NACS 645 – Connections

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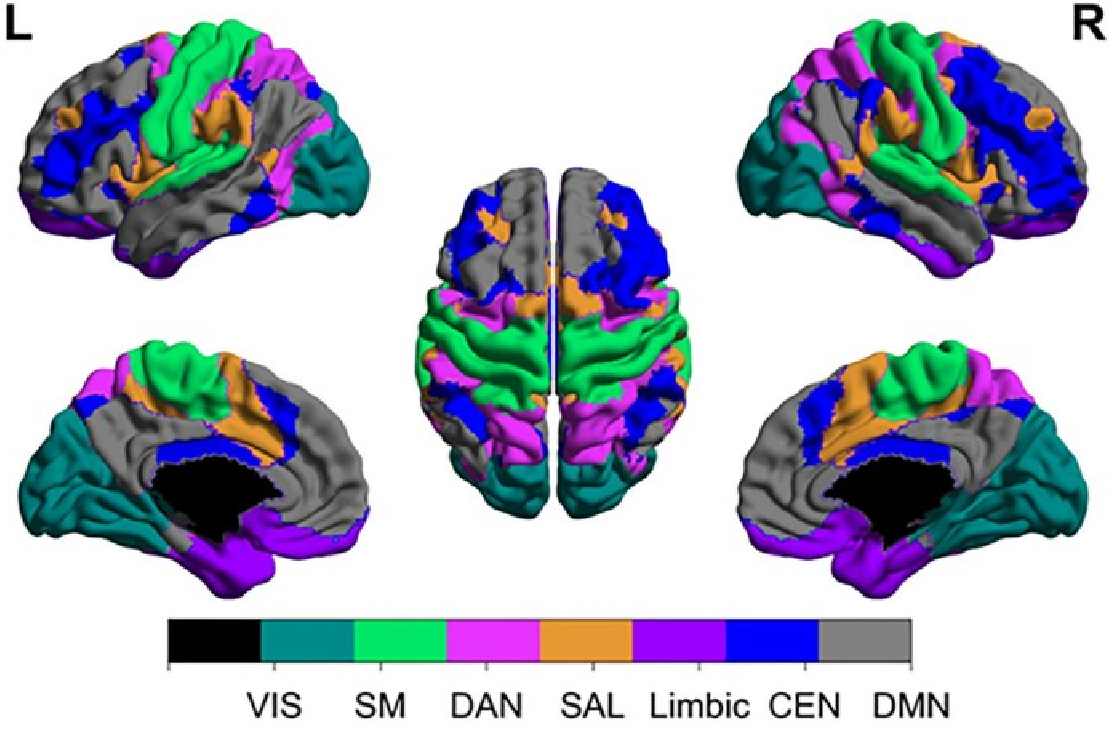
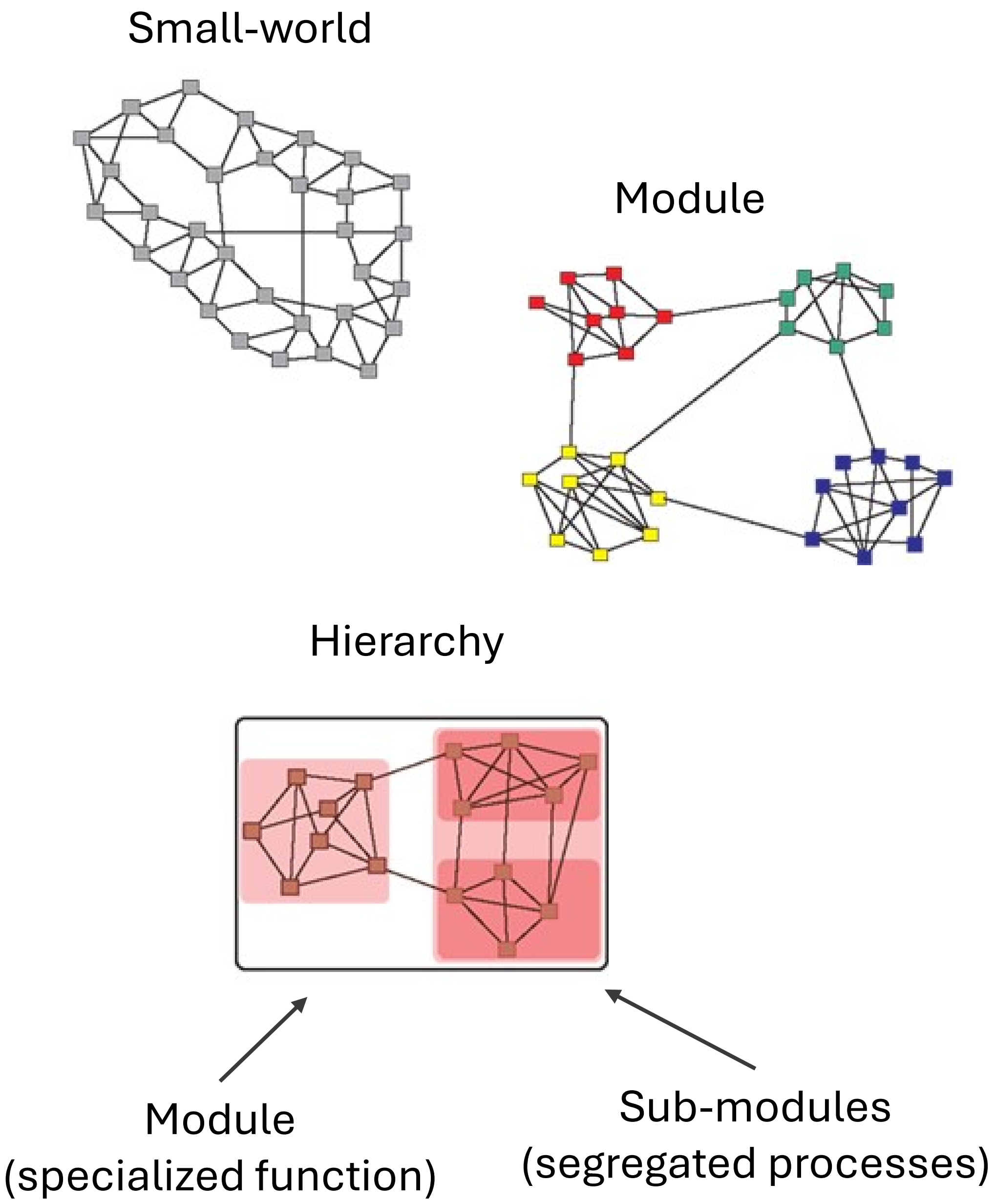
Topological Modularity: Early networks

