Resilience in Infrastructure Systems

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DARPA Workshop

COMPASS: Critical Orientation of Mathematics to Produce Advancements in Science and Security

05 March 2025

Today's Agenda

Act I: Societal Need for Infrastructure Resilience

Act II: (Getting Stuck in) Modeling + Simulation of Lifeline Infrastructure Interactions as a Path to Resilience

Act III: A Need for Different Mathematics (enabled by new science based on patterns)

Acknowledgments: Daniel Eisenberg (NPS) and David Woods (Ohio State)

This work was supported by the Office of Naval Research, the Air Force Office of Scientific Research, the Defense Threat Reduction Agency, and the DOD Strategic Environmental Research and Development Program.

Nouns vs Verbs

Resilience is not about what you have,
it's about what you do!

Question: Are our mathematics too focused on nouns?

Resilience as a verb in the future tense?

See also: Woods, D. D. (2018). "Resilience is a verb." In Trump, B. D., Florin, M.-V., & Linkov, I. (Eds.). *IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems.* Lausanne, CH: EPFL International Risk Governance Center. Available on irgc.epfl.ch and irgc.org.

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Economics in nouns and verbs

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Computational economics

ABSTRACT

Standard economic theory uses mathematics as its main means of understanding, and this brings clarity of reasoning and logical power. But there is a drawback: algebraic mathematics restricts economic modeling to what can be expressed only in quantitative nouns, and this forces theory to leave out matters to do with process, formation, adjustment, and creation—matters to do with nonequilibrium. For these we need a different means of understanding, one that allows verbs as well as nouns. Algorithmic expression is such a means. It allows verbs—processes—as well as nouns—objects and quantities. It allows fuller description in economics, and can include heterogeneity of agents, actions as well as objects, and realistic models of behavior in ill-defined situations. The world that algorithms reveal is action-based as well as object-based, organic, possibly ever-changing, and not fully knowable. But it is strangely and wonderfully alive.

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The study of critical infrastructure systems is not new…

- ***Critical Infrastructure (CI)***: "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" ***-- Section 1016(e) of the USA PATRIOT Act of 2001***

Image Source: European Commission Newsletter, "Critical Infrastructure Resilience: News, Updates and Events," https://publications.jrc.ec.europa.eu/repository/handle/JRC135769

The study of critical infrastructure systems is not new…

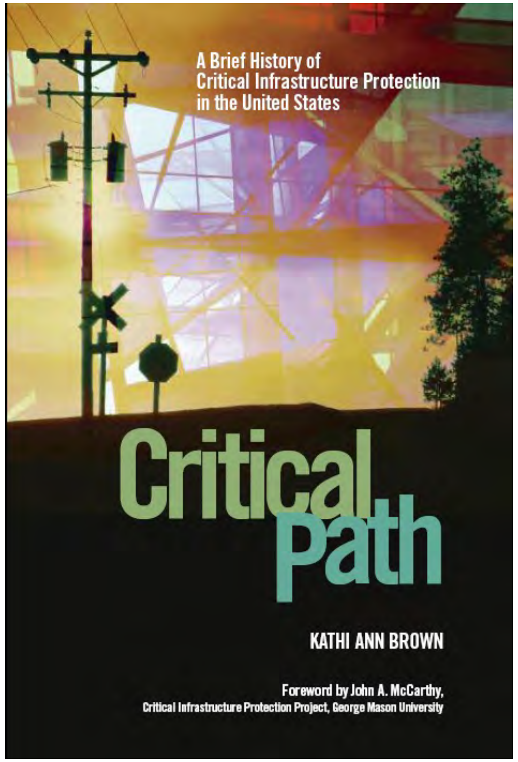
Within the U.S., the development and understanding of critical infrastructure systems was closely tied to war mobilization

- World Wars I & II

1950s-1970s:

- Identification of key assets and facilities (organized as lists)
- Connections to civil defense

Brown, K.A. (2006), Critical Path: A Brief History of Critical Infrastructure Protection in the United States, Fairfax, VA: Spectrum.



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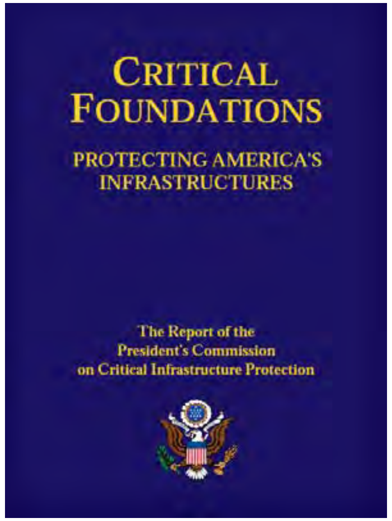
The study of critical infrastructure systems is not new…

1997

Drivers



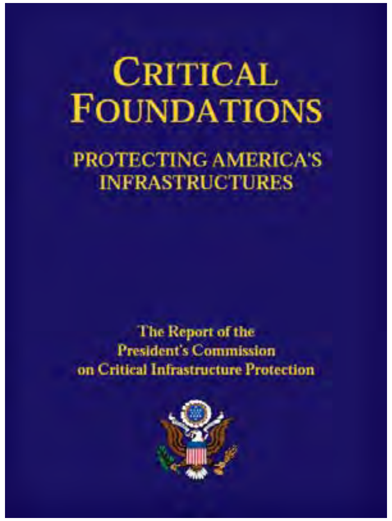
President's Commission on Critical Infrastructure Protection

The study of critical infrastructure systems is not new…

Act I: The US Infrastructure Resilience Renaissance

1997 → **2001 – 2005** → **2009 – 2010** → **2012 – 2013**

Drivers | **Theories** | **Frameworks** | **Policies**



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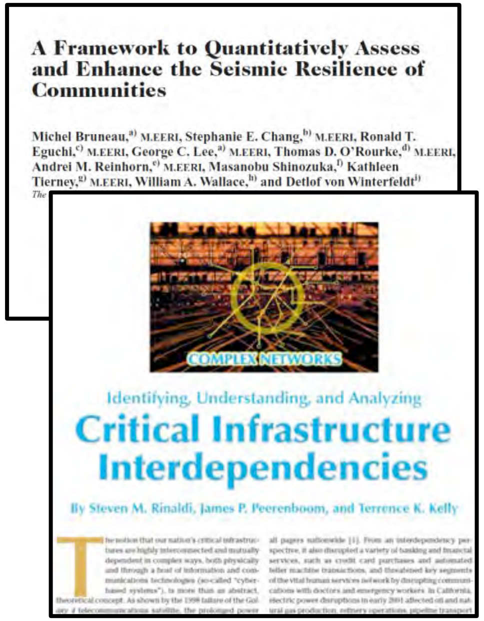
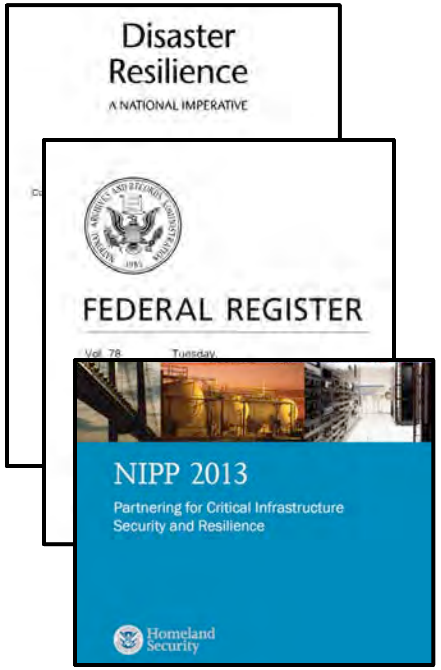




