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Formalizing the Panarchy Adaptive Cycle with the Cusp Catastrophe

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Formalizing the Panarchy Adaptive Cycle with the Cusp Catastrophe

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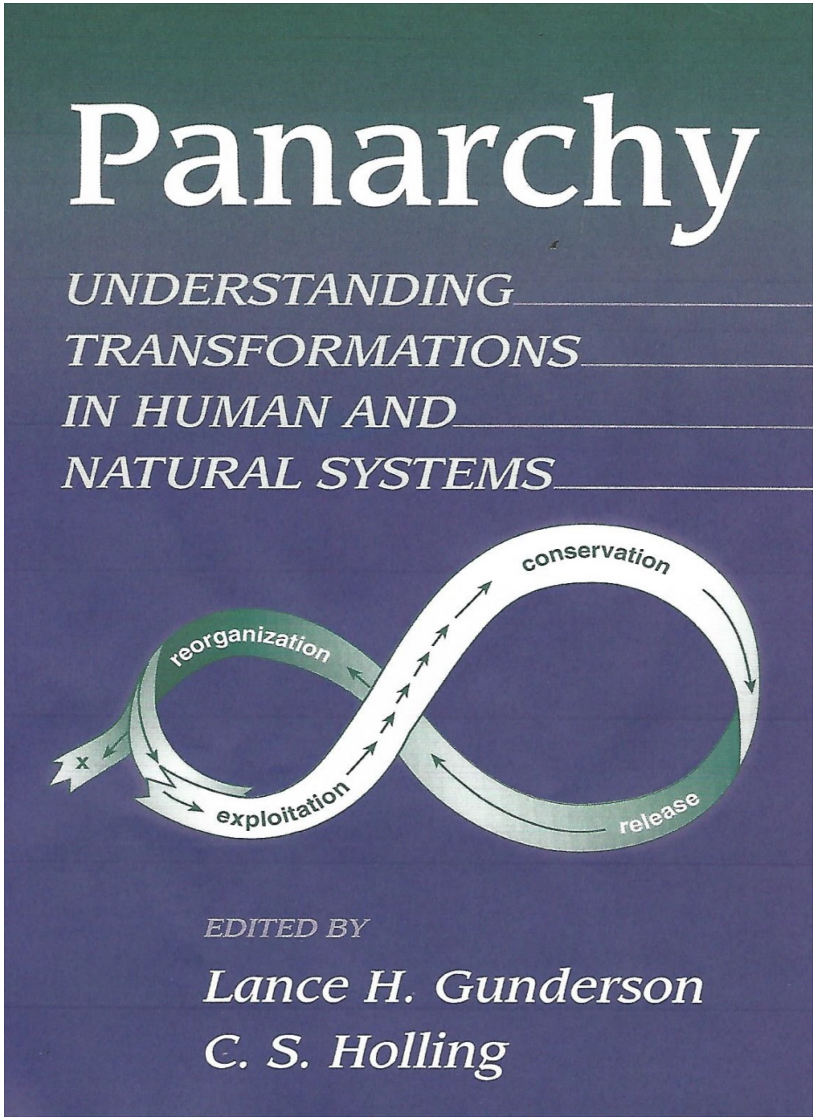
Abstract

The panarchy adaptive cycle, a general model for change in natural and human systems, can be formalized by the cusp catastrophe of René Thom's topological theory. Both the adaptive cycle and the cusp catastrophe have been used to model ecological and socio-economic systems in which slow & small continuous changes in two control variables produce fast & large discontinuous changes in system behavior. The panarchy adaptive cycle has been used so far only for qualitative descriptions of typical dynamics of such systems. The cusp catastrophe, while also often employed qualitatively, is a mathematical model capable of being used quantitatively.

If the control variables from the adaptive cycle are taken as the parameters in the equation for the cusp catastrophe, a cycle very similar to the adaptive cycle can be constructed. Formalizing the panarchy adaptive cycle with the cusp catastrophe may provide direction for more rigorous applications of the adaptive cycle, thereby augmenting its usefulness in guiding sustainability efforts.

