Grand Research Challenges

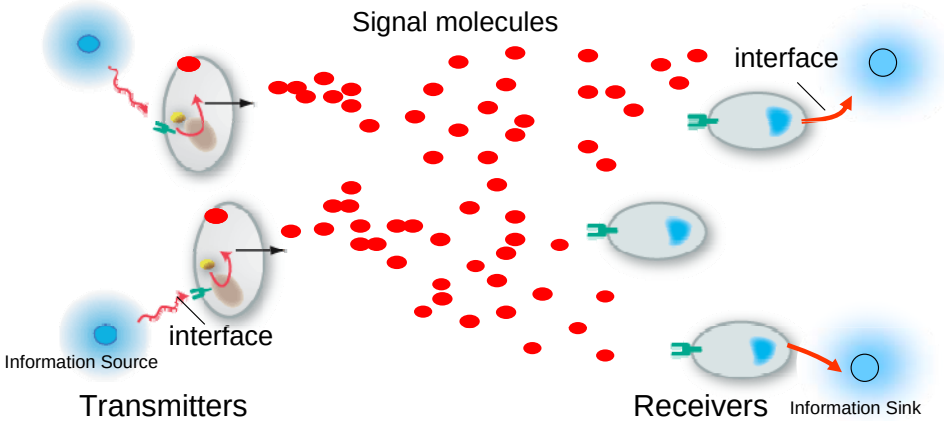
NSF Workshop on
Molecular Communication
Biological Communications Technology

(2/20-21, 2008)

Communication Components and Systems

Objectives

- Networks of components that can be interfaced with biological systems at the cellular and molecular scales.
- Real-time, label-free sensing of biologically-relevant variables in multiple modalities, time scales and spatial scales.
- Decision-making logic to interpret sensory data and drive actuation.



Components for Chemical Communication

Technical Challenges

- Devise and evaluate alternative approaches to signal transmission: electromagnetic, electromechanic, chemical, …
- Develop components for communication systems: encoders, decoders, transmitters, receivers, amplifiers, ...
- Power sources for network nodes.
- Biocompatibity and stability of embedded components.

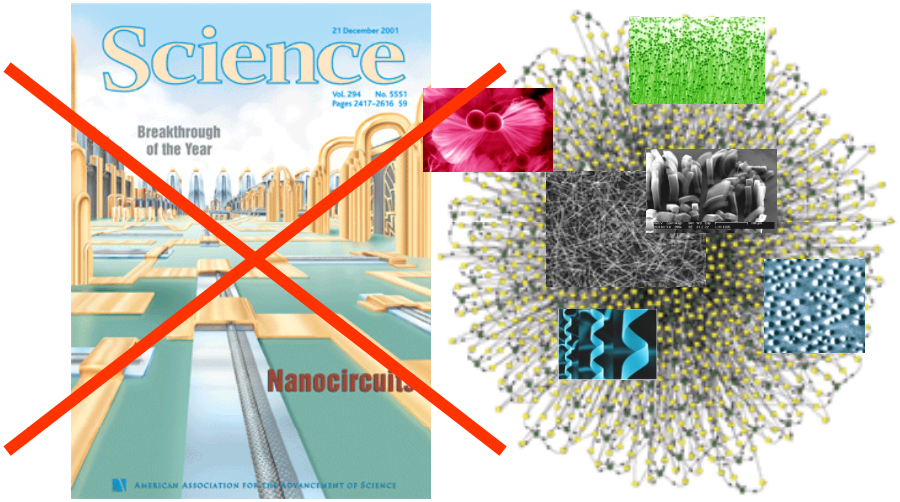
Impact

- Understanding of biological function through experimentation, modeling , analysis and model refinement, using data acquired by Instrumented Cell Systems, sensor nets embedded in cellular systems (and eventually in whole animal bodies).
- Understanding the computational and engineering implications of the interplay between the networks and their biological environment.
- In the long run, health care applications.

Identify, understand and apply biological architectures for networking at the extremes of density, scale, and stochasticity

Objectives

- Discover conserved architectures in biological networks that control sensing, decision, response, and evolvability
- Elucidate laws governing conservation and distribution of noise and understand biological strategies for its systematic management
- Synthesize networks applying these in biologically relevant scales and densities



Technical Challenges

- Experimental and theoretical tools for characterizing cell/cellular environments and architectures as networked systems
- Design methodologies for genome-scale network integration
- Embracing noise as a functional element in system design

Impact

- Solving the density-power challenge of networks-on-chips
- Realization of the functional promise of networks of synthetic nanoscale elements
- Creating synthetic systems with a level of functionality rivaling that of living system

