Brain Networks

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Cambridge Complex Networks Network
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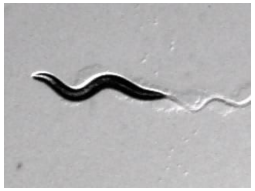
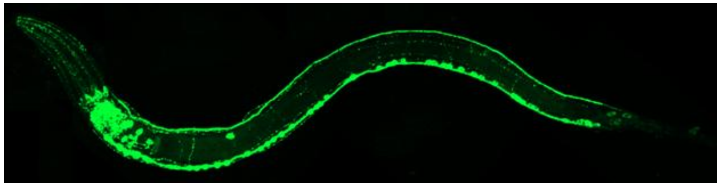
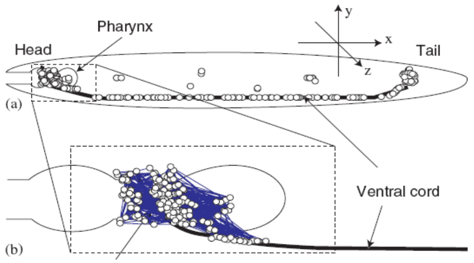
The small world of the worm's brain



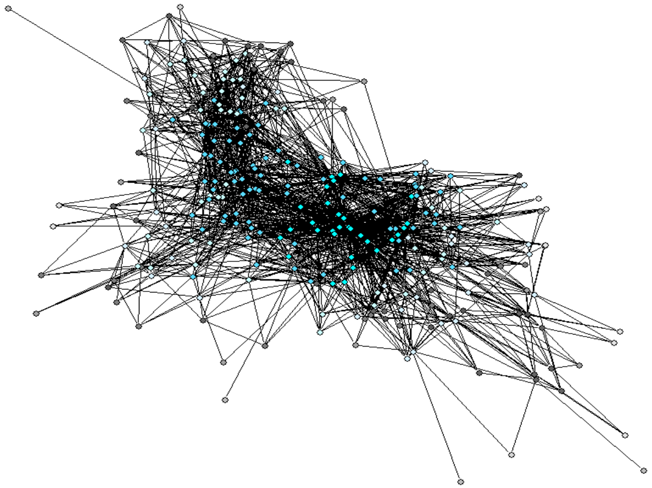
Caenorhabditis elegans



Anatomy (277 neurons, 7000 synapses)

