Navigating Seas of Complexity

Even if the world were perfect, it wouldn't be. Yogi Berra

David Woods

Director

Complexity in Natural, Social & Engineered Systems

The Ohio State University

&

Cognitive Systems Engineering Laboratory (C/S/E/L)

Dept. of Integrated Systems Eng.

The Ohio State University

&

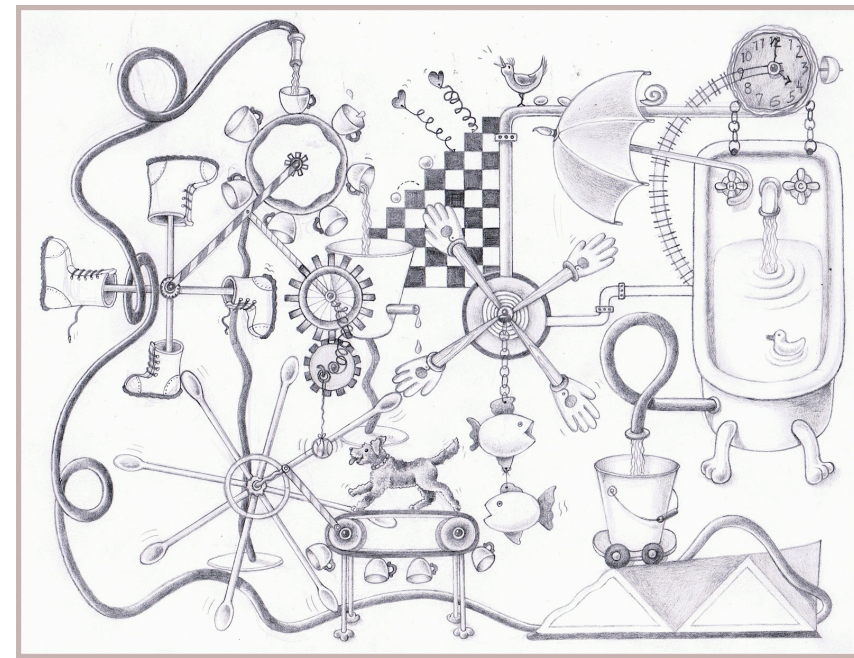Past-President, Resilience Engineering Association (REA)

Resilience Engineering Association

THE OHIO STATE UNIVERSITY

Complexity in Natural, Social & Engineered Systems
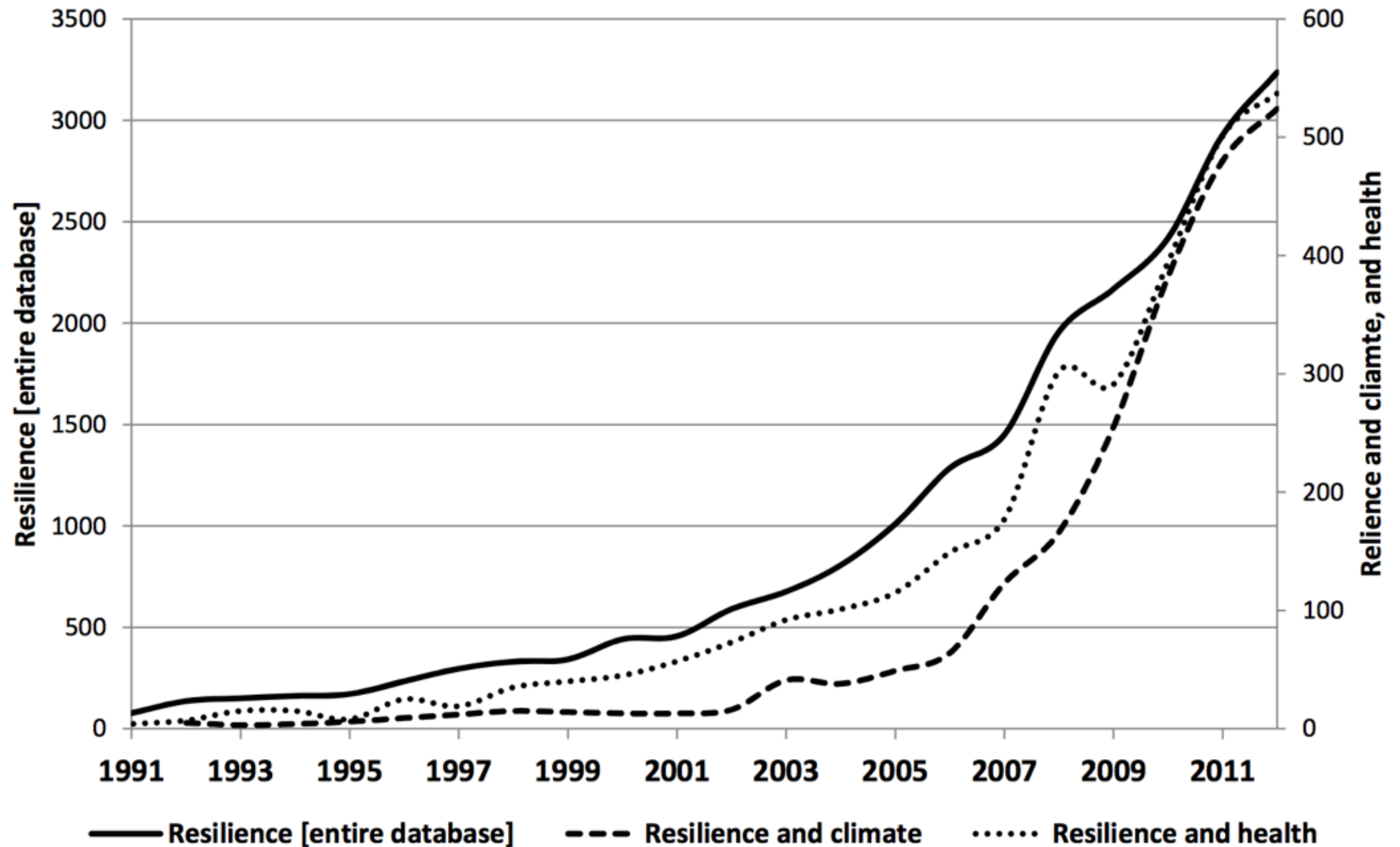
Outmaneuvering Complexity

Releasing the Adaptive Power of Human Systems

The Adaptive Universe

- emerging comprehensive account of complex adaptive systems that serve human purposes
- technical foundations emerging
- multi-role multi-echelons networks with
- extensive, hidden interdependencies
- confront surprise that challenge boundaries
- build and sustain resilience