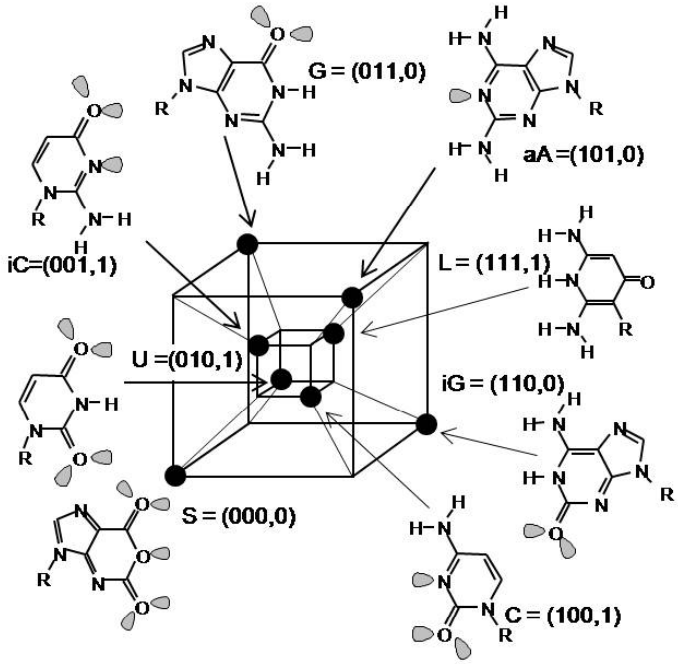
Understanding Biology using Information and Coding Theory

Objectives

- To understand how information and coding theories apply to biological systems with the objective of developing biology as a rigorous theoretical science.

Technical Challenges

- Identify biological systems that can be investigated experimentally using information theory.
- Given currently available or experimentally generated data, test the application of information and coding theory to biology.
- What is the structural/physical basis of codes in molecular biology?
- How closely do individual biological systems approach the channel capacity?
- What information/coding assumptions must be relaxed or modified to apply information theory to molecular systems?
- Develop a consensus on terminology to eliminate fundamental confusions.
- Understand how noise affects biological systems.



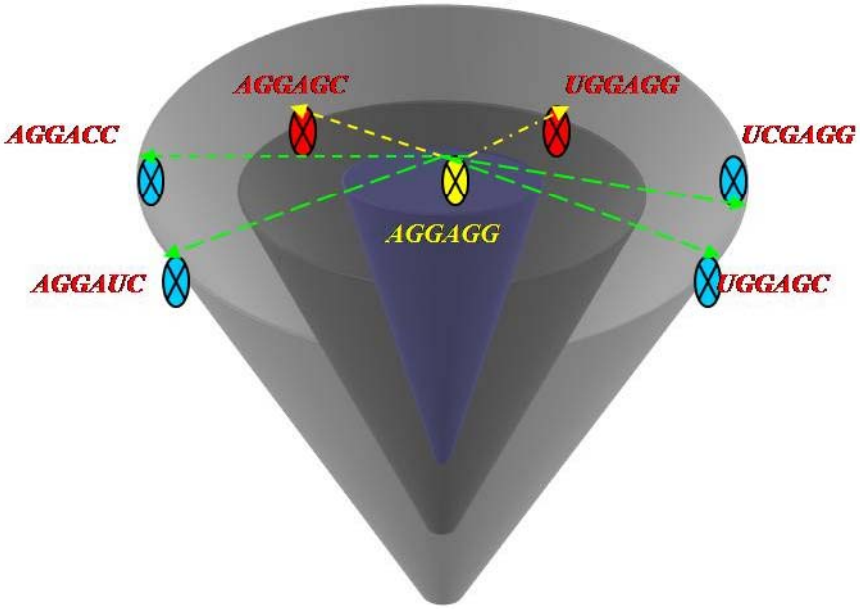
Impact

- Paradigm shift of biology from a descriptive science to one with a theoretical foundation.
- Information theory can provide the underlying explanations for molecule-to-molecule biological interaction parameters which can then be used in the construction of higher level systems biology.

Understanding Information and Coding Theory using Biology

Objectives

- To advance coding and information theory by learning from biological information systems at all scales.



Technical Challenges

- Determine whether the kinds of codes used by biological systems have been studied previously.
- Understand how multidimensional coding is generated and used in proteins and other biological structures.
- Learn how three dimensional coding, such as found between the surfaces of interacting proteins, operates.

