large differences in inputs).

At least three observations are in order to help explain and motivate this reconstruction of general friction. First, this revised list is shorter than any of those offered in chapter 4. The reason is that the reconstruction attempts to focus on the most fundamental or elementary sources of friction. Derivative sources, such as poor intelligence or human reactions to the imminent threat of death or mutilation inherent in combat, are clearly implied, but need not be called out separately.

Given the emphasis that Scharnhorst and Clausewitz both placed on chance,[281] it may be surprising to see chance, too, apparently reduced to a derivative source of friction. In this instance, however, a more accurate description would be that chance has been distributed across all three of general friction's sources. The participation of finite human beings, the dispersal of explicit and tacit information in war, and unpredictabilities of nonlinear processes give rise to surprising and unforeseen discrepancies that cannot be eliminated, and we are right to gather them, in all their diverse guises, under the notion of chance. Poincaré's view was that even if human ignorance could be set aside, chance would still manifest itself in several guises. These unavoidable manifestations of chance include imperceptible small causes that have large and noticeable effects, the reverse in which great differences in inputs yield small differences in results, and causes either too complex or too numerous for us to grasp.[282] When nonlinear processes amplify such structural differences and uncertainties, they render large-scale results unpredictable and give rise to ever larger differences between what we expect and what happens that, in turn, feed back into nonlinear processes. Chance in its various guises, therefore, is rendered pervasive but, once again, without letting go of causality.

Second, the reconstructed list of friction's sources suggests a way of dealing with a recurring objection to the entire concept of general friction. The objection, which has been consciously ignored to this point, is that the unified concept of a general friction (*Gesamtbegriff einer allgemeinen Friktion*) embraces so much of war that it does not provide a very precise instrument for analyzing the phenomena at issue.[283] If we return to the notion of general friction as the entire panoply of factors that distinguishes real war from war on paper, Clausewitz's reason for pulling so diverse a collection of things together under a single concept is clear: general friction was the bridge between war in the abstract and war in reality. Still, the objection suggests that some parsing of his unified concept into separable-but-fundamental components could prove fruitful. Whether the three proposed in this chapter will do so remains to be seen. However, constraints on military operations stemming from the physical and cognitive limits of human participants, uncertainties rooted in the spatial-temporal distribution of the information on which action in war is unavoidably based, and the unpredictabilities inherent in nonlinear dynamics seem more precise and, potentially, more promising as conceptual tools than any of the decompositions of general friction in chapter 4.

Third, the principal merit of the late 20th-century recasting of Clausewitzian friction proposed in this chapter is the transparency it gives to general friction's place in military affairs. Human limitations, informational uncertainties, and nonlinearity are not pesky difficulties better technology and engineering can eliminate, but *built-in* or *structural* features of the violent interaction between opposing polities pursuing incommensurable ends we call war.

As a consequence, general friction's *potential* to *dominate* outcomes, as proposition I in chapter 8 implied, seems likely to persist regardless of what changes technological advances bring to pass in the means of combat. Why? Because at least one of the root sources of friction lies, when all is said and done, not in the weapons we wield but in ourselves. The presence of humans in the loop—with all the diverse frailties, physical and cognitive limits, purposes, and decisions which their presence and participation entail—alone seems sufficient to render friction impossible to eliminate entirely and, in all likelihood, extraordinarily difficult to reduce greatly in any permanent sense. At the same time, human participation cannot be isolated from the spatial-temporal distribution of information on which combatants act, and those actions, in turn, involve processes that can be highly nonlinear. On this reconstruction of Clausewitz's concept, therefore, general friction arises, to paraphrase Wohlstetter, from fundamental aspects of the human condition and unavoidable unpredictabilities that lie at the very core of combat processes.

Chapter 11

Implications for Future War

Our original point of departure was the notion that foreseeable advances in sensor technologies and information systems may (or will) enable the side exploiting them more effectively to eliminate its fog of war while turning the opponent's into a "wall of ignorance."[284] Implicit in this view is the presumption that "knowing everything that is going on" in a volume of battlespace is a problem that technological advances will eventually "solve" once and for all.[285]

Better weaponry, like superior training or operational concepts, can certainly provide leverage for shifting the relative balance of friction decidedly in one's favor, especially against an adversary lacking comparable means altogether. The potential that two prototype JSTARS E–8s demonstrated during the Gulf War to track enemy vehicular movements over large areas of terrain was not only something ground commanders had seldom, if ever, enjoyed heretofore but also was truly breathtaking in the synoptic vision of the battlespace it provided, and no one in their right mind would consciously prefer to go to war with inferior equipment. However, driving one's own friction to zero while, simultaneously, rendering the enemy's effectively infinite is not, at its core, a technical problem.

In the first place, even in an information-rich environment, there is only so much that any human can absorb, digest, and act upon in a given period of time. The greater the stress, the more data will be ignored, noise mistaken for information, and information misconstrued, and the greater will be the prospects for confusion, disorientation, and surprise. Second, the spatial and, especially, temporal distribution of information relevant to decisions in war means that some key pieces will be inaccessible at any given time and place. Those who have held senior positions in corporations or military services need only reflect on how much they did not know about what was taking place in their own organizations to appreciate the reality of information being spatially or temporally inaccessible (or both). Third, the empirical fact of nonlinear dynamics, when coupled with the unavoidable mismatches between reality and our representations of it, reveal fundamental limits to prediction, no matter how much information and processing power technological advances may one day place in human hands. However fervently one may wish that Laplace had been right in viewing the world as a predictable clockwork, this outlook no longer appears defensible in the 21st century either in practice or in theory.

To push the implications of these three points a bit further, the ways in which friction will manifest itself in future conflicts, too, undoubtedly involves human foibles, inaccessible information, and nonlinear dynamics feeding on the enormous variability of combat interactions. No matter how much technological advances may constrain general friction in some areas, the evidence and arguments mounted in the second half of this paper suggest that it will simply balloon in others—often in ways that we cannot anticipate, much less predict. Technological innovation in the means of combat introduces novelty into warfare, and the indirect effects and second-order consequences of novelty are never predictable with any high degree of certainty.[286] Who among International Business Machines executives genuinely foresaw in the early 1980s that, first, minicomputer servers and, then, personal computers would so rapidly erode the company's traditional mainframe business that "Big Blue" would post a record $5 billion loss in 1992, lay off tens of thousands of workers, and lose forever its earlier dominance of the computer industry?[287] Who could have predicted that the main benefit the Israelis would find in their early battlefield experience with remotely piloted vehicles would turn out to lie in tracking their own forces rather than in locating enemy targets?[288] And who would have guessed that the invention of the post box would contribute to women's liberation by enabling new generations of young ladies to post letters to their sweethearts without their parents' knowledge?[289] The social consequences of technological innovation are especially hard to predict, and war is, after all, a social enterprise.

Looking ahead to how friction may one day manifest itself in future conflict, one should also consider the susceptibility of "digitized battlespace" to subtle forms of misinformation and deception. The more the U.S. military embraces digital networks and synthetic environments, the greater will be the potential for subtle manipulation of our situation awareness by a sophisticated adversary, to say nothing of simply confusing ourselves with an overabundance of information. Indeed, it is entirely possible that applying information technologies to future war will expand, perhaps enormously, the potential for deception. Similarly, the more "transparent" battlespace becomes, the more human participants may feel pressured to make life-or-death decisions in shorter and shorter spaces of time.[290] Hence, there appear to be good reasons to expect that the wholesale introduction of state-of-the-art information technologies into future war, far from eliminating Clausewitzian friction, will simply give rise to new and unexpected manifestations.

Yet, despite all that has been said, might one not still hold out for some reduction in the overall "magnitude" of Clausewitzian friction as advanced sensors and information systems make ever greater inroads into the conduct of war? As initially broached at the end of chapter 5, this question raises a host of difficulties concerning the actual measurement or quantification of frictional differences between opponents. Decision-cycle times and viable options in possibility space were introduced to try to put some substance behind the intuition that general friction's magnitude in and influence on *Desert Storm* in 1991 did not seem to be noticeably less than its magnitude and aggregate influence had been during the German assault on France and the Low Countries in May 1940. If anything, the differential in attractive options may have been somewhat less in 1991 than in 1940 because the Iraqis had more "maneuver room" than the Allies, despite the coalition's one-sided access to advanced sensors and information systems, including satellite imagery and JSTARS data.

Whether notions such as decision-cycle times and viable options in possibility space can be extended in the future to lend more precision and completeness to these judgments remains to be seen. On the one hand, they appear useful in supporting judgments about general friction's rough magnitude at different times in this century, and those judgments seem comparable to the kinds of conclusions that biologists such as Richard Dawkins have drawn about "large" versus "small" leaps in genetic space.[291] On the other hand, Alan Beyerchen's caution that attractive option sets for either adversary over the course of a conflict are best envisioned as a dynamic "shape" in a multidimensional phase space, rather than as a single number, indicates the immense difficulties of precise quantification in concrete situations. Of course, to repeat a point made in chapter 5, cycle times and options in possibility space do not capture all aspects of general friction. The matter of a good fit between ends and means in war, for instance, falls outside both of these candidate metrics. Hence decision-cycle times and option sets in possibility space do not exhaustively quantify the waxing and waning of general friction during military operations; instead, they merely suggest a direction in which progress toward some degree of quantification appears possible.

A further thought, however, is that we may be longing for simple, quantitative metrics where none are possible. One can measure temperature or mass readily enough with a single number, but social utility or the second-order consequences of wartime decisions years afterward may be another matter entirely given the spatial-temporal distribution of the relevant information and the limits of human cognition.

A related point that emerged most vividly in chapter 9 is that high situation awareness by one side need not be equivalent to a favorable balance of friction. Crystal-clear awareness that defeat or death is imminent is of little value if one's option set of viable responses has reached the vanishing point. Even perfect information is useless if there no longer remain real alternatives to the defeat or destruction of one's forces. A comparatively high level of battlespace awareness vis-à-vis the opponent may be—barring the "unbarrable" exception of Clausewitz's *Glück und Unglück* (good luck and bad)—a necessary condition for success in war, but it is certainly not a sufficient one.

What might be some of the more salient implications of general friction's relatively undiminished persistence in future war for military theory? To begin with a minor but unavoidable point, there has been some resurgence of anti-Clausewitzian sentiment since the fall of the Berlin Wall in 1989. Martin van Creveld, to cite one example, has argued that because future wars will be low-intensity conflicts waged by nonstate actors against whom the "modern regular forces" of states like Israel, Britain, Russia, and the United States are "all but useless," the age of large-scale, conventional warfare on the Clausewitzian, "trinitarian" model appears to be "at its last gasp."[292] This view, whatever its merits insofar as the character of war in the post-Cold War era is concerned, does not really touch the subject of this paper, general friction. Indeed, van Creveld himself recognizes that "inflexibility, friction, and uncertainty" will continue to apply in future warfare, even if its new form does turn out to resemble most closely the more primitive kinds of conflict that preceded the Peace of Westphalia in 1648.[293]

The second point concerns what a scientific theory of warfare might be like. The four propositions advanced toward the end of chapter 8 are not such a theory, although they represent a plausible start should one choose to begin with the problem of friction in war. The recasting of Clausewitz's original concept in chapter 10 suggests that starting there would be a good idea since the three "frictional" components highlight some of the most enduring features of real war as opposed to war on paper. Emphasis on these kinds of "structural" features had its inspiration in the great clarity Scharnhorst and Clausewitz had concerning what actually occurred and reoccurred on the battlefields of their day. In this sense, their theoretical emphasis on friction, particularly as reconstructed in chapter 10, was as legitimately scientific as Darwin's notion of the evolution of biological species by means of natural selection.

Third, it is easy at this stage to clarify friction's place in Clausewitz's thought. On the one hand, the Prussian soldier and theorist has not been spared in this paper. Where his thinking about friction and related matters warranted correction, extension, or wholesale revision in light of later knowledge and military experience, changes have been made without hesitation. On the other hand, Richard Simpkin expressed the opinion in *Race to the Swift* that friction was, to his mind, "Clausewitz's most important contribution to military thought."[294] It turns out that John Boyd had reached the same conclusion by the spring of 1982 based on his willingness to connect Clausewitzian friction with the second law of thermodynamics.[295] At a minimum, this paper has shown how central the unified concept of a general friction (*Gesamtbegriff einer allgemeinen Friktion*) was to Clausewitz's understanding of war.

This paper, however, had a more ambitious goal: to build a case for the conclusion that general friction will continue to be central to future warfare regardless of technological changes in the means of combat. Perhaps the single most important theme woven into the tapestry of the essay's argumentation is summarized in proposition III in chapter 8: the realization that it is the differential between levels of general friction on both sides that matters in combat outcomes. If what counts in real war is not the absolute level of friction that either side experiences but the relative frictional advantage of one adversary over the other, then the question of using technology to reduce friendly friction to near zero can be seen for what it is: a false issue that diverts attention from the real business of war. Even comparatively small frictional advantages can, through nonlinear feedback, have huge consequences for combat outcomes, as the air-to-air experience detailed in chapter 9 confirms. Moreover, such relative advantages hinge fundamentally on: (1) constraints imposed by human physical and cognitive limits; (2) informational uncertainties and unforeseeable differences stemming from the spatial-temporal dispersion of information in the external environment, military organizations, and the brains of individual participants; and (3) the structural nonlinearity of combat processes.

One may or may not choose to gather these diverse structural features of combat and war under a single unified concept of general friction, as Clausewitz did. Nonetheless, they seem destined to remain the root sources of one side's relative frictional advantage over the other—even in the age of so-called information-based warfare. Consider, after all, how much would have to be overturned or rejected to conclude otherwise. Among other things, one would need to overthrow nonlinear dynamics, the second law of thermodynamics, the fundamental tenets of neo-Darwinian evolutionary biology, and all the limiting metatheorems of mathematical logic, including the famous incompleteness theorems by Kurt Gödel and the extension of Gödel's work by Gregory Chaitin to demonstrate the existence of randomness in arithmetic. No small task indeed!

Afterword

At the end of chapter 8, I suggested that evolutionary biology might offer a better exemplar for an overarching theory of war than quantitative or hard sciences such as physics. Behind that suggestion lay the suspicion that the parallels between the various levels of war and the hierarchy of biological organisms may be more than superficial. A key concept of evolutionary biology is *emergence*, meaning "that in a structured system, new properties emerge at higher levels of integration which could not have been predicted from a knowledge of the lower-level components."[296] Emergence, according to Ernst Mayr, is one of the two major pillars in the explanatory framework of modern biology, the other being the concept of genetic programs that evolve through natural selection.

