Large-Scale Biomimetic Computational Systems

Ted Berger, Kwabena Boahen, David Coleman, Semahat Demir, Dan Hammerstrom, Dan Koditschek, Jose Principe, Dawn Taylor, Nitish Thakor, Evangelia Tzanakou

An important mission is to incorporate principles of the brain into devices and systems that are useful in science, technology, and society

We are experiencing a revolution in the study of the brain:

- we are now capable of recording the activity of hundreds if not thousands of neurons with both fine temporal and spatial resolution
- we can observe that activity with a diverse array of sensors and imaging technologies
- we can simulate complex processes underlying the functions of synapses and neurons
- we can implement models of neural processes in silicon
- we have developed first-generation brain-machine interfaces and decoding algorithms that support novel neural prosthetic systems
- we have built and deployed autonomous robots with control systems inspired by properties of the spinal cord and PNS

Large-Scale Biomimetic Computational Systems

We see substantial challenges (and opportunities) moving forward:

- we do not have the analytical tools to decode information from, or determine the state of, numbers of neurons as large as we can observe
- we do not have methods to integrate ("fuse") the information contained in the rich variety of sensors available
- our mathematical methods for modeling the nervous systems do not incorporate its obvious hierarchical organization, and multiple space and time scales
- our detailed models of the processes underlying the function of synapses and neurons do not scale to any level approaching the number of neurons underlying cognition or behavior
- the hardware in our real-world computational systems (e.g., Pentiums) incorporate none of the established advantages of the nervous system
- current brain-machine interfaces are uni-directional (brain-to-machine) and can support only very limited prosthetic functions
- our bio-inspired robotics systems do not incorporate "brain-like" operations

Large-Scale Biomimetic Computational Systems

We see a Biomimetic Computational Grand Challenge to:

Develop large-scale, multi-input/multi-output, biomimetic systems capable of interacting with multiple levels of the nervous system in real-time

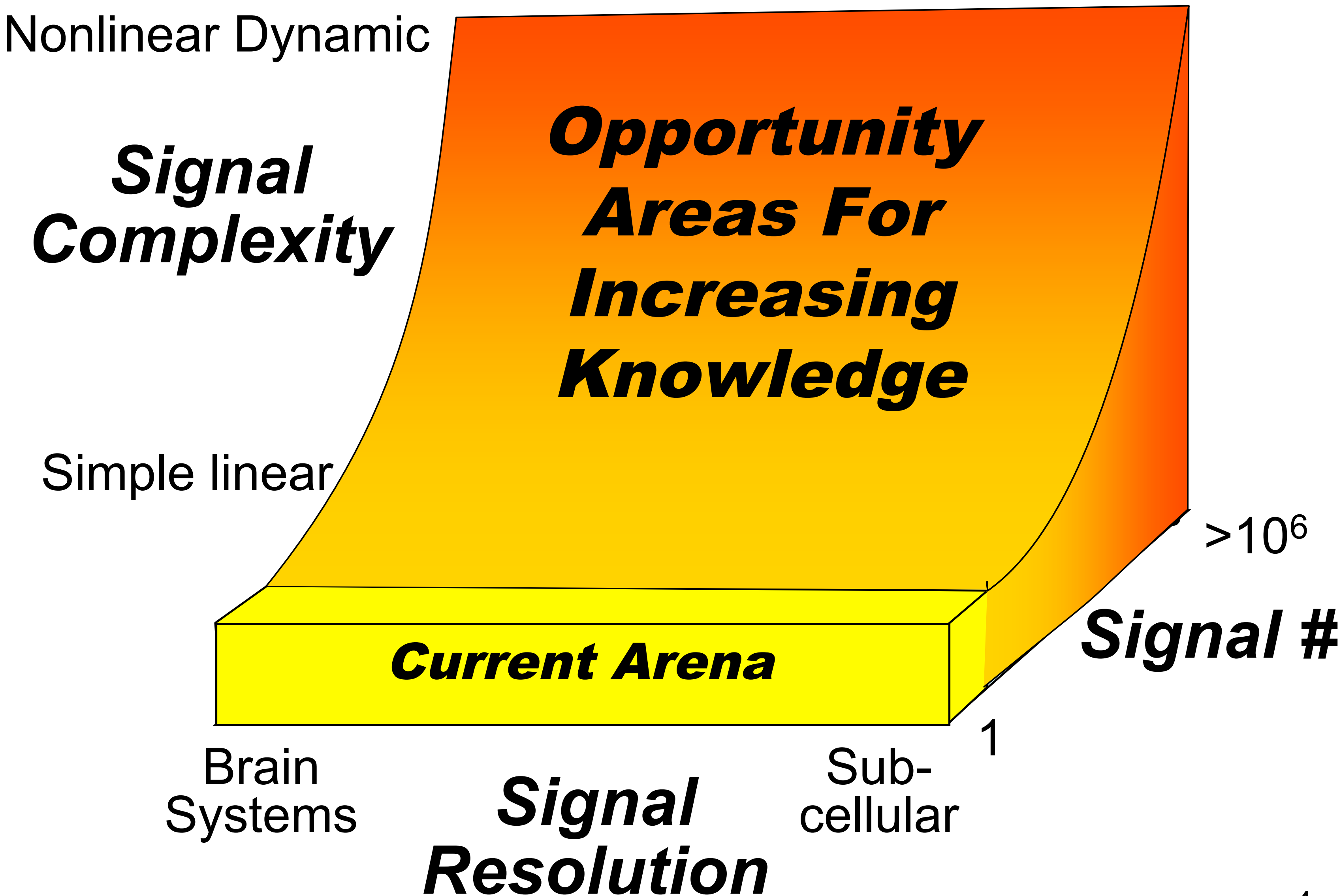
These systems would incorporate a new family of neuro-centric principles that will re-energize research and development in signal processing, computer science, complexity management, and other fundamental scientific fields