Complexity in Natural, Social & Engineered Systems

Resilience as topic, in the Web of Science, 1991-2012

Legend: Resilience [entire database] — Resilience and climate ••••• Resilience and health

Outmaneuvering Complexity

Story Line

Setting	Operating in a Network with Extensive, Hidden Interdependencies
Antagonist	Linear Thinking
Story	Escaping & failing to escape Simplifications
Driver	Surprises and Cascades
Tensions	Dramatic Failures in Brittle Systems
Dead Ends	Unintended Consequences
Hope	Where People Stretch to Outmaneuver Complexity
Forward	Generating and Sustaining the Capacity for Maneuver

Afghanistan Stability / COIN Dynamics
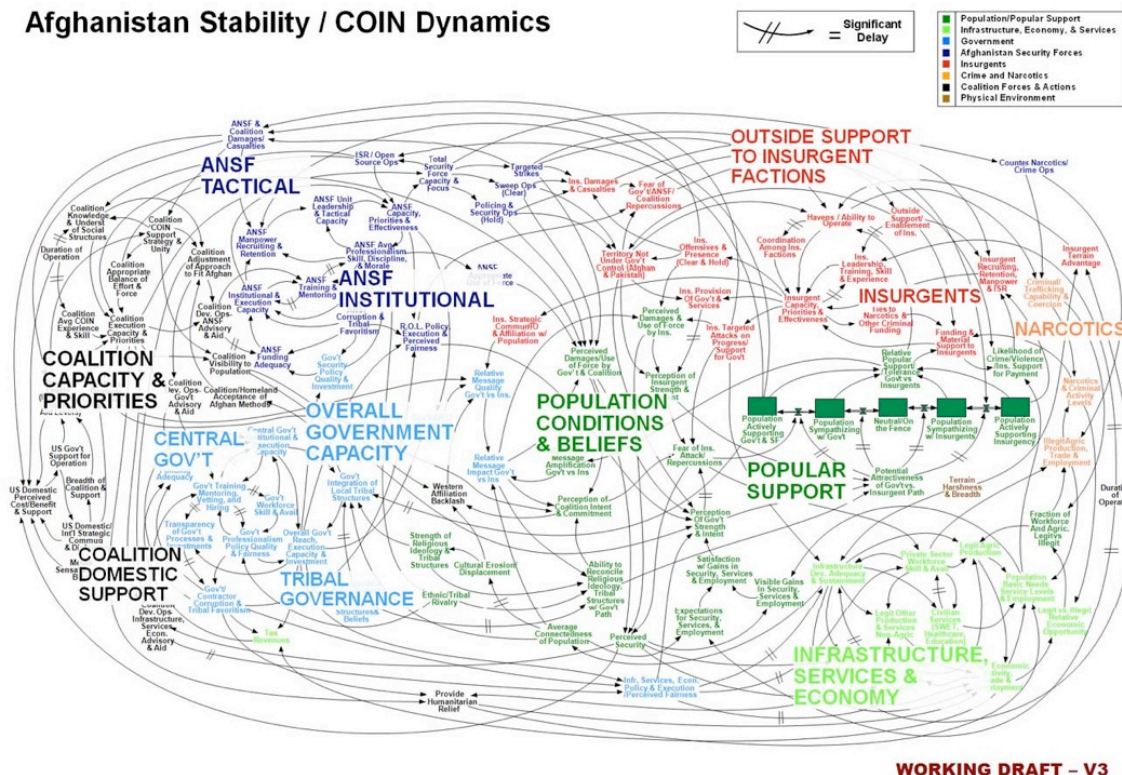
Global Hawk UAV, 98-2003, 19991206, FSPM 1201A

NASA failure history captures creeping complexity
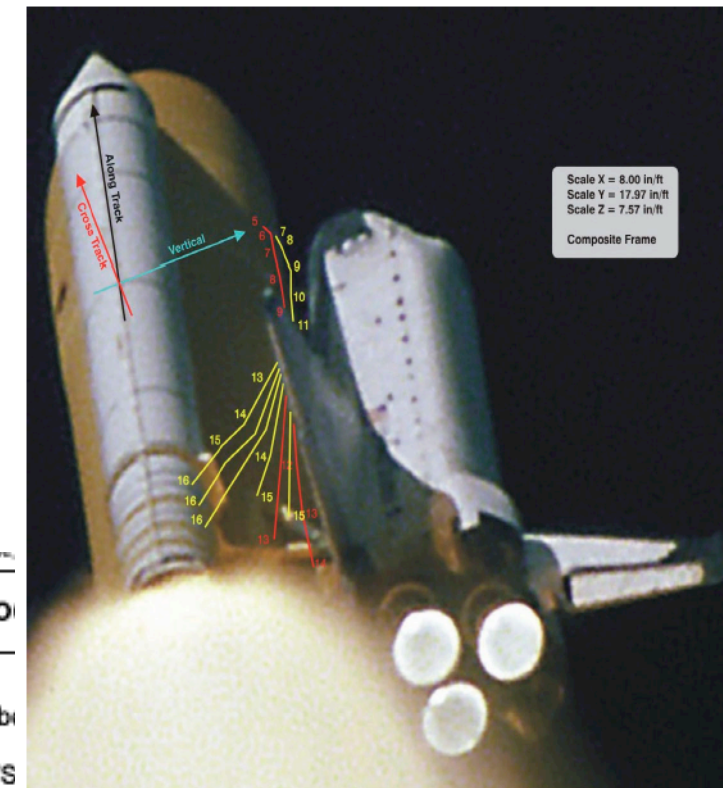
1999: 3 space exploration failures

Report on Project Management in NASA

by the
Mars Climate Orbiter
Mishap Investigation Board

March 13, 2000

increasingly brittle systems under
faster, *better*, cheaper (FBC)
pressure

2003: Run up to Columbia accident

Scale X = 8.00 in/ft
Scale Y = 17.97 in/ft
Scale Z = 7.57 in/ft

Composite Frame

STS-112/ET-115 Bipod

- **Rationale for Flight**
  - Current bipod ramp closeout has not b[...]
  - The Orbiter has not yet experienced "S[...] of Flight" damage from loss of foam in 112 flights (including 3 known flights with bipod ramp foam loss)
  - There have been no design / process / equipment changes over the last 60 ETs (flights)
  - All ramp closeout work (including ET-115 and ET-116) was performed by experienced practitioners (all over 20 years experience each)
  - Ramp foam application involves craftmanship in the use of validated application processess
  - No change in Inspection / Process control / Post application handling, etc
  - Probability of loss of ramp TPS is no higher/no lower than previous flights
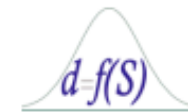 - *The ET is safe to fly with no new concerns (and no added risk)*