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*

The brain is hierarchically modular, with modules and sub-modules.



Boerger et al., 2023.
Frontiers in Human Neuroscience



Topological Modularity: Modularity of anatomy and functions

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*
Seguin, Sporns et Zalesky, 2023. *Nature reviews neuroscience*

Cognitive modularity

- Modularity is a property of brain regions
  - Mind organized into **modules**: specialized systems for processing certain inputs (vision, language)
  - Modules defined by: **domain specificity** (operate only on certain inputs), **encapsulation** (insulated from other knowledge), **automaticity** (mandatory operations), relatively **fixed neural architecture**
  - *Psychological-level* definition: modules are computational “boxes” in the mind

Network modularity (predictive coding -compatible)

- Modularity is a property of networks that optimizes information communication
  - A module is a cluster of brain regions with **dense internal connectivity, sparse external connectivity and recursivity**
  - Brain networks are **hierarchically modular**: large modules (e.g., visual network) subdivided into smaller submodules (ventral vs. dorsal visual pathways) subdivided into smaller submodules
  - Modularity provides **computational advantages**: efficiency, robustness, balance between segregation (specialization) and integration (coordination)
  - Modules forward information **with dedicated paths and diffusion processes** to achieve *optimal signalling delay*

Why are brain networks expected to be modular?

- **Small-world design:** high clustering within modules supports **locally segregated processing** (e.g., visual motion detection) at low wiring cost, while short path lengths **enable global integration** for generic functions (e.g., working memory)
- **Rich non-linear dynamic behaviors**: Modularity supports **fast intra-modular and slower inter-modular processes**; neural activity can remain **locally encapsulated**; **neural activity is balanced**: *activity doesn't die, doesn't spread network-wise*; **redundancy of signal; flexibility and stability** by allowing modules and submodules **reconfiguration**
- **Origins**: Modular networks arise naturally when structure and dynamics co-evolve. Connections between regions that tend to synchronize are reinforced; weak or unsynchronized links are pruned. Specialized submodules can be reused