- Adaptive Cycle
- Cusp Catastrophe
- Modeling Adaptive Cycle with the Cusp
- Discussion

Adaptive Cycle



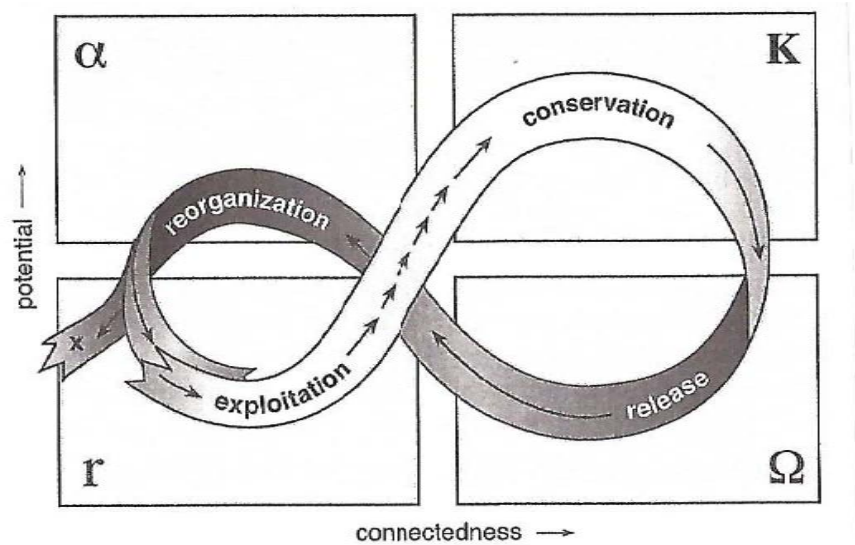
Adaptive Cycle

- Theory developed by Holling & colleagues
- Applicable to ecological & socio-economic systems
- AC is a three-variable model
- Potential = function(connectedness, resilience)

- Potential = ‘capital’ of system, e.g., biomass, assets
- Connectedness = strength, pervasiveness of network of relations
- Resilience = basin structure of dynamic system => basin stability
  - Closeness of attractor to basin boundary, size of basin, etc.

- AC is “archetypal” behavior, but other behaviors are possible
- “Panarchy” applies the AC to multiple spatial-temporal scales
- AC is an extension of familiar S-shaped (r-K) growth model

Adaptive Cycle



- G&H, p.34: P, potential; C, connectedness; R = resilience
- **r-phase** (*exploitation*): Exponential increase of dominant species: C ↑, P ↑, R ↑
- **K-phase** (*conservation*): Complexification; C ↑ (until over-connected), P ↑↓(peaks), R ↓
- **Ω-phase** (*release*): Collapse: C ↓, P (major drop) ↓
- **α-phase** (*reorganization*): "Hundred flowers blossom": C ↓, P ↑↓ (minor drop), R ↑

Cusp Catastrophe

- Part of Rene Thom's catastrophe theory
  - Popularized by E.C. Zeeman
- Applicable to systems of widely differing type in natural/social sciences

- Theory rigorously applies only to gradient systems, $dy/dt = k\, dV/dy$
  - y is state ("behavior," "effect") variable or vector
  - V is "potential" – NOT related to "potential" of AC
  - $V = V(y, x)$, where x is a control ("causal") parameter or vector of parameters

- This is a topological theory
  - Applies only "near" the singularity
  - Equilibrium surfaces can be stretched but not torn. (Will use this later…)
  - Topological character makes empirical testing difficult but not impossible

