Evolving Security: Societal Immunity and Competing Demons or Cooperating Angels

Chapter Eighteen

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The economic and cultural ties that connect people, states, and regions are the source of both cooperation and conflict.[1] Even during this prolonged period of economic growth and peace[2]—or at least the absence of open warfare between great powers—the international system remains a competitive environment that presents many threats from global actors, most notably Russia and China. The international system also encompasses environments in which conflict might need to be contained (e.g., Syria) or in which the rules of the road are actively contested (e.g., cyberspace). In this chapter, we examine international competition waged through exponential technologies—most notably, modern social networking technologies whose reach and value scales exponentially with each new user[3]—through the lens of biological evolution and adaptation.

The proliferation and expansion of capabilities for exerting influence through social networks—such as ubiquitous access to tailored information—have exposed vulnerabilities that can be manipulated to create fissures within states by malevolent actors who are seeking and exploiting new methods of influence.[4] These methods include the intentional manipula-

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[1] James R. Watson, Laura E. R. Peters, and Jamon van den Hoek, "Supersystem Risk and the End of the Anthropocene," *Tera*, Vol. 1, No. 1, Fall 2020.

[2] On economic growth, see Martin Ravallion, *The Economics of Poverty: History, Measurement, and Policy*, New York: Oxford University Press, 2016. On peace, see Steven Pinker, *The Better Angels of Our Nature: Why Violence Has Declined*, New York: Penguin, 2011. For an important counterpoint on the increasing peacefulness of the international system, see Bear F. Braumoeller, *Only the Dead: The Persistence of War in the Modern Age*, New York: Oxford University Press, 2019.

[3] In formal terms, these technologies are characterized by increasing returns to scale rather than decreasing or diminishing returns, and they have profound and unpredictable systemic consequences. See W. Brian Arthur, *Increasing Returns and Path Dependence in the Economy*, Ann Arbor, Mich.: University of Michigan Press, 1994; and W. Brian Arthur, *Complexity and the Economy*, New York: Oxford University Press, 2015.

[4] Jim Isaak and Mina J. Hanna, "User Data Privacy: Facebook, Cambridge Analytica, and Privacy Protection," *Computer*, Vol. 51, No. 8, August 2018.

tion of individuals and subgroups that make up a nation through tools that resemble viruses, bacteria, and other pathogens that negatively affect their hosts.

In this chapter, we first discuss the international system as a biological ecosystem. Afterward, we provide two discussions of contemporary security challenges that the United States faces in this biological framework.

The International System as a Biological Ecosystem

A useful first step in addressing these new forms of competitive engagement is to recognize that contemporary international competition has analogues to competition in other complex adaptive systems.[5] The application of the concept of complex adaptive systems—to the interaction and adaption of cells, organisms, individuals, nation states, or global networks of financial and public health systems—essentially "means little more than taking an ecological approach to such systems, investigating the interplay among processes at diverse scales and the interaction between systems and their environments."[6] Thus, *complex adaptive systems* refers to those systems in which

> elements interacting in a system create overall patterns, and how these patterns, in turn, cause the elements to change or adapt in response. The elements might be cells in a cellular automaton, or cars in traffic, or biological cells in an immune system, and they may react to neighbouring cells' states, or adjacent cars, or concentrations of B and T cells.[7]

In many ways, biological competition and international competition are analogous. The *state of nature*—the fundamental persistent struggle for survival—has provided the model for theories of relations between sovereign actors for centuries—a model in which interaction occurs in the absence of an accepted higher authority to resolve disputes and in which self-preservation is an expected and acceptable justification for action, including the use of force.[8] We contend that, if the mapping of the known properties of biological organisms and ecosystems can be successfully related to the structure and dynamics of the international system, it can help policymakers in defending the rules-based international order from current and

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[5] J. Stephen Lansing, "Complex Adaptive Systems," *Annual Review of Anthropology*, Vol. 32, No. 1, October 2003.

[6] Simon A. Levin, "Preface," in Simon A. Levin, ed., *The Princeton Guide to Ecology*, Princeton, N.J.: Princeton University Press, 2009, p. vii.

[7] W. Brian Arthur, "Foundations of Complexity Economics," *Nature Reviews Physics*, Vol. 3, No. 2, February 2021, p. 136.

[8] Thomas Hobbes, *Hobbes: Leviathan: Revised Student Edition*, Richard Tuck, ed., New York: Cambridge University Press, 1996.

future threats.[9] To further our understanding of international competition in the 21st century, solutions for managing competition in nature can be applied to national security. These are the key concepts discussed in this chapter:

- **viral disinformation**, which is defined as false information propagated with the intent of deceiving and manipulating public opinion to stimulate or blunt collective action. This information is very difficult to debunk with facts or logical argument given the social value and context in which it is transmitted and reinforced and the underlying psychological propensity for emotional[10] and motivated reasoning.[11]
- **resilience and immunity**, which is a biological metaphor for the body politic's ability to suppress or defeat foreign threats. It is analogous to biological defenses, notably the immune system's ability to identify self and non-self actors; as we will show, it can be exploited, resulting in several long-term problems.
- the **Darwinian Demon**, which is a theoretical construct that describes an organism that is not constrained by physiological trade-offs.[12] In nature, species tend to evolve strategies that adhere to certain constraints—one can hunt prey but not photosynthesize. The Demon is not so constrained and can do everything: fly, swim, photosynthesize, burrow, etc. On the national stage, frontier technologies, such as artificial intelligence (AI), may create states that resemble Darwinian Demons that simultaneously maximize their ability to explore and exploit solutions to their strategic challenges.[13] The possibility of multiple states becoming such Demons has strong implications for long-term competition and international order.

In general, these concepts leverage structural similarities between biological or evolutionary systems and social systems. Figure 18.1 shows the mapping between the biological and social worlds. It depicts their structural parallels in terms of the base unit of analysis—genes or information—and the consequences of that base level on individuals in their respective systems (i.e., phenotypes or behavior and preferences). At the systemic level, these individuals engender ecological or socioeconomic competition around which units are organized (i.e., species or states). In both systems, there is a hierarchy of scales. Genes encode a phe-

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[9] The examination of the international system and national security echoes previous work seeking similar patterns and discovery. See, for example, Raphael D. Sagarin and Terence Taylor, eds., *Natural Security: A Darwinian Approach to a Dangerous World*, Berkeley, Calif.: University of California Press, 2008.

[10] Garth S. Jowett and Victoria O'Donnell, *Propaganda and Persuasion*, 7th ed., Los Angeles, Calif.: Sage Publications, 2019.

[11] Ziva Kunda, *Social Cognition: Making Sense of People*, Cambridge, Mass.: MIT Press, 1999, pp. 211–263.

[12] Richard Law, "Optimal Life Histories Under Age-Specific Predation," *American Naturalist*, Vol. 114, No. 3, September 1979.

[13] James G. March, "Exploration and Exploitation in Organizational Learning," *Organization Science*, Vol. 2, No. 1, February 1991; see also Aaron B. Frank, "Gaming AI Without AI," *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, February 2022.

FIGURE 18.1

Schema for Analogizing Biological and Social Systems

	Biology	Society	
Evolution	Ecological competition	Socioeconomic competition	Technological adaptation
	Phenotype	Behavior or preferences	
	Genes	Information	

NOTES: The figure is a mapping between biological and social evolution. The left side shows the basic units and levels of selection that enable biological evolution to occur. The right side depicts a mapping of the units and levels in the social world.

notype that provides traits used in ecological competition. Surrounding this competition is evolution: Natural selection changes which genes are present in a population. Similarly, in socioeconomic systems, information acts like genetic material, creating behaviors and preferences that affect competition with other (local and global) actors. Technological adaptation (broadly defined) resembles evolution in biology. Adaptation underpins everything. In biological systems, species evolve, developing new traits through natural selection; in society (and in the context of this chapter), the main form of adaption by states and nonstate actors is through the discovery of *novel technologies*—broadly defined as both physical and computational artifacts, as well as organizational designs and processes that are selected according to competitive pressure within and between states.[14]

The remainder of this chapter develops and explores biological systems as a model for international relations and security in two short discussions. In the first discussion, we examine the immune system as a model for intelligent and adaptive systems in general. In the second discussion, we consider the potential transition from Darwinian Demons to Darwinian Angels given the systemic risks associated with failing to transform competition into coordination and cooperation in infinite games.[15]

Each of the following discussions touches on the challenges posed by undergoverned spaces (UGS) in different ways. The first, focusing on viral disinformation and defenses against it, directly addresses assaults on "common knowledge" and the collective confidence in governance institutions, as opposed to governance outcomes, that undergirds the legiti-

[14] Philip Bobbitt, *The Shield of Achilles: War, Peace, and the Course of History*, New York: Anchor Books, 2011; J. R. McNeill and William H. McNeill, *The Human Web: A Bird's-Eye View of World History*, New York: W. W. Norton & Company, 2003; and William H. McNeill, *The Pursuit of Power: Technology, Armed Force, and Society Since A.D. 1000*, Chicago, Ill.: University of Chicago Press, 1982.

[15] James P. Carse, *Finite and Infinite Games: A Vision of Life as Play and Possibility*, New York: The Free Press, 1986; and Simon Sinek, *The Infinite Game*, New York: Portfolio, 2019.

macy of the system.[16] The second emphasizes the problems posed by adaptive competitors operating in unbounded, infinite games, discussed in Chapters Three and Six of this report.[17] In both arguments, the state is viewed as a central actor—partially because of our own conceptual limitations in imagining and labeling the actors with the highest levels of influence and ability to mobilize resources for competitive and destructive purposes in the international system, and partially because defending the institutions of democratic governance is itself an act that places the state as something to value and protect.

