Complexity and Variety: Twin Pillars of Resilience

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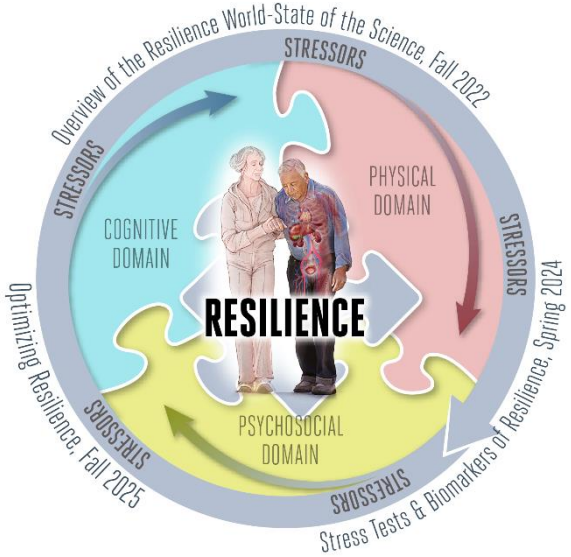


The One-hoss Shay!

- Have you heard of the wonderful one-hoss shay,
  That was built in such a logical way
  It ran a hundred years to a day,
  And then, of a sudden, it-oh, but stay,
  I'll tell you what happened without delay …
  You see, of course, if you're not a dunce,
  How it went to pieces all at once,
  All at once, and nothing first,
  Just as bubbles do when they burst.
  End of the wonderful one-hoss-shay.
  Logic is logic. That's all I say

Oliver Wendell Holmes Sr. (from "The Deacon's Masterpiece")

Alas!

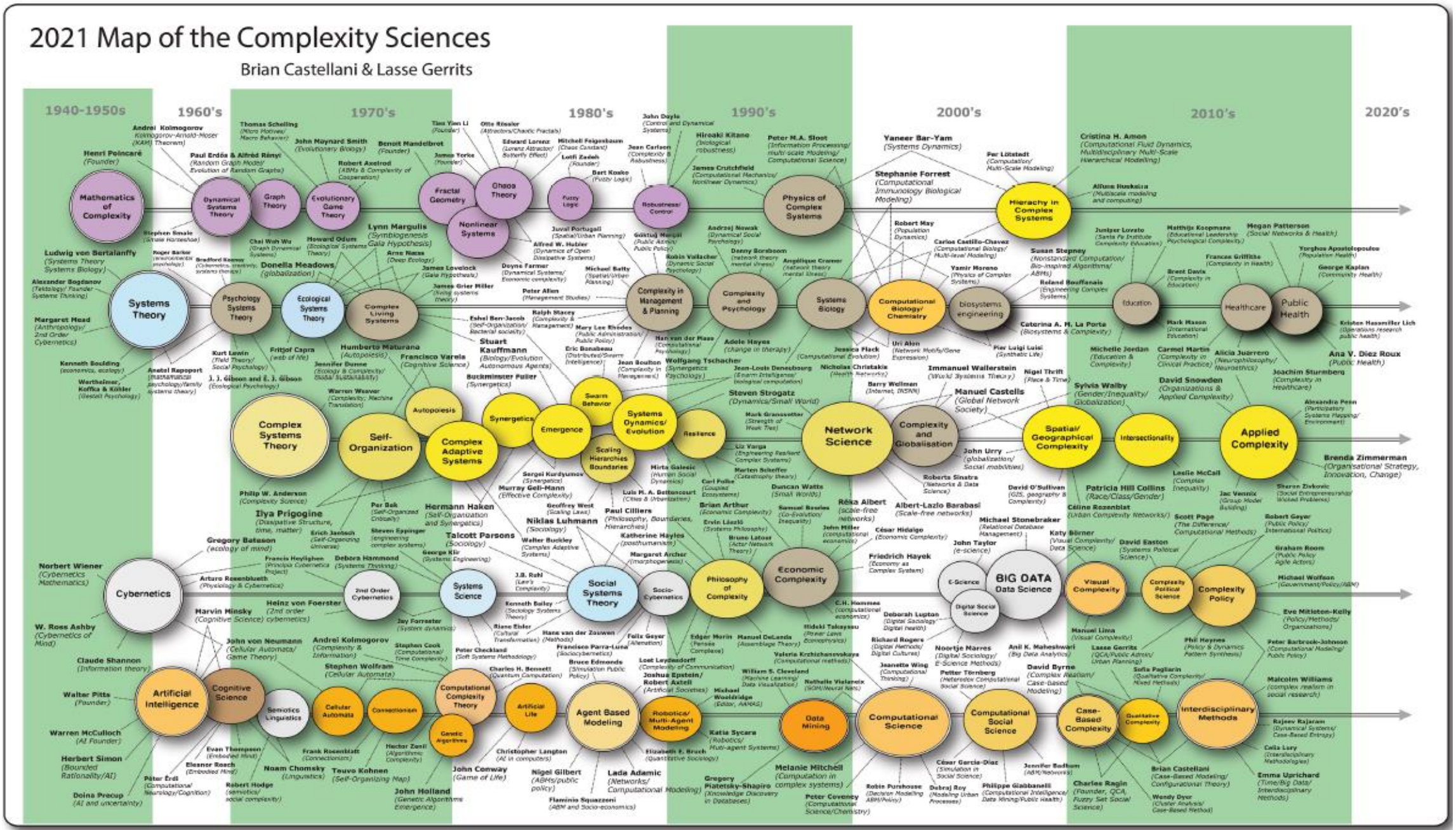
- Unfortunately (or fortunately!), human beings are not designed so perfectly logically and uniformly
- Life would be too insipid
- Variety is the spice of life!
- Complexity and variety are the hallmarks of biological systems