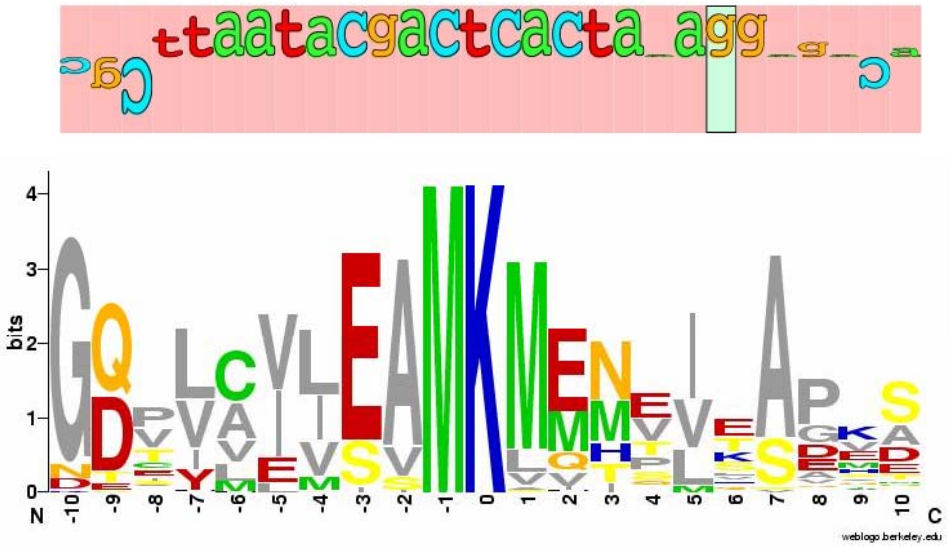
Impact

- Creation of novel coding techniques that approach the channel capacity for application at both the molecular nanotechnology and macroscopic levels.

Applying Information and Coding Theory to Bioinformatics and Bio/Nanotechnology

Objectives

- To extend the application of information theory to novel biotechnological and nanotechnological problems.



Technical Challenges

- Understanding the limits of binding site predictions using individual information.
- How can we apply increasing knowledge of biological codes to technological applications, as in construction of coded molecular systems such as the Medusa™ DNA Sequencer?
- Development of multiple, gapped sequence alignment algorithms to avoid systematic bias in phylogenetic analysis.

Impact

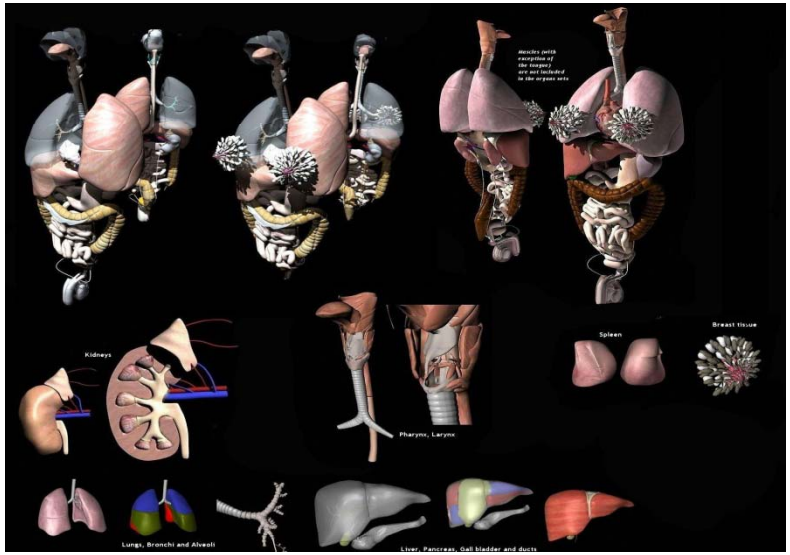
- Improved clinical diagnosis from information theoretic analysis of genetic sequences.
- Development of robust coded nanotechnologies.
- Understanding the quantitative medical aspects of how cells communicate with neighbors and diseases as communication disruptions.

Artificial Morphogenesis

Understanding and Engineering a Growing Complex 3D System

Objectives

- Understand and engineer complex 3D bio-molecular computing and communicating systems.
- Develop methods and technologies for controlling growth, shape and functionality of 3D macroscopic bio-systems using engi-neered or synthetic cells.
- Identify the conditions that allow for learning, adaptation, autonomy and self repair.



Technical Challenges

- Develop decentralized, adaptive, and robust control mechanisms.
- Ensure far from equilibrium operation
- Reach brain-/Avogadro-scale complexity
- Establish principles of molecular commu-nication and computing in large 3D struc-tures.

