

Functional Connectivity & Network Analysis

Basic concepts and practical applications

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Contents

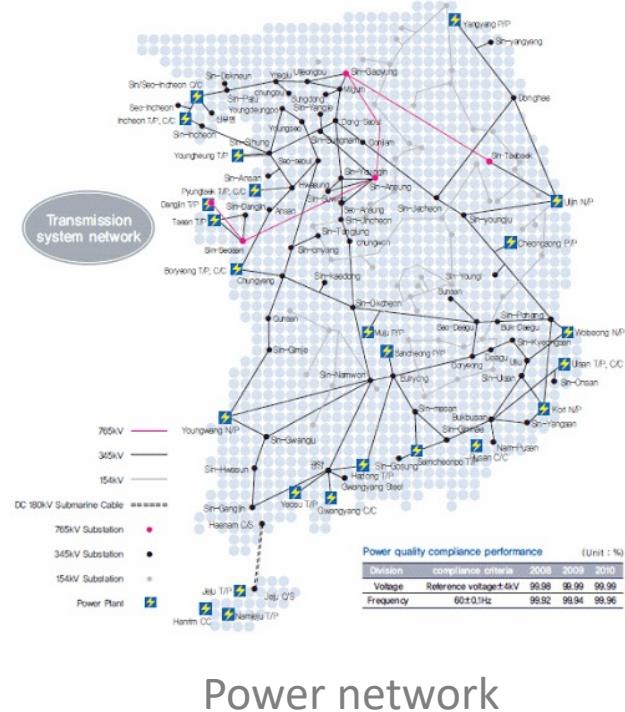
An introduction to the functional connectivity and network analysis

1. Functional connectivity: Overview
2. Functional connectivity: Practice
3. Network analysis: Overview
4. Network analysis: Practice

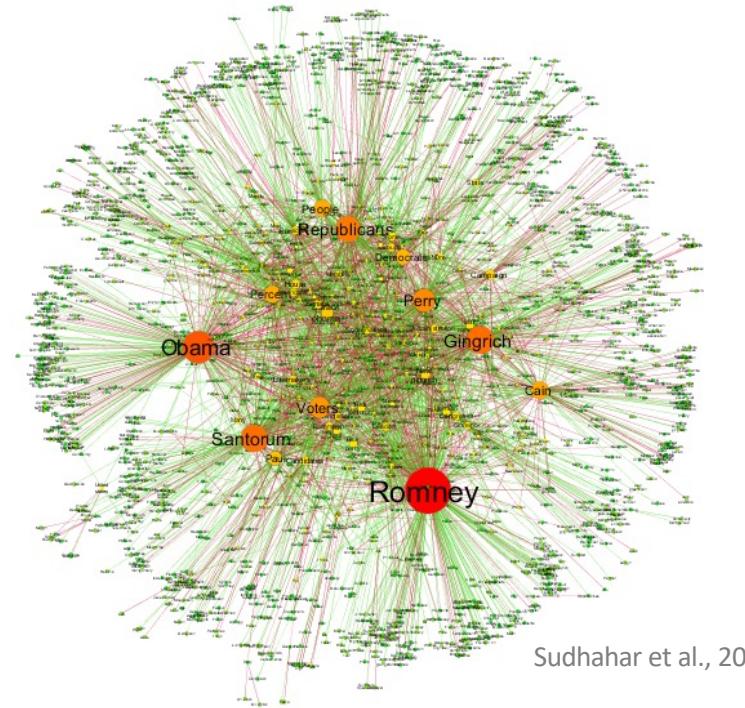


What is network analysis?

Networks are everywhere!