Operations Research has enabled the development of an “optimized world”

Image Source: European Commission Newsletter, “Critical Infrastructure Resilience: News, Updates and Events,” https://publications.jrc.ec.europa.eu/repository/handle/JRC135769

Operations Research has enabled the development of an “optimized world”

“Optimized” == “Efficient”

Faster, Better, Cheaper

no waste, no slack ⟷ brittle, fragile

increasing complexity

nonlinear behavior

large scale

hidden dependencies

changing tempos of activity

new goals

re-prioritization

accidents

extreme weather

surprise events

failures

attacks

unintended consequences

cascading failures

system collapse

mission failure

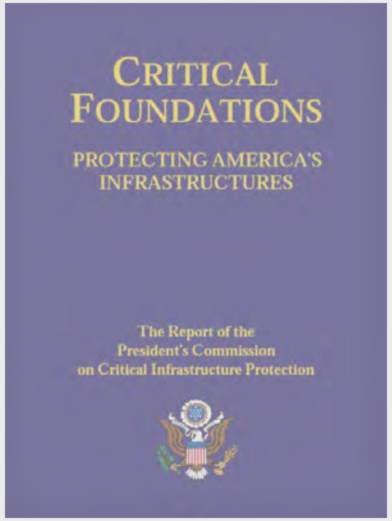
Image Source: European Commission Newsletter, “Critical Infrastructure Resilience: News, Updates and Events,” https://publications.jrc.ec.europa.eu/repository/handle/JRC135769

The study of critical infrastructure systems is not new…

Act I: The US Infrastructure Resilience Renaissance

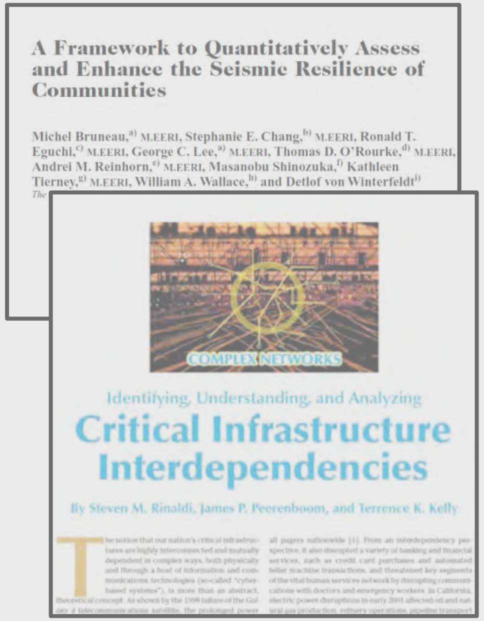
1997 → **2001 – 2005** → **2009 – 2010** → **2012 – 2013** → **Act II: 2013 – now**

Drivers



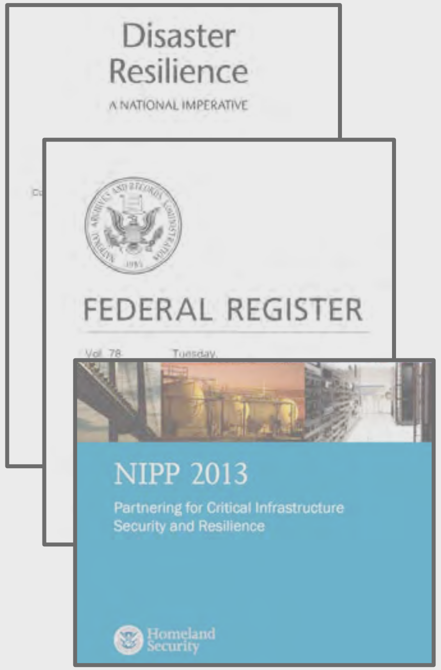
President's Commission on Critical Infrastructure Protection

Theories



Frameworks

Policies



Modeling
+
Simulation

Conferences
Journals
National Funding
Centers of Excellence

Universities
National Laboratories
FFRDCs
Defense Contractors

The Premise

- We can map out our infrastructure systems
- And their dependencies
- And ***model*** their operation
- To identify vulnerabilities
- Then fill holes and/or block cascading consequences
- And doing all this will allow us to build resilience…
- …and assure the mission!

Act II:

2013 – now

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+
Simulation

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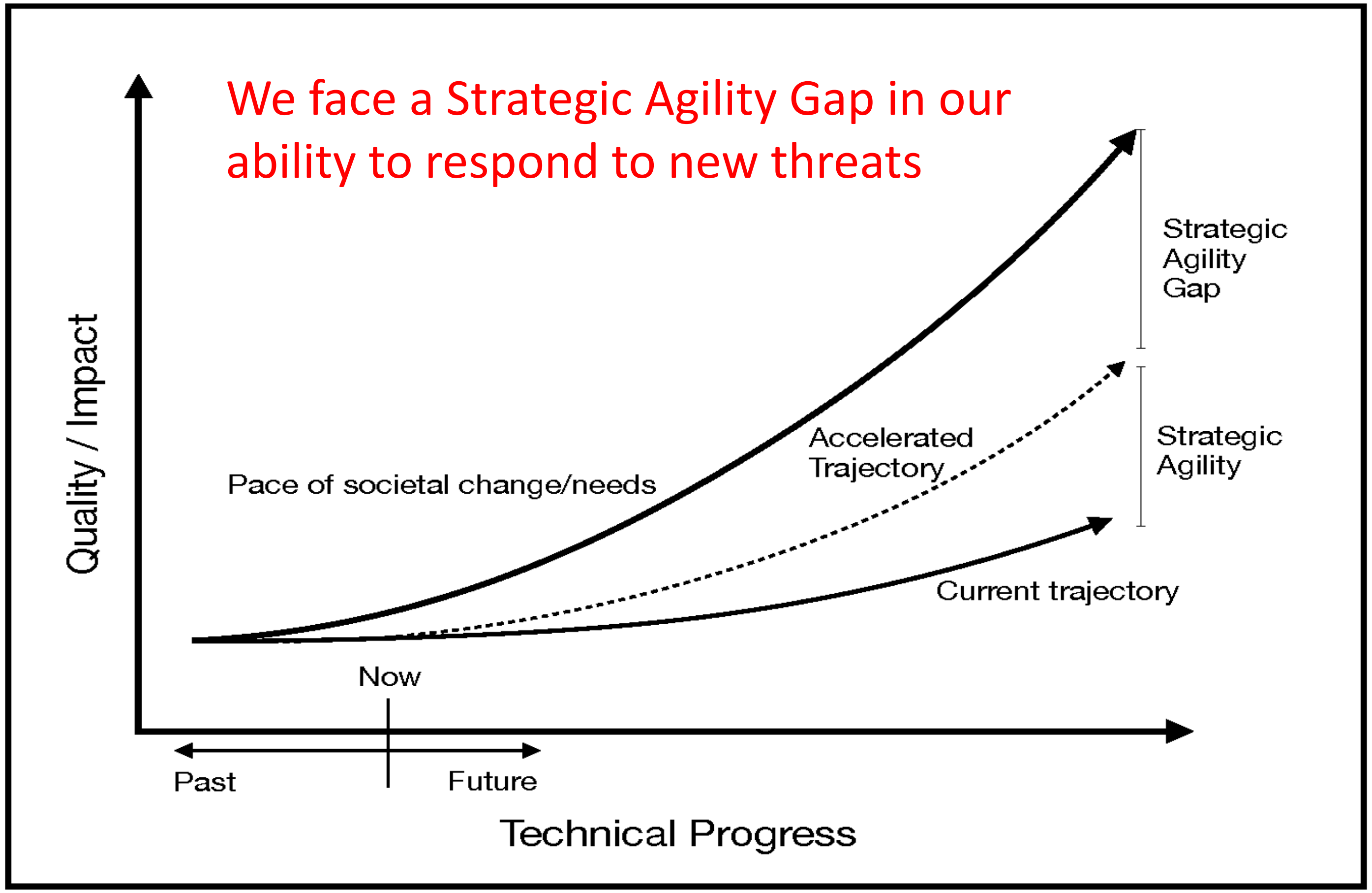
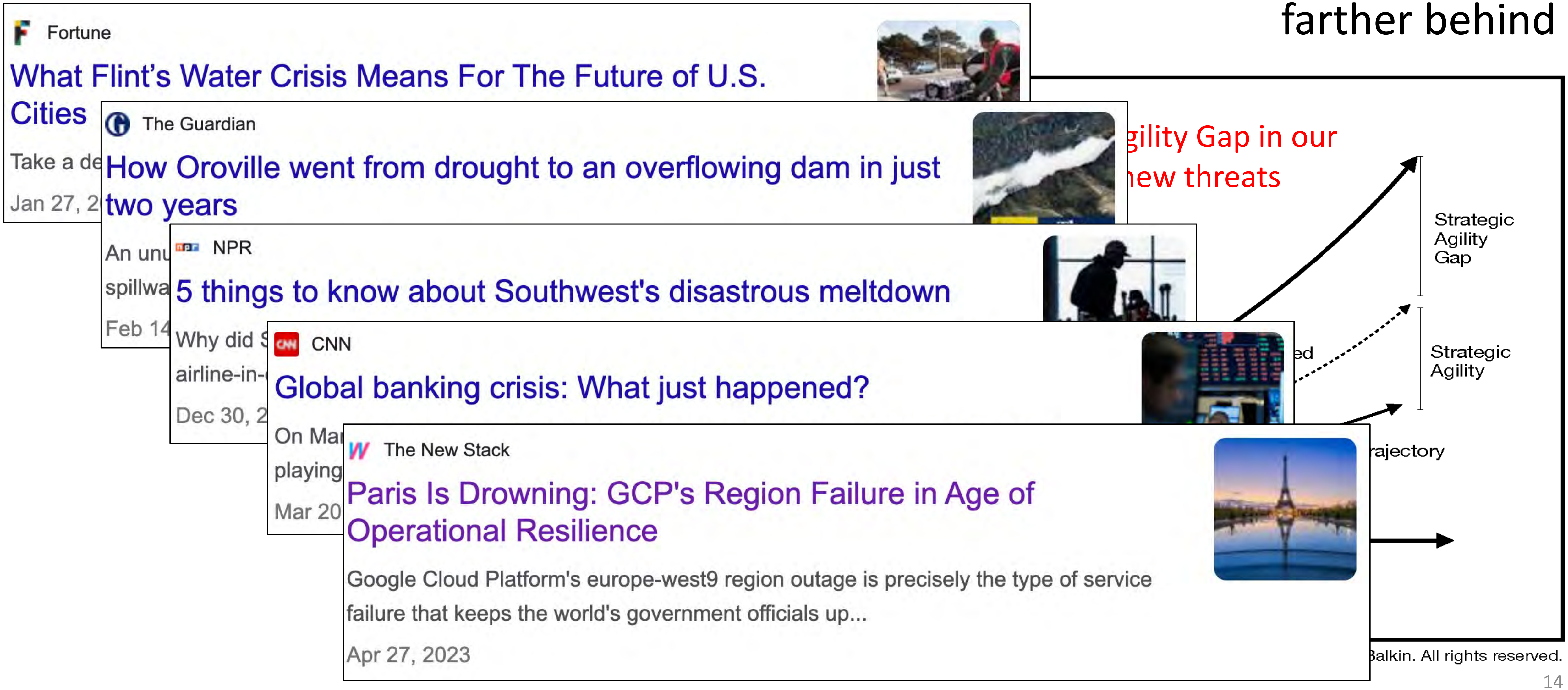
But it hasn't worked out this way. If anything, we seem to be falling farther behind



Evidence that we are stuck in the Gap:

- *According to Plan*, things appear to be going great.
- Getting better and better, or so it seems! Until it isn't.
- And then it's *bad*... And unclear how to respond.

But it hasn't worked out this way. If anything, we seem to be falling farther behind



Journal of Critical Infrastructure Policy • Volume 2, Number 2 • Fall / Winter 2021

Strategic Perspectives

Progress toward Resilient Infrastructures: Are we falling behind the pace of events and changing threats?

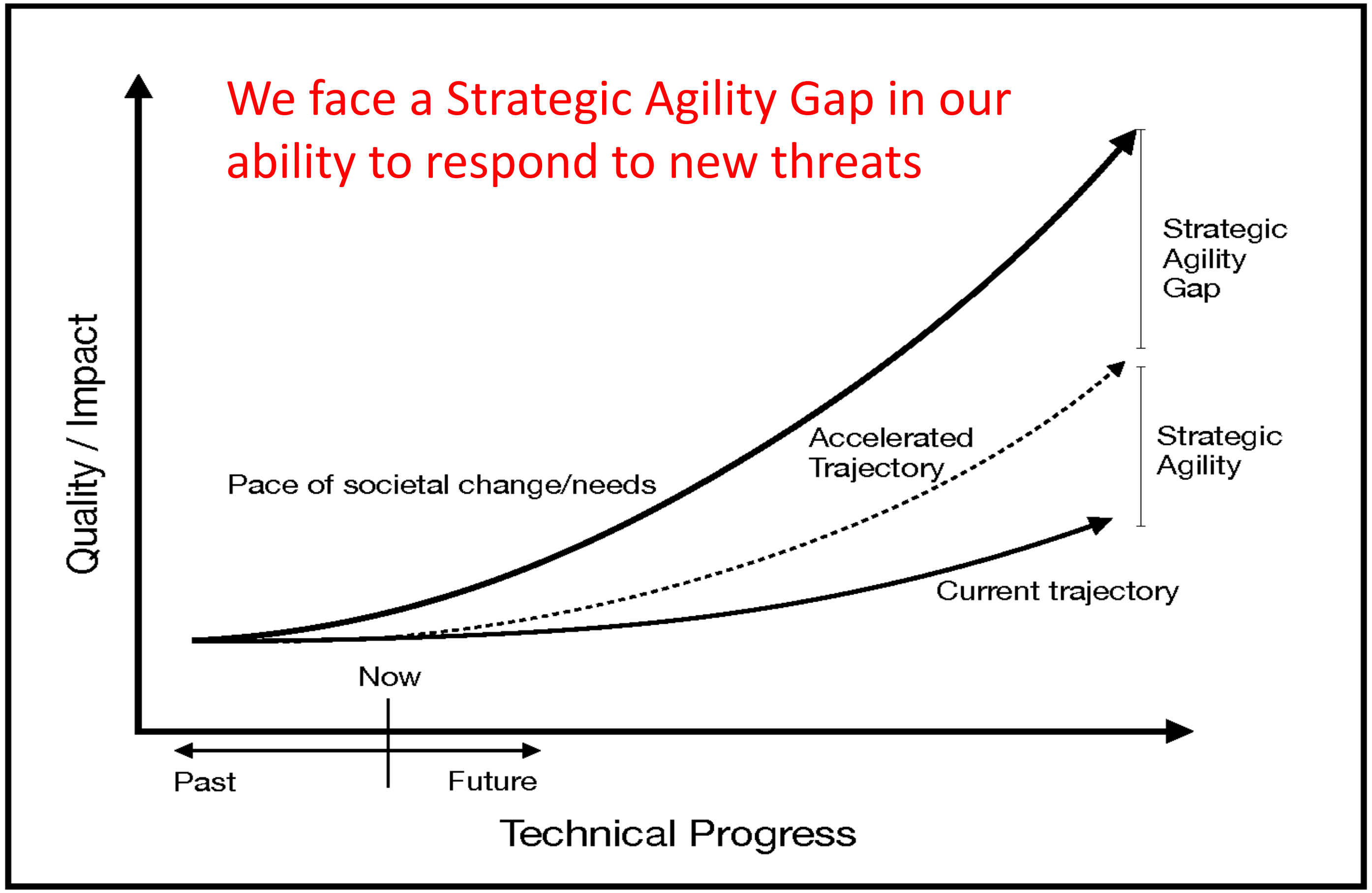
David D. Woods[1] and David L. Alderson[2]