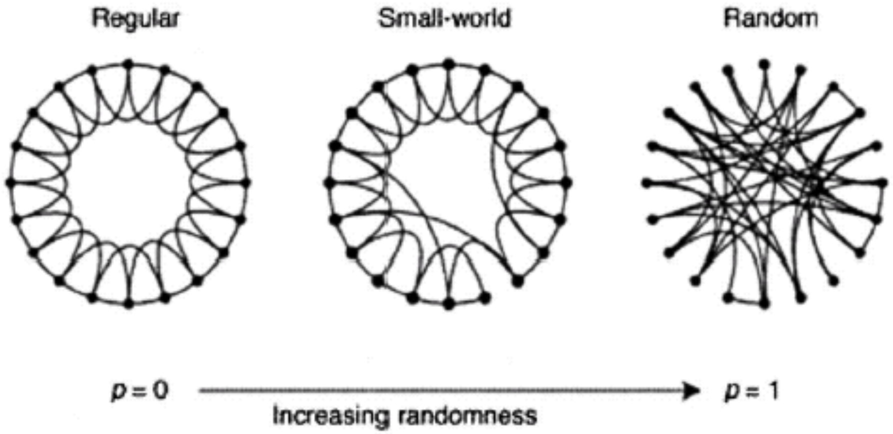


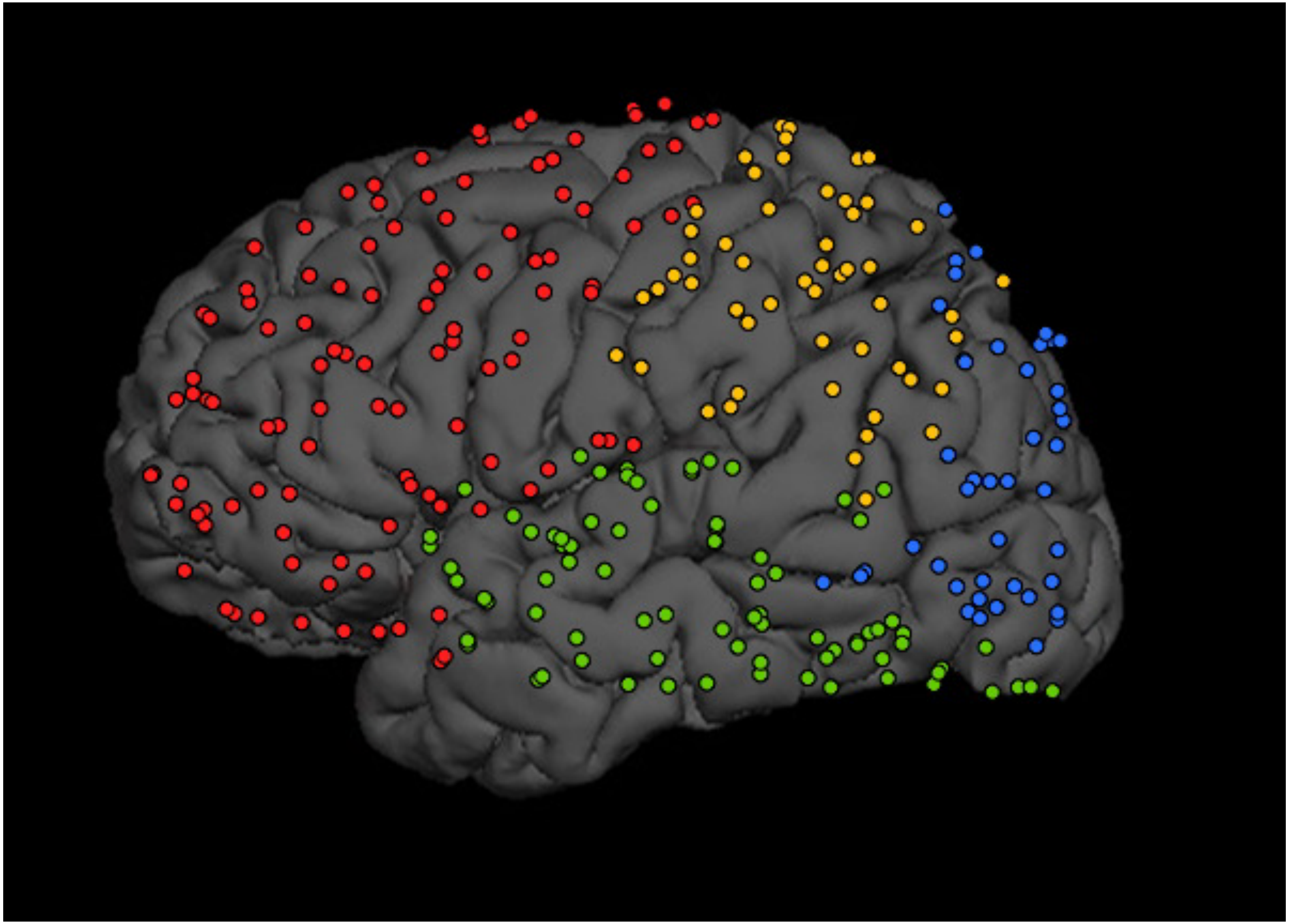
Topology (277 nodes, 7000 edges)



- Small-world
  - *High clustering or cliquishness of connections between neighboring nodes*
  - *Short path length or high efficiency of communication between any pair of nodes*
- Cost-efficient
  - *40% maximum efficiency of information transfer for only 4% maximum connection cost*