Emergence is also the fundamental concept of the relatively new field of artificial life. Typical experiments in this field involve setting up artificial worlds or environments inside a computer. These worlds generally contain "agents, an environment, and rules that define and govern agent-agent, agent-environment, and environment-environment interactions."[297] Artificial life experiments then consist of allowing the world to evolve in order to see what happens. Here, too, emergence refers to "the appearance of higher-level properties and behaviors" possessed by the "whole" rather than by any of its individual parts, the point being that "an air molecule is not a tornado and a neuron is not conscious."[298] In one such artificial society created by Joshua Epstein and Robert Axtell and dubbed *Sugarscape*, macroscopic social patterns emerged such as agent "tribes" and "certain stable wealth distributions."[299]

What this line of thought suggests is that the most general aim of combatants at every level of combat—tactical, operational, and strategic—is to achieve emergent effects at the next higher level. This formulation not only recognizes the inherent uncertainties of combat interactions between opposing polities, military forces, and individual combatants, but also may offer a more fruitful point of departure for constructing a positive theory of war than the injunction in chapter 8 to seek frictional advantages over the opponent.

The various agents just mentioned—from opposing polities to individual combatants—can, of course, be understood as instances of complex adaptive systems. Indeed, because military units and polities contain individual humans, one ends up with complex adaptive systems inside other, higher-order complex adaptive systems. This perspective obviously parallels biological hierarchies.

In the first edition of this paper, I tried to base the case against a Laplacian understanding of combat processes on nonlinear dynamics. However, explicitly recognizing that in war the opposing sides at every level—from individual combatants to large forces, nations, and polities—are complex adaptive systems further reinforces the implication that friction is unlikely to be eliminated from future war regardless of technological advances. Artificial life experiments, whether of societies or opposing military forces, have consistently given rise to emergent properties and patterns that were unexpected based on examination of the rules governing their interactions. Or, expressed somewhat differently, the variability of combat interactions at a theater level is far greater than is commonly realized, as Paul Davis observed in the late 1980s.[300] Finally, to return to the argument in chapter 7, Hayek's claim that markets are fundamentally more efficient in allocating resources than central economic planners could ever be was based on viewing markets as an emergent order whose complexities and structures could not be fully foreseen by any individual or group of individuals. In other words, he saw markets as complex adaptive systems with emergent properties.

The salient feature of complex adaptive systems is how they handle information. The dynamical systems of physics, whether linear or nonlinear, process information strictly through mechanical iteration. By contrast, complex adaptive systems look for regularities or patterns that can be condensed into concepts or schemata describing aspects of reality.[301] In the case of individual biological organisms, the schemata are at least partly embodied in the organism's genome, and the success of genetic schemata is tested in the real world by the fitness for survival of the phenotype for which the genome is a recipe (not a blueprint). In the case of a military unit, its schemata reside in operational concepts, tactics and procedures, doctrine, organizational arrangements, and attendant cultures; mission orders, together with the enemy, provide selection pressures. However, neither individual combatants nor military units can realistically aspire to obtain complete or perfect information about a combat situation. The schemata on which they unavoidably act are, therefore, imbued not merely with uncertainties, but also with gaps and errors; they are inherently incomplete descriptions. Moreover, neither having more information, nor processing it faster, automatically translates into better decisions, especially under the stresses of combat, as Michael Schrage has rightly pointed out in both economics and military affairs.[302]

In closing, I append here two sets of observations, one concerning contemporary attitudes regarding Clausewitzian friction and the other regarding military theory. Those most strongly inclined toward Laplacian deterministic views of war remain unmoved by the arguments and evidence I offered in 1996 disputing the recurring hope that friction can be eliminated from future war by technological progress in the means of combat. As William Owens recently reasserted, changes in military affairs—based on technical advances in battlespace awareness, command, control, communications, computer systems, and intelligence (C^4I), and the precision use of force—challenge "all the hoary dictums about the fog and friction of war, and all the tactics, operations concepts, and doctrine pertaining to them."[303] To say the least, the two of us disagree on this matter, and I suspect we will continue to do so. To update my own viewpoint in light of post-*Desert Storm* combat experience, I saw no indications during the 78-day North Atlantic Treaty Organization air campaign in 1999 against the Federal Republic of Yugoslavia under Slobodan Milosevic that the technologies to which Owens appeals had made even the faintest progress toward eliminating general friction. As for Operation *Iraqi Freedom*, the growing difficulties that have beset American efforts to establish physical security, the rule of secular law, and a modicum of democracy throughout Iraq since the end of major combat operations in May 2003 provide eloquent testimony to the persistence of Clausewitzian friction.

On the other side of this debate, I was pleasantly surprised to discover a thoroughly Clausewitzian account of friction in *Joint Vision 2020*, the successor to *Joint Vision 2010*:

> Friction is inherent in military operations. The joint force of 2020 will seek to create a "frictional imbalance" in its favor by using the capabilities envisioned in this document, but the fundamental sources of friction cannot be eliminated. We will win—but we should not expect wars in the future to be either easy or bloodless.[304]

Equally encouraging is the list of sources or components of general friction in *Joint Vision 2020*:

- effects of danger and exertion
- existence of uncertainty and chance
- unpredictable actions of other actors
- frailties of machines and information
- humans.

All things considered, this list offers a reasonable taxonomy of general friction and maps readily into that offered in chapter 10. Especially noteworthy is the explicit inclusion of humans as a source of friction. Insofar as military units are literally complex adaptive systems with humans in the loop, it is hard to imagine how machines and information, which have their own frailties and limitations, can eliminate those inherent to human participants.

To reiterate the argument that runs the length and breadth of this paper, general friction arises from structural aspects of combat interactions so deeply and irretrievably embedded in violent interactions between humans-in-the-loop systems that technological advances cannot eliminate friction, although they can certainly alter its manifestations. The most concise formulation of the basis for this argument arises from considering the sources or components of general friction. Table 2 contains five different lists of those sources: two taken directly from book I of *Vom Kriege*; the expanded list I derived from a reading of *On War* that took friction to be so fundamental to the notion of war as it actually is that its components cannot be limited to those explicitly listed in book I; the account of friction's sources in *Joint Vision 2020*; and, lastly, the reconstruction of general friction I offered in chapter 10 in light of certain developments in late 20th-century science. Regardless of which list one prefers, the central claim is that, save for the two incomplete lists in the first column, each rendition of the components of friction can be mapped into the others without obvious loss or distortion. If one accepts this claim, then the persistence of Clausewitzian friction in future war follows almost by inspection of its sources.

Turning to military theory, in the 20th century, the British tank proponent J.F.C. Fuller, who is also widely credited with formulating the familiar principles of war (unity of command, the objective, the offensive, economy of force, mass, maneuver, surprise, simplicity, and so forth), tried as much as anyone to put military theory on something approaching a scientific basis.[305] Fuller aimed to do for war what Copernicus had done for astronomy, Newton for physics, and Darwin for natural history.[306] Unfortunately, his efforts were based on a Laplacian understanding of both

Table 2: Sources of General Friction

Clausewitz in Book I of *Vom Kriege*	**Author's Reading of *On War***	***Joint Vision 2020***	**Author's Reconstruction (1996)**
■ Danger ■ Exertion ■ Uncertainty ■ Chance or ■ Danger ■ Physical exertion ■ Intelligence ■ Friction	■ Danger ■ Physical exertion ■ Uncertainties and imperfections in the information on which action in war is based ■ Friction in the narrow sense of resistance within one's own forces ■ Chance events ■ Physical and political limits to the use of military force ■ Unpredictability stemming from interaction with an enemy ■ Disconnects between ends and means in war	■ Effects of danger and exertion ■ Existence of uncertainty and chance ■ Unpredictable actions of other actors ■ Frailties of machines and information ■ Humans	■ Constraints imposed by human physical and cognitive limits ■ Informational uncertainties and unforeseeable differences between perceived and actual reality ■ The nonlinearity of combat processes

scientific methodology and physical reality; as was true of Laplace, Fuller envisioned physics, along with other quantitative sciences, in terms of being able to predict the outcomes of thoroughly deterministic processes.[307] Given this error, it is hardly surprising that he was unable to provide an adequate foundation for what he termed a *science of war*. In this regard, John Morgan and Anthony McIvor have recently called for a reexamination of the longstanding principles of war, which they characterize as having been derived from the 19th-century combat experience.[308] Rethinking is clearly long overdue. However, the kinds of principles suggested in this essay are of a different type altogether from those advanced by Fuller.

A secondary theme in this paper was the notion that if one could reach an empirically grounded understanding of the role of friction in war, that understanding might also provide a basis for improving our theoretical description of war in general and combat interactions in particular. The four propositions offered in chapter 8 were intended as a friction-derived point of departure for advancing military theory beyond where Clausewitz left the subject in 1831. The additional principle proposed in this afterword—that the most general aim of combatants at every level of combat is to achieve emergent effects at the next higher level—could also be added to this list. The fact that deep disagreement still persists at the beginning of the 21st century as to whether technological advances can "lift the fog of war" suggests how little military theory has advanced since Clausewitz's death. The stark difference between the principles suggested herein and traditional principles of war only reinforces this view. A more satisfactory theory of war will certainly not resemble Newtonian physics.

Endnotes

[1] Hans Rothfels, quoted in Peter Paret, *Clausewitz and the State: The Man, His Theories, and His Times* (Princeton, NJ: Princeton University Press, 1976), 124, note 3. Clausewitz married Marie von Brühl in December 1810. Once married, Marie Clausewitz identified herself whole-heartedly with her husband's work and "acted as his amanuensis and after his death as his editor," presiding over "what still remain[ed] the complete edition of his works which she published in 1832–4" (Michael Howard, *Clausewitz* [Oxford: Oxford University Press, 1983], 8).

[2] Carl von Clausewitz, *Vom Kriege*, ed. Werner Hahlweg (Bonn: Dümmler, 1980), 265; Carl von Clausewitz, *On War*, trans. Peter Paret and Michael Howard (Princeton, NJ: Princeton University Press, 1976), 119.

[3] The March 1992 edition of *Air Force Manual 1–1: Basic Aerospace Doctrine of the United States Air Force* states that war is characterized by "fog, friction, and chance" (I, 2). The reigning view in the U.S. Army is that "[a]mbiguity, uncertainty, fog, friction, danger, stark fear, and chance . . . continue to describe accurately the conditions with which military forces have to contend and will continue to contend" (Gordon R. Sullivan and James M. Dubrik, "Land Warfare in the 21st Century," U.S. Army War College, Strategic Studies Institute, 4th annual conference on strategy, February 1993, 26). Also see U.S. Marine Corps, *Warfighting, Fleet Marine Field Manual 1*, March 6, 1989, 4–7.

[4] "[William A.] Owens Says Technology May Lift 'Fog of War': Breakthroughs Could Give Forces Total Command of Future Battlefield," *Inside the Navy*, January 23, 1995, 3. See also William A. Owens, "Introduction: The Emerging U.S. System of Systems," in *Dominant Battlespace Knowledge: The Winning Edge*, ed. Stuart E. Johnson and Martin C. Libicki (Washington, DC: National Defense University Press, 1995), 14–15; and Owens, "System-of-Systems: U.S.' Emerging Dominant Battlefield Awareness Promises To Dissipate the 'Fog of War'," *Armed Forces Journal International*, January 1996, 47. The meaning initially associated with Owens' notion of dominant battlefield awareness was that, by connecting largely existing sensors and shooters together via appropriate information and command-and-control systems, it should be possible to detect, track, and classify most (or all) of the militarily relevant objects moving on land, the surface of the ocean, through the air, or in space within a cube of battlespace some 200 nautical miles on a side.

[5] Michael J. Mazarr, Jeffrey Shaffer, and Benjamin Ederington, "The Military Technical Revolution: A Structural Framework," final report of the Center for Strategic and International Studies study group on military technical revolution, Washington, DC, March 1993, 58.

[6] While the ideas in this paper are the author's responsibility alone, Andrew W. Marshall encouraged exploration of the possibility that warfare might possess structural or built-in features that could not be wholly eliminated by advances in the means of combat. Marshall, however, was also willing to entertain the possibility that advances in the information aspects of conflict could substantially attenuate the magnitude of frictional impediments, particularly at the operational level of future war.

[7] Paret, *Clausewitz and the State*, 71, 74–75.

[8] Clausewitz to Marie von Brühl, September 29, 1806, quoted in Paret, *Clausewitz and the State*, 124. The three commanders in chief were King Frederick William III, who chose to accompany the army; Duke Karl of Brunswick, the nominal commander; and Prince Hohenlohe-Ingelfingen, who was given command of half the army. See Clausewitz, "From Observations on Prussia in Her Great Catastrophe," *Historical and Political Writings*, ed. and trans. Peter Paret and Daniel Moran (Princeton, NJ: Princeton University Press, 1992), 44. Scharnhorst was one of the two chiefs of staff, but "no one high or low in the congresslike headquarters of the army had the kind of confidence in him that his task demanded" (ibid., 53).

[9] Howard, *Clausewitz*, 14, 16; Clausewitz, "From Observations on Prussia," 63. Frederick II's desperate gamble in the first Silesian War (1740–1742) to seize the Austrian province of Silesia through an unprovoked lightning attack almost doubled the size of his small kingdom. See R.R. Palmer, "Frederick the Great, Guilbert, Bülow: From Dynastic to National War," in *Makers of Modern Strategy: From Machiavelli to the Nuclear Age*, ed. Peter Paret with Gordon A. Craig and Felix Gilbert (Princeton, NJ: Princeton University Press, 1986), 96. By the close of the Seven Years' War (1756–1763), which stripped France of her overseas empire, Prussia had become one of the main components in the European balance of power, even though its size and population were considerably smaller than those of the other major powers (ibid., 104–105). At Jena and Auerstädt, the French under Napoleon came close to eliminating Prussia as a state.

[10] Clausewitz, "Über das Leben und den Charakter von Scharnhorst," *Historisch-politische Zeitschrift, I* (1832), quoted in Paret, *Clausewitz and the State*, 71; also see Clausewitz, *Historical and Political Writings*, 90.

[11] Clausewitz, quoted in Paret, *Clausewitz and the State*, 191. The "little war" of detachments that was the subject of this lecture referred to the use of small units to guard an army, disrupt the enemy's forces, or gather intelligence.

[12] Paret, *Clausewitz and the State*, 197–198.

[13] Ibid., 202. Paret has argued that with the final section of Clausewitz's April 1812 essay to the Prussian crown prince, he had developed the word *friction* "into a comprehensive theoretical concept" for describing the vast gulf between theory and actuality in war (ibid.,197).

[14] Ibid., 148, 150, 156, 361–363.

[15] Ibid., 256; Clausewitz, *On War*, 119.

[16] Marie von Clausewitz, June 30, 1832, in Clausewitz, *On War*, 65.

[17] Paret, *Clausewitz and the State*, 202. On the view expressed in chapters 5–8, book 1, of *On War*, the diverse factors that distinguish real war from war on paper include the former's intense physical demands, its mortal danger, pervasive uncertainties, and the play given to chance in battlefield processes.