After Final Foam Trim
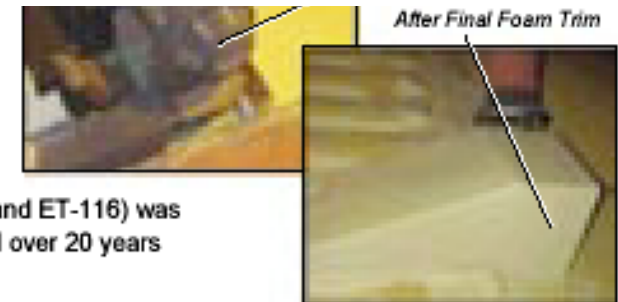
Bipod Attach Fitting

NASA failure history captures cumulative complexity circa 2000

Creating Safety Under Pressure

$d-f(S)$

NASA in a changing environment under performance demands and resource pressures:

- Drive down the cost of launch

- Shorter, aggressive mission schedules

- New partners and relationships

- New roles

- Skill erosion

- Heightened public interest

"Risk, therefore, becomes the "fourth dimension" of project management—treated equally as important as cost and schedule."

Cases/Studies of Resilience / Brittleness

Space accidents: Mars series 1999, Ariane 501, Columbia brittleness grows under faster, better, cheaper pressure - but mission control, ...

Defense Science Board (2012) need to overcome brittleness in drones and autonomous vehicles - but rapid adoption, ...

Health Care:
~ adverse events with patient harm reveal hidden sources of resilience & brittle points
~ Emergency Medicine as brittle point in US national healthcare system
- but, transplants, ...

Business Continuity/Viability:
~ hidden interdependencies; hidden potential for cascades
  (e.g. extreme weather)
~ brittleness of vital digital infrastructure
- but people innovate to block cascades, ...

Story Line

Operating in a Network with Extensive, Hidden Interdependencies

Linear Thinking & Over-Simplifications

Events Cascade into Dramatic Failures

Failure to Anticipate the Potential for Surprise

Reveal Brittleness in Systems

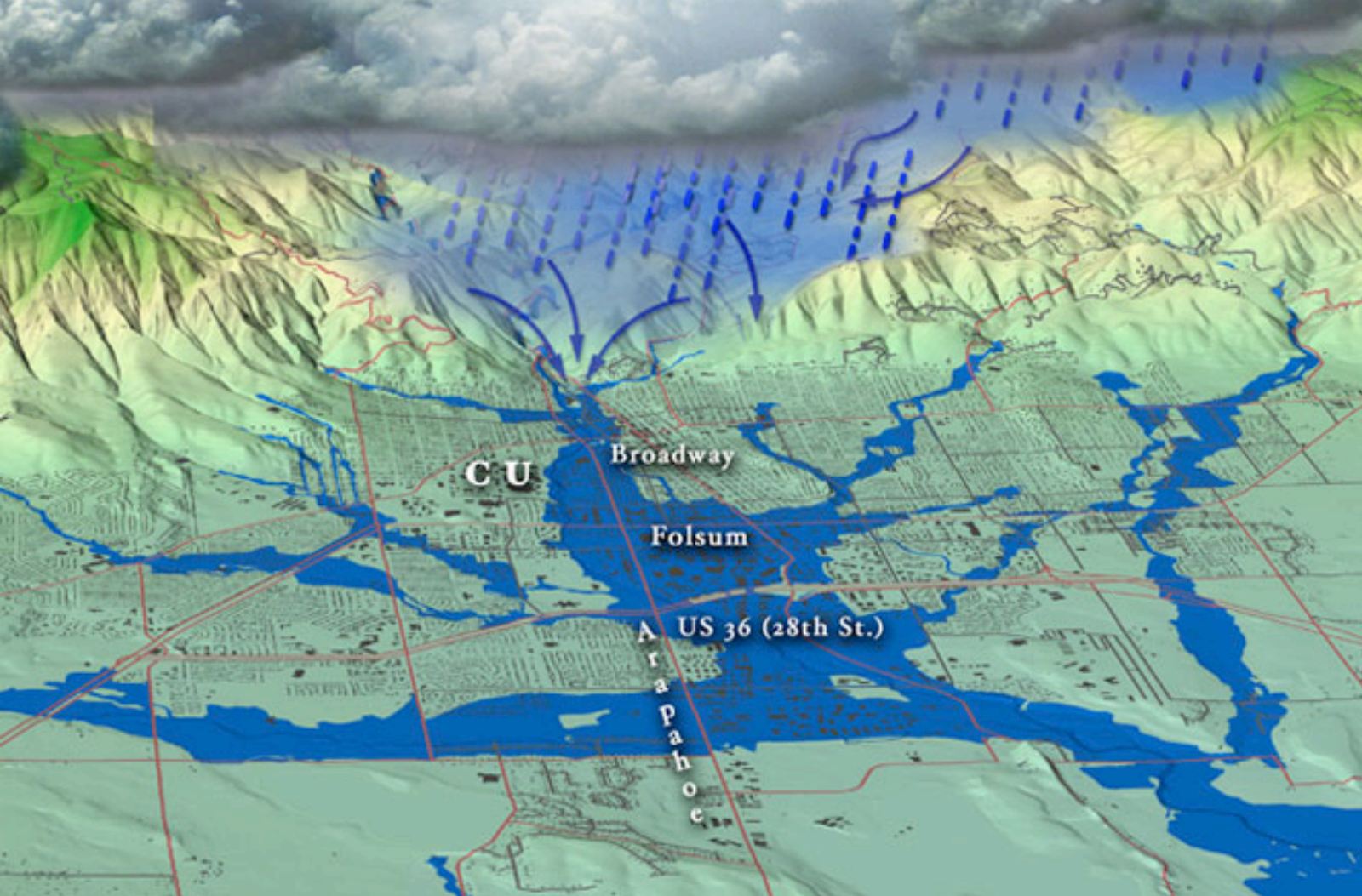Denver Post **Colorado** and industry working to assess damage in **flooded** oil fields

Vail Daily News **Colorado flooding** triggers oil spills, shutdowns

How to Outmaneuver Complexity?