Our goal in presenting these discussions is to use biological analogies as sources of inspiration for new ontological concepts and analytic methodologies for conceptualizing national security. We hope that these discussions will expand how solutions to the nation's most pressing needs are conceived and will provide possible solutions to the challenges they pose.

Going Viral: Information Attack and Defense in the Body Politic

In nature, we can think of species playing an infinite game in which the goal is to keep playing.[18] Through evolution, species develop the means to survive and not go extinct. Importantly, to continue playing this infinite game, species evolve traits and strategies that are different from those that would exist if they played a finite game, in which the objective is to defeat an adversary in the moment rather than having the capacity to continuously adapt to new challenges. Thus, in evolution, success is never final, as surviving one challenge only means that future ones will be found.[19]

The Immune System at the Level of the Individual

One such strategy for long-term survival that has evolved over millennia is the vertebrate immune system. In an infinite game in which the search for a competitive edge is both con-

[16] Henry Farrell and Bruce Schneier, *Common-Knowledge Attacks on Democracy*, Cambridge, Mass.: Berkman Klein Center, Harvard University, Research Publication No. 2018-7, October 2018.

[17] Aaron B. Frank, "Building Strategies for Long-Term Competition: Infinite Games and Adaptive Planning," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022; and Adam R. Grissom, "Undergoverned Spaces and the Challenges of Complex Infinite Competition," in Aaron B. Frank and Elizabeth M. Bartels, eds., *Adaptive Engagement for Undergoverned Spaces: Concepts, Challenges, and Prospects for New Approaches,* Santa Monica, Calif.: RAND Corporation, RR-A1275-1, 2022.

[18] Carse, 1986.

[19] The military historian Geoffrey Parker has borrowed the concept of *punctuated equilibrium* from evolutionary theory to characterize how the world's most powerful empires and religions, regardless of their accomplishments, eventually succumbed to future challenges, often arising as a consequence of their earlier victories (Geoffrey Parker, *Success Is Never Final: Empire, War, and Faith in Early Modern Europe*, New York: Basic Books, 2002).

tinuous and pregnant with the potential to change the game itself, resilience to an uncertain future is key to avoiding extinction.[20] The vertebrate immune system is a marvel of evolution, in which an elaborate system of fixed defenses and adaptive countermeasures provides the body with an ability to deal with all kinds of problems—both known and unknown. In general, the vertebrate immune system is composed of four major components:[21]

- barriers to invasion
- an innate or general immune system that buys the body time to develop an adaptive response
- an adaptive immune system that develops specific solutions to a given pathogen
- immunological memory that preserves the ability to deal with previously encountered threats and new ones that are similar.

First and foremost, one of the most important features of the immune system is rarely recognized: The body's skin, hair, mucosal membranes, tears, saliva, and more create a protective barrier that filters out, traps, and kills pathogens that might cause harm if they gain access to its internal organs and systems. This first level of defense presents would-be invaders with barriers to entry, much as castle walls protect those behind them from foreign invaders.[22]

Second and third, if a pathogen successfully invades the body, it must confront two immune systems: the innate, or general, immune system and the adaptive, or acquired, immune system. The former is represented by a host of mechanisms that provide an ability to detect a non-self entity and contain and eliminate it through a series of generalized attack mechanisms. The latter provides a tailored response, specific to the invader. In this regard, the general immune system serves as a set of forward-deployed forces whose mission is to blunt and hold enemy forces until follow-on forces can arrive. The adaptive immune system is akin to special operations forces that are trained and deployed to perform specific missions using tailored tactics, techniques, and procedures.

The general and adaptive immune systems are assisted by the body itself. Cells, whether damaged through trauma or infection, "die loudly," signaling that something is wrong. Thus, the specialized cells and resources that are committed to the body's defense are assisted by those that they protect through a vast communications network that provides warning when something goes wrong. As we will discuss later, interfering in the signaling within the body is how many of the most-difficult and most-complex threats have learned to attack.

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[20] In this context, *resilience* can be defined simply as the ability to remain in the game regardless of what competitors might do, what new actors might appear, or how the payoffs of interactions themselves might change.

[21] Paul Klenerman, *The Immune System: A Very Short Introduction*, New York: Oxford University Press, 2017.

[22] Claude Combes, *The Art of Being a Parasite*, trans. Daniel Simberloff, Chicago, Ill.: University of Chicago Press, 2005, pp. 12–15.

The last part of the vertebrate immune system that makes it intelligent is the process by which it remembers pathogens that it has encountered, thus enabling learning to occur over time. This allows the immune system to react quickly to a reinfection or to the presence of a new infection by a pathogen that resembles one that has previously been encountered. Thus, the body's search for solutions to new threats proceeds by building on the tactics, techniques, and procedures that worked against old threats. This learning mechanism is distributed throughout the body—it is not controlled by any one central "commander" like the brain. Responses are quick and resilient to damage because the lymph nodes, which generate and train the immune system's warriors, are spread throughout the body. Equally important, the ability to rapidly generate, train, and deploy the defenders from multiple sites allows for the preservation of energy because the high costs of defense do need not to be carried full time.

The Extended Immune System

In addition to an individual's immune system, society has developed an "extended immune system" in which defenses are enhanced through the coordinated actions and biological experiences of others.[23] This occurs primarily through two mechanisms. The first consists of the additive benefits that accrue at the societal level as the number of people who have acquired immunity to a pathogen reduces its chance to encounter vulnerable members of the group. The second is the body's response to infection—a response that produces both changes in behavior and visible signals that alert others to the presence of an infection; such a response indicates the need to isolate or otherwise avoid contact with an individual who might host a contagious pathogen.[24]

Contemporary technologies have built on these core capabilities and enhanced the ability to protect society from infections. Vaccines offer a way to quickly achieve herd immunity, which limits the ability of pathogens to find hosts to infect. In a way, vaccines are a shortcut to innate learning, a type of "false memory" within the immune system,[25] just as the adoption of rules, values, and technologies that have been pioneered by others offer a shortcut to societal learning and stability. Likewise, public health systems can amplify the warning signals of and mitigate the potential spread of infections. Medical surveillance practices can provide warning regarding the presence and levels of disease within a population, while access to care might involve treating infected individuals in specialized facilities with medicines that

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[23] While this chapter discusses the extended immune system based on the social interactions between members of society, there is increasing recognition that organisms and the environment itself further support individual and collective needs for access to resources, energy, and protection (e.g., ants foraging for plants with antiviral or antifungal properties); this provides another level of consideration. See Ask Nature, "Bacteria Fight Fungus," webpage, last updated August 18, 2016. For a discussion of the concept of the *extended organism*, see J. Scott Turner, *The Extended Organism: The Physiology of Animal-Built Structures*, Cambridge, Mass.: Harvard University Press, 2002.

[24] Klenerman, 2017, p. 28.

[25] Klenerman, 2017, p. 55.

limit the severity of symptoms that accelerate the spread of infections. In addition, economic practices (e.g., paid sick leave) can help slow the spread of a disease through limiting social contact with contagious individuals.

Viral Disinformation as a Pathogen

A challenge that faces the existing security infrastructure in the United States is that the exponential technologies that are propelling global society through a fourth industrial revolution are also allowing for the rapid generation of novel information-based pathogens, specifically viral disinformation.[26] To develop a societal immune system that is capable of dealing with viral disinformation, several important questions must be answered about how the parasite metaphor can be applied to defend society from manipulation, subversion, and attack. To be clear, we are not the first, nor will we be the last, to make this analogy.[27] However, we hope that the questions posed in this chapter further illuminate the extent to which the analogy provides insights and concepts that members of the National Security Enterprise find useful.

What Does Immunity Cost?

In thinking about national security and the creation of new capabilities and concepts for their employment, one of the first major questions to arise concerns the costs, or the "means," that constrain strategic options. In the social realm, *means* are the financial resources, human expertise, time to plan and make decisions, and opportunity costs that arise given that resources committed to achieving one objective might be unavailable to pursue others. Regardless of how costs are considered, society's resources are finite.

In biological terms, the cost of the immune system is measured metabolically, and the immune system is energetically expensive. All of human energy comes from the food that people eat, and it is partitioned to various bodily functions. The larger the metabolic cost of the immune system is, the less energy there is for other functions. In many cases, it is not possible to increase the intake of energy, which places hard limits on what sorts of bodily functions can be sustained. This speaks to a key biophysical trade-off in terms of the traits that species can adopt and realize.[28]

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[26] The *fourth industrial revolution* generally refers to the entrance of AI, machine learning, the Internet of Things, and other adaptive technologies into industrial and economic use. See Klaus Schwab, "The Fourth Industrial Revolution: What It Means, How to Respond," World Economic Forum, January 14, 2016; and Klaus Schwab, *The Fourth Industrial Revolution*, New York: Crown Business, 2017.

[27] For examples, see Axelle Devaux, "How to Contain the Disinformation Virus," *RAND Blog*, April 9, 2020; Miriam Matthews, Katya Migacheva, and Ryan Andrew Brown, *Superspreaders of Malign and Subversive Information on COVID-19: Russian and Chinese Efforts Targeting the United States*, Santa Monica, Calif.: RAND Corporation, RR-A112-11, 2021; and Peter W. Singer and Eric B. Johnson, "The Need to Inoculate Military Servicemembers Against Information Threats: The Case for Digital Literacy Training for the Force," *War on the Rocks*, February 1, 2021.

