Naval War College Review

Volume 43
Number 1 *Winter*

Article 14

1990

Chaos: Making A New Science

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everywhere and nowhere. Hawking is at ease with these seeming contradictions and shows us how each is equally useful and leads to a better understanding of the larger concepts.

One of the unique aspects of subatomic physics is that each subatomic particle is first postulated as a necessary condition to satisfy higher level observations and then found by clever experiments. For readers of this review, it is worth noting that one of the first crucial experiments in modern physics, the determination of the invariance of the speed of light, was done by Albert Michelson of naval and Nobel fame.

Ultimately, Hawking ties all this together in the two great themes of modern physics: the search for an understanding of the origin and fate of the universe, and the search for a grand unified theory. The latter, which has attracted but eluded physicists throughout the 20th century seeks to link the four fundamental forces of physics: gravity, which causes Newton's apple to fall and the planets to remain in orbit; the electromagnetic force, which governs all that we know as electricity and magnetism; the weak nuclear force, which gives rise to radioactivity; and the strong nuclear force, which binds the atomic nucleus. Gravity is the problem; though apparently simple, it does not seem to yield to the laws of quantum theory. Hawking poses and dissects the question, Can we get there or is the search confined to one of better and better approximations?

Physicists seem closer to understanding the origin of the universe than its ultimate fate. There are several promising theories to account for how that dense and homogeneous cauldron of energy and mass at the big bang clumped itself into the bits of discontinuity that have become the galaxies, suns and planets. If we can get our minds into that initial microsecond after the big bang, we will have come close to the mind of God. Physics, as Hawking describes it, may ultimately tell us how it began and where it goes. Religion and philosophy tell us how to comport ourselves along the way.

Reading Hawking is like his search for the grand unified theory of physics: it requires great imagination, and a complete understanding seems near but always elusive. Along the way, one deals with the most extraordinary and challenging ideas and concepts. For these alone, the trip is worth the intellectual exercise.

Gleick, James. *Chaos: Making A New Science*. New York: Penguin Books, 1987. 352pp. $8.95

In the spring of 1919, legend has it, two veteran sergeant-majors from the Austro-Hungarian army met in a Viennese cafe. After tearful embraces, they began to reminisce. Recalling their glory days, they waxed nostalgic about the shined

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shoes of the enlisted, the polished swords of the officers, the brushed splendor of the horses. "What an army!" exclaimed Hans. "Yes," said Franz. "And what did they do with that army?" asked Hans. "They sent it to war!" cried Franz.

The story is intended to poke fun at the military, but it could serve equally well for ridiculing much of science. In both cases, there is an unspoken differentiation between the manageable and the unmanageable, the predictable and the chaotic. Science, like the military, has traditionally preferred the orderly and the predictable. Both establish artificial and arbitrary rules for maintaining control. Whenever reality intrudes into either domain, whether in the form of war for the soldier or nonlinearities for the scientist, the explosion of understandable phenomena into new, unexpected behaviors has mostly been dismissed as "noise."

Unfortunately, the world beyond parade grounds and textbooks has more noise than order. For that reason, both conventional military machines and traditional scientific disciplines have had a rough time in the twentieth century. Neither has been able to escape with its contrived idealizations unscathed. The story of how science is responding to punctured illusions is told in James Gleick's *Chaos: Making A New Science.* It is a story rich with lessons for the military.

Written with style and verve by a well-informed *New York Times* reporter, this history of the "chaos revolution" begins about a generation ago when several scientists and mathematicians began to encounter strange bodies of data and to generate new concepts. Straddling the boundaries of established disciplines, they were all rebelling against professional restraints, excessive quantification, and irrelevant theorizing. Inspired to find underlying uniformities between the sciences, to deepen their qualitative understanding, and to make practical contributions, men like Edward Lorentz, Stephen Smale, James Yorke, and Christopher Shaw independently, and sometimes unwittingly, stumbled into new ways of thinking. Their ideas often depended upon the increasing computational power of electronic computers, whose graphic capacities helped make the chaos revolution possible.

Advanced computers could create visual images of immensely complex phenomena. The results bore little resemblance to traditional scientific or mathematical charts and graphs. Indeed, they looked "chaotic." But beneath the appearance of disorder, scientists found hidden patterns. These patterns were irregular, their details never exactly repeating themselves, and they leaped from place to place in unpredictable ways. Despite the deep structure, catastrophic effects were often precipitated by insignificant causes. Many of these results resembled the ear-splitting, mind-destroying screeches caused by positive feedback in public address systems—or, perhaps, the sounds of battle.