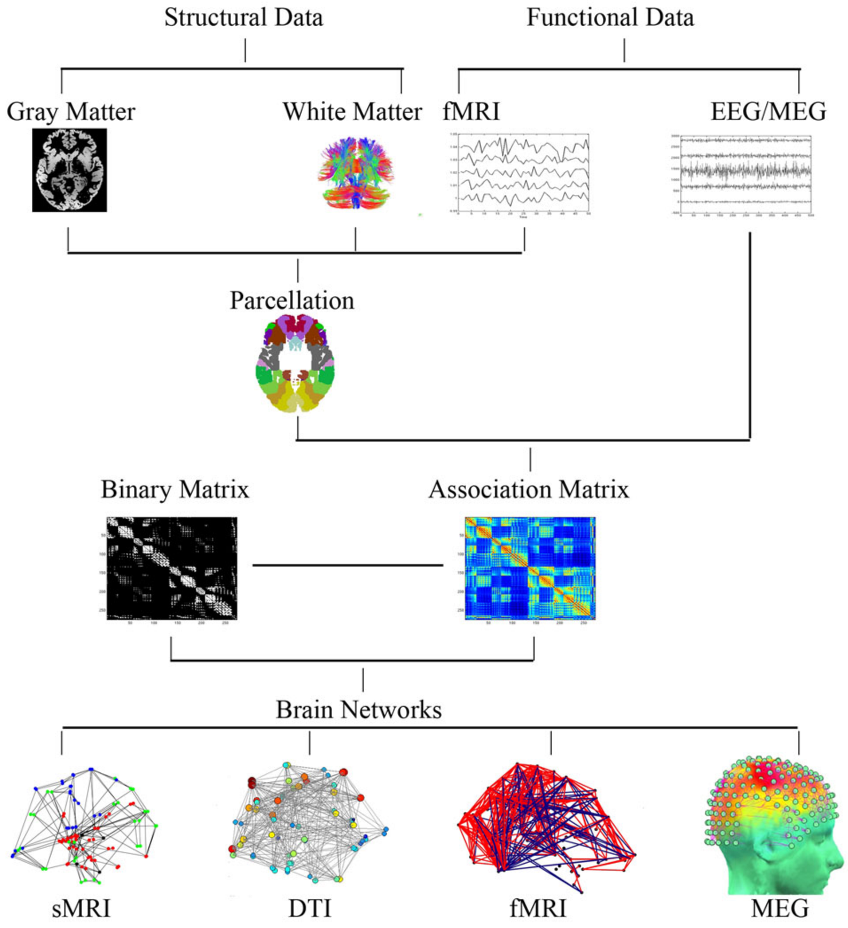
Watts & Strogatz (1998) *Nature;* Latora & Marchiori (2001) *Phys Rev Lett*





Vertes et al (2011) *YouTube*
(search on neuro tweets)

From neuroimaging to brain graphs



1. Estimate an association matrix from the data
   - What are the nodes?
   - What metric of connectivity?
2. Generate an adjacency matrix from the association matrix
   - What are the edges?
3. Measure topological properties of each graph
4. Make comparisons between graphs

Brain graphs are statistical models entailing assumptions and trade-offs which influence parameter values

Brain graph parameters make sense relativistically, not absolutely; comparison between graphs is not trivial

Bassett & Bullmore (2010) *Curr Op Neurol;* Bullmore & Bassett (2011) *Annu Rev Clin Psychol*

Many network properties are conserved across many scales and kinds and species of brain graphs