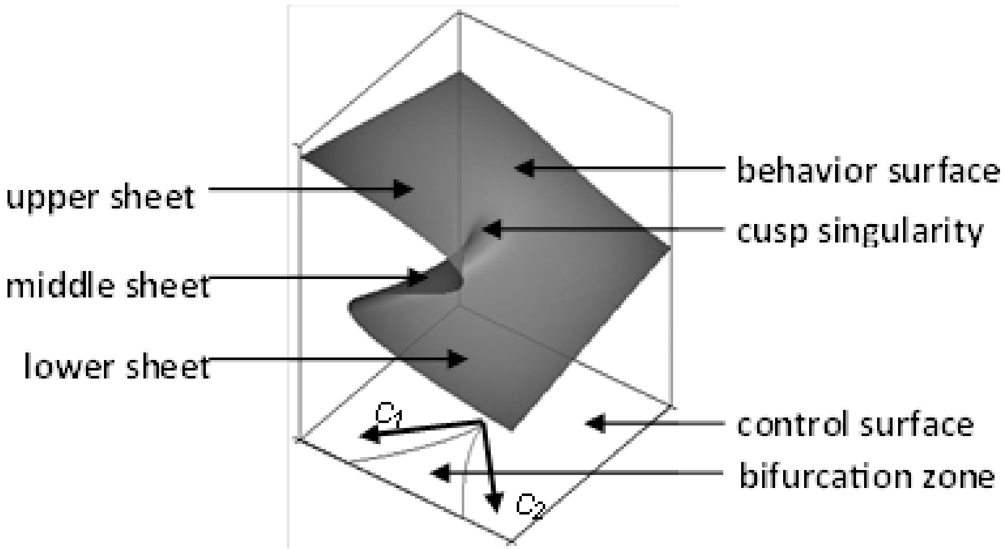
Cusp Catastrophe

- Cusp catastrophe is an "elementary" catastrophe; these ECs are limited to ≤ 5 control parameters
- Cusp is a three-variable (2 control parameters) model: y, n, s

- Potential, V, that is maximized/minimized by gradient system is:
- $V = \frac{1}{4} y^4 - n\, y - \frac{1}{2} s\, y^2$
  - 1 behavior (effect) variable, y
  - 2 control (causal) parameters, n & s, normal & splitting factors
- Alternative control parameters: conflicting factors c_1 & c_2, which are sum & difference of n & s

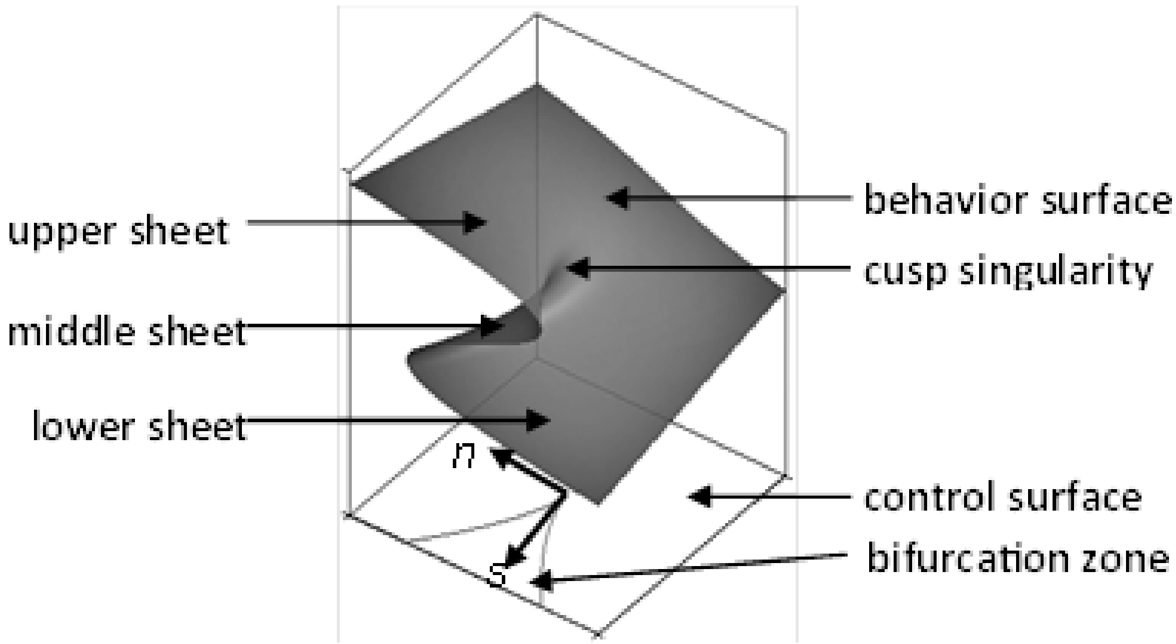
- Behavior (equilibrium) surface: $dy/dt = dV/dy = 0 = y^3 - n - s\, y$
- Behavior surface is bimodal, with a 3rd inaccessible surface

