

Dealing with femtorisks in international relations

Aaron Benjamin Frank^{a,1}, Margaret Goud Collins^{b,2}, Simon A. Levin^{c,1,2}, Andrew W. Lo^{d,2}, Joshua Ramo^{e,2}, Ulf Dieckmann^b, Victor Kremenyuk^f, Arkady Kryazhimskiy^{b,g,3}, JoAnne Linnerooth-Bayer^b, Ben Ramalingam^h, J. Stapleton Royⁱ, Donald G. Saari^j, Stefan Thurner^{b,k}, and Detlof von Winterfeldt^l

^aDepartment of Computational Social Science, George Mason University, Arlington, VA 22030; ^bInternational Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria; ^cDepartment of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544; ^dSloan School of Management, Massachusetts Institute of Technology, Cambridge, MA 02142; ^eKissinger Associates, New York, NY 10022; ^fInstitute for US and Canadian Studies, Russian Academy of Sciences, Moscow 123995, Russia; ^gSteklov Institute of Mathematics, Russian Academy of Sciences, Moscow 119991, Russia; ^hOverseas Development Institute, London, United Kingdom; ⁱKissinger Institute on China and the United States, The Wilson Center, Washington, DC 20004; ^jInstitute for Mathematical Behavioral Sciences, University of California, Irvine, CA 92697; ^kMedical University of Vienna, A-1090 Vienna, Austria; and ^lDaniel J. Epstein Department of Industrial & Systems Engineering, University of Southern California, Los Angeles, CA 90089

Edited by Kenneth W. Wachter, University of California, Berkeley, CA, and approved October 17, 2014 (received for review July 6, 2014)

The contemporary global community is increasingly interdependent and confronted with systemic risks posed by the actions and interactions of actors existing beneath the level of formal institutions, often operating outside effective governance structures. Frequently, these actors are human agents, such as rogue traders or aggressive financial innovators, terrorists, groups of dissidents, or unauthorized sources of sensitive or secret information about government or private sector activities. In other instances, influential “actors” take the form of climate change, communications technologies, or socioeconomic globalization. Although these individual forces may be small relative to state governments or international institutions, or may operate on long time scales, the changes they catalyze can pose significant challenges to the analysis and practice of international relations through the operation of complex feedbacks and interactions of individual agents and interconnected systems. We call these challenges “femtorisks,” and emphasize their importance for two reasons. First, in isolation, they may be inconsequential and semiautonomous; but when embedded in complex adaptive systems, characterized by individual agents able to change, learn from experience, and pursue their own agendas, the strategic interaction between actors can propel systems down paths of increasing, even global, instability. Second, because their influence stems from complex interactions at interfaces of multiple systems (e.g., social, financial, political, technological, ecological, etc.), femtorisks challenge standard approaches to risk assessment, as higher-order consequences cascade across the boundaries of socially constructed complex systems. We argue that new approaches to assessing and managing systemic risk in international relations are required, inspired by principles of evolutionary theory and development of resilient ecological systems.

complex adaptive systems | systemic risk | risk analysis | contagion | resilience

Recent events and analyses have highlighted the limitations of traditional approaches to measuring systemic risk in complex adaptive systems (CAS) in the sphere of international affairs. Many recent developments related to international systems—for example the 2008 financial crisis; the Arab Spring of 2011–2012; the Ukrainian crisis of 2014; the rapidly changing Arctic; Hezbollah’s increasing embeddedness in regional and global politics; and global health risks arising from zoonoses—reveal significant limitations to understanding of 21st century international systems and the risks posed by financial, political, and technological developments. The destabilizing potential consequences of the actions of small-scale actors introduce a new element to the analysis of complex international systems, and indicate that new approaches to analyzing and coping with threats within CAS are required (1).

These risks reveal the challenges posed by increasing interdependence in the international

sphere as the coupling of multiple natural systems (e.g., climate, energy resource, and ecological) with artificial, socially constructed, and purposeful systems (e.g., financial, health care, and technological) become tighter (2–5). We introduce the term “femtorisks” to refer to threats that confront international decision makers as a result of the actions and interactions of actors that exist beneath the level of formal institutions or operate outside of established governance structures. We chose that term, using the prefix that denotes a factor of 10^{-15} , to highlight the apparent insignificance of the individual actor that might be a source of such a risk, and to emphasize the status of the femtorisk as a semiautonomous agent, responding to and acting in its local environment. The use is analogous to the deployment of the terms “femtocell” vs. “picocell” in the world of cellular communications (6); that is, following the use in cellular communications, “femto-” here does not mean literally something 15 orders-of-magnitude smaller than

the macro scale, but just something many orders-of-magnitude smaller.

Femtorisks may be pictured as small fissures inside nodes arrayed along network topologies of various sorts. The primary feature of such risks is that they only become apparent when the system topology shifts in some fashion. The “revealing” of femtorisks can be for internal or external reasons (i.e., inside or outside the node or system where the risk is present) but the effect is the same: What once appeared solid and risk-free becomes a locus for systemic change, often in a catastrophic

Author contributions: A.B.F., M.G.C., S.A.L., A.W.L., J.R., U.D., V.K., A.K., J.L.-B., B.R., J.S.R., D.G.S., S.T., and D.v.W. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

¹To whom correspondence may be addressed. Email: afrank3@gmu.edu or slevin@princeton.edu.

²M.G.C., S.A.L., A.W.L., and J.R. contributed equally to this work.

³Deceased November 3, 2014.

fashion with phase-transition and hysteresis as possible outcomes.

