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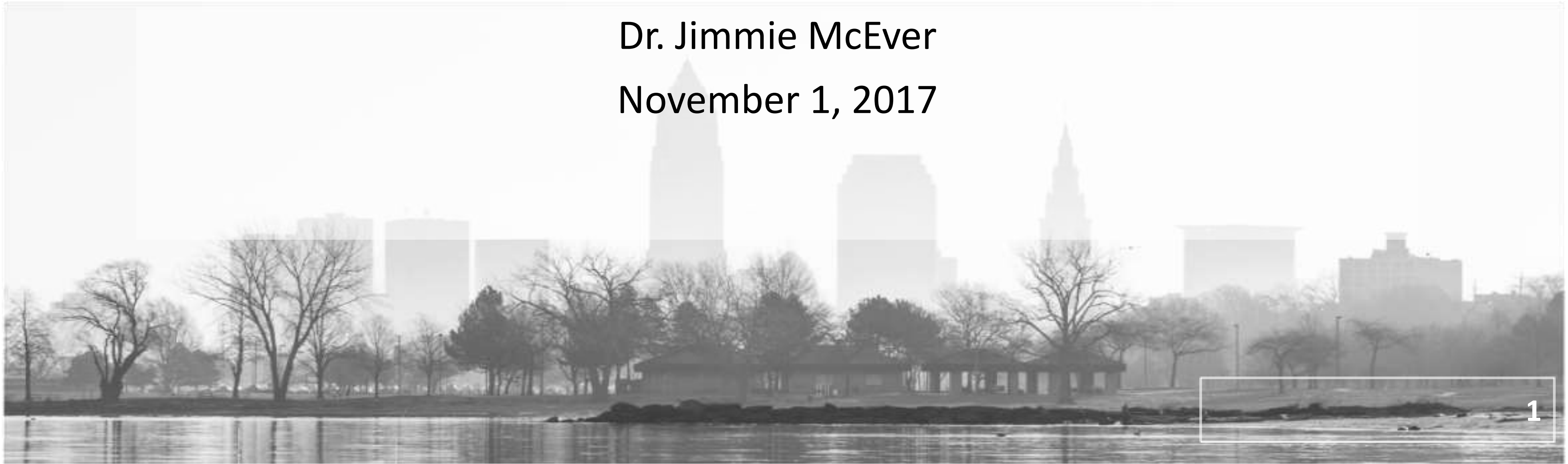
Dealing with Complexity in Engineered Systems

Dr. Jimmie McEver

November 1, 2017

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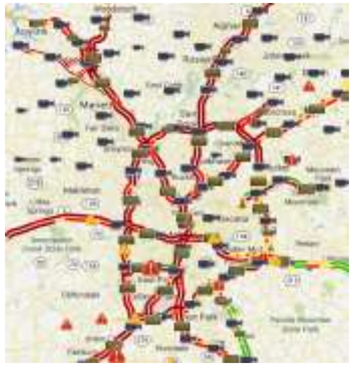
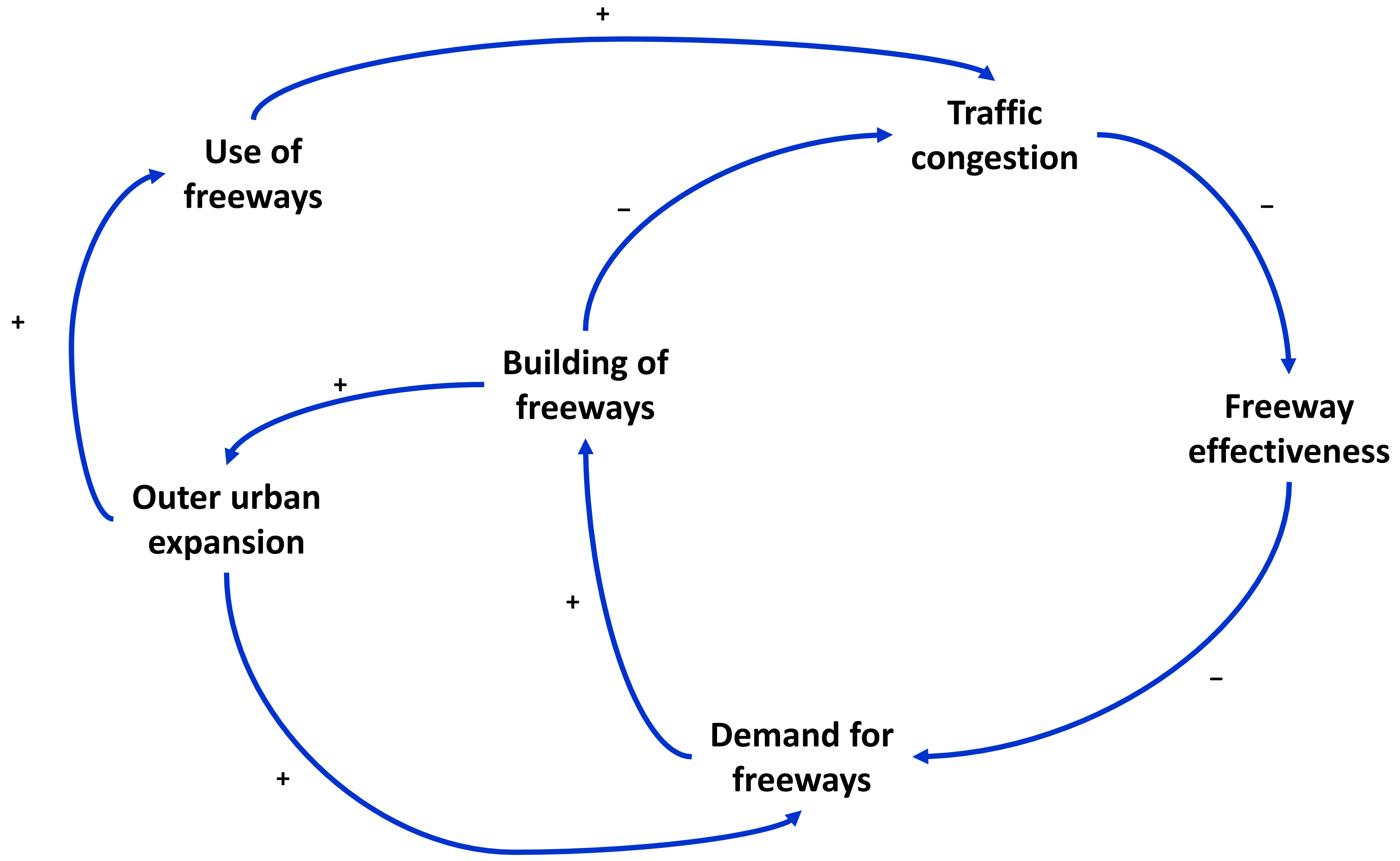
Fragility of Traffic Systems “at the edge”

JAN 2014
1” – 2” snow

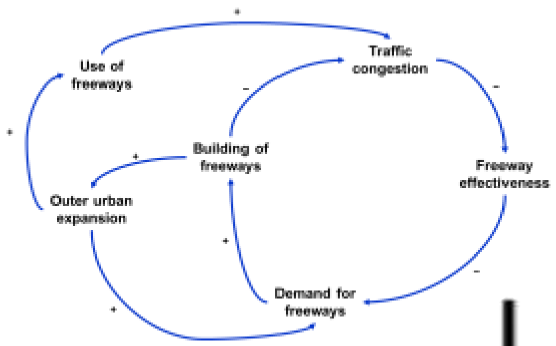


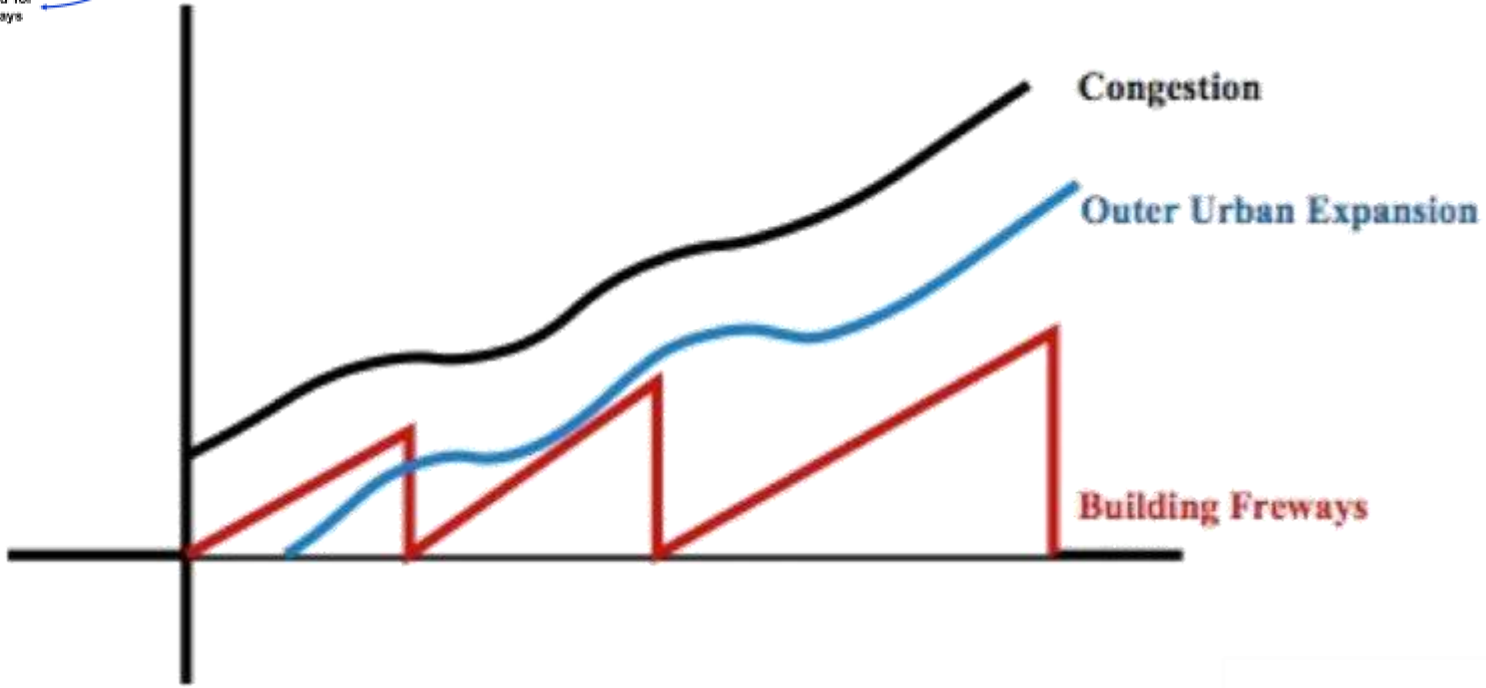
30 MAR 2017
I-85 bridge fire
and collapse

