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Systems Resilience: A New Analytical Framework for Nuclear Nonproliferation

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Systems Resilience: A New Analytical Framework for Nuclear Nonproliferation

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Abstract

This paper introduces the concept of systems resilience as a new framework for thinking about the future of nonproliferation. Resilience refers to the ability of a system to maintain its vital functions in the face of continuous and unpredictable change. The nonproliferation regime can be viewed as a complex system, and key themes from the literature on systems resilience can be applied to the nonproliferation system. Most existing nonproliferation strategies are aimed at stability rather than resilience, and the current nonproliferation system may be over-constrained by the cumulative evolution of strategies, increasing its vulnerability to collapse. The resilience of the nonproliferation system can be enhanced by diversifying nonproliferation strategies to include general international capabilities to respond to proliferation and focusing more attention on reducing the motivation to acquire nuclear weapons in the first place. Ideas for future research, include understanding unintended consequences and feedbacks among nonproliferation strategies, developing methodologies for measuring the resilience of the nonproliferation system, and accounting for interactions of the nonproliferation system with other systems on larger and smaller scales.

Acknowledgement

The author is grateful for having had the opportunity to explore this new field during her time as a visiting scholar at Stanford University's Center for International Security and Cooperation (CISAC) in 2009 / 2010. In particular, she would like to acknowledge the helpful reviews and advice of Lynn Eden, Scott Sagan, and Sig Hecker. She also is grateful to Michael Krepon and Charles Ferguson of Sandia's Distinguished Advisory Panel on Nonproliferation, and Sharon DeLand and Robert Glass of Sandia National Laboratories.

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Acronyms, Initialisms, and Abbreviations

IAEA	International Atomic Energy Agency
NATO	North Atlantic Treaty Organization
NPT	Nuclear Nonproliferation Treaty
NSG	Nuclear Suppliers Group
NWS	Nuclear Weapon States
NNWS	Non-nuclear Weapon States

PSI	Proliferation Security Initiative
UNSCR	United Nations Security Council Resolution

1 Introduction

A complex system is a dynamic network of many interconnected elements, in which changes in some elements produce changes elsewhere. Resilience is a measure of a system's ability to absorb continuous and unpredictable change and still maintain its vital functions. The goal of this paper is to introduce the concept of systems resilience as a new analytical framework for thinking about the future of nonproliferation.

First, I discuss the concept of a "complex system" and argue that the set of actors, instruments, and strategies that make up the nonproliferation regime can be viewed as a complex system whose vital function is maintaining an international norm against the spread and use of nuclear weapons. Next, I introduce key themes from the literature on systems resilience and apply them to nonproliferation: 1) the difference between resilience and stability; 2) the need for evolution to maintain function in a changing environment; 3) the importance of functional diversity; and 4) thresholds between fundamentally different system states. I show that most existing nonproliferation strategies are aimed at stability rather than resilience, and that the evolution of strategies has been focused too narrowly on limiting technical capability. The result is a lack of diversity in the strategies of the nonproliferation system, which is compounded by bureaucratic and political constraints that inhibit development of innovative new approaches. According to the literature on systems resilience, this situation decreases resilience and increases vulnerability to collapse.

I suggest that the resilience of the nonproliferation system can be enhanced by acknowledging that it may not be possible to keep all determined states from acquiring nuclear weapons. Rather than focusing exclusively on prevention, efforts should be expanded in two areas: developing general international response capabilities that increase overall security and can respond to proliferation events, and reducing the motivation to acquire nuclear weapons in the first place. The result will be a greater diversity of nonproliferation strategies and champions that can respond to a broad range of future challenges.

The new analytical framework presented here represents a small first step. Much additional work will be required to fully apply the ideas and methodologies of systems resilience to nonproliferation. Topics for future research include: understanding unintended consequences and feedbacks among nonproliferation strategies, and developing methods to measure the resilience of the nonproliferation system. It is also important to keep in mind that the nonproliferation system interacts with other systems on larger and smaller scales. It would therefore be important to explore how measures outside of the nonproliferation regime itself could enhance the regime.

2 Complex Systems

A complex system is a dynamic network of many interconnected elements, in which changes in some elements (or the relations among them) produce changes elsewhere. In addition, the properties of the system as a whole are different from the properties of its individual elements. This is referred to as emergent behavior. It is difficult to predict, control, or understand the effects of actions in a complex system, especially when its elements are tightly connected and disturbances propagate easily. Actions always have unintended consequences, as positive and negative feedbacks among system elements cannot be known in advance. Coherent behavior, if it occurs, arises from competition and cooperation among the system elements, and results from very large numbers of individual actions. Order is emergent, rather than pre-determined.[1]

Example of a Complex System: Managed Forest Ecosystem

As an example of a complex system, consider a forest that has matured over decades and is now under active management. System elements include plants (trees, grasses, shrubs), animals (carnivores, herbivores, insects), sources of water (streams, lakes) and nutrients (decaying vegetation, runoff from surrounding land), as well as human managers. The forest provides a number of ecosystem services of value to both forest inhabitants and humans, such as clean water, habitat, flood protection, timber, and food. These ecosystem services are emergent properties of the forest system: they result from the interaction of all system elements, rather than being attributable to any one individually.

The elements of the ecosystem are interconnected. Trees provide habitat for birds and small mammals. Predators, such as wolves and mountain lions, control the population of herbivores, such as deer, which in turn control the growth of grasses and other herbaceous species. Healthy forest vegetation provides shade that both protects and limits plants in the understory, as well as mitigating storm runoff and regulating nutrients flowing into streams. Humans try to manage the system to optimize the benefits they derive.

Because of the connectivity of all system elements, disturbances (both natural and human-caused) reverberate throughout the entire system, with results that are difficult to control or predict. Human actions rarely have straightforward results. For example, killing top predators to enhance livestock production or to improve human safety can result in an overpopulation of deer, which then consume an excessive amount of grass and small plants, reducing the forage for livestock. Suppression of fire can result in excessive shrubby undergrowth that competes with grasses suitable for livestock forage and lays the groundwork for explosive fire conditions in the future. It can also change distribution of plant species, since some seeds require fire to germinate. Timber harvesting, human settlements and livestock grazing can deplete forest cover, which increases storm runoff, which pollutes streams. Agricultural waste from livestock and farming exacerbates pollution.

As long as disturbances due to human actions or natural disasters are not too large, the forest can continue to deliver a range of services. However, its ability to resume functioning after a major shock will depend on its overall resilience.