Complexity

What is Complexity?

- Complexity is a difficult notion that eludes precise definition and simple characterization
- Complexity science has evolved since 1950s (systems theory, cybernetics, algorithmic complexity, chaos and nonlinear dynamics, complex adaptive systems, systems biology)

What is Complexity?



What is Complexity?

- *Complex system is hierarchical containing layers of subsystems (spanning multiple spatial and temporal scale), each with heterogeneous components, interacting (nonlinearly) within and across layers in multifarious ways, with the consequence that the response (or adaptation) of the system to (external and internal) perturbations is difficult to explain, control, and predict*
- *Explanation* – giving an account of causal structure (why did it happen?)
- *Control* – ability to guide/limit/bound the response of the system
- *Prediction* – ability to pre-determine the response of the system to perturbation

Architecture of Complexity

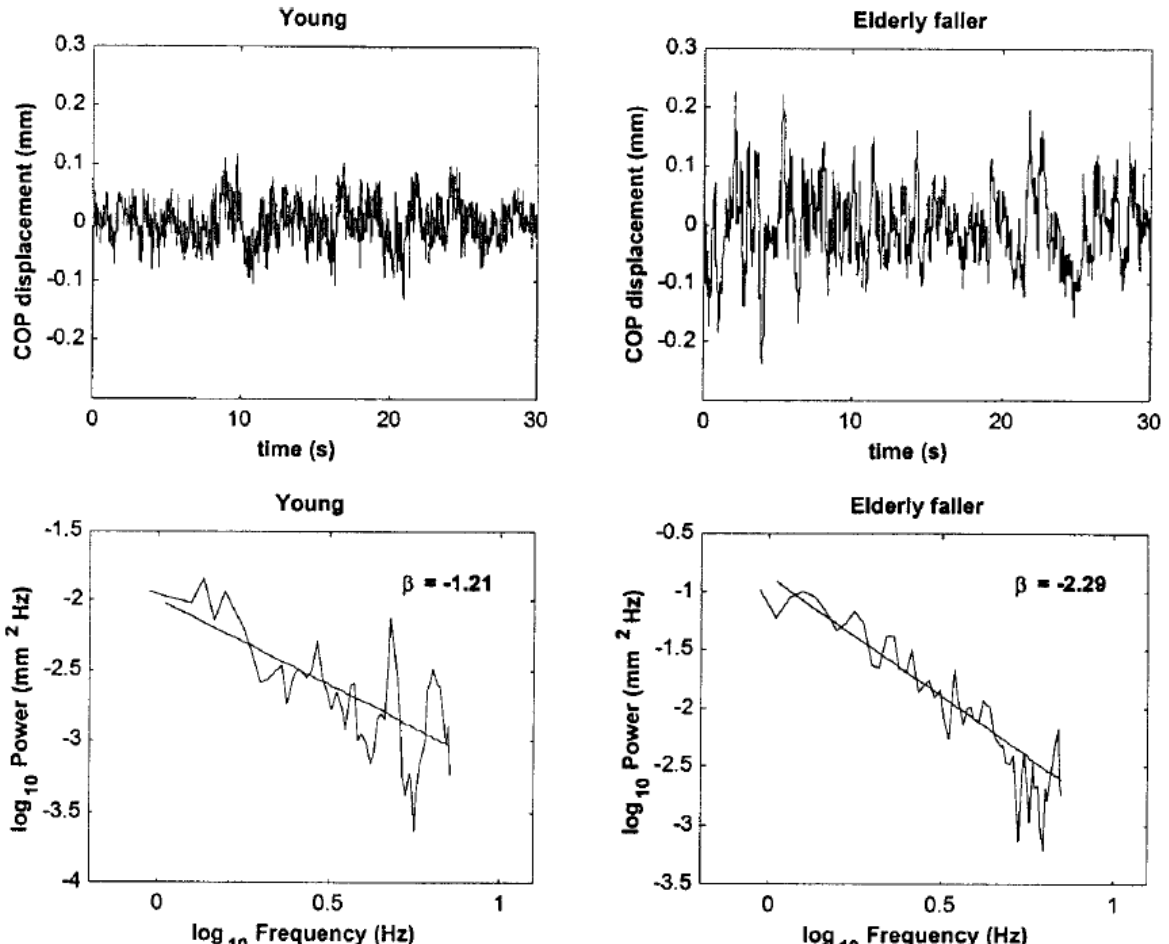
- Herbert Simon (1960) argued cogently that hierarchical structure is an essential element of architecture of complex systems
  - Fundamental particles of physics, nuclear particles, cells, tissues, organs, people, society, countries, planets, galaxies, … ("Powers of 10")
- Evolution employs hierarchical design to *efficiently* create higher-level organisms from basic elements
- Complex systems are not simply hierarchical like nested Russian dolls
- Due to a web of multi-level interactions, they are *not fully decomposable*
- Some aspects of complex systems may be nearly decomposable due to weak interactions (traditional reductionism provides good account of system behavior)
- Other aspects of the system may not be decomposable due to strong interactions (new approaches are needed)
- Bidirectionality is highlighted (downward, as well as upward causation)

Complexity, Aging, and Resilience (Lipsitz 2002)

- Healthy physiologic systems exhibit complex (seemingly irregular) dynamics
- Represents interaction of regulatory processes across multiple spatial and temporal scales
- When perturbed, the system invokes a closed-loop response to restore equilibrium ("*reactive tuning*")
- Aging and disease are associated with a loss of complexity in basal dynamics and maladaptive response to perturbations
- This loss of complexity leads to functional decline and vulnerability to stressors

Complexity and Aging

- Quantifying the dynamics of physiologic signals using spectral analysis and nonlinear mathematics
- For instance, aging is associated with a loss of long-range correlations (deviation from *1/f* pattern)