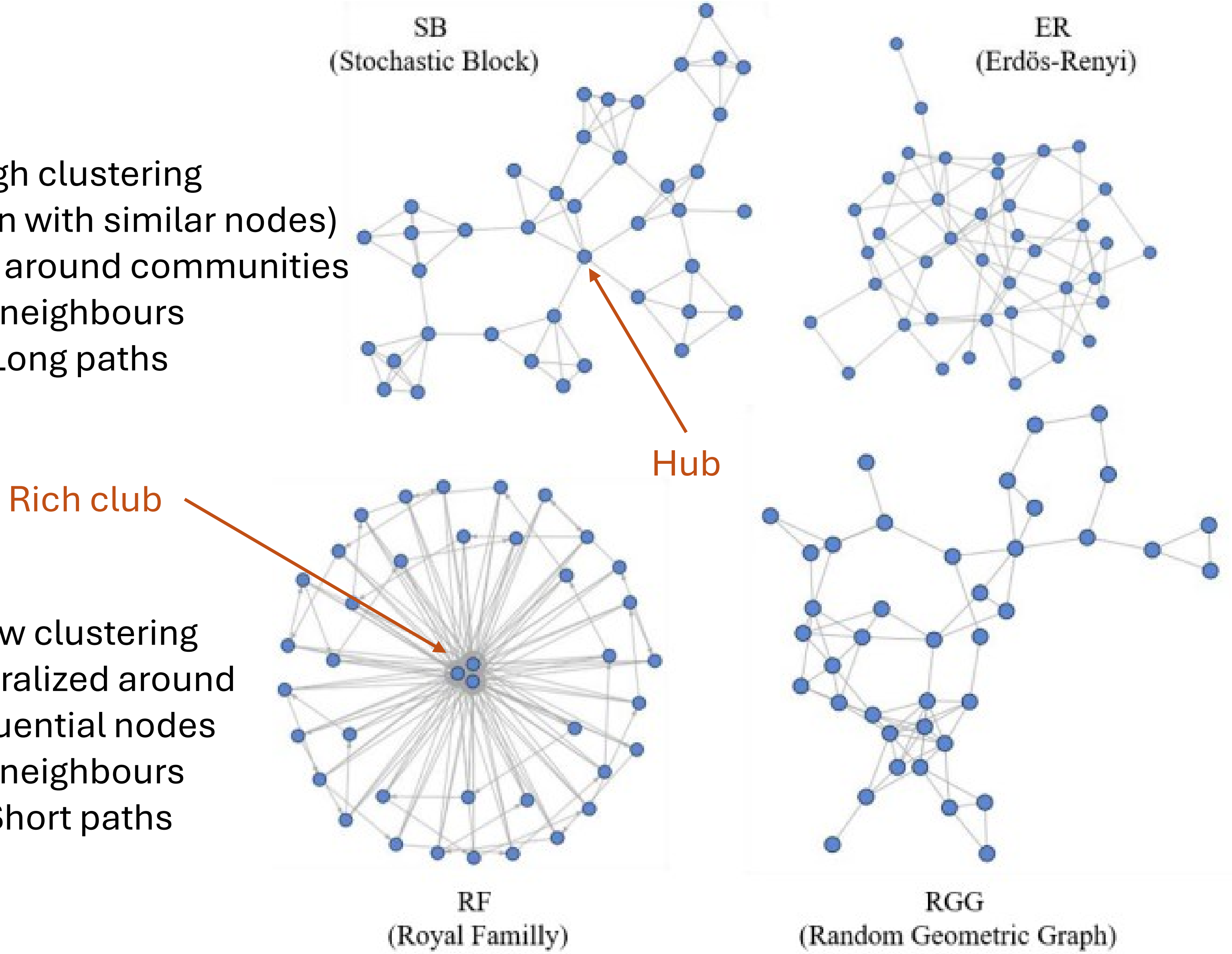
Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*

Choi, Goyal et Moisan, 2023. *Management Science*

Network structures in the nature

- High clustering (connection with similar nodes)
- Centralized around communities
- 4 neighbours
- Long paths

- Mid clustering
- Decentralized
- 2.5 neighbours
- Mid paths

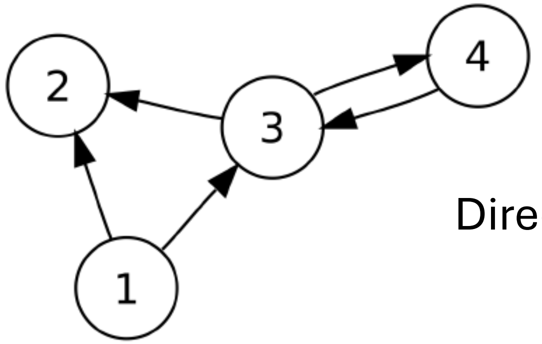


- Low clustering
- Centralized around influential nodes
- 2 neighbours
- Short paths

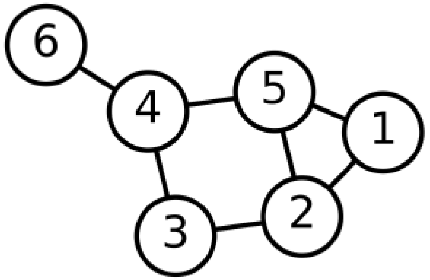
- Mid clustering
- Decentralized
- 2 neighbours
- Long paths