[1] Three books have informed much of the discussion of complex systems in this paper: Jervis, Robert, *Systems Effects: Complexity in Political and Social Life* (Princeton, NJ: Princeton University Press, 1997); Wildavsky, Aaron, *Searching for Safety* (Piscataway, NJ: Transaction Publishers, 1988); and Per Bak, *How Nature Works* (New York, NY: Copernicus Press, 1996)

3 The Nonproliferation System

The set of actors, instruments, and strategies focused on preventing the spread and use of nuclear weapons can be thought of as a complex system. Its elements include:

Actors:

- States Nuclear Nonproliferation Treaty (NPT) nuclear weapon states (NWS) and non-nuclear weapon states (NNWS); states outside the NPT)
- International bodies (the International Atomic Energy Agency (IAEA), the Nuclear Suppliers Group (NSG))
- Non-state actors (terrorist organizations, black-market supply networks)

Instruments

- Treaties (NPT, arms control treaties)
- Export control regimes
- United Nations Security Council Resolutions (e.g., UNSCR 1540)
- The Proliferation Security Initiative (PSI)

Nonproliferation strategies

- Controlling supply of nuclear weapons relevant technology, material, and expertise
- Reducing motivation for acquiring nuclear weapons
- Responding to proliferation.

Because actors in the nonproliferation system are motivated by a wide variety of interests it is difficult to predict the impact of nonproliferation strategies in advance. Indeed, strategies always have unintended consequences. For example, when states with advanced nuclear industries control the supply of sensitive nuclear technology the intended impact is to limit access to the material and technology needed to make nuclear weapons. However, controlling supply could be perceived as unfairly limiting access to nuclear technology, and might increase demand. If such technology is not available through legal channels and demand is high enough, illicit supply networks (which are difficult to detect, much less to control) may evolve to fill the gap. To illustrate this point further, Table 1 provides a list of nonproliferation strategies, their intended impacts and possible unintended consequences.

Table 1. Nonproliferation strategies, their intended impacts, and possible unintended consequences

Strategy	Intended Impact	Possible Unintended Consequences
Classification of Information	Restrict access to nuclear weapon (NW) relevant information.	False sense of security.
Security Alliances	Increase security of states in alliance.	Could decrease security of states outside alliance.
IAEA Safeguards	Restrict availability of nuclear material (implemented only in non nuclear weapon states (NNWS)	Asymmetric implementation could reinforce sense that NW bring status.
Diplomatic Pressure	Reduce motivation to pursue NW.	If public, could fuel domestic political arguments for NW.
Sanctions	Punish states with suspected NW programs to reduce their motivation for pursuing NW.	If perceived as unjust could reinforce sense that NW bring status.
Export Control	Limit availability and prevent acquisition of nuclear technology, material and expertise (NTME).	Could be perceived as unjust and reinforce sense that NTME bring status. Short supply could increase demand for NTME.
Military Action	Disrupt process of acquiring NW or NTME. Reduce motivation of others to acquire NTME or NW. Forcefully disarm a state with NW.	Could reinforce sense that NW bring both security and status. Could decrease security in states that fear they could be future targets.
Cooperative Threat Reduction	Limit availability and prevent acquisition of nuclear weapons and NTME through cooperation.	
Missile Defense	Increase security of shielded states. Deny military value of NW to proliferators, thereby reducing their motivation to acquire NW.	Could decrease security of states outside protective shield. Unilateral efforts could seem unfair and reduce commitment to NPT.
IAEA Additional Protocol (AP)	Disrupt the process of acquiring NTME / NW by early detection of clandestine activities.	Could be perceived as unjust by NNWS, and reinforce sense that NW brings status.
Proliferation Security Initiative (PSI)	Disrupt the process of acquiring NTME / NW by detecting and interdicting illicit shipments of nuclear material and technology	Could be perceived as against international law, and reduce commitment to NPT.
Capacity Building	Restrict availability of NTME by improving international capabilities to prevent theft or unauthorized transfer.	Enable potential proliferators to avoid detection.
Reduce NW Stockpiles and Salience	Enhance commitment to NPT by NNWS. Decrease linkage of NW with status and security.	Decrease security of states under so-called "nuclear umbrellas.

NOTE: Additional work would be required to determine the relative strengths of strategies and the likelihood of unintended consequences.

Despite these complexities, decades of engaging in the practice of nonproliferation (e.g., placing civilian nuclear material under International Atomic Energy Agency (IAEA) safeguards, controlling exports, and protecting nuclear material and weapons) and publicly embracing the NPT have created an international norm against the spread and use of nuclear weapons. This norm can be thought of as an emergent property of the nonproliferation system. Although its strength is difficult to measure, I suggest that maintaining this norm is the vital function of the nonproliferation system.

4 Systems Resilience

Resilience is a measure of a system's ability to absorb continuous and unpredictable change and still maintain its vital functions. After a significant disturbance, some of the system's elements might change, or be related to each other in different ways, but if the system can adapt sufficiently so that it continues to perform its vital functions, it is resilient. In contrast to resilience, stability is a measure of a system's ability to resist change and to bounce back to its original configuration after a perturbation. The study of "systems resilience" seeks to understand how complex systems respond to major disturbances. It has been the subject of significant research in the last thirty years for systems as diverse as electrical grids, transportation infrastructure, and social-ecological systems.[2] Several themes are particularly relevant to the nonproliferation system:

- The difference between resilience and stability,
- The need for evolution to maintain function in a changing environment,
- The importance of functional and demographic diversity, and
- The need to understand thresholds that separate fundamentally different system states.

4.1 Difference between Resilience and Stability

Strategies to promote system resilience will be fundamentally different than strategies to promote stability. Strategies for stability will emphasize avoiding danger and controlling both system elements and the external environment. They will focus on development of detailed plans to prevent a broad range of hypothetical threats. On the other hand, strategies for resilience will acknowledge the inevitability of change and focus on establishing general capabilities to respond to unknown hazards as they occur. Rather than seeking to control the environment, strategies for resilience will use an experimental approach to probe the environment, continuously seeking to test strategies against new scenarios.[3]

Successful systems management will require a mix of strategies for stability and strategies for resilience. However, because stability measures are easier to quantify, they are often over-emphasized. Strategies to develop the energy, endurance, and skill that are essential to recovering

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[2] In this paper, I draw most heavily on the literature of social-ecological systems. For a good overview see Walker, Brian and David Salt, *Resilience Thinking* (Washington, DC: Island Press, 2006). For an example of the application of the concept of resilience to homeland security, see Flynn, Stephen, *The Edge of Disaster*: *Rebuilding a Resilient Nation* (New York, NY: Random House, 2007).