[28] This argument fits within a broader understanding of research on biology and the energetic trade space that prioritizes the commitment of resources for critical functions, maintenance, and growth. See

As mentioned, the energetic cost of the immune system is high. For example, a 2°F fever in a 175-lb male uses approximately 250 calories per day, which, for comparison, is between the total number of calories used by the heart, 168, and the brain, 373.[29] Moreover, research on modified mice has shown that the energetic costs of mounting a defense against an infection are even higher in the absence of an adaptive immune system;[30] if necessary, the body will divert resources away from many nonessential functions, thus imposing further costs in terms of decreased biological and social functioning.[31]

Given these costs, many additional considerations arise that add nuance to how the immune system is understood because it must be constrained in its use. For example,

- How strong should the immune response to an infection be?
- How does the immune system differentiate the self from the non-self entities?
- How does the immune system consider context?
- How does the immune system ramp up and wind down?
- What bodily functions are prioritized for protection?

Answers to these questions, which we present in the following subsections, offer nuance to the inner workings of the immune system and provide additional detail for developing and testing concepts for defending society.

How Strong Should the Immune Response to an Infection Be?

The vertebrate immune system provides resilience to both known and unknown pathogens. However, could it be better? Why do we not have stronger immunity? Perhaps surprisingly, the strength of the vertebrate immune system varies from species to species. Sharks are said to never get sick, and whales and other large animals do not get cancers.[32] So, why do we? Ultimately, this comes down to evolution and the trade-offs between fitness and immunity. There is not an increasing monotonic relationship between fitness and immunity. Instead, it is concave, with some optimum largely defined by one's environment (i.e., one's needs). We

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Christopher P. Kempes, Peter M. van Bodegom, David Wolpert, Eric Libby, Jan Amend, and Tori Hoehler, "Drivers of Bacterial Maintenance and Minimal Energy Requirements," *Frontiers in Microbiology,* Vol. 8, 2017; and Christopher P. Kempes, Stephanie Dutkiewicz, and Michael J. Follows, "Growth, Metabolic Partitioning, and the Size of Microorganisms," *Proceedings of the National Academy of Sciences*, Vol. 109, No. 2, January 10, 2012.

29 Suzanne C. Segerstrom, "Stress, Energy, and Immunity: An Ecological View," *Current Directions in Psychological Science*, Vol. 16, No. 6, 2007, p. 326.

30 Lars Råberg, Mikael Vestberg, Dennis Hasselquist, Rikard Holmdahl, Erik Svensson, and Jan-Åke Nilsson, "Basal Metabolic Rate and the Evolution of the Adaptive Immune System," *Proceedings of the Royal Society B: Biological Sciences*, Vol. 269, No. 1493, April 22, 2002.

31 Lucy Bird, "Getting Enough Energy for Immunity," *Nature Reviews Immunology*, Vol. 19, No. 5, May 2019.

32 Andrei Seluanov, Vadim N. Gladyshev, Jan Vijg, and Vera Gorbunova, "Mechanisms of Cancer Resistance in Long-Lived Mammals," *Nature Reviews Cancer*, Vol. 18, No. 7, July 2018.

do not have stronger immune systems because, if we did, our overall fitness would diminish; autoimmune diseases would be rife; and we would be allergic to everything and unable to maintain commensal flora that provide essential biochemical services. In contrast, if the immune system were less strong, we would not suffer from these autoimmune issues but would die more frequently, simply from infection. Evolution optimizes this trade-off and has led to a balance between these two outcomes.

Two aspects of the immune system that limit its strength are its decentralization and its localization. If the immune system were centrally managed—say, if the brain were in control—then it would not be resilient to attack (that is, in a decentralized system, there is no one weak point). If the immune system were not localized—if the body were able to counter infection only by ramping up an immune response in every part of the body—then the immune system would be too sensitive, leading to increased instances of autoimmune problems and an increase in bioenergetic demand. This is why the whole body does not react to a cut on the finger; the distributed immune response is designed to amplify a response only to the area around the cut.

How Does the Immune System Differentiate the Self from the Non-Self Entities?

The most fundamental problem that the immune system deals with is separating the self from the non-self within the body. From the perspective of complex adaptive systems, the organism's immune system is synonymous with its identity.[33] Determining self and non-self is essential; a multitude of immune disorders demonstrate the problems that arise if the system is too inclusive, accepting of too many pathogens, or too exclusive, resulting in attacks on the body's own organs or mutualistic partners (e.g., the gut microbiome). The result of failures to differentiate self from non-self is a spectrum of issues: At one end are primary and acquired immune deficiencies; at the other, immune responses that are too active and threaten the body itself (e.g., allergies and autoimmune diseases).[34]

Central to the immune system's ability to distinguish self from non-self is its use of small proteins, called *antigens*, and other signaling molecules on the cell surface. In brief, the immune system relies on antigens and, more generally, major histocompatibility complex molecules as tags for self and non-self entities. The process of antigen recognition includes a somewhat complex process of training for *T-cells*—the hunter cells that seek out foreign invaders—which rely on *antigen-presenting cells*. These antigen-presenting cells are heterogeneous immune cells that mediate the cellular immune response by processing and presenting antigens for recognition by T-cells to prove that they belong in the body.

The threats posed by an improperly tuned immune system are severe. As a result, the body makes a significant investment in regulating the immune system's performance and ensuring

[33] John H. Holland, *Hidden Order: How Adaptation Builds Complexity*, Heather Mimnaugh, ed., New York: Perseus Publishing, 1996, p. 2.

[34] Johns Hopkins Medicine, "Disorders of the Immune System," webpage, undated; and National Center for Biotechnology Information, "Diseases of the Immune System," in *Genes and Disease*, Bethesda, Md., 1998.

that activated T-cells are well trained and capable of acting in a distributed fashion outside centralized control. To regulate one's immune response to one's own body, large numbers of T-cells are produced and trained in the thymus. This training involves exposing T-cells to a wide variety of proteins that are found in cells across the body, from the pancreas to the brain. Those that show too much recognition to self-antigens, or too little, are eliminated and are not released to defend the body.[35]

How Does the Immune System Consider Context?

Defending self from non-self entities is complex because the boundary between them is dynamic. Context matters greatly, indicating that what is regarded as foreign or threatening is contingent on where interactions occur. The decentralized nature of the immune system means that it is not applied with the same strength across the body. Instead, it is "turned on" to a varying degree by a secondary system. Scientists have discovered that cells not generally thought of as part of the immune system actually play an important role in protecting certain organs from immune system attack. For example, many bacteria that would be harmful to bodily organs peacefully coexist on the skin, such as *Staphylococcus aureus*, which can create severe tissue damage in many bodily organs but is carried harmlessly at the entrance to the nostrils in one in four people.[36] Likewise, the gut microbiome contains an estimated 90 percent of the body's cells that assist in maintaining the body's health, yet if these bacteria were to move a few millimeters across the gut wall they would pose a major threat.[37]

The immune system uses several mechanisms to control its response to the same pathogens in a variety of settings. Certain cells found in lymph nodes throughout the body suppress the immune system. As mentioned, the immune system uses antigens to distinguish between normal and foreign agents. In parts of the body, such as the pancreas, that are sheltered from the outside environment, *dendritic cells* display the antigens of their normal neighbors in a way that puts the immune system "at ease." By reading these antigens without being on alert, the immune system's T-cells learn that such cells are off limits to attack. For example, antigens in the walls of the small intestine suppress immune response and protect the local microbiome.[38]

The production of immunosuppressive antigens on a local level allows for the regulation of immunological responses within the body to occur according to context, thus enabling diverse forms of competition and cooperation to occur between the same actors.

How Does the Immune System Ramp Up and Wind Down?

Another important set of questions revolves around the time required for the immune system to ramp up to fight an infection and to wind down after the threat has been mitigated. As

[35] Klenerman, 2017, p. 74.

[36] Klenerman, 2017, p. 9.

[37] Klenerman, 2017, pp. 10, 87.

[38] Dana-Farber Cancer Institute, "Why Doesn't the Immune System Attack the Small Intestine? New Study Provides Unexpected Answer," *ScienceDaily*, January 10, 2007.

already indicated, maintaining a heightened state of immunological vigilance can be damaging, at best depriving other bodily needs of resources and at worst perhaps stimulating an autoimmune disease. Therefore, the rate at which the immune system is mobilized and demobilized has significant implications for the body's overall health.

The body stimulates its immune system in reaction to an infection in many ways. The immune system is byzantine, and even the shortest description of the ways in which the immune system ramps up in response to an infection can appear like a textbook. Briefly, a normal immune response can be broken down into four main components: (1) Pathogens are recognized by cells of the innate immune system; (2) the innate immune system triggers an acute inflammatory response to contain the infection; (3) meanwhile, antigen presentation takes place with the activation of specific helper T-cells, which then (4) coordinate a targeted antigen-specific immune response involving a number of other processes and factors.