Cusp Catastrophe



- Vertical dimension = behavior variable, y
- Control parameters = conflicting factors c_1 & c_2
- Behavior (equilibrium) point always above control point

Cusp Catastrophe



- Vertical dimension = behavior variable, y
- Control parameters = normal & splitting factors, n & s

Cusp Catastrophe

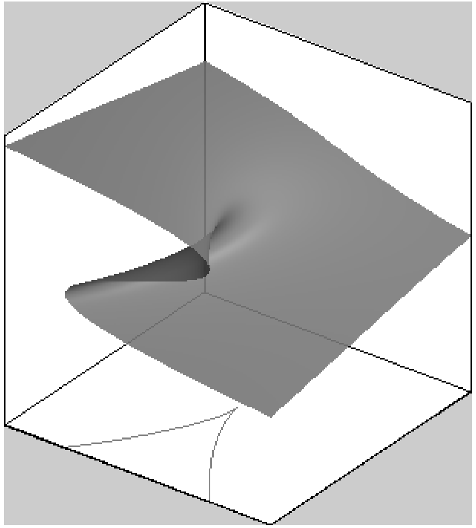
- User (*not* catastrophe theory) specifies trajectory of control parameters
  - In applying CC to AC, we'll assume elliptical trajectory
  - Alternatively, a back-and-forth trajectory would show hysteresis

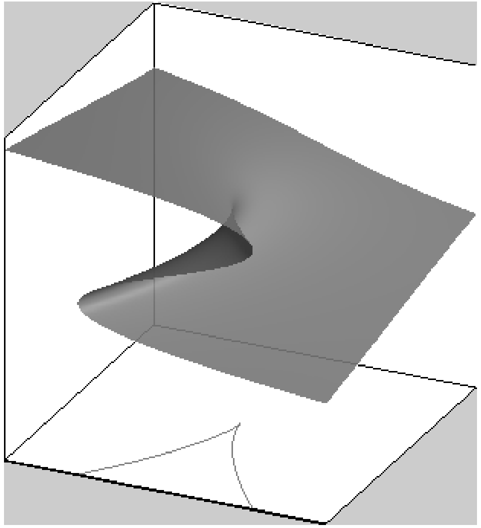
- Catastrophe theory then specifies motion of state variable above the control point on behavior surface

- Basic CT dynamics can be augmented by
  - Stochasticity of control or behavior point
  - Feedback of state variable, y, on control parameters, x

Cusp Catastrophe

- Simulations: user-specified trajectories (green) & resulting behavior (red)
- For motion in normal direction, back-and-forth generates hysteresis
- Splitting Normal Cyclic



