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Emergent Behavior of Systems-of-Systems

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The Boeing Company

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Systems-of-Systems

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Authors

- **John Hsu**
 - Ph.D. in Mechanical & Aerospace Engineering, M.S. in Nuclear Engineering, M.S. in Mechanical engineering and Registered Professional Engineer
 - 30 years of diversified experience in Systems, Aerospace, Mechanical and Nuclear engineering, Software Development and Engineering Management.
 - Started the systems engineering process, tool, template, and method for Boeing Airlift & Tanker Program.
 - 30 honor and awards, 20 systems engineering papers, AIAA Associate Fellow and immediate past Chair of Systems Engineering Technical Committee; Chair of Net-Centric Operations Working Group of INCOSE.
- **Marion Butterfield**
 - Boeing Associate Technical Fellow that specializes in System of Systems Engineering (SoSE) Processes and System of Systems Architecture development and modeling.
 - 40 years in Thor Delta space launch, counter-countermeasure algorithms, Systems Engineering and SoSE process development.
 - Held a series of systems engineering technical and management positions.



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Presentation Outlines

- **Introduction**
- **Existence of Emergence**
- **Definition of Emergence**
- **Discuss System-of-Systems Emergent Behavior**
- **Four Principles of Emergence**
- **Discuss Impact of Emergent Behavior on Systems-of-Systems Engineering**
- **Model the Emergent Behavior**
- **Conclusion**



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Introduction

- **System-of-Systems Engineering (SoSE) is a new branch of Systems Engineering.**
- **SoSE is not the summation of component systems due to the emergent behavior between component systems.**
- **This paper will discuss what is emergent behavior and how it contributes to the SoSE behavior.**
- **Modeling the emergent behavior for Systems-of-Systems (SoS) will be explored.**



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Existence of Emergence

- **The term ‘emergence’ was first used by the English philosopher G. H. Lewes well over 100 years ago.**
- **The process of emergence itself remained unknown and unknowable until the advent of ‘complexity theory’.**
- **Emergence became thought of as one of the defining properties of complex systems and over the last twenty years there has been a wide-ranging debate about its nature and causes.**



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Natural Emergent Behavior

- **Crickets tend to synchronize their mating calls - calling all at once at the same speed.**
- **Seasonal birds fly in large groups that seem to behave as one.**
- **The individual ants do not know about coordinated foraging; the hive as a whole knows.**



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Human Emergent Behavior

- **The slowing of traffic before the entry to a tunnel even there are no traffic signals to post the speed limit.**
- **The stock market is an example of emergence on a grand scale.**
- **Some philosophers of mind suggest that consciousness is an emergent property of brains.**
- **When a bunch of neuron switches is strung together in the right way, emergent behavior suddenly occurs.**
- **Gore used the emergent behavior to model the increasingly complex, and cognitively demanding work domain for pilots taxing on runways in O'Hare Airport.**

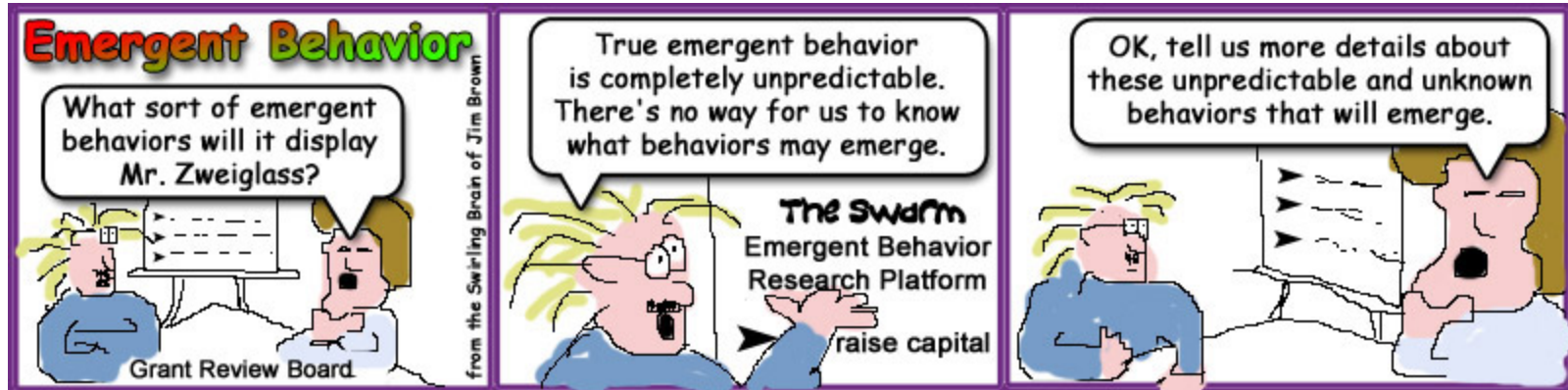


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Emergent Behavior





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Definition of Emergence

Stacey defined Emergence as

“Emergence is the production of global patterns of behavior by agents in a complex system interacting according to their own local rules of behavior, without intending the global patterns of behavior that come about. In emergence, global patterns cannot be predicted from the local rules of behavior that produce them. To put it another way, global patterns cannot be reduced to individual behavior.”