It is important to know that the immune system responds differently depending on the pathogen. For example, for extracellular infections (e.g., bacterial infections), the body starts with a humoral immune response with B-cells and antibodies. In contrast, for intracellular infections (e.g., viral infections), the body turns to a cell-mediated immune response with activated antigen-presenting cells and cytotoxic T-cells. One particularly relevant example that is specific to viral infections is the actions of *interferons*, which alert the immune system to the presence of an invader, assist in identifying the invader, tell immune system cells to attack, and inhibit the replication of viruses or cancer cells.[39]

The ideal immune response is rapid, proportionate, and effective. Crucially, it must also be finite. An inflammatory response that is disproportionate or lasts too long risks injury to the host; chronic unregulated inflammation in autoimmune diseases is one example of this. Thus, mechanisms to regulate and ultimately terminate immune responses are central to a healthy immune system. Although there is extensive knowledge of what drives immune responses, knowledge of what terminates immune responses remains relatively sparse. Such processes are clearly more complex than a one-dimensional homeostatic balance. Recent discoveries have revealed increasingly nuanced mechanisms of signal termination, such as intrinsically self-limiting signals—multiple inhibitory mechanisms acting in tandem and activating proteins that behave differently in a variety of contexts.[40]

What Bodily Functions Are Prioritized for Protection?

In general, the decentralized nature of the immune system means that there are no "direct orders" to prioritize any one place, given multiple threats or injuries. However, the localized amplification of the immune system and the feedback between body subsystems mean that immune responses are directed and proportional to specific threats. All body systems work

[39] C. Le Page, P. Génin, M. G. Baines, and J. Hiscott, "Interferon Activation and Innate Immunity," *Reviews in Immunogenetics*, Vol. 2, No. 3, 2000.

[40] Philippa Marrack, James Scott-Browne, and Megan K. L. MacLeod, "Terminating the Immune Response," *Immunological Reviews*, Vol. 236, No. 1, July 2010.

together to some degree and are dependent on outputs from other body systems. The most relevant example is in the case of stress or injury, which leads to increases in epinephrine, which, in turn, lead to peripheral vasoconstriction and, ultimately, more blood flow to vital organs. The body does not invest more resources to heal the most-threatening injuries but instead prioritizes the maintenance of blood flow to the most-vital organs, most notably the brain. This is also manifested in someone developing kidney or liver failure (from ischemia) to maintain cerebral (brain) perfusion pressure. Put another way, the body does not "sacrifice" any one subsystem via a planning process; any that are "lost" are lost when the local immune response is unable to deal with trauma.

National Security Through the Lens of Immunity

In this subsection, we provide some preliminary thoughts on using the workings of the immune system as a model for defending society from viral information attacks. As with conventional approaches to strategy and national security, the immune system model is ultimately constrained by trade-offs. Of interest, however, is that the immune system analogy provides insight into protective mechanisms that may have social analogues and that the mimicry of immunological processes reveals risks and costs posed by underinvesting and overinvesting in security.

Basic Features of an Immunity-Based Defense

The four core tenets of the immune system provide an initial framing for how the parts of a defensive system might look: (1) a boundary that filters and contains viral information so that it does not enter into the population, (2) a set of general defenses that protect society and its institutions from disinformation, (3) a reserve capacity of defenses that can be adapted to cope with any threat that is not quickly or easily contained by the general defenses, and (4) an institutional memory that provides the ability to flexibly commit and decommit resources to security, allowing the rapid restoration and adaptation of defenses. These defenses may be extended through the ability to accelerate individuals' ability to identify and fight infection within themselves and to change their own behavior in ways that break the chain of transmission to vulnerable members of society.

Of these features, the first is perhaps the most challenging and controversial in a society that places a premium on free access to information and speech. For example, starting with the naïve assumption that all disinformation is foreign in origin, a vision of national security might simply be to disallow information from the external world to enter the nation's digital communications. With this simplistic premise that all falsehoods are exogenous, it is possible to believe that no conspiracies or divisive movements may arise without foreign subversion, but such an outcome would occur at the cost of freedom of speech and the ability to engender positive transformative social and political change. Moreover, it is logical to assume that any defensive strategy that placed a premium on walling off the country from the global information environment would be equally vigilant in surveilling communications within its borders, a fact that has become evident as the world's most technologically savvy and oppressive regimes have restricted both external and internal information flows in the construction of modern surveillance states.[41] Strengthening the boundaries surrounding the information environments of democratic societies seems counterproductive, and resources should flow instead to the other three features of an information immune system.

An immunity-based defense provides an important division of labor: Defenders that represent the role of the general immune system can reside within the population and should be focused on containing threats and separating infected population members from other vulnerable members, while surging defenders eliminate the infection using tailored means. In the social context, this might be difficult to translate into practice because, even if it is clear when citizens believe notable falsehoods, precisely what should be done about it once they do is unclear. Thus, although the immune system model has been applied using the idea of vaccination or inoculation to reduce the susceptibility of population members to viral disinformation prior to exposure,[42] determining how to contain those who are infected, limit their effect on others, and ultimately rid them of infection remains problematic.

Finally, the immune system model poses a significant organizational challenge given the extreme shifts in resources that it requires. As noted, at its peak, the immune system is on par with the body's major organs in terms of cost. Yet the adaptive system largely exists to limit the energetic requirements of protecting the body from infections through a combination of memory of effective counterattacks on invaders and the surges of energy needed to perform them. In organizational terms, significant shifts in staffing, financing, and more would prove to be impractical for developing and maintaining a highly professionalized security organization.

The Costs of Immunity

When the immune system is engaged, its metabolic demands are high. In societal terms, an organization replicating the functions of the immune system would likely scale to be on par with other major government departments in meeting temporary surge demands while maintaining a steady-state capability for surveillance and engagement, mirroring the roles of the general and adaptive immune systems. Functional needs include low levels of resourcing that rely on local surveillance and response as part of the body's general maintenance,

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[41] A notable example is the national surveillance system for monitoring and regulating social interaction in China. See Diana Fu, *Mobilizing Without the Masses: Control and Contention in China*, New York: Cambridge University Press, 2017; Margaret E. Roberts, *Censored: Distraction and Diversion Inside China's Great Firewall*, Princeton, N.J.: Princeton University Press, 2018; and Kai Strittmatter, *We Have Been Harmonized: Life in China's Surveillance State*, New York: Custom House, 2020.

[42] John Cook, "Inoculation Theory: Using Misinformation to Fight Misinformation," *The Conversation*, May 14, 2017; Sander van der Linden, Jon Roozenbeek, and Josh Compton, "Inoculating Against Fake News About COVID-19," *Frontiers in Psychology*, Vol. 11, October 2020; Sander van der Linden and Jon Roozenbeek, "The New Science of Prebunking: How to Inoculate Against the Spread of Misinformation," *On Society*, blog, October 7, 2019; Gordon Pennycook and David G. Rand, "Fighting Misinformation on Social Media Using Crowdsourced Judgments of News Source Quality," *Proceedings of the National Academy of Sciences*, Vol. 116, No. 7, February 12, 2019; Dietram A. Scheufele and Nicole M. Krause, "Science Audiences, Misinformation, and Fake News," *Proceedings of the National Academy of Sciences*, Vol. 116, No. 16, April 16, 2019; and Gayathri Vaidyanathan, "Finding a Vaccine for Misinformation," *Proceedings of the National Academy of Sciences*, Vol. 117, No. 32, August 11, 2020.

the scanning of every tissue in the body in search of invaders and damaged cells,[43] and the redirecting of the body's resources away from all but the most critical of functions to fight off severe infection. For perspective, the fiscal year 2021 budget request for the U.S. Department of Homeland Security was $49.7 billion, on par with that of the U.S. Department of State ($40.8 billion) and more than that of the U.S. Department of Justice ($31.7 billion). Each of these departments is dwarfed by an order of magnitude by the U.S. Department of Defense ($705 billion).[44] Yet none of these models might be appropriate for security organizations committed to surveilling the national information ecosystem.

An alternative set of organizations might be Google, Facebook, Snapchat, and Twitter, which are much like government organizations in terms of the scale on which they operate. Comparing the value that they provide to society is complex. For example, the respective market cap and revenue of each organization, shown in Table 18.1, show significant gaps between the total value that investors believe the company provides to the economy and the total that consumers have paid for the company's goods and services.[45]

Although the vast majority of these organizations' staff and operations are not committed to the surveillance and protection of the information environment, the size of their investments in content moderation and its shortcomings suggests that just establishing the initial capabilities required to meet the needs of the general immune system would cost several billion dollars.[46] Such costs may indicate only what is needed for surveilling and purging the

TABLE 18.1
Market Cap and Revenue for Selected Internet and Social Media Companies

Company	Market Cap	Revenue
Google	1.8 trillion	196 billion
Facebook	995.7 billion	84 billion
Snapchat	94.5 billion	2.81 billion
Twitter	55.5 billion	9.94 billion

SOURCE: Yahoo! Finance, homepage, undated.
NOTES: Market data were taken on June 7, 2021.
Revenue is based on trailing 12-month totals.

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[43] Klenerman, 2017, p. 43.

[44] Office of Management and Budget, *A Budget for America's Future*, Washington, D.C., 2020.

[45] Importantly, budget figures for government organizations reveal the costs of their operations but provide little information about the value they provide to the nation and its citizens. Alternatively, because commercial firms are capable of both earning profits and collecting debt, revenues may exceed or fall short of operational costs.

[46] Gilad Edelman, "Stop Saying Facebook Is 'Too Big to Moderate,'" *Wired*, July 28, 2020; Charlotte Jee, "Facebook Needs 30,000 of Its Own Content Moderators, Says a New Report," *MIT Technology Review*, June 8, 2020; and Katie Schoolov, "Why Content Moderation Costs Billions and Is So Tricky for Facebook, Twitter, YouTube and Others," CNBC, February 27, 2021.

information environment of viral disinformation; these figures do not include the costs of "healing" infected members of society.