Congestion/construction influence diagram (simple)

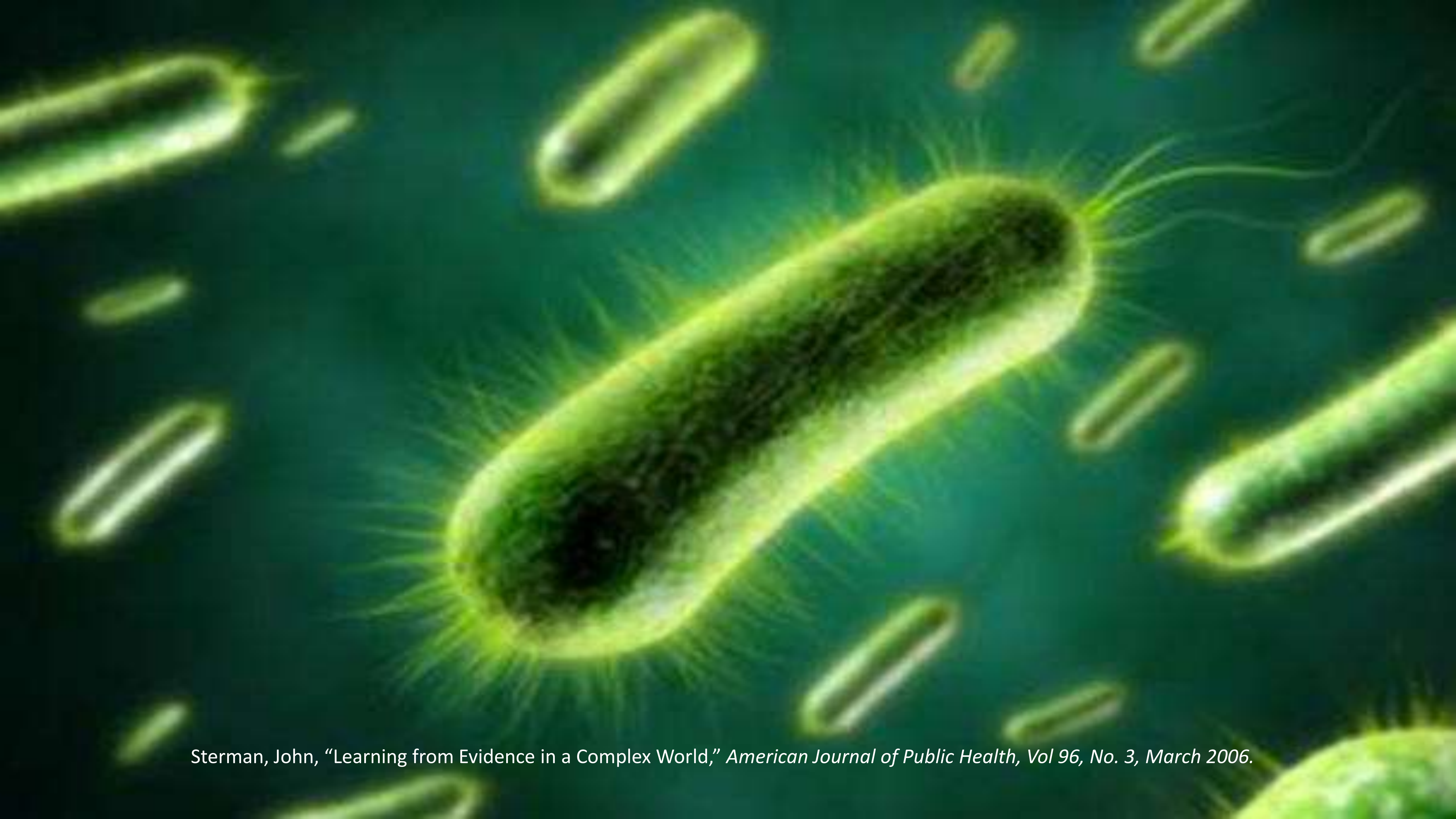


System dynamics can result in unintended consequences





Source: Dr. Tim Haslett, http://linchpin.org/site/?page_id=716



Sterman, John, “Learning from Evidence in a Complex World,” *American Journal of Public Health, Vol 96, No. 3, March 2006.*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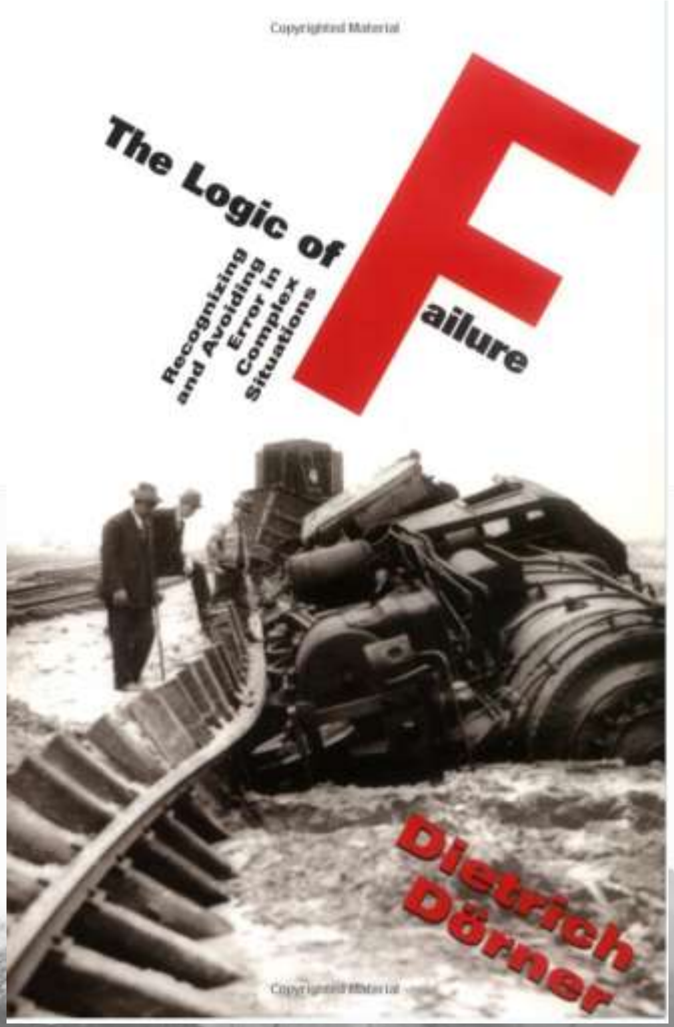
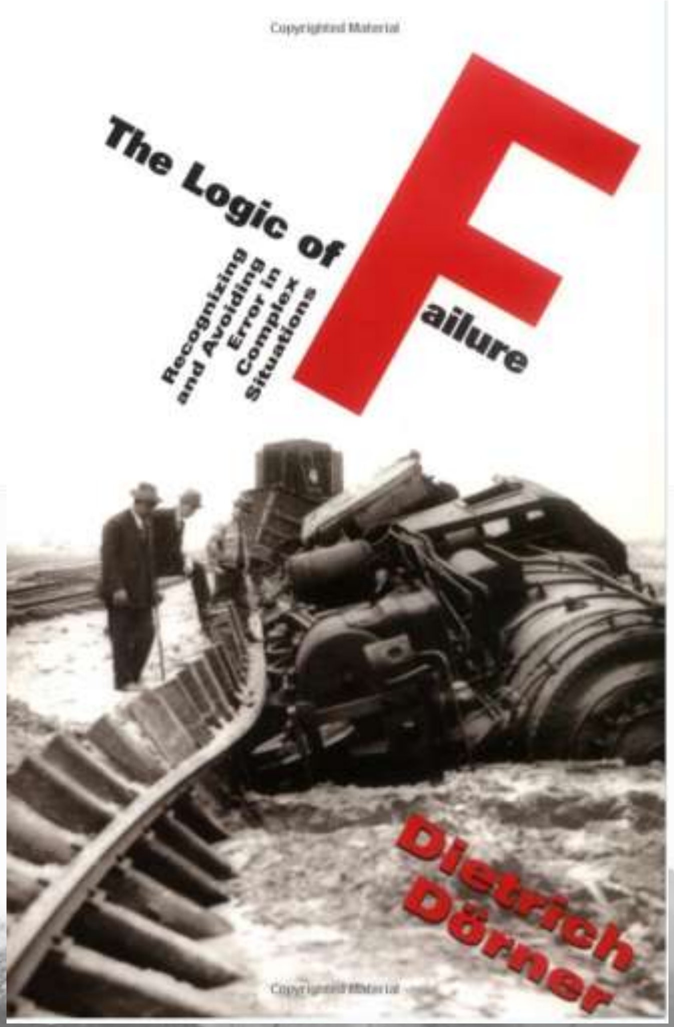
The Logic of Failure

- The Setup
  - Computer simulation of an African village called Tanaland.
  - Players given authoritarian power to achieve the goal to “improve the wellbeing of the people”
- The Experiment
  - Players made policy decisions, simulation ran for 10 years to see effect, players given another turn
  - Players could influence farming, medical care, education, law enforcement, infrastructure, etc.
- The Results
  - >90% of players: disaster
  - But a few players (very few) did well
  - No correlation with background, education, etc.
- The Question
  - When failure was the rule, what led to the exceptions?