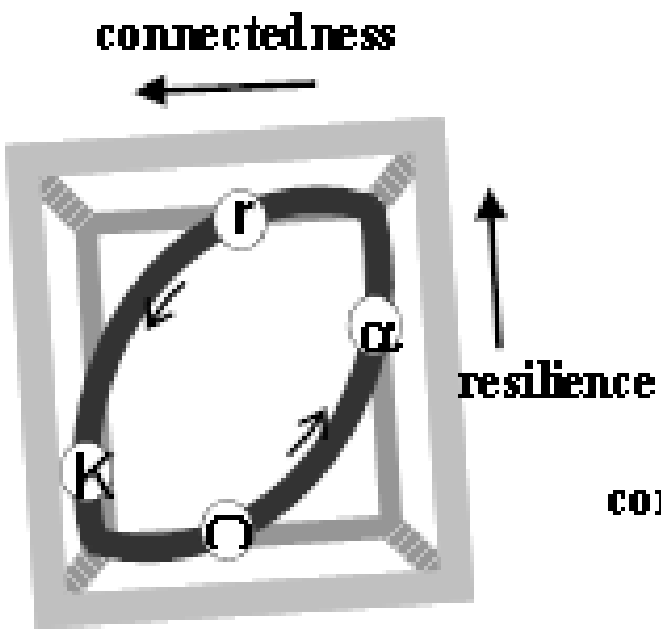


Modeling the AC with the CC

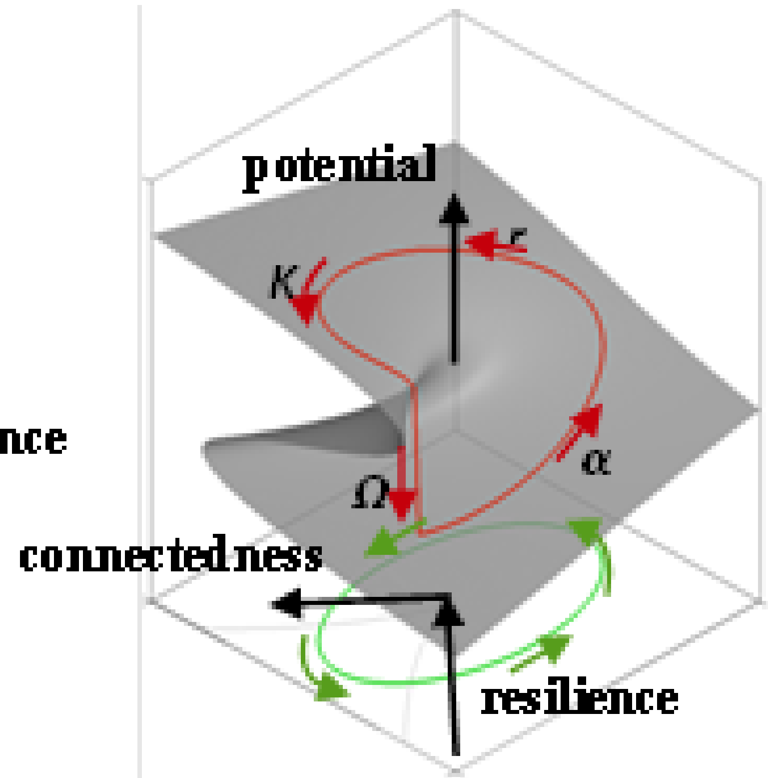
- Both AC and CC have 1 effect and 2 cause variables
- In both, continuous causal change => discontinuous effects
- Take AC potential as the behavior variable and connectedness, resilience as the control parameters of the Cusp
- Assume elliptical control point trajectory (or similar closed path)