The Strength and Context of the Immune Response

The vision of the immune system filtering and hunting for foreign pathogens lacks necessary nuance for understanding how a vibrant heterogeneous society might be defended. As previously noted, the immune system is the body's identity, but this identity is sensitive to context. The gut microbiome provides essential capabilities that enable both the extraction of energy and nutrients from food and the regulation of bodily functions, yet it presents a high-risk threat if it comes into contact with the body outside the walls of the digestive tract. In the same way, information, even false information, might be a necessary feature of a vibrant civil society yet also harmful depending on context.

The question, then, is not whether information is true or false, or foreign or domestic in origin, but rather under what circumstances it enriches the functioning of a democratic society and under what circumstances it threatens it. For example, just as falsely yelling "fire" in a crowded theater is prohibited given the risk of causing panicked patrons to trample one another in search of an exit, it might be the case that the ability to express doubts in the validity of governing processes and decisions must be tempered by the identities of the speaker and the audience. For example, is the speaker a private citizen, a government employee, or an elected official? Is the audience composed of aggrieved voters, legal experts, or students in a classroom simulation?

From an immunological perspective, the question of context is not only about information as the content of a message; it is about the joint features of the content, source, and audience. Just as the body maintains a hierarchy of bodily functions, the combination of content, sender, and audience recognizes that all citizens do not play equally in the same information space and that positions must be defended differently.

For ramping up defenses, the training of T-cells is instructive. Significant energy is expended to ensure that T-cells trained in the thymus exist in a Goldilocks range that makes them appropriately tolerant when distinguishing self from non-self. This training is critical because it limits the prospects of self-harm resulting from an overactive immune system.

In societal terms, overly aggressive defenses produce excesses, such as the internment of U.S. citizens of Japanese descent during World War II or the domestic intelligence operations that targeted the leaders of the civil rights movement during the 1960s.[47] Likewise, too little defense leaves society unprotected from macropredators—those humans that prey on others—whose threats have motivated the evolution of society and the technologies of offense and defense since the earliest of civilizations.[48] Just as the training of the immune system is a necessary step that qualifies it to commit violence within and potentially against the body in

[47] David Cunningham, *There's Something Happening Here: The New Left, the Klan, and FBI Counterintelligence*, Berkeley, Calif.: University of California Press, 2004.

[48] McNeill, 1982.

pursuit of security, significant investments in the training and professionalization of society's security forces are needed if they are to navigate the delicate boundaries between preserving individual rights and differences and containing and defeating threats.

With the clearing of an infection, the security posture should change significantly; force drawdown and demobilization should happen quickly. However, demobilization should not be considered disarmament. When the immune system winds down, it retains a memory of the attack and consistently trains to reengage previously defeated pathogens on more-efficient grounds in the future, again conserving the energy needed in future fights. Likewise, because the immune system is distributed throughout the body, it continues to hunt for invaders at low energetic levels.

The Signaling of Self and Non-Self Entities Within Society

The immune system operates within an elaborate network of cellular signaling. Its cells regularly patrol the body, scanning in search of antigens that signal whether they belong or not. In a social context, this requires not only surveillance and tuning, as noted, but a broader understanding of the interfaces between citizens and security forces. Under what conditions should security forces interrogate citizens to determine whether they belong or not? More subtly, in what context (i.e., time and place) is an individual considered "self" or "non-self"?

Given that the immune system is decentralized and that there is variation in how it is tuned, its operations remain unpredictable in both time and place. For example, rogue T-cells periodically leak from the thymus that, lacking the discipline and restraint of rigorous training, challenge the body.[49] This process defends against foreign invaders that have learned to present proteins that are like those of the body itself. In social terms, mimicking such behavior would constitute the risky step of governors periodically violating agreements with citizens (i.e., the governed) to test the veracity of an individual's commitment to the social order. Such a process is obviously problematic and likely counterproductive in that efforts by the government's security forces to compel loyalty to society are likely to undermine the legitimacy of the government itself.

Likewise, the establishment of context and tolerance for non-self entities—a necessary condition for preserving the body's overall health—is achieved by cells releasing localized immunosuppressant antigens that reduce or turn off the immune response. In a social context, this would suggest a highly complex and differentiated social, economic, and political landscape in which behaviors and discourse would not have absolute protections but would instead be handled differently, as previously noted. The interesting question involves not so much the need for context or nuance, but rather the mechanism by which it is established. The zones by which regulation is decreased are not based on the immune system's determination (i.e., the determination of society's security institutions) but rather the cells, or citizens, that determine the level of security or regulation they require.

[49] Klenerman, 2017, p. 75.

Signaling within the body politic becomes the locus of internal governance and regulation. Although at the systemic level communication between the governed and the governors might appear balanced and well ordered, at the micro-level it would appear highly contentious. As with the immune system's operations, we would expect to see occasional risky or overzealous challenges to citizens about whether they truly belong in society or have been singled out as deviants. Likewise, collective action by citizens can establish local boundaries of enforcement, tuning the security response to the requirements or desires of the population—which would at times demand greater flexibility to explore and experiment with new social, economic, or political practices, while at other times requiring strict conformity and commitment to collective action.

The Defense of the Defenders

The perils of immune deficiencies and autoimmune diseases have already been noted. Importantly, many of these problems result from pathogens that attack the immune system itself, disarming it or otherwise repurposing it for other ends.[50] In some cases, viral infections attack the immune system itself, preventing it from mounting an effective response. In other cases, viral infections repurpose the body's defenders to attack healthy cells to further weaken the body and create new areas of infection and reservoirs for reproduction within the body. Although the specific mechanisms by which viruses attack and defeat the immune system itself are still being investigated, the complex and highly specialized processes of the general and adaptive immune systems clearly provide a target-rich attack surface.[51]

Society too has wrestled with this problem for millennia. If the immune system is the guardian of society, then we return to Plato's *The Republic* to discuss the question of who guards the guardians.[52] Viral disinformation that affects the beliefs and behavior of society will not leave those who are entrusted and empowered with its defense unaffected. Thus, two pathways for threatening the social immune system must be noted. The first pathway for defeating a social immune system might follow the strategies used by viruses to disarm and attack the immune system itself and render it ineffective at fighting infections. Society must ensure that law enforcement organizations are adequately resourced (and monitored) in terms of manpower, authorities, money, technology, and more to defend themselves from direct challengers, just as military organizations are scaled to pacing threats.

The second pathway is that individuals and groups that have been entrusted with the power and privilege to commit sanctioned acts of violence could be repurposed toward mate-

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50 Robert S. Fujinami, "Viruses and Autoimmune Disease—Two Sides of the Same Coin?" *Trends in Microbiology*, Vol. 9, No. 8, August 2001.

51 Maria K. Smatti, Farhan S. Cyprian, Gheyath K. Nasrallah, Asmaa A. Al Thani, Ruba O. Almishal, and Hadi M. Yassine, "Viruses and Autoimmunity: A Review on the Potential Interaction and Molecular Mechanisms," *Viruses*, Vol. 11, No. 8, August 19, 2019.

52 Plato, *The Republic of Plato*, trans. Allan Bloom, New York: Basic Books, [375 B.C.] 1968. See also Leonid Hurwicz, "But Who Will Guard the Guardians?" *American Economic Review*, Vol. 98, No. 3, June 2008.

rial or ideological ends that are not consonant with society's ideals. This process should be vigorously guarded against. Both pathways call into question the legitimacy of society itself, and, just as the malfunctioning immune system exposes the body to systemic risks posed by secondary infections, a society whose guardians are either overwhelmed or cease to operate in accordance with its laws and principles risks further exposure to threats and vulnerabilities.[53]

The Demand for a Functional Understanding of Information and Society

Using the immune system as a model for a successful defense of society from viral information requires a functional understanding of society and the role of information within it. Effective defense requires more than basic capabilities to surveil, contain, and heal. Determining the level of the response and the context in which active defenses may be employed requires an understanding of the role of information, both truthful and not, in society and its social practices. This is a complex endeavor, because processes that explore novel social, economic, and political activities that undergird innovation require the maintenance of heterogeneity within society, from which social, economic, and political experimentation and innovation occur. Alternatively, processes that reinforce past success and solidarity, a form of societal exploitation, press for homogeneity or at least adherence to well-defined organizational and individual roles and processes.

Establishing baselines of social functions and processes would also provide a critical link for connecting citizens and security forces representing the general and adaptive responses to threats. Just as the immune system listens for alerts from cells that are under attack or otherwise damaged, a society that is adapted to be secured according to the principles of the immune system's operations would have distinct and observable changes in behavior when under the influence of viral disinformation. This requires a strong civil society in which constructive participation in social, economic, and political processes is both observable and inconsistent with information infections.