What was the problem?

- Linear extrapolation
- Delayed Feedback
- Definition of Goals
- Priorities and Conflicting Goals
- Information overload
- Reductive Hypotheses that did not change in response to data



Will Sergent, Terse Systems blog: https://tersesystems.com/2011/06/10/the-logic-of-failure/

Successful Behaviors

- The players who did well were the ones who could tolerate uncertainty.
- They defined clear goals and priorities.
- They made many small decisions in different areas, and followed up on the expected vs actual results of most, if not all of those decisions.
- They took probing actions, reinforcing successes and abandoning failures
- They kept an eye on the overall processes of the system, and did not succumb to flow experiences.

Reflective practice based on iterative experience seems key

Adapted from Will Sergent, Terse Systems blog: https://tersesystems.com/2011/06/10/the-logic-of-failure/

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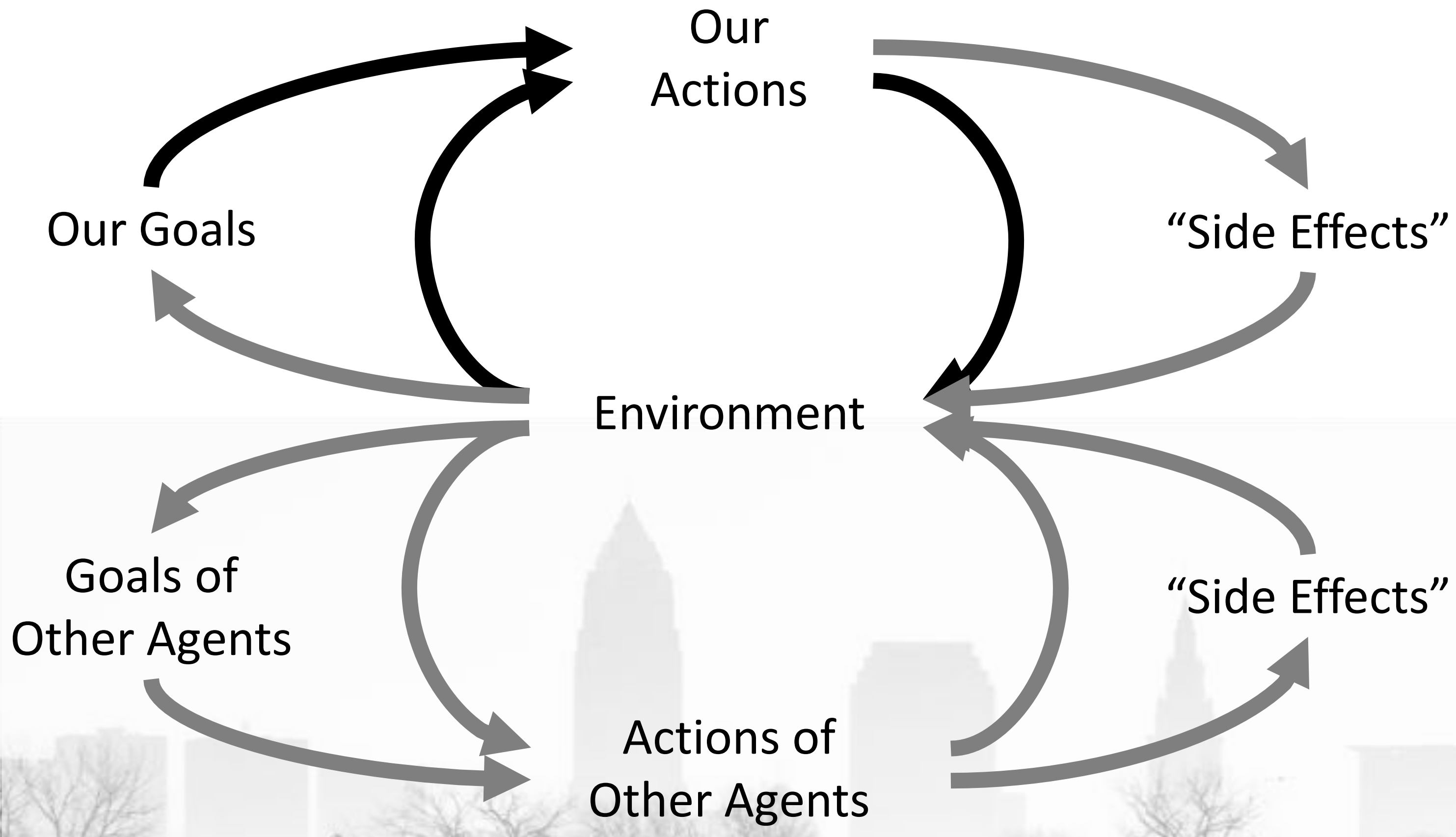
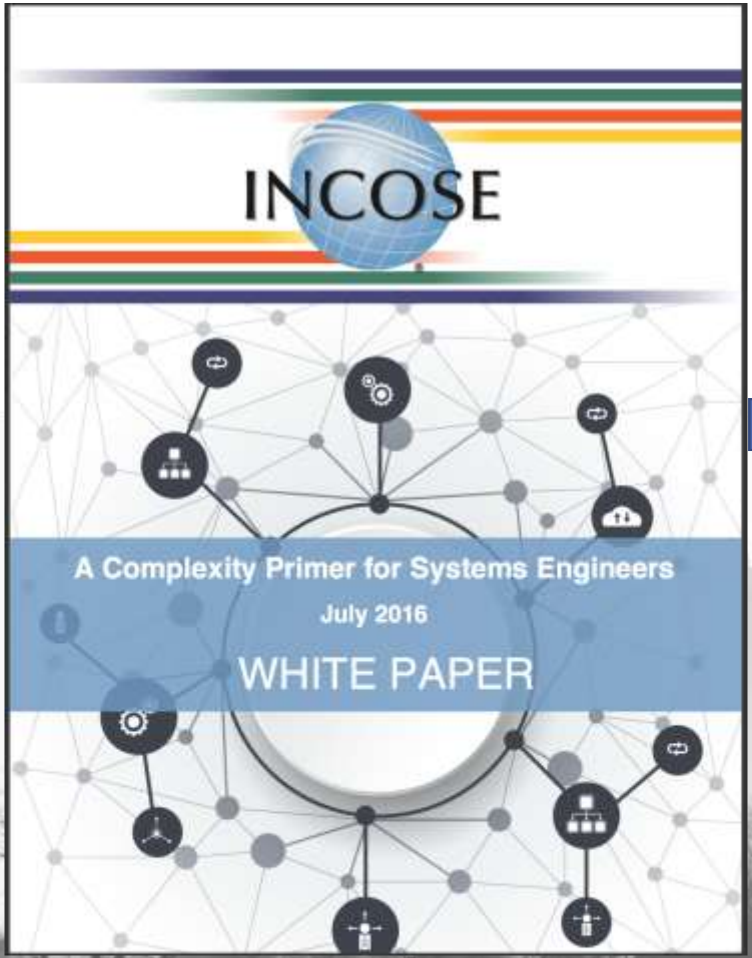
Recognized and Unrecognized Feedback



Sterman, John, "Learning from Evidence in a Complex World," *American Journal of Public Health, Vol 96, No. 3, March 2006.*

A Complexity Primer



Sarah Sheard
Eric Honour
Jimmie McEver
Dorothy McKinney
Alex Ryan
Stephen Cook
Duane Hybertson
Joseph Krupa
Paul Ondrus
Robert Scheurer
Janet Singer
Joshua Sparber
Brian White

What do we mean by complexity?

A system with **many interacting active components**, whose **interactions are non-trivial or non-linear**, leading to **unpredictable** behavior. *Especially such systems whose components are learning or modifying their behavior in some way while the system is operating*

- Stephanie Forrest, UNM

What is a Complex *Adaptive System?*

- Those complex systems which have the additional important property of being adaptive – i.e. the structure and behavior of the system changes over time in a way which *tends* to increase its 'success'. This requires that
  - there is a concept of 'success or failure', (technically known as '*fitness*'), for the system in the context of its environment;
  - there is a source of *variation* in some internal details of the system, and
  - there is a *selection* process, i.e. the system preferentially retains/discards variations which enhance/decrease its fitness, which requires
  - some way of evaluating the impact of a variation on the system's fitness – generally achieved through some kind of external *interaction and feedback*.
  - Thus over time the system generates and internalizes variations which tend to increase its fitness or success – amounting to incorporation of information into the system.