Variety

Ashby's Law of Requisite Variety

- Ross Ashby (1903-1972) – English psychiatrist & systems theorist
- He formulated laws that govern the regulatory processes in living things and machines
  - Ashby is one of the pioneers of cybernetics – the science of communication and control
- Mathematical characterizations of physiological concepts such as homeostasis, adaptation, memory, and foresight (anticipatory)
- Frailty is often viewed as the decreased ability to recover from disturbances that is due to loss of adaptive capacity
- Ashby's theory could provide insights for studying resilience and frailty

Law of Requisite Variety

- Consider a dynamical system that can be exposed to one of several disturbances D
- System can deploy one of several responses R to cope with D
- R typically includes control mechanisms such as feedback, feedforward, and buffering
- System can achieve one of several states denoted by E
- If the system has a sufficiently wide repertoire of responses (i.e. sufficiently large R) relative to D, then it can achieve any of the favorable states within E with a high probability
- “Only variety in R can force down the variety due to D; variety can destroy (absorb) variety”

Law of Requisite Variety

- We will use H(.), Shannon's entropy, to quantify variety,

$$H(X) = -\sum_i^K P(Xi) \log_2 [P(Xi)]$$

where X is a random variable with K possible values with a probability mass function P(X)

- The larger the entropy, the greater the information (uncertainty)
- Ashby's law states: $H(E) \geq H(D) + H(R \mid D) - H(R)$
- The goal of the system is to achieve control by reducing the uncertainty in E, i.e. to minimize H(E)
- Goal of the regulatory system is to achieve a smaller desirable subset of E (those states that are viable for the organism) with a high probability