In many cases, the actors that pose these risks are human agents, such as rogue traders or aggressive financial innovators, terrorists, groups of dissidents, or unauthorized sources of sensitive or secret information that reveal government or private sector activities. In other instances, these “actors” may take the form of developments in climate change, communications technologies, or socioeconomic globalization. Any of these can alter interactive circumstances between human agents and produce events that exist far in the tails of probability. These changes can pose significant challenges to the governance and management of major elements of global societal support systems through the operation of complex feedbacks and interactions of individual agents in profoundly interdependent systems (7).

In isolation, femtorisks may be small and inconsequential; but when embedded in CAS, their potential to propel systems down paths of instability poses a significant challenge to the complex network of formal and informal arrangements that underlie modern economies and political systems. Because the influences of femtorisks stem from interactions at the interfaces of multiple systems (e.g., social, financial, political, technological, ecological, and so forth), complex interactions between actors can often produce macroscopic outcomes that cannot be derived from examinations of individual choices and action in isolation (8). These complex interactions confound standard approaches to risk assessment by creating low-probability/high-impact events as second- and third-order consequences cascade across systems’ boundaries (4, 9).

Broadly speaking, innovative ways of refining the estimation and management of femtorisks come in two complementary forms. The first form requires improvements in the quality of predictions about increasingly small-scale actors, low-probability events, and the cross-scale implications of rapidly evolving technologies and relationships. The second form involves the creation of new ways of coping with uncertainties that do not depend on precise forecasts of the probability and consequences of future events, but rather develop approaches to negotiation, governance, and regulation that incorporate an understanding of CAS and the development of new means for measuring and enhancing their robustness and resilience under uncertainty (10). Although continued scientific research in a variety of domains will make better predictions possible, we argue that the latter

approach provides greater utility to risk managers across a variety of domains that are responsible for the governance of elements of the systems upon which globalized society depends. By drawing upon lessons learned from evolutionary theory and biological systems, new governing regimes can be developed, ones designed to cope with—even benefit from—the uncertainty and dynamism in CAS.

Examples of Femtorisks in International CAS

2008 Financial Crisis. The 2008 Financial Crisis provides an example of a CAS in which investors, regulators, and policymakers were all lulled into a false sense of security by focusing on variables that suggested the financial system was stable and threats relatively unimportant, while neglecting the increasing complexity and scale that laid the foundations for extraordinary losses. In 1998, Commodities and Futures Trading Commission Chairman Brooksley Born warned of systemic risks resulting from credit default swaps (CDS) and other derivatives securities. However, at the time this market was relatively small, stable, and highly liquid. The aggregate notional exposure of the CDS market in 1998 was \$180 billion, a small fraction of the financial industry’s total assets, leading regulators to believe that intervention was unnecessary. Thus, Born’s warnings were dismissed by the Federal Reserve Chairman, Treasury Secretary, and other regulators. However, the rapid and unsupervised growth of the CDS market led to aggregate notional exposures of \$6 trillion in 2004 and \$58 trillion in 2007. Market volatility that was regarded as unimportant just a few years earlier brought down AIG, one of the largest and most respected insurance companies in the world. The nature of regulatory mechanisms as either “on” or “off” meant that regulators and other stakeholders failed to notice or adapt to the changing circumstances of the market, the amount of capital concentrated among a handful of big institutions, and the dynamic characteristics of its risk exposures. Thus, systemic risk increased without notice and ultimately led to the worst financial crisis since the Great Depression (11).

2010–2012 Arab Spring. The Arab Spring began with the self-immolation of Mohammad Bouazazi in Tunisia in December 2010 and persisted into 2012. During this period, regimes in Tunisia, Egypt, and Yemen all changed under the pressure of popular protest, whereas Libya’s dictatorship fell in the face of armed rebellion supported by NATO military

forces, and the Syrian state descended into civil war that persists into the present. In addition to those states that experienced regime change or civil war, Algeria, Iraq, Jordan, Kuwait, Morocco, Sudan, Mauritania, Oman, and Saudi Arabia all experienced social protests that invited political reforms, drew harsh responses by government security forces, or both. The events of the Arab Spring demonstrated how small-scale actions could combine with distinctive local features of individual states and long-term historical, regional and global factors to produce unexpected, rapid changes in composition of the region’s political structure (12).

The sources postulated in academic and diplomatic analyses of the contagion of protest and regime change of the Arab Spring are varied, with outcomes seen as the intersection between local circumstances, short-term choices, and long-term trends, and vulnerabilities established over decades. Factors identified by experts on the region’s history and politics include demographics, unemployment, aging dictatorships, corrupt and weak political institutions, nationalism, food prices, social media, external influences, the role of Mosques in social mobilization, poor decision-making by political and military leadership, and contagion dynamics (12–15). For example, agricultural policies across the region rendered the states of the Middle East and North Africa among the world’s largest importers of cereals: the Arab states imported 50% of their food between 2006 and 2010, making regimes acutely vulnerable to rising food prices (16). The weak agricultural system in the region encouraged migration to cities, which ensured a deep reserve of unemployed youth, primed for action. New social media and communications technologies offered that restless demographic the means for social mobilization and a route to global attention; from these converging elements, the coordination and diffusion of antiregime activities emerged.

The many competing explanations for the Arab Spring highlight the challenges facing risk managers and policy analysts in the international system. Although many signals of political, economic, and societal fragility can be identified *ex post facto*, no analytic or conceptual framework was in place to provide policy makers with analyses that could mitigate threats to, or ease the transition of, established regimes (17).

2013–2014 Ukraine Crisis. The local uprising on Maidan Square in Kiev, Ukraine, in the winter of 2013–2014 displays many characteristics of femtorisks, with the full consequences of their manifestation to be

determined in the months and years ahead. The Maidan demonstrations began in response to the government's decision not to establish closer European economic integration in November 2013. After a violent effort by the government to disperse the protestors, popular mobilization against the government expanded, eventually forcing Viktor Yanukovich from power in February 2014 (18).