[18] In an unfinished note believed to have been written in 1830, the year before Clausewitz died, he offered this appraisal of the manuscript his widow published after his death under the title *Vom Kriege*: "The manuscript on the conduct of major operations that will be found after my death can, in its present state, be regarded as nothing but a collection of materials from which a theory of war was to have been distilled. . . . I regard the first chapter of Book One alone as finished. It will at least serve the whole by indicating the direction I meant to follow everywhere" (Clausewitz, *On War*, 70). In all probability, this chapter was the last part of *On War* that Clausewitz wrote before he died (Edward J. Villacres and Christoper Bassford, "Reclaiming the Clausewitzian Trinity," *Parameters* 25, Autumn 1995, 18).

[19] Paret calls this process *phenomenological abstraction* and associates it with Edmund Husserl's term *Wesenschau* (*Clausewitz and the State*, 357–358). However, this sort of analysis of pure concepts can be traced back at least to Immanuel Kant's *Critique of Pure Reason*, which was first published in 1781. There is no evidence that Clausewitz ever read Kant (ibid., 150). As Michael Howard has noted, the ideas that form the basis of Kantian philosophy—particularly the distinction between the ideal and its imperfect manifestations in the real world—were so much a part of Prussian intellectualism that Clausewitz did not need to read the critiques to be familiar with this (*Clausewitz*, 13–14). Regardless, Johann Gottfried Kieswetter, who was one of the permanent faculty at the Berlin Institute for Young Officers when Clausewitz was a member of the first class overseen by Scharnhorst (1801–1804), was an influential popularizer of Kantian philosophy and is usually credited with having "strongly influenced Clausewitz's awakening interest in philosophic method" (Paret, *Clausewitz and the State*, 69). Paret is sometimes inclined to discuss the method employed in *On War* in terms of Georg Wilhelm Friedrich Hegel's "dialectic of thesis and antithesis," but Clausewitz's analysis of the pure concept of war is probably closer to Kant than Hegel (ibid., 84, note 13).

[20] Clausewitz, *On War*, 77.

[21] Ibid., 78.

[22] Ibid., 85–86.

[23] Ibid., 119.

[24] Ibid., 120, 579.

[25] Marie von Clausewitz, quoted in Clausewitz, *On War*, 65.

[26] Charles Edward White, "The Enlightened Soldier: Scharnhorst and the *Militärische Gesellschaft* in Berlin, 1801–1805" (Ph.D. diss., Duke University, 1986), 19–26, 33–36.

[27] Paret, *Clausewitz and the State*, 62. "Scharnhorst," Howard has noted, "is rightly revered as one of the giants in the creation of Germany, a man as distinguished as a thinker and a statesman as he was as a soldier" (*Clausewitz*, 6).

[28] Clausewitz (and Gneisenau), "On the Life and Character of Scharnhorst," *Historical and Political Writings*, 89. This official biography of Scharnhorst was believed at the time to have been written by August Wilhelm Neidhardt von Gneisenau (1760–1831) but was "almost certainly written in collaboration with Clausewitz" (ibid., 85).

[29] Paret, *Clausewitz and the State*, 63; White, "The Enlightened Soldier," 36.

[30] Paret, *Clausewitz and the State*, 64. For the final paragraph of Hammerstein's report on the retreat from Menin, see Clausewitz (and Gneisenau), "On the Life and Character of Scharnhorst," *Historical and Political Writings*, 89–90.

[31] Paret, *Clausewitz and the State*, 64. Prussia's involvement in the War of the First Coalition ended with the Treaty of Basel in 1795 (Howard, *Clausewitz*, 6).

[32] Gunther E. Rothenberg, "Maurice of Nassau, Gustavus Adolphus, Raimondo Montecuccoli, and the 'Military Revolution' of the Seventeenth Century," *Makers of Modern Strategy: From Machiavelli to the Nuclear Age*, 32. Rothenberg argues that it was during the period 1560–1660 that "modern armies, founded on the principle of hierarchical subordination, discipline, and social obligation, took the shape they have retained to the present day" (36–37).

[33] Howard, *Clausewitz*, 15.

[34] Clausewitz, *On War*, 590–591.

[35] Howard, *Clausewitz*, 15.

[36] White, "The Enlightened Soldier," 42.

[37] Clausewitz, *On War*, 592.

[38] Howard, *Clausewitz*, 7; also see Clausewitz, *On War*, 609.

[39] Howard, *Clausewitz*, 7.

[40] Paret, *Clausewitz and the State*, 64.

[41] Ibid.; Howard, *Clausewitz*, 7; White, "The Enlightened Soldier," 42–43, 95–99. An early product of Scharnhorst's speculations on what he had observed in the War of the First Coalition was a 50-page essay, "The Basic Reasons for French Success [*Entwicklung der allgemeinen Ursachen des Glücks der Franzosen in dem Revolutionskreige*]," which he and his friend Friedrich von der Decken published in their periodical *Neue Militärische* in 1797 (Paret, *Clausewitz and the State*, 32, note 25, 64).

[42] Paret, *Clausewitz and the State*, 33; Clausewitz, *On War*, 610.

[43] Howard, *Clausewitz*, 17.

[44] Palmer, "Frederick the Great, Guilbert, Bülow: From Dynastic to National War," 95.

[45] The foremost American proponent of the hypothesis that the early 21st century would see a combined-systems revolution in how wars are fought, driven by technological advances, is Andrew W. Marshall. See, for example, Marshall, "Some Thoughts on Military Revolutions," Office of Net Assessment (OSD/NA) memorandum, July 27, 1993, especially 1–5; James R. FitzSimonds and Jan M. van Tol, "Revolutions in Military Affairs," *Joint Force Quarterly*, no. 4 (Spring 1994), 24–31; and Thomas E. Ricks, "Warning Shot: How Wars Are Fought Will Change Radically, Pentagon Planner Says," *The Wall Street Journal*, July 15, 1994, A1. Soviet military thinkers such as Nikolai Ogarkov began talking openly in the early 1980s about the possibility that advances in nonnuclear weaponry—including the development of so-called automated reconnaissance-and-strike complexes (that is, long-range and high-accuracy munitions and electronic-control systems)—"make it possible to sharply increase (by at least an order of magnitude) the destructive potential of conventional weapons, bringing them closer, so to speak, to weapons of mass destruction in terms of effectiveness" (Interview with Ogarkov, "The Defense of Socialism: Experience of History and the Present Day," *Krasnaya zvezda* [*Red Star*], May 9, 1984, 2–3).

[46] Howard, *Clausewitz*, 17.

[47] Paret, *Clausewitz and the State*, 65.

[48] Ibid. During the years 1795–1801, Scharnhorst also longed for his own command, "but his superiors politely declined his requests" (White, "The Enlightened Soldier," 40).

[49] Paret, *Clausewitz and the State*, 68.

[50] Howard, *Clausewitz*, 7.

[51] Paret, *Clausewitz and the State*, 76.

[52] Ibid., 60, 71.

[53] Howard, *Clausewitz*, 13.

[54] John Shy, "Jomini," in *Makers of Modern Strategy: From Machiavelli to the Nuclear Age*, 148–150. Antoine-Henri Jomini (1779–1869) felt that "he owed his greatest intellectual debt to General Henry Lloyd" (148). Scharnhorst was also stimulated by Lloyd's writings, but quite differently from Jomini (White, "The Enlightened Soldier," 28).

[55] In his so-called laws of war, Frederick W. Lanchester (1868–1946) postulated two distinct relationships—his *linear* and *square* laws—between casualties, force ratios, and defeat in tactical engagements, depending on whether the opposing sides are armed with "ancient" weapons such as swords, or with "modern long-range" weapons like rifles. See Lanchester, *Aircraft in Warfare: The Dawn of the Fourth Arm* (London: Constable and Company, 1916), 40–41. Lanchester's approach used differential equations to develop his so-called laws, and his pioneering work was included in the classic Navy textbook on operations research. See Philip M. Morse and George E. Kimball, "Operations Evaluation Group Report No. 54: Methods of Operations Research," Chief of Naval Operations, Washington, DC, 63–74. For those uncomfortable with differential equations, a purely arithmetic illustration of Lanchester's square law can be found in Wayne P. Hughes, Jr., *Fleet Tactics: Theory and Practice* (Annapolis, MD: Naval Institute Press, 1986), 66–69.

[56] Henry Lloyd, quoted in Howard, *Clausewitz*, 13. Since the 1991 Persian Gulf War, many in the United States have raised Lloyd's idea of bloodless or, to use the current term, *nonlethal* warfare. By the time Clausewitz began the manuscript that we know as *On War*, he had experienced war three times: as an adolescent in 1794 and 1795, when "he was swept, passive and uncomprehending, into a stream of exertion, violence, and suffering"; briefly in 1806 when, as a young officer, he participated in Prussia's bitter defeat at Auerstädt; and, between 1812 and 1815, when "he took part in, or was able to observe at close hand, the unfolding of great strategic combinations, as well as major battles, detached operations, arming of the people, and political-military negotiations," including "the human reality of 'corpses and dying men among smoking ruins, and thousands of ghostlike men [who] pass by screaming and begging and crying in vain for bread'" (Paret, *Clausewitz and the State*, 222). Small wonder, then, that in the fifth paragraph of *On War* Clausewitz wrote: "Kind-hearted people might of course think there was some ingenious way to disarm or defeat an enemy without too much bloodshed, and might imagine this is the true goal of the art of war. Pleasant as it sounds, it is a fallacy that must be exposed: war is such a dangerous business that mistakes which come from kindness are the very worst" (75). One also cannot help but wonder whether these words will prove any less true in the wars of the 21st century.

[57] Paret, *Clausewitz and the State*, 92. The young Clausewitz, writing in 1805, raised numerous objections to Bülow's attempts to reduce the conduct of war to quantitative principles, not the least of which was that Bülow's own historical illustrations showed that campaigns had been won from an inadequate base of operations, and lost with a base that met Bülow's criteria (ibid.). In *On War*, the mature Clausewitz was even harsher, rejecting the sort of geometrical result produced by Bülow's principles as "completely useless" fantasy (135, 215).

[58] Clausewitz (and Gneisenau), "On the Life and Character of Scharnhorst," *Historical and Political Writings*, 90.

[59] Paret, *Clausewitz and the State*, 71. Paret is clear that Scharnhorst never fully resolved the conflict between theory and war as it actually is in his own mind.

[60] "In war . . . all action is aimed at probable rather than certain success. The degree of certainty that is lacking must in every case be left to fate, chance, or whatever you like to call it. . . . But we should not habitually prefer the course that involves the least uncertainty. That would be an enormous mistake. . . . There are times when the utmost daring is the height of wisdom" (Clausewitz, *On War*, 167). In the 20th century, the exploitation of the opportunities provided by chance is something that became second nature to top-performing World War II armor commanders, such as Heinz Guderian and John S. Wood. See BDM Corporation, "Generals Balck and von Mellenthin on Tactics: Implications for NATO Military Doctrine," BDM/W–81–399–TR, July 1, 1981, 26, 31–32, 39; also see Hanson W. Baldwin, *Tiger Jack* (Fort Collins, CO: Old Army Press, 1979), 39–46, 61–69.

[61] Clausewitz, *Vom Kriege*, 237; Clausewitz, *On War*, 104.

[62] Clausewitz, *On War*, 122.

[63] Ibid., 114–115, 117, 119.

[64] See Harold G. Moore and Joseph L. Galloway, *We Were Soldiers Once . . . And Young* (New York: Random House, 1992); and Avigdor Kahalani, *The Heights of Courage: A Tank Leader's War on the Golan* (Westport, CT: Greenwood Press, 1984).

[65] Clausewitz, *On War*, 117.

[66] Ibid., 84–85.

[67] Paret, *Clausewitz and the State*, 373.

[68] John G. Hines and Daniel Calingaert, "Soviet Strategic Intentions, 1973–1985: A Preliminary Review of U.S. Interpretations," RAND working draft WD–6305–NA, December 1992, 4–7.

[69] Clausewitz, *On War*, 139, 149.

[70] Ibid., 605–608.

[71] Scharnhorst, "*Entwicklung der allgemeinen Ursachen des Glücks der Franzosen*," quoted in White, "The Enlightened Soldier," 43–44.

[72] Stanley Karnow, *Vietnam: A History* (New York: Viking Press, 1983), 17.

[73] The author included a fairly similar reconstruction of general friction in the backup material for a lecture last given to the Air War College in the fall of 1992. See Barry D. Watts, "U.S. Doctrine for Strategic Air Attack in World War II," lecture slides, Air War College, Maxwell AFB, AL, September 1992, backup slide 27B ("General Friction: A Reconstruction").

[74] For a recent historian's explication of friction in the tradition of Peter Paret, see Christopher Bassford, *Clausewitz in English: The Reception of Clausewitz in Britain and America: 1815–1945* (Oxford: Oxford University Press, 1994), 25–26. For an interpretation that connects friction with nonlinearity (as well as with the increasing degradation toward randomness that is the essence of entropy), see Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War," *International Security*, Winter 1992/1993, 75–77. While Beyerchen's essay clearly invites readers to reconsider Clausewitzian concepts in light of modern fields like nonlinear dynamics, it does not specifically attempt a wholesale reconstruction of Clausewitz's unified concept of a general friction.

[75] Clausewitz, *On War*, 100–103, 122.

[76] Ibid., 17, 167, 198, 407–408, 560. John R. Boyd has long criticized Clausewitz for focusing almost exclusively on reducing one's own (internal) friction, and failing to explore the rich possibilities for "magnifying [the] adversary's friction/uncertainty." See Boyd, "Patterns of Conflict," briefing dated April/June/July 1979, slide 24; in the December 1986 version of this briefing, see slide 41. Boyd is correct. Granted, in a few places, the mostly unfinished manuscript that Clausewitz's widow published as *Vom Kriege* does raise friction's positive potential to influence outcomes by increasing its magnitude on the enemy's side (Paret, "The Genesis of *On War*," in Clausewitz, *On War*, 17). Nonetheless, Boyd and Paret are correct in noting that "Clausewitz never sufficiently explored the various ways in which one side influences the other" (Ibid., 25).

[77] The proposition that for every action there is always an opposed-and-equal reaction was one of Newton's three laws of motion.

[78] Immanuel Kant, *Critique of Pure Reason*, trans. Norman Kemp Smith (New York: St. Martin's Press, 1929), 55–58. As Kant remarked, since a pure science of nature—meaning Newton's astonishingly effective mathematical formulation of physics—existed, it is quite proper to ask how such a science is possible (56).

[79] Clausewitz, *On War*, 119, 120. Note that virtually these same words occurred in Clausewitz's historical account of the 1812 campaign in Russia. See Clausewitz, "From The Campaign of 1812 in Russia," *Historical and Political Writings*, 165–167.

[80] Thomas A. Keaney, discussion of a partial draft of this paper, July 10, 1995.