Example: extreme weather near Boulder Colorado Sept. 2013

Events Cascade along Interdependencies

Physical Geography - canyons, flood plains,

Environment - fires, insects, drought, extreme rains

Human Activity Terrain - oil and natural gas, waste storage, pipe lines, expanding populations

**General Patterns Illustrated in Extreme Weather Events
Boulder CO Sept. 2013**

Operating in Seas of Complexity

- hidden dynamic **interdependencies**

- no matter how well planned, events will **challenge** boundaries

- produce **potential for surprise** and **cascade**

- how to prepare for **surprise**?

- how is system **brittle** and how does system bring **extra** adaptive capacity to bear?

- requires managing and sustaining **capacity for maneuver**

- how does the organization **anticipate**, sustain **readiness to respond**, and **learn** from challenge events?

- change inadvertently produce **unintended consequences** from **adaptive shortfalls**, people adapt to fill the gap.

- change opens new **niches** seized to better achieve goals which in turn open more opportunities triggering adaptive **florescence**.

Progression of concepts about 'Resilience'

- **rebound** from traumatic event (to equilibrium)

- more **robust**: expand 'base' capacity to handle disruptions

_____

Complex Adaptive Systems

- **brittleness** versus graceful degradation:

  bring 'extra' adaptive capacity to bear in the face of potential for surprise

- manage/regulate adaptive capacities:

  governance and architectures that tend to find hard limits in tradeoff spaces - **resilient control**

How to be Prepared to be Surprised?

Potential for surprise is related to
- the next anomaly or event that practitioners will experience and
- how that next event will challenge pre-developed plans and algorithms in smaller or larger ways.

To assess potential for surprise in a setting,
ask how the above generalization applies?
- *how do plans survive or fail to survive contact with events*?
- search for the kinds of situations and factors that challenge the **competence envelope** or *base adaptive capacity*

Uncovering Adaptive Histories

analyze cycles of [co-] adaptive reverberations across network

collecting, sharing, analyzing settings of resilience/ brittleness in action

patterns in Adaptive Cycles

Assessing the Precarious Present

more brittle than realized (miscalibration)
higher risk of 3 patterns of adaptive breakdown
unintended consequences dominate results from changes

where/how Precarious in Present

anticipate surprise for Resilient Future

Creating a Resilient Future?

how to manage and sustain Capacity for Maneuver (CfM) across units/roles/echelons for resilient control

common thread:
anticipate and mange risk of saturating control

patterns in Adaptive Cycles

Charting Cycles of Adaptation

Adaptive Cycles: charting how changes *reverberate* through networks

each response to change by some unit triggers adaptive responses across other units

where/how Precarious in Present

anticipate surprise for Resilient Future

Reverberation: the degree that *changes in one area tend to recruit or open up beneficial changes in many other aspects of the network* - which opens new opportunities across the network, ...

stall ⟵——————⟶ **florescence**

reverb

State of RE: wrt Adaptive Histories

reverb

stall ⟵⟶ **florescence**

patterns in Adaptive Cycles

**where/how
Precarious in Present**

**anticipate surprise for
Resilient Future**

State

- empirical, natural labs at scale
- general patterns - especially sub-patterns of stalls
- greatest success / unique contribution

Next Steps

- better representations of patterns in co-adaptive cycles
- more data on processes of florescence
- expand scales

common thread:

anticipate risk of saturating control

patterns in Adaptive Cycles

**where/how
Precarious in Present**

**anticipate surprise for
Resilient Future**

Precarious Present:
RE as a new form of risk analysis

- failure is due to brittleness
- collapses are puzzling
- unintended consequences result from adaptive stalls
- miss shortfalls and sources of resilience

- how does system stretch in face of surprise
- adaptive landscapes: stress-strain is most comprehensive
- measures of brittleness
- ↑ risk of falling into 3 patterns of adaptive breakdown
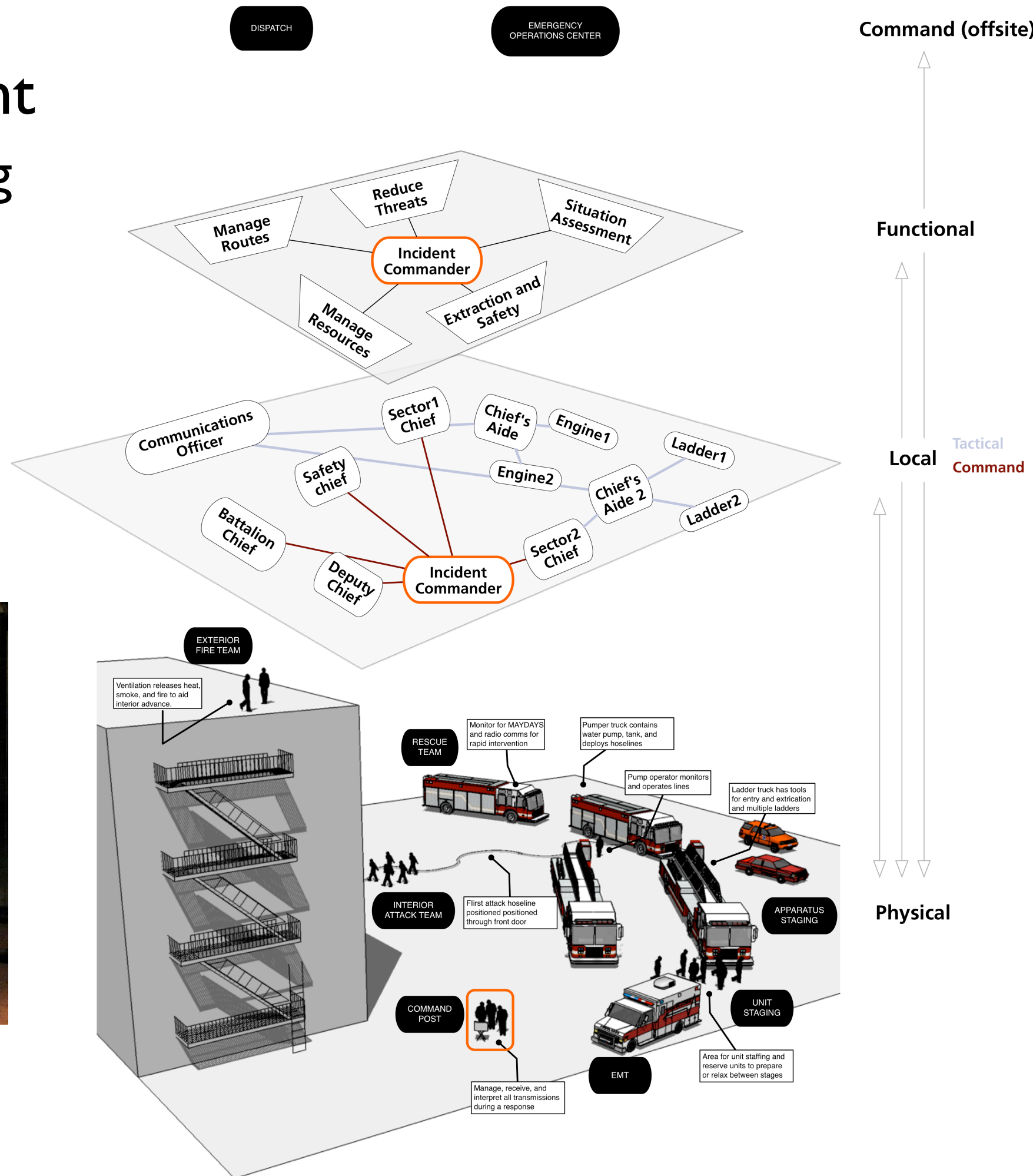- miscalibration wrt sources of resilience widespread

