

Chaos, Complexity, and all That

One Physicist's Perspective

David K. Campbell, 9/27/00

- **Background:** “Chaos” and “Complexity” are much-hyped emergent paradigms for advancing science and technology in the 21st century (**NB: buzzwords!**): but what are they really and what can they teach us?
- **Mandate:** Provide overview of key concepts of chaos and complexity, with appropriate caveats (in 20 minutes!!)
- **Suggests Film:** “Mission Impossible”. In fact, a more appropriate film, for reasons that will shortly be clear, is
“Jurassic Park”

Lessons from “Jurassic Park”

- “Chaos” has captured public imagination.
- “Talking the talk” does *not* imply “walking the walk”: Jeff Goldblum does not know chaos.
- **Misplaced metaphors**: in film, chaos is morphed into a cosmic “Murphy’s Law.”
- Need for **interdisciplinary teams** of researchers, experts in each subfield, for success in this area.
- No film yet on “**Complexity**”---opportunity for Spielberg?

Characteristics of Complexity: I

- **Nonlinearity**: from feedback, interactions
- **Interactions/Connections**: local in space/time vs. long-range in space, retarded in time: connections $\sim N^p$ vs. e^N vs. $N!$
- **Irreducibility**: lose behavior if system is broken into pieces
- **Hierarchies**: multiple scales in space and time; explicit vs. “emergent”
- **Emergent/self-organizing behavior**: no central control or plan; “more is different”; reductionism does not imply constructivism [cf. P. W. Anderson, *Science* **177**, 393 (1972).]

Characteristics of Complexity: II

- Many nearly degenerate/equivalent configurations: rugged landscapes, fitness, competition
- **Adaptation**: ability to respond to changes in environment; explicit or emergent; relation to stability
- **Biological/“life-like” behavior**: self-reproducing, adaptive, evolving, learning?
- **“Intelligent agents”**: individual parts of systems have internal schema, “if/then” rules:
[NB: Intelligent agents are neither necessary nor sufficient for intelligent behavior of the whole system: cf. the brain and the Congress.]

What do we really *know*?

Terra Firma extends through first six characteristics of complexity (nonlinearity, interaction/configurations, irreducibility, hierarchies, emergent/self-organizing behavior, many degenerate/equivalent configurations) in the sense that these reflect developed analytic and computational methodologies and many Experimentally accessible systems. But much still to be explored.

Final three characteristics (adaptation, biological/life-like behavior, intelligent agents) remain *terra incognita*: very limited analytic insight, theorems, general principles, many model but in this area limited experimentation possible (e.g., socio-political systems, observational vs. experimental).

=>

Start from *terra firma* with examination of paradigms of nonlinearity: 1) chaos, 2) solitons/coherent structures, and 3) patterns.

Chaos

Chaos: even very simple nonlinear systems (eg, “logistic map,”
 $x_{n+1} = rx_n(1-x_n)$, or systems of 3 coupled, first order ODEs) can exhibit
“exponential sensitivity” so that a tiny change in initial conditions leads
to an enormous change in final conditions, and long-term prediction is
essentially impossible, as if system were random.

Examples: Logistic map attracting set, S_1 - S_2
Phase space of standard map, S_3 - S_8

Caveat auditor: Modeling effects of SDI on strategic balance:
Model I had 3 ODEs, *predicted* chaos
Model II had 2 ODEs, *excluded* chaos
NB: Modelers knew what they were doing!

Solitons and Patterns

Nonlinearity (“nonlinear science”) further challenges our common sense with its two other paradigms:

Solitons/Coherent Structures: even very complicated nonlinear systems can exhibit great regularity, creating ordered, persistent spatio-temporal structures

Examples: Red Spot of Jupiter (S_9), nonlinear ocean waves (S_{10}), optical solitons (S_{11}): [reflect **interactions/connections**, **emergence**, and “**adaptation**” in sense of stability]

Patterns: spatially uniform, homogeneous state is often (typically?) unstable to formation of non-uniform, heterogeneous patterns:

Examples: Fluid experiments (S_{12} - S_{16}), Belusov-Zhabotinsky chemical reaction (S_{17}) vs. slime mold (S_{18})

Caveat auditor: Beware “**Similarity Science**”: **BZ/slime mold similarity is very suggestive, but is it real? [In this case, yes! See work of Levine, Kessler, and Reynolds, Phys Rev Lett 66, 2400 (1991) and 68, 401 (1992).]**

Tripartite Methodology

Key to tremendous advances in understanding nonlinearity has been **interdisciplinarity** (cross disciplinary applicability of paradigms) and **tripartite methodology**:

- **“Experimental Mathematics”**: use of extensive computation, including interactive graphics and visualization
- **High precision measurements**: made across many traditional disciplines, confirming “universality”
- **Rigorous mathematical studies**: novel analytic methods, theorems, and results.

Caveat auditor: This coordinated, interdisciplinary methodology will be even more essential in studying “complexity”/complex systems

“The greatest lies behind..”

Systems that adapt, evolve, learn, or involve intelligent agents *and* still have all the subtleties we've seen in “simple” nonlinear systems exhibit huge new universe of possibilities:

Examples: self-reproducing cellular automata (S_{19} - S_{22}) (note that these “agents” *do* have *schema*, but all the same);
self-assembling (model of a) bacteriophage (S_{23} - S_{29});
intelligent agents: “El Farol” and “voting” problems, modeling the economy as an ecology of agents with different strategies, “Sugarscape”, “Swarm”

Conclusions and Useful “Links”

Conclusion: Despite excessive hype, chaos (generalized to reflect all paradigms of nonlinearity) and complexity are here to stay. Need to (1) be aware of limitations; (2) work in interdisciplinary teams; and (3) avoid similarity science; but (4) **“boldly go”** !

- **www.comdig.org**: very broad compilation, updated weekly, on complex systems theory and applications
- **www.santafe.edu**: web site of the Santa Fe Institute, a leading research institute focusing on “complex adaptive systems,” including economics and social sciences, as well as natural sciences.
- **www.necsi.org**: web site of the New England Complex Systems Institute, a research institute focusing on “complex systems” with very broad annual conference.