Why study cognitive science?
Pure Science – Understand the Nature of the Mind
Research Path → Graduate School
networks

cooperation

social relations

learn

communicate

natural sciences

complex biological systems

the brain!!
networks:

1. connect levels of organization in the brain
2. help link structure to function
Understanding complexity in the human brain

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“...science is concerned with the structure, behavior and evolution of complex systems such as cells, brains, ecosystems, societies, or the global economy.”

Olaf Sporns, Networks of the Brain

need knowledge of elementary components and how they interact and the emergent properties of the interaction.
large data sets

powerful computers

record, analyze and model

behavior of systems

all such complex systems display characteristic diverse and organized patterns.

"Your recent Amazon purchases, Tweet score and location history makes you 23.5% welcome here."
Connectivity comes in many forms:
all complex systems form networks of interacting components
different systems can generate strikingly similar patterns
Scientists discover the molecular heart of collective behavior


Scientists have long wondered what is happening at the cellular and molecular level to bring about this amazing coordination of so many individual animals, insects and organisms into groups. It's a choreography seen throughout nature from the large-scale to the miniscule, with synchronized movements as precise as the dance lineup of a Broadway musical.

Is there a secret drum major, a leader among the group setting the pace and instigating participation? Or is it that organisms and cells already are moving rhythmically but independently and then find themselves provoked into harmony by an external beat?

A group of scientists seeking the answer to the mystery of collective motion has found strong evidence pointing to a third possibility -- collective behavior can arise in cells that initially may not be moving at all, but are prodded into action by an external agent such as a chemical. Research led by Thomas Gregor, an assistant professor of physics at Princeton, and Satoshi Sawal, a former postdoctoral

Slime Mold Proves to Be a Brainy Blob

By HENRY FOUNTAIN
Published: January 25, 2010

Let's hear it for slime molds.

Researchers in Japan have shown that a slime mold can design a network that is as efficient as one developed by humans over many years: the Tokyo rail system. Furthermore, the slime mold can build its network in a day.

A slime mold is what scientists refer to as a single-celled amoeboid organism. When foraging for food, it spreads out as an amorphous mass and then builds tubular connections between the food sources.

It may be just a blob, but it is a smart one. “We’ve found an unexpected high ability of information processing in this organism,” said Toshiyuki Nakagaki, a researcher at Hokkaido University who has long studied slime molds.

“I wanted to pose a complicated program to this slime mold, to design a large network,” Dr. Nakagaki said. “This kind of program is not so easy, even for humans.”
Collective actions of individual nerve cells linked intricately in a web of connectivity shape thoughts, control behavior, form and retrieve memories and create consciousness.
How does one solve the mind-body problem?

- Start small.
- Look at relationships between different areas in the brain.
- “Connect the dots.”
- Model it.
The human brain is complex!
It has 100 billion neurons.
One neuron has 10,000 synapses!
At the cellular level: one thousand trillion components.
Complexity is a characteristic of biological systems.
Use mathematical tools and concepts to understand the system.

Brain networks span multiple spatial scales. Levels do not operate in isolation. Each level is interconnected and interdependent.

- Identify networks of cells that are coherent populations
- Determine the functional brain regions
- Understand how the regions act as a system
- No longer have a mind body problem – linked organism

Multi-scale systems

Embodied organisms
Cognitive systems
Synapsing cells
Individual cells
Schematic of the multiscale hierarchical organization of brain networks.

Brain function or cognition can be described as the global integration of local (segregated) neuronal operations that underlies hierarchical message passing among cortical areas, and which is facilitated by hierarchical modular network architectures.
“There is an organizational principle characterizes the structure of the human cortex over multiple spatial scales. Hierarchical network structure is consistently displayed at increasing spatial resolutions in which the brain is parcellated into more and more regions of interest (ROIs).”
Brain graph construction

Nodes

Anatomical connectivity

Functional connectivity

Brain graph

Parietal

Occipital

Subcortical

Temporal

Frontal
Cartographic representation of the metabolic network of *E. coli*.

“Each circle represents a module and is colored according to the KEGG pathway classification of the metabolites it contains.

Certain important nodes are depicted as triangles (non-hub connectors), hexagons (connector hubs) and squares (provincial hubs).

Interactions between modules and nodes are depicted using lines, with thickness proportional to the number of actual links.

Each node is colored according to the ‘main’ color of its module, as obtained from the cartographic representation.”

Basic network metrics

The node degree is simply the number of edges attached to a given node.
The clustering coefficient expresses the extent to which a node’s topological neighbors are connected among themselves.

Networks can be uniquely decomposed into subgraphs of motifs.

2 TYPES OF 3 NODE MOTIFS

The length of the shortest path corresponds to the (topological, not metric) distance between two nodes.

Here, the two nodes A and B connect to each other in three steps, with a shortest path that travels through two intermediate nodes (here shown in gray).

The example network shown here can be decomposed into two main clusters or modules that are interconnected by a single hub node.

Modules, cores, and rich clubs.

A schematic network composed of four modules that are linked by hub nodes (black).

With the addition of further inter-module connections hub nodes now form a densely interconnected rich club, consisting of 5 nodes with a degree of 4 or higher.

The same network as shown in (B), but now shown after core decomposition, (ie, the iterative removal of low degree nodes, shown here in gray). This procedure results in a core network comprising 4 nodes with a minimal degree of 3.

