ESD.84 Doctoral Seminar – Session 8 Notes
Guests Presenting: Seth Lloyd, Joe Sussman, Neil Gershenfeld

Session Design:

- Welcome and Overview and Introductions (5-10 min.)
- Generating Key Questions from Readings (10-15 min.)
- Core Concepts in the Study of Complexity Science (45-60 min.)
  - Seth Lloyd and Joe Sussman
- Break
- Student Presentations
  - The Potential for Application of Output from the Sciences of Complexity to Engineering, Management and Policy Research – Jeroen Struben
  - A Critical Analysis of the Emergence of Complexity Science as a Field of Study – Marcus Sarofim
- Book Reviews (5-10 min. each):
  - Holland, *Adaptation in Natural and Artificial Systems* (1992) – Ben Koo
- Additional Dialogue on Complexity and Engineering Systems (20-30 min.)
  - Neil Gershenfeld
- Next Steps (10-15 min.)

Potential Discussion Questions:

- What do we see when we look at complexity through the lens of engineering systems?
- How to manage complexity in an engineering system – to know how to take advantage of complexity?
- What are the differences between engineering systems and systems engineering – what do we gain from this contrast
- How to understand "Bits and Bucks" – especially in reference to quantum computing?
- On page 516 of Wolfram's book there is discussion of space/time relativity and the use of Plank's constant – how does this help us in understanding small-scale systems?
- Do we start from complexity science theory and then look for applications – or start with application problems and then link back to the theory?
- Say more about the link to Doyle's model and the view that accidents are inevitable in a complex system
- Issues around the non-uniqueness of initial states that generate emergent behavior
- In "Complex Systems: A Review" – is it possible to come up with a meaningful definition of complexity? If we can't define "life" how can we hope to define complexity?
- Engineering are taught to decompose problems into smaller bits – but does that make sense for engineering systems

Complexity Simplified – Seth Lloyd:

- What characterizes complex systems is that they resist simple characterizations
- Santa Fe talk – began with 31 distinct measures of complexity (corresponding to Baskin and Robins 31 flavors of ice cream), including:
    - Information
    - Algorithmic complexity
    - Computation complexity
    - Organizational complexity
    - Logical depth
    - Sophistication
    - and many others
- Practical issues around whether a large program involves more bits than there is space on your computer or whether problems involve factoring large numbers or other operations that can take a long time or issues around the interface of the drive train on a car
- It is a good thing that this concept has many different measures – reflecting its use in many different settings
- Unifying themes
    - Simplex is one-fold, Duplex is two-fold, complex is many fold
    - Complex systems are characterized in terms of how they register and process information
    - Complex systems are hard to describe – 10^{30} molecules in a human body is one way of appreciating the information involved in a description of a person, but even that is well short of what is important about this systems
- Question 1 – "Effective complexity:"
    - How much information is required to describe the important aspects of a complex system?
    - Thus the number of molecules in an LCD projector may be less important than the information contained in the blue prints for the projector or the list of functional requirements for the projector
    - Of the various mathematically specific measures of complexity – roughly half are associated with distilling how much information is required to describe the important aspects of a system
- Question 2:
    - How much effort is required to perform a complex task?
    - This could include computational complexity, money, and other factors
- Grand theories of complex systems may or may not be useful for engineering systems
- Based on quantum computers – focus is on information flowing throughout a system – but it could also be money or other factors flowing throughout a system – hence bits versus bucks
- Biologic systems have a very high degree of complexity – even in a single cell the information processing is large – an important quantity to understand
- On the issue of trade offs between complexity and fragility form Doyle and the power law distributions around bad things happening – it tends to be in geometric systems that have power law constraints – other systems may have log normal constraints which are not so frightening
- It may not be impossible to have complex systems that are not fault tolerant
- The first use of cellular autonomy was Von Neumann – long before Wolfram