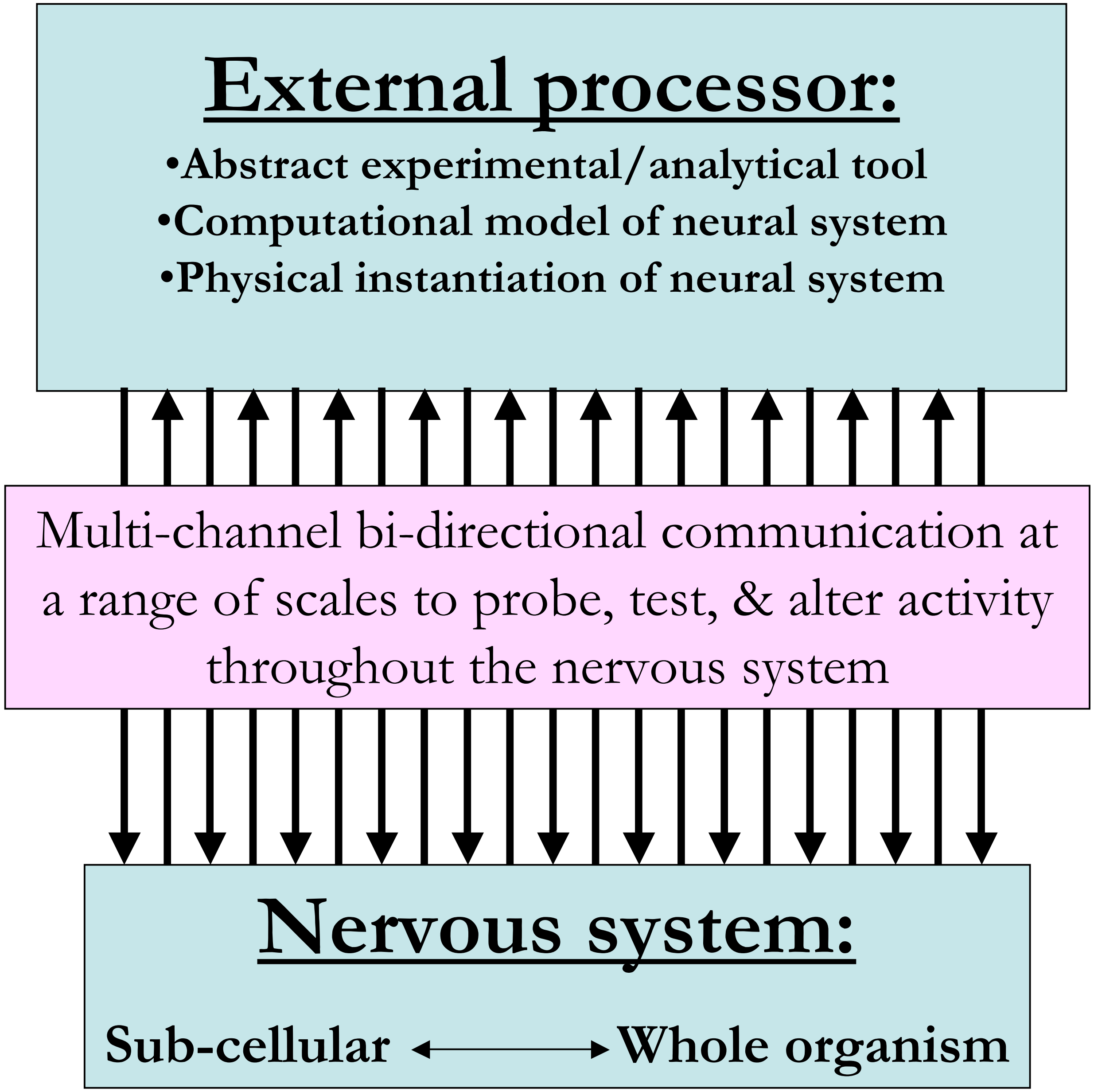
Achieving this Grand Challenge requires:

- beyond state-of-the-art analytical tools, mathematical models, and experimental/computational technology
- dealing with a problem space that is characterized by three main axes: scale, complexity (heterogeneity and nonlinearity), and nonstationarity
- a fundamentally different approach to multi-disciplinary research:

  neuroscience ←→ engineering/computer sci ←→ mathematics/physics

  neuroscience ←→ mathematics/physics


Nonlinear Dynamic
Signal Complexity
Simple linear
Opportunity Areas For Increasing Knowledge
Current Arena
>10^6
Signal #
1
Brain Systems
Signal Resolution
Sub-cellular


External processor:
•Abstract experimental/analytical tool
•Computational model of neural system
•Physical instantiation of neural system
Multi-channel bi-directional communication at a range of scales to probe, test, & alter activity throughout the nervous system
Nervous system:
Sub-cellular
Whole organism

Large-Scale Biomimetic Computational Systems

Components of a Biomimetic Computational Grand Challenge:

1. develop mathematical models and analytical tools capable of:
   - application to large-scale numbers of neural processes (10,000 elements and greater),
   - and for the multiple levels of organization typical of the nervous system (3 levels and greater)
   - accounting for strong nonlinearities, adaptation and learning
2. develop bi-directional brain-computer interfaces that allow such large-scale models to interact in real-time with the living brain
3. develop an understanding of the relations between signals generated at multiple levels of the nervous system
4. develop biologically-inspired hardware computing platforms that incorporate fundamental properties of neurons and neural systems, including nonlinear dynamics, massive parallelism, and probabilistic behavior
5. develop new sensor and actuator systems required for high density connections with the brain

Large-Scale Biomimetic Computational Systems

<u>Benefits of Meeting a Biomimetic Computational Challenge to Society</u>:

1. scientific: advanced tools for understanding higher-level brain function
2. engineering: nonlinear, nonstationary systems characterization methods; multi-input, multi-output modeling approaches
3. mathematical:
    - theoretical and modeling frameworks for multi-level, hierarchically organized dynamical systems
    - fundamental tools for studying complex systems
4. medical: new diagnostic, therapeutic, and neural prosthetic systems
5. computational: advanced simulation platforms; next-generation computing platforms
6. robotics: form-function control systems