[81] The Gulf War Air Power Survey was commissioned on August 22, 1991, by then-Secretary of the Air Force Donald B. Rice "to review all aspects of air warfare in the Persian Gulf." See Thomas A. Keaney and Eliot A. Cohen, *Gulf War Air Power Survey: Summary Report* (Washington, DC: U.S. Government Printing Office, 1993), ix, xi. The survey was directed by Cohen of the Johns Hopkins University School of Advanced International Studies. This author was task-force chief for operations and effects.

[82] Keaney and Cohen, "Missions" database, ATO [Air Tasking Order] Day 3, entries for the 48th Tactical Fighter Wing. Coalition air planners were able to devote some 5 months to scripting the first 2 days of the air campaign in meticulous detail. The third day of the war was the first planned "in real time" and rightly came to be known as "the ATO day from hell."

[83] Keaney and Cohen, 16.

[84] While minimum "medium-altitude" release altitudes for individual aircraft varied considerably prior to the beginning of the ground campaign on February 24, release altitudes in the vicinity of 14,000 to 17,000 feet were not unheard of during Operation *Desert Storm* for F–16 pilots dropping unguided bombs using 45° to 60° dive angles. For these release parameters, the slant range to the aim

point at bomb release is around 20,000 feet, and the combined system error could be 120 feet "even if the pilot did everything right and the [continuously computed-impact point bombing] system worked perfectly" (Richard J. Blanchfield et al., "Part I: Weapons, Tactics, and Training in Gulf War Air Power Survey," vol. IV, *Gulf War Air Power Survey: Weapons, Tactics, and Training and Space Operations* [Washington, DC: U.S. Government Printing Office, 1993], 86). Since pilots seldom perform perfectly under actual combat conditions, one suspects that miss distances of 200 feet or more were not uncommon for visual dive bombing from medium altitude, particularly early in the campaign.

[85] The author must stress the fact that coalition air commanders explicitly lifted the restrictions on bombing altitudes initiated after the third day of *Desert Storm* on the first day of the ground offensive. The message dispatched by Buster C. Glosson to the 10 fighter wings under his command at 1900 local on February 24, 1991, authorized flight leads to determine release altitudes and weapon parameters "consistent with the risks to American and Allied troops" (Message, RESTRICTN.LFT, 241600Z Feb. 1991).

[86] Clausewitz, *On War*, 120.

[87] Barry D. Watts and Thomas A. Keaney, "Part II: Effects and Effectiveness in Gulf War Air Power Survey," vol. II, *Gulf War Air Power Survey: Operations and Effects and Effectiveness* (Washington, DC: U.S. Government Printing Office, 1993), 388–389.

[88] Buster C. Glosson, *Gulf War Air Power Survey* interview, April 14, 1992.

[89] Haywood S. Hansell, Jr., *The Air Plan That Defeated Hitler* (Atlanta: Higgins-McArthur/Longino and Porter, 1972), 121.

[90] The anticipated fielding in quantity of precision weapons such as the Joint Direct Attack Munition (JDAM) in the first decade of the 21st century may, at last, begin to ameliorate the frictional impediment that adverse weather in the target area has long posed for bombing operations by fixed-wing aircraft. Of course, this conjecture assumes that the Global Positioning System data necessary for reasonable accuracy with the initial JDAM weapons cannot be denied or degraded by enemy countermeasures, especially around high-value targets. Thus, this example also illustrates the inherent limits of purely technological solutions to friction at the tactical level.

[91] Watts and Keaney, 111.

[92] Ibid., 109.

[93] Lewis D. Hill, Doris Cook, and Aron Pinker, "Part I: A Statistical Compendium in Gulf War Air Power Survey," vol. V, *Gulf War Air Power Survey: A Statistical Compendium and Chronology* (Washington, DC: U.S. Government Printing Office, 1993), 241; Department of Defense (DOD), *Conduct of the Persian Gulf War: Pursuant to Title V of the Persian Gulf Conflict Supplemental Authorization and Personnel Benefits Act of 1991* (Public Law 102–25) (Washington, DC: U.S. Government Printing Office, April 1992), 152. The actual figure for Iraqi "shooter" sorties is ~ 430. However, it is likely that the Iraqis flew some sorties that were not observed by coalition forces or intelligence.

[94] *Gulf War Air Power Survey*, CHC–10, "Point Paper Information: Iraqi Aircraft Bunker Vulnerabilities (U)," SECRET, January 24, 1991. Within 3 days of the first laser-guided bomb attacks on hardened Iraqi aircraft shelters, Iraqi combat aircraft began fleeing to Iran (Watts and Keaney, 129).

[95] Watts and Keaney, 234; and Williamson Murray, "Part I: Operations in Gulf War Air Power Survey," vol. II, *Gulf War Air Power Survey: Operations and Effects and Effectiveness* (Washington, DC: U.S. Government Printing Office, 1993), 70, 92–94.

[96] Norman Cigar, "Iraq's Strategic Mindset and the Gulf War: Blueprint for Defeat," *The Journal of Strategic Studies*, March 1992, 3–5, 14–16, 18–20; also, Watts and Keaney, 126–127, 234.

[97] Watts and Keaney, 239–240. The Tactical Air Control Center log indicated that the diversion of strike aircraft in response to Joint Surveillance Target Attack Radar System (JSTARS) detection of what were later identified as elements of the Iraqi 3d Armored and 5th Mechanized Divisions was under way by 2200 hours Riyadh time on January 30, 1991.

[98] George H.W. Bush, "Address to the Nation Announcing the Deployment of United States Armed Forces to Saudi Arabia," August 8, 1990, in *Public Papers of the Presidents of the United States: George Bush, 1990*, vol. 2, Book II—July 1 to December 31, 1990 (Washington, DC: U.S. Government Printing Office, 1991), 1108.

[99] DOD, *Conduct of the Persian Gulf War*, 95.

[100] Watts and Keaney, 79. The other two primary centers of gravity were (1) the forces of the Republican Guard and (2) Iraqi leadership together with national-level means of command and control (USCINCCENT OPORD 91–001 for Operation *Desert Storm*, paragraphs 1D, 3A, 3B).

[101] Prior to Operation *Desert Storm*, coalition intelligence believed that the Iraqis were some years, if not a decade or more, away from fielding a nuclear weapon. In the wake of intrusive, on-site inspections carried out by International Atomic Energy Agency (IAEA) inspectors operating under the auspices of the United Nations (UN) Security Council after *Desert Storm*, a very different assessment emerged: "At the time of the Gulf War Iraq was probably only 18 to 24 months away from its first crude nuclear device and no more than 3 to 4 years away from advanced, deliverable weapons." See David A. Kay, "Denial and Deception Practices of WMD Proliferators: Iraq and Beyond," *The Washington Quarterly*, Winter 1995, 85. Kay was chief inspector on three of the early UN nuclear weapons inspections in post-Gulf War Iraq.

[102] Postwar International Atomic Energy Agency (IAEA) inspections eventually uncovered some 39 nuclear facilities at 19 different geographic locations in Iraq (UN Security Council, "Report on the Seventh IAEA On-Site Inspection in Iraq under Security Council Resolution 687 [1991]: 11–22 October 1991," Report S/23215, November 14, 1991, 8, 63); and Michael Eisenstadt, *Like a Phoenix from the Ashes? The Future of Iraqi Military Power* (Washington, DC: Washington Institute for Near East Policy, 1993), 92–93. By contrast, as of February 27/28, 1991, U.S. intelligence was holding only eight nuclear targets, of which five were believed destroyed, two damaged, and one still operational (J–2/JCS Daily BDA Assessment: Operation *Desert Storm*, GWAPS NA 353, briefing slides for January 27/28, 1991).

[103] Jeb C. Snyder, "The Road to Osiraq: Baghdad's Quest for the Bomb," *Middle East Journal*, Autumn 1983, 567–568, 576–578.

[104] Ibid., 577–578.

[105] Eight Israeli F–16s put fourteen 2,000-pound Mk–84s into Osirak's dome; the two other bombs that were dropped destroyed an adjacent building. See Dan McKinnon, *Bullseye One Reactor* (Shrewsbury, England: Airlife Publishing, 1987), 172, 178–179.

[106] Watts and Keaney, 314.

[107] Rolf Ekeus, UN Security Council, Report S/23165, October 25, 1991, "Annex: Report by the Executive Chairman of the Special Commission established by the Secretary-General pursuant to paragraph 9(b)(i) of Security Council resolution 687 (1991)," 4.

[108] Kay, "Denial and Deception Practices," 87–98.

[109] David A. Kay, letter to author, October 20, 1992, GWAPS, NA–375.

[110] Like the frictional impediment of adverse weather, failure to understand the functionality of a target system has antecedents at least as far back as World War II. In the case of the Anglo-American Combined Bomber Offensive (CBO) against Germany, the most telling example is the "coal/transport nexus" that both distributed the lifeblood of German war production—coal for power—and provided the division of labor that enabled the war economy to adapt to specific bombing attacks. See Alfred C. Mierzejewski, *The Collapse of German War Economy, 1944–1945: Allied Air Power and the German National Railway* (Chapel Hill: University of North Carolina Press, 1988), 178–179. The fundamental CBO goals were to "accomplish the destruction and dislocation of the German military, industrial and economic system and the undermining of the morale of the German people to a point where their capacity for armed resistance is fatally weakened." See U.S. Eighth Air Force, "The Combined Bomber Offensive from the U.K.," April 12, 1943, U.S. National Archives, RG 218, CCS 381, Box 594, 2. The collapse of German war production was in fact achieved by January 1945 due to the collapse of the country's transportation. See Ernest W. Williams and Elbridge L. Shaw, *The Effects of Strategic Bombing on German Transportation*, vol. 200 (Washington, DC: U.S. Strategic Bombing Survey, Transportation Division, 1947), 89–91. However, at the very point in the war that this long-sought goal was achieved, H.H. "Hap" Arnold was lamenting to his chief bomber commander in Europe, Carl Spaatz, that with all the tremendous striking power at Spaatz's disposal we should be getting "much better and much more decisive results than we are getting now." See John E. Fagg, "The Climax of Strategic Operations," in *The Army Air Forces in World War II*, vol. 3, ed. Wesley F. Craven and James L. Cate (Washington, DC: U.S. Government Printing Office, 1951), 716.

[111] Revealing insofar as general friction's persistence is concerned, H. Norman Schwarzkopf appears to have still believed some time after the war ended that the Iraqi nuclear program had been destroyed during Operation *Desert Storm*. See Schwarzkopf with Peter Petre, *The Autobiography: It Doesn't Take a Hero* (New York: Linda Grey/Bantam Books, 1992), 499. The author can also testify that the head intelligence officer for Air Force Central Command during the war adamantly subscribed to this same conviction in March 1992.

[112] Michael R. Gordon and Bernard E. Trainor, *The Generals' War: The Inside Story of the Conflict in the Gulf* (New York: Little, Brown and Company, 1995), 304, 371, 376.

[113] Robert H. Scales, Jr., *Certain Victory: The United States Army in the Gulf War* (Washington, DC: Office of the Chief of Staff, U.S. Army, 1993), 216–223.

[114] Richard M. Swain, *"Lucky War": Third Army in* Desert Storm (Fort Leavenworth, KS: U.S. Army Command and General Staff College Press, 1994), 230; also see Schwarzkopf with Petre, 453–454.

[115] Gordon and Trainor, 379; Swain, 236–237.

[116] Swain, 238. Swain argues that as early as February 25 the use of imprecise language by VII Corps and Third Army in communicating their intentions to Schwarzkopf's headquarters in Riyadh began to open a gap in perception between the theater commander and his subordinate field commanders (247).

[117] John H. Cushman, "*Desert Storm*'s End Game," *Proceedings*, October 1993, 76.

[118] As of March 1, 1991, some 840 tanks (at least 365 of which were Republican Guard T–72s), 1,412 other armored vehicles (mostly armored personnel carriers), and 279 pieces of artillery of various types were still in the hands of surviving Iraqi forces and outside of coalition control. See Central Intelligence Agency, Office of Imagery Analysis, "Operation *Desert Storm*: A Snapshot of the Battlefield," IA 93–10022, September 1993. Of the totals cited, at least 39 tanks and 52 other armored vehicles belonging to the Republican Guard's Hammurabi Division were destroyed in the early morning hours of March 2, 1991, by the American 24th (Mechanized) Infantry Division as the Iraqis attempted to reach the Hawr al Hammar causeway and escape northward.

[119] By around midnight (Riyadh time) on the night of February 25/26, JSTARS was showing heavy traffic moving north from Kuwait City toward Al Basrah; at 0135 hours Riyadh time on February 26 (1735 hours on February 25 in Washington, DC), Baghdad radio announced an Iraqi withdrawal from Kuwait, and by morning of the 26th, coalition intelligence in the theater was reporting a mass exodus led by the Iraqi III Corps in the east (Swain, 250); also see the review of JSTARS tapes for the night of February 25/26, 1991, conducted at the Pentagon in April 1995.

[120] CIA, "Operation *Desert Storm*," IA 93–10022.

[121] In a controversial article, James G. Burton was the first to criticize Generals Franks and Schwarzkopf for preferring a synchronized phalanx attacking head-on into the Republican Guard units in the rear of the Kuwaiti theater rather than encirclement and annihilation. See James G. Burton, "Pushing Them Out the Back Door," *Proceedings*, June 1993, 37–42. In later issues of *Proceedings*, Burton's criticism elicited heated responses, particularly from U.S. Army participants in *Desert Storm* who sought to defend their service's performance. Burton's June 21, 1995, briefing, "*Desert Storm*: A Different Look," provides an in-depth examination of the publicly available evidence bearing on this controversy. Burton's conclusion from his 1995 analysis is, once again, that the U.S. Army "did not know how to conduct a deep thrust to the enemy's rear."

[122] As early as 1926, German army maneuvers stressed the tactical innovation of having units advance boldly ahead without "maintaining a continuous front" or "regard for troops on their flanks." See James S. Corum, *The Roots of Blitzkrieg: Hans von Seeckt and German Military Reform* (Lawrence, KS: University of Kansas Press, 1992), 185. During World War II, Balck and "P" Wood proved themselves to be among the most skilled practitioners of this approach to mobile, armored warfare. See BDM Corporation, "Generals Balck and von Mellenthin on Tactics," 26, 31–32, 39; and Baldwin, *Tiger Jack*, 39–46, 61–69. By contrast, Third Army in *Desert Storm* emphasized the use of phase lines and global positioning system receivers to maintain the geographic alignment of the flanks of adjacent units as they rotated, like the spoke of a "Great Wheel," from a northward- to eastward-facing phalanx. See Scales, *Certain Victory*, 252–254; and DOD, *Conduct of the Persian Gulf War*, 287.

[123] Schwarzkopf with Petre, 384, 499.