The collapse of the Yanukovich regime has triggered an ongoing governmental and international crisis. The predominantly Russian ethnic population of Crimea voted to secede from Ukraine in February 2014, with the aim of joining the Russian state. Continuing unrest within the Russian-speaking population of eastern Ukraine has resulted in increasing Russian political and military isolation and provocative diplomatic and military maneuvers between Russia and NATO members. Moreover, regular and irregular military forces within Ukraine have maneuvered to capitalize on the vacuum of power and legitimacy that followed the collapse of the old regime, catalyzing an escalation in the use of deadly weaponry in eastern Ukraine—sometimes by poorly trained and disciplined forces—that resulted in the downing of Malaysian Air Flight 77 (19). As a result, what started as a series of political demonstrations against the Yanukovich government's reluctance to deepen Ukraine's integration into European economic and political life, and its complementary tilt toward closer economic and social integration with Russia, has provoked the largest crisis between great powers since the end of the Cold War (20, 21).

1980s to Present Hezbollah. Hezbollah is one of the world's more sophisticated and capable violent nonstate actors. The organization emerged during Lebanon's 15-y civil war, 1975–1990, and offered an official manifesto declaring loyalty to Iran's Ayatollah Ruhollah Khomeini, demanding the expulsion of United States, French, and Israeli forces from Lebanese territory, and calling for the destruction of Israel in 1985. Since that time, it has been responsible for a variety of terrorist attacks in the Middle East, Europe, and Latin America. Hezbollah's attacks have included the use of hijacking, car and suicide bombings, political assassination, kidnapping, and a campaign of rocket attacks launched from Lebanon into Israeli territory. In addition, Hezbollah has established political and military autonomy over several regions of Lebanon, and maintains the ability to operate in Lebanon's Shia communities along the southern border with Israel, the Eastern

border with Syria, and the southern sectors of Beirut.

Through a combination of political and civic activities, Hezbollah has embedded itself within the Lebanese state, operating a series of parallel governance structures that provide political, military, economic, and social services that have established its local legitimacy and autonomy from the official Lebanese government. Over the last decade, the extent to which Hezbollah has grown capable of autonomously affecting regional conflict and stability has become increasingly apparent through notable events, such as its suspected assassination of Rafic Hariri in 2005 and the 2006 conflict with Israel.

Climate Change in the Arctic. Climate warming in the Arctic is triggering changes in the region's environmental, economic, resource development, transportation, employment, population, and cultural systems, embodying a CAS in which established actors are adapting to changing strategic circumstances and to new entrants into region's physical and political domain: for example, the 2013 addition of six observer nations into the Arctic Council, most notably including China (22). The rapid increase in accessibility has increased interest in the region because of the economic opportunities represented by mining, energy resources, new shipping routes, and increased tourism.

New mining opportunities in Greenland offer an example of these cascading implications for the Arctic region. Geologists have identified abundant deposits of rare earth elements among the island's rich mineral resources, and mining companies from around the world are competing for the opportunity to develop these critical raw materials for 21st century technologies. The ramifications are already apparent in Greenland's politics and governance arrangements with Denmark, as the mining scenarios could transform the icy island's economics, and challenge its environmental regulation framework (23). However, the production of rare earth elements could also effect profound change on the global supply of those crucial minerals, and the debate on environmental standards illuminate the challenges facing the governments of these sparsely inhabited regions. Moreover, the opportunities for mineral resources are setting off a reexamination of national boundaries, with both Canada and Russia having announced intentions to extend territorial claims to, and beyond, the North Pole (24, 25).

Failure Modes of Conventional Risk Assessment Approaches

Conventional risk assessment approaches rely on the ability to accurately estimate the probability and consequences of events that may occur in the future (26–29). These estimates rely on historical events and an understanding of the systems characterizing the risk. In the case of femtorisks, as the examples noted above reveal, historical experience and an understanding of the systems are lacking. Risk assessment has thus failed to provide decision-makers with the means to manage some of the most difficult challenges facing public and private sector governance. Although they are not mutually exclusive, these failure modes can be placed into three categories: the static nature of risk analysis with the need to estimate risk beyond the predictive limits of CAS, the improper orientation of risk analysts in their treatment of missing information and slow variables, and inertia within decision-making processes that limit the effectiveness of risk assessments for organizational reasons.

Structure and Dynamics of CAS. The first type of failure is grounded in conventional risk management and policy-making paradigms that assume that the behaviors of systems are predictable, either with certainty or probabilistically. This approach emphasizes the design of rational, utility-maximizing choices and seeks improvements through the development and refinement of predictive models. An implicit assumption in such predictive efforts is that the world is a stable system and historical data can be used to infer the probabilistic structure of the future.

However, CAS are composed of interacting units that adapt and change in response to actors buried deep within the system, as well as to each other (30, 31). Moreover such systems often accelerate the propagation of randomness that emerges inside the system. As a result, the ability of conventional risk models to reflect the adaptations and feedbacks of CAS, such as natural selection, social learning, or strategic calculation, may be limited, particularly when models incorporate the assumption that historical patterns and relationships will persist into the future (32). In fact, several CAS have demonstrated a propensity for rapid restructuring or transformation as innovative behaviors diffuse, and result in periods where formerly successful predictions fail quickly based on the popularity of particular strategies or behaviors.

In an example from the financial sector, the employment of Sharpe's Capital Asset

Pricing Model (33) in the 1970s led to the practice of “passive investing” in broadly diversified portfolios of securities that replicated indexes, such as the S&P 500, and has become so widespread that virtually every worker with an employee-sponsored pension fund is now invested in such products. Although the multitrillion-dollar index-fund business successfully provided investors with attractive returns at low fees for decades, its popularity also implies a much more tightly coupled system of investors in which a small decline in the S&P 500 can quickly turn into panic selling and a stock-market crash, as we discovered on October 19, 1987.