[3] Wildavsky, Aaron, devotes much of his book *Searching for Safety* to the difference between strategies for resilience and strategies for prevention.

from major disasters may seem unfocused and therefore be harder to justify. The willingness to invest in activities that provide more general benefits is a sign of a management strategy that incorporates resilience.

The Difference between Resilience and Stability in Ecological Systems

The ecologist C.S. Holling* was among the first to articulate the difference between resilience and stability in his classic paper "Resilience and Stability of Ecological Systems" published in 1973. In this paper, he shows that instability, in the sense of large fluctuations in system parameters, may be necessary for a system's resilience, i.e., its capacity to absorb change and persist over long time scales. The interaction between the budworm and a spruce-fir forest in eastern Canada is used to illustrate this point.

Since the early 1700s there have been six budworm outbreaks in this forest. Each outbreak causes major destruction of balsam fir in the mature forests, leaving only the less susceptible spruce and the non-susceptible white birch. In more immature stands of forest there is less damage and more fir survives. Between outbreaks of disease, under normal conditions, the budworm population is very low, and young balsam firs grow, along with spruce and birch, to form dense stands. In these stands, the spruce and birch suffer from crowding, and eventually the fir dominates.

If a series of dry years occurs when there is a preponderance of fir, budworm populations begin to increase rapidly. Eventually they cause enough mortality in the fir population that the forest collapses, returning to a predominantly spruce-birch forest. The budworm population returns to low levels.

Between outbreaks, fir is favored over spruce and birch whereas the reverse is the case during an outbreak. This interplay maintains the populations of spruce and birch, which would otherwise be eliminated through competition with fir. The fir persists because of its ability to regenerate and because of the interplay of forest growth rates and climatic conditions that determine the timing of budworm outbreaks. Large fluctuations in budworm population are essential to the resilience both of the forest and the budworm itself: "successive generations of forest are replaced, assuring a continued food supply for successive generations of budworm and the persistence of the system."

The resilience of the forest ecosystem as a whole is thus a function of the instability of its elements. Attempts to stabilize these individual elements, e.g., to eliminate budworm outbreaks, put overall system resilience at risk. The management practice of "maximum sustainable yield" is an example of an attempt to stabilize ecological systems to maximize yield of particular resources. In practice it inevitably leads to system collapse.

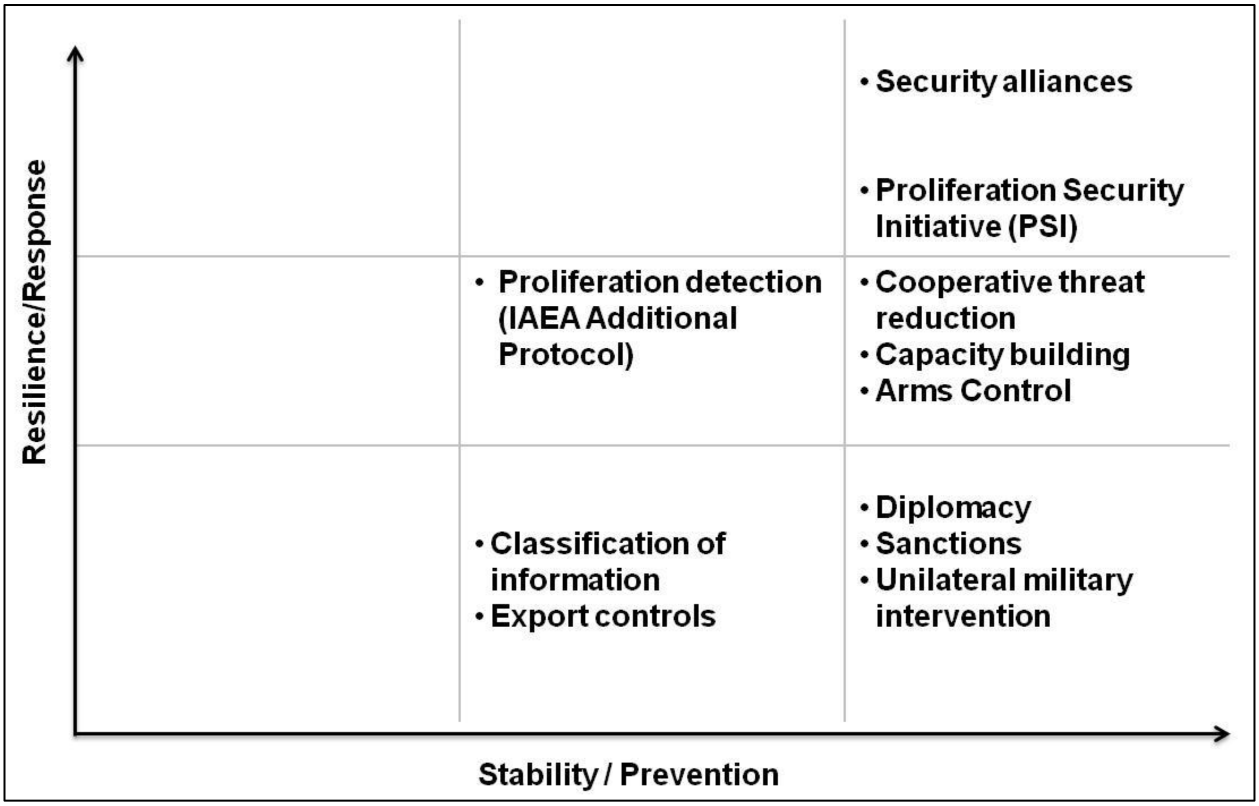
* Holling, C.S., "Resilience and Stability of Ecological Systems," *Annual Review of Ecological Systems*, 4 (1973) p. 1.

Almost by definition, most existing nonproliferation strategies are strategies for stability: emphasizing control and prevention. Export controls are explicitly designed to prevent additional states and non-state actors from acquiring the means to make nuclear weapons. International Atomic Energy Agency (IAEA) safeguards are intended to prevent diversion of nuclear material from civilian to military use, and cooperative efforts to secure nuclear weapons and material are aimed at preventing unauthorized access or illicit transfer across and within national borders. Military intervention has been used only occasionally, but again the aim has been to prevent or delay acquisition of capabilities to produce nuclear weapons. Diplomatic pressure and sanctions offer a combination of carrots and sticks to change the motivational calculus.