- Wolfram's approach is not quantum mechanical and it is conceivable that the universe could be complex in quantum mechanical ways rather than the approach taken by Wolfram
- How to think about the need for new mathematical methods – quantum mechanics is a powerful body of theory that explains behavior at small scales – with thousands of effective proofs – but with in-elegant math and counter intuitive concepts
- The definition of complexity is context sensitive

Linking Complexity to Engineering Systems – Joe Sussman:

- ESD is a counter cultural development – in the ways it cuts across disciplines to focus on "Engineering Systems" – but we still lack a common definition
- There is debate as to whether this is a field or a discipline (with scholarly debate that this is multi-disciplinary and political debate that the concept of a discipline is threatening to discipline-based departments)
- In the background are many critical contemporary issues that are important and involve complexity – productivity, social equity, new technology, etc.
- Purposeful systems
    - Input vector
    - Sub-systems
    - Boundary
    - Performance vector
    - Feedback
- CLIOS
    - Complex
    - Large-scale
    - Integrated
    - Open
    - Systems
- Detail complexity versus dynamic complexity – more than just complicated systems
- Technical versus social complexity
- Kinds of complexity
    - Complexity in behavior
        - Butterfly effect
        - Local and distant effects
        - Network relations
        - and others
    - Complexity in internal structure
    - Complexity in evaluation – views of outcomes
- An engineering systems is a CLIOS with an important technology component
- The discipline of engineering system is the development of a structured set of models and frameworks together with appropriate methods of qualitative and quantitative analyses – and their application to a broad set of CLIOS with important technology components
- It includes a coherent interdisciplinary approach to engineering system design (or discernment) and a broad-based context for studying critical contemporary issues

- Nested complexity – physical systems surrounded by policy or institutional systems – with layers of these combined systems embedded in one another
    - Physical and institutional systems interact and then these interactions are set in relation to others
- Engineering systems and systems engineering – a particular view on these concepts:
    - Engineering systems as particular types of systems
    - Systems engineering as a process – which may or may not be useful in studying a given engineering system

Additional Discussion:

- In the history of the Santa Fe institute there was a careful strategy to attract new people – is the situation here comparable? What is our key strategy for communicating this new field?
- Comment from Seth as a member of the Santa Fe external faculty since 1988 and as a member of ESD – the Santa Fe concept was to bring smart people together and see what happens – which did lead to some strongly motivated efforts to advance the thinking – then some well defined sub-disciplines did emerge from Santa Fe – such as the work in economics, artificial life that have been very successful, as well as efforts in entropy and physics that have not been as successful so far
- How to reconcile the bounding of a system with the measurement of complexity? The challenges lie at the interfaces
- Note critique by Santa Fe of engineering systems approach that it is not self organizing and emergent – hence not truly complex
- How to deal with issues of malevolence in complex systems

Presentation: "The Potential for Application of Output from the Sciences of Complexity to Engineering, Management and Policy Research" by Jeroen Struben

- Contrast between Micro and Macro perspectives
- Emergence of methods and applications in the field

Generalized Methods	Original Concept/Field	Example of application
Deterministic Chaos (1927)	Physics, mathematics, ecology, biology, world phenomena	(2<D>Large), construction, health(ECG's), weather,..
System Dynamics (late 1950's)	Control theory	Policies, Socio-Economics
Genetic Algorithms (1960)	Evolutionary theory	Artificial Intelligence, Cellular Automata, Genetics, Evolutionary Economics/Organizations (NK),…
Fractals (Cantor 1872/ Mandelbrot 1960)	Theoretical Mathematics	Chaotic Systems (Finance), Art
Catastrophy theory (Zeman 1977)	Non-linear dynamics, physics	Economics, engineering,
Self Organized Criticality (1988)	Statistical physics, non-linear dynamics	Meteorology, Biology,…
Neural Networks (late 1980's)	Neuroscience (psychology)	Artificial Intelligence, Social networks
Ecological Systems (1990's)	Theoretical biology	Complex Species Interactions, Technological/Organizational Ecology,...
Econo-physics (1990's)	Physics, game theory, applied mathematics	Economics
Protocols (2002)	Genetics (biology)	Information architecture,…?!