Power network

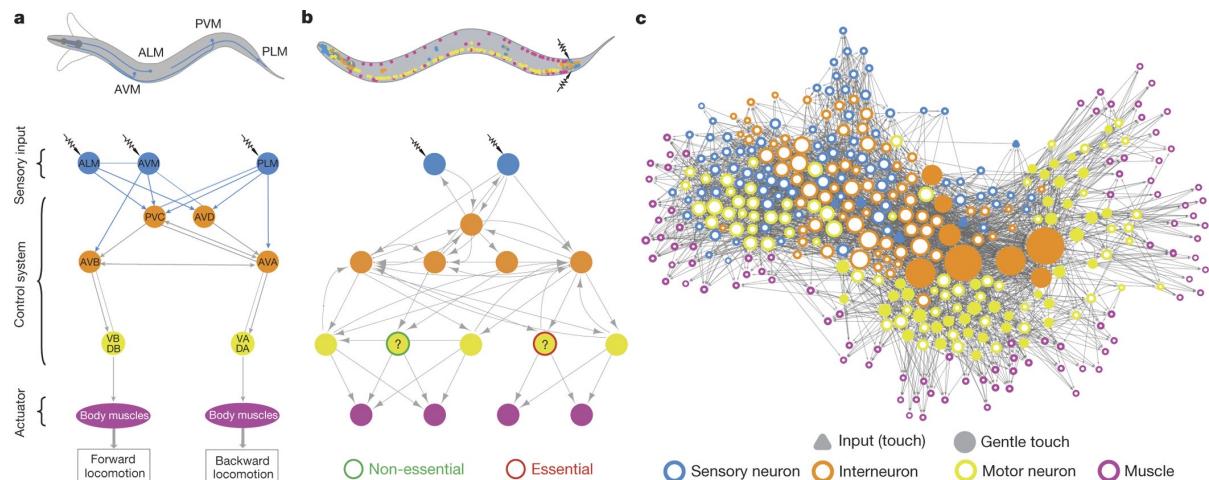


Narrative network

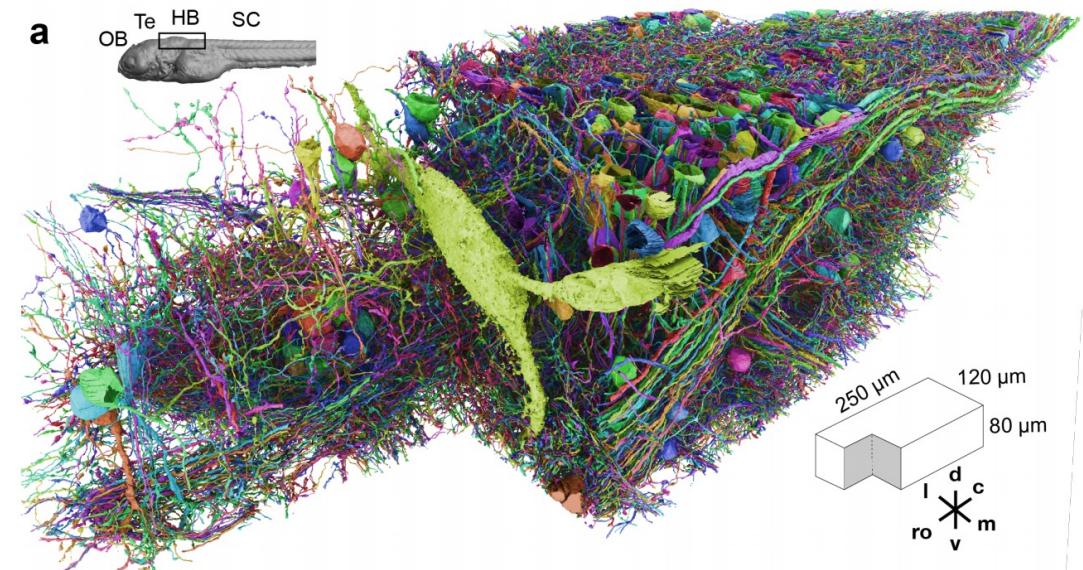


Why network analysis?

Brain as a complex network



Yan et al., 2017

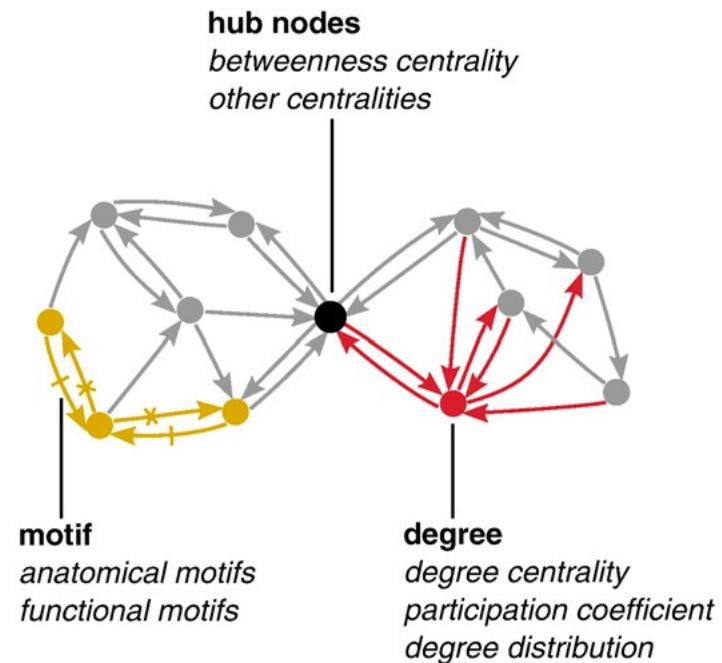
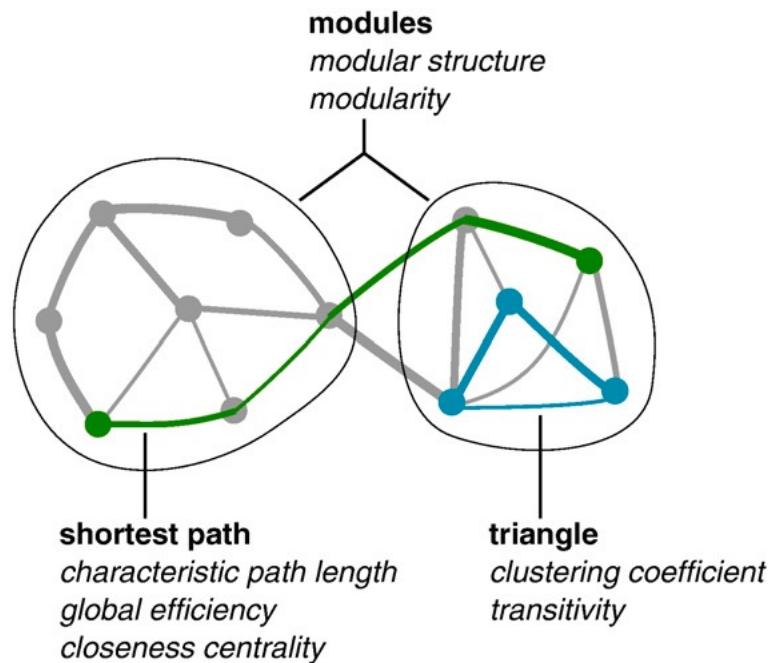


Vishwanathan et al., biorxiv



Why network analysis?

Network analysis helps to understand complex system.



Rubinov and Sporns, 2010

Global-level

- Integration
- Segregation
- Resilience

Intermediate-level

- Community

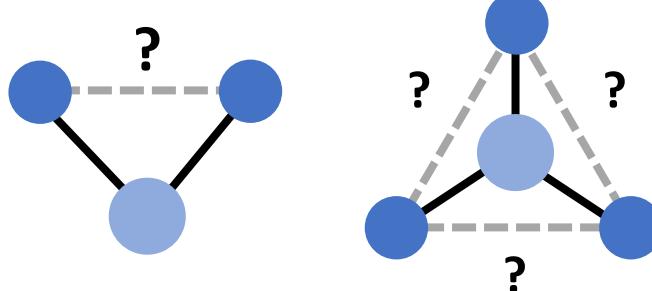
Nodal-level

- Centrality



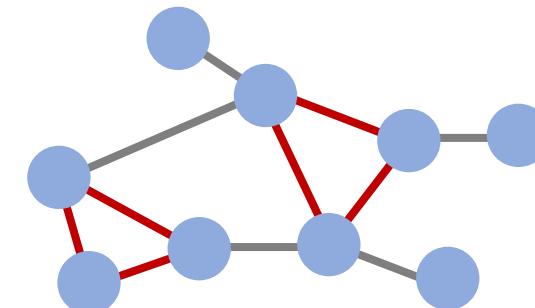
Network attributes

Clustering coefficient / Transitivity



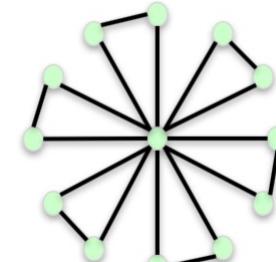
How often my neighbors are
connected to each other?