Impact

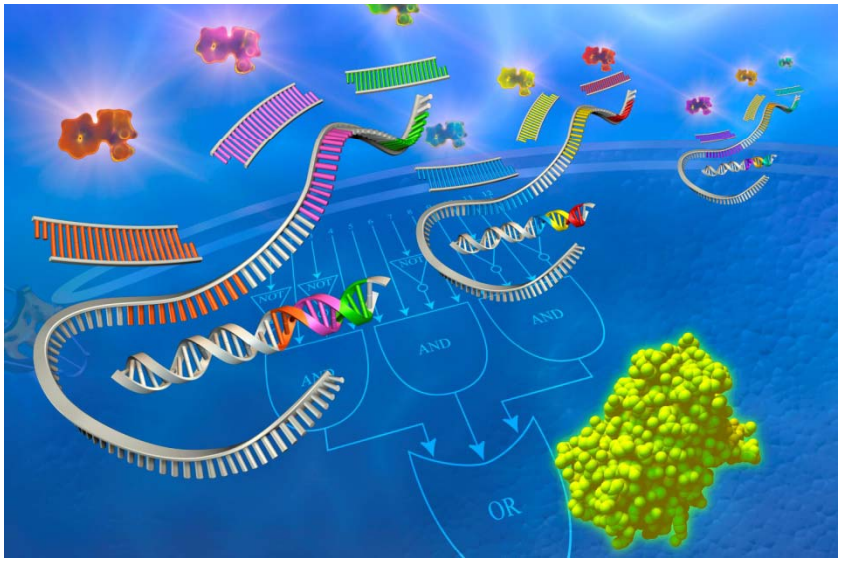
- Prosthetic devices and regeneration med-icine
- Micro/nano/molecular robots that grow, self-repair, and self-heal
- Bio-technological micro-factories
- In vivo information processing devices

Living Matter as Computing and Communication Media

Paradigms, Design Principles, and Experimental Exploration

Objectives

- Understanding and applying the principles of information processing and transmission in natural systems.
- New communication and computing paradigms that respect the media.
- Combine theory and experiments to establish viable, application-oriented engineering discipline.
- Identify the risks and benefits of bio-computing devices, limit their autonomy, regulate waste and legal issues, educate.



Technical Challenges

- Control and exploit noise, unreliability, and stochasticity
- Deal with massive numbers of components
- Design methodologies, including validation, simulation, and testing.
- Self-* properties
- Develop tools for rapid prototyping and testing

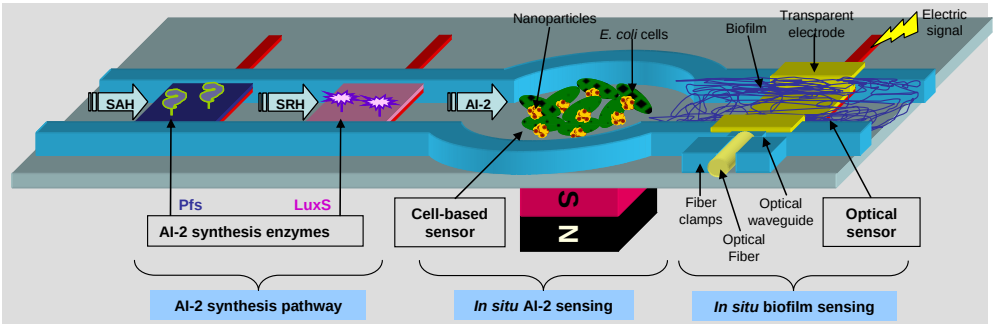
Impact

- New hardware and software for hard and massive-scale problems
- Enables the other grand challenges
- Enabling technology for bio-molecular devices
- Interfacing with biological systems
- Go beyond rational design
- New generation of diagnostic and thera-peutic tools for personalized medicine.

Biological Communication (Molecules, Networks, and Populations) and its Applications

Objectives

- Elucidate design principles of biological communication and information processing.
- Integrate biological substrates, systems, etc., with "classical" communications modalities (cell phones, laptops, microfabricated devices).
- Translate biological communication architectures to other existing networks and to generate new architectures and modes for communication.
- Develop novel applications by exploiting biological communications



Technical Challenges

- Identify regulatory modules at multiple levels (molecular, cellular, populations)
- Devise methods to transform information flow to effective communication
- Develop interfaces between electronic and biological communication
- Controlling and exploiting biological uncertainty.
- Integrating diverse disciplines (e.g. NSF Directorates) to understand problem and cultivate solutions and applications.
- Need for foundational technologies for analyzing biological communication networks experimentally and computationally
  - Methods to engineer biological components (e.g., directed evolution), observe communication (e.g., photonics), "wire" biological communication onto "classical" electron-mediated devices.
  - Modeling formalisms, software support platforms.

Impact/Applications

- Biotechnology – biofilms, protein engineering, bioreactors, cellular engineering
- Bioenergy – microbial fuels cells, electron transport
- Biosensing/actuation – exploit natural recognition capabilities, new recognition elements, transduction modalities, and actuation (e.g. biohybid devices).
- Hybrid communications devices that incorporate biological elements.
- Environmental testing, improving sustainability, enhancing human health.
- New synthesis processes that are environmentally benign, efficient, and less costly
- Educate and inspire future, interdisciplinary engineers and scientists.

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