Taken from Luigi Sciarretta on *Medium*

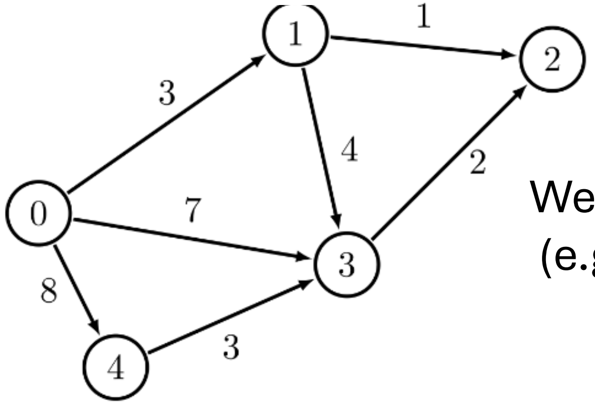
Network graphs



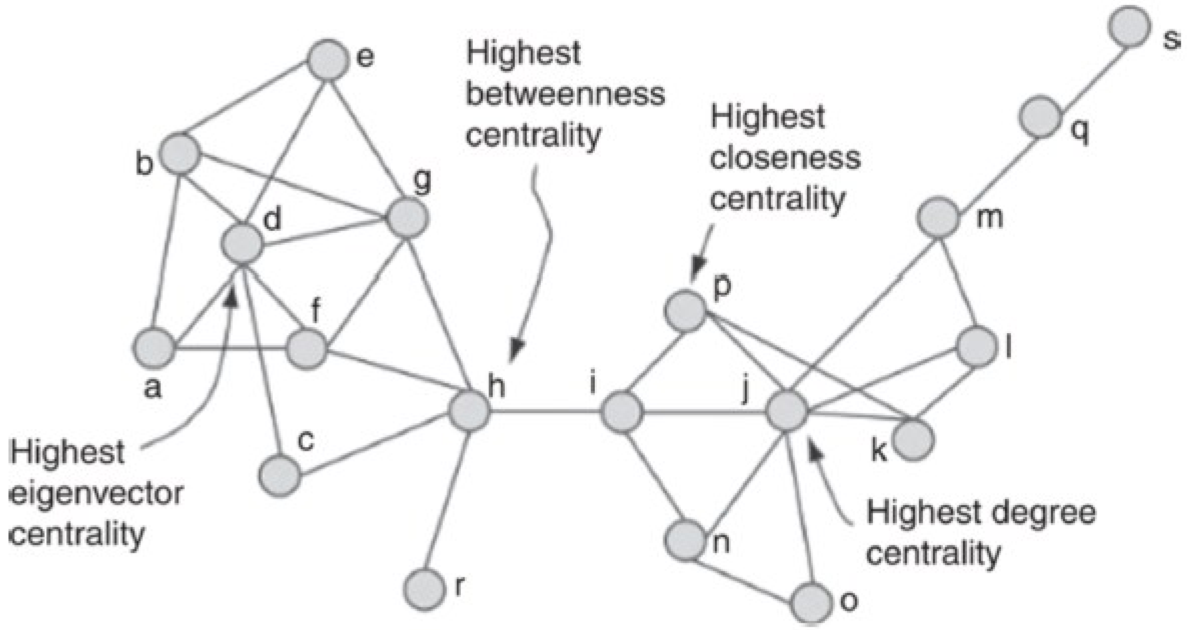
Directed graph



Undirected graph



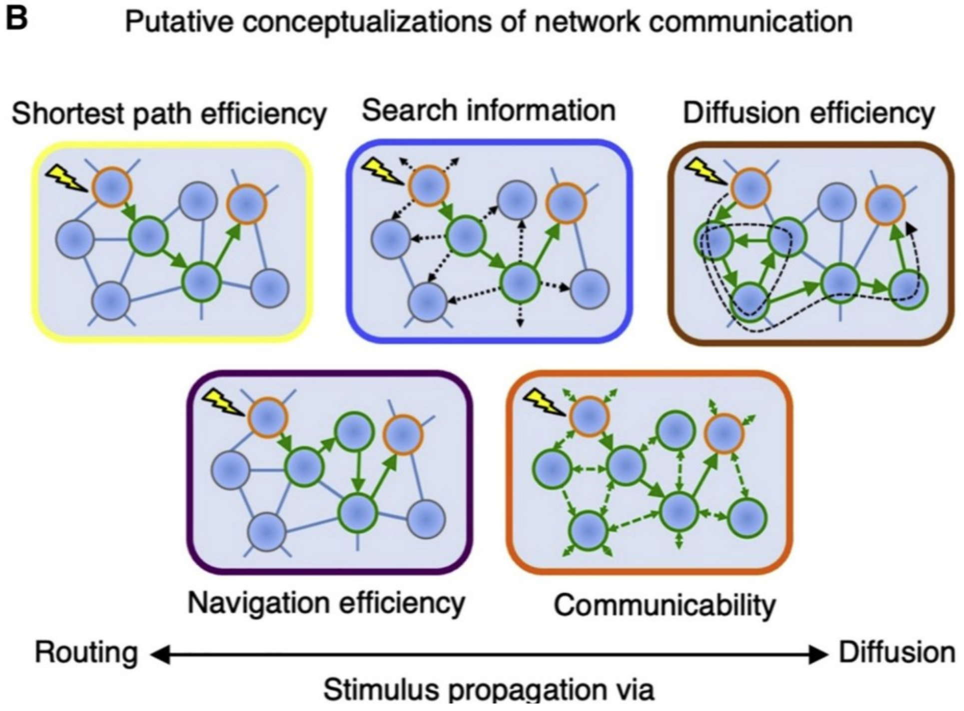
Weighted graph (e.g., distance, affinity)