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Emergent Behavior for SoS

- **Emergent behavior is one of the five characteristics of a SoS (Maier 1996).**
- **The Internet exhibits a rich set of emergent behaviors represented by the complex distributed applications that run on top of the communication substrate.**
- **The most complex of these is the World Wide Web, itself a virtual or collaborative system-of-systems.**
- **There are many software examples (Fisher 2006).**



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Understanding Emergent Behavior

- **Little is known today about applying emergent behavior to the design of a SoS.**
- **Emergent behaviors are characteristics that arise from the cumulative actions and interactions of the constituents of a SoS.**
- **SoS displays a global complexity that cannot be adequately managed by hierarchical structures and central control.**
- **Traditional systems engineering and management approaches are inadequate and insufficient for a SoS.**



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Exploiting Emergent Behavior for SoS

- **A SoS depends on emergent behaviors to achieve its purpose.**
- **It offers great potential for SoS not only to overcome the problems of interoperation but also to achieve levels of adaptability, scalability, and cost-effectiveness not possible in traditional systems.**
- **Unfortunately, today's systems engineering practitioners do not have the methods and tools they need.**
- **New systems engineering methods that manage emergent behavior and exploit emergent effects to offer the possibility of cost-effective and predictable solutions in SoS.**



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Principles of Emergence (1)

- **Condition of Emergence**
 - An avalanche condition, or a critical state, has to exist prior to the occurrence of emergence.
 - For systems engineering applications, it infers to SoS.
- **Emergent behavior is inversely proportional to the degree of bondage between systems**
 - The more tightly the component systems are coupled the less likely that the global emergent behavior will prevail.
 - Emergent behaviors do not arise in closed hierarchically structured systems.



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Principles of Emergence (2)

- **Emergent behavior is non-linear**
 - Emergent behavior is more than the sum of added component systems.
 - the output is not proportional to the inputs.
- **Emergent behavior is self-organized**
 - Self-organization is a process in which the internal organization of a system, normally an open system, increases in complexity without being guided or managed by an outside source.
 - This is a bottom-up process.



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Emergence Major Impacts

- **Top down development via functional decomposition**
- **System-of-System specification structure & contents**
- **Functional and performance requirements flow down**
- **Requirements traceability**
- **Requirements validation and verification**



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Emergent Behavior Impacts Functional Decomposition

- **Functional decomposition will not work due to the emergent behaviors between component systems.**
- **There is no simple way to relate the functions of component systems to the functions of SoS.**
- **Lack of functional decomposition prevents allocation and flowdown.**



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The Way Ahead

- **Emergence is not the enemy - We can learn how to use it to develop flexible, adaptable, and robust Systems-of-Systems.**
- **Emergence can contribute to avoiding “stovepipes.”**
- **Proposed development principles for SoS**
 - ✓ **Define initial set of elements, interfaces, and protocols**
 - ✓ **Use model based evolutionary development**
 - ✓ **Model and simulate at SoS level of abstraction**
 - ✓ **Agent based simulation**
 - ✓ **Demonstrate in “field” periodically**



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Modeling the Emergent Behavior

- **Predicting the emergent behavior for a to-be-designed SoS will be a formidable challenge.**
- **Are we able to predict all the emergent behaviors?**
 - **Most likely our predictions will be probabilistic.**
- **Agent-based modeling is expected to be used to examine emergent behavior as structure and pattern develop from the micro-level interactions.**
 - **Agent-based modeling focuses on how local interactions among agents serve to create larger and perhaps global structures and patterns of behavior.**
 - **Many IF-and-THENS will be defined for the bondage situations between component systems.**



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Conclusion (1)

- **Emergent behaviors exist in biological system, physical system, human performance and economics.**
- **Emergence can be beneficial and harmful.**
- **Success in SoS requires recognition, effective management, and exploitation of emergence.**
- **The modeling efforts for emergent behavior presented here are conceptual and only at the beginning stage for this new endeavor to integrate emergent behavior into architecture models.**



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Conclusion (2)

- **Flexible and adaptable open system architecture is very important in dealing with these emergent behaviors.**
 - **The SoS architectural models should be modularized and therefore easily modified to account for the newly discovered emergent behaviors.**
- **It is suggested to explore the integration of agent-based modeling and neural network methodology with SysML.**
- **A network centric architectural model including the emergent behaviors could very well be the basis for a beneficial design for a Network Centric Company.**