Grisogono, AM, *CAS Implications for Command and Control*, 2006 Command and Control Research and Technology Symposium, www.dodccrp.org

Implications of Complexity

- No one ever has complete understanding
- Complex systems will always surprise us
- There will always be unintended consequences
- Similar conditions lead to very dis-similar outcomes
- Best practices don’t work
- Just putting someone in charge doesn’t help

Opportunities from Complexity

- Richer possibility spaces
- Potential for greater resilience, adaptability, and anti-fragility
- Order for free
- Can perform better in complex and changing environments

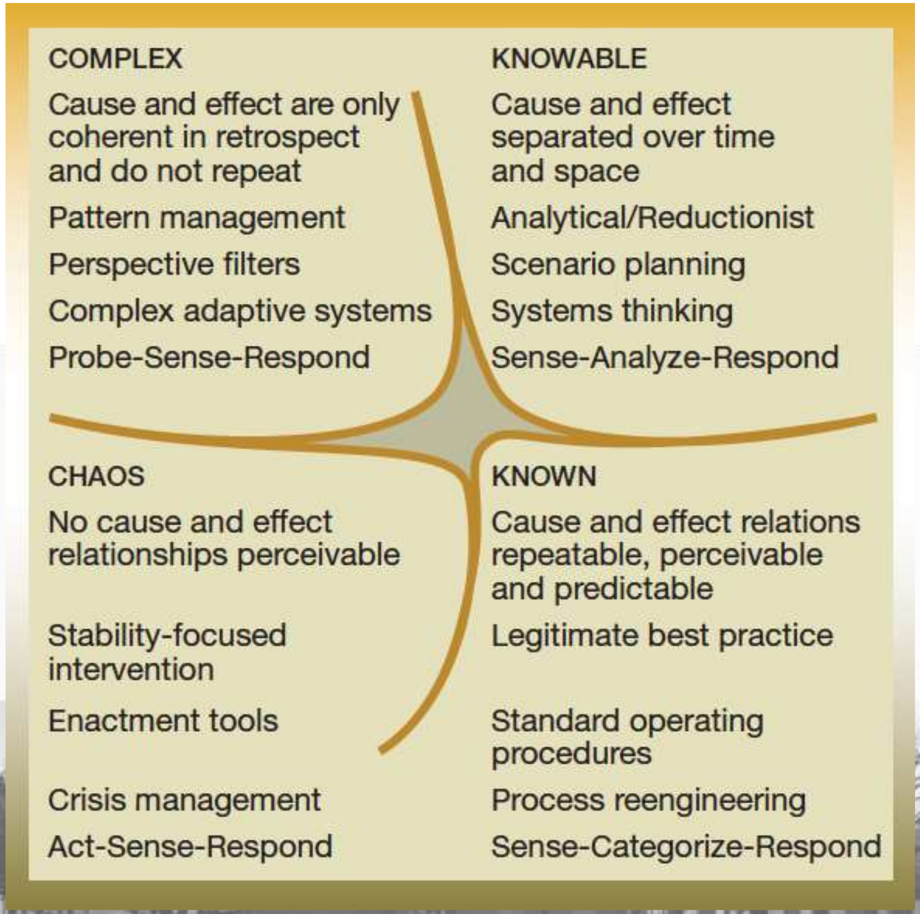
Complicated vs Complex

Classes of Systems Problems: the Cynefin Framework

Complex systems, characterized by interdependence, self-organization, and emergence – new tools and approaches are needed

Massively- complicated systems present challenges of *scale* and *interface accounting* – extensions of traditional methods/tools can help

Cynefin domains

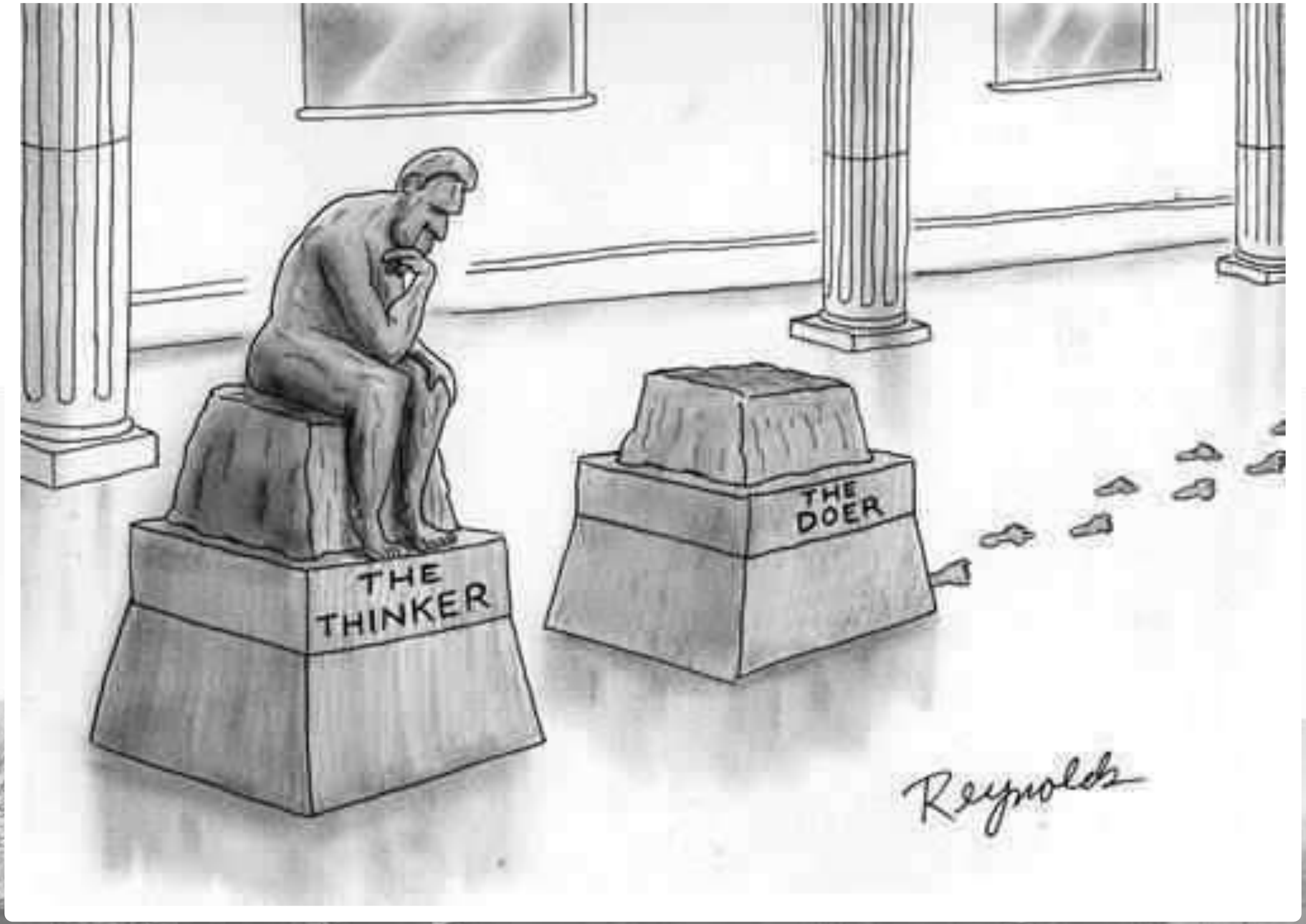


Source: Kurtz and Snowden, "The new dynamics of strategy: Sensemaking in a complex and complicated world," *IBM Systems Journal*, **42** (3), 2003.

Chaotic systems can only be reacted to; can attempt to transform into another domain

Simple and complicated systems are straightforward to deal with using traditional systems engineering / mgmt approaches

Complex Systems Engineering
A Mindset AND a Toolset



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Think like a gardener not a watch-maker