Small worldness

- high clustering
- short path length or high efficiency

Cost-efficiency

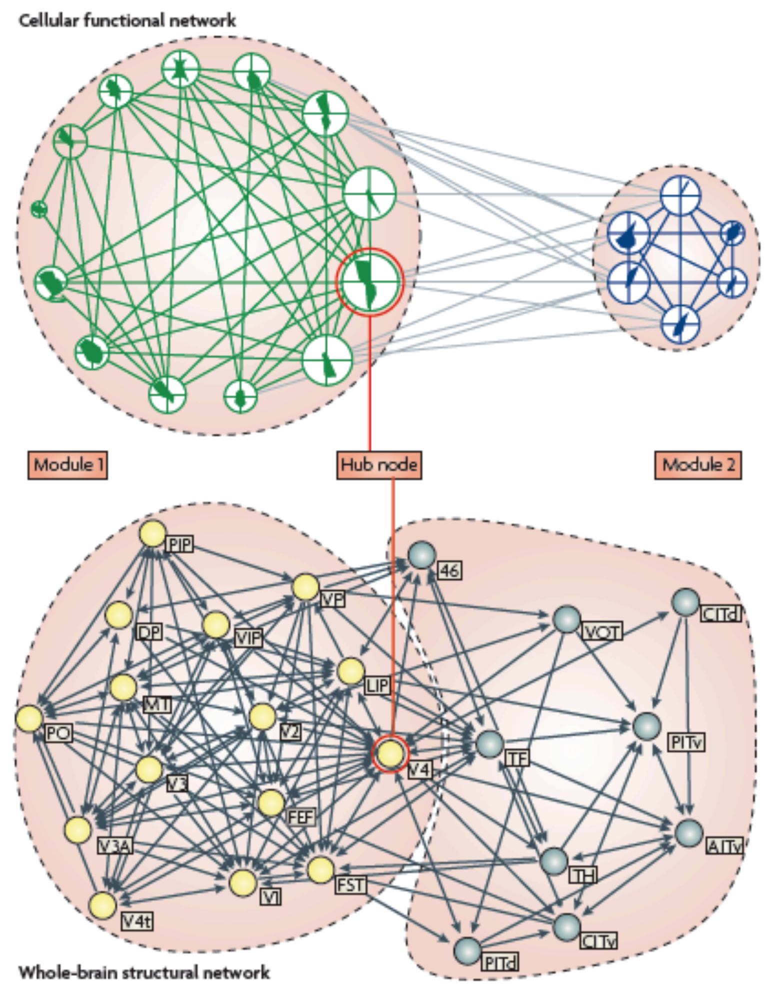
- high efficiency of information transfer for relatively low connection cost

Hub nodes

- fat-tailed degree distributions

Modularity

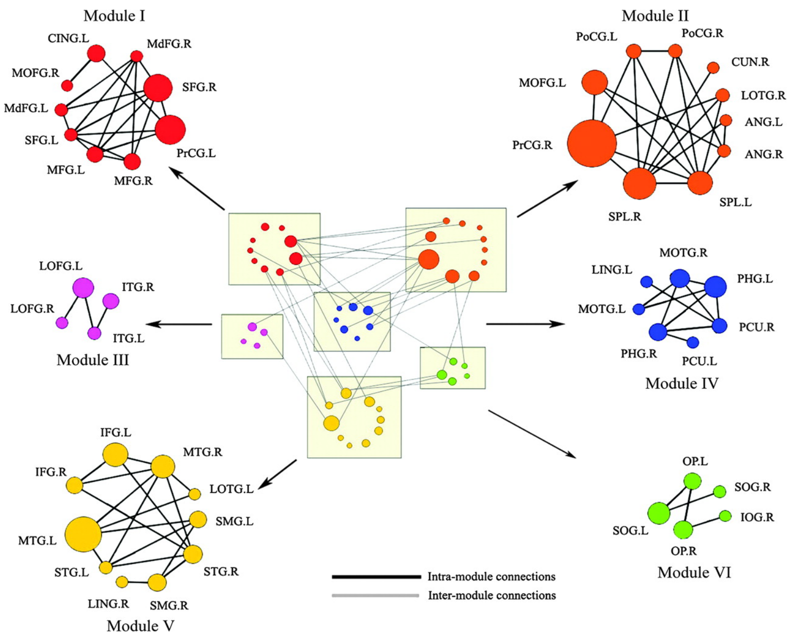
- nodes are more densely connected to other nodes in the same module than to nodes in other modules

