

Mathematical Models of Emergence in Complex System of Systems

W. Clifton Baldwin

Stephanie Hostetler

Wilson N. Felder





Bio

- W. Clifton Baldwin
 - Senior Technical Advisor at the FAA's WJH Technical Center
 - ESEP – INCOSE
 - PMP – PMI
 - Post Doctoral Researcher at Stevens Institute of Technology (2010 – present)



System of Systems (SoS)

A composite system composed of autonomous, diverse constituent systems that are dynamically connected and belong through contributions to the goals of the composite system

- Autonomy = independence of goals
- Belonging = contribution to other's goals, as well as the overall SoS
- (Dynamic) Connectivity = connecting with other constituent entities, as needed
- Diversity = differences in goals and capabilities



Emergence

Manifestation of behavior and functions that appear from the whole and cannot be traced to any particular sub-element

An emergent outcome

1. different than any individual's properties
2. not simply the sum of the individual's properties
3. not easily predicted from the individual's properties



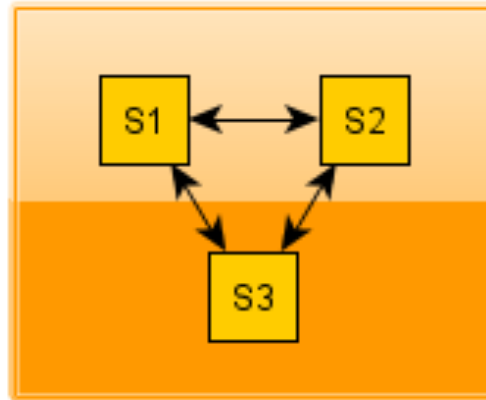
Emergence in SoS

- **Simple**
 - Readily predictable SoS-level behavior
- **Complicated**
 - Theoretically predictable SoS-level behavior (difficult but not impossible)
- **Complex**
 - Truly unpredictable SoS-level behavior



Case 1 – Simple

Linear Programming

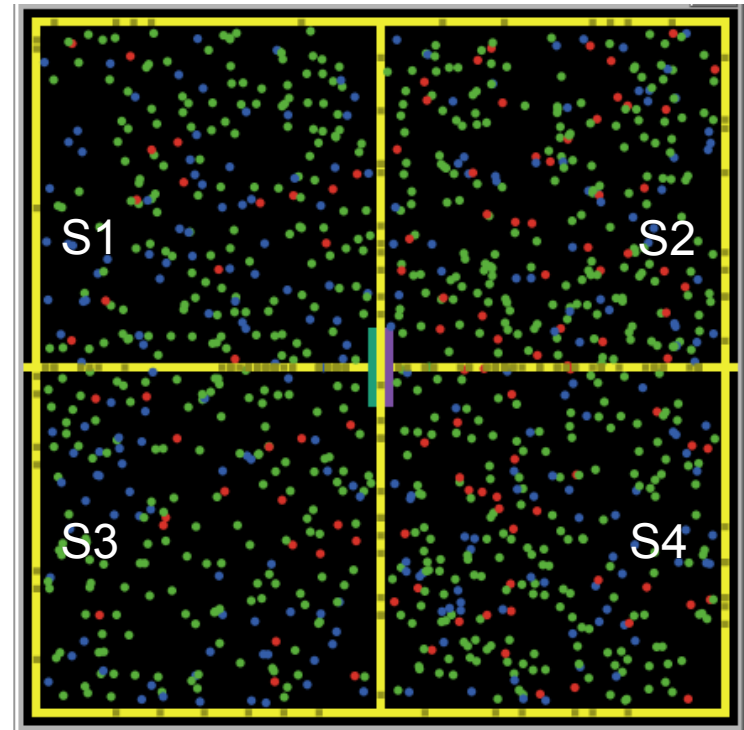
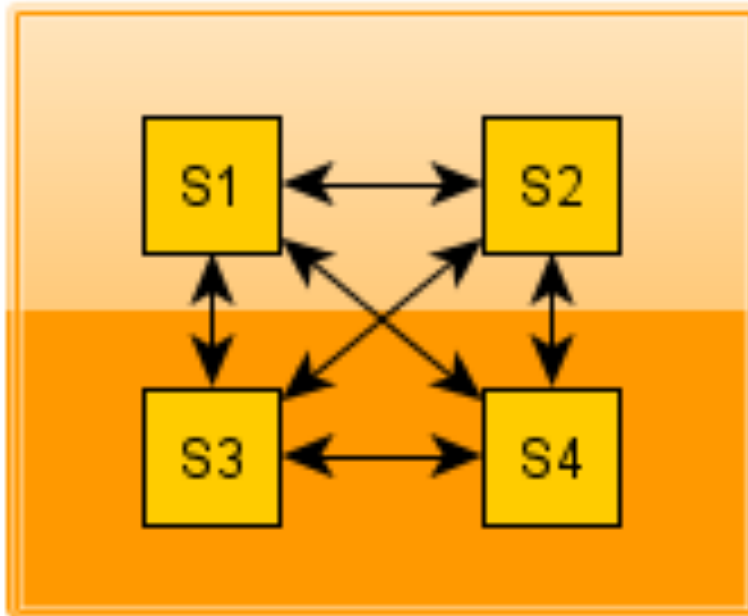


