Classes of Network Connectivity and Dynamics

by Sporns and Tononi (2002)

CPSC 644

Presented by Yoonsuck Choe

Introduction

- Complex systems with patterns of temporal correlation: Arise from functional interactions within a structured network.
- The brain is an example.
- Activation and coactivation patterns (or functional connectivity) underlies perceptual and cognitive functions.
- Tools to investigate structure-function relation.

Connectivity

- Anatomical
  - Area-to-area connectivity known.
  - Some detailed connectivity known.
- Functional
  - Temporal correlation or deviation from statistical independence.
  - Segregation (functional units) and integration needed.
  - Covariance matrix (second-order effects) can express these aspects.
  - "Complexity" measure.

Computational Methods for Analysis

- Graph theory: vertices and edges, connection matrix, graph space, path, path length, cluster index, etc.
- Functional dynamics: sigmoidal activation units (with noise), covariance matrix derived from connectivity matrix and noise.
  - Entropy: overall statistical independence

$$H(X) = 0.5 \cdot \ln((2\pi e)^n |\mathbf{COV}(X)|).$$

  - Integration: deviation for statistical independence

$$I(X) = \sum_i H(x_i) - H(X).$$

  - Complexity: degree of segregation and integration (next page)

Complexity

- Complexity: size n and connectivity k

$$
\begin{aligned}
C_N(X) &= \sum (k/n)I(X) - \langle I(X_j^k)\rangle \\
&= \sum_k \langle MI(X_j^k; X - X_j^k)\rangle
\end{aligned}
$$

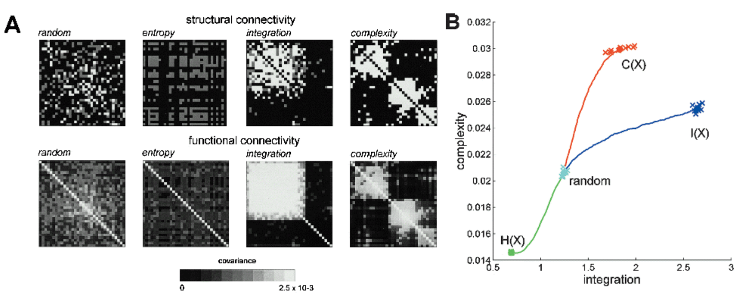
$$
\begin{aligned}
C(X) &= H(X) - \sum_i H((x)_i | X - \mathbf{x}_i) \\
&= MI(\mathbf{x}_i; X - \mathbf{x}_i) - I(X) \\
&= (n-1)I(X) - n\langle I(X - \mathbf{x}_i)\rangle
\end{aligned}
$$

- $C(X)$ high if single elements are highly informative about the system while not being overly alike.

Graph Selection

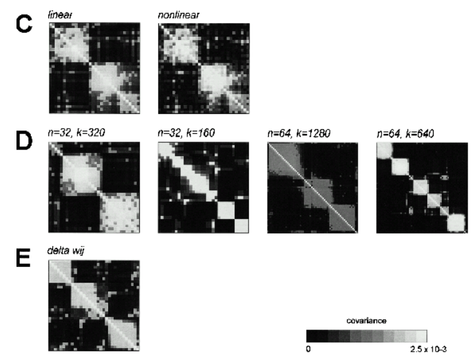
- Randomly generate and simulate graphs.
- Try maximizing different measures.
- Perform various measures on connectivity and dynamic properties.

Networks Optimized for Different Criteria



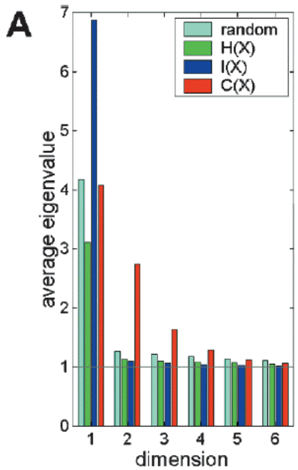
- A(top): Connection matrix (static): unidirectional (gray), bidirectional (white)
- A(bottom): Covarianve matrix (dynamic)
- B: $I(X)$ vs. $C(X)$ in networks optimized for three quantities.

Covariance Matrix Analysis: Dynamics



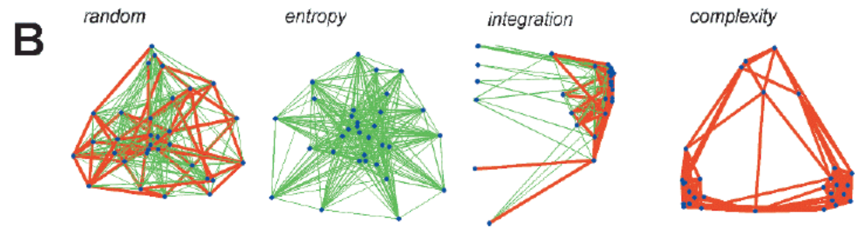
- C: Analytic (linear) vs. simulation (nonlinear).
- D: Varying network size n and connectivity k.
- E: Redistributing synaptic weight rather than connections themselves.