Because they are generally nonstationary, CAS do not conform to risk analysts’ characterizations of “known” or even “unknown” systems, whose properties are well suited for traditional approaches to risk measurement and management. Portrayal of “known” systems denotes that the probability distributions of future states are completely specified, as in the case of automobile- or life-insurance claims (in the absence of large-scale events, such as mass-casualty terrorist attacks or natural disasters), whereas “unknown” systems occur when all possible states of the future system can be enumerated but the probabilities associated with entering into them cannot (27). Instead, CAS present risk analysts and decision-makers with ignorance, or deep uncertainty, where all possible future states and their associated probabilities cannot be specified (34–37).

Analytic Orientation. A second source of failure in traditional risk approaches concerns the analytic orientation of those responsible for measuring and managing risk sources and levels. These analysts may improperly focus their attention on the collection and analysis of information that cannot detect risks posed by impending phase transitions or regime changes in CAS (i.e., rapid changes in the system’s structure and dynamics). In these instances, the information necessary to provide accurate assessments of risk may be available to analysts and decision-makers, but the data have not been collected or properly interpreted. As a result, events that catch decision-makers unprepared might have been anticipated through the use of a different analytic and data-collection framework.

The Arab Spring offers an important example of this phenomenon. In the cases of Tunisia and Egypt, the protesters were predominantly urban and secular youth, many of whom had no prior history of political activism. They demanded democratic reforms and the strengthening of state institutions through

the rule of law and abolition of endemic corruption. Their relative size and demands surprised governments and observers alike, each of which had previously focused on the traditional sources of antiregime rhetoric and action from well-organized Islamist organizations. Without a model for a leaderless revolution, the threats to these established regimes from spontaneously formed crowds of secular protesters could not be accurately assessed (38).

Emerging concerns in areas of cybersecurity offer another set of examples. So-called “zero-day exploits” or “advanced persistent threats” are examples of risks embedded inside existing systems that are amplified as systems become increasingly connected, where integration creates complex feedbacks between units that were designed to perform specialized or individual purposes. Such risks are not visible until after they have been exploited, presenting a challenge to traditional modeling. Indeed, the strategies introduced for controlling and providing stability in highly complex technological systems have been known to have the opposite effect, inadvertently increasing the risk of cascading impacts in response to unforeseen changes (4).

Ensuring that risk analysts are properly oriented can be particularly difficult to achieve in CAS because collecting information may alter the behavior of the system’s units, provoking undesired or unintended adaptive responses. For example, national intelligence organizations carefully guard their sources and methods because they implicitly recognize that their revelation may invite adaptive changes in their target’s behavior, undermining their future use, transforming them into channels for passing deceptive information, and damaging relations with other actors (39, 40).

Another problem associated with achieving a proper analytic orientation within CAS regards establishing the necessary depth and breadth of analysis. The system and its components change, and actors perceive and adapt to their environment as a result of their unique experiences. Their behavior may deviate from the expectations of utility maximization or rational choice, and analysts are faced with a challenge of adjusting the orientation of their risk models to incorporate the effects these nontraditional factors on the broader systems.

Finally, CAS contain dynamics that operate on multiple temporal scales. Thus, the presence of slow-variables, such as cultural or environmental changes, may be difficult to perceive and harder to quantify because they are often masked by higher-frequency

dynamics. These slow variables often establish boundary or threshold conditions that inform faster-paced changes in systems. In the contemporary social systems, these variables may include demographic structures, educational and technical skillsets within populations, changes in ideological worldviews, access to credit, Internet penetration within populations and sub-populations, the diffusion of small arms, and so forth. Although none of these may be determinative of a femtorisk’s materialization, they may enable or hinder the ability of a CAS to transition into a new state with little or no warning. Traditional risk assessments consider only visible dynamics that occur on faster time scales (41–43).

Improper analytic orientation enables small systemic risks, which may be easy to mitigate early on, to grow into crises by the time they are recognized. Moreover, devoting continuous attention and resources to variables that possess little dynamism or cannot be affected by individual or collective action imposes opportunity costs by robbing attention and resources from alternative interventions that could be more successful in avoiding or mitigating the social costs posed by systemic risks. This aspect is particularly true for strategies that must interact with and shape global systems, and cannot rely on discrete “on/off” interactions and or use “exit strategies” whenever contact between actors is persistent.

Decision-Making Inertia. Asymmetries exist in CAS. The actions of individuals or small groups of well-positioned actors may push the system beyond bounds of functionality, thus creating femtorisks. The effective prevention of systemic breakdown requires collective action by multiple stakeholders. Therefore, effective risk management of international CAS is often dependent on social processes related to the interaction of analysts and decision makers, even within the same organization, with challenges compounded when the regulation of different systems in different national governance structures require coordination. In addition to the complexities of analytic assessments of CAS, these social processes introduce new sources of complexity as personal and organizational politics of negotiation and power come into play (44). Thus, the relationships between those who assess systemic risks and those who make decisions about how to address them often determine how successfully analysis is used in decision-making processes. Even if analysts correctly assess risks within CAS, decision-makers may be vested in preserving their hard-won political agreements

or economic advantages, or may question the accuracy of analyst's conclusions based on their own expertise and experiences. As a result, organizational decision-making often reveals highly confrontational relationships between analysts and decision-makers that influence how information and knowledge about risks are used (35, 45–50).