common threads:
miss bottlenecks ahead, squeeze other units
CfM, increasing risk of saturating control

Crisis Management

eg Urban Firefighting

~ distributed roles
~ multiple echelons
~ disrupting factors
~ multiple goals
~ interdependencies
~ all responsible in part

THE OHIO STATE UNIVERSITY

DISPATCH

EMERGENCY OPERATIONS CENTER

Command (offsite)

Functional

Local   Tactical   Command

Physical

Functional layer

Manage Routes

Reduce Threats

Situation Assessment

Incident Commander

Manage Resources

Extraction and Safety

Local / Tactical Command layer

Communications Officer

Sector1 Chief

Chief's Aide

Engine1

Ladder1

Safety chief

Engine2

Chief's Aide 2

Ladder2

Battalion Chief

Incident Commander

Sector2 Chief

Deputy Chief

Physical layer

EXTERIOR FIRE TEAM

Ventilation releases heat, smoke, and fire to aid interior advance.

RESCUE TEAM

Monitor for MAYDAYS and radio comms for rapid intervention

Pumper truck contains water pump, tank, and deploys hoselines

Pump operator monitors and operates lines

Ladder truck has tools for entry and extrication and multiple ladders

INTERIOR ATTACK TEAM

Flirst attack hoseline positioned positioned through front door

APPARATUS STAGING

COMMAND POST

UNIT STAGING

EMT

Area for unit staffing and reserve units to prepare or relax between stages

Manage, receive, and interpret all transmissions during a response

Maladaptive Patterns and Critical Incidents in Urban Firefighting
(Branlat et al., 2009)

Decompensation
- If request resources when need is definitive, it is already too late
- Regulate additional adaptive capacity (tactical reserves)
  ~ maintain **capacity for maneuver** (CfM=ability to handle next surprise)
  ~ "avoid all hands situations" (incident command)
- Bumpy transfers of control

Working at cross-purposes (both horizontal and vertical)
- Actions of one group increase threats to other groups (opposing fire hoses; rendering escape routes or protected areas unaccessible)
- Failure to resynchronize
- Goal priorities/conflicts in response to distressed firefighter

Getting stuck in outdated behaviors
- Failures to modify plan in progress as situation changes

# Patterns of Adaptive Breakdown - How Control Saturates

Complexities in time --> **Decompensation**: exhausting capacity to adapt as disturbances/challenges cascade.
   breakdown occurs when challenges grow and cascade faster than responses can be decided on and deployed to effect.

Complexities over scales --> **Working at cross-purposes**: behavior that is locally adaptive, but globally maladaptive
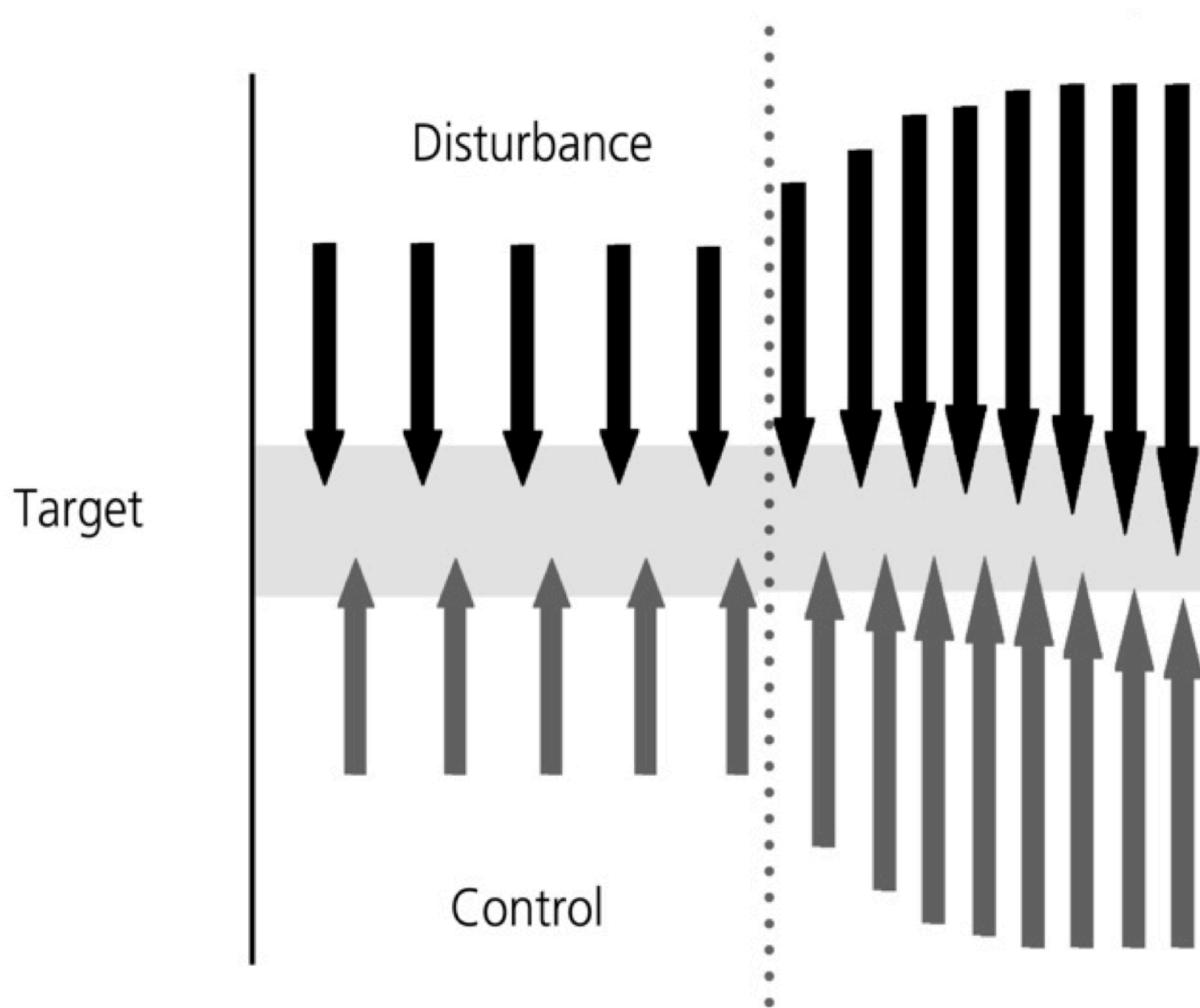   inability to coordinate across roles, units, & echelons as goals conflict.