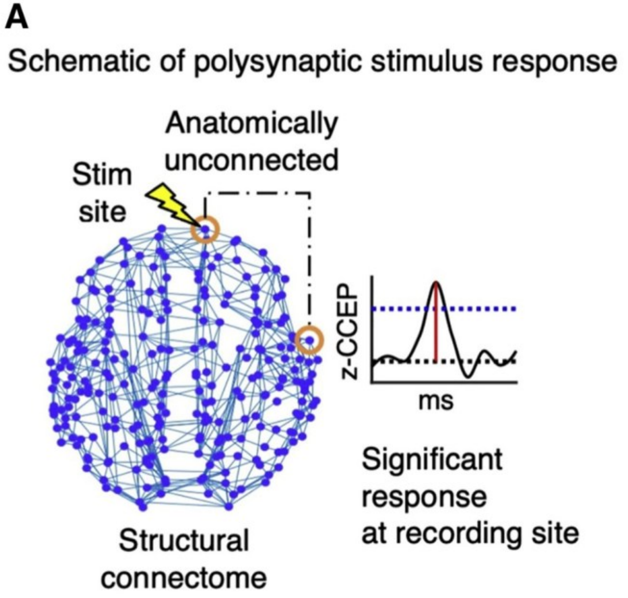


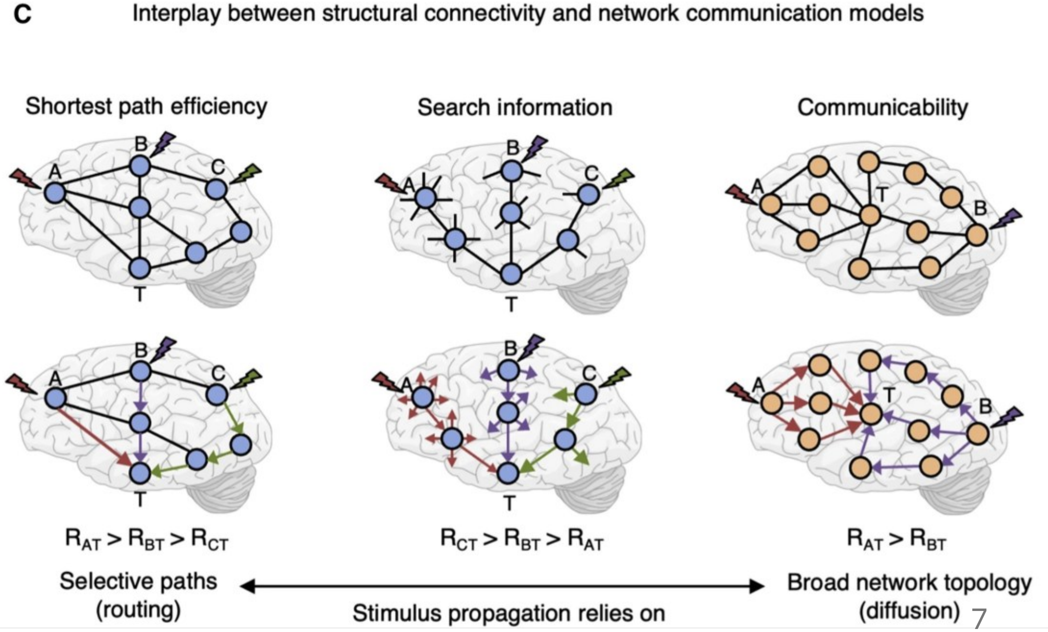
- **Degree Centrality**: number of incident edge on the node (in-degree vs out-degree)
- **Closeness Centrality**: how quickly/efficiently the node can reach the rest of the network
- **Betweenness Centrality**: how a node finds itself along the shortest path between other pairs of nodes in the graph
- **Eigenvector Centrality**: the node is linked both to many nodes and to other important nodes

Signal propagation

- Structural connectivity alone doesn't fully predict how stimulation or neural signals propagate
- Information travels via short path, long paths, polysynaptic (multiple indirect) paths, broadcasting via multiple routes, random walks, etc.
- The mode of propagation is not fixed by the wiring, but constrained by task demands, network topology, physiological state, trade-offs