This relationship has repeatedly undermined the assumptions of rational action inherent in risk management and the belief that states and firms are unified actors. Instead each has distinctive roles in the assessment and management of risk. Analysts focus on the substantive aspects of systems, whether financial markets, critical infrastructure, international development, climate, and so forth. Decision-makers wrestle with a wider range of concerns, but may possess a narrower organizational or even personal set of interests, and focus their efforts on the types of actions that they and other stakeholders can agree to or impose given their relative power. Because decision-makers are involved in a political process, as opposed to a technical engineering or design process, they are often reluctant to change policies, particularly if the costs of doing so would open existing commitments to renegotiation or damage their reputation or participation in future negotiations. Once committed, decision makers often neglect new information that might indicate that their policies are failing, or ignore the analysis of specialists that contradicts their expectations (51, 52). This willful blindness can allow the harmful effects of small risks to proliferate, diffuse, and amplify.

Biological Models of Adaptation for Coping with Uncertainty

Adaptive evolution is to large extent shaped by uncertainty, and the need to respond to that uncertainty through averaging mechanisms, plasticity, or genetic change. Many environmental features confronting organisms, like diurnal or seasonal cycles, are predictable in a probabilistic sense, and have shaped a range of physiological and behavioral responses; others, however, such as which pathogens will attack an organism, are unpredictable and have evolutionarily led to adaptive responses, such as the vertebrate immune system. Rather than seek to design robust institutions and strategies that may fare well only against specified futures, risk measurement and management professionals would benefit from imitating how evolution has dealt with unknowable challenges, and take steps toward assuring those responsible for sustaining global stability and prosperity possess sufficient learning capabilities and

adaptive capacity to detect and mitigate the effects of novel risks (53, 54).

In any complex system, robustness [often termed resilience in the ecological literature (55)] depends upon the balance among three interrelated aspects (56): (i) the diversity of the units within the system, which encodes its adaptive capacity; (ii) the extent to which the system contains functional redundancies, providing insurance against the loss of key elements; and (iii) the degree of modularity with respect to the coupling between components.

When taken as a whole, the trade-offs among these three features enable a system to keep functioning in the face of changes in its environment, and provide opportunities for experimentation to tolerate disruptions and produce innovations without placing the entire system at risk (3).

One of the most remarkable triumphs of evolution, the vertebrate immune system, provides a model for how to design resilient systems that can withstand the shocks produced by femtorisks and mitigate systemic risks. The key features of this model include: (i) the maintenance of a set of generic defenses that can rapidly identify and respond to threats, (as the body does when it recognizes a pathogen and rushes generalized antibodies to the site of the threat); (ii) persistent engagements that enable rapid learning through interaction with threatening actors or processes (as the body produces specialized antibodies in response to the invader); (iii) translation lessons from prior experiences into customized, localized defenses against previously encountered threats (the body produces permanent, or at least long-lasting, defenses against the infection); and (iv) the maintenance of an archive of previously experienced threats and the addition of successful countermeasures to the set of generic responses to mitigate future encounters rapidly (the body's antibody repertoire).

As a result, the vertebrate immune system is able to allow organisms to persist despite constantly encountering novel threats through continuous learning and adaptation. The traditional rational actor model of decision-making emphasizes observation, calculation, and periodic action, all of which limit engagements and therefore provide few opportunities to interact and learn. The evolutionary approach proposed as an alternative basis for risk management and governance encourages sustained engagement and feedback to create learning opportunities that enhance the adaptive capacity of international institutions in many domains.

Enriching Policy

Many of the aspects of the immune system model have comparable features in international relations. For example, studies of military innovation often emphasize the complexity of peacetime developments, when uncertainties about the capabilities and strategies of other forces proliferate because of a lack of engagement. Military planners have recognized the resulting need to maximize flexibility through the creation of generic capabilities that can be modified as new information about rivals' goals, strategies, tactics, and technologies become available (57–59). Military organizations often study one another's successes and failures for insights into their own capabilities, as demonstrated by the United States analysis of Israeli's air campaign against Hezbollah in 2006. In addition, military organizations simulate conflict scenarios with unproven capabilities or unfamiliar rivals to generate insights into threats to maintain an archive of possible countermeasures for use in an array of possible future encounters (60, 61). Likewise, foreign policy professionals often argue in favor of maintaining ties with rogue states to strengthen perspective, insights, and strategic context, and increase opportunities to evolve specialized defenses, and enhance the coevolution of symbiotic systems (62).

Clearly, some quarters have recognized that the development of resilient risk-management schemes, which can cope with novelty, surprise, and inaccuracies in predictions, can have important benefits for public and private sector governance. For example, an adaptive approach based on learning through interaction and feedback accords with the boundedly rational foundation of human cognition and organizational behavior (63–65). This approach shifts the evaluative criteria of policy options away from optimal, often brittle solutions that require accurate predictions, in favor of resilient solutions that can be adapted in response to new information and experiences.

Moreover, diminishing the role of predictions in the formulation of risk-management strategies and policy can alter the conduct of decision-making itself by reducing tensions between multiple stakeholders, risk analysts, and decision-makers. As long as predictions serve as the basis of decision-making within organizations, strong incentives exist to control analytic processes and features, such as the terms of reference and scope of analysis, sources of data, methodology, and so forth, to ensure that particular personal or organizational perspectives

prevail in agenda setting. By moving toward an increasingly adaptive risk-management framework, decision-making rewards those actors that can more rapidly gather, process, and react to new information, activities that are enriched by searching across broad ranges of possible futures generated by alternative, competing perspectives on the system (34). Thus, analytic frameworks for addressing systemic risks may be more successful at solving collective action problems associated with the governance of CAS by accepting uncertainty, allowing stakeholders to discover shared interests and concerns about potential futures that support the formation of coalitions willing to invest in learning actions, rather than in practices that reward bureaucratic maneuvering to see one set of future risks thrive at the expense of other views.

Together, these benefits address the problems associated with the limits of prediction in CAS, the challenge of proper orientation by risk analysts, and the need to reduce inertia in decision-making processes by improving relations between analysts and decision-makers.