Complexities in learning --> **Getting stuck** in outdated behaviors
   the world changes but the system remains stuck in what were previously adaptive strategies.
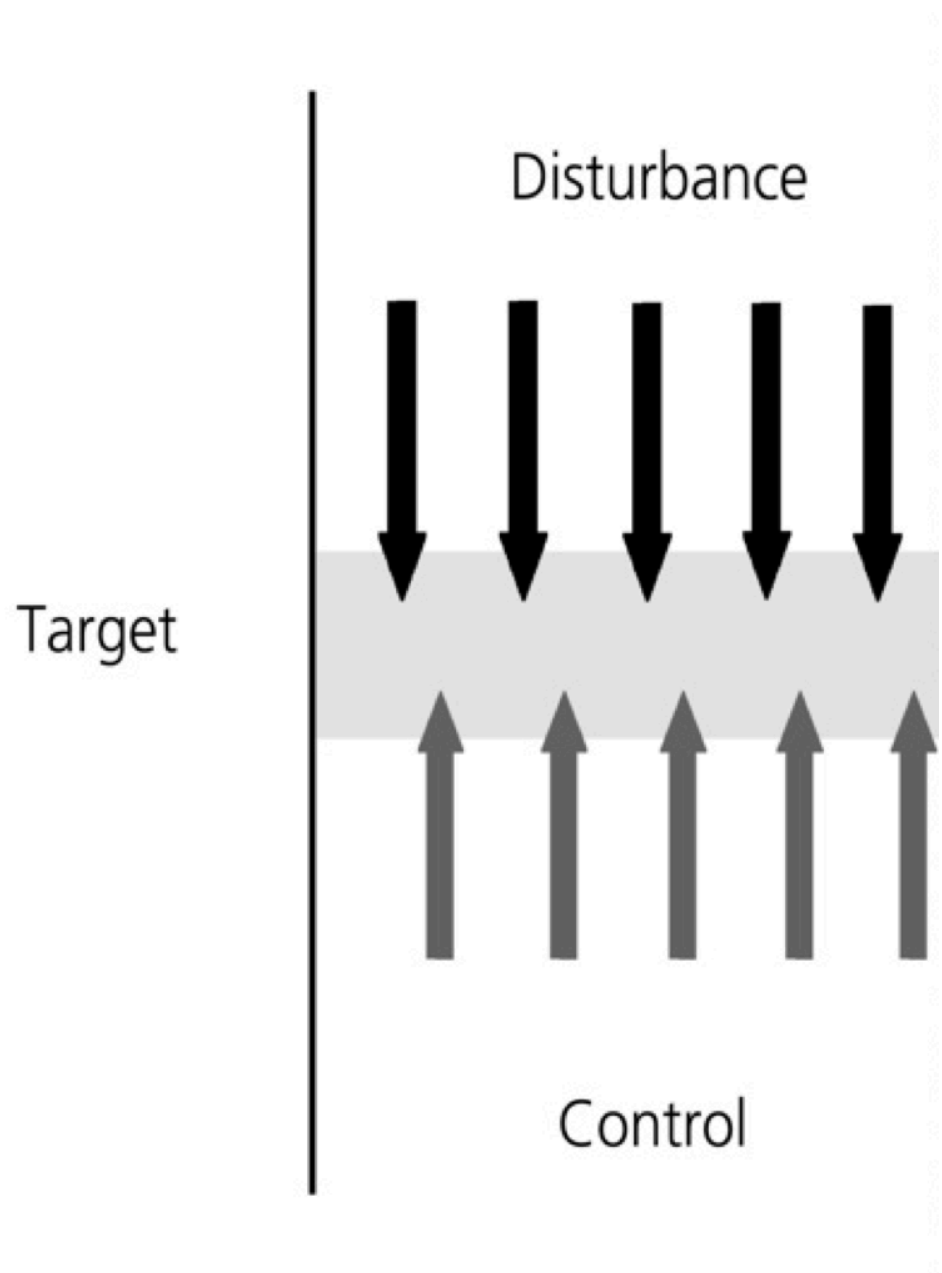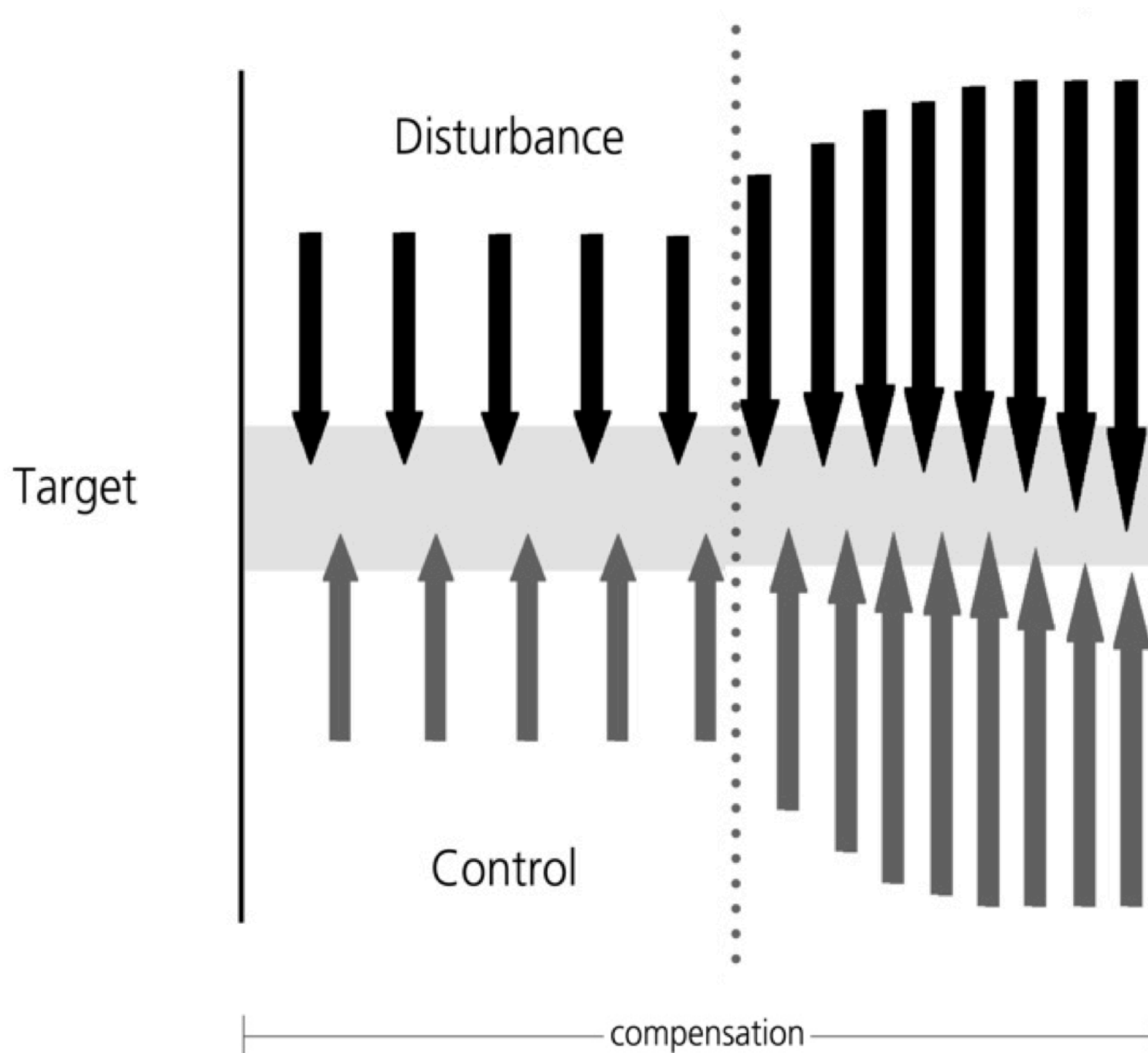
Disturbance