[1] Professor Emeritus, Dept of Integrated Systems Engineering, Ohio

[2] Professor, Operations Research Dept, Naval Postgraduate School, d

But it hasn't worked out this way. If anything, we seem to be falling farther behind

- Growing system complexity
- New conflicts & threats
- Changing environment
- Changing tempos of activity



The Premise

- We can map out our infrastructure systems
- And their dependencies
- And ***model*** their operation
- To identify vulnerabilities
- Then fill holes and/or block cascading consequences
- And doing all this will allow us to build resilience…
- …and assure the mission!

…This Is Not Working!!

- We don't know our systems in their absolute entirety, and we never will!
- There is no single vantage point from where we can "see" everything
- And things are always changing
- There will always be hidden dependencies
- There will always be surprises!

The Premise

- We can map out our infrastructure systems
- And their dependencies
- And ***model*** their operation
- To identify vulnerabilities
- Then fill holes and/or block cascading consequences
- And doing all this will allow us to build resilience…
- …and assure the mission!

…This Is Not Working!!

Resilience is not about what you have,
it's about what you do!

- We are focused on the wrong things
- Nouns = the stuff we have
- Verbs = the processes for adaptation
- Need to focus: time, tempo, process.
- Our math is stuck on nouns
- We need (better) math for verbs

Critical Digital Services & Internet "Survivability"

Internet function is more than routing!

- all the value-added layers above routing
- an ecosystem of ***critical digital services***

"cyber" is noun-centric

Both transactions + controls!

All the software that enables critical digital services!

- ***You will never have complete knowledge of the system*** (components, software, users)
- The ***tangle of dependencies*** does not conform to traditional network layering (OSI 7-layers)
- You can ***learn only by operating*** it.
- The system is always adapting. Can we learn fast enough?

ACT II: Modeling + Simulation
Making sense of "Resilience"

- The concept of resilience is important and popular
  - Represents a new societal need, particularly given frequent surprise

- Over the last 10+ years, it has been overused to mean many different things
  - It has bureaucratic definitions that are not helpful for assessing systems
  - The use of resilience as a term is noisy and confusing

Notions of resilience have become noisy

Four ways that *resilience* is used.

easier to understand ↓	$\mathbb{R}_1$	***rebound***	return to previous levels of performance
	$\mathbb{R}_2$	***robustness***	copes successfully from well-modeled challenges
	$\mathbb{R}_3$	***graceful extensibility***	stretches to meet challenges at the boundaries
more generality	$\mathbb{R}_4$	***sustained adaptability***	sustains the ability to adapt over cycles of change

modified from Woods DD. Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety* 141 (2015) 5-9.

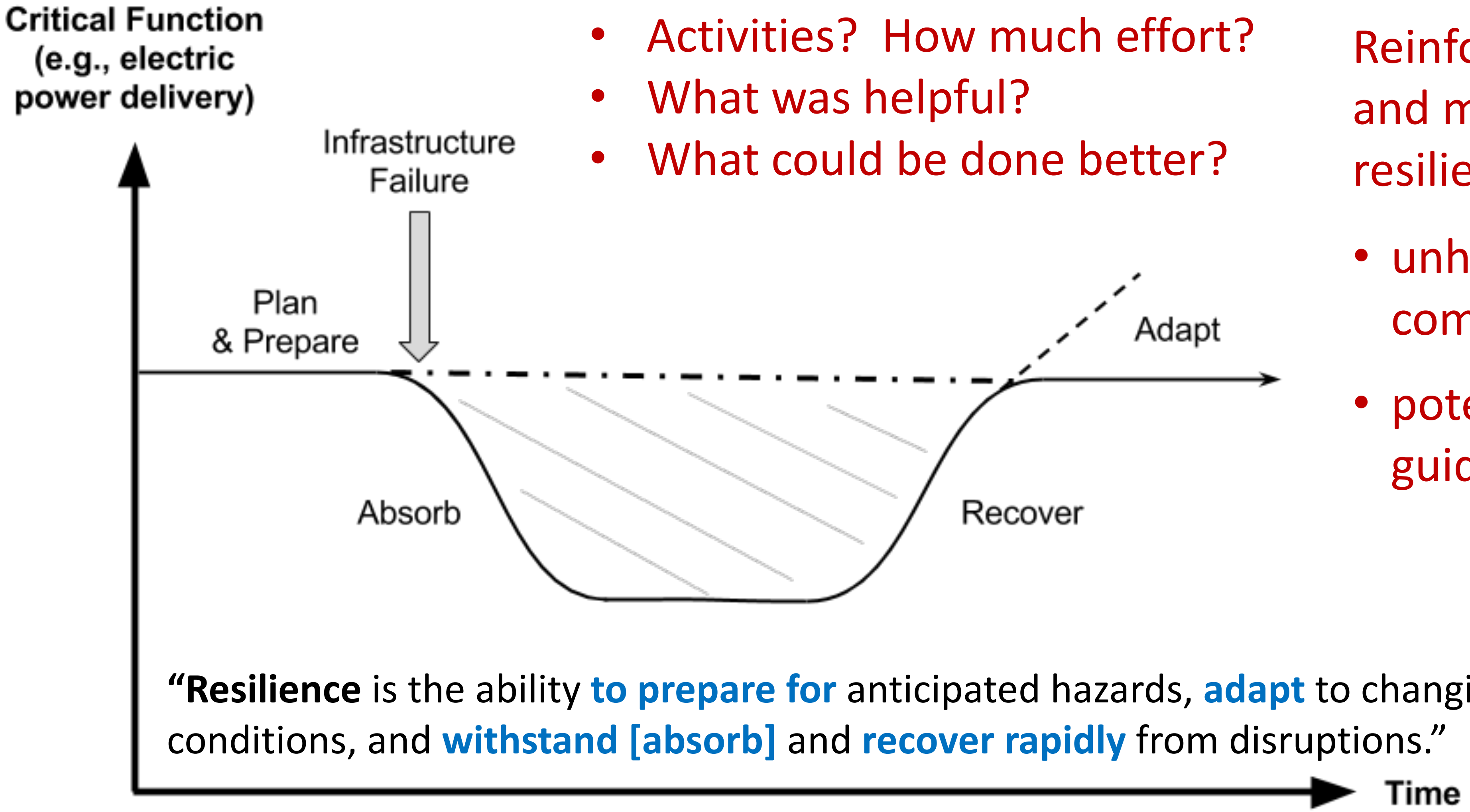
The “Rebound Curve” is a Poor Model of Resilience

Process-Outcome Confusion

- Activities? How much effort?
- What was helpful?
- What could be done better?