- Analogies and metaphors defined
- A successful analogies – Holland on Genetic Algorithms – adaptive behavior
- Another successful analogy – Systems dynamics from control theory
- Failed analogy – social Darwinism (Herbert Spenser, 1857)
- Open issue – self-organized criticality (at the edge of chaos)
- Another open issue – Doyle on Highly Optimized Tolerance

Advantages	Disadvantages
Energy saving	Different questions, reduced adequateness
Potential unexpected benefits	Loss of strength of metaphor through transformation losses
Potential for emergence of new recombination	Potential dominance, lack of creative potential of well developed construct

- What are the measures or indicators of success with metaphors and analogies?

Presentation: "A Critical Analysis of the Emergence of Complexity Science as a Field of Study" by Marcus Sarofim

- Key terms:
    - Emergent Properties
    - Edge of Chaos
    - Complex System
    - Cellular Automata
    - Chaos Theory
    - Increasing Returns
    - Lock-In
    - Adaptive Systems
- Relevant fields:
    - Economics
    - Biology
    - Computation
    - Physics
    - Chaos Theory
    - Transportation
- Timeline for Complexity Science:
    - 1920s: Lenz + Ising develop the "Ising Model" which describes ferromagnetic properties.
    - 1930s: Alan Turing invents the universal Turing machine
    - 1940-1945: First computers developed
    - (Colossus, Mark I, ENIAC, etc.)
    - 1948: Von Neumann invents cellular automata
    - 1963: Edward Lorenz at MIT discovers extreme sensitivity to initial conditions, and thereby chaos.
    - 1970: John Conway creates the Game of Life.
    - 1971: Kaufmann postulates autocatalytic sets
    - 1972: Philip Anderson: "More Is Different" (Science)
    - "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe"
    - 1983: Wolfram publishes his first cellular automata papers, along with Class I->IV descriptions

    - Early 1980s: Brian Arthur talks about increasing returns, economy as a self-organizing system.
    - 1984: Santa Fe institute established under George Cowan, Murray Gell-Mann
    - 1991: Endogenous evolution demonstrated in-silico in a program named Tierra by Tom Ray
    - 1994: Echo developed by Holland
    - 2002: Wolfram publishes A New Kind of Science
- We are on a ramp up in the whole domain of complexity science – so the full impact remains to be seen
- It may be naïve to think of eco-systems as vertical chains rather than as a closed loop where the little ones at the bottom of the chain eat the dead big ones at the top of the chain

Book Reviews: Holland on *Adaptation in Natural and Artificial Systems* (1992) – Review by Ben Koo

- The book's popularity has depended on the environment – which is now much more receptive
- This is very different math than optimization
- The concept of adaptation is about flexibility

Presentation by Neil Gershenfeld:

- The Center for Bits and Atoms as the context for these remarks
    - Internet architecture for the physical worlds – what is termed internet 0
    - Fabrication labs deployed around the world – to establish capability to produce products
    - Paintable computing and computing inks
    - Quantum computing
- Given the prospect of Avogadro scale engineering here is the problem:
    - Micro/toy-style demonstrations of emergent engineering concepts don't scale
    - Deep thinking about emergent engineering doesn't produce outcomes that work
- The challenge to be both rigorous and relevant
- Much of the interesting work is not using the labels of complexity science – but it is in this domain – such as work on scaling and numerical analysis and network architecture
- One of a handful of examples:
    - Rent's rule: The number of functional entities in a box have a power law relationship – experiment with a robust fault tolerant architecture using Rent's rule as a point of departure
    - Cray computers are powerful because they are appropriately balanced – not something easily taught
- Contrast between probabilistic nature of ether net and the Rent's law insight
- Coupling of geometric nature of information and the technology