Relatively little attention has been focused on developing broad international capabilities to respond to proliferation when it occurs. Security alliances provide an organizational structure for a broad range of military and diplomatic actions and establish a framework for potential response. On a smaller scale, the IAEA Additional Protocol improves the IAEA's ability to detect clandestine nuclear activities and provide early warning, which would enable response if broadly implemented. Other efforts to improve international nuclear detection and forensics capabilities are also underway.[4] The Proliferation Security Initiative (PSI) aims to detect and interdict illicit shipments of proliferation-relevant material or technology as a preventive measure, but could also enable international response to proliferation events. Missile defense is yet another strategy to enable response, although current approaches are not broadly international and aimed at very specific threats.

To stimulate discussion, Figure 1 provides a nominal mapping of nonproliferation strategies onto a two dimensional framework of stability and resilience. Developing objective methods to measure a strategy's contribution to stability or resilience would be a topic for future research. It should also be noted that although resilience and stability are shown as orthogonal to each other, they should not be viewed as mutually exclusive.

[4] For example, see Jacob Goodwin, GSN: *Global Security News*, "DNDO wants to develop a "global nuclear detection architecture,"" www.gsnmagazine.com/article/21061/dndo_wants_develop_%E2%80%9Cglobal_nuclear_detection_archi , accessed July 14, 2010.



NOTE: Developing objective methods to measure a strategy's contribution to stability or resilience would be a topic for future research.

Figure 1. Notional mapping of nonproliferation strategies

4.2 The Need for Evolution to Maintain Function

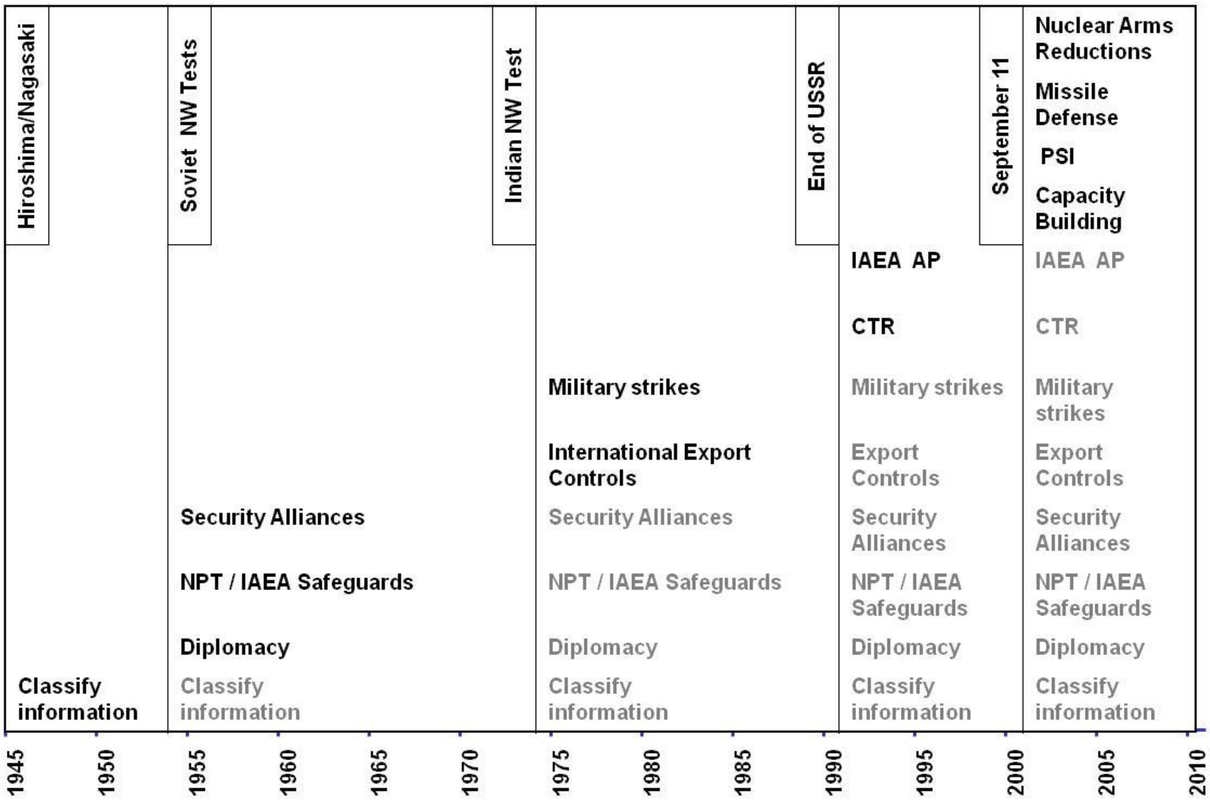
Systems must continuously evolve to maintain their performance in a changing environment, much less to improve. In biology, species mutate randomly, constantly changing the "fitness landscape" in which they and other species exist.[5] Rapid evolution may be required just to keep a constant level of fitness.

Evolution includes two types of change: strengthening existing capabilities, and developing new ones. For example, in response to decreases in winter temperature over a long time scale, mutations might strengthen an animal's existing survival capabilities (e.g., produce thicker fur), or result in new capabilities (e.g., the ability to burrow under the ground). Continued strengthening of existing capabilities without adding new ones is likely to be insufficient over the long run: if the animal's fur gets too thick it may be slower in fleeing predators or may be ill equipped for summer temperatures. On the other hand, development of new capabilities increases overall options: the ability to burrow under the ground not only improves survivability in colder winters, but also opens up new sources of food and provides better protection from predators.

The nonproliferation system has evolved over the decades in response to a changing international environment, as depicted in Figure 2. After the failure of the Baruch Plan to win international support in 1946, the primary U.S. nonproliferation strategy was classification of information

[5] For an interesting discussion of the concept of fitness landscapes, see "Interacting Dancing Fitness Landscapes" in Per Bak, *How Nature Works*, (New York, NY: Springer-Verlag, 1996), pp. 118 – 127.

related to the nuclear fuel cycle and nuclear weapons. When Soviet and British nuclear weapons tests in the late 1940s and early 1950s demonstrated weaknesses of this approach, classification guidelines were modified, but not abandoned. The IAEA was created to promote nuclear power for peaceful purposes and also to safeguard civilian nuclear material. IAEA safeguards coupled with diplomacy (mostly bilateral) were the prevailing nonproliferation strategies until the Indian nuclear test in 1974, which triggered much more intensive efforts on international export control and the formation of the Nuclear Suppliers Group.



NOTE: Most evolutionary change has strengthened the ability to control supply of nuclear material, technology and expertise.