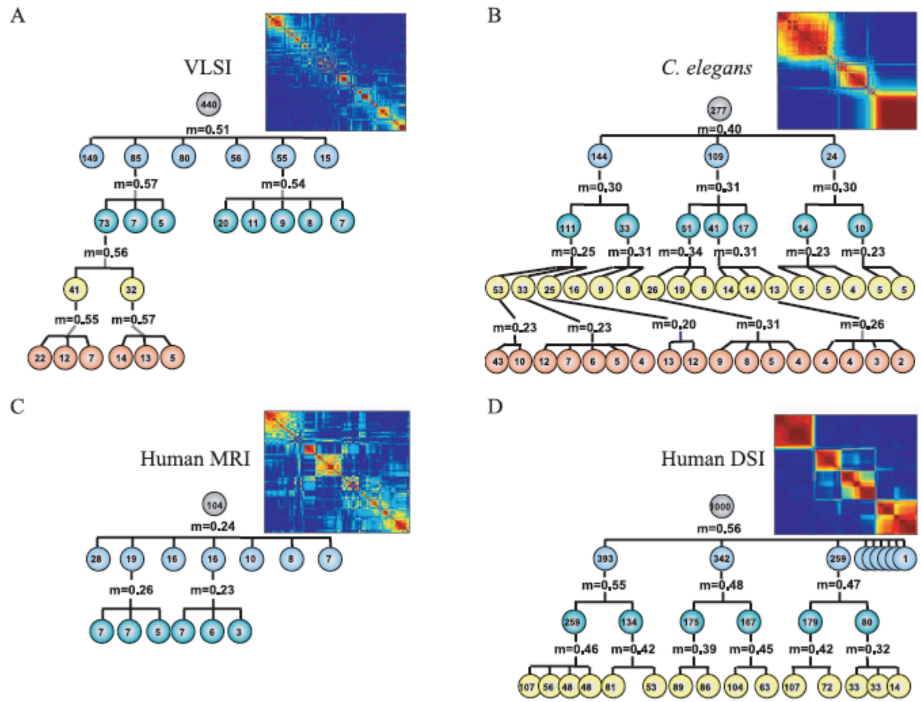


Bullmore & Sporns (2009) *Nat Rev Neurosci*

Sporns et al (2007) *PLoS ONE;* Yu et al (2008) *Cereb Cortex;* Meunier et al (2010*) Front Neurosci*

Human brain graphs and other information processing networks are hierarchically modular





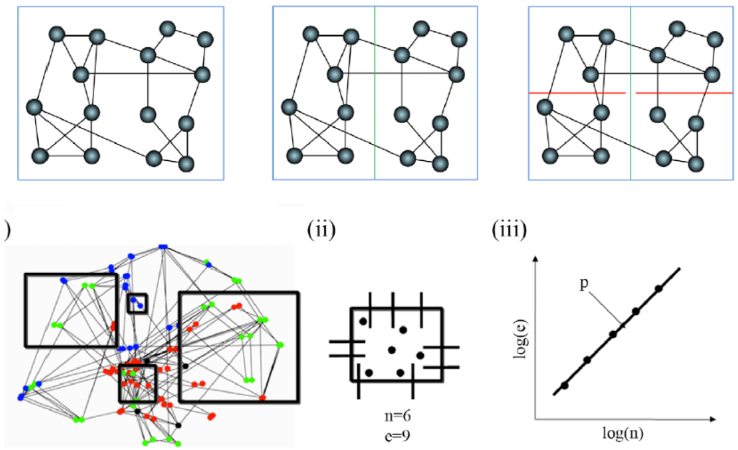
Nodes in the same module are often, but not always, anatomical as well as topological neighbours: so intra-modular edges will be shorter distance than inter-modular edges

Brain graphs typically have modules within modules

Meunier et al (2010) *Front Neurosci*; Bassett et al (2010) *PLoS Comp Biol;* Chen et al (2008) *Cereb Cortex*