Target

Control

compensation

Complexity in Natural, Social & Engineered Systems

THE OHIO STATE UNIVERSITY

Anticipate bottlenecks ahead

new disturbances arise, grow, and cascade

Disturbance

Target

Control

compensation
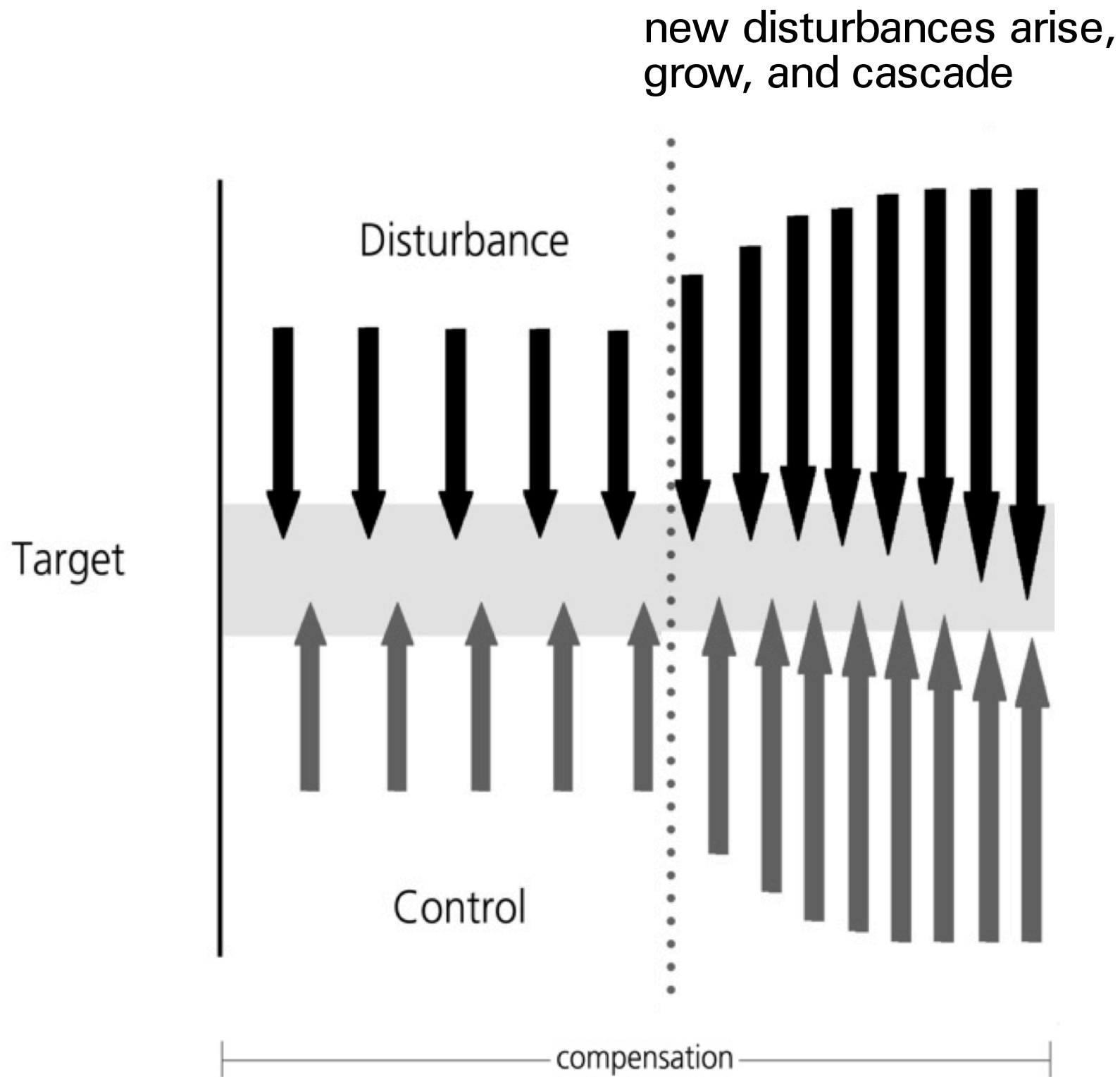
capacity to respond saturates as disturbances increase and cascade