[124] Between October 3 and 9, 1994, the Iraqis massed as many as 70,000 troops, including 2 Republican Guard divisions and over 1,000 tanks, on Kuwait's northern border. See David A. Fulgham, "Iraq Invasion Threat Reassessed by Military," *Aviation Week and Space Technology*, November 14, 1994, 18–19; and John H. Cushman, "Back to the Gulf," *Proceedings*, December 1994, 35. Over the next 10 days, various force elements and some 14,000 American personnel, including marines and elements of the U.S. Army's 24th Mechanized Infantry Division, were rushed to the Gulf.

[125] These difficulties measuring the frictional imbalance between opposing sides recall Andrew Marshall's concerns about the measurement of military power. As he wrote in the mid-1960s, the "conceptual problems in constructing an adequate or useful measure of military power have not yet

been faced. Defining an adequate measure looks hard, and making estimates in real situations looks even harder" (Marshall, "Problems of Estimating Military Power," RAND P–3417, August 1966, 9).

[126] For classic accounts of Allied friction in May 1940, see J.F.C. Fuller, *The Conduct of War, 1789–1961: A Study of the Impact of the French, Industrial, and Russian Revolutions on War and Its Conduct* (London: Minerva Press, 1968), 255–261; and Antoine de Saint Exupéry, *Flight to Arras*, trans. Lewis Galantière (New York: Harcourt, Brace and World, 1942), 56. For insight into German friction during this campaign, especially during the crucial crossings of the Meuse River, see Robert Allan Doughty, *The Breaking Point: Sedan and the Fall of France, 1940* (North Haven, CT: Archon Books, 1990), 131–165, 323–324, 329–332.

[127] Winston S. Churchill, *The Second World War* (Boston: Bantam Books, 1949), II–100.

[128] The author is indebted to Alan Beyerchen for the ensuing discussion of differences in "decision-cycle times" and option sets in possibility space as rough indicators of the relative balance of friction between opposing sides. As he rightly pointed out in May 1996, the contention in this section that the gross magnitude of the frictional imbalance between opponents did not appear to be very different in 1991 from what it had been in May 1940 can be defended only if such indices can be found and, at a minimum, qualitatively described.

[129] Doughty, *The Breaking Point*, 325.

[130] Ibid., 224.

[131] As a campaign unfolds, the attractive options tend to contract for both adversaries. For instance, on the first day of the German May 1940 offensive, the options of going either to Paris or to the Channel coast were both open. By the time the panzer units in Army Group Center began wheeling toward the Channel on May 15, though, the option of going to Paris was far less attractive from a German perspective due to the way the campaign had unfolded than it had been 5 days earlier.

[132] Phase or state space is a way of visualizing the behavior of a dynamical system. Its coordinates are the "degrees of freedom of the system's motion." See James P. Crutchfield et al., "Chaos," *Scientific American*, December 1986, 49. In the case of a simple pendulum, for example, the relevant phase space only requires two coordinates: the pendulum's velocity over time and its position or displacement left or right of center. Once initially set in motion, a frictionless pendulum describes a circle in phase space, whereas one subjected to friction follows an orbit that spirals to a point.

[133] Alan Beyerchen, email message to author, May 31, 1996.

[134] Jules Henri Poincaré (1854–1912) was perhaps the first to develop a mathematically rigorous basis for believing that physical systems could exhibit long-term unpredictability. See Ian Stewart, *Does God Play Dice? The Mathematics of Chaos* (Oxford: Basil Blackwell, 1989), 64–72. However, the significance of Poincaré's work "was fully understood only in 1954, as a result of the work of the Russian academician A.N. Kolmogorov, with later additions by two other Russians, Vladimir Arnold and J. Moser (the three being known collectively as KAM)." See John Briggs and F. David Peat, *Turbulent Mirror: An Illustrated Guide to Chaos Theory and the Science of Wholeness* (New York: Harper and Row, 1990), 41–42. The current view of nonlinear dynamics is that the detailed behavior of nonlinear systems in their "chaotic" regions is unpredictable.

[135] "The greatest obstacle to the establishment of the theory of evolution was the fact that evolution cannot be observed directly like the phenomena of physics, such as a falling stone or boiling water, or any other process that takes place in seconds, minutes, or hours during which ongoing changes can be carefully recorded." See Ernst Mayr, *The Growth of Biological Thought: Diversity, Evolution, and Inheritance* (Cambridge, MA: Belknap Press, 1982), 310.

[136] For a poignant account of the visceral impact that news of the Japanese attack on Pearl Harbor had on most Americans, see Robert Ardrey, *The Territorial Imperative: A Personal Inquiry into the Animal Origins of Property and Nations* (New York: Atheneum, 1968), 229–231. And while Ardrey's views of human behavior have been much maligned, he was certainly right to connect the universality and depth of the feelings most Americans experienced when they heard of the attack to evolutionary biology.

[137] Roberta Wohlstetter, *Pearl Harbor: Warning and Decision* (Stanford: Stanford University Press, 1962), 387.

[138] Ibid., 1–2. Wohlstetter noted, however, that the nontechnical meaning of the word *signal* cited had been inspired by and was compatible with "its usage in the contemporary theory of information." This comment requires some clarification. In the mathematical theory of communication developed by Claude Shannon and Warren Weaver, *The Mathematical Theory of Communication* (Urbana, IL: University of Illinois Press, 1949), 8–9, information is a measure of one's freedom of

choice when selecting a message, not a measure of its meaning. It is precisely this association of the information content of communications processes with uncertainty, rather than with meaning, that enabled Shannon to show that information could be represented mathematically by an equation having the same form as Ludwig Boltzmann's famous equation for the entropy or disorder of a thermodynamic system (27, 48–51).

[139] Wohlstetter, 31, 382–384. To the six categories of signals cited, Wohlstetter added a seventh: public and classified information on American plans, intentions, moves, and military vulnerabilities (384). Her point was that in the final months and weeks preceding the Japanese attack on Pearl Harbor, U.S. evaluations of the accumulating signals could not be done in isolation from what was being done by or intended on the American side.

[140] Ibid., 345, 349.

[141] Ibid., 339.

[142] Ibid., 55, 387, 392. The interwoven phenomena of noise obscuring relevant signals or rendering their interpretation problematic have been persistent features of cases of strategic surprise since Pearl Harbor. For unambiguous evidence of relevant signals being lost in background noise during the 1962 Cuban Missile Crisis, see Dino A. Brugioni, *Eyeball to Eyeball: The Inside Story of the Cuban Missile Crisis* (New York: Random House, 1992), 145, 153. Evidence of surrounding noise making the interpretation of signals the main problem is evident in the 1973 Arab attack on Israel and Iraq's 1990 seizure of Kuwait (both of which are discussed later in this section).

[143] Wohlstetter, 393.

[144] Ibid., 354–355. The deployment of the U.S. Pacific fleet to Pearl Harbor in the spring of 1940 was seen in Washington as a deterrent, whereas the Japanese saw a target (89).

[145] Ibid., 396.

[146] Ibid, 360–361. The devil lay in the details. Unbeknownst to American intelligence, the Japanese had found ways to extend the range of the Zero just enough to reach targets in Manila from Formosa.

[147] Ibid., 389.

[148] Ibid., 397.

[149] Avi Shlaim, "Failures in National Intelligence Estimates: The Case of the Yom Kippur War," in *The Art and Practice of Military Strategy*, ed. George E. Thibault (Washington, DC: National Defense University Press, 1984), 380, 381. This chapter originally appeared as an article in the April 1976 issue of *World Politics*.

[150] Richard K. Betts, *Surprise Attack: Lessons for Defense Planning* (Washington, DC: The Brookings Institution, 1982), 75, note 95. For example, as late as October 3, 1973, the Defense Intelligence Agency assessed the force buildups on the Syrian and Egyptian fronts as coincidental rather than related and "not designed to lead to major hostilities." The Central Intelligence Agency clung to a similar position as late as October 5.

[151] Eliot A. Cohen and John Gooch, *Military Misfortunes: The Anatomy of Failure in War* (New York: The Free Press, 1990), 105, 108.

[152] Schwarzkopf with Petre, 294; Gordon and Trainor, 7, 26.

[153] "If the study of Pearl Harbor has anything to offer the future, it is this: We have to accept the fact of uncertainty and learn to live with it" (Wohlstetter, 401). "The search for an infallible system of advance warning of an attack is the search for a will-o'-the-wisp" (Shlaim, 402). "Intelligence failures are not only inevitable, they are natural. . . . [T]he intractability of the inadequacy of intelligence, and its inseparability from mistakes in decision, suggests one final conclusion that is perhaps most outrageously fatalistic of all: tolerance for disaster" (Richard K. Betts, "Analysis, War, and Decision: Why Intelligence Failures Are Inevitable," in *The Art and Practice of Military Strategy*, 378–379). "History does not encourage the potential victims of surprise attack. One can only hope to reduce the severity—to be only partly surprised, to issue clearer and more timely warnings, to gain a few days for better preparations—and to be more adequately prepared to minimize the damage once a surprise attack occurs" (Ephrain Kam, *Surprise Attack: The Victim's Perspective* [Cambridge: Harvard University Press, 1988], 233).

[154] Kam, 214.

[155] Cohen and Gooch, 119. The likelihood that the Egyptians and Syrians intended to go to war in May 1973 but were stopped at the last minute by the Soviets is based on classified research by a number of prominent members of the Israeli intelligence community into their own files.

[156] The intractability of the traveling salesman, or Steiner shortest network, problem is as follows. As the number of cities to be visited (*n*) increases, the number of calculations required to solve the problem increases more rapidly—in fact by an exponential function of *n*. With these sorts of problems, solutions eventually become infeasible using all currently known methods because the times required to solve them using the fastest computers conceivable soon exceeds human, or even cosmic, time scales. For a summary of recent efforts to circumvent this kind of intractability by relaxing the requirement for the accuracy of the result to be within an arbitrarily small error threshold, see Joseph F. Traub and Henryk Wozniakowski, "Breaking Intractability," *Scientific American*, January 1994, 102–107. Whether more efficient solutions exist to the class of "hard" problems epitomized by the Steiner problem remains "the preeminent problem in theoretical computer science" (Marshall W. Bern and Ronald L. Graham, "The Shortest Network Problem," *Scientific American*, January 1989, 88).

[157] The terms *adaptive* and *adaptation* are intended in John H. Holland's expansive sense of encompassing the algorithmic information processing and search problems that "occur at critical points in fields as diverse as evolution, ecology, psychology, economic planning, control, artificial intelligence, computational mathematics, sampling, and inference." See Holland, *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence* (Cambridge, MA: MIT Press, 1992), 1.

[158] *The Collected Works of F.A. Hayek*, ed. W.W. Bartley III, vol. 1, *The Fatal Conceit: The Errors of Socialism* (Chicago: University of Chicago Press, 1988), 7. Hayek was a prolific writer. Bartley's plan to publish a new standard collection of Hayek's works envisioned 22 volumes as of 1988, when *The Fatal Conceit* appeared as volume I. Written when Hayek was in his late eighties, *The Fatal Conceit* represented the culmination of decades of original and productive thought.

[159] "In Praise of Hayek," *The Economist*, March 28, 1992, 75.

[160] Hayek, *The Fatal Conceit*, 14.

[161] Bruce Caldwell, *Hayek's Challenge: An Intellectual Biography of F.A. Hayek* (Chicago: University of Chicago Press, 2004), 247.

[162] Ibid., 29–30.

[163] Ibid., 31.

[164] Ibid., 42.

[165] Ibid., 77.

[166] Ibid., 84.

[167] Ibid., 71.

[168] Ibid., 62. That limits to human knowledge exist in certain areas seems so undeniable at this late juncture in the 20th century that reiterating evidence for the claim may seem unnecessary. However, since the most incontrovertible evidence comes from fields such as mathematical logic and nonlinear dynamics, which are not widely understood by nonspecialists, it may be useful to cite two cases in point. First, Kurt Gödel's landmark 1931 paper "On Formally Undecidable Propositions in *Principia Mathematica* and Related Systems I" established hard limits to what can be formally proved within any axiomatic system sufficient for ordinary arithmetic. Gödel's so-called first incompleteness theorem states that in any formal system strong enough for the counting integers (1, 2, 3 . . .) and arithmetic operations like addition and multiplication, it is always possible to construct a formula that, when properly interpreted (from outside the formal system), can be seen to be true, yet is neither provable nor disprovable (that is, *decidable*) within the system. See Gödel, "On Formally Undecidable Propositions in *Principia Mathematica* and Related Systems I," in *From Frege to Gödel: A Source Book in Mathematical Logic, 1879–1931*, ed. Jean van Heijenoort (Cambridge, MA: Harvard University Press, 1967), 597. In more recent years, Gregory J. Chaitin has extended Gödel's work by showing "that the logical structure of arithmetic can be random" (Ian Stewart, "The Ultimate in Undecidability," *Nature*, March 10, 1988, 115); also see Gregory J. Chaitin, *Information, Randomness, and Incompleteness: Papers on Algorithmic Information Theory*, 2d ed. (London: World Scientific Publishing, 1990, especially 14–19, 307–313). Second, Edward N. Lorenz's 1963 discovery of nonperiodic solutions to a relatively simple set of atmospheric convection equations is widely understood today to have established the impossibility of making accurate, long-range weather predictions more than 10 days to 2 weeks into the future. See Lorenz, "Deterministic Nonperiodic Flow," in *Chaos*, ed. Hao Bai-Lin (Singapore: World Scientific Publishing Company, 1984), 282, 292–293 (Lorenz's article originally appeared in the March 1963 issue of *The Journal of Atmospheric Sciences*, 130–141); see also Philip E. Ross, "Lorenz's Butterfly: Weather Forecasters Grapple with the Limits of Accuracy," *Scientific American*, September 1990, 42.

[169] Hayek, *The Fatal Conceit*, 98.

[170] Ibid., 97.

[171] Daniel C. Dennett, *Darwin's Dangerous Idea: Evolution and the Meanings of Life* (New York: Simon and Schuster, 1995), 97.

[172] Ibid., 98.

[173] Ibid., 99, 103. "Species have an extension in space and time; they are structured and consist of populations which, at least in part (when they are isolated), are independent of each other" (Mayr, *The Growth of Biological Thought*, 408). Put another way, the boundaries between species are surprisingly fuzzy, both spatially and temporally. See Richard Dawkins, *The Blind Watchmaker: Why the Evidence of Evolution Reveals a Universe without Design* (New York: W.W. Norton, 1987), 262–267.

[174] Hayek did not, of course, claim that the extended order associated with capitalist or market economies produced anything approaching a perfect allocation and use of resources, only that the "order generated without design can far outstrip plans men consciously contrive" (*The Fatal Conceit*, 8). The result of socialist economic experiments in the Soviet Union, Cuba, China, Yugoslavia, Vietnam, and Tanzania seem to provide compelling proof of Hayek's contention that market economics are more efficient. For an illuminating account of the counterintuitive properties of genetic or adaptive algorithms, see John R. Koza, *Genetic Programming: On the Programming of Computers by Means of Natural Selection* (Cambridge, MA: MIT Press, 1992), 1–8. Genetic programming, Koza emphasizes, "works only with admittedly incorrect solutions and it only occasionally produces the correct analytic solution to the problem" (5).