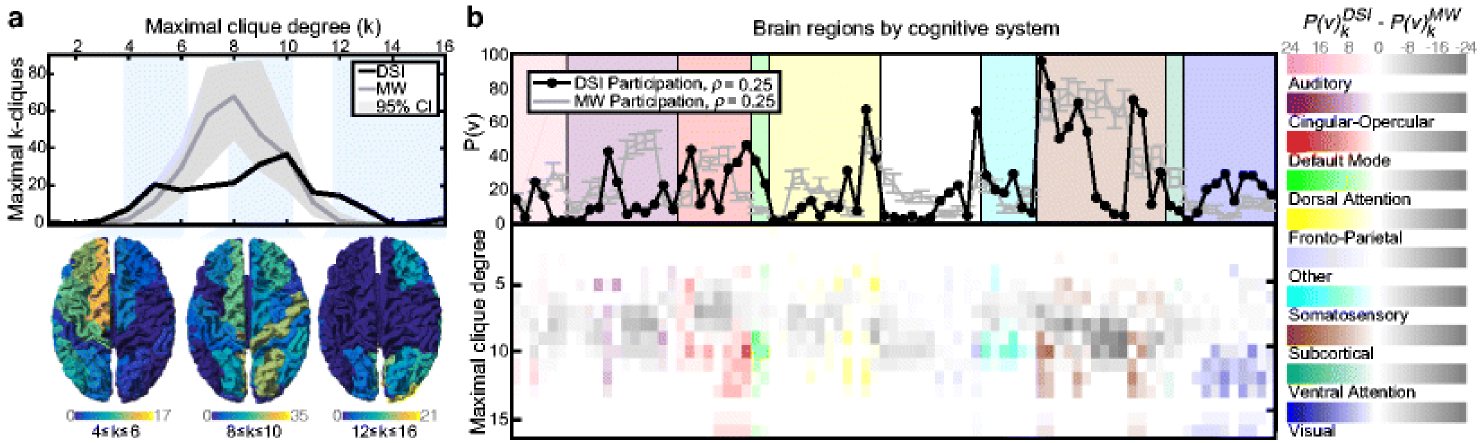


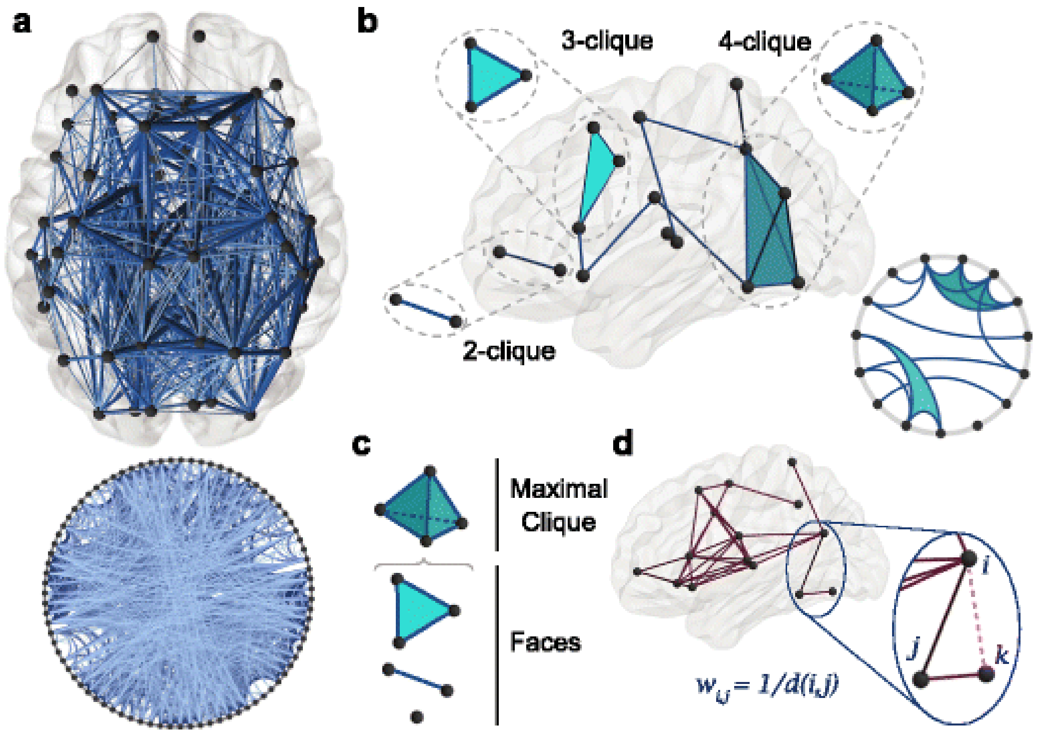


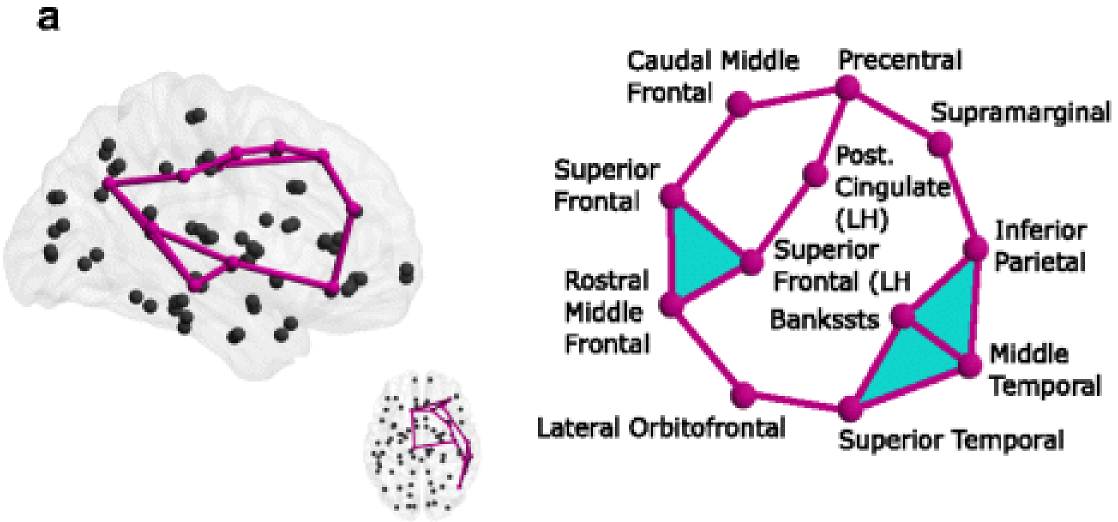
Seguin et al., 2023. *Neuron*

Structures of cliques and cavities

Sizemore et al., 2017. *Journal of Computational Neuroscience*







Cliques: local neighborhoods in structural brain networks; a single neuron can join multiple cliques