Modeling the AC with the CC

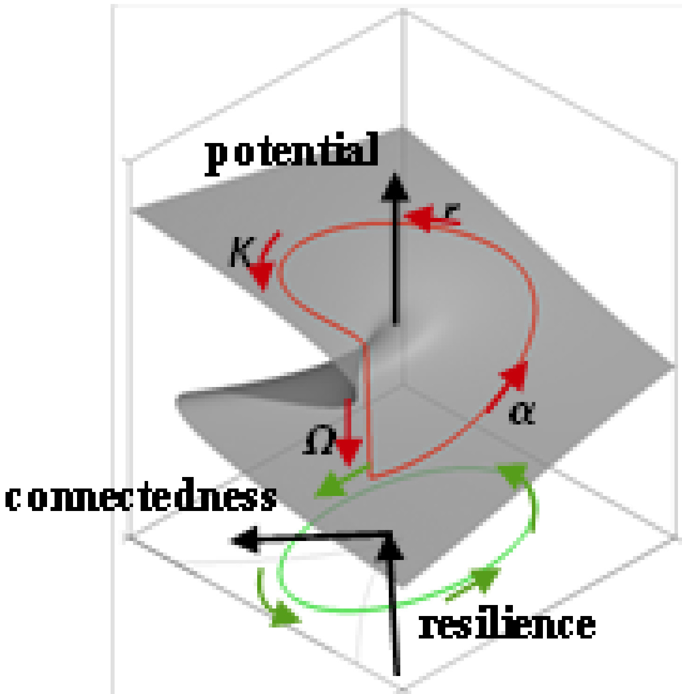
Adaptive cycle



Modeled with cusp catastrophe

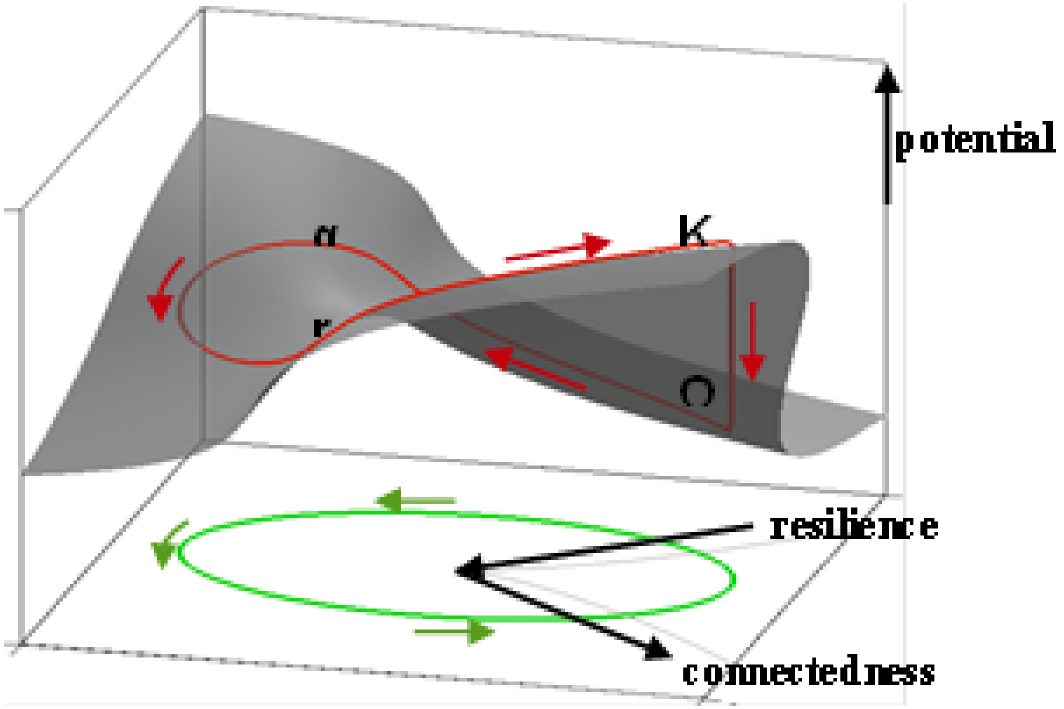


Simulating the AC with the CC



Modeling the AC with the CC

Taking advantage of topological character of theory:
adding 2nd (less prominent in AC theory) drop in potential in α-phase



Discussion

- Modeling AC with Cusp implicit (but *not* explicit) in Gunderson & Holling book: Scheffer et al (e.g., p. 207) refer to & show "catastrophic folds," which exhibit hysteresis (stress = normal factor):