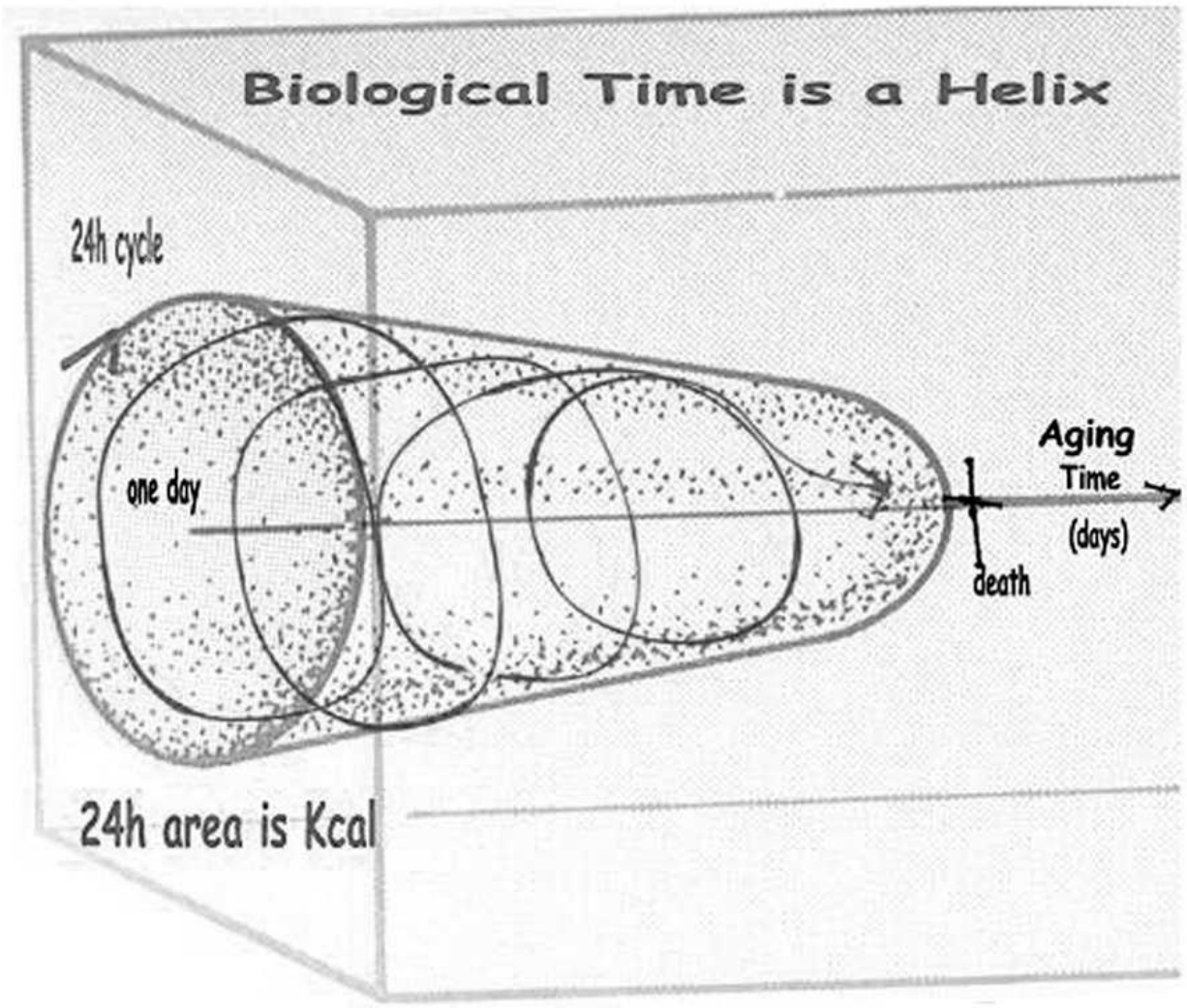
Law of Requisite Variety

- Ashby's law: $H(E) \geq H(D) + H(R|D) - H(R)$
- RHS should be minimal in a healthy organism
- H(D) can be decreased by limiting exposure to disturbances
- H(R) can be increased
- H(R|D) can be minimized, even made 0, if the system knows how (and is able) to respond to every disturbance to achieve a desirable state within set E (c.f. Lew Lipsitz' reactive tuning!)

Law of Requisite Variety

- Frailty may be the consequence of both a decrease in H(R) and an increase in H(R|D)
- H(R) loss of complexity and the constriction of physiological space associated with frailty
- H(R|D) is the increase in uncertainty in finding an appropriate response to a disturbance (loss of reactive tuning)
- H(R|D) is the loss of adaptive capacity
- In fact, as H(R|D) decreases the system may compensate by limiting the range of exposures, i.e. by decreasing H(D) - the constriction of life-space associated with frailty

Constriction of Physiological Space



(courtesy: Eugene Yates)

Constriction of Life Space

"As a younger person he was fully engaged in running his farm, including the surrounding hills. As a 75 year old, he was somewhat impaired in his mobility. Thus, he concentrated on his garden. As a 90 year old, he could hardly walk and his hearing and sight were impaired. At that time, his houseplants received special care. Later he focused on the flowers on the window hedge near his chair in the living room. The window became a center of his goal striving and subjective well-being."

(Gilbert Brim, Ambition 2000)

- Life-space is a fascinating measure of health and physiological reserve of older adults
- Allmann and Barker (UAB) developed an instrument (LSA) to measure this

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UAB STUDY OF AGING LIFE-SPACE ASSESSMENT

Interview (Follow-up) Month
○ 8 ○ 1 ○ 6 ○ 12 ○ 18 ○ 24 ○ 30 ○ 36 ○ 42 ○ 48 ○ 54 ○ 60

