Foundations \( \cap \) Structure

Information and Uncertainty in the Sciences

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Outline
I. Dynamics and Feedback in Nature
II. Some Overarching Themes
III. Example: Synthetic Biology
IV. Some Thoughts on Going Forward
**Biological Systems**

**“Systems Biology”**
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements

**Key features of biological systems**
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level

**Design and analysis of biological systems**
- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key
Ecological Systems

Populations and ecosystems
- Example: bacterial networks
- Multiple layers of feedback ⇒ complexity
- Get robust functionality to individual cell
- And system level robustness for colony
- Q: how does evolution shape this?

Fire management
- Power law distributions ⇒ many existing tools are not appropriate
- Multi-scale behavior: fuel to atmosphere
- Q: prevention, planning, policy?

Role of Dynamics and Feedback
- Multi-scale dynamics
- Robust yet fragile behavior
Physics: Quantum and Geophysical Systems

Quantum Systems

- Rational design and empirical optimization of open loop control strategies (eg, NMR)
- Real-time feedback methodology for controlling quantum systems
- Role of interconnection is critical and very different from most engineering applications

Geophysical Systems (earthquakes)

- Reduced order models emerging for non-crystalline solids, soils, and related geophysical materials that explain complex physical behaviors
- Extreme multi-scale behavior of interconnected components
Overarching Themes

Multiscale modeling, analysis and computation
- rigorous techniques for model reduction and efficient, robust simulation becoming essential

Feedback as a tool for uncertainty management
- feedback as a fundamental organizing principle
- enables "network robustness"

Integrated communication, computing and control
- nature uses dramatically different mechanisms to communicate and process information

Current tools not capable of addressing many interesting problems
Example: Synthetic Biology

Crawling Neutrophil “Chasing” a Bacterium

- Human polymorphonuclear leukocyte (neutrophil) on blood film
- Red blood cells are dark in color, principally spherical shape.
- Neutrophil is "chasing" Staphylococcus aureus microorganisms, added to film.

Tom Stossel, June 22, 1999 (John Stossel, 195?)
http://expmed.bwh.harvard.edu/projects/motility/neutrophil.html

MIT Bio-Bricks program

Synchronization of a repressilator, IAP ‘03

Elowitz and Lieber, 2000
Synthetic Biology Competition 2004

Boston U, Caltech, MIT, Princeton, U Texas
- Caltech: 7 undergrads + 3 grad students + 3 faculty
- Project #1: alternative oscillator designs
- Project #2: serial counter with digital readout

Features:
- Multiscale dynamics
- Uncertainty management via feedback
- Integrated communication, computing and control
New CDS research is required

- Integration of computing, communications, control
- “High risk” applications in biology, quantum, geophysics, ecosystems
- Maintain rigorous mathematical approach

New approach to education

- Make CDS tools accessible to broad audience of scientists and engineers
- Provide training required to work on interdisciplinary applications in science and engineering