Figure 2: Evolution of nonproliferation strategies

The end of the Soviet Union in 1991, which resulted in fears of unsecured nuclear weapons and material, was a significant shock to the nonproliferation system and resulted in creation of a broad range of cooperative threat reduction efforts to improve nuclear security. Cooperation with the Russian Federation to protect nuclear weapons and weapons-useable material was unprecedented and involved a high degree of innovation. It also set the stage for a broad range of cooperative efforts with other countries (including those from the former Soviet Union, Iraq, and Libya) to prevent unauthorized access or transfer of nuclear material, technology and expertise. In the same time frame, the failure of the IAEA to detect the Iraqi nuclear program eventually led to the IAEA Additional Protocol, which provides mechanisms for detecting nuclear activities at undeclared locations.

The shock of the September 11, 2001 terrorist attacks in the United States, together with revelations about the A.Q. Khan black-market, raised the specter of nuclear terrorism and stimulated the development of a number of new approaches. These range from capacity building to helping developing countries implement nonproliferation obligations, to the Proliferation Security Initiative aimed at interdicting illicit shipments, to limited ballistic missile defense, to preemptive war in Iraq. The Obama administration has embraced yet another strategy: reducing the salience (and numbers) of nuclear weapons. The idea is to demonstrate U.S. commitment to NPT Article VI, and thereby increase support by nonnuclear weapon states for implementation of stronger nonproliferation measures.[6]

Analysis of the evolution of nonproliferation strategies indicates that most change has strengthened capabilities to control supply of nuclear material, technology and expertise. In addition, the evolution has been cumulative: new control mechanisms are added but none are retired. Few qualitatively new strategies have evolved. The Proliferation Security Initiative is one example of a new approach. As a "coalition of the willing" it lies outside the bounds of the traditional international nonproliferation instruments and has no formal secretariat. Although nominally focused on preventing proliferation, its emphasis on international interdiction exercises builds capacity that could also contribute to general response capabilities.[7]

4.3 The Importance of Diversity

Diversity is essential for resilience. For example, the resilience of ecological systems is enhanced if different organisms performing the same ecological function respond differently to environmental perturbations, thereby enhancing the likelihood that the service will be maintained throughout a wide range of conditions.[8] Loss of diversity increases the chances for ecosystem collapse. In the business world, diversity in workplace skills, personalities, and perspectives is believed to enhance creativity and innovation and to improve decision-making and problem-solving, leading to better products. A demographically diverse workforce also may have a better understanding of the demographics of the marketplace, enhancing its competitive edge.

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[6] NPT Article VI requires that all treaty parties undertake to pursue negotiations in good faith on nuclear disarmament. For full text, see: http://www.fas.org/nuke/control/npt/text/npt2.htm.

[7] For a description of the PSI, see http://www.state.gov/t/isn/c10390.htm, and http://www.armscontrol.org/factsheets/PSI. For analysis of the PSI, see Nikitin, Mary Beth, *The Proliferation Security Initiative (PSI)*, The Congressional Research Service, January 2010, http://www.fas.org/sgp/crs/nuke/RL34327.pdf.

[8] For a good discussion of the importance of diversity to resilience, illustrated with the example of Caribbean coral reefs, see Walker, Brian and David Salt, *Resilience Thinking* (Washington, DC: Island Press,2006), pp. 64 – 73.

The Importance of Functional Diversity: Caribbean Coral Reefs

The collapse of coral reefs in the Caribbean following the 2004 hurricane season provides a good example of how decreasing functional diversity weakens resilience. Three functional groups of fish are particularly important: bio-eroders that remove dead corals and pave the way for new settlement; scrapers that remove algae and sediment, which facilitates growth and survival of existing corals; and grazers that remove seaweed, which compete with corals for resources. If any of these functional groups are lost, the ability of the coral ecosystem to absorb disturbance is significantly diminished.

For decades prior to 2004 the general health of the Caribbean reefs had been declining: fish stocks were depleted through overfishing and sediment and nutrient levels increased as the land was developed. As a result, the functional diversity of fishes that play a role in the recovery of coral reefs declined dramatically.

By the late 1960s the diversity of grazers in the Caribbean had diminished to the point where no fish were supplying this function. Only one species of sea urchin was controlling the growth of seaweed. However, the feeding action of the sea urchin eroded the hard coral framework of the reef. This was an additional compromise on its health, which was already in decline due to increasing sediment levels. Then, in the late 1980s the sea urchin population was decimated by a disease outbreak. The growth of seaweed was now uncontrolled by grazers and exacerbated by high nutrient levels. The result was a coral population in rapid decline: unable to compete with the rapid growth of seaweed and increasingly affected by disease.

In contrast to the Caribbean, the Great Barrier Reef in Australia historically has had far greater diversity – both in types of fish and of coral. (Today, the Caribbean has only 28 percent of the fish species as does the Great Barrier Reef, and only 14 percent of the species of corals.) Although the Great Barrier Reef is also experiencing problems, they are significantly less severe than in the Caribbean.

How diverse are the actors, instruments, and strategies of the nonproliferation system? There is significant diversity within the actors of the nonproliferation system, both in terms of their motivations and the functions they perform. Indeed, broad international support for the nonproliferation system emerges in part from the diversity of motivations: some actors emphasize that security for all states is increased by limiting the spread of nuclear weapons, others support nonproliferation as a means to the elimination of nuclear weapons world-wide, some are primarily interested in maintaining existing international balance of power, yet others emphasize access to peaceful nuclear technology.

Actors in the nonproliferation system also perform a number of different functions: there are the champions, the participants, and the challengers. Western states and their allies are the most vocal champions of nonproliferation, with the United States the most prominent. In the face of challenges such as Iran, there has been some diversity in response, at least in the initial stages (e.g., the EU-3 approach to Iran initially emphasized engagement versus the U.S. emphasis on compliance), but the U.S. view generally prevails in the long run. Other states, such as China, Russia, and Brazil are supporters of nonproliferation, but may not prioritize it as highly as does the United States.

The moderate geopolitical diversity of nonproliferation champions might be linked to the lack of diversity in nonproliferation strategies and instruments. Although the diversity of strategies for controlling supply of nuclear technology, material and expertise is high, such strategies, especially those associated with export control, are sometimes seen as inequitable. The diversity of strategies to reduce demand is low: indeed, security alliances are mostly limited to western states and their allies, and sanctions and diplomatic pressure may be seen as coercive. There is also low diversity of strategies to respond to proliferation events. Aside from the Proliferation Security Initiative, most response strategies, such as military strikes or missile defense, have been unilateral or narrowly multilateral.

4.4 Thresholds

A threshold is a crossing point that separates system states with completely different behaviors. Understanding thresholds and maintaining the appropriate distance from them are critical to managing system resilience.[9]

[9] Carpenter, Steve, Brian Walker, J. Marty Anderies, and Nick Abel, "From Metaphor to Measurement: Resilience of What to What?" *Ecosystems* 4(2001) p. 765; Walker and Salt, *Resilience Thinking*, pp. 53 – 63.