Subject Number ☐☐☐☐☐☐

Date: ☐☐ / ☐☐ / ☐☐☐☐

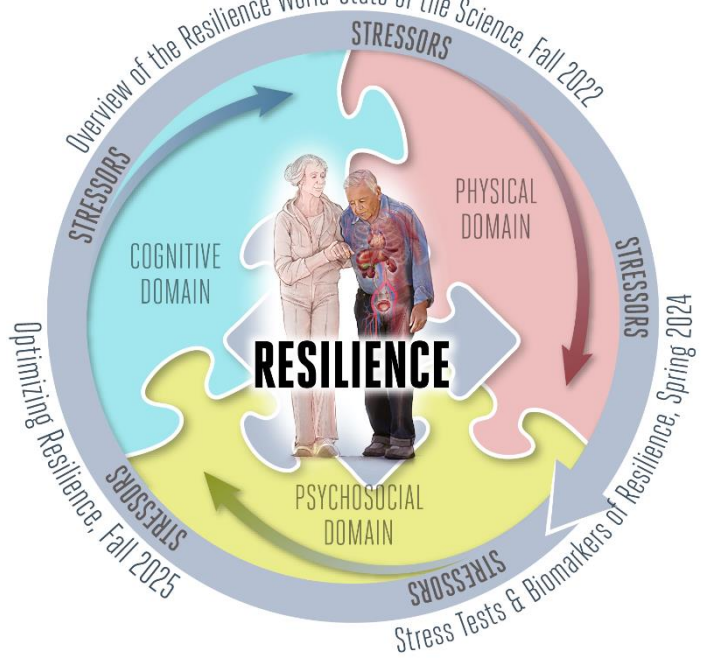
THE NEXT QUESTIONS REFER TO YOUR ACTIVITIES JUST WITHIN THE PAST MONTH. DURING THE PAST FOUR WEEKS HAVE YOU . . .			A. IN THE LAST FOUR WEEKS, HOW OFTEN HAVE YOU BEEN TO (Name of appropriate Life-space)? Frequency				HOW DID YOU GET THERE? B. DID YOU USE AIDS OR SPECIAL EQUIPMENT TO GET TO (Name of Life-space)?		C. DID YOU NEED HELP FROM ANOTHER PERSON TO GET TO (Name of Life-space)?	
☐☐ Subject Status	Yes	No	Less than once a week	1-3 times a week	4-6 times a week	Daily	Yes	No	Yes	No
BEEN TO OTHER ROOMS OF YOUR HOME besides the room where you sleep? *LIFE-SPACE 1**	○	○	○	○	○	○	○	○	○	○
BEEN TO AN AREA OUTSIDE YOUR HOME such as your porch, deck or patio, hallway (of an apartment building) or garage, in your own yard or driveway ? *LIFE-SPACE 2*	○	○	○	○	○	○	○	○	○	○
BEEN TO PLACES IN YOUR NEIGHBORHOOD, other than your own yard or apartment building? *LIFE-SPACE 3*	○	○	○	○	○	○	○	○	○	○
BEEN TO PLACES OUTSIDE YOUR NEIGHBORHOOD, but within your town? *LIFE-SPACE 4*	○	○	○	○	○	○	○	○	○	○
BEEN TO PLACES OUTSIDE YOUR TOWN? *LIFE-SPACE 5*	○	○	○	○	○	○	○	○	○	○

*PERSONS WHO RESPOND "NO" TO LIFE-SPACE 1 ARE ASSIGNED TO LIFE-SPACE 0.

Concluding Remarks

- Complexity and variety are hallmarks of living organisms
- Lipsitz and others (e.g., Cohen et al 2022) have articulated the potential of complexity science
- Can insights from complexity improve control? prediction? suggest interventions?
- The law of requisite variety can provide useful insights for understanding and enhancing resilience of older adults
- For example, promoting variety in the activities of older adults (cognitive challenge, physical exertion, social interaction, spiritual disciplines) can be a powerful strategy for enhancing resilience
- Resilience goes beyond individual: family and societal support mechanism can enhance resilience by increasing H(R) and lowering H(R|D)

Thank you!


Overview of the Resilience World-State of the Science, Fall 2022
STRESSORS
STRESSORS
PHYSICAL DOMAIN
COGNITIVE DOMAIN
RESILIENCE
PSYCHOSOCIAL DOMAIN
STRESSORS
STRESSORS
Optimizing Resilience, Fall 2025
Stress Tests & Biomarkers of Resilience, Spring 2024