See through new eyes

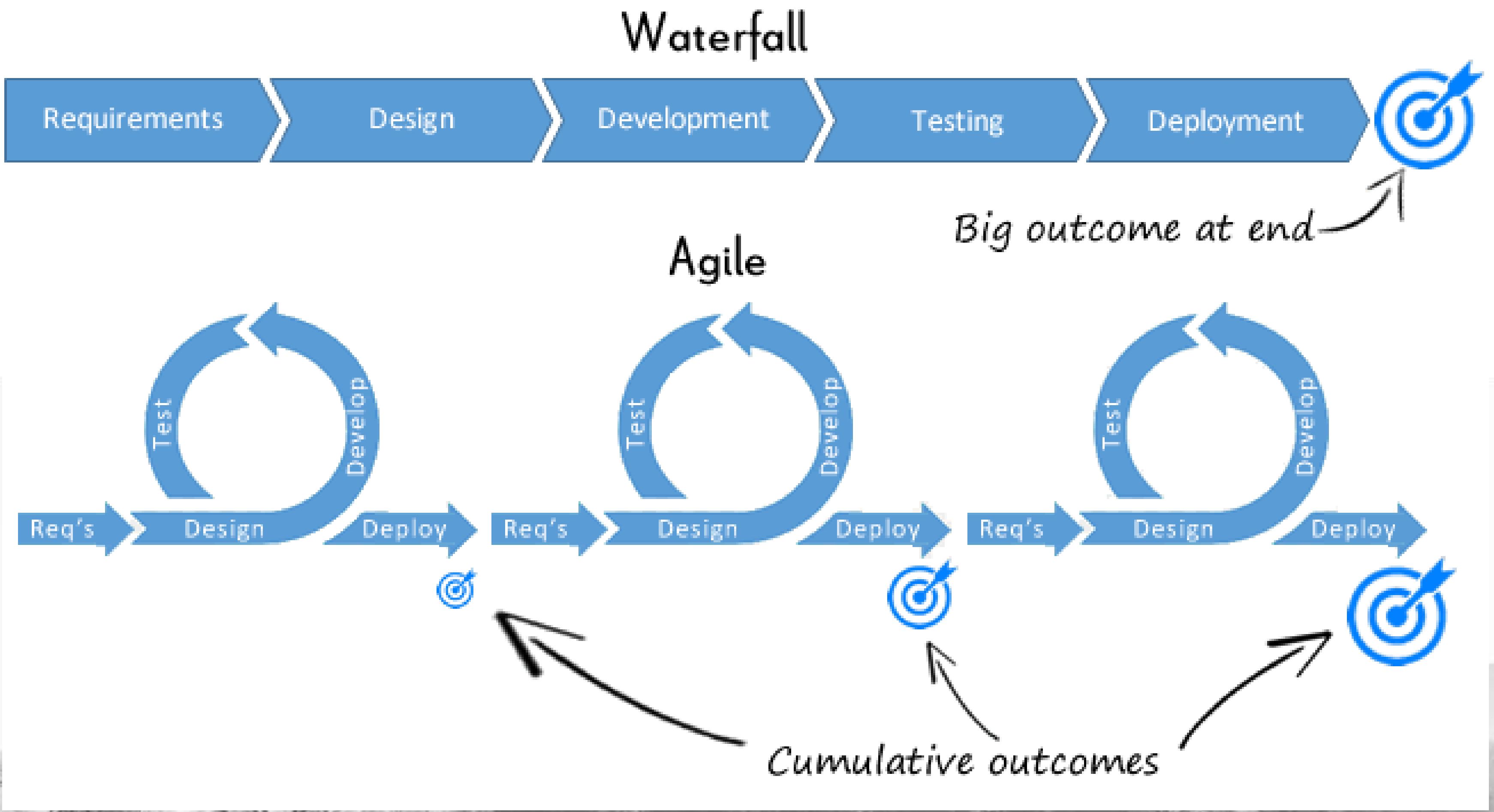
Earthrise, William Anders, NASA, 1968.

Combine courage with humility

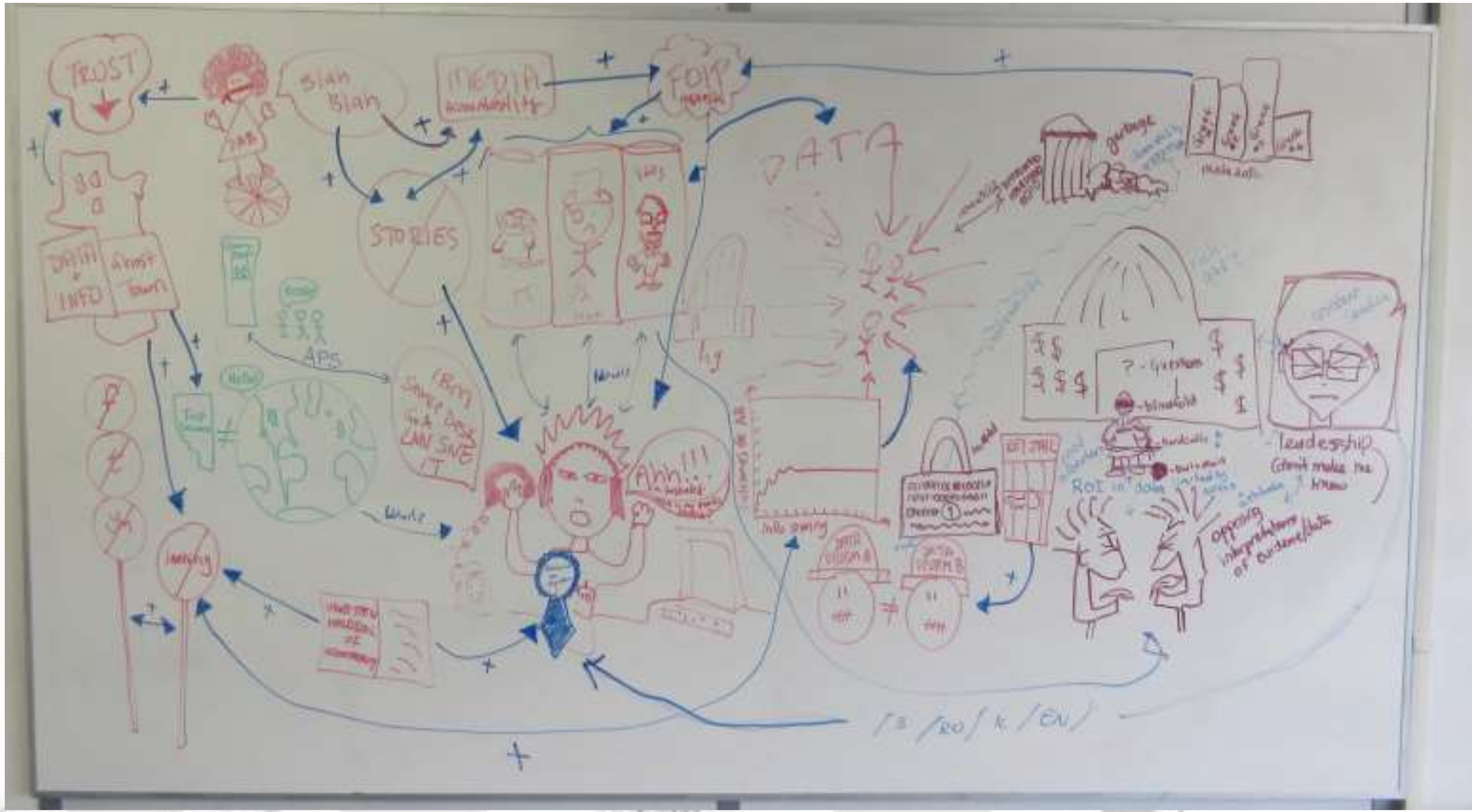
Atticus Finch as a model of courageous and humble leadership in *To Kill a Mockingbird*