: Clustering coefficient

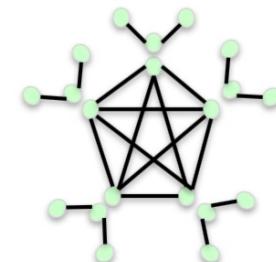


How many there are
closed triplets in a network?

: Transitivity



High averaged clustering coefficient
Low transitivity

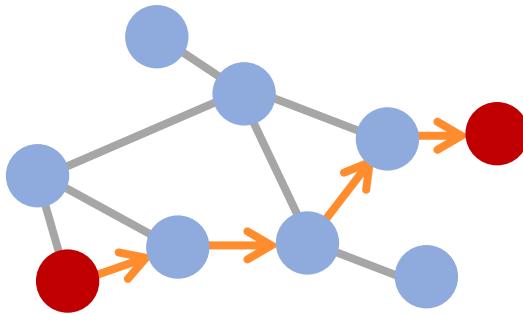


Low averaged clustering coefficient
High transitivity



Network attributes

Characteristic path length / Global efficiency



How long it will take to move
from a node to the other node?
: Shortest path length

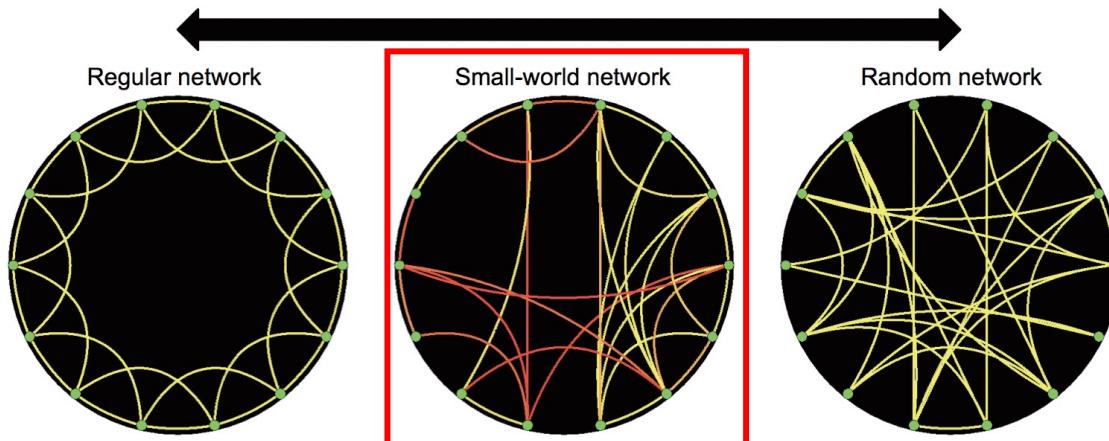
Characteristic path length
: Average of shortest path length

Global efficiency
: Average of $1 / \text{shortest path length}$

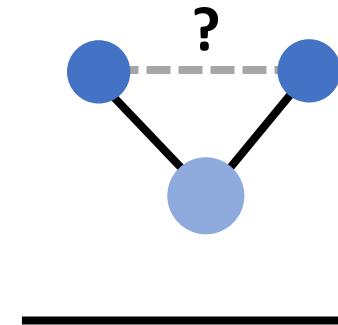


Network attributes

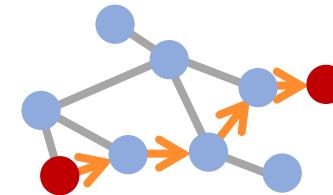
Small-worldness



Averaged clustering coefficient

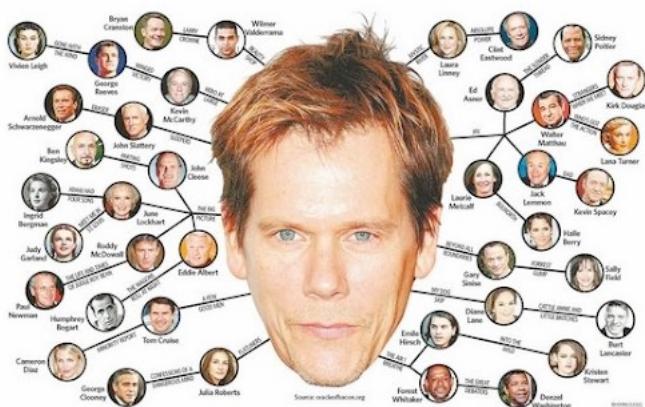


Characteristic path length



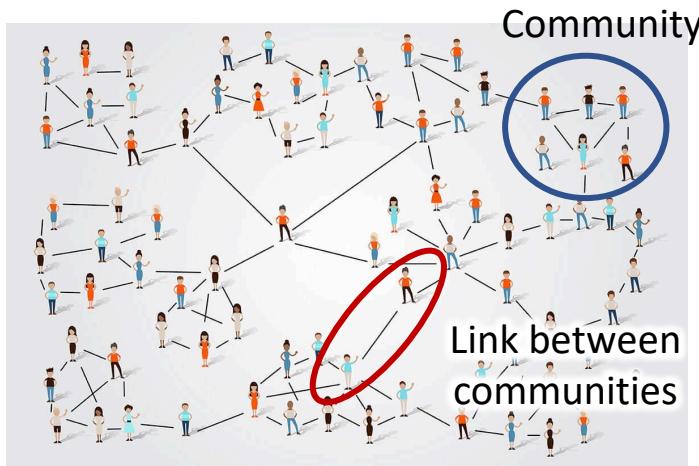
Network attributes

Small-worldness



Six degrees of separation (Stanley Milgram)

High clustering & Low distance



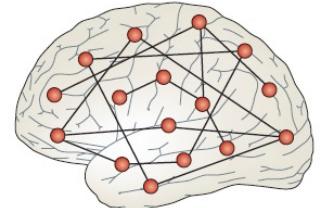
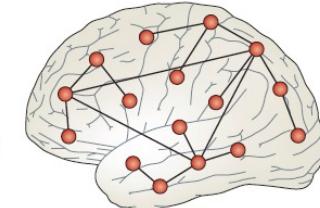
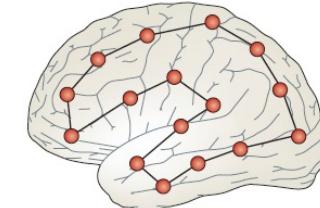
Community