[175] Given the mathematical immensity of biological "design space," coupled with the fact that in that multidimensional space there are vastly more ways of being dead than alive, Dawkins is doubtful that we will ever know enough to be able to choose phenotypes by selecting the relevant genotype (*The Blind Watchmaker*, 9, 73). For lucid introductions to the structure, dimensionality, and vastness of biological "design space," see Dennett, chapter 5, 104–123; see also, Dawkins, chapters 3 and 4, 43–109.

[176] R. Jeffrey Smith, "U.N. Says Iraqis Prepared Germ Weapons in Gulf War," *The Washington Post*, August 26, 1995, A1.

[177] See James G. Burton, "Pushing Them Out the Back Door," *Proceedings*, June 1993, 37–42; Ronald H. Griffith, "Mission Accomplished—In Full," *Proceedings*, August 1993, 63–65; Paul E. Funk, *Proceedings*, September 1993, 22, 24; and James G. Burton, *Proceedings*, November 1993, 19–25.

[178] The meltdown of a nuclear reactor at Three Mile Island in 1980 illustrates how uncertain judgments about cost effectiveness can remain years after the event itself. As Dennett has noted regarding the incident, we cannot yet say whether the meltdown was a good or a bad thing. The problem is not one "of insufficiently precise measurement; we can't even determine the sign, positive or negative, of the value to assign to the outcome" (*Darwin's Dangerous Idea*, 498).

[179] John R. Boyd has been especially clear that the orientation following observation in his observation-orientation-decision-action cycle (or "OODA loop") is "shaped by *genetic heritage*, *cultural tradition*, *previous experiences*, and *unfolding circumstances*" ("Organic Design for Command and Control," May 1987, slide 13 in Boyd, "A Discourse on Winning and Losing," unpublished compilation of various presentations, including "Patterns of Conflict," as well as Boyd's 1976 essay "Destruction and Creation").

[180] Michael Polanyi, *Knowledge and Being*, ed. Marjorie Grene (Chicago: University of Chicago Press, 1969), 123, 133–134, 164, 212, 218. Polanyi argued that the structure of tacit knowledge explained how the intuitions often underlying scientific discovery were possible (143).

[181] During the Six-Day War of June 5–10, 1967, the Israeli air force is believed to have destroyed some 450 Arab aircraft, of which at least 60 were downed in air-to-air combat; the Israelis lost 50 planes, 3 in aerial combat and the rest to antiaircraft artillery (Zeev Schiff, "The Israeli Air Force," *Air Force Magazine*, August 1976, 34; Born in Battle, no. 2, 1978, Israel's Air Force: The Air War in the Mid East, Eshel-Dramit, 36). In the Yom Kippur War of October 6–24, 1973, the Israeli air force claimed to have downed some 265 Egyptian and 130 Syrian planes, mostly in air-to-air combat; while admitting to losing 102 aircraft, of which 3 or 4 were lost air-to-air, around 40 to surface-to-air missiles, and most of the rest to antiaircraft artillery (Schiff, "The Israeli Air Force," 37). Other sources have put total Arab losses in October 1973 at 442 aircraft, including 21 Iraqi planes, and the air-to-air box score at no less than 370 Arab planes for as many as 10 Israeli air-to-air losses (David Nicolle, "The Holy Day Air War," *Air Enthusiast International*, May 1974, 248). During 7 days of intense air combat in June 1982 associated with Israel's invasion of Lebanon, Israeli pilots claim to have downed

80 Syrian MiG–21s, MiG–23s, and Su-20s, plus 5 helicopters; the Israelis are thought to have lost at least 13 aircraft, though none in air-to-air combat (Victor Flintham, *Air Wars and Aircraft: A Detailed Record of Air Combat, 1945 to the Present* [New York: Facts on File, 1990], 70).

[182] For summaries of how the brain works based on current research, see Daniel C. Dennett, *Consciousness Explained* (Boston: Little, Brown and Company, 1991), 253–256; also see William H. Calvin, "The Emergence of Intelligence," *Scientific American*, October 1994, 101–107. Dennett's account especially seems more than adequate to explain how Polanyi's tacit knowledge, including scientific intuition, is possible.

[183] Yves Coppens, "East Side Story: The Origin of Humankind," *Scientific American*, May 1994, 89, 94–95; also see Meave Leakey, "The Dawn of Humans," *National Geographic*, September 1995, 41–42.

[184] Rick Gore, "The Dawn of Humans: Neandertals," *National Geographic*, January 1996, 11–12, 30; David Pilbeam, "The Descent of Hominoids and Hominids," *Scientific American*, March 1984, 96. Pilbeam puts the emergence of modern man at 40,000 to 45,000 years ago; Gore, writing a decade later, states that in the 1980s the remains of modern humans were unearthed that lived at least 90,000 years ago.

[185] Charles Darwin, *The Origin of the Species by Means of Natural Selection*, vol. 49, *Great Books of the Western World*, ed. Robert Maynard Hutchins (Chicago: Encyclopædia Britannica, 1952), 239. For an overview of Darwin and the theory of natural selection as formulated in *The Origin of the Species*, see Mayr, *The Growth of Biological Thought*, chapters 9–11, 394–534. From 1859 to 1872, six editions of *The Origin of the Species* appeared, and Darwin vacillated a great deal throughout his life on some issues, notably speciation (410 and 424).

[186] Dennett, *Darwin's Dangerous Idea*, 20.

[187] Dawkins, *The Blind Watchmaker*, 114.

[188] Dennett, *Darwin's Dangerous Idea*, 20. Mayr, for example, is generally credited with the modern theory of speciation by initial geographical separation (Dawkins, *The Blind Watchmaker*, 239).

[189] Dennet, *Darwin's Dangerous Idea*, 19. For those whose minds are not entirely closed but, nonetheless, see neo-Darwinism as being substantially in doubt, Dennett's *Darwin's Dangerous Idea* and Dawkins' *The Blind Watchmaker* provide excellent overviews of the modern synthesis and the evidence supporting it.

[190] Stephen Jay Gould, "The Evolution of Life on the Earth," *Scientific American*, October 1994, 85. In 1972, Gould and Niles Eldredge put forward a theory of punctuated equilibrium that described the pattern of biological evolution as being one of long periods of relative stasis punctuated by short evolutionary bursts in which new species emerge. This theory has been interpreted—falsely it turns out—by many outside the fields bearing on evolutionary theory as a refutation of Darwin. Gould's position in his overview of evolutionary theory for the October 1994 issue of *Scientific American* does not support this interpretation. For an overview of the punctuationist controversy, see Dawkins, *The Blind Watchmaker*, chapter 9, 223–252.

[191] Richard Dawkins, "Darwin Triumphant: Darwinism as a Universal Truth," *Man and Beast Revisited*, ed. Michael H. Robinson and Lionel Tiger (Washington, DC: Smithsonian Institution Press, 1991), 38; also see *The Blind Watchmaker*, 317. Dawkins' claim regarding adequate explanations of adaptive complexity should not be construed as implying that core Darwinism is anything other than an empirical theory. As Dawkins has stressed, discovery of "a single, well-verified mammal skull . . . in 500-million-year-old rocks" would utterly destroy core Darwinism (*The Blind Watchmaker*, 225). Darwin himself was equally clear about the empirical nature of natural selection: "If it could be demonstrated that any complex organ existed, which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down" (Darwin, cited in *The Blind Watchmaker*, 249).

[192] Swain, "Lucky War," 300.

[193] Ibid., 300–301.

[194] The loss of focus, particularly on leadership targets, that became evident toward the end of the first week of the *Desert Storm* air campaign among coalition air planners in Buster C. Glosson's "Black Hole" planning cell indicates that the frictional problem Swain highlighted in the case of coalition ground operations surfaced among airmen as well.

[195] John R. Boyd deserves credit for reminding the author that mechanized forces such as German panzer units in May 1940 had been able to sustain offensive operations longer than 4 days by allowing participants to "cat nap" at every opportunity.

[196] Lionel Tiger, "The Cerebral Bridge from Family to Foe," in *Sociobiology and Conflict: Evolutionary Perspectives on Cooperation, Violence, and Warfare*, ed. J. Von Der Dennen and V. Falger (London: Chapman and Hall, 1990), 103.

[197] This formulation was consciously patterned on John R. Boyd's observation-orientation-decision-action (OODA) "cycle" or "loop." The roots of the OODA loop, as it is usually termed, can be traced at least back to his August 4, 1976, briefing "New Conception for Air-to-Air Combat," which stressed such ideas as achieving faster operational tempos than the adversary. Boyd first coined the term *observation-orientation-decision-action cycle* in early 1978.

[198] Don S. Gentile, as told to Ira Wolfert, *One-Man Air Force* (New York: Stratford Press, 1994), 11. Today, Gentile is officially credited with 19.83 air-to-air kills of German aircraft in Europe during World War II. However, during some of his wartime service, the U.S. Eighth Air Force also credited German aircraft destroyed on the ground as "kills." Gentile's wartime tally when he completed his last operational sortie in April 1944 was 23 German aircraft destroyed in the air and 7 on the ground (Mark M. Spagnuolo, *Don S. Gentile: Soldier of God and Country* [East Lansing, MI: College Press, 1986], 298).

[199] Robin Fox, "Aggression: Then and Now," *Man and Beast Revisited*, ed. Michael H. Robinson and Lionel Tiger (Washington, DC: Smithsonian Institution Press, 1991), 89.

[200] John R. Boyd had concluded by 1977 that it was the differential in friction between the two sides that mattered most in combat outcomes.

[201] Isaac Newton (1642–1727), *Mathematical Principles of Natural Philosophy*, vol. 34, *Great Books of the Western World*, ed. Robert Maynard Hutchins (Chicago: Encyclopædia Britannica, 1952), 14.

[202] Mayr, *The Growth of Biological Thought*, 33. In key instances in which biological and physical thought conflicted, as in William Thomson's calculation that the age of the Earth had to be several orders of magnitude less than the "several thousand million years" postulated by Darwin, the biologists turned out to be right and the physicists wrong (428). As Mayr has also noted, the skepticism about evolution expressed to him by physicists as prominent as Niels Bohr and Wolfgang Pauli seems to have been based in no small part on an "oversimplified understanding of the biological processes involved in evolution" (429).

[203] For a summary of the main facts and generalizations that constituted Darwin's original theory of evolution by natural selection, see Mayr, *The Growth of Biological Thought*, 479–480. Illustrative of the generalizations or principles involved in natural selection is the following: "Survival in the struggle for existence is not random, but depends in part on the hereditary constitution of surviving individuals. This unequal survival constitutes a process of natural selection" (480). For the main principles of neo-Darwinian population genetics, see *The Growth of Biological Thought*, 551. An example of the qualitative principles underlying population genetics is: "There is only one kind of variation, large mutations and very slight individual variants being extremes of a single gradient."

[204] Michael Scriven, "Explanation and Prediction in Evolutionary Theory," *Science*, August 28, 1959, 477.

[205] Henri Poincaré, *Science and Method*, trans. Francis Maitland (New York: Dover, 1952), 15–24. Much the same point can be made about mathematics itself. While rapid growth computational capabilities have given rise to a kind of empirical mathematics not previously practicable, the hallmark of mathematical truth remains provability, and the ultimate criteria for what is accepted as mathematical proof remains both qualitative and subjective. An example is the intuitionist's rejection of the law of the excluded middle (p or not-p) in order to limit mathematical existence to denumerable sets, thereby eliminating the "nonintuitive" transfinite sets first explored by Georg Cantor as meaningless (L.E.J. Brouwer, "Intuitionism and Formalism," in *Philosophy of Mathematics: Selected Readings*, ed. Paul Benacerraf and Hilary Putnam [Englewood Cliffs, NJ: Prentice Hall, 1964], 70–71). Logically this rejection amounted to excluding negation elimination (not-not-p implies p) as a permissible rule of inference in mathematical proofs. Few working mathematicians today embrace the position that mathematics must be bounded by our intuitions of the natural numbers. Their disinclination to do so, however, rests on historical, pedagogical, and anthropological reasons that defy clearly quantification (Philip J. Davis and Reuben Hersh, *The Mathematical Experience* [Boston: Birkaäuser, 1981], 395).

[206] Stewart, *Does God Play Dice? The Mathematics of Chaos*, 116–118.

[207] Ibid., 87.

[208] While the idea of getting a rough "feel" for a magnitude that we can neither directly nor precisely measure may initially seem peculiar, it is no different from discussions of "generic distance" in "animal design space" in the field of evolutionary biology. As Dawkins, Fisher, and others have

demonstrated, we cannot today measure "genetic distance" other than in a conceptual or qualitative sense. Yet just as examining "Poincaré sections" (surfaces in phase space used to test the periodicity of dynamic systems) yields qualitative insights into dynamical systems not attainable by crunching standard equations, discussions of small versus large leaps in animal design space yield fruitful insights into evolution (see, for example, Dawkins, *The Blind Watchmaker*, 72–74, 231).

[209] Jon M. van Tol deserves thanks for reminding the author that even complex air-to-air engagements have seldom involved the numbers of discrete "shooters" typical in tactical interactions on the ground.

[210] Carl H. Builder, *The Masks of War: American Military Styles in Strategy and Analysis* (Baltimore: The Johns Hopkins University Press, 1989), 23; also Perry M. Smith, *The Air Force Plans for Peace 1943–1945* (Baltimore: The Johns Hopkins University Press, 1970), 18.

[211] Mark E. Hubbard, in William E. Kepner, "The Long Reach: Deep Fighter Escort Tactics," Eighth Fighter Command, May 29, 1944, 10. This wartime publication was developed by asking some of the Eighth Air Force's more seasoned fighter pilots and fighter leaders for accounts of their own experiences flying long-range-escort missions over occupied Europe in late 1943 and early 1944 (3). It consists of 26 such accounts plus Kepner's introduction.

[212] Kepner, "The Long Reach," 33. John C. Meyer (24 air-to-air kills in World War II plus 2 more in Korea), Robert S. Johnson (27 kills in World War II), and George Preddy (26.83 kills) also emphasized the importance of avoiding the unseen attacker (39, 42, 53).

[213] Raymond F. Toliver and Trevor J. Constable, *The Blond Knight of Germany* (New York: Doubleday, 1970), 173. Hartmann had exceptional visual acuity that usually enabled him to spot enemy planes long before his comrades.