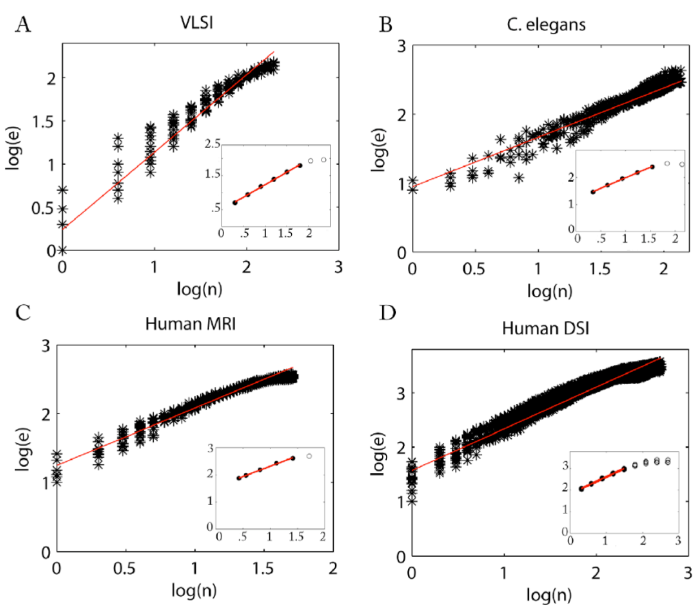
Rentian and allometric scaling in brains