Eigenvalue Spectra for Correlation Matrix



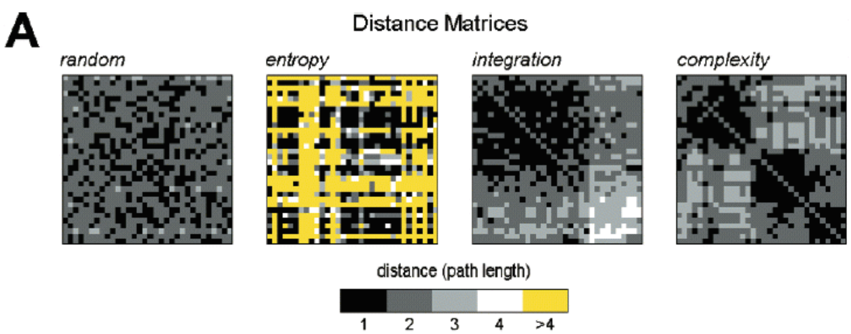
- For complex networks, two to three terms dominate.

Multidimensional Scaling for Measuring Distance



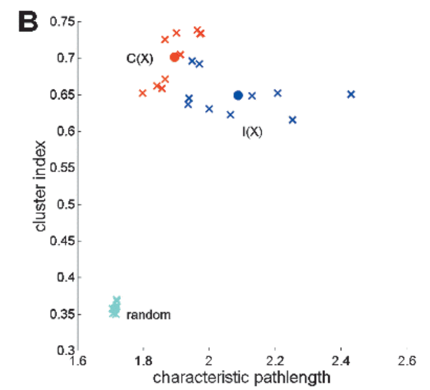
- Bidirectional connections (red); unidirectional connections (green)
- Some have spatial ordering, while some don't.
- Complex networks show clustering and long-range interconenctions: functionally segregated subsets emerge (reduced dimensionality).

Distance Matrices: Structural Feature



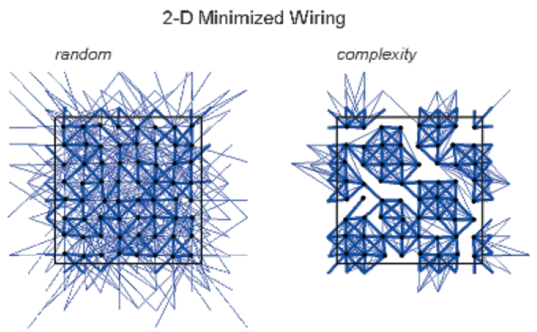
- Path length in different networks.
- Entropy: long distance.
- Integration: short distance between core, long distance to outliers.
- Complexity: short distance within cluster, long distance across cluster.

Characteristic Path Length: Structural Feature



- CPL: global average of the distance matrix.
- Cluster index: number of connections among immediate neighbors / all possible connections among immediate neighbors.
- High complexity: High cluster index and low path length.

Wire-Length Minimization



- Map graph onto 2D space: Vertices are given (x, y) locations.
- How to map to minimize wiring length?: Run optimization program.
- Complex networks give short total wire length compared to random networks.

Conclusion

- It is important to understand functional connectivity based on anatomical connectivity.
- Complexity is an interesting measure of simultaneous segregation and integration: Not too ordered, not too random.
- Cortical networks: found to be complex.
- Role of complexity in evolution: wiring length reduction may be a side effect of maximizing complexity.

Organization, development, and function of complex brain networks

by Sporns et al. (2004)

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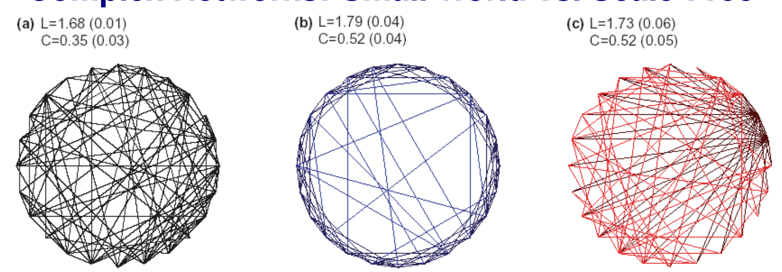
Presented by Yoonsuck Choe