Take an adaptive stance

Tools: Agile and SCRUM



Tools: Soft Systems Methodology



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Tools: Serious Play

Tools: Human and Artificial Intelligence

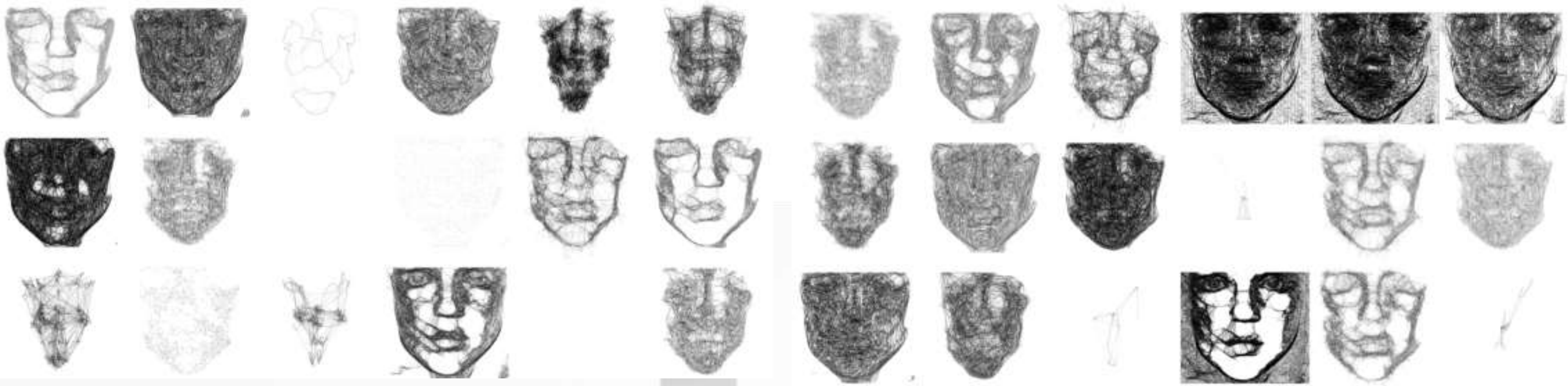


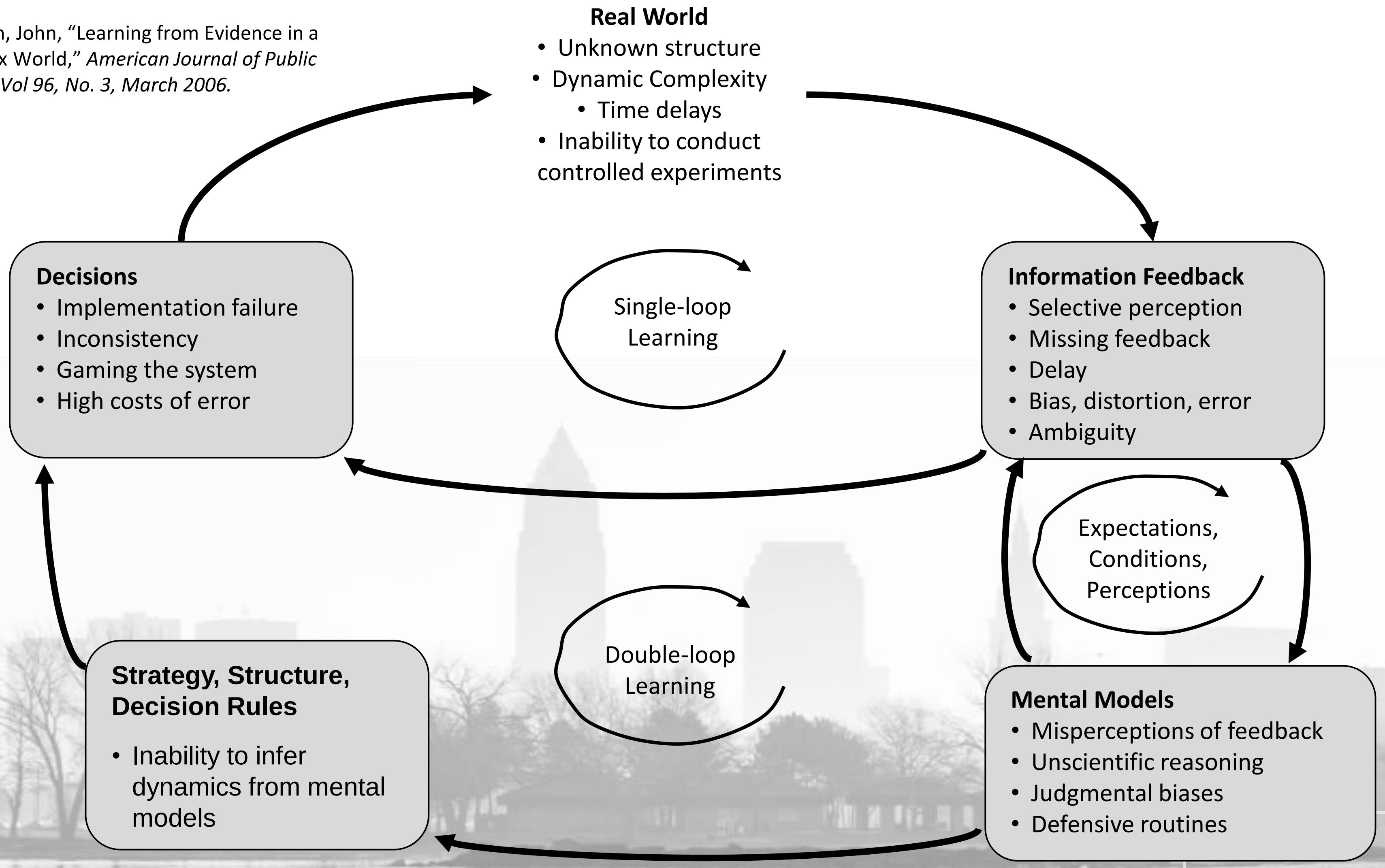
Image source: David Bliss, http://davidbliss.com/tag/genetic-algorithm/

Learning and MetaLearning

- Learn from problems.
  - In a changing context, with an evolving system, where elements are densely interconnected, problems and opportunities will continually emerge, often in surprising ways, due to phase transitions, cascading failures, fat tailed distributions, and “black swan” (Taleb, 2007) events.
  - A traditional approach to risk management and mitigation should be augmented by a complexity mindset that balances risk management with exploiting opportunity and expects and learns from error.
- Meta-cognition.
  - Meta-cognition, or reflecting on how one reflects, helps to identify bias, make useful patterns of thinking more frequent, and improve understanding of a complex situation.

Learning as a Response – and Why it's Hard

Sterman, John, "Learning from Evidence in a Complex World," *American Journal of Public Health, Vol 96, No. 3, March 2006.*



Improving Learning in Adaptation

- Adaptive action: changing the use of existing sensing, decision and action capabilities
- Learning: changing the sensing, decision and action capabilities themselves
- Learning to learn: changing the system's adaptive processes (how changes in action and learning are generated and adopted)
- Defining success: changing the internalized proxies for "goodness" or success used in adaptive processes
- Co-adaptation: determining how the system allocates resources, responsibilities and decision rights to its components and allied systems

Adapted from Grisogono, AM, *CAS Implications for Command and Control*, 2006 Command and Control Research and Technology Symposium, www.dodccrp.org

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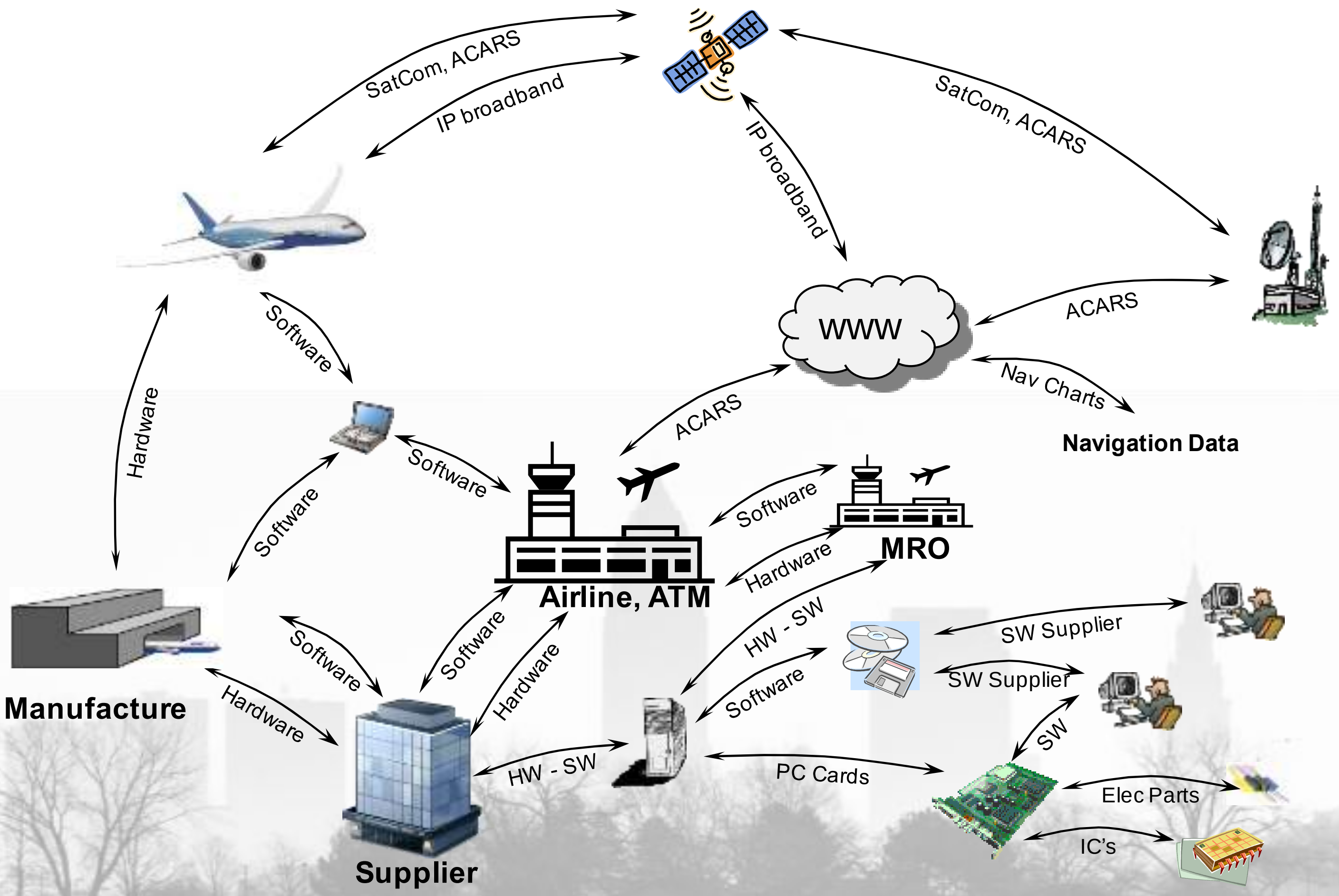
The Commercial Aviation Cyber Landscape