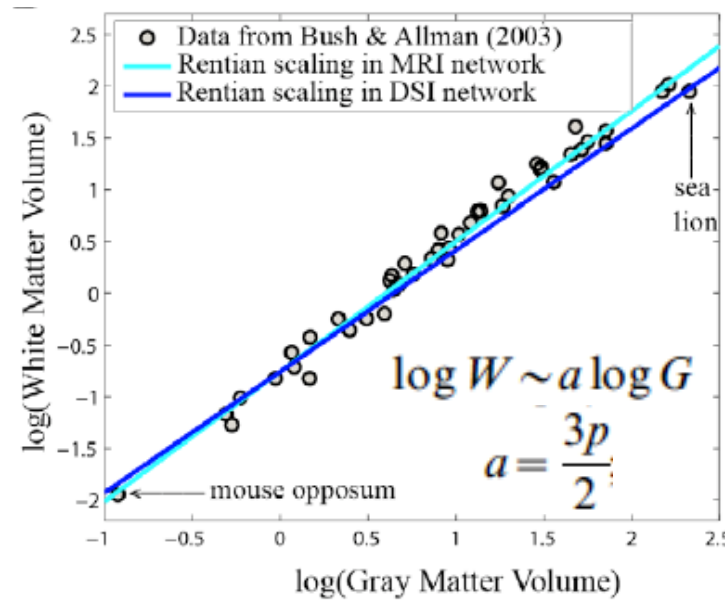
Bassett et al (2010) *PLoS Comp Biol*



Rent's rule

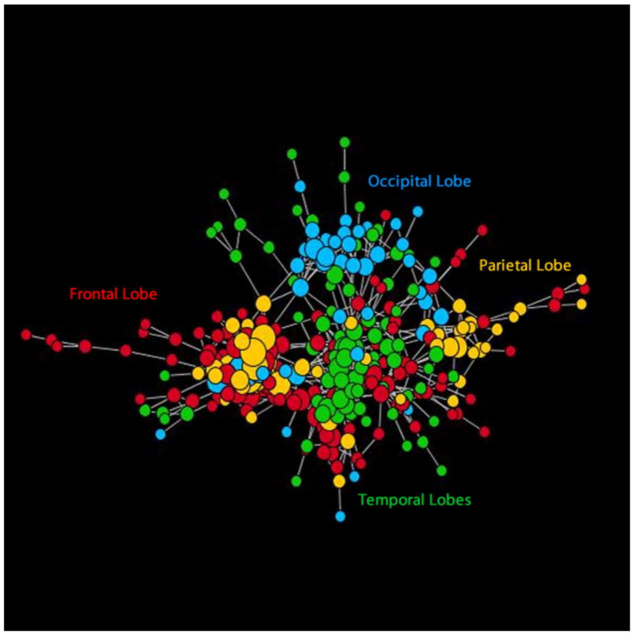
$$C = k\,N^p$$

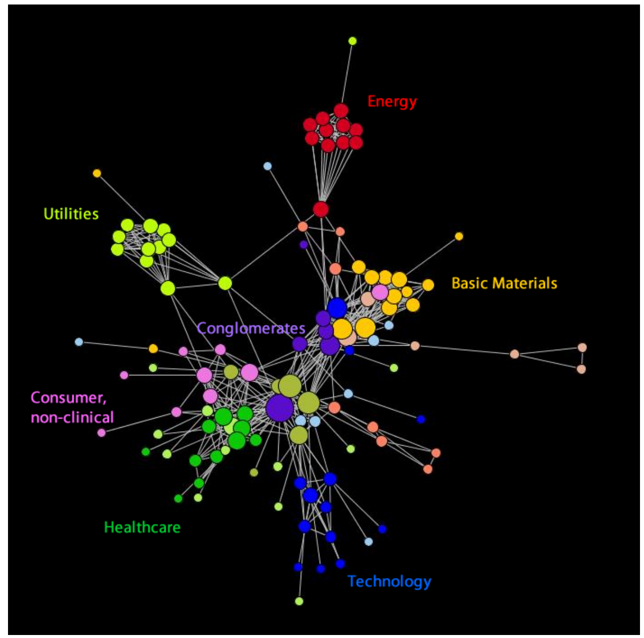


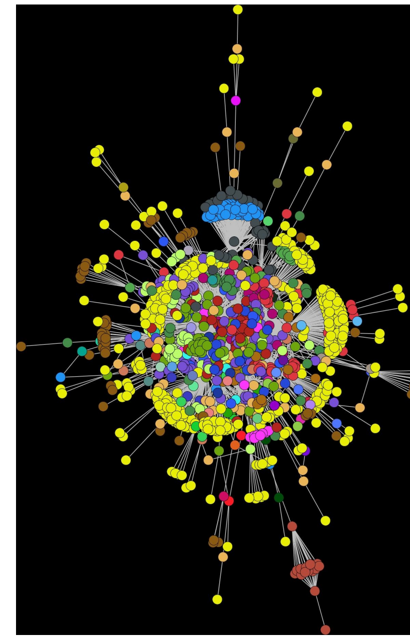


Allometric scaling of mammalian brains is approximated by Rentian scaling of human brain

What’s special and what’s universal about human brains compared to other information networks?