The evolutionary model of risk management in CAS provides the additional benefit of aligning with boundedly rational decision-making exemplified by individuals and groups. In this approach, decision-makers reach satisfaction by eliminating options that are believed to ineffectively manage risks until they identify an option or set of options that meet their needs. This approach does not produce optimal outcomes, but allows for decision-makers to engage in a continuous process of adaptation as situations change and new information about policy opportunities and threats become known.

Another common feature of successful risk-management strategies and biological systems is the importance of building on solutions or capabilities with multiple benefits. For example, improved border security provides benefits to counterterrorism, counternarcotics, and illegal immigration. Similarly, improvements in public health monitoring and access to medical services provide the foundation for the early detection and mitigation of natural epidemics and bioterror attacks. Just as in biology, successful risk mitigation strategies may be generic, allowing for their reuse in multiple domains or for many purposes. Thus, rather than emphasize point solutions that may be optimized to particular risks, risk managers should prefer capabilities that have positive externalities and spillover effects.

Evolution provides promising models for coping with risks because of those models'

ability to cope with uncertainty and relax the rationality assumptions embedded in traditional analytic approaches. However, important differences remain between social systems and biological ones. In biological evolution, adaptation occurs as a result of random search, building upon designs that worked in the past. By comparison, adaptation in social systems is not purely random as the search for new solutions to challenges is based on the interests, ethics, and strategic anticipation of actors. Although we advocate the need for an evolutionary model that emphasizes engagement, learning, and resilience as opposed to predictability and optimality, the evolutionary dynamics of international relations may differ from those observed in biological systems because of fundamental differences in their search processes.

Conclusions

The conceptual framework provided by biological models of evolution for coping with threats to the functioning of international systems calls for new approaches to measuring and managing risk under uncertainty CAS (66–68). Approaches based on biological evolution and resilience, which aim for sustaining systemic functions without relying on predictions about the future state of the world, offer a promising model. Integrating this perspective with the game-theoretical and systems-theory approaches developed by social science disciplines and communities of practice for managing systemic risk can offer new perspectives on public- and private-sector governance over a multitude of CAS spanning international systems, from global financial networks, to critical infrastructure, to the diffusion of social movements and the rapid collapse of established regimes (1). These are, however, games of a different nature than classic theory, emphasizing the interplay between many individuals in large populations in which individual agency is essential in explaining macroscopic consequences. In recent years, such extensions of game theory have been termed “mean-field games,” and hold great potential for addressing the problems considered here (69–71).

A world of femtorisks makes risk-calculation much more challenging, as it seems likely that the probability of some femtorisk inside critical systems may hover near 1—or at least should be assumed to be at that level for planning purposes—although this itself becomes a challenging problem. For example, it has been argued by leading bankers, such as Bank of England Chief Economist Andrew Haldane, that the problem of the 2008 financial crisis was the addition of risk to a system that was already risk-critical because of competitive searches for yield by financial groups (72). Adding in subprime risk was one grain of sand too many by this logic. However, what if the issue was not the addition of more risk, but rather the addition of more connectivity, which activated embedded femtorisks? In this sense femtorisks allow us to begin adding precision to the important fact that connectivity is risk, and offer the elements of connectivity as areas for examination.

Globalization will continue to allow new femtorisks to emerge, as different cultures, economies, and ecological imperatives create new frictions in new configurations. With humility and openness, the new forum proposed herein will develop fresh tools and perspectives to examine approaches to evolving complex problems, and might spawn the conversations and community required to gather lessons from the broad experience of this diverse network, and deploy that experience to help to understand and solve networked problems.

ACKNOWLEDGMENTS. We thank the participants in the International Institute for Applied Systems Analysis's (IIASA) 2011 international conference *Security in the Age of Systemic Risk: Strategies, Tactics and Options for Dealing with Femtorisks and Beyond* for their contributions. The perspectives offered in this paper extend ideas originally expressed during conference discussions and published by IIASA in 2012. Conference participants not listed among the coauthors of the present paper include Michael Clegg, Zvi Shtauber, Karl Sigmund, Jonathan Tepperman, and Wang Yiwei. The original conference report is available at www.iiasa.ac.at/publication/more_IR-12-010.php. Financial support for the conference was provided by IIASA and by the National Academy of Sciences, through National Science Foundation Grant 0738129, for the support of National Academy of Sciences activities related to its responsibilities as the United States National Member Organization for IIASA.

1 Jervis R (1998) *System Effects: Complexity in Political and Social Life* (Princeton Univ Press, Princeton, NJ).

2 Stein A (1990) *Why Nations Cooperate* (Cornell Univ Press, Ithaca, NY).

3 Simon H (1996) *The Sciences of the Artificial* (MIT Press, Cambridge, MA).

4 Perrow C (1984) *Normal Accidents: Living with High-Risk Technologies* (Princeton Univ Press, Princeton, NJ).

5 Keohane R, Nye J (2011) *Power and Interdependence* (Longman Classics in Political Science, Boston).

6 Chambers D (2008) What's the difference between picocells and femtocells? *Think Small Cell*. Available at www.thinksmallcell.com/FAQs/whats-the-difference-between-picocells-and-femtocells.html. Accessed June 1, 2014.

7 Levin S, et al. (2012) Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environ Dev Econ* 17(6):1–22.

8 Schelling T (1978) *Micromotives and Macrobehavior* (Norton, New York).

9 Cohen M, Kunreuther H (2007) Operations risk management: Overview of Paul Kleindorfer's contributions. *Prod Oper Manag* 16(5):525–541.