[214] *Project Red Baron III: Air-to-Air Encounters in Southeast Asia*, vol. 3, *Tactics, Command & Control, and Training* (Nellis AFB, NV: U.S. Air Force Tactical Fighter Weapons Center, June 1974), 49, 63, 66, 71–72. During 1965–1973, the number of *encounters*, meaning situations in which the crew of a U.S. aircraft was aware of an enemy aircraft as either a potential target or a potential threat, was considerably larger than the number of decisive engagements. From April 1965 to November 1, 1968, nearly 1,400 encounters were documented by Red Baron I and Red Baron II, but only 172 decisive engagements (ibid., "Executive Summary," 1). Similarly not all engagements, meaning encounters in which at least one participating aircraft took an offensive or defensive action, were decisive. Red Baron III, which covered November 1968 to January 1973, documented 394 engagements, of which only 112 were decisive (ibid., 2).

[215] *Project Red Baron III*, vol. 1, 24. Of the 112 aircraft lost in decisive engagements analyzed by Project Red Baron III (75 MiGs and 37 U.S. aircraft), 60 percent (67 of 112) of all American and North Vietnamese aircrews "were apparently unaware of the attack," and another 21 percent (24 of 112) "became aware of the attack too late to initiate adequate defensive action" (*Project Red Baron III*, vol. 3, 61). As of the summer of 1975, instructors at the U.S. Navy Fighter Weapons School (Topgun) were briefing that 55 to 60 percent of the American crews downed in Southeast Asia did not see their attacker until after they were hit, and another 25 percent saw the bogey before weapons impact but not in time to do anything about it (Barry D. Watts, personal notes, Topgun Class 04–75, June 24, 1975 lecture). Israeli experience in 1982 revealed a similar pattern. Israeli F–16 pilots, who accounted for about half of Israel's kills in 1982, reported that, excluding gun kills, 60 percent of their victims did not react prior to weapons impact (James G. Burton, "Letting Combat Results Shape the Next Air-to-Air Missile," unclassified briefing, January 1985, slide 6).

[216] *Project Red Baron III*, vol. 1, 24. Situation awareness did not become widespread in the thinking of the U.S. fighter community until some years after Red Baron III was published.

[217] The complex, unfolding dynamic of some options falling aside or receding while others emerge or approach underscores the genius of Clausewitz's image of "an interplay [*Spiel*] of possibilities [*Möglichkeiten*], probabilities [*Wahrscheinlichkeiten*], good luck and bad [*Glück und unGlück*]" weaving its way throughout the length and breadth of the tapestry of war. Clausewitz's image may be "merely" a metaphor. Yet given how much effort is needed to improve upon it, to say nothing of adding anything new, it is a powerful metaphor nonetheless.

[218] During the advanced medium-range air-to-air missile operational utility evaluation (AMRAAM OUE), *situation awareness* (SA) was defined as "the perception of the whole picture, not only location but also likely future activity, both friendly and enemy" forces (Veda, "The Influence of 'Operational Factors' (U)," briefing slides, February 14, 1985, unclassified slide entitled "(U) Definitions (Continued)." SA involves processing enough information to have a reasonably accurate picture of

where all the participants in an aerial engagement are, and where they are likely to be in the near term (measured in seconds). By 1988, U.S. Air Force pilots were generally using the term *situational awareness* in lieu of *situation awareness* (Donald Stiffler, "Graduate Level Situational Awareness," *USAF Fighter Weapons Review*, Summer 1988, 15–20). Pilots like Stiffler also identified SA with the orientation step of John R. Boyd's observation-orientation-decision-action loop. Boyd's appreciation of the central importance of SA in air combat can be traced back to a 1974 briefing that focused on a concept for creating "an outstanding air superiority fighter while reversing the increasing cost trend normally characteristic of such an endeavor" ("Conception," Development Plans and Analysis, slide 2, Air Staff, Washington, DC, summer 1974).

[219] Clarence A. Robinson, Jr., "Fighter, Missile Gains Pressed," *Aviation Week and Space Technology*, April 4, 1977, 2.

[220] R.E. Guild, "AIMVAL Analysis," Headquarters, U.S. Air Force, Studies and Analysis, briefing, slide 3 ("Test Objectives"), February 25, 1978. For details on the five intermediate-range missile concepts tested on F–15s and F–14s during air intercept missile evaluation (AIMVAL), see Clarence A. Robinson, Jr., "Aerial Combat Test to Advance," *Aviation Week and Space Technology*, April 25, 1977, 28–30.

[221] E.J. Griffith, "ACEVAL: Origin, Description, Results, Applicability," briefing, slide 2 ("ACEVAL [air combat evaluation]"), undated. Griffith was the Blue Force commander.

[222] Guild, "AIMVAL Analysis," slide 6 ("Test Trial Matrix for AIMVAL").

[223] Griffith, "ACEVAL," slide 8 ("Test Matrix").

[224] "No-Win War at Dogbone Lake," *U.S. News and World Report*, January 9, 1978, 56.

[225] I.A. Kaufman, "Multiple Air Combat Evaluation (U)," WSEG Report 247, Institute for Defense Analyses Study S–440, September 1974, 2.

[226] For a hardware-oriented reading of AIMVAL, see Frederick C. Blesse, "The Changing World of Air Combat," *Air Force Magazine*, October 1977, 34–37. Blesse was credited with shooting down 10 MiG–15s during the Korean War. For an interpretation of AIMVAL that highlights human interactions rather than hardware differences, Barry D. Watts, "The Changing World of Air Combat, or *Plus Ça Change, Plus C'est la Même Chose*," *Air Force Magazine*, December 1977, 35–35. By the end of ACEVAL, the overriding concern expressed by most of the aircrew participants was that the results would "be incorrectly interpreted and used to support weapon systems concepts reflecting industry's desires and not operational needs" (John R. Boyd and Burkley, trip report after visit to Nellis AFB, NV [December 7–9, 1977], December 29, 1977, 1).

[227] S.R. Dvorchak, "Getting It On in the All-Aspect Arena (U)," *Tactical Analysis Bulletin* 79, no. 2 (July 25, 1979), 3–4, 18. As Dvorchak later observed, if one views ACEVAL strictly as a test of competing hardware, the results become "incomprehensible" (telephone conversation with author, October 6, 1986).

[228] Veda, "AMRAAM OUE Lessons Learned Briefing (U)," slide 9 ("(U) AMRAAM OUE Test Matrix"), Dayton, Ohio, April 11, 1984.

[229] Guild, "AIMVAL Analysis," slide 7 ("Summary Observations—Test Environment"); Griffith, "ACEVAL: Origin, Description, Results, Applicability," slide 3 ("Test Design"), slide 7 ("Test Hardware").

[230] S.R. Dvorchak, "On the Measurement of Fog," briefing to the Military Operations Research Society, slide 7 ("Foggy Variables Are Important"), June 1986. The source of this conclusion was Veda's "AMRAAM OUE Lessons Learned Briefing (U)," SECRET, August 3, 1983, slide 41 ("(U) Overall Comments"). This slide was later declassified.

[231] The Red fighters that were initially not targeted quickly inflicted two losses on the Blue side, thereby reducing the fight to a messy 2-v-2.

[232] The primary source of this observation was the ACEVAL 4-v-4s, including training missions, invalid trials, and valid trials. These some 140 engagements were examined for sorting well after the test was flown. Not a single case of perfect sorting was found (Dvorchak, phone conversation with author, December 1, 1995).

[233] Sparks, phone conversation with author, March 1, 1984.

[234] Clausewitz, *On War*, 119, 120.

[235] Hill, Cook, and Pinker, "Part I: A Statistical Compendium in Gulf War Air Power Survey," vol. V, *Gulf War Air Power Survey: A Statistical Compendium and Chronology* (Washington, DC: U.S. Government Printing Office, 1993), 653–654; John M. Deur, "Wall of Eagles: Aerial Engagements and Victories in *Desert Storm*," unpublished page proofs. Prior to Operation *Desert Storm*, U.S. and Israeli

pilots had only recorded a total of four BVR missile kills during *Rolling Thunder* (1965–1968), *Linebacker I/II* (1972–1973), the Yom Kippur War (1973), and Operation *Peace for Galilee* (1982)—see James G. Burton, “Letting Combat Results Shape the Next Air-to-Air Missile,” briefing, slide 3, January 1985. Note that in at least 3 of the 16 *Desert Storm* engagements that began with beyond-visible-range shots, the kill was either accomplished by another missile launched within visual range or, in one case, by the Iraqi fighter running into the ground.

[236] “Darts and Laurels,” *Armed Forces Journal International*, October 1995, 80; 390th Fighter Squadron, 366th Wing, “F–15C JTIDS Operational Special Project (OSP),” briefing, Mountain Home AFB, ID, undated; and discussions with Gary L. Crowder, July 31 and November 8, 1995. The 390th OSP ran from September 1993 to September 1994 and involved 20 F–15Cs equipped with Joint Tactical Distribution Systems (JTIDS) (“F–15C JTIDS Operational Special Project (OSP),” slides 6 and 7). Engagements varied in size and complexity from 4-v-4 to 8-v-18 with the JTIDS F–15s having airborne warning and control system (AWACS) support on 70 percent of the scheduled missions (slide 7). JTIDS–equipped F–15 pilots reported their “situation awareness drastically increased” (slide 11). Besides knowing where the friendlies and adversaries were, JTIDS greatly enhanced accurate sorting and targeting.

[237] Beyerchen, “Clausewitz, Nonlinearity, and the Unpredictability of War,” 87–88.

[238] While this description of nonlinear dynamics and chaos is adequate for purposes of reconstructing general friction, it overlooks definitional controversies and details that are far from trivial, particularly to mathematicians. For example, the “absence of periodicity has sometimes been used instead of sensitive dependence [on initial conditions] as a definition of chaos.” See Edward N. Lorenz, *The Essence of Chaos* (Seattle: University of Washington, 1993), 20. However, if a system is not *compact*—meaning that “arbitrarily close repetitions” need never occur—“lack of periodicity does not guarantee that sensitive dependence is present” (17, 20). Readers interested in exploring various definitions of chaos should consult Lorenz, 3–24, 161–179; and James A. Dewar, James J. Gillogly, and Mario L. Juncosa, “Non-Monotonicity, Chaos, and Combat Models,” RAND Corporation, R–3995–RC, 1991, 14–16.

[239] Lorenz, *The Essence of Chaos*, 10, 23–24.

[240] Ibid., 8.

[241] Heinz-Otto Peitgen, Harmut Jürgens, and Dietmar Saupe, *Chaos and Fractals: New Frontiers of Science* (New York: Springer-Verlag, 1992), 585–587; also Stewart, *Does God Play Dice?* 155–164. For a rigorous treatment of the logistic mapping (alias the “quadratic iterator”), see chapter 11 in Peitgen, Jürgens, and Saupe: the final-state or “Feigenbaum diagram” (after the physicist Mitchell Feigenbaum) for the logistic mapping “has become the most important icon of chaos theory” (587). Mathematica’s built-in function NestList renders the research mathematics needed for a basic understanding of the logistic mapping almost trivial. However, the same calculations can be easily carried out on a calculator such as the Hewlett Packard HP–48SX.

[242] Lorenz’s discovery of chaos was precipitated by an attempt to take a research shortcut. At the time, he was trying to develop a weather model and making successive runs on a computer. The output of the model was calculated weather patterns over a period of “months.” At a certain stage in the research, he made some adjustments to the model, and then, rather than completely running it from the beginning as he had done previously, Lorenz tried to save time in generating a new run by entering the weather data from midway through the last run to three decimal places rather than six. As a result of this minor change, Lorenz saw his weather “diverging so rapidly from the pattern of the last run that, within just a few months, all resemblances had disappeared.” See James Gleick, *Chaos: Making a New Science* (New York: Viking, 1987), 15–16.

[243] Readers interested in nonmathematical introductions to nonlinear dynamics may wish to consider Gleick, *Chaos: Making a New Science*, Briggs and Peat, *Turbulent Mirror*, or Lorenz, *The Essence of Chaos*.

[244] For the crucial excerpt from Ruggero Giuseppe Boscovich’s (1711–1787) most famous and widely read work, his 1758 *Philosophiae Naturalis Theoria Reducta ad Unicam Legem Virium in Natura Existentium* [*A Theory of Natural Philosophy Reduced to a Law of Actions Existing in Nature*], see John D. Barrow, *Theories of Everything: The Quest for Ultimate Explanation* (New York: Fawcett Columbine, 1991), 54. While it is not certain how far the *Theoria* influenced the subsequent development of atomic theory, this work was widely studied, especially in Britain where Michael Faraday, William Hamilton, James Clerk Maxwell, and Lord Kelvin stressed the theoretical advantages of the

Boscovichian atom over rigid atoms. See Lancelot L. Whyte, "Boscovich, Roger Joseph," in *The Encyclopedia of Philosophy*, ed. Paul Edwards (New York: Macmillan and the Free Press, 1967).

[245] R. Harré, "Laplace, Pierre Simon de," in *The Encyclopedia of Philosophy*.

[246] Isaac Newton, *Optics*, vol. 34, *Great Books of the Western World*, 542; also Richard S. Westfall, *Never at Rest: A Biography of Isaac Newton* (New York: Cambridge University Press, 1980), 777–778.

[247] Harré, 392.

[248] Ibid.

[249] James R. Newman, "Commentary on Pierre Simon de Laplace," *The World of Mathematics: A Small Library of the Literature of Mathematics from A'h-mosé the Scribe to Albert Einstein*, vol. 2 (Redmond, WA: Tempus, 1956, repr. 1988), 1296. Laplace's *Théorie analytique* appeared in 1812 and was dedicated to Napoleon.

[250] Pierre Simon de Laplace, "Concerning Probability," *The World of Mathematics*, vol. 2, 1301–1302; the cited selection is an excerpt from *Essai philosophique sur les probabilitiés* of 1814.

[251] For Laplace, the fundamental objects of probability theory were not "chance events, but degrees of belief" necessitated by the imperfections of human knowledge. See Theodore M. Porter, *The Rise of Statistical Thinking: 1820–1900* (Princeton, NJ: Princeton University Press, 1986), 72.

[252] David Ruelle, *Chance and Chaos* (Princeton, NJ: Princeton University Press, 1991), 45–47; Lorenz, *The Essence of Chaos*, 77–110.

[253] While the contrast between the gross behavior of tides and detailed perturbations in the weather at a given location is legitimate, it is not the entire story. The Earth's weather exhibits predictable regularities such as higher average temperatures in the summer than during winter, and even something as "regular" as the times of future sunrises can be delayed or advanced a millisecond or so as a result of measurable decreases or increases in the Earth's speed of rotation. Lorenz, therefore, has a fair point in noting that "when we compare tidal forecasting and weather forecasting, we are comparing prediction of predictable regularities and some lesser irregularities with prediction of irregularities alone" (*The Essence of Chaos*, 79). In this sense, nonlinear science is not so much an alternative to the classic physics of Laplace as an expansion that puts irregular processes on equal footing with regular ones. In this regard, Lorenz is on record as objecting to the presumption that regular behavior is more fundamental or "normal" than chaotic behavior (*The Essence of Chaos*, 69).