Minimize the total costs to run the systems such that the systems satisfy their own goals



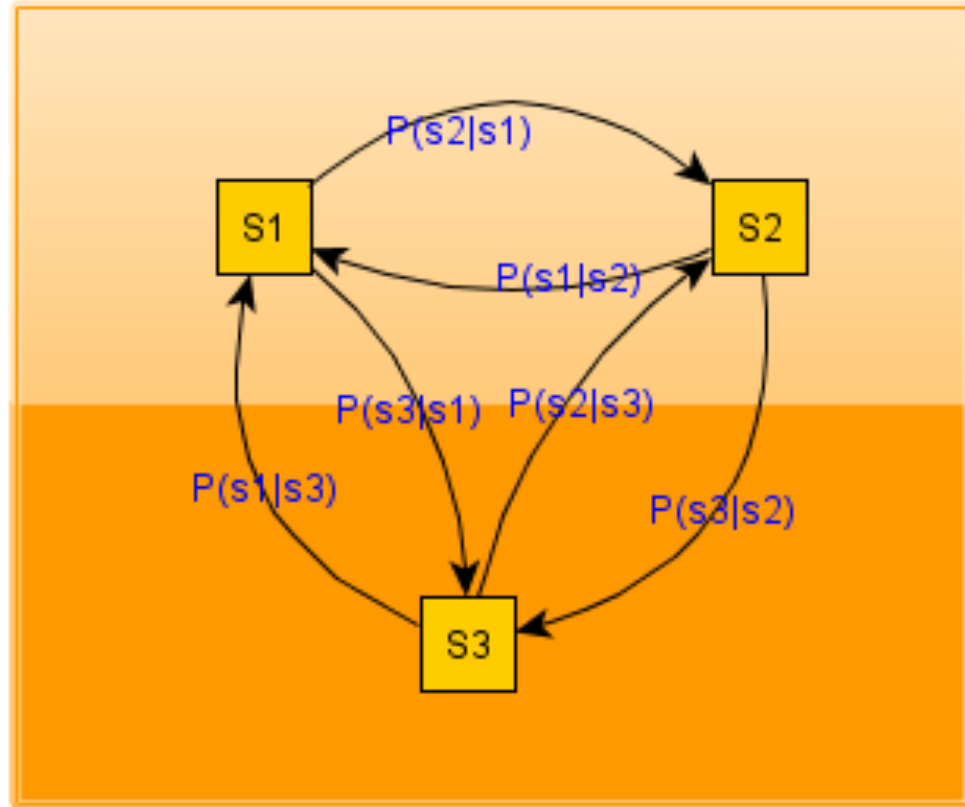
Case 2 – Complicated

- Statistical Mechanics



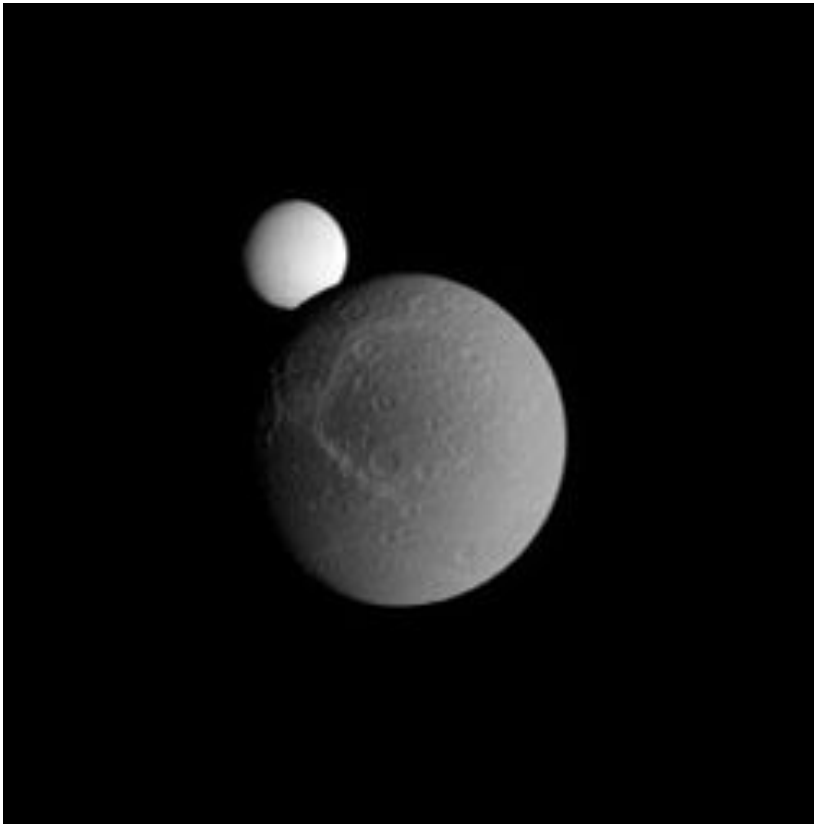
Case 3 – Complicated/Complex

- Markov chain

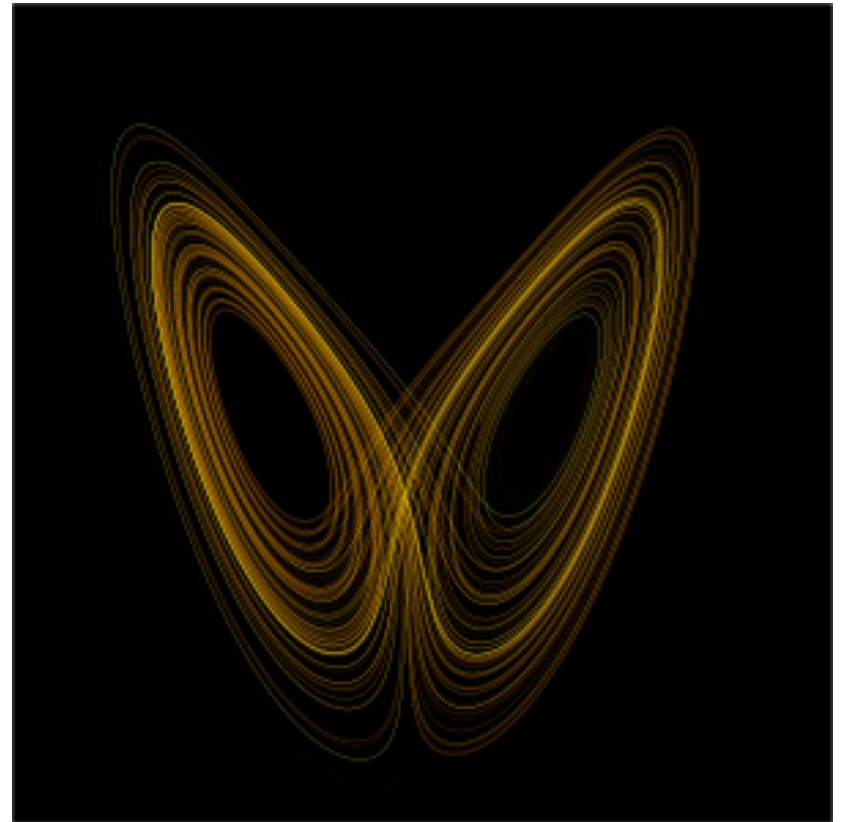


Case 4 – Complex

- Three-body problem



- Lorenz equations
- Rossler equations



Case 5 – Multiple

- Predator-Prey
 - Lotka–Volterra equation



Conclusion

- We need a better understanding of emergence to handle SoS
- Results implicate feedback
- Emergence of tangible output and emergence of patterns
- Much more research is needed!



Questions

W. Clifton Baldwin, PhD, ESEP
Clifton.Baldwin@faa.gov