> ***Thresholds: Example from a Lake Ecosystem***
>
> For example, consider a lake ecosystem that provides ecological services to a region, such as clean water and fish. The lake receives nutrients, such as phosphorus, in runoff from the surrounding land. High water phosphorus levels encourage algal growth, which, if unimpeded, turn the water murky, and fish die. Water phosphorus levels are determined by two factors: phosphorus in runoff from the surroundings (which can change quickly) and phosphorus in the lake sediment (which changes slowly). As long as sediment phosphorus levels are below a certain threshold, the system is resilient, i.e., it can recover from runoff events and continue to supply clean water and fish. However, if the phosphorus level in the sediment exceeds the threshold, the system dynamics change: the feedback from sediment phosphorus to phosphorus released into the water is greatly increased. Water phosphorus levels rise steeply, and soon the lake can no longer provide clean water and fish. The new state is itself highly resilient, but the "services" it provides no longer benefit the region.

Are there thresholds in the nonproliferation system that cannot be crossed if global norms against the spread and use of nuclear weapons are to be maintained? This question is much debated in the context of discussions about nuclear tipping points, albeit in slightly different terms. Intuitively, the threshold between the current state (international norms against the spread and use of nuclear weapons) and a state in which pursuit of nuclear weapons was common and acceptable would depend on at least two variables: technological capability and motivation.

Strategies to control supply of nuclear technology and material can be thought of as strategies for maintaining a distance from this threshold. However, more and more states have access to uranium enrichment and spent fuel reprocessing capabilities, and this number could grow with the expansion of nuclear energy world-wide. Coupled with increased accessibility of nuclear technology through illicit channels, it would be safe to assume that in the future, supply side controls alone will be insufficient to avoid crossing the threshold. Like a heavily armed dinosaur whose defensive mechanisms were of little use when the environment changed, controlling supply may eventually become irrelevant.

In the future, therefore, the most important variable could be motivation. In fact, keeping motivation low will be the only barrier to crossing the threshold in a world of wide-spread nuclear latency.

5 The Adaptive Cycle

The concept of an adaptive cycle has been developed to inform discussions of resilience in ecological systems.[10] According to this concept, systems do not tend toward a stable equilibrium. Rather, they pass through characteristic phases associated with growth, conservation, release, and reorganization, as shown in Figure 3. A resilient system can maintain its function over time as it

[10] This concept is developed through a series of articles and case studies in Gunderson, L.H. and C. S. Holling, eds., *Panarchy: Understanding Transformations in Human and Natural Systems*, Washington, DC: Island Press, 2002. There is also a good non-technical overview in Walker, Brian and David Salt, *Resilience Thinking*, Washington, DC: Island Press, 2006, pp. 74 – 95.

passes through one or more cycles. In contrast, a non-resilient system, such as a sand-pile accumulating more and more sand until it finally collapses, cannot recover.[11]

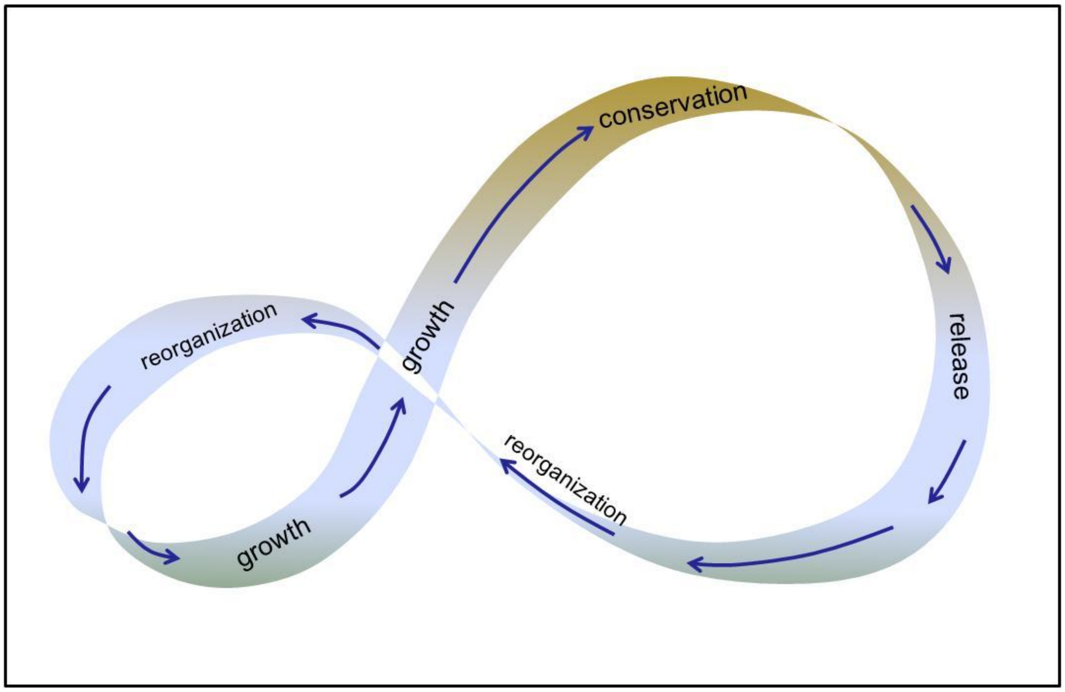

Figure 3. The adaptive cycle

The growth phase is characterized by great innovation and exploitation of opportunities and resources. In ecosystems, opportunists such as annual plants and fast-growing trees prosper during the growth phase. In economic systems, entrepreneurs start up new companies. During the growth phase, relationships have not yet solidified, the system's components are weakly interconnected, and there is great flexibility.

As the system matures, innovation and experimentation slow as it enters the conservation phase, characterized by specialization and high connectivity among all system elements. Few new elements (e.g., actors, ideas or species) are able to establish themselves during this phase and the competitive edge shifts from opportunists to specialists. Costs increase for maintaining the status quo, leaving fewer resources available to explore new opportunities; and rules and processes to control system elements are emphasized. At this stage, the system is increasingly vulnerable to disturbance.

Eventually a perturbation arrives that stresses the system past its breaking point and triggers collapse. During the subsequent (and brief) release phase, resources that were tightly bound are now released and capital leaks out of the system. In ecosystems, for example, fires can trigger the release of accumulated biomass and nutrients.