Competing Demons or Cooperating Angels

In nature, the outcomes of species interactions are driven by the evolutionary need for fitness (i.e., the ability to survive and reproduce). Although it is often assumed that the pursuit of fitness is achieved through dominance or the *competitive exclusion* of other species, there is no willful intent by any given species to exterminate another—examples of this happening

[53] Although the decline of the Soviet Union is often thought of as an economic collapse caused by increasingly costly military competition, scholarship has shown that the regime's intellectual "guardians" turned on its ideology, rendering it vulnerable to Western influence that robbed the communist government of its legitimacy and ability to access or mobilize society's resources to continue the Cold War. See Robert D. English, *Russia and the Idea of the West: Gorbachev, Intellectuals, and the End of the Cold War*, New York: Columbia University Press, 2000; and Matthew Evangelista, *Unarmed Forces: The Transnational Movement to End the Cold War*, Ithaca, N.Y.: Cornell University Press, 2002.

in nature are simply the result of strategies that have evolved for the purpose of long-term survival. Moreover, nature is replete with examples of higher levels of fitness being achieved through cooperation, including mutualism, and evolutionary transitions that build increasingly large and complex organisms and communities from individuals.[54] The quest to survive leads to the creation of *niches*, which describe how a species interacts with its environment and others within it.[55] While natural selection results in the selection and propagation of an organism's genotypes, niches are defined by organisms' phenotypic properties and represent the specialized roles that they develop to live within complex ecosystems affecting flows of biomass and energy (e.g., food webs and environmental structures).[56] Such ecological interactions are governed by species' traits, which are selected for through trade-offs according to their contributions to fitness and biophysical constraints.

Individuals, firms, and nations also carve niches for themselves, competing for natural, technological, and societal resources. In many ways, these socioeconomic interactions resemble ecosystems. In socioeconomic systems, there are similar constraints, in terms of financial, technical, and social capital. As a result, states have differentiated traits and occupy the niches within regional and global systems. This is a form of constrained optimization with distinct trade-offs: Given what a nation has in terms of financial wealth, technical ability, and social capital (i.e., its *core competencies*[57]), what are its best available socioeconomic strate-

[54] John Tyler Bonner, *The Evolution of Complexity by Means of Natural Selection*, Princeton, N.J.: Princeton University Press, 1988; Douglas H. Boucher, ed., *The Biology of Mutualism: Ecology and Evolution*, New York: Oxford University Press, 1988; Brett Calcott and Kim Sterelny, eds., *The Major Transitions in Evolution Revisited*, Cambridge, Mass.: MIT Press, 2011; Peter Godfrey-Smith, *Philosophy of Biology*, Princeton, N.J.: Princeton University Press, 2014; Richard E. Michod, *Darwinian Dynamics: Evolutionary Transitions in Fitness and Individuality*, Princeton, N.J.: Princeton University Press, 2000; Samir Okasha, *Evolution and the Levels of Selection*, New York: Oxford University Press, 2009; Samir Okasha, "Units and Levels of Selection," in Jonathan B. Losos, David A. Baum, Douglas J. Futuyma, Hopi E. Hoekstra, Richard E. Lenski, Allen J. Moore, Catherine L. Peichel, Dolph Schluter, and Michael C. Whitlock, eds., *The Princeton Guide to Evolution*, Princeton, N.J.: Princeton University Press, 2017; Ricard Solé, "The Major Synthetic Evolutionary Transitions," *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 371, No. 1701, August 19, 2016; and M. Tokeshi, *Species Coexistence: Ecological and Evolutionary Perspectives*, Malden, Mass.: Wiley-Blackwell, 1998.

[55] F. John Odling-Smee, Kevin N. Laland, and Marcus W. Feldman, *Niche Construction: The Neglected Process in Evolution*, Princeton, N.J.: Princeton University Press, 2003.

[56] Odling-Smee, Laland, and Feldman, 2003; Mercedes Pascual and Jennifer A. Dunne, eds., *Ecological Networks: Linking Structure to Dynamics in Food Webs*, New York: Oxford University Press, 2005; and Turner, 2002.

[57] The notion of core competencies has been at the center of thinking about long-term competition for commercial firms and military organizations. For examples, see Andrew Krepinevich and Barry Watts, *The Last Warrior: Andrew Marshall and the Shaping of Modern American Defense Strategy*, New York: Basic Books, 2015; C. K. Prahalad and Gary Hamel, "The Core Competence of the Corporation," *Harvard Business Review*, Vol. 68, No. 3, May–June 1990; and Barry D. Watts and Andrew D. May, "Net Assessment After the Cold War," in Thomas G. Mahnken, ed., *Net Assessment and Military Strategy: Retrospective and Prospective Essays*, Amherst, N.Y.: Cambria Press, 2020.

gies? New technologies (or acquired cumulative knowledge–based applications) are sought after and continually created to change the socioeconomic trade-offs that constrain nations.

The strategies that species use and that end up defining the niches they occupy are found through the combined processes of genetic drift and natural selection. Genes encode the phenotypes of individuals, which translate into traits and strategies that provide affordances for competition with rivals. The dominant force shaping the traits and the strategies that species employ is natural selection. Through competitive exclusion, certain traits are selected for, and species ultimately sort themselves into niches. In addition, genetic drift through random mutation and such neutral processes as stochastic environmental shocks also affect which genes and traits are present in a population, thus effectively creating an exploratory frontier in the biological trait space.[58] Drift and selection are always factors that affect which genes are present in a population, and the presence of environmental stochasticity means that there is a continual source of randomness to the realized fitness of different species.

Ultimately, randomness is one of the key ingredients for Darwinian evolution. Through the input of randomness into natural selection, species are constantly exploring the open-ended trait space.[59] Whatever traits a species acquires provide a competitive advantage that maximizes its *fitness*, which biologists describe as the number of offspring that can survive and reproduce. Essentially, fitness can be interpreted as minimizing the risk of going extinct; species play an infinite game in which the goal is to keep playing.[60]

Such processes do not only apply in biology. The history of individual states may also be viewed as having been influenced by randomness, or at least the micro-level choices of individuals whose consequences cannot be predicted when embedded in complex networks of national and international interaction and feedback.[61] For example, despite being one of the leaders in the adoption of field artillery, Charles the Bold, Duke of Burgundy, died in Nancy, France, in 1477 after leading a cavalry charge against Swiss pikemen rather than waiting for the arrival of his cannons. This decision ultimately resulted in the erasure of Burgundy as an independent political unit because the duke's lands were subsequently divided between the French king, Louis XI, and the Hapsburg heir, Maximilian.[62] Just as in ecosystems, the selec-

[58] Andreas Wagner, *Robustness and Evolvability in Living Systems*, Princeton, N.J.: Princeton University Press, 2007, p. 227.

[59] Kenneth O. Stanley, Joel Lehman, and Lisa Soros, "Open-Endedness: The Last Grand Challenge You've Never Heard of," O'Reilly Media, December 19, 2017.

[60] Carse, 1986.

[61] Philip E. Tetlock and Aaron Belkin, eds., *Counterfactual Thought Experiments in World Politics: Logical, Methodological, and Psychological Perspectives*, Princeton, N.J.: Princeton University Press, 1996; and Philip E. Tetlock, Richard Ned Lebow, and Geoffrey Parker, eds., *Unmaking the West: "What-If?" Scenarios That Rewrite World History*, Ann Arbor, Mich.: University of Michigan Press, 2009.

[62] William H. McNeill, *The Age of Gunpowder Empires, 1450–1800*, Washington, D.C.: American Historical Association, 1989, p. 8.

tion pressures exerted on states occur in time and place and are the aggregation of multiple interactions that inhibit or enable access to resources.

For the remainder of this discussion, we consider the way in which evolutionary competition drives the acquisition of biological traits, the constraints on the search for traits, and the implications posed by a hypothetical organism—a Darwinian Demon—that could adapt in the absence of those constraints. We then consider the implications of its societal equivalent—the Societal Demon—that might be closer to reality than its biological cousin because of the increasingly capable applications of frontier technologies to the discovery of new technologies. We conclude by discussing the transition from Demons to Angels and the need to become equally adept at employing technology for cooperative purposes and employing it for competitive ones.

Trade-Offs and Optimization

Long-term competition between species is not simply an ecological brawl, in which the metrics of fitness capture only instantaneous interactions.[63] Instead, species are locked into a continual arms race, in which they are constantly adapting to changing conditions and exploring the trait space to find a strategy that provides them with a stable niche in which they can survive. At the heart of evolution is the core tension between *exploration*, which is when actors search for new solutions to problems, including developing novel biological traits or technologies, and *exploitation*, which is when actors improve upon their existing problem-solving approaches, which may enhance existing traits and technological capabilities.[64] If the environment becomes stable for some period, species will sort into niches. That is, some species will die off, and those that survive will have evolved traits that work—those that minimize their risk of extinction and maximize their biological fitness. Over time, they will become more and more specialized in their respective niches, losing traits that are costly and that do not confer any marginal gain in fitness. However, if the environment were to suddenly change, these highly specialized species could potentially experience dramatic decreases in fitness.[65] To weather these environmental changes, species require the ability to maintain a robust set of diverse traits as part of their biological strategies.

In nature, robustness is promoted through random mutations leading to drift in the trait space. Moreover, evolving robustness points to the selection of the mutation rate itself and spe-

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[63] A *brawl* is an open-ended contest for survival in which the winner is typically determined by some variant of "last person standing." Risk and free-for-all Starcraft are examples. Note that brawls are built by taking a two-player game and adding more players, thus converting two-player, zero-sum games into general-sum games. Brawls are distinct from *races*, in which the objective is to be the first player to attain a particular achievement, a high score, or a competitive position that terminates the contest. See George Skaff Elias, Richard Garfield, and K. Robert Gutschera, *Characteristics of Games*, Cambridge, Mass.: MIT Press, 2012.

[64] March, 1991.