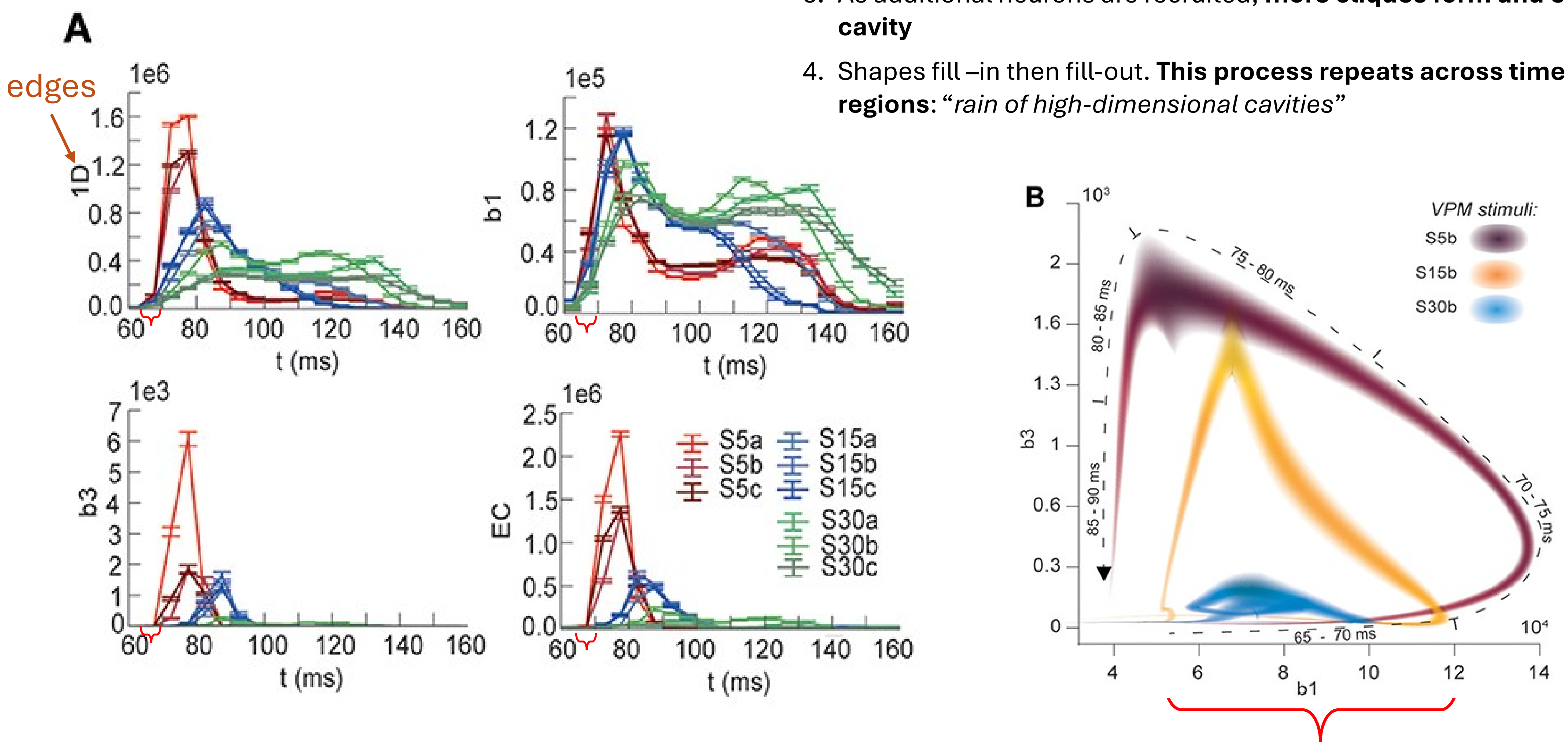
Cavities: joints of cliques; appear [*void* enclosed by *simplices* (2+ cliques)] then disappear as we add more simplices

Long-lived cavities show that the connectome is organized in a multi-scale, higher-order way, rather than just edges and triangles.