Complex Networks: Small World vs. Scale-Free

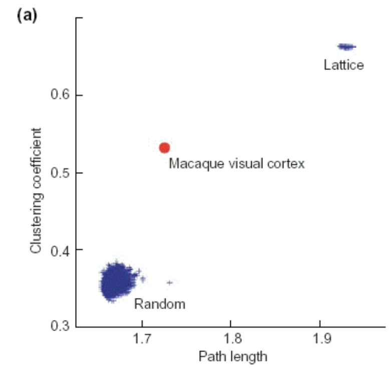


- Random
- Small-world: dense local connetions, occasional long-distance connections. Often found in nature.
- Scale-free: degree distribution follows a power-law. Different degree values exist at every scale (scale-free). Often found in artifacts.
- L: characteristic path length; C: clustering coefficient

Brain Connectivity

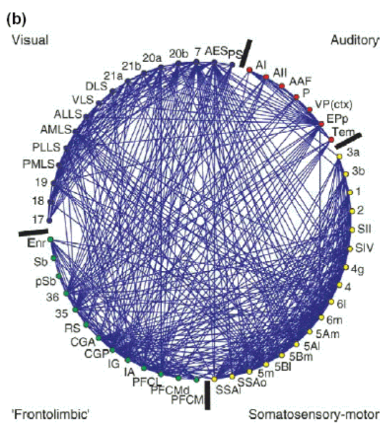
- Anatomical connectivity: actual physical connections
- Functional connectivity: activation/coactivation patterns.
- Effective connectivity: causal effects of one element over another. Not model-free: requires causal model with parameters. Use perturbation to infer connectivity.

Characterization of Networks



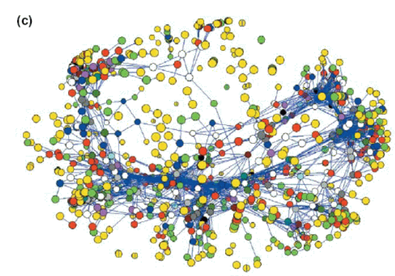
- Area-wise connectivity in Macaque visual cortex: High cluster coefficient, low path length.

Cat Corticocortical Connectivity



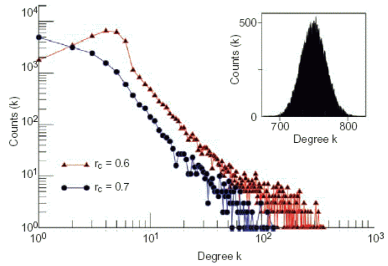
- Closer nodes represent higher inter-linked areas.
- Clusters (separated by bars) correspond to visual, auditory, somatosensory-motor, and frontolimbic cortices.

Functional Connectivity in Human fMRI Data



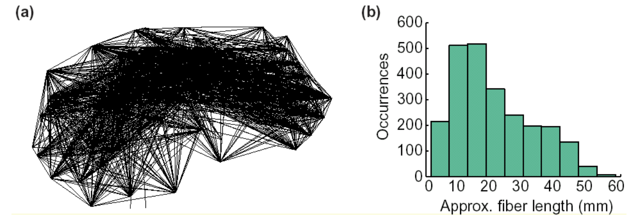
- Areas treated as connected when correlation is above a certain threshold.
- Degree: yellow=1, green=2, red=3, blue=4, other $>$ 4.

Degree Distribution in Human fMRI Data



- Power-law is observed regardless of the correlation threshold: It seems to be scale-free?
- Random graphs show a unimodal degree distribution.

Growth: Local Rules vs. Global Design



- Structure largely determined by growth and development.
- Growth mechanims governed by constraints gives rise to different kinds of networks.
- Role of experience-dependent plasticity?
- Local growth rules: preferential attachment vs. distance-modulated spatial growth mechanism.
- Global network design

Questions for Future Research

Box 4. Questions for future research

• What are the best experimental approaches to generate large and comprehensive connectional datasets for neural systems, especially for the human brain?
• What is the time scale for changes in functional and effective connectivity that underlie perceptual and cognitive processes?
• Are all cognitive processes carried out in distributed networks? Are some cognitive processes carried out in more restricted networks, whereas others recruit larger subsets?
• Does small-world connectivity reflect developmental and evolutionary processes designed to conserve or minimize physical wiring, or does it confer other unique advantages for information processing?
• What is the relationship between criticality, complexity and information transfer?
• Is the brain optimized for robustness towards lesions, or is such robustness the by-product of an efficient processing architecture?
• What is the role of hubs within scale-free functional brain networks?
• How can scale-free functional networks arise from the structural organization of cortical networks?

Conclusion

- Systematic and global regularities in brain networks.
- Segregation and integration.
- Small-world attributes: Why? – for signal transformation?
- Relation to cognitive functions?

References

Sporns, O., Chialvo, D. R., Kaiser, M., and Hilgetag, C. C. (2004). Organization, development and function of complex brain networks. *Trends in Cognitive Sciences*, 8:418–425.

Sporns, O., and Tononi, G. (2002). Classes of network connectivity and dynamics. *Complexity*, 7:28–38.