The reorganization phase begins to sort out the players and to constrain the system's dynamics. In an economic system, entrepreneurs released during the upheaval may coalesce around new efforts. New ideas, policies, or species can arise and the system can develop a new identity. Early

[11] The allusion to a sand-pile comes from Per Bak in *How Nature Work, 1996, Copernicus Press, NY*.

in the reorganization phase, the future is uncertain: the system could repeat the previous cycle, it could enter an entirely new state of accumulation and growth, or it could collapse into a degraded state.

Because the release and reorganization phases are times of uncertainty and lack of control, great efforts are generally focused at maintaining the conservation phase in human-managed systems. A good example is the policy of "maximum sustainable yield" in environmental management. However, no system can be kept in the conservation phase indefinitely. Unless there is a deliberate effort to simplify the complexity, to release some of the constraints and move back toward the rapid growth phase, a significant collapse is inevitable.

Looking at the nonproliferation system through the lens of the adaptive cycle, which phase is it in? An argument could be made that it is in the late conservation phase and therefore particularly vulnerable to major shocks: The cumulative evolution of the nonproliferation system has resulted in an inflexible and heavily bureaucratized system that is not agile enough to respond to the challenges ahead, challenges that certainly will require greater adaptability and innovation. Although methods to limit access to nuclear material, technology and expertise have been perfected, there is little ability to respond when states evade them. The inability of the international system to denuclearize North Korea or to curb Iran's uranium enrichment program are cases in point.

On the other hand, some new ideas are emerging. Although attempts to change the existing system after the shocks of 2001 have had limited success, experimentation with new approaches falling outside the traditional structure of the nonproliferation regime has begun. These include the Proliferation Security Initiative, efforts to include Russia in plans for NATO missile defense, and a renewed emphasis on nuclear arms reductions. However, the impact of many of the newer approaches remains unknown and broad international support is not assured. In addition, the standard approaches and institutions remain and may ultimately stifle innovation. The critical question is how to increase the resilience of the nonproliferation system at this critical time? Will collapse of the existing system be required to free up resources for new approaches? Or can the controls be loosened, providing flexibility for change?

6 New Approaches to Enhance Resilience

In the discussion of the nonproliferation system, I suggested that its vital function is maintaining an international norm against the spread and use of nuclear weapons. If this is the case, the system would be considered resilient as long as this norm is maintained, even if one or two additional states acquire nuclear weapons. Such events would be considered "point failures" within the nonproliferation system, rather than system failures.

Therefore, strategies aimed at enhancing the resilience of the nonproliferation system should focus on sustaining this norm, rather than focusing solely on preventing additional states from acquiring nuclear weapons. In fact, an important first step in enhancing system resilience may be to acknowledge that not all determined states can be prevented from acquiring nuclear weapons. This could free up the intellectual and economic resources to initiate new efforts. In particular, efforts could be initiated in two areas: developing general international response capabilities that increase overall security and that can also respond to point failures; and reducing the motivation to acquire nuclear weapons in the first place. The result will be a greater diversity of strategies and champions that can respond to a broad range of future challenges. Effective international response capabilities might also reduce motivation of countries to develop or threaten to use nuclear weapons, since it would limit their military (or destructive) potential.[12]

6.1 General International Response Capabilities

The Proliferation Security Initiative offers features that would be valuable in a general response capability. The mission of the PSI is to stop shipments of nuclear, biological or chemical weapons and associated delivery and production capabilities to terrorists and potential state proliferators. Participating countries aim to interdict cargo at sea, in the air and on land. The PSI is designed to make it more costly and risky for proliferators to acquire the weapons or materials they seek, thereby (hopefully) dissuading them from pursuing weapons in the first place or significantly delaying in their acquisition efforts. Only 11 countries signed up to the PSI in 2003, and many others expressed concerns about its legality. Since then, however, an additional 73 countries, including Russia, have committed to it. PSI participants have conducted nearly 30 interdiction exercises, which include mock ship boardings. The exercises are intended to increase the participants' capabilities to cooperate with one another. They are also intended to put a public face on the initiative and act as a deterrent to potential proliferators.

A new type of international response capability would be nuclear incident response teams. International capabilities could be based on domestic programs, such as the U.S. Department of Energy's Nuclear Emergency Support Team (NEST), which provides technical assistance to coordinate search and recovery operations for nuclear materials, weapons, or devices; and assistance in identifying and deactivating radiological devices.[13] An international nuclear incident response capability, that included regular exercises to test procedures and technologies, could be valuable not only for proliferation or terrorism incidents, but could also provide a framework for responding to civilian nuclear disasters. The recent experience with the Fukushima nuclear reactor in Japan demonstrates the need for more effective international coordination and response in the civilian sector. Although the IAEA provides training in emergency response, it does not include international exercises that allow full-scale simulation of response operations.[14]

Multilateral missile defense would be another example. However, to contribute to the resilience of the international nonproliferation system, it would need to contribute to the security of more than a small subset of countries. Understanding potential unintended consequences of missile defense and taking steps to reduce them would be essential to its making a positive contribution to the international nonproliferation system. Recent discussions between NATO and Russia on cooperative missile defense are a positive development.[15] In addition to nuclear threats, missile defense could be used against conventional threats.

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[12] This argument mirrors that of Stephen Flynn in *The Edge of Disaster* (Random House, NY, 2007), where he argues that rather than invest the majority of counter-terrorism resources in preventing terrorism, the United States would be better off, for example, by investing more resources to strengthen aging infrastructure. Not only would this enhance the foundations of economic security and improving resilience to natural disasters, it would also make it a less attractive target for terrorists and reduce their motivation to attack.

[13] See www.nv.doe.gov/library/FactSheets/NEST.pdf.

[14] www-ns.iaea.org/training/rw/e-training.asp?s=9&l=74.

[15] Anischuk, Alexei and David Brunnstrom, "NATO, Russia to Cooperate on Missile Defense," *Reuters,* November 20, 2010, www.reuters.com/article/idUSTRE6AJ1EA20101120 , Saradzhyan, Simon, "Missile Defense: Game-

6.2 Reduce Motivation to Acquire Nuclear Weapons

Motivation to pursue a nuclear weapons program is generally thought to stem from a combination of several causes: national security concerns, domestic politics, and prestige derived from the symbolic value of nuclear weapons.[16] However, few nonproliferation strategies are intended to impact these factors. In fact, Table 1 shows that many nonproliferation strategies may inadvertently contribute to the sense that nuclear weapons convey both security and status.