Dynamics of cliques and cavities

Reimann et al., 2017. *Frontiers in Computational Neuroscience*

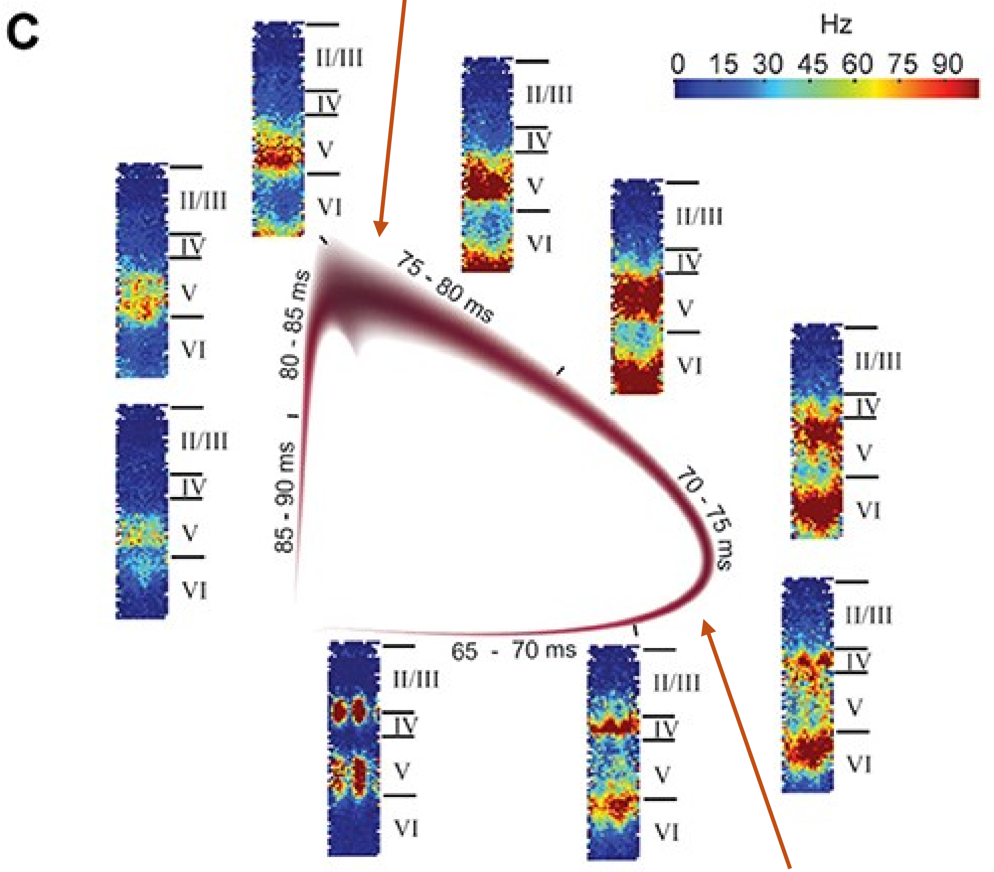
1. As activity propagates, **small groups of neurons fire together and form fully connected cliques** (simplices)
2. When **these cliques overlap, they bound a cavity** (a higher-dimensional void).
3. As additional neurons are recruited, **more cliques form and eventually fill in the cavity**
4. Shapes fill –in then fill-out. **This process repeats across time and across regions**: “*rain of high-dimensional cavities*”



Sizemore et al., 2017. *Journal of Computational Neuroscience*

Dynamics of cliques and cavities

High β_3: cavities bounded by higher-order cliques



High β_1: edges connect neurons such that we obtain loops (with hole)

- **Cliques** show **feedforward local motifs**: *neurons are tightly connected*
- **Cavities** show how local **cliques are organized in relation to each other**: *many tightly connected groups are arranged together such that it leaves a gap*
- **High β_1** (many 1D cavities / loops)
  - Activity has spread such that it generates many separate cycles
  - This reflects a **more distributed pattern**
- **High β_3** (many 3D cavities / voids bounded by tetrahedra)
  - Activity has escalated into *cohesive, high-order cliques* (4+ neurons, fully interconnected, overlapping)
  - This reflects **stronger coordination**, where many neurons fire together in structured ensembles
- Tracking **cliques** show **local motifs of information flow**
- Tracking **cavities** show **global scaffolding of information flow**