Disturbance

Target

Control

decompensation
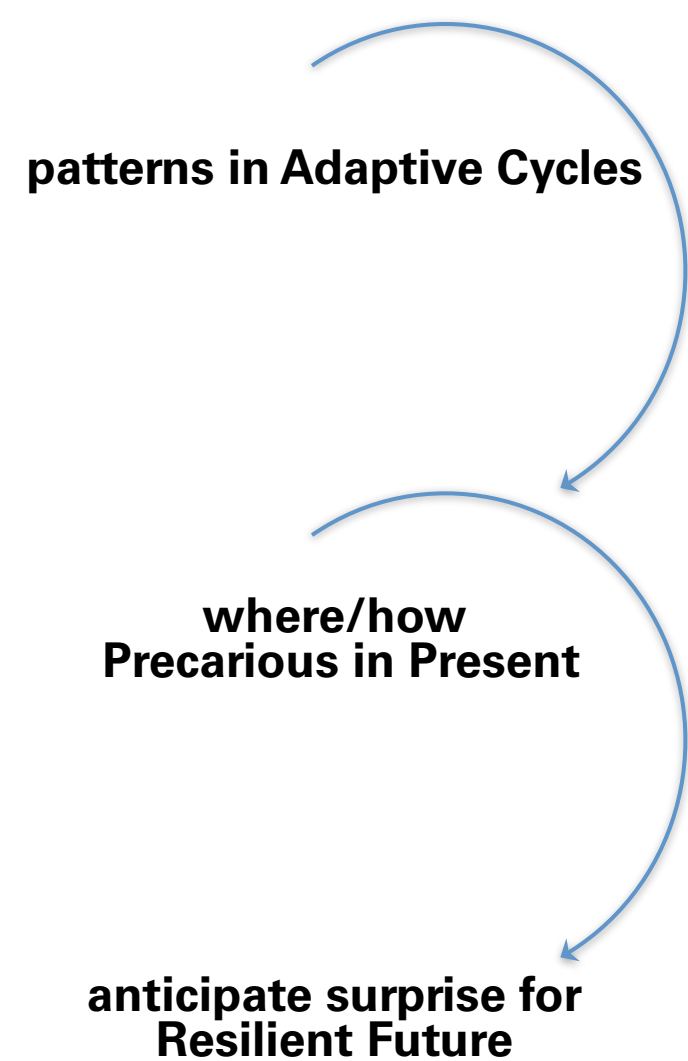
State of RE: wrt **Precarious Present**

State
- utilize adaptive landscapes to map changing fitness
- general patterns of stalls
- potential explanatory power
- slow progress on measures of brittleness

Next Steps
- new risk analysis on
  - ~ stalls in co-adaptive cycles
  - ~ 3 patterns of breakdown
- reduce miscalibration across perspectives
- more data on processes of florescence
- expand scales and cross scale interactions

patterns in Adaptive Cycles

where/how Precarious in Present

anticipate surprise for Resilient Future

**Resilient Future?:
RE as mechanisms for resilient control**

patterns in Adaptive Cycles

where/how
Precarious in Present

anticipate surprise for
Resilient Future

Agenda and Opportunities
- technical foundation ---> positive interventions (eng.)
- predicting unintended consequences
- assess and achieve stability of control - in the face of hidden interdependencies and shape of surprise to come

- saturation of control
- build resilient control - regulate Capacity for Maneuver across centers of adaptive behavior
- existence proofs for (biology, human systems)
- integrate fundamental trade-offs
- new architectures for multi-role multi-echelon networks of centers of adaptive behavior

common thread:
anticipate bottlenecks ahead to manage risk of saturating control

Complex Adaptive Systems

Anomalies are what happens when something else was planned; whatever the plan, something else always happens

Given finite resources, uncertainty, and change:

Algorithms/Plans/Models   vs.   Complexity/Variability/Surprise

Events inevitably challenge boundary conditions -->
brittleness, literal-mindedness ('right' thing in the wrong world)

Fundamental tradeoffs
   ~ optimality - brittleness (Doyle)
   ~ acute-chronic (FBC, Woods)
   ~ efficiency-thoroughness (Hollnagel)

Resilient Control Architectures balance improving plans with preparing for surprise (existence proofs in biology & human systems)

Monitor/Regulate **Capacity for Maneuver** *CfM*:

Cushion of potential actions and additional resources that allows the system to continue functioning despite unexpected demands.

How much active control margin or capability is left to handle the next event or disturbance?

Failure to maintain a margin of CfM leaves the system too brittle and increases the risk of falling into the maladaptive traps (eg, locally adaptive, globally maladaptive)

Each adaptive unit works to create, maintain, and manage their margin of maneuver.

Resilient systems are able to anticipate how capacity for maneuver is expanding or contracting relative to the potential for surprise.

Adjust *CfM* to avoid risk of saturating control

Strong Angel future of crisis management drill 2008

Uncovering Adaptive Histories

analyze cycles of [co-] adaptive reverberations across network

collecting, sharing, analyzing settings of resilience/brittleness in action

Assessing the Precarious Present

more brittle than realized (miscalibration)
higher risk of 3 patterns of adaptive breakdown
unintended consequences dominate results from changes

Creating a Resilient Future

how to manage and sustain Capacity for Maneuver (CfM) across units/roles/echelons in a network exercising resilient control

common thread:

anticipate and mange risk of saturating control

there are
Laws that Govern the Adaptive Universe

support ability to
Outmaneuver Complexity

help you answer
Is it Safe to Simplify?
(sometimes, not for too long, not without energy)

Can You Engineer Resilience?
(overcome tendency to underestimate brittleness)
yes

monitor at the *borderlands*,
anticipate changing *risks* of adaptive breakdown,
adjust **readiness to respond**,
remain **open to learn** and revise as change occurs

sustain the ability to prepare for surprise at the boundaries
by escaping oversimplifications