To the extent that security concerns are the primary motivators behind a nuclear weapons program, reducing regional tensions and increasing the number of states that are covered by security assurances could be considered.[17] Positive security assurances, a feature of many security alliances, are widely believed to have been instrumental in preventing proliferation in Europe and Asia. However, if positive security assurances are understood to carry the promise of a nuclear response, they might inadvertently increase the perceived value of nuclear weapons as the ultimate security guarantor. In addition, unless countries such as Russia and China were included in development of new security arrangements, it could exacerbate their own security concerns.

The use of high-volume public pressure to convince countries to give up nuclear weapons programs should be reconsidered, given that it likely increases domestic support for nuclear weapons programs in the face of threatening international rhetoric. Better results might be obtained by taking this debate out of the public eye and pressuring countries in private forums. Similarly, rather than publicly seeking commitments by others not to pursue enrichment and reprocessing capabilities, states with the greatest stake in nonproliferation could lead by example and establish multinational enrichment and spent fuel reprocessing facilities. Commitments with individual states to not develop sensitive nuclear technologies could still be pursued privately as part of establishing nuclear cooperation agreements, although it may be unwise to force states to choose irrevocably.

Reducing the salience of nuclear weapons in national security strategies could reduce both their perceived security value as well as their symbolic importance. In the final analysis, however, as long as the most powerful states in the world (including all permanent members of the U.N. Security Council) continue to view nuclear weapons as indispensible to their security, it will be hard to convince all others that such weapons are not worth pursuing. This is why many argue that the two-tiered approach that is inherent in the existing nonproliferation system must end. As a first step, some argue for a ban on nuclear weapons use analogous to the Geneva Protocol that banned the use of chemical and biological weapons in 1925.[18] Even though it took almost seventy

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Changer in NATO- Russia Relations," *ISN Insights*, January 25, 2011, www.isn.ethz.ch/isn/Current-Affairs/ISN-Insights/Detail?lng=en&id=126409&contextid734=126409&contextid735=126408&tabid=126408 .

[16] Sagan, Scott D., "Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb," *International Security* 21 (3) Winter 1996/1997), pp. 54 – 86.

[17] See, for example, Robinson, C. Paul, "Developing a Realistic Strategy to Control the Spread of Nuclear Weapons." *Nature* 432(November 25, 2004), pp. 441-442.

[18] For two discussions of this idea see Johnson, Rebecca, "Nuclear Weapons: Beyond Nonproliferation," Open Democracy, April 29, 2010, www.opendemocracy.net/5050/rebecca-johnson/nuclear-weapons-beyond-non-proliferation; Perkovich, George and James M. Acton, "Outlaw Use of Nuclear Weapons?" The Carnegie Endowment for International Peace, Abolition Debate Series, Part 5 or 8, April, 21, 2010, www.carnegieendowment.org/publications/index.cfm?fa=view&id=40645.

years to achieve the Chemical Weapons Convention that banned their production and use, the Geneva Protocol was an important first step in their de-legitimization.

7 Discussion and Next Steps

The analytical framework of systems resilience offers a new way of thinking about the evolution and future of the nonproliferation system. Reframing the nonproliferation challenge from "preventing of acquisition of nuclear weapons" to "strengthening international norms against the spread and use of nuclear weapons" may stimulate the development of new approaches. To fully explore the implications of this new approach, much work remains. In addition to conceptual analysis, tools, and methodologies that have been developed to understand the behavior of complex adaptive systems in other disciplines could be applied to nonproliferation.[19]

Achieving a better understanding of the unintended consequences and feedbacks among nonproliferation strategies would be an important topic for future research. New methodologies to solicit expert opinion and to analyze historical data would be required to assess the relative strengths of nonproliferation strategies and their potential unintended consequences. Techniques using systems dynamic modeling could then be used to explore new combinations of strategies.[20]

Developing methods to measure the resilience of the nonproliferation system would be another priority for future research.[21] Are there ways to assess general levels of motivation to acquire nuclear weapons? What are the most important measures of system diversity? How tightly coupled are the elements of the nonproliferation system, and where might controls be loosened?

Strengthening international capabilities to respond to security challenges, including proliferation or the use of nuclear weapons, will be critical to achieving resilience. To stimulate discussion, I suggested international nuclear incident response teams and international missile defense as two options, but much more thought is required. Analyzing interactions of the nonproliferation system with systems on larger and smaller scales would be an important consideration. Indeed, security and status, thought to be important motivators for seeking nuclear weapons, are ultimately indicators of standing in a much broader global system. It would therefore be important to explore

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[19] As examples, see work done on large value payment systems which model global financial flows, www.sandia.gov/CasosEngineering/payment_systems.html) and Strategies for Mitigating Pandemic Influenza (http://www.sandia.gov/CasosEngineering/pandemic_influenza.html).

[20] For an initial effort to use systems dynamics to model nonproliferation strategies, see Pregenzer, Arian, Adam Williams, Robert U. Glass, Arlo Ames, Walter E. Beyeler, and Sharon M. DeLand, "A Systems Approach to Assessing Nonproliferation Strategies," Proceedings of the 52nd Annual Meeting of the Institute of Nuclear Materials Management, July 17 – 21, 2011, Palm Desert, California, www.inmm.org//AM/Template.cfm?Section=Meeting_Home.

[21] Although still in the early stages, methodologies for assessing system resilience are being developed in many other disciplines. As examples, see: Vugrin, Eric D., Drake E. Warren, Mark A. Ehlen, and R. Chris Camphouse, "A Framework for Assessing the Resilience of Infrastructure and Economic Systems," in *Sustainable and Resilient Critical Infrastructure Systems*, (Springer Berlin Heidelberg, 2010), pp. 77 – 116, www.springerlink.com/content/n2m74m83184079w4/; Tierney, Kathleen and Joseph Trainor, "Networks and Resilience in the World Trade Center Disaster," which focuses on measures of resilience in communities and individuals: www.mceer.buffalo.edu/publications/resaccom/04-sp01/11_tierney.pdf; and "Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners," Version 2.0, downloadable from the Resilience Alliance Website, www.resalliance.org/index.php/resilience_assessment.

how measures outside of the nonproliferation system, such as new cooperative security structures or economic cooperation could enhance the regime.

Finally, although many worry about the repercussions of a nuclear capable Iran or developments in the North Korean nuclear program, it is impossible to predict the nature or timing of the next major challenge to the nonproliferation system. In fact, events emerging from the larger external environment, e.g., the dissolution of the Soviet Union and the September 11 terrorist attacks, have produced the most significant changes in the approach to nonproliferation. Acknowledging both the inevitability and unpredictability of future shocks, and relaxing the urge for control may be the most important way to foster a climate for continued innovation that will underpin any ultimately resilient system.

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