Cortical Hubs Revealed by Intrinsic Functional Connectivity: Mapping, Assessment of Stability, and Relation to Alzheimer's Disease
“Recent evidence suggests that some brain areas act as hubs interconnecting distinct, functionally specialized systems.

... Prominent hubs were located within posterior cingulate, lateral temporal, lateral parietal, and medial/lateral prefrontal cortices.”

The size of the node reflects the estimate of the betweenness centrality of each region. The five regions with the greatest betweenness centrality are colored in blue and labeled a through e. Note that the majority of hubs link to a single integrated network (I), whereas a subset reflect a distinct network (II).
A consensus estimate of cortical hubs from 127 participants. To provide our best estimate of the locations of cortical hubs, the data for all available participants were pooled and a map of hubs based on degree connectivity computed.

The pattern of Aβ deposition in Alzheimer's disease. Aβ deposition was measured using PiB–PET imaging and is plotted on the cortical surface. As can be appreciated visually, those regions showing high functional connectivity primarily overlap those regions showing Aβ deposition.
TEMPORAL SCALING

“...evident across the inherent rhythms of brain activity that vary in frequency and relate to different cognitive capacities.”

Self-similarity of spatial distribution of highly connected network nodes or “hubs” in the frequency range 2–38 Hz (64).

Bassett D S et al. PNAS 2006;103:19518-19523
State-related differences in spatial configuration of the highest frequency γ network.

Bassett D S et al. PNAS 2006;103:19518-19523
"The components of a system can be categorized according to their functions."

"The entire brain system can be decomposed into subsystems or modules."

RELATIONSHIP BETWEEN STRUCTURE AND FUNCTION.

The human connectome project

- “Navigate the brain in a way that was never before possible; fly through major brain pathways, compare essential circuits, zoom into a region to explore the cells that comprise it, and the functions that depend on it.”

- “The Human Connectome Project aims to provide an unparalleled compilation of neural data, an interface to graphically navigate this data and the opportunity to achieve never before realized conclusions about the living human brain.”

http://www.humanconnectomeproject.org/

Images © by the Laboratory of Neuro Imaging, UCLA
• Relationship viewer

• Click on a specific region to visualize its relationship with other anatomical areas.
• Warmer colors mean stronger connections.

http://www.humanconnectomeproject.org/

Images © by the Laboratory of Neuro Imaging, UCLA
Wiring diagram of *Caenorhabditis elegans*
CONSCIOUSNESS: AN EMERGENT PROPERTY?

emergence

- Fundamental property of the brain
- Occurs between physical and functional levels of the brain.

reductionism

- System phenomena
- Reducing the system down to smallest particle.

the behavior of the system is more than the sum of the system’s parts at any particular level.
TYPES OF EMERGENCE

Substance
• a baby emerges from a mother

Conjunction
• two parts can perform a different function than either part separately

Property
• wetness is not a property of a molecule but of a group of molecules

Structural
• three lines make a triangle

Functional
• letters form words

Real
• a cell is alive unlike the molecules of which it is made
“The mind–brain emergence therefore requires a tailored definition. Mental states emerge from physical states by strong emergence, that is in a nonreducible and highly dependent manner: mental properties do not exist or change unless physical properties exist or change.”
<table>
<thead>
<tr>
<th>Glossary</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Complex network theory</td>
<td>A modeling framework that defines a complex system in terms of its subcomponents and their interactions, which together form a network.</td>
</tr>
<tr>
<td>Complex system</td>
<td>A system whose overall behavior can be characterized as more than the sum of its parts.</td>
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<tr>
<td>Connectome</td>
<td>A complete connectivity map of a system. In neuroscience, the structural connectome is defined by the anatomical connections between subunits of the brain whereas the functional connectome is defined by the functional relations between those subunits.</td>
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</tbody>
</table>

- **Emergence**
  - the manner in which complex phenomena arise from a collection of relatively simple interactions between system components.

- **Ising model**
  - a historically important mathematical model of a phenomenon in physics known as ferromagnetism that displays several characteristics of complex systems including phase transitions and the emergence of collective phenomena.

- **Modularity**
  - a property of a system that can be decomposed into subcomponents or ‘modules’, which can perform unique functions and can adapt or evolve to external demands.
<table>
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<tr>
<th>Nonfundamental causality</th>
<th>• the concept that parts of a system that are not its smallest parts (i.e. nonfundamental) can have significant causal power in terms of system function, facilitating mutual manipulability between multiple levels of the system and multiple realizability of system function.</th>
</tr>
</thead>
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<td>Reductionism</td>
<td>• in philosophy, a view that a complex system can be modeled and understood simply by reducing the examination to a study of the system's constituent parts.</td>
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<tr>
<td>Scaling</td>
<td>• the term scaling indicates a similarity of some organizational structure of phenomenon across multiple scales of a system. Spatial scaling therefore indicates that a principle or phenomenon is consistently displayed at multiple spatial resolutions. Temporal scaling indicates that a principle or phenomenon is consistently displayed at multiple temporal resolutions.</td>
</tr>
<tr>
<td>Wiring diagram</td>
<td>• a map of the hard-wired connectivity of a system. In neuroscience, the term is usually used to refer to the map of connections (e.g. synapses) between neurons specifically but can also be used to refer to the map of larger scale white matter connections between brain regions</td>
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Cognitive linguistics looks at the relationship of language to the mind. Cognitive linguistics sees language as embedded in the overall cognitive capacities of man.