Reinforces oversimplifications and misconceptions about resilience

- unhelpful for understanding complex systems
- potentially dangerous for guiding decisions



“**Resilience** is the ability **to prepare for** anticipated hazards, **adapt** to changing conditions, and **withstand [absorb]** and **recover rapidly** from disruptions.”

Official Definition for Resilience from NIST, DHS, FEMA, etc.

The "Rebound Curve" is a Po

Process-Outcome Confusi

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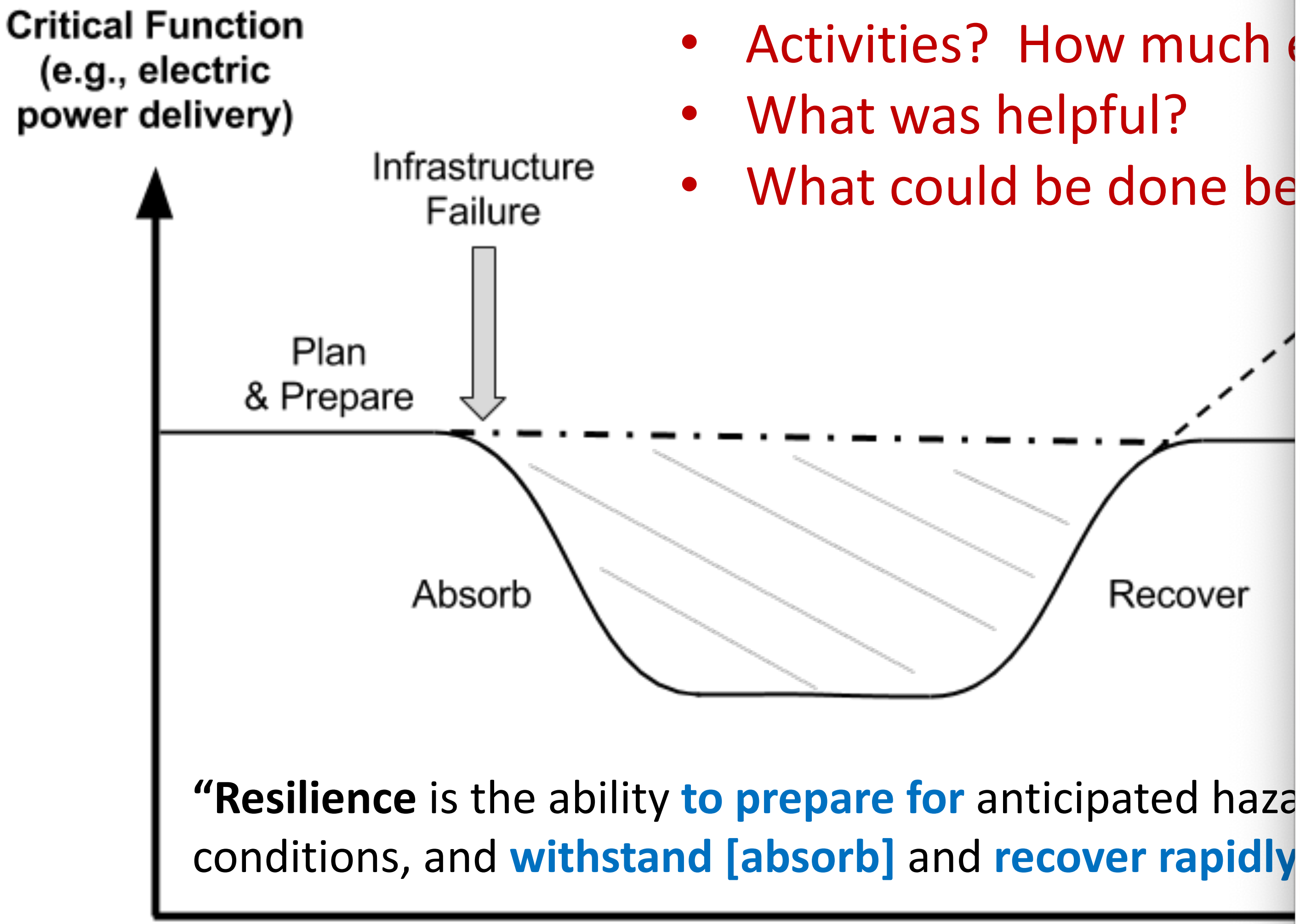

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JOURNAL ARTICLE ACCEPTED MANUSCRIPT

The rebound curve is a poor model of resilience

Daniel A Eisenberg, Thomas P Seager, David L Alderson

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Abstract

The *rebound curve* remains the most prevalent model for conceptualizing, measuring, and explaining resilience for engineering and community systems by tracking the functional robustness and recovery of systems over time. (It also goes by many names, including the resilience curve, the resilience triangle, and the system functionality curve, among others.) Despite longstanding recognition that resilience is more than rebound, the curve remains highly used, cited, and taught. In this article, we challenge the efficacy of this model for resilience and identify fundamental shortcomings in how it handles system function, time, dynamics, and decisions — the key elements that make up the curve. These oversimplifications reinforce misconceptions about resilience that are unhelpful for understanding complex systems and are potentially dangerous for guiding decisions. We argue that models of resilience should abandon the use of this curve and instead be reframed to open new lines of inquiry that center on improving adaptive capacity in complex systems rather than functional rebound. We provide a list of questions to help future researchers communicate these limitations and address any implications on recommendations derived from its use.

PDF
Help

Keywords: Resilience, Critical Infrastructure, Engineering, Emergency Management

Subject: Civil and Environmental Engineering, Sustainability Science (Physical Sciences and Engineering)

Issue Section: Perspective

ns

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Notions of resilience have become noisy

Four ways that *resilience* is used.

easier to understand → more generality

$\mathbb{R}_1$	***rebound***	return to previous levels of performance
$\mathbb{R}_2$	***robustness***	copes successfully from well-modeled challenges
$\mathbb{R}_3$	***graceful extensibility***	stretches to meet challenges at the boundaries
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- Woods DD, 2015, "Four concepts for resilience and the implications for the future of resilience engineering," *Reliability Engineering and System Safety* 141: 5-9.
- Woods DD, 2018, "The theory of graceful extensibility: basic rules that govern adaptive systems," *Environment Systems and Decisions*, 38(4):433–457.
- Sharkey TC, Nurre Pinkley SG, Eisenberg DA, Alderson DL, 2020. "In search of network resilience: An optimization-based view," *Networks* 77(2): 225-254. https://doi.org/10.1002/net.21996

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Another Way Forward

We need to study these ***patterns of complexity*** as empirical phenomena

- Patterns of **behavior in time**, not just structure
- Patterns in how systems fail
- Patterns in how systems adjust, adapt, and survive

Where we agree…

Oversimple abstractions don't work
(at least, not for long)

✗ Linear systems with predictable cause-effect

✗ Root-cause analysis (e.g., blame the human!)