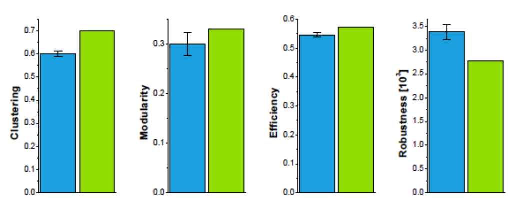




Human Brain Network
Resting state FMRI

Economic Network
New York Stock Exchange

Social Network
Twitter #gadaffi

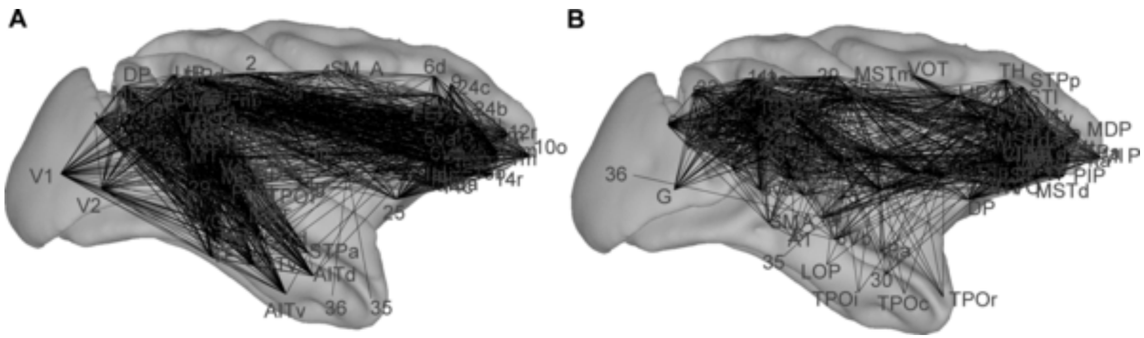


Blue = Brain
Green = Market

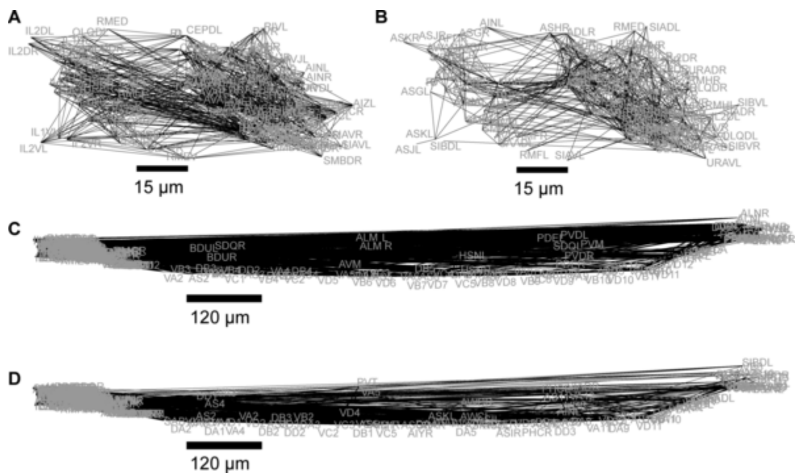
Vertes et al (2011) *Front Sys Neurosci*

Brain networks are economically wired but do *not* strictly minimise wiring cost

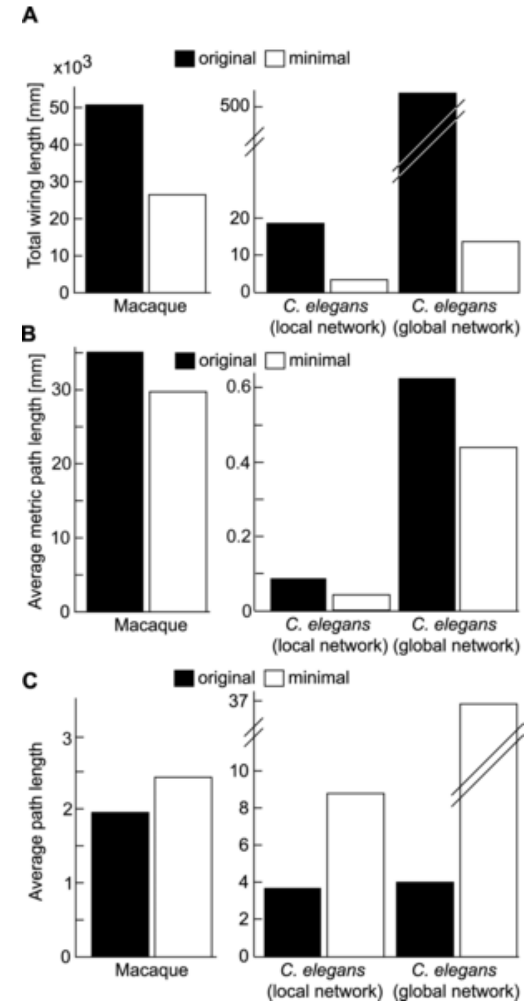
Original   Minimal



Macaque

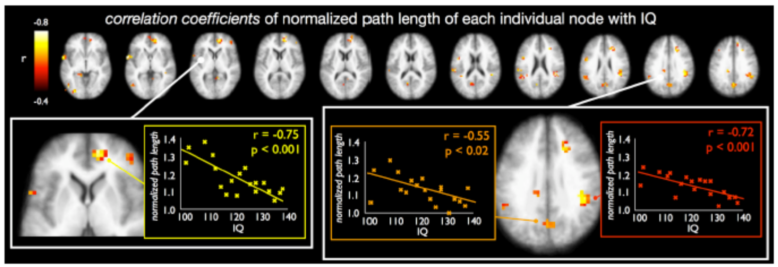


C. elegans