[65] Niles Eldredge, *Macroevolutionary Dynamics: Species, Niches, and Adaptive Peaks*, New York: McGraw-Hill, 1989.

cies searching for the optimal balance of exploiting an existing trait and exploring new ones.[66] Genetic drift through mutation guarantees that species are constantly exploring the trait space; in doing so, they obtain resilience to changing conditions. Importantly, all other species are doing the same. Consequently, staying still in the trait space is never a viable option. This points to *Red Queen dynamics*, in which species are constantly adapting to survive.[67]

Adaptation, Constraints, and Stability

Critically, there are trade-offs between the traits that species can acquire to achieve a competitive advantage; the laws of physics and the environment present themselves as constraints on what traits can be acquired, sustained, and propagated. To be extremely strong requires large amounts of muscle mass. This muscle mass guarantees that a person will be slow relative to a person who is lithe. It is too bioenergetically costly to both photosynthesize and have the appendages required for predation. Furthermore, ecological competitiveness (i.e., biological fitness) emerges from a combination of multiple traits or strategies that are also constrained by these trade-offs. One species might evolve to adopt a *generalist strategy*—that is, a strategy in which the species can do many things reasonably well by expanding the dimensionality of its niche—while another species might adopt a *specialist strategy*, evolving to be very good at doing one thing.

The success of adopting a specialist or generalist strategy depends on the stochasticity of the environment. Generalists are better able to minimize their risk of extinction (i.e., they do well in infinite games), which is important in stochastic environments in which change and novelty are persistent; specialists, however, can win in terms of competitive exclusion (i.e., in finite games), but this is a risky strategy and confers long-term competitive advantage only when the environment is stable. This point raises the issue of timescales, because nothing in nature is stable in the long term and species are constantly exploring the trait space to find strategies that minimize their risk of extinction.

Being the most abundant species or being able to exterminate a competitor is never entirely the goal; it is simply the outcome of species searching for a competitive advantage in the trait space. Given the nature of all species constantly seeking a competitive advantage over one another in a multidimensional trait space, the notion of optimality is never entirely appropriate. One can consider the multidimensional trait space as defining a fitness landscape, and species move over this landscape looking for local optima. However, as they evolve and change, they alter the shape of the fitness landscape itself.[68] If an "optimal combination

[66] Andreas Wagner, "Robustness and Evolvability: A Paradox Resolved," *Proceedings of the Royal Society B: Biological Sciences*, Vol. 275, No. 1630, January 7, 2008.

[67] William P. Barnett, *The Red Queen Among Organizations: How Competitiveness Evolves*, reprint ed., Princeton, N.J.: Princeton University Press, 2016.

[68] Stuart A. Kauffman and Sonke Johnsen, "Coevolution to the Edge of Chaos: Coupled Fitness Landscapes, Poised States, and Coevolutionary Avalanches," *Journal of Theoretical Biology*, Vol. 149, No. 4, April 21, 1991.

of traits" exists at a given point in time, evolving toward it makes it suboptimal, because other species adapt to account for these changes. Importantly, the many traits that make up a species' strategy suggest the existence of *evolutionary stable strategies*, which are reduced sets of strategies that confer long-term survival—species evolve toward them.

Darwinian Demons

The constraints that characterize the trade-offs in the multidimensional trait space are a fixed outcome of the biophysical properties of an organism's physiology. In noting this, an important thought experiment appears: What if there were an organism that was not constrained by these biophysical trade-offs? This organism, called *Darwin's Demon*,[69] would be able to photosynthesize and predate on other organisms. It would be able to fly, burrow, and breathe underwater. In general, the Demon would defy the physical and bioenergetic trade-offs that limit which traits and strategies organisms are able to adopt. Why does this Demon not exist in nature? In addition to there being strong physiological trade-offs in certain traits, the bioenergetic costs associated with maintaining multiple appendages or traits are too costly for any one organism to have. Essentially, it is not evolutionarily stable to acquire as many traits as possible because doing so would create an energy deficit that would end up diminishing fitness.

The realization that the number of traits an organism can possess is constrained raises the prospect of being able to change the trade-offs between traits. What if the materials used to construct human bodies were improved? Might it then be possible to both photosynthesize and be a hunter-gatherer? Might it be possible to be both fast and strong? This is essentially what Darwin's Demon points to; the Demon is constructed from different materials with properties that allow it to actualize many traits at once and greatly reduce the bioenergetic costs of maintaining those traits. For society, this is the critical difference: New technologies might allow the emergence of Societal Demons.

Frontier Technologies for Long-Term Competition

Societal Demons do not play by the same rules as everyone else. They have technologies that defy the trade-offs that determine the traits and strategies that limit others. They reconfigure the basic materials that serve as the building blocks for what traits they can employ. For example, a societal analogy to biologically available energy in nature is a nation's economic output. One important rule to change to become a Societal Demon is to improve the economic efficiency underpinning the internal workings of public and private (security) enti-

[69] Janusz Uchmánski, Anita Kaliszewicz, and Violetta Hawro, "Darwinian Demons," *Academia*, Vol. 1, No. 9, September 2006; and David C. Krakauer, "Darwinian Demons, Evolutionary Complexity, and Information Maximization," *Chaos: An Interdisciplinary Journal of Nonlinear Science*, Vol. 21, No. 3, September 2011.

ties.[70] *More efficiency* in this context means lower costs for the delivery of an equivalent service. These saved opportunity costs could then be used to fund other important research into and development of new security measures, economic productivity, or other investments that increase societal fitness.

Another trade-off is between system size and the ability to execute decisions as a collective. As systems get bigger, simply in terms of the number of individuals that they are composed of, information spreads more slowly. That is, information must traverse many more nodes before all actors whose participation is needed for successful collective action are informed. This effect is seen in large businesses and public agencies.[71] The constraint is in the information technology used to source and disseminate information. In society, information is disseminated through many digital platforms, from email to Twitter, and the trade-off is evidenced in terms of the signal-to-(harmful)-noise ratio. While society's ability to communicate has increased in terms of both speed and volume, the noise in the information that is communicated has risen dramatically too. This has effectively reduced the speed at which relevant, accurate, and truthful information is created, communicated, and assimilated by the actors that make up social systems. Developing technologies that enable individuals to find the signal in the noise and carefully manage decisionmakers' attention would be one step toward becoming a Societal Demon.

Preserving information quality and transmission speed becomes increasingly important as social systems increase in the number of nodes and overall connectivity and become more prone to *information drift*: random mutations in information as it is passed from node to node (like in the telephone game played by kids). Irrelevant information may proliferate and overwhelm decisionmakers. Moreover, the natural degradation of information quality seen with increases in system size is likely to be exacerbated as adversaries take measures to sow disinformation and subversion. The preservation of information quality and the speed and integrity of communications within a society might be a key enabler of competitiveness and cohesion in long-term competition.

What would a Societal Demon look like, then, in terms of its ability to maintain quality information as a core necessity even as it grows in size and complexity? Certainly, for example, the weaponization of information through social media demands new technologies for automated fact-checking. Likewise, research into the reproducibility of scientific findings hints at the value of ensuring that the information used to support decisionmaking is reli-

70 The efficiencies with which states and military organizations convert resources into capabilities and power have been long-standing concerns within national security and sit at the core of net assessment and its concern with competitive strategies. See Peter deLeon and James Digby, *Workshop on Asymmetries in Exploiting Technology as Related to the U.S.-Soviet Competition: Unclassified Supporting Papers*, Santa Monica, Calif.: RAND Corporation, R-2061/1-NA, 1976; Krepinevich and Watts, 2015; and Thomas G. Mahnken, ed., *Competitive Strategies for the 21st Century: Theory, History, and Practice*, Palo Alto, Calif.: Stanford University Press, 2012.

71 Leonard R. Sayles and Margaret K. Chandler, *Managing Large Systems: Organizations for the Future*, New York: Routledge, 2017.

able.[72] These capabilities act like the cancer-suppressing genes in large-bodied organisms.[73] In these animals, these cancer-suppressing genes essentially "call bullshit" on bad DNA;[74] they provide an example of the kinds of governing institutions and technologies that might do the same for bad information floating in informational environments (i.e., social media).

Continuous Research and Development for an Intelligent System

While it is obvious that it is good to be more efficient economically, or to have an ability to make decisions faster, or to have the ability to maintain the quality of information in organizational and social communication, it is less obvious how to identify new technologies that might facilitate such improvements. Again, we can imagine a Demon that has an infinite ability to adapt. If it does not know how to photosynthesize yet, it can learn to do so instantaneously. Clearly this is impossible in nature, but exponential technologies in society are reducing the time it takes to discover and diffuse novel solutions for new and old problems. These abilities reflect the growing capacity for basic research to rapidly translate into applied solutions. Automation, hybrid human-AI teaming, and gamification are all examples of technologies that help people learn faster and participate in the collective search for and adoption of new solutions and, in some instances, overcome "paralysis by analysis."[75]

When basic research is necessary to identify and confirm the utility of a new solution, there can be a delay in its uptake because of a lack of consensus. This is at the heart of the divergence of theory and perfect evidence. For example, the testing and evaluation of AI and autonomous systems is complicated by alternative beliefs about the merits and risks of optimality versus satisficing in developing systems. Pursuing optimality requires exploring and exposing all possible modes of a system's behavior and proving that it behaves optimally in each case. Satisficing, however, targets system behaviors that are good enough at obtaining desired goals, while avoiding specified failure modes. In doing so, the bar is lowered for satisficers in terms of the number of solutions that need to be identified. Yet another level of assessment exists about meta-heuristics and hyperparameters of systems that focus less on the particular solutions that are discovered and more on the processes by which discoveries are made in the first place.[76]

Here, it is worth remembering the difference between optimization in ecology—i.e., at any given time, there is a set of traits that provide a species improved chances of survival—and an optimal rate of exploration—i.e., a species' biological machinery is tuned to ensure

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[72] Greg Witkop, "Systematizing Confidence in Open Research and Evidence (SCORE)," webpage, Defense Advanced Research Projects Agency, undated.