✗ Stationarity in time

Where it's noisy…

- What are the patterns?
- What drives them?
- How to represent them?
- What to do about them?

Making infrastructure more operational (My take)

- Infrastructure is not static. Things are moving. In support of a mission.
- Operations will be contested (meaning there are disruptions).
- We want the mission to succeed, even when disrupted.

- ***Viability*** (not readiness) should be the primary system objective
- ***Systems are always adapting***
  - ***pursuing opportunity*** (growth in the face of constraints)
  - ***handling challenge*** (extensibility in the face of brittle collapse)
- They are doing both simultaneously
- The same processes are at work for both
- ***Management of tradeoffs / constraints is fundamental***

What are the patterns that matter? (My take)

- A plan is in progress over an infrastructure network (perhaps logistics)
- ***How do you modify the plan in-progress*** as you discover changes in obstacles, goals, priorities, objectives?
  - (Particularly when you can’t go back and rerun the original planning tools because things are moving and changing)
  - Your plan will become stale. Your model of the world will become stale.
  - Redirecting things on the move imposes ***friction*** and ***lag*** (how to represent this?)

- *What can I adjust midstream?*
- *What do I need to have around to maximize my ability to adjust midstream?*
- *If I can get you another [X], would that make a big difference?*

adaptive capacity

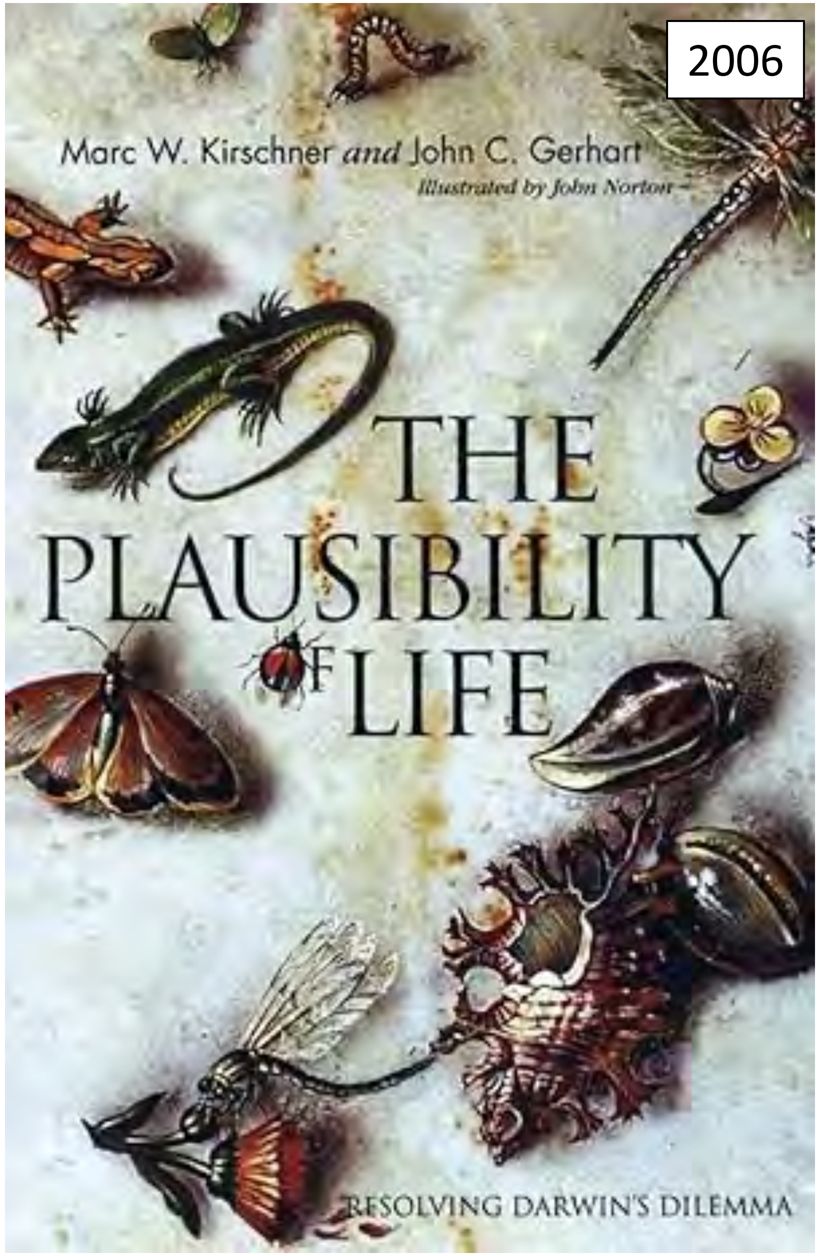
A system's capacity to adapt to challenges ahead,
when the exact challenge to be handled
***cannot* be specified completely in advance.**

We need mathematics to help us understand the complex dynamics of building deployable adaptive capacity.

Biology-inspired mathematics

Question: Is infrastructure viability more like biology than engineering?