The science of chaos deals with such unpredictable leaps and nonlinear relations in a logical manner. It is a branch of dynamical systems theory, which describes systems whose evolution is controlled by deterministic rules. It deals with peculiar kinds of "attractors"—the geometric forms toward which these processes are drawn—and with the dramatic transitions, the "bifurcations," occurring when complex structures evolve to new levels of complexity. Remarkably, these geometrical beasts seem to describe the kinds of realities that previously eluded scientific analysis: examples include the weather, the rhythmic behavior of animal hearts, and the firing of neurons in brains.

It is possible that complex social structures, ranging from battles through institutions to civilizations, may also be chaotic attractors. All are self-organizing processes whose iterated behavior can become incredibly complex even when the rules directing it are relatively simple and clear. The navy has used the science of chaos effectively in technical applications, e.g., naval architecture, but only a few pioneers, such as Gottfried Mayer-Kress at Los Alamos and The University of California, Santa Cruz, have begun to examine complex human experiences. Mayer-Kress' work on arms races, however, indicates that this new science has reached the level of subtlety necessary to probe social processes accurately.

Successes like these, combined with readable volumes like Gleick's, are bound to create a chaos fad. Such bandwagon effects, themselves examples of chaos, are usually to be lamented because they are fueled by assumptions that some new ideal will solve all the world's problems. But chaos has built-in checks on excess enthusiasm, which make the prospects of popularity less dangerous than usual. Chaos, for instance, tells military planners that there are obstacles—not just limitations—to predictability. Even though the formulas are deterministic, the behavior characterizing chaotic attractors is inherently unpredictable. Complex structures laced with nonlinearities, they are so sensitive to knowledge of initial conditions that even the slightest observational error will quickly lead to unpredictable results. Thus, no true believer can deceive us with claims that chaos models make long-range predictions certain.

If the new science will not enable us to control the world, why, then, all the hubbub? I think the reasons are threefold. First, the models produce beautiful pictures (some of which are included in Gleick's book), and esthetic considerations often drive scientific enthusiasms. Second, planners and executives see in chaos a device for locating the deep structures hidden in extremely complex phenomena, while the obstacles to prediction reinforce the value of their otherwise inarticulable "gut reactions." Finally, and most importantly, the results of analyzing problems using chaos models vastly deepen our appreciation of natural and social processes. We may not be able to control events, and every run made by our computers may produce different results, but when we study these models and their results we can begin to understand intellectually what was previously appreciable only after years of experience.

The computer programmed with chaos models may be the peacetime substitute for experience that was lacking in the Austro-Hungarian Empire—and the Cold War Pentagon. It is a school whose knocks are realistic without being devastatingly hard. Chaos models have the ability to show us how the unpredictable happens; they remind us that information is generated bottom-up, from the "bloomin' buzzin' confusion" of thermodynamic reality. Using chaos models may even nurture concepts of leadership more attuned to the demands of a technologically dynamic, continually evolving environment.

Gleick's book introduces readers to some of the subtleties, most of the themes, and all of the major figures involved in the chaos revolution, but it does not show how the science of chaos can be practically applied. There are no mathematics here. However, the book will whet appetites for similar works.

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O'Connell, Robert L. *Of Arms and Men: A History of War, Weapons, and Aggression.* New York: Oxford Univ. Press, 1989. 367pp. $24.95

Evangelista, Matthew. *Innovation and the Arms Race: How the United States and the Soviet Union Develop New Military Technologies.* Ithaca, NY: Cornell Univ., 1988. 300pp. $34.95

Given the proliferation of books addressing the relationship between technology, weapons, and warfare, a good historiographical introduction would be a welcome addition to one of them. Although Robert L. O'Connell's *Of Arms and Men* features no such introduction, it does contain a prefatory justification for its existence. As a historian, civil servant and member of the U.S. delegation to the Conference on Disarmament in Geneva, O'Connell was dissatisfied with the way weapons had been studied. He was predisposed to believe "that the relationship between man and his weapons is a great deal more intimate and complex than heretofore has been admitted." Our intimacy with weapons has developed over the millennia and is more the consequence of prehistoric man's existence in a state of nature (the hunt) than our experience with total war. O'Connell examines how these aptitudes have governed innovation and warfare from ancient Sumeria to the present.

The particular insight which distinguishes Mr. O'Connell's work from others is his examination of human belligerence from a perspective normally reserved for anthropologists and biologists. Central to his analysis is the distinc-