[73] Seluanov et al., 2018.

[74] Carl T. Bergstrom and Jevin D. West, *Calling Bullshit: The Art of Skepticism in a Data-Driven World*, New York: Random House, 2020.

[75] Nicky Case, "How to Become a Centaur," *Journal of Design and Science*, January 8, 2018.

[76] Sean Luke, *Essentials of Metaheuristics*, Fairfax, Va.: George Mason University, 2013.

that its traits and strategies are robust to constantly changing environmental conditions, including the entrance of new organisms into the ecosystem. In this sense, the notion of *meta-technologies*—the technologies for finding new technologies—is vital. Existing institutions, such as the Defense Advanced Research Projects Agency, play this role already and have directives to identify new technologies rather than foster incremental change in existing ones. Tech incubators, accelerators, and high-risk–high-reward research and development business units and organizations (e.g., the X company)[77] occupy a similar role in the private sector. The path to becoming a Societal Demon, then, is ultimately characterized as the development of meta-technologies that increase the likelihood and decrease the costs of discovering game-changing technologies, thus allowing states to be more efficient in their use of resources and to maintain a broader variety of competencies and capabilities.[78]

Angels and Demons

Evolutionary biologists know that sometimes organisms cooperate to achieve greater successes in competition at higher levels of organization than they can achieve independently, and that the great transitions in evolution (e.g., the emergence of multicellular organisms from single-celled ones and the emergence of complex organisms with specialized and differentiated organs) occurred as individuals specialized—shedding some previously critical functions—while becoming increasingly interdependent, relying on others.[79] This allowed for the creation of larger, more-complex units with fitness levels that were previously unattainable. Although natural selection is characterized as a perpetual competition between species, this is an incomplete description. Cooperation, mutualism, and the coexistence between species are equally important in the development and maintenance of ecosystems.

The interconnectedness of today's world means that states are intimately connected on a global scale, and one of the challenges posed by long-term competition is recognizing that even the most capable rivals of the United States cannot be strictly defined as "the other" as long as it remains beneficial for all great powers and regional rivals to remain integrated into a single global international system.[80] From an evolutionary perspective, the prospect that leading states could evolve into Darwinian Demons highlights perhaps the greatest

[77] X, homepage, undated.

[78] Henry Etzkowitz, "Innovation in Innovation: The Triple Helix of University-Industry-Government Relations," *Social Science Information*, Vol. 42, No. 3, September 1, 2003.

[79] Eörs Szathmáry and John Maynard Smith, "The Major Evolutionary Transitions," *Nature*, Vol. 374, March 16, 1995, pp. 227–232.

[80] Rebecca Lissner and Mira Rapp-Hooper, "A Foreign Policy for the Day After Trump," *Foreign Affairs*, September 30, 2020; Mira Rapp-Hooper and Rebecca Friedman Lissner, "The Open World: What America Can Achieve After Trump," *Foreign Affairs*, Vol. 98, No. 3, May–June 2019; Anne-Marie Slaughter, "How to Succeed in the Networked World: A Grand Strategy for the Digital Age," *Foreign Affairs*, Vol. 95, No. 6, November–December 2016; and Fareed Zakaria, "The New China Scare: Why America Shouldn't Panic About Its Latest Challenger," *Foreign Affairs*, Vol. 99, No. 1, January–February 2020.

existential threat: **The world simply is not big enough for multiple global actors to compete while possessing unlimited adaptive capacity and an unlimited ability to harness resources for competition.**

What is the alternative, then, if the incentives to create new technologies are driven by competition and if these very technologies increase the intensity and scale of that competition? Long-term survival might require a collective break from competition as the driving motivation behind technological advancement. Instead, the scale and connectivity of global society might reward embracing cooperation (or at least coordination) as a necessary component to long-term survival. To put it another way, instead of becoming societal Darwinian Demons, states must learn to become Darwinian Angels that seek new technologies that promote cooperation and increase the chances of collective survival.

Competition is one of many forms of exchange between socially interdependent actors—other modes of interaction are cooperation, collaboration, coordination, and, of course, coercion and compellence. Each provides an alternative way of thinking about the pursuit of one's interests. For many decades, observers of international relations have noted that the international system has become increasingly heterogeneous as actors other than states have become increasingly prominent in both quantity and quality.[81] In acknowledging this change, observers have reimagined the basic logic about the organizing principles of the international system as moving away from authority-driven systems (or command systems) or market-driven mechanisms of simultaneous coordination toward networks in which interactions are based on reciprocity and asynchronous payoffs between actors.[82]

In such a system, access to resources and security might be better secured through the accumulation of trust, reputation, and the ability to delay needed payoffs from exchanges. Such cooperative practices may be regarded as the interactive skills of Angels and present the possibility of achieving security by situating oneself in key positions in networks of exchange. Such a change means accepting risk in the short term, or "lower fitness" in evolutionary terms, yet such a change carries the prospect of enhancing long-term security and survival by creating new federations that collectively mitigate, manage, and diffuse risks. When discussing how cooperative interactions between individuals affect selection processes, Richard E. Michod noted, "Cooperation drives the passage from one level of fitness to another, because cooperation trades increased fitness at the higher level for decreased fitness at the lower level."[83]

[81] David Ronfeldt, *Tribes, Institutions, Markets, Networks: A Framework About Societal Evolution*, Santa Monica, Calif.: RAND Corporation, P-7967, 1996; Richard Rosecrance, *The Rise of the Virtual State: Wealth and Power in the Coming Century*, New York: Basic Books, 1999; and Susan Strange, *The Retreat of the State: The Diffusion of Power in the World Economy*, New York: Cambridge University Press, 1996.

[82] Mark Bevir, *Governance: A Very Short Introduction*, illustrated ed., New York: Oxford University Press, 2012; and Anne-Marie Slaughter, *The Chessboard and the Web: Strategies of Connection in a Networked World*, New Haven, Conn.: Yale University Press, 2017.

[83] Michod, 2000, p. 6.

If this conjecture is correct, cooperation is more than an act of altruism that leaves one vulnerable to exploitation. Instead, it is a pathway to achieving a robust status by occupying a niche that others in the system value and are committed to protecting. The structure and persistence of complex ecosystems provide inspiration. As Geerat J. Vermeij has noted,

> The organizational properties that enable biological entities to cope with unpredictable circumstances may likewise have originated as adaptations to everyday problems, but they more directly transform unpredictable phenomena to predictable ones. They do so by cooperation, creating multiple novel combinations of preexisting components, preventing threats from spreading, or creating larger biological units that have a longer life span and therefore the means to retain and accumulate information about rare events.[84]

To address the challenges posed by global, long-term competition, the United States would be well served as a competitor by improving its capabilities to be a strategic cooperator. Increasingly complex challenges, such as global pandemics, climate crises, and financial contagions, may all be regarded as Great Filters confronting humanity.[85] Great Filters are thought of as the existential biological, technological, and societal challenges that must be overcome for organisms and societies to continue to thrive. Withstanding these challenges will require the development of robust and adaptive global governance regimes that must simultaneously be developed through cooperative agreements and vigorously defended from external challengers and internal defection.

Concluding Thoughts

The discussions in this chapter have drawn on lessons from evolutionary biology and ecology to deepen our understanding of international competition. In each case, we argue that analogies involving the inner workings of natural systems can offer valuable lessons for competing in and securing human societal systems. In the example of fighting viral disinformation, the innate and general immune systems provide an attractive model for defense. However, the speculations that we have provided indicate that real challenges exist in bringing this analogy into action. Although research that has applied lessons from the immune system has focused on preventing infection from viral disinformation, efforts to replicate how the immune system fights infection once the body has been infected will prove more complex. For example, the immunity model suggests that effective defenses will require significant on-demand surges in resources, technologies for surveilling the information content circulating within society, high-quality training for security personnel (and AI), high levels of

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[84] Geerat J. Vermeij, "Security, Unpredictability, and Evolution: Policy and the History of Life," in Raphael D. Sagarin and Terence Taylor, eds., *Natural Security: A Darwinian Approach to a Dangerous World*, Berkeley, Calif.: University of California Press, 2008, p. 36.

[85] Nick Bostrom, "Where Are They?" *MIT Technology Review*, April 22, 2008.

trust between citizens and the government, and a reinvigorated understanding of freedoms of thought and speech. These will not be easy to achieve and might ultimately determine whether a societal immune system is possible within a free society.

Our second example applied a thought experiment about Darwinian Demons—those organisms that are unconstrained by biological trade-offs—to international competition. Technological change is producing new capabilities for global actors to master technologies for finding technologies, which has made the prospect of competing states with nearly unlimited adaptive potential a possibility, thus bringing Darwin's Demon to life in the social world. We argue that conflict between multiple Societal Demons would be catastrophic and that the world's most capable global competitors might look to the strategic advantages that accrue from cooperative expertise as an alternative way of meeting their security needs in the long term. Such a transition from Demons to Angels might be crucial for surviving the major challenges that humanity faces in the future. Whether the conjectures provided in this chapter ultimately play out as we describe, we believe that there is value in continuing to look to nature as a rich source of lessons about long-term survival, particularly in open-ended infinite games, including those characterized as UGS.

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