[254] Westfall, 430. A second edition of *Principia Mathematica* appeared in 1713 and a third in 1726, the year before Newton's death.

[255] Ibid., 540.

[256] Ibid., 543; Lorenz, *The Essence of Chaos*, 114.

[257] The history of mathematics is littered with impossible problems. A classic example from antiquity is the problem posed by the Greeks of "squaring the circle, that is, constructing a square with an area equal to that of a given circle" with the aid of a straight-edge and compass (Howard DeLong, *A Profile of Mathematical Logic* [New York: Addison-Wesley Publishing, 1970], 29). While some of the Greeks suspected that this problem was impossible under the stated condition, it was not until the 19th century that a proof was finally given that showed, once and for all, that such a construction is logically impossible (ibid., 69). The impossibility in this case was tied to the specified means, and the calculus of Newton and Gottfried Wilhelm Leibniz provided an alternative method that allowed the circle to be squared, if not exactly, at least to whatever degree of precision might be practically required. By comparison, Gödel's incompleteness theorems present a more severe type of mathematical impossibility because there do not appear to be, even in principle, alternative means to the deductive methods of inference to which these theorems apply (ibid., 193). The "impossibility" associated with the three-body problem is somewhat different. The impossibility is not that there are no solutions at all, or even no stable ones, but that in certain regimes the dynamics become so unstable that future states of the system cannot be predicted even approximately.

[258] Laplace, quoted in Newman, "Commentary on Pierre Simon de Laplace," 1293.

[259] Tony Rothman, "God Takes a Nap: A Computer Finds that Pluto's Orbit Is Chaotic," *Scientific American*, October 1988, 20.

[260] Gerald Jay Sussman and Jack Wisdom, "Numerical Evidence That the Motion of Pluto Is Chaotic," *Science*, July 22, 1988, 433; also Sussman and Wisdom, "Chaotic Evolution of the Solar System," *Science*, July 3, 1992, 56.

[261] Stewart, *Does God Play Dice?* 70–72. For Lorenz's discussion of George William Hill's "reduced" version of the three-body problem, see *The Essence of Chaos*, 114–120, 192–193.

[262] Crutchfield et al., 46.

[263] Poincaré, 67–68. This passage has been often quoted by nonlinear dynamicists. See, for example, Crutchfield et al., 48. Insofar as it recognizes other sources of "chance" than human ignorance, the passage constitutes an explicit rejection by Poincaré of Laplace's "demon" or vast intelligence. Does it also recognize "chaos"? As Lorenz has noted, Poincaré's work on the three-body problem was not begun in search of chaos. Instead, Poincaré sought "to understand the orbits of the heavenly bodies" and found chaos in the process (*The Essence of Chaos*, 121). And while we cannot be certain, "we are left with the feeling that he must have recognized the chaos that was inherent in the equations with which he worked so intimately" (ibid., 120).

[264] Madhusree Mukerjee, "Profile: Albert Libchaber—Seeing the World in a Snowflake," *Scientific American*, March 1996, 42. Libchaber and Maurer first published their discovery of chaotic behavior in superfluid hydrogen in 1978 (Bai-Lin, 559).

[265] Tien-Yien Li and James A. Yorke first introduced the term *chaos* in their 1975 paper "Period Three Implies Chaos" to denote the unpredictability observed in certain "deterministic" but nonlinear feedback systems (Bai-Lin, 3, 244). Their choice of this term remains, at best, mischievous because it tends to blur the notion of randomness with that of local unpredictability within predictable global bounds. For example, the well-known "chaotic" attractor named after Lorenz is unpredictable in that "even when observed for long periods of time," it does not ever appear to repeat its past history exactly, yet the beautiful "owl's mask" pattern it generates in state space is by no means wholly random (Lorenz, "Deterministic Nonperiodic Flow" in Bai-Lin, 282, 289). In their 1975 paper, however, Li and Yorke insisted on using the term *chaotic* to describe the nonperiodic dynamics of certain equations despite advice from colleagues that they "choose something more sober," but the term has stuck (Bai-Lin, 245; Gleick, 69).

[266] Bai-Lin, 67–71. For more recent evidence of chaotic dynamics in a physical system, see "Chaotic Chaos in Linked Electrical Circuit," *Science News*, January 14, 1995, 21–22.

[267] Peitgen, Jürgens, and Saupe give an estimated value of 3.5699456 . . . for the onset of chaos in the quadratic iterator (612).

[268] Clausewitz, *On War*, 85, 86.

[269] Clausewitz, *Vom Kriege*, 207, 237.

[270] Clausewitz, *On War*, 119.

[271] John R. Boyd, "Conceptual Spiral," unpublished briefing, slides 14, 31, July–August 1992. Boyd lists nine features of the various theories, systems, and processes that we use to make sense of the world, which, unavoidably, generate mismatches or differences, whether large or small, in initial or later conditions. These features include the numerical imprecision inherent in using the rational and irrational numbers in calculations and measurement; mutations arising from replication errors or other unknown influences in molecular and evolutionary biology; and the ambiguities of meaning built into the use of natural languages such as English or German, as well as the interactions between them through translations.

[272] Dewar, Gillogly, and Juncosa, iii.

[273] Ibid., v.

[274] Ibid., v, 4–5. Note that because this model is "piecewise continuous, not continuous," Dewar, Gillogly, and Juncosa's "definition of chaos was similar to, but not the same as, definitions of chaos found elsewhere in the literature" (45; for their definition see 18).

[275] Ibid., 5.

[276] Ibid., 16, 42.

[277] Ibid., 43.

[278] Ibid., vi.

[279] Clausewitz, *On War*, 139.

[280]As the afterword explains, both military organizations and the humans in them can be understood as complex adaptive systems. Complex adaptive systems act on the basis schemata created to describe or predict how reality works. In this sense, both military organizations and individual combatants act on the basis of constructs or perceptions of reality. Insofar as those constructs or perceptions diverge from reality, there will always be informational differences whose long-term effects can be amplified by nonlinear processes.

[281] As Beyerchen has noted, "nowhere" does Clausewitz provide "a succinct definition of chance" in war (77).

[282] Poincaré, 67–70, 72–76. Beyerchen has argued that Poincaré left the door open to yet another form of chance: the unpredictability of interaction between the "slice" of the universe we can

apprehend and some other part that we, as finite beings, do not or cannot. "Is this a third way of conceiving of chance?" Poincaré asked. In reply, he wrote: "Not always; in fact, in the majority of cases, we come back to the first or second" (76). Given that Poincaré said, "Not always" rather than "Never," there appear to be, on this understanding, three aspects of chance that transcend human ignorance as well as Laplace's demon: imperceptible microcauses that, through amplification, have noticeable effects; the stochastic effects of causes too multitudinous or complex to be unraveled; and the interaction of causes arising from different "slices" of universe that inevitably surprise us because we cannot take in the universe as a whole. Beyerchen speculates that Poincaré was less concerned about this third guise of chance than was Clausewitz. For Lorenz's discussion of Poincaré's treatment of chance, see *The Essence of Chaos*, 118–120.

[283] Andrew W. Marshall reiterated this concern as recently as November 1995, after reviewing the first complete draft of this paper.

[284] Ed Felker, "Information Warfare: A View of the Future," *A Common Perspective: Joint Warfighting Center's Newsletter*, September 1995, 18.

[285] Larry Lynn, "Battlefield Dominance and ARPA Focus," Advanced Research Projects Agency (ARPA) memorandum, June 29, 1995, 2.

[286] R. Boyd has identified the differences or mismatches (whether large or small) that unavoidably exist between the world and our understanding of it at any point in time as the root source of novelty in science, engineering, and technology ("Conceptual Spiral," slide 23).

[287] Paul Carroll, *Big Blues: The Unmaking of IBM* (New York: Crown Publishers, 1993), 217–222, 325–328, 347. IBM executives had ample warning of the changes that would restructure their industry. "They commissioned months-long task forces with loads of smart people and forecasted the changes in the market that would cripple IBM, but IBMers couldn't quite bring themselves to do anything about those cataclysmic changes" (3).

[288] Andrew W. Marshall provided this anecdote. The Israeli intent was to use remotely piloted vehicles (RPVs) primarily to locate targets beyond friendly lines. To get there, however, the vehicles had to overfly friendly units and soon began revealing that friendly forces were often not located precisely where they claimed to be. While the RPVs were indeed used in their intended role, the Israelis felt that imposing much greater discipline on position reports by their own units constituted the larger tactical benefit.

[289] "A Survey of Telecommunications: The Death of Distance," *The Economist*, September 30, 1995, 28.

[290] Andrew W. Marshall suggested this possibility.

[291] Dawkins, *The Blind Watchmaker*, 73. The basic idea of Dawkins, Fisher, and other biologists is that large leaps in animal design space have a much lower probability of being viable than small ones.

[292] Martin van Creveld, *The Transformation of War* (New York: The Free Press, 1991), ix–x, 2, 29, 62, 224–225.

[293] Ibid., 245. It is relevant given the interpretation of Clausewitz in chapter 2 and chapter 3 to add that van Creveld's reading on *Vom Kriege* is rather odd. For instance, he asserts without any discussion or argument that *Vom Kriege* uses the "axiomatic method" and is "mainly deductive in character" (35). One can only conclude that van Creveld has little familiarity with axiomatic methods, whether those of Euclid, Giuseppe Peano, Gottlob Frege, or their successors. Those interested in pursuing this particular criticism may wish to compare Clausewitz's method with that in Patrick Suppes' *Axiomatic Set Theory* (New York: Dover, 1972).

[294] Richard Simpkin, *Race to the Swift: Thoughts on Twenty-First Century Warfare* (London: Brassey's Defence Publishers, 1985), 106.

[295] Early versions of the second law of thermodynamics arose from studying irreversible processes in which some of the energy in a system becomes unavailable for useful work. Rudolf Clausius (1822–1888), for instance, formulated the second law as the principle that "No process is possible in which the sole result is the transfer of energy from a cooler body to a hotter body" (Peter W. Atkins, *The Second Law* [New York: W.H. Freeman and Company, 1984], 25). Entropy, whose unit of measurement is energy/temperature (joules/degree Kelvin, for example), was introduced to label the manner in which energy is stored in thermodynamic systems (ibid., 38). A more modern statement of the second law is that if an isolated system in thermodynamic equilibrium has a state function, *S*, which is the entropy or degree of disorder of the system, then dS/dt ? 0 (Grégoire Nicolis and Ilya Prigogine, *Exploring Complexity: An Introduction* [New York: W.H. Freeman and Company, 1989],

61–62). *When* Boyd first connected Clausewitzian friction and the second law of thermodynamics is hard to determine precisely. However, a critique of his "Patterns of Conflict" briefing, written by a military historian following its presentation to the faculty of the U.S. Army Command and General Staff College in May 1982, confirms that he was describing friction as Clausewitz's most important contribution to military thought at that time. It was Ludwig Boltzmann (1844–1906) who related the macroscopic state of a thermodynamic system to its microscopic arrangements. Boltzmann's formulation of this relationship takes the form S = k logW, where *S* is entropy, *k* is Boltzmann's constant, and *W* represents the number of microscopic arrangements of the system associated with entropy *S* (Atkins, 65–79). In the 1940s, Claude E. Shannon's early work on information theory revealed that information, understood as a measure of one's freedom of choice when selecting a message, has the same form as Boltzmann's famous equation for entropy. See Claude E. Shannon and Warren Weaver, *The Mathematical Theory of Communication* (Urbana: University of Illinois Press, 1949), 9, 27, 48–53. Perhaps more than anything else, it was Boyd's appreciation of this connection between information (in the sense of uncertainty) and entropy (or disorder) that led him to connect Clausewitzian friction with the second law of thermodynamics.

[296] Ernst Mayr, *This Is Biology: The Science of the Living World* (Cambridge: Belknap Press of Harvard University Press, 1997), 19.

[297] Caldwell, *Hayek's Challenge*, 363.

[298] Andrew Ilachinski, "Irreducible Semi-Autonomous Adaptive Combat (ISAAC): An Artificial-Life Approach to Land Warfare (U)" (Alexandria, VA: Center for Naval Analyses, CRM 97–61.10, August 1997), 7.

[299] Caldwell, *Hayek's Challenge*, 364. For the original account, see Joshua Epstein and Robert Axtell, *Growing Artificial Societies: Social Science from the Bottom Up* (Washington, DC: Brookings Institution Press, 1996).

[300] Paul K. Davis, *The Role of Uncertainty in Assessing the NATO-Pact Central Region Balance* (Santa Monica, CA: RAND, 1988), N–2839–RC.

[301] Michael Schrage, *Perfect Information and Perverse Incentives: Cost and Consequences of Transformation and Transparency* (Cambridge, MA: MIT Security Studies Program Working Paper, May 2003).

[302] Ibid.

[303] William A. Owens with Ed Offley, *Lifting the Fog of War* (New York: Farrar, Straus and Giroux, 2000), 15. The author is by no means alone in having doubts about Admiral Owens' conviction that warfare can be reduced to "seeing" the battlespace. See, for example, Frank Hoffman, "It's Time for the Revolution," *Proceedings*, May 2000, 12–13. That said, the author does have sympathy for the Owens view that the military services have done far less than they could have done over the last decade to adapt their ways of fighting and modernization programs to the needs of the post-Cold War security environment. On this point he is right.

[304] *Joint Vision 2020* is available at <http://dtic.mil/jv2020>.

[305] J.F.C. Fuller developed what he took to be a comprehensive list of the principles of war during the years 1911–1919 (*The Foundations of the Science of War* [London: Hutchinson and Company, 1925], 13–14). In 1920, Fuller's principles of war were incorporated into the British Army's Field Service Regulations. They persist in British and American doctrinal manuals to this day.

[306] Ibid.

[307] Ibid.

[308] John G. Morgan and Anthony D. McIvor, "Rethinking the Principles of War," *Proceedings* 129 (October 2003), 38.

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Clausewitzian Friction and Future War

REVISED EDITION

Friction is an inevitable impediment to effective action and was a significant factor in war long before Clausewitz popularized the term. Modern observers, however, have speculated that technological advances will reduce, if not eliminate, friction.

Barry Watts addresses three questions about friction in the information age: Could it be amenable to solutions? If it is in fact enduring, could the effects of friction be reduced in future conflicts? And do advances in warfighting demand revision of Clausewitz's original concept?

To answer these questions, Watts clarifies the notion of friction in Clausewitz by reviewing its evolution and extending the mature concept. He then subjects the concept to the test of empirical evidence, using the Persian Gulf War to show the persistence of friction in recent times. To explore the more complex issue of friction in future conflicts, the author offers three indirect arguments for its undiminished persistence. Finally, he exploits the notion of nonlinearity to reconstruct Clausewitz's concept in modern terms.