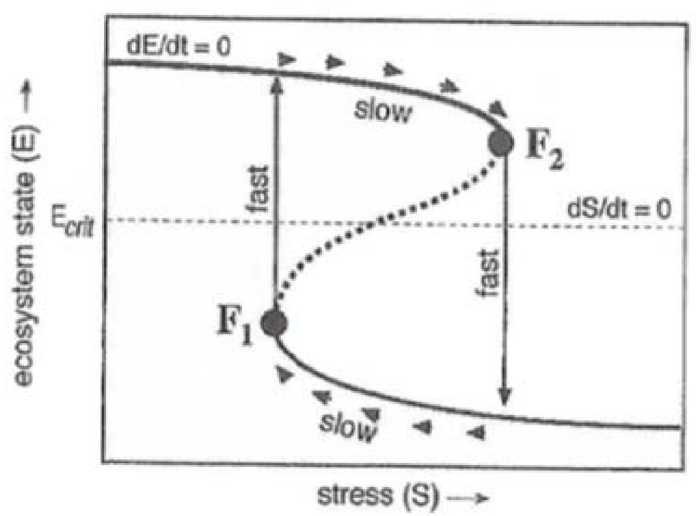


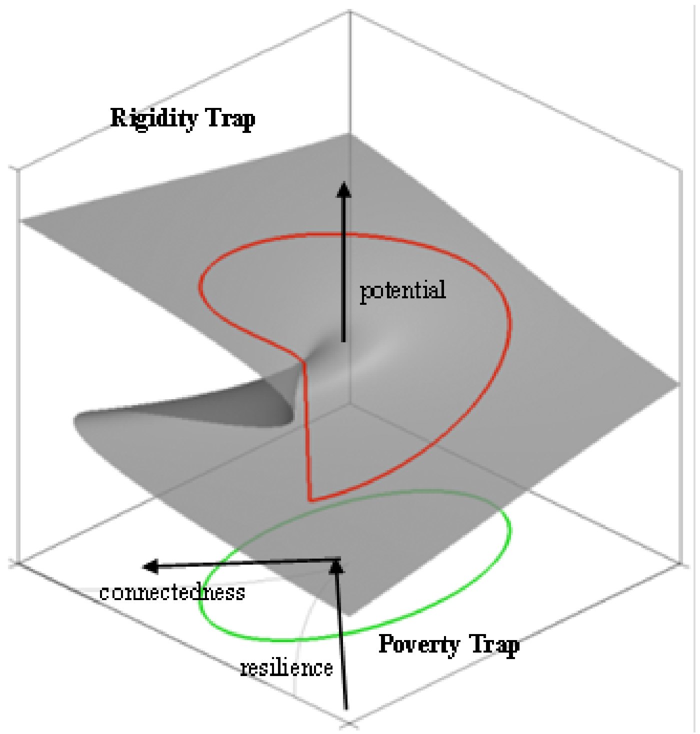
Figure 8-5. Cycles can occur if stress (S) responds in a dynamic way to ecosystem state such that below a critical level of the state indicator (E_{crit}), stress decreases slowly, whereas above that level, it increases.

Discussion

- Also, spruce budworm model by Holling and other ecological models explicitly use CT
- While other frameworks might formalize AC, CC is a “natural” way of doing so
- Why didn’t G&H propose this? We don’t know, but…
- Controversy over catastrophe theory (over-reaction to hype by Zeeman) may account for non-explicitness in G&H

Discussion

- Other paths/locations of CC control point might help model other (non-archetypal) possibilities discussed in panarchy literature:
- “poverty trap”: low connectedness, resilience, & potential
- “rigidity trap”: high connectedness, resilience, & potential



Discussion

- Conclusion: Comparison of the panarchy adaptive cycle, a general model of change in natural and human systems, with the cusp catastrophe shows that the adaptive cycle can be formalized by this elementary catastrophe. Other ways of formalizing the adaptive cycle are possible, but the widespread use of the cusp in ecological modeling makes this a natural approach to formalization.

- By using the control variables from the adaptive cycle as parameters in the behavior equation for the cusp catastrophe, a cycle very similar to the adaptive cycle can be constructed. Modeling the adaptive cycle with the cusp may provide direction for more rigorous and diverse applications of the panarchy framework.

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- Thank you

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