- 10 Ramo J (2009) *The Age of the Unthinkable: Why the Now World Disorder Constantly Surprises Us and What We Can Do About It* (Little Brown and Company, New York).
- 11 Khandani A, Lo A, Merton R (2013) Systemic risk and the refinancing ratchet effect. *J Financ Econ* 108(1):29–45.
- 12 Pollack K, et al. (2011) *The Arab Awakening: America and the Transformation of the Middle East* (Brookings Institution, Washington, DC).
- 13 Murphy C (2012) The Arab Spring: The uprising and its significance. *Trinity Magazine*. Available at www.trinitydc.edu/magazine-2012/the-arab-spring-the-uprising-and-its-significance/. Accessed June 1, 2014.
- 14 Srinivasan R (2012) Taking power through technology in the Arab Spring. *Al Jazeera*. Available at www.aljazeera.com/indepth/opinion/2012/09/2012919115344299848.html. Accessed June 1, 2014.
- 15 Grand S (2014) *Understanding Tahrir Square: What Transitions Elsewhere Can Teach Us About the Prospects for Arab Democracy* (Brookings Institution, Washington, DC).
- 16 Anonymous (May 17, 2012) Let them eat baklava. *The Economist*. Available at www.economist.com/node/21550328. Accessed June 1, 2014.
- 17 Gause FG (2011) *The Middle East Academic Community and the "Winter of Arab Discontent": Why Did We Miss It? Seismic Shift: Understanding Change in the Middle East* (Stimson Center, Washington, DC), pp 11–28.
- 18 McMahon R, ed (2014) Ukraine in Crisis: Background. *Council on Foreign Relations*. Available at www.cfr.org/ukraine/ukraine-crisis/p32540. Accessed June 14, 2014.
- 19 Biddle S, Oelrich I (July 21, 2014), Why the Ukraine separatists screwed up: Badly organized insurgents can't master complex weapons systems. *Washington Post Monkey Cage*. Available at www.washingtonpost.com/blogs/monkey-cage/wp/2014/07/21/why-the-ukraine-separatists-screwed-up-badly-organized-insurgents-cant-master-complex-weapons-systems/. Accessed September 1, 2014.
- 20 Pifer S (2014) Ukraine, Russia and the U.S. Policy Response. *Testimony of Steven Pifer, Brookings Institution, Before the Senate Foreign Relations Committee*, June 5, 2014. Available at www.brookings.edu/research/testimony/2014/06/05-ukraine-russia-us-policy-response-pifer. Accessed September 1, 2014.
- 21 Moss W (2014) Are we starting another Cold War over Russian actions in Ukraine? *History News Network: George Mason University*, May 4, 2014. Available at <http://historynewsnetwork.org/article/155525>. Accessed September 1, 2014.
- 22 Myers SL (May 15, 2013) Arctic Council adds 6 national as observer states, including China. *New York Times*. Available at www.nytimes.com/2013/05/16/world/europe/arctic-council-adds-six-members-including-china.html. Accessed September 1, 2014.
- 23 Gravggaard A (2014) Greenland's rare earths gold rush. *Foreign Affairs*, October 28, 2013. Available at www.foreignaffairs.com/features/letters-from/greenlands-rare-earths-gold-rush. Accessed June 1, 2014.
- 24 Macalister T (January 5, 2014) Greenland explores Arctic mineral riches amid fears for pristine region. *The Guardian*. Available at www.theguardian.com/world/2014/jan/05/greenland-mines-arctic-fears-pristine-environment. Accessed June 1, 2014.
- 25 Yenikeyeff S, Krysiak TF (2007) The battle for the next energy frontier: The Russian polar expedition and the future of Arctic hydrocarbons. *Oxford Energy Comment*, Oxford Institute for Energy Studies. Available at www.oxfordenergy.org/wpcms/wp-content/uploads/2011/01/Aug2007-TheBattleforthenextenergyfrontier-ShamiliYenikeyeff-and-TimothyFentonKrysiak.pdf. Accessed September 9, 2014.
- 26 Hubbard D (2009) *The Failure of Risk Management: Why It's Broken and How to Fix It* (John Wiley & Sons, Hoboken, NJ).
- 27 Diebold F, Doherty N, Herring R, eds (2010) *The Known, the Unknown, and the Unknowable in Financial Risk Management* (Princeton Univ Press, Princeton, NJ).
- 28 Vose D (2009) *Risk Analysis: A Quantitative Guide* (Wiley, New York).
- 29 Bedford T, Cooke R (2001) *Probabilistic Risk Analysis* (Cambridge Univ Press, New York).
- 30 Holland J (1996) *Hidden Order: How Adaptation Builds Complexity* (Helix Books, New York).
- 31 Miller J, Page S (2007) *Complex Adaptive Systems* (Princeton Univ Press, Princeton, NJ).
- 32 Popper K (2004) *The Poverty of Historicism* (Routledge, New York).
- 33 Sharpe WF (1964) Capital asset prices—A theory of market equilibrium under conditions of risk. *J Finance* XIX(3):425–442.
- 34 Lempert R, Popper S, Bankes S (2003) *Shaping the Next One-Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis* (RAND, Santa Monica, CA).
- 35 Knight F (2006) *Risk, Uncertainty and Profit* (Dover, Mineola, NY).
- 36 Granger C (2010) Risk: A decision maker's perspective. *The Known, the Unknown, and the Unknowable in Financial Risk Management*, eds Diebold F, Doherty N, Herring R (Princeton Univ Press, Princeton, NJ), pp 31–46.
- 37 Zeckhauser R (2010) Investing in the unknown and unknowable. *The Known, the Unknown, and the Unknowable in Financial Risk Management*, eds Diebold F, Doherty N, Herring R (Princeton Univ Press, Princeton, NJ), pp 304–343.