2017

e-Enabled Environment



The Cyber Landscape is a Complex Adaptive System

Cybersecurity: Operational Assurance via Resilience

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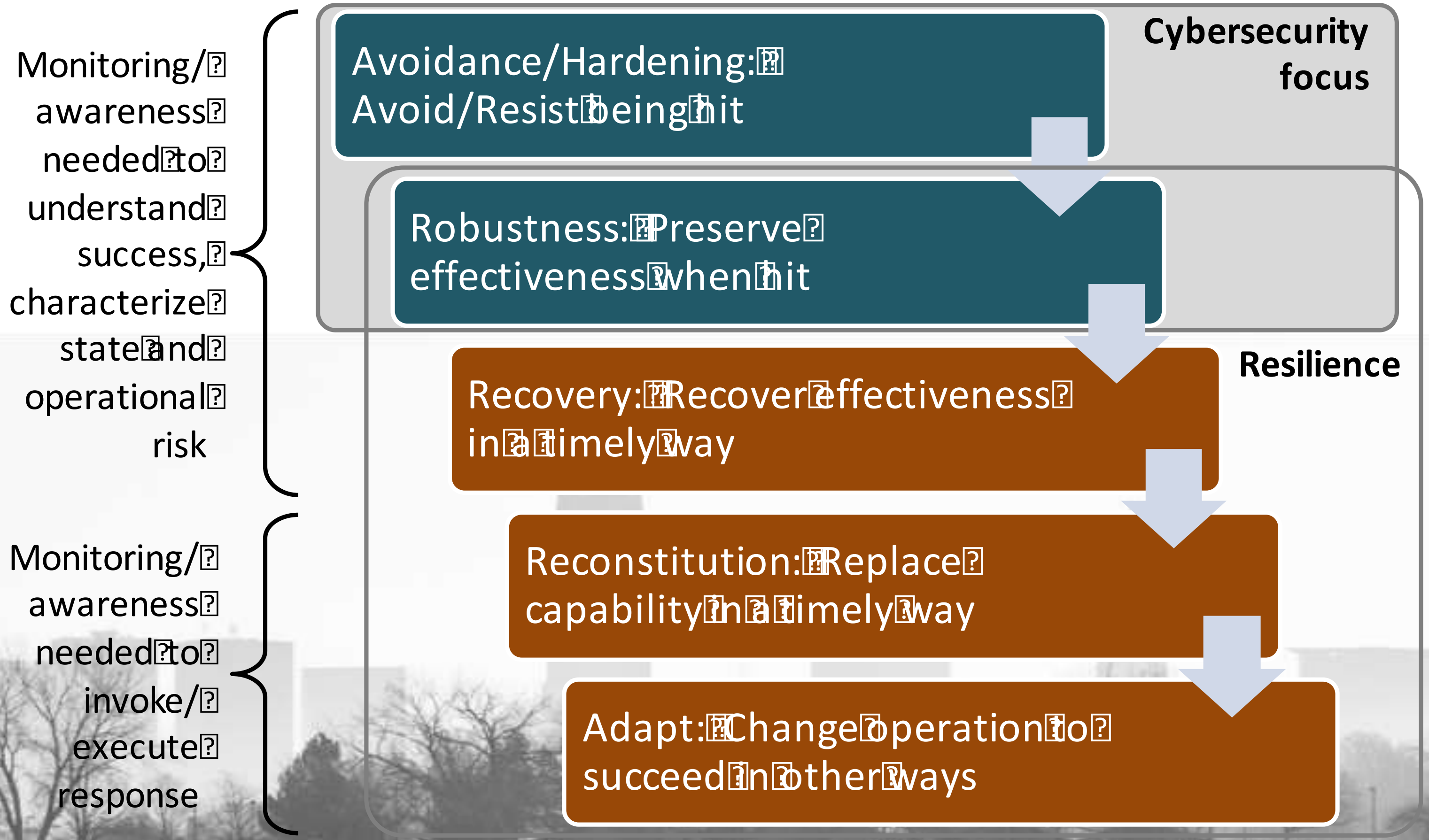
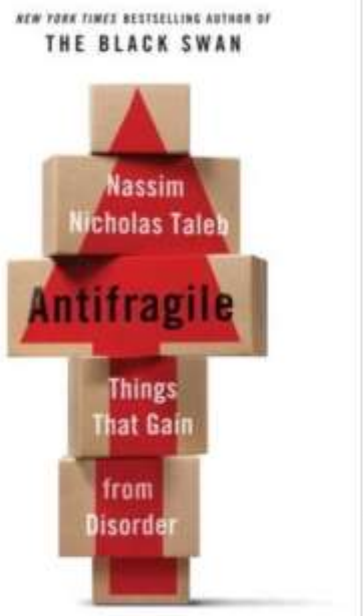
Elements of Survivability in a Contested Cyber Environment



Antifragility (Nassim Taleb)

- Fragile systems
  - Harmed by variability and stress
  - Overly optimized for specific situations/environments
  - Prediction-based
  - Typically large – subject to "fail big"
- Resilient/robust systems
  - Resistant to or able to quickly recover from variability and stress
- Antifragile
  - Benefit from variability and stress
  - Thrives on randomness



Extracted from Naresh Jain, "Decline and Fall of Agile: Antifragile Mindset to the Rescue," https://www.slideshare.net/nashjain/the-decline-and-fall-of-agile-antifragile-mindset-to-rescue

Properties of Antifragile Systems

- Layers of redundancy to localize negative impacts
- Decentralized system with buffers and inventories
- Dislike consistency/standardization
  - Variation to take advantage of opportunities
- Less is more – large is vulnerable
- Retain optionality – defer closing off options until you have to
- Avoid prediction
- Safe-fail, fail-frequently, fail-diversely
- Extract maximum learning from failure (via negativa)

Robust-First Computing

David H. Ackley

I am an associate professor of Computer Science at the University of New Mexico, with degrees from Tufts and Carnegie Mellon. Over thirty years my work has involved neural networks and machine learning, evolutionary algorithms and artificial life, and **biological approaches to security, architecture, and models of computation**.

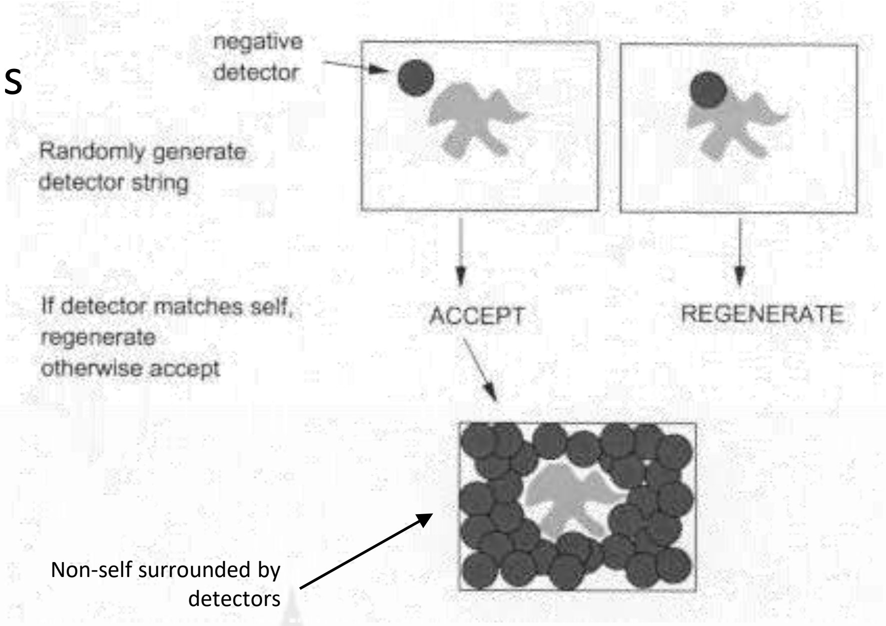
https://www.youtube.com/watch?v=7hwO8Q_TyCA&list=PLm5k2NUmpIP-4ekppm6JoAqZ1BLXZOztE

Intro: 0:00 – 4:05
Demo: 4:05 – 11:01
Outcome: 11:01 –

Biologically Inspired Approaches to Cybersecurity

Biological immune systems → Computer immune systems

- Antibodies: Many simple detectors swarming to non-self
- Fewer more complex detectors
- Distributed signature detection and sharing
- Danger theory – damage as an indicator of anomaly
- Diversity
- Epidemiology



Couple detection and response via lower-level feedback loops

- Alter how routing and procedure calls are handled to disproportionally affect malicious activity

Matthew Williamson, "Biologically Inspired Approaches to Computer Security," HP Laboratories, Bristol, http://www.hpl.hp.com/techreports/2002/HPL-2002-131.pdf

Useful Starting Points

- Don’t ignore the human/ behavioral part of the problem
- Explicitly characterize and quantify uncertainty
- Take risk management seriously
  - Not just a checklist
  - Consider the “Impact” part of the equation – not just threats and vulnerabilities
- Don’t optimize and be wary of efficiency
- Employ Red and Blue teams in your assessments -- continuously

Transform your thinking

- Shift to a framework of Cyber Resilience
- Work toward Antifragility
- Robust-first computing
- Biologically-inspired security

A Call to Action

- Cannot solve problems using the same thinking that created them
- Success requires more than just improving and scaling current approaches
- A whole that is *different* than the sum of its parts
- Fundamental transformation is needed

Guiding Principles for Working in Complexity

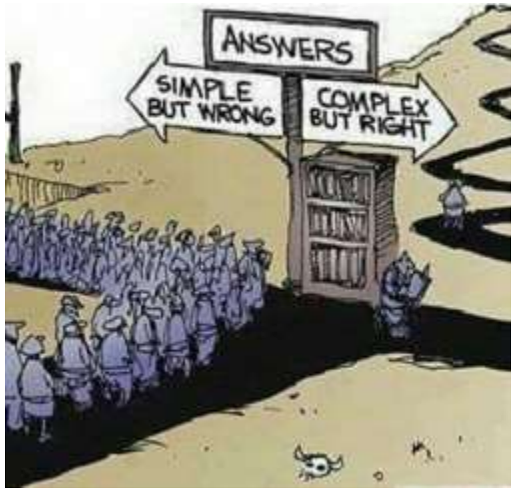
Hallmarks of complexity	Impact on Decision Maker
Inter-dependence	Cannot treat by decomposition
Nonlinearities	Extrapolation of current conditions → error
Open boundaries	Cannot focus only on processes inside boundary
Multi-scalarity	Have to address all relevant scales
Causal & influence networks	Challenge: develop ‘requisite’ conceptual model within time and information resource constraints
Emergence	Unknown risks and unrecognized opportunities
Complex goals	Goals may change, be unrealistic, vague
Adaptation & innovation	Rules change, interventions stimulate adaptation
Opaqueness	Many possible hypotheses about causal paths, insufficient evidence to discriminate

Adapted with permission from Grisogono, Anne-Marie and Vanja Radenovic, The Adaptive Stance –Steps towards Teaching more Effective Complex Decision-Making, International Conference on Complex Systems, June 2011.