2006



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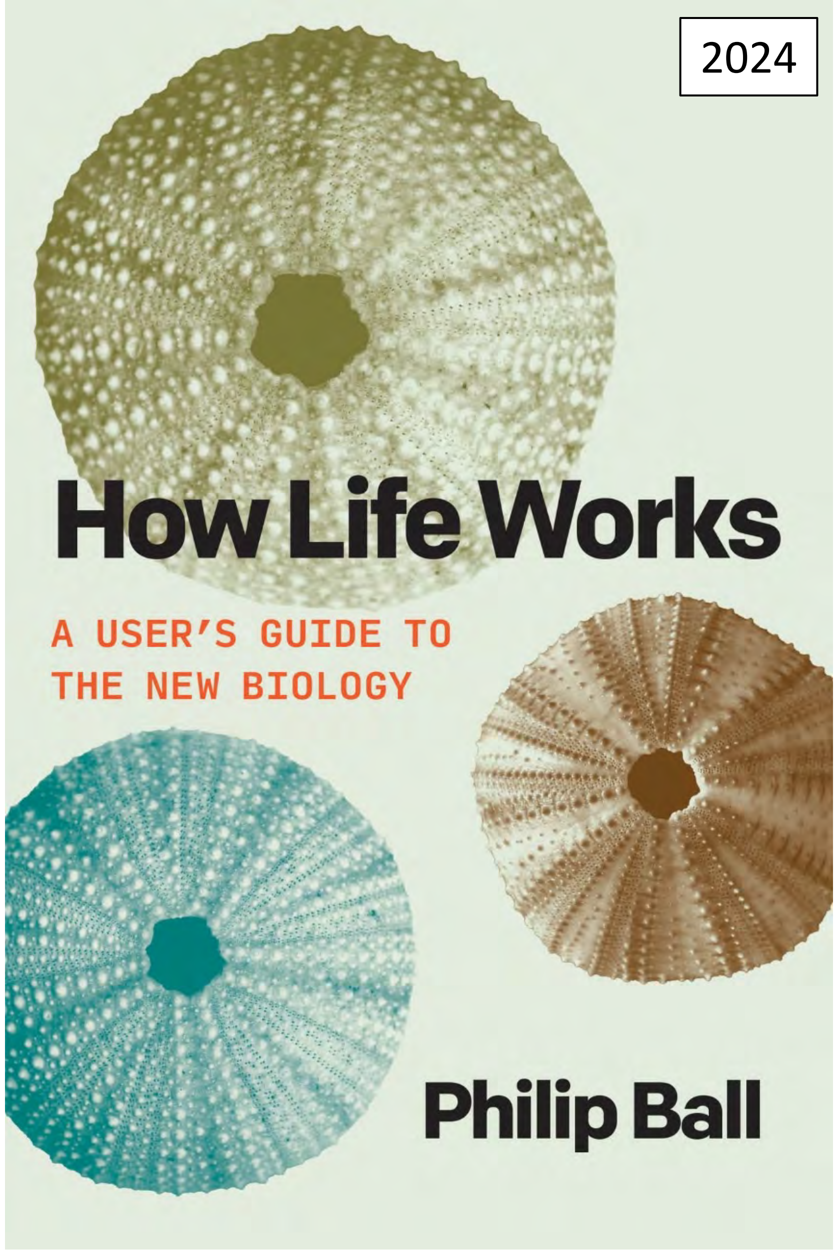
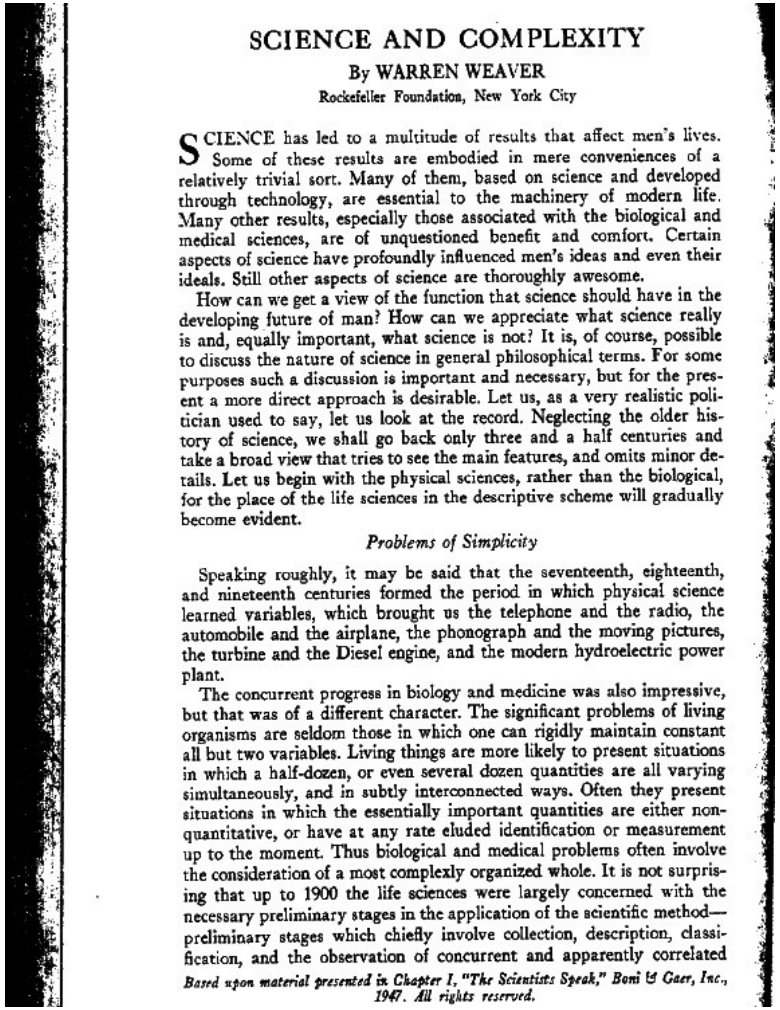


Role of Organization



SCIENCE AND COMPLEXITY

By WARREN WEAVER

Rockefeller Foundation, New York City

SCIENCE has led to a multitude of results that affect men's lives. Some of these results are embodied in mere conveniences of a relatively trivial sort. Many of them, based on science and developed through technology, are essential to the machinery of modern life. Many other results, especially those associated with the biological and medical sciences, are of unquestioned benefit and comfort. Certain aspects of science have profoundly influenced men's ideas and even their ideals. Still other aspects of science are thoroughly awesome.

How can we get a view of the function that science should have in the developing future of man? How can we appreciate what science really is and, equally important, what science is not? It is, of course, possible to discuss the nature of science in general philosophical terms. For some purposes such a discussion is important and necessary, but for the present a more direct approach is desirable. Let us, as a very realistic politician used to say, let us look at the record. Neglecting the older history of science, we shall go back only three and a half centuries and take a broad view that tries to see the main features, and omits minor details. Let us begin with the physical sciences, rather than the biological, for the place of the life sciences in the descriptive scheme will gradually become evident.

Problems of Simplicity

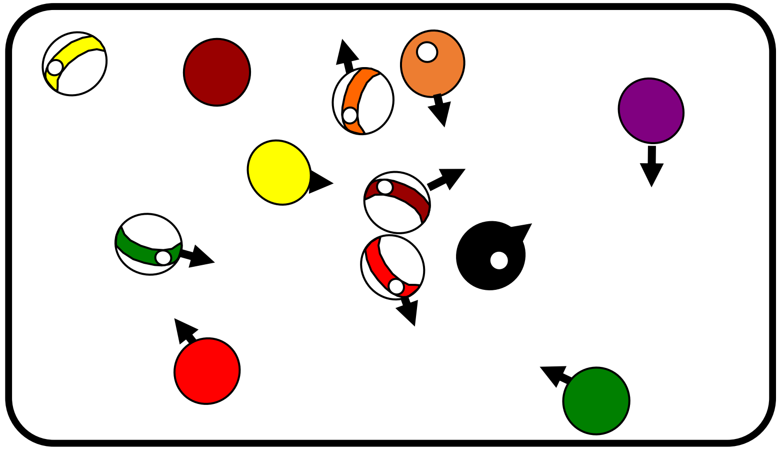
Speaking roughly, it may be said that the seventeenth, eighteenth, and nineteenth centuries formed the period in which physical science learned variables, which brought us the telephone and the radio, the automobile and the airplane, the phonograph and the moving pictures, the turbine and the Diesel engine, and the modern hydroelectric power plant.

The concurrent progress in biology and medicine was also impressive, but that was of a different character. The significant problems of living organisms are seldom those in which one can rigidly maintain constant all but two variables. Living things are more likely to present situations in which a half-dozen, or even several dozen quantities are all varying simultaneously, and in subtly interconnected ways. Often they present situations in which the essentially important quantities are either non-quantitative, or have at any rate eluded identification or measurement up to the moment. Thus biological and medical problems often involve the consideration of a most complexly organized whole. It is not surprising that up to 1900 the life sciences were largely concerned with the necessary preliminary stages in the application of the scientific method—preliminary stages which chiefly involve collection, description, classification, and the observation of concurrent and apparently correlated

Based upon material presented in Chapter I, "The Scientists Speak," Boni & Gaer, Inc., 1947.