- 38 Merlini C, Roy O, eds (2012) *Arab Society in Revolt: The West's Mediterranean Challenge* (Brookings Institution, Washington, DC).
- 39 Bruce J, Bennett M (2008) Foreign denial and deception: Analytical imperatives. *Analyzing Intelligence: Origins, Obstacles, and Innovations*, eds George R, Bruce J (Georgetown Univ Press, Washington, DC), pp 122–137.
- 40 Lowenthal M (2011) *Intelligence: From Secrets to Policy* (Congressional Quarterly Press, Washington, DC).
- 41 Holling CS (1996) Engineering resilience versus ecological resilience. *Engineering Within Ecological Constraints*, ed Schulze P (National Academies Press, Washington, DC), pp 31–44.
- 42 Jansson B, Jansson A (2002) *The Baltic Sea: Reversibly Unstable or Irreversibly Stable? Resilience and the Behavior of Large-Scale Systems*, eds Gunderson L, Pritchard L (Island Press, Washington, DC), pp 71–109.
- 43 Walker BH, Carpenter SR, Rockstrom J, Crépín A-S, Peterson GD (2012) Drivers, "slow" variables, "fast" variables, shocks, and resilience. *Ecol Soc* 17(3):30.
- 44 George R, Rishikoff H, eds (2011) *The National Security Enterprise: Navigating the Labyrinth* (Georgetown Univ Press, Washington, DC).
- 45 Hilsman R (1956) *Strategic Intelligence and National Decisions* (The Free Press, Glencoe, IL).
- 46 Kent S (1968) Estimates and influence. *Studies in Intelligence* 3(2):11–21.
- 47 Meldman M (1989) *Order Without Design: Information Production and Policy Making* (Stanford Univ Press, Stanford, CA).
- 48 Betts R (2007) *Enemies of Intelligence: Knowledge & Power in American National Security* (Columbia Univ Press, New York).
- 49 Terverton G (2008) Intelligence analysis: between "politicization" and irrelevance." *Analyzing Intelligence: Origins, Obstacles, and Innovations*, eds George R, Bruce J (Georgetown Univ Press, Washington, DC), pp 91–106.
- 50 Rovner J (2011) *Fixing the Facts: National Security and the Politics of Intelligence* (Cornell Univ Press, Ithaca, NY).
- 51 Jervis R (2010) *Why Intelligence Fails: Lessons from the Iranian Revolution and the Iraq War* (Cornell Univ Press, Ithaca, NY).
- 52 Nickerson R (1998) Confirmation bias: A ubiquitous phenomenon in many guises. *Rev Gen Psychol* 2(2):175–220.
- 53 Aven T (2011) On some recent definitions and analysis frameworks for risk, vulnerability, and resilience. *Risk Anal* 31(4): 515–522.
- 54 Scholz R, Blumer T, Brand F (2012) Risk, vulnerability, robustness, and resilience from a decision-theoretic perspective. *J Risk Res* 15(3): 313–330.
- 55 Levin S, Lubchenco J (2008) Resilience, robustness, and marine ecosystem-based management. *Bioscience* 58(1):27–32.
- 56 Levin S (1999) *Fragile Dominion: Complexity and the Commons* (Perseus Publishing, Cambridge, MA).
- 57 Rosen S (1994) *Winning the Next War: Innovation and the Modern Military* (Cornell Univ Press, Ithaca, NY).
- 58 Murray W, Millett A, eds (1998) *Military Innovation in the Interwar Period* (Cambridge Univ Press, New York).
- 59 Murray W, Knox M (2001) Conclusion: The future behind us. *The Dynamics of Military Revolution, 1300–2050*, eds Knox M, Murray W (Cambridge Univ Press, New York), pp 175–194.
- 60 Arkin W (2007) Divine victory for whom? Airpower in the 2006 Israel-Hezbollah War. *Strategic Studies Quarterly* 1(2):98–141.
- 61 Herman M, Frost M, Kurz R (2009) *Wargaming for Leaders: Strategic Decision Making from the Battlefield to the Boardroom* (McGraw Hill, New York).
- 62 Brzezinski Z, Gates R (2004) *Iran: Time for a New Approach* (Council on Foreign Relations, New York).
- 63 March J, Simon H (1993) *Organizations* (Blackwell, Cambridge, MA).
- 64 Simon H (2000) Bounded rationality in social science: Today and tomorrow. *Mind Soc* 1(1):25–39.
- 65 Kahneman D (2011) *Thinking Fast and Slow* (Farrar, Strauss and Giroux, New York).
- 66 Sagarin RD, et al. (2010) Decentralize, adapt and cooperate. *Nature* 465(7296):292–293.
- 67 Sagarin R (2012) *Learning from the Octopus: How Secrets from Nature Can Help Us Fight Terrorist Attacks, Natural Disasters, and Disease* (Basic Books, New York).
- 68 Ramalingam B (2013) *Aid on the Edge of Chaos: Rethinking International Cooperation in a Complex World* (Oxford Univ Press, Oxford).
- 69 Jovanovic B, Rosenthal RW (1988) Anonymous sequential games. *J Math Econ* 17(1):77–87.
- 70 Lasry JM, Lions PL (2007) Mean field games. *Jpn J Math* 2(1): 229–260.
- 71 Huang MY, Malhame RP, Caines PE (2006) Large population stochastic dynamic games: Closed-loop McKean–Vlasov systems and the Nash certainty equivalence principle. Special issue in honor of the 65th birthday of Tyrone Duncan. *Communications in Information and Systems* 6(3):221–252.
- 72 Haldane AG (2012), *Tails of the unexpected*, speech given at "The Credit Crisis Five Years On: Unpacking the Crisis" Conference, University of Edinburgh Business School, Edinburgh, Scotland. June 8, 2012. Available at www.bankofengland.co.uk/publications/Documents/speeches/2012/speech582.pdf. Accessed October 14, 2014.