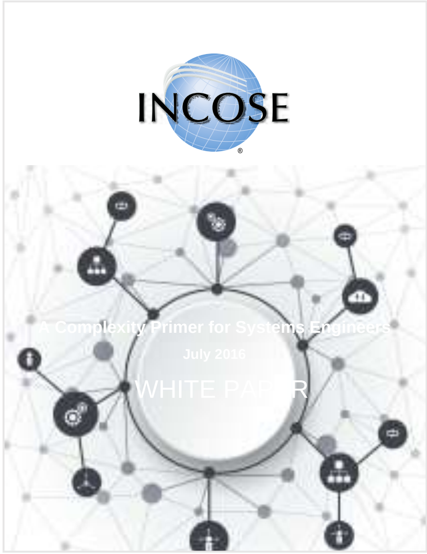
Think like a gardener, not a watchmaker

Take an adaptive stance

Think at multiple levels and from multiple points of view



- Combine courage with humility
- Use free order
- Identify and use patterns
- See through new eyes
- Collaborate
- Achieve balance
- Learn from problems
- Meta-cognition
- Focus on desired regions of the outcome space rather than specifying detailed outcomes
- Understand what motivates autonomous agents
- Maintain adaptive feedback loops
- Integrate problems



The INCOSE Complex Systems Working Group has drafted a primer to introduce complexity concepts and approaches to practicing systems engineers

Backup

Abstract

- There is a growing recognition that complexity poses new and different engineering challenges, requiring not only extension and enhancement of current state-of-the-art practices, but also the ability to understand and reason about systems and engineering activities in fundamentally different ways.
- In complex systems, many interacting active components interact in non-trivial or non-linear ways, resulting in attributes/behaviors for which there are fundamental limits to prediction.
- Especially challenging are complex systems whose components are learning or modifying their behavior in some way while the system is operating.
- Transformation is needed in our thinking and in our practice

Complex Problems Actively Resist Solutions

- Road building programs designed to reduce congestion have increased traffic, delays, and pollution.
- Low tar and nicotine cigarettes actually increase intake of carcinogens, carbon monoxide, etc., as smokers compensate for the low nicotine content by smoking more cigarettes per day, by taking longer, more frequent drags, and by holding the smoke in their lungs longer.
- Antilock brakes and other automotive safety devices cause some people to drive more aggressively, partially offsetting their benefits.
- Forest fire suppression causes greater tree density and fuel accumulation, leading to larger, hotter, and more dangerous fires, often consuming trees that previously survived smaller fires unharmed.
- Flood control efforts, such as levee and dam construction, have led to more severe floods by preventing the natural dissipation of excess water in flood plains. The cost of flood damage has increased as flood plains were populated in the belief they were safe.
- Antibiotics have stimulated the evolution of drug-resistant pathogens, including multi-drug-resistant strains of tuberculosis, *Staphylococcus aureus*, and sexually trans- mitted diseases.
- Pesticides and herbicides have stimulated the evolution of resistant pests, killed off natural predators, and accumulated up the food chain to poison fish, birds, and, in some cases, humans.
- Highly active antiretroviral treatment has dramatically reduced mortality among those living with HIV, but has increased risky behaviors, including unprotected sex and substance abuse, among youth and other groups, causing a rebound in incidence while multiply-resistant strains of HIV proliferate.
- Despite dramatic gains in income per capita and widespread use of labor-saving technology, Americans have less leisure today than 50 years ago and are no happier.

Sterman, John, “Learning from Evidence in a Complex World,” *American Journal of Public Health, Vol 96, No. 3, March 2006.*

Outline/Concepts

- Logic of Failure – motivation
- Blink
- CxSWG material
- Extracts from Cybersecurity slides
- Netlogo models
    - Look at Complexity Explorer site
    - Icosystem
- Rainey material – engineering emergence
- Highly optimized tolerance v anti-fragility
- Tensions
    - Efficiency v Agility
- Exercises/thought experiments

System Attributes Leading to Policy Resistance

- Constantly changing. Heraclitus said, “All is change.” What appears to be unchanging is, over a longer time horizon, seen to vary. Change occurs at many time scales, and these different scales sometimes interact. A star evolves over billions of years as it burns its hydrogen fuel, but can explode as a supernova in seconds. Bull mar- kets can rise for years, then crash in a matter of hours.
- Tightly coupled. The actors in a system interact strongly with one another and with the natural world. Everything is connected to everything else. “You can’t do just one thing.”
- Governed by feedback. Because of the tight couplings among actors, our actions feed back on themselves. Our decisions alter the state of the world, causing changes in na-ture and triggering others to act, thus giving rise to a new situation, which then influences our next decisions.
- Nonlinear. Effect is rarely proportional to cause, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity often arises from basic physics: insufficient inventory may cause you to boost production, but production can never fall below zero no matter how much excess inventory you have. Nonlinearity also arises as multiple factors interact in decisionmaking: Pressure from the boss for greater achievement increases your motivation and effort—up to the point where you perceive the goal to be impossible. Frustration then dominates motivation—and you give up or get a new boss.
- History-dependent. Many actions are irreversible: you can’t unscramble an egg (the second law of thermodynamics). Stocks and flows (accumulations) and long time delays often mean doing and undoing have fundamentally different time constants: during the 50 years of the Cold War arms race, the nuclear nations created more than 250 tons of weapons-grade plutonium (239Pu). The half-life of 239Pu is about 24000 years.
- Self-organizing. The dynamics of systems arise spontaneously from their internal structure. Often, small, random perturbations are amplified and molded by the feed- back structure, generating patterns in space and time. The stripes on a zebra, the rhythmic contraction of your heart, and persistent cycles in measles and the real estate market all emerge spontaneously from the feedbacks among the agents and elements of the system.
- Adaptive and evolving. The capabilities and behaviors of the agents in complex systems change over time. Evolution leads to selection and proliferation of some agents while others become extinct. People adapt in response to experience, learning new ways to achieve their goals in the face of obstacles. Learning is not always beneficial, however, but often superstitious and parochial, maximizing local, short-term objectives at the expense of long-term success.
- Characterized by trade-offs. Time delays in feedback channels mean the long-run response of a system to an intervention is often different from its short-run response. Low-leverage policies often generate transitory improvement before the problem grows worse, whereas high-leverage policies often cause worse-before-better behavior.
- Counterintuitive. In complex systems, cause and effect are distant in time and space, whereas we tend to look for causes near the events we seek to explain. Our attention is drawn to the symptoms of difficulty rather than the underlying cause. High-leverage policies are often not obvious.
- Policy resistant. The complexity of the systems in which we are embedded over- whelms our ability to understand them. The result: many seemingly obvious solutions to problems fail or actually worsen the situation.

Sterman, John, “Learning from Evidence in a Complex World,” *American Journal of Public Health, Vol 96, No. 3, March 2006.*

Challenges of Operating in Complexity

- Challenge of creating adaptivity
- Challenge of complex objectives
- Challenge of complex networked causation
- Challenge of limitations of human cognition
  - Handle Cause and Influence networks with larger scale/complexity
  - Produce effective adaptation at larger scales of organization
- Challenge of complexity in our own systems
- Draw on selected concepts from complex adaptive systems:
  - Multi-level structure and multiscale analysis
  - Adaptation
  - Properties of networked causation

Drawn from Grisogono and Ryan, Adaptive Campaigning, 2007 CCRTS, www.dodccrp.org

Adaptive Campaigning

- Act:
  - Probing actions to stimulate a response in order to learn or test assumptions or understanding – contributing to the ability to learn about the context,
  - Decisive actions to prosecute a course of action to create effects (while still allowing for adaptive changes in real time as the actions unfold), and
  - Modifying actions, where the target of action is the force's own operations, in other words, adapting its sensing, deciding or acting.
- Sense:
  - Sensing to provide input for effective adaptation - the collection plan must enable observation of the reactions and adaptations of threat and population groups alike
  - Sensing to support learning what is important to observe – the collection plan must also include a strategy for its continuous refinement to allow the force to improve its awareness of what is relevant, and
  - Sensing to measure effectiveness – the collection plan must include monitoring the effectiveness of land force actions across all five lines of operation.
- Decide:
  - Deciding the meaning of a sensed response to a probing action, and
  - Deciding what should be done next given what is learned about the situation.
- Adapt:
  - Moreover, dealing with an intelligent and adaptive adversary requires
  - Learning how to learn, - continuously improving one's ability to learn from both successes and mistakes, including
    - learning how to derive lessons from experience, and how to implement those lessons in an effective way leading to successful adaptation – i.e. knowing when and what to change, and
    - maintaining agility and robustness to deception, by adopting a stance of constant challenging of one's understanding and perceptions at every level of the land Force.

Drawn from Grisogono and Ryan, Adaptive Campaigning, 2007 CCRTS, www.dodccrp.org

Recognizing CAS in Operational Contexts

- We consider a system to be complex when:
  - Causality is complex and networked: i.e.simple cause-effect relationships dont apply – there are many contributing causes and influences to any one outcome; and conversely, one action may lead to a multiplicity of consequences and effects
  - The number of plausible options is vast: so it is not possible to optimise (in the sense of finding the one best solution in a reasonable amount of time),
  - System behaviour is coherent: there are recurring patterns and trends, but
  - The system is not fixed: the patterns and trends vary, for example, the ‘rules’ seem to keep changing – something that ‘worked’ yesterday may not do so tomorrow, and
  - Predictability is reduced: for a given action option it is not possible to accurately predict all its consequences, or for a desired set of outcomes it is not possible to determine precisely which actions will produce it.

Grisogono, *CAS Implications for Command and Control*, 2006 CCRTS, www.dodccrp.org