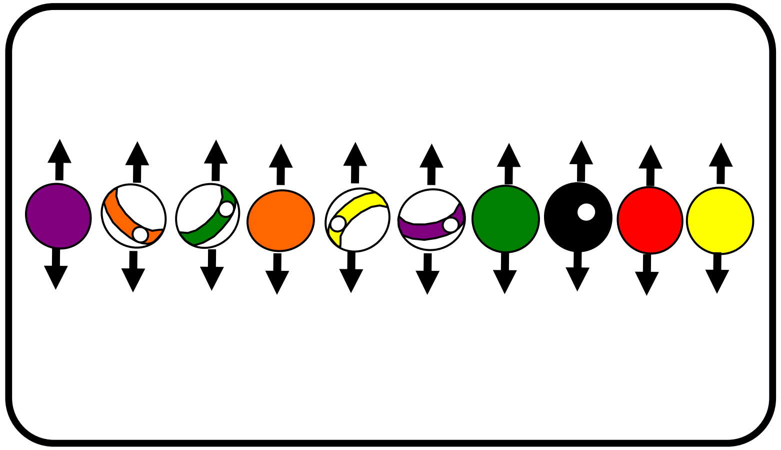
Weaver, W. 1948. Science and complexity. *American Scientist* 36 536-544.

Disorganized



"The methods of statistical mechanics are valid only when the balls are distributed, in their positions and motions, in a helter-skelter, that is to say a disorganized, way."

Organized



"For example, the statistical methods would not apply if someone were to arrange the balls in a row parallel to one side rail of the table, and then start them all moving in precisely parallel paths perpendicular to the row in which they stand. Then the balls would never collide with each other nor with two of the rails, and one would not have a situation of disorganized complexity."

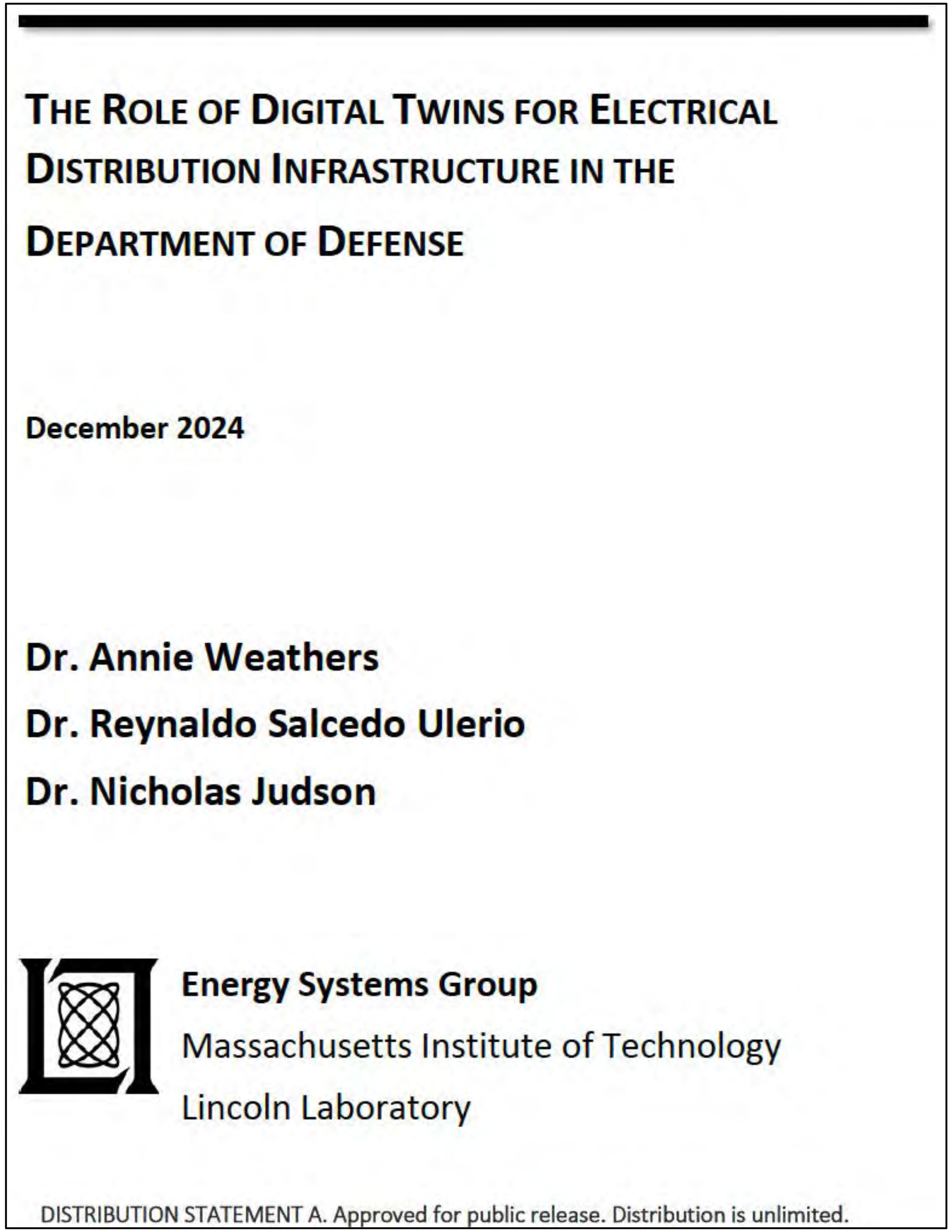
See also:

Alderson, D.L., and Doyle, J.C., 2010, Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructures. IEEE Transactions on Systems, Man, and Cybernetics-Part A, 40(4): 839-852.

Alderson, D.L., 2008, Catching the "Network Science" Bug: Insight and Opportunity for the Operations Researcher. Operations Research 56(5): 1047-1065.

Digital Twins

- A specious approach to infrastructures
- Useful, but only in limited ways
- Models become stale!



THE ROLE OF DIGITAL TWINS FOR ELECTRICAL DISTRIBUTION INFRASTRUCTURE IN THE DEPARTMENT OF DEFENSE

December 2024

Dr. Annie Weathers

Dr. Reynaldo Salcedo Ulerio

Dr. Nicholas Judson

Energy Systems Group

Massachusetts Institute of Technology

Lincoln Laboratory

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Nouns vs Verbs

Resilience is not about what you have,
it's about what you do!

Question: Are our mathematics too focused on nouns?

Resilience as a verb in the future tense?

See also: Woods, D. D. (2018). "Resilience is a verb." In Trump, B. D., Florin, M.-V., & Linkov, I. (Eds.). *IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems.* Lausanne, CH: EPFL International Risk Governance Center. Available on irgc.epfl.ch and irgc.org.

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Economics in nouns and verbs

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A R T I C L E I N F O

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Mathematics in economics
Algorithms
Complexity economics
Computational economics

A B S T R A C T

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If we all agree on [resilience], why don't we have it already?

Four barriers to resilience

1. AWARENESS: We don't know we need it
2. KNOWLEDGE: We don't know how to create it
3. INCENTIVES: We can't justify the investment in it
4. GOVERNANCE: Incompatibilities across organizational boundaries that lead to working at cross purposes

REFS:
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Looking Forward

We need a different type of **architecture** for our mission critical systems.

One that goes beyond traditional optimization and design.

The principles are different, but ubiquitous in the real world.

We cannot escape the complexity traps if we don't build **adaptive capacity**.

How can mathematics help us achieve these outcomes?

We need to reframe how we think about resilience.

Adaptive capacity is about **more than handling challenge**.

It is about **seizing opportunity**.

The same processes are at work. We should stop using an emergency management / risk mindset.

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