Link between
communities

Lattice topology

Complex topology

Random topology



Low Efficiency → High Cost

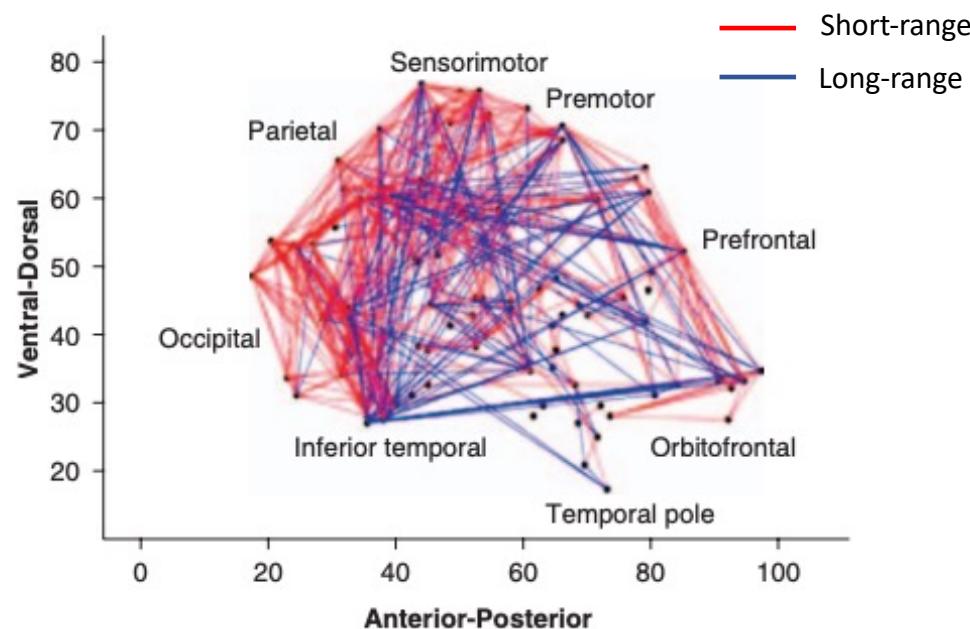
Bullmore and Sporns, 2012

Cost-effective structure



Network attributes

Small-worldness



Achard et al., 2006

TABLE I. Average statistical properties of the brain functional networks.

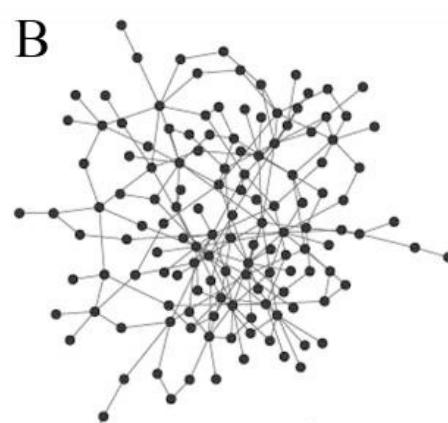
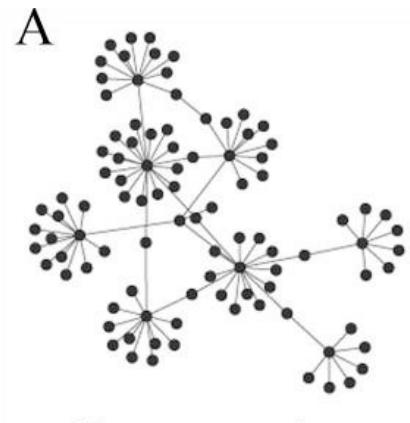
r_c	N	C	L	$\langle k \rangle$	γ	C_{rand}	L_{rand}
0.6	31 503	0.14	11.4	13.41	2.0	4.3×10^{-4}	3.9
0.7	17 174	0.13	12.9	6.29	2.1	3.7×10^{-4}	5.3
0.8	4891	0.15	6.0	4.12	2.2	8.9×10^{-4}	6.0

Eguiluz et al., 2005

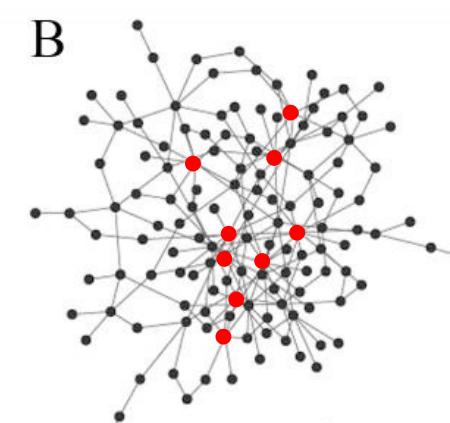
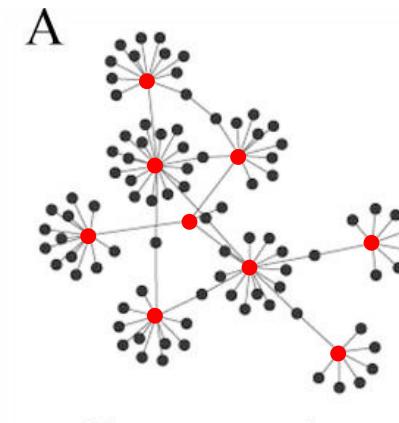


Network attributes

Assortativity (Homophily)



Hao et al., 2011



● Attack

How similar are the degrees
(number of connections)
of two connected nodes?

: Assortativity

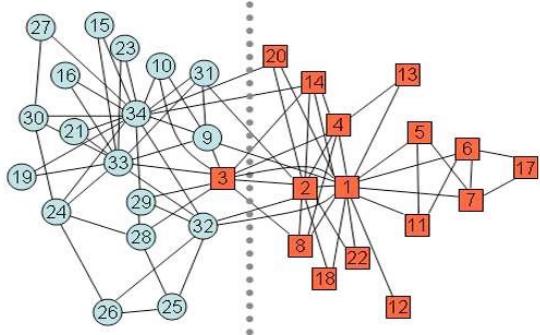
Related with resilience!



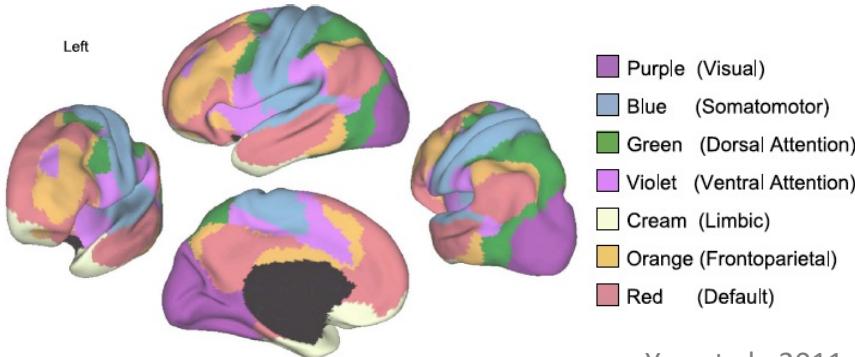
Network attributes

Community & Modularity

Zachary's Karate club

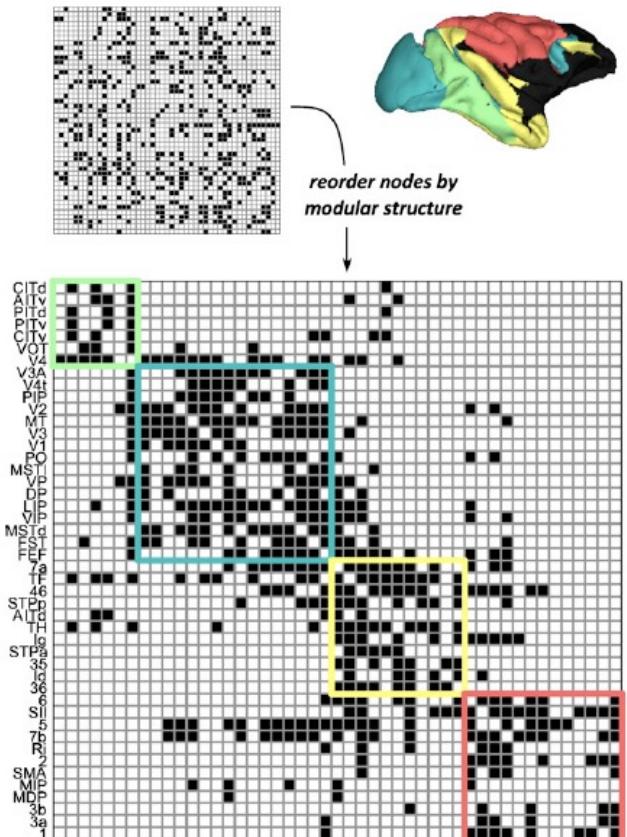


Human cortical networks



How well a network can be divided into distinct modules?
: **Modularity** (Within-module ↑, Between-module ↓)

Community detection

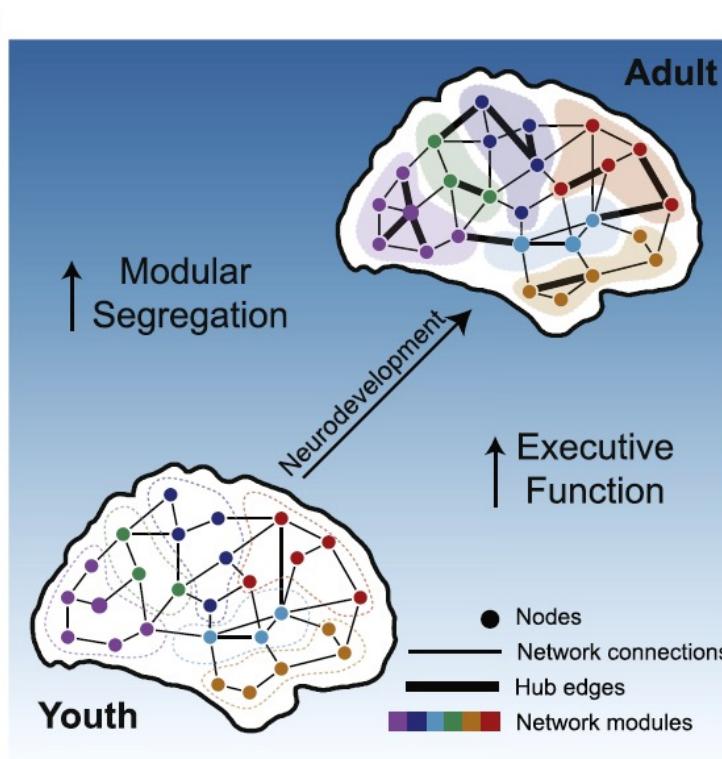
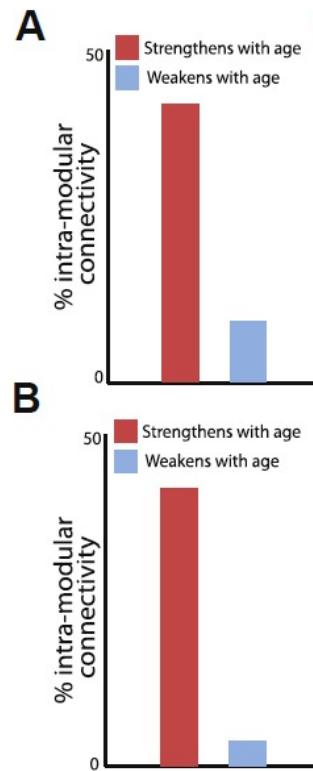


Rubinov and Sporns, 2010

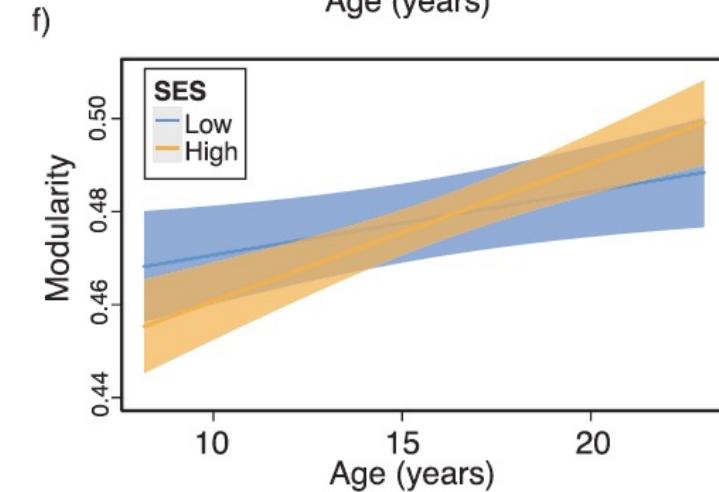
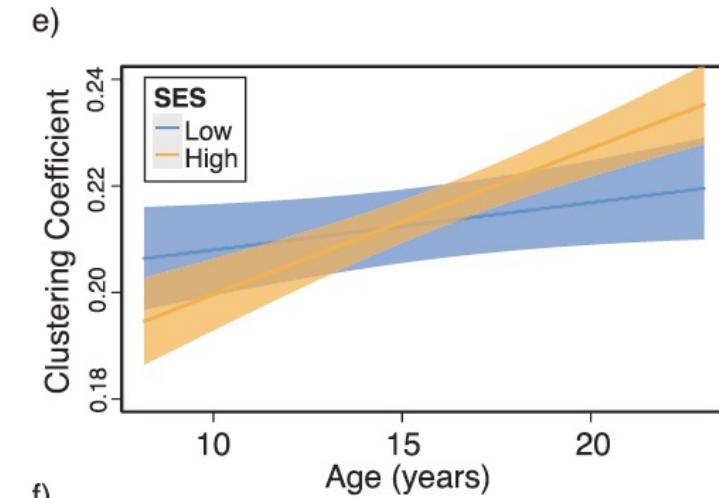


Network attributes

Community & Modularity



Bassett et al., 2018



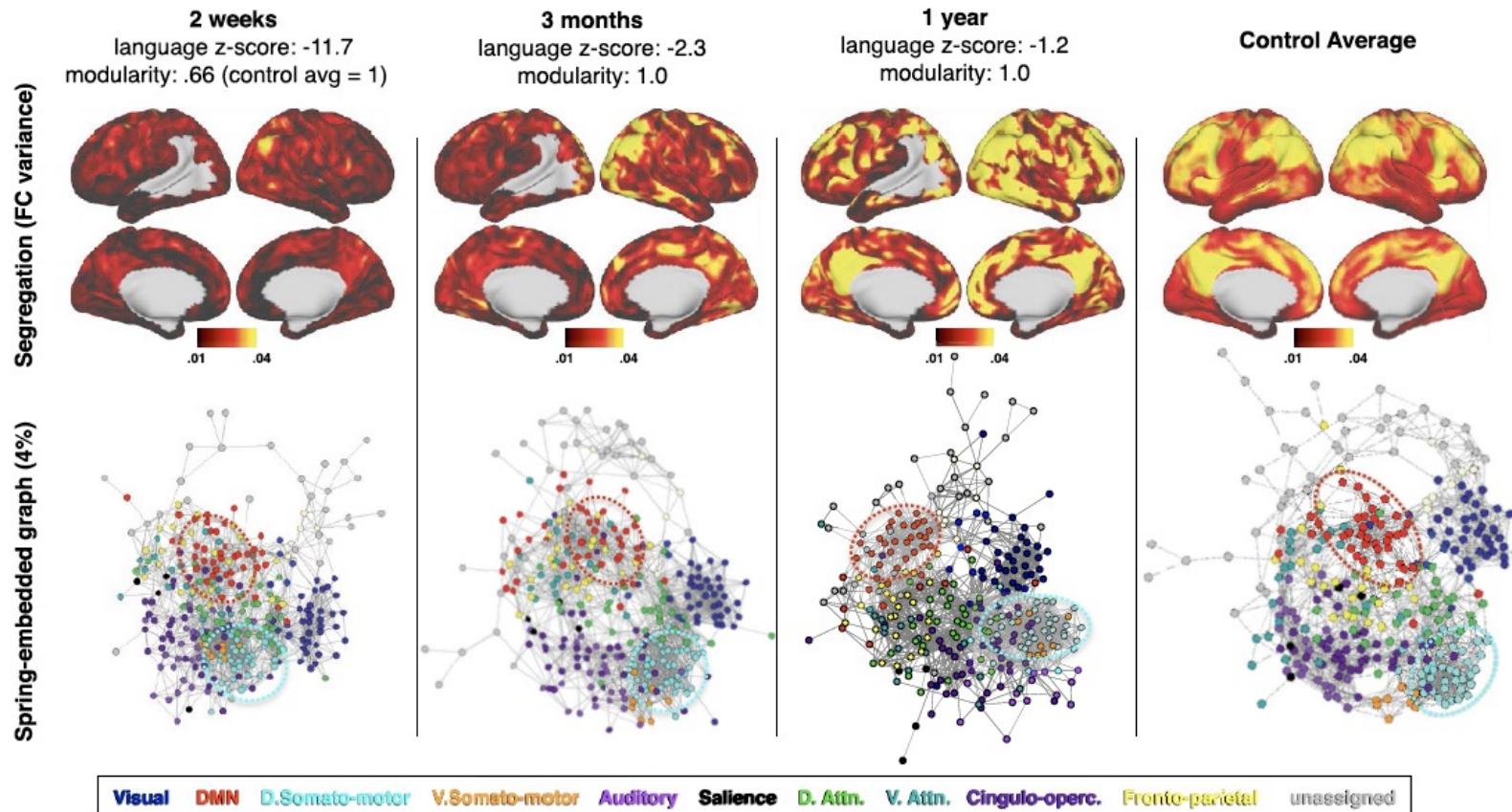
Tooley et al., 2019



Network attributes

Community & Modularity

Brain after stroke
: Recovery of Modularity

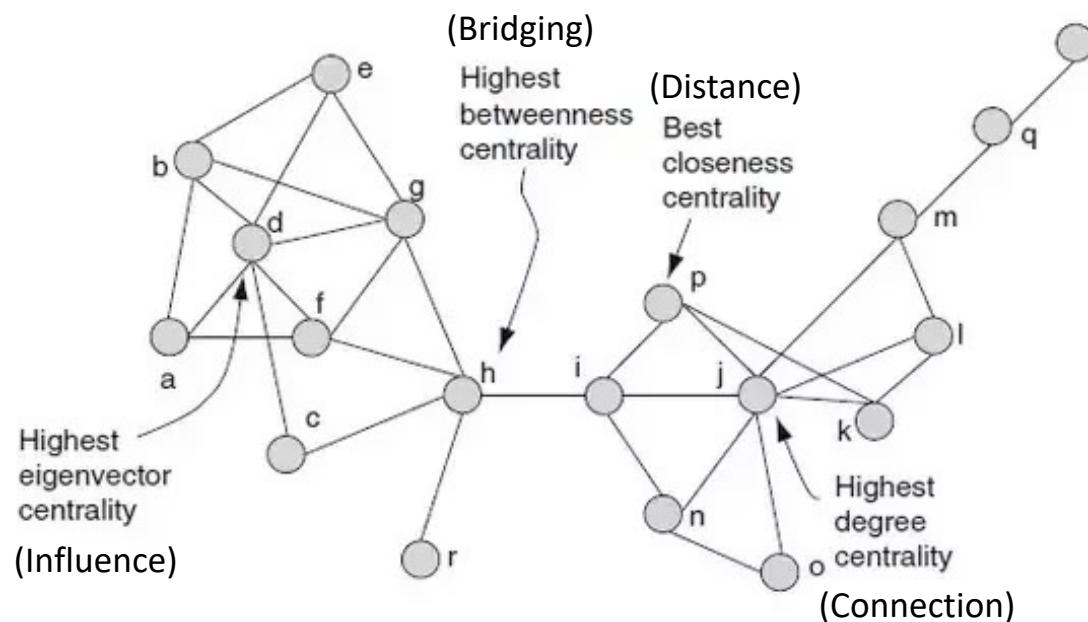


Siegel et al., 2018

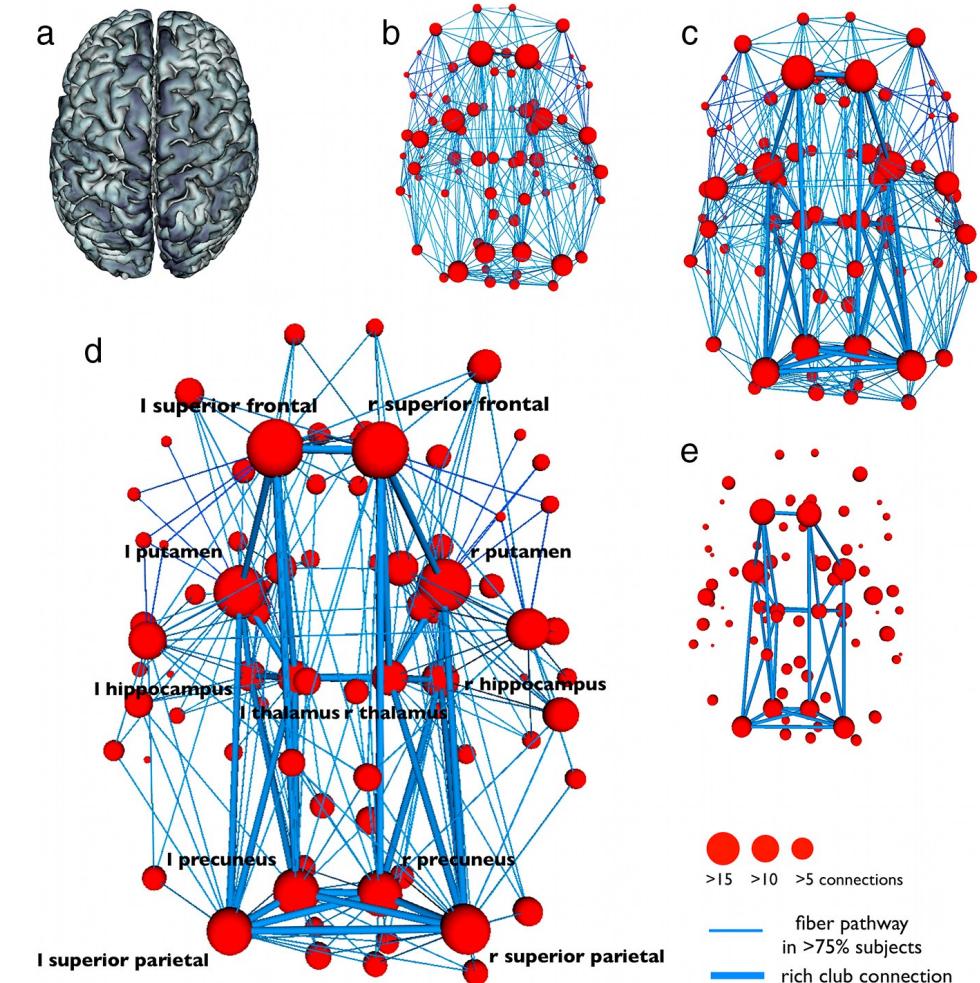


Network attributes

Centrality



<https://ultrabpm.wordpress.com/>



van den Heuvel and Sporns, 2011



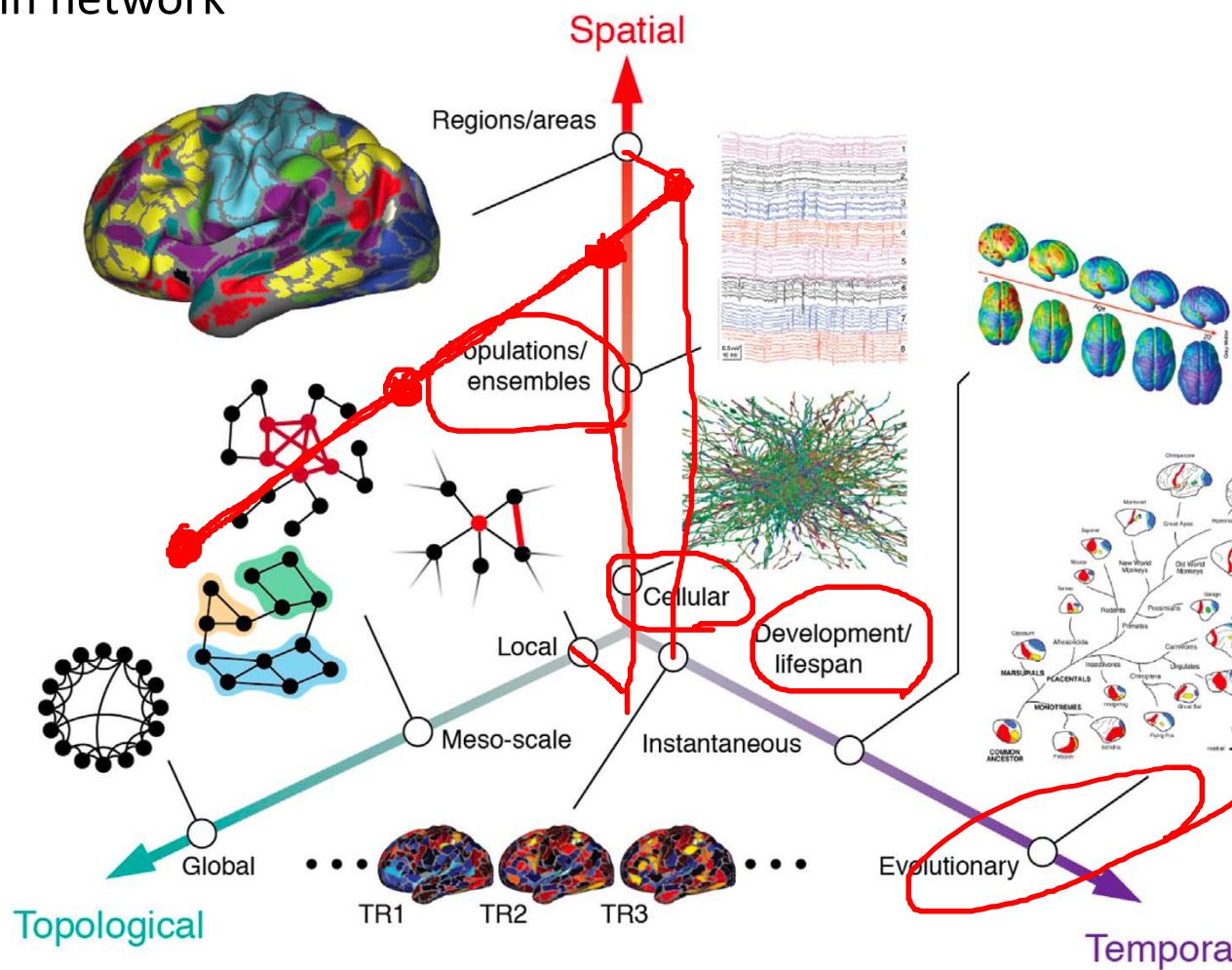
Network attributes

- **Clustering coefficient / Transitivity:** Functional segregation, clustering
- **Characteristic path length:** Functional segregation, distance
- **Global efficiency:** Functional integration, distance
- **Small-worldness:** Functional integration, clustering & distance
- **Assortativity:** Resilience, degree correlation
- **Community / Modularity:** Decomposability
- **Centrality (Degree, Closeness, Betweenness, Eigenvector):** Importance, hubness
- Great care is needed for network construction, comparison, and interpretation
 - ✓ Functional connectivity vs. Structural connectivity
 - ✓ Whole brain vs. Sub-network
 - ✓ Voxel-level vs. Region-level (and parcellation scheme)
 - ✓ Weighted vs. Binary
 - ✓ Thresholding (Proportional vs. Absolute) and its level
 - ✓ Raw vs. Normalized (compared to random network)



Network attributes

Multiple scales of brain network

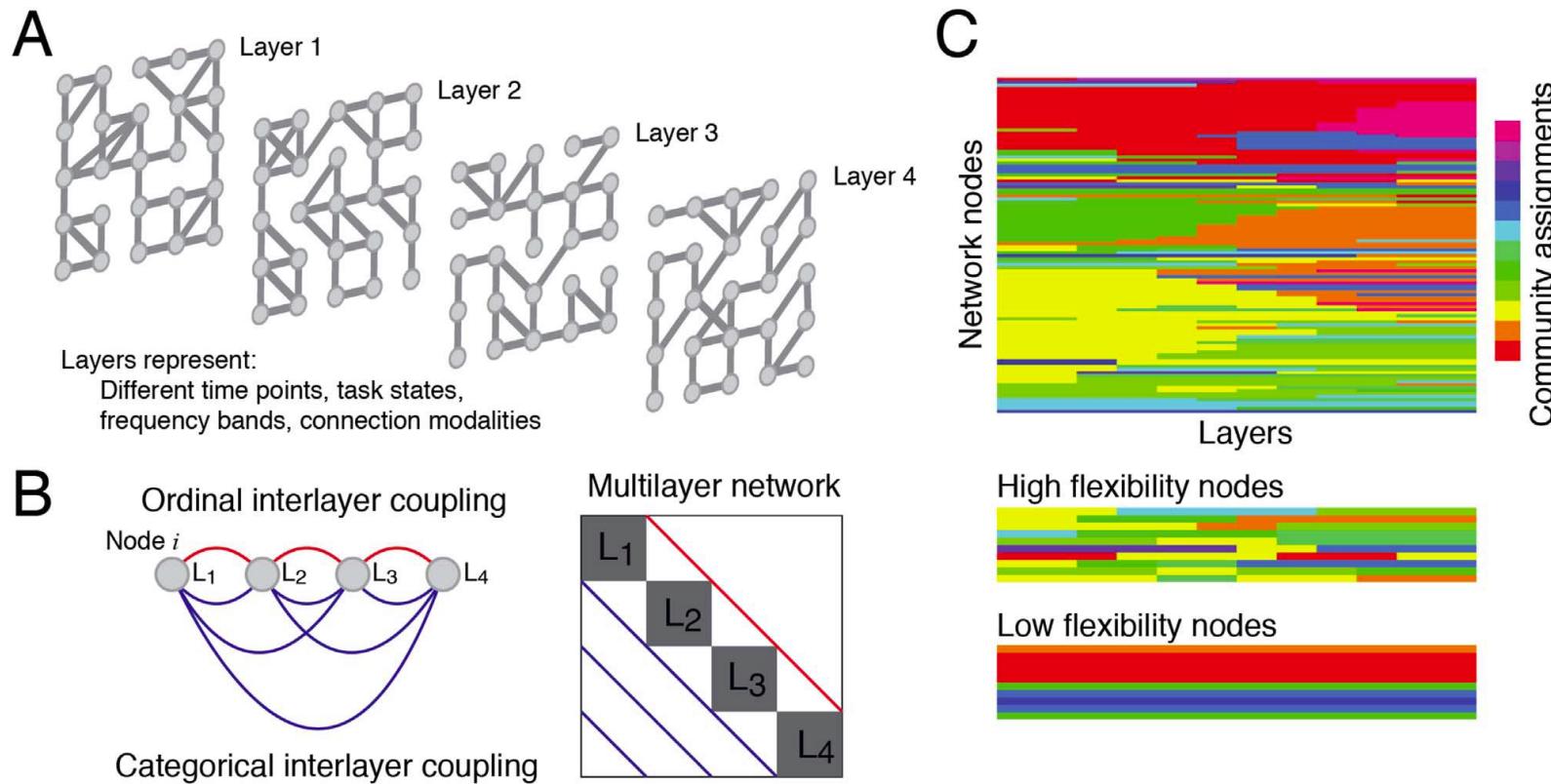


Betzel and Bassett, 2017



Network attributes

Multi-layer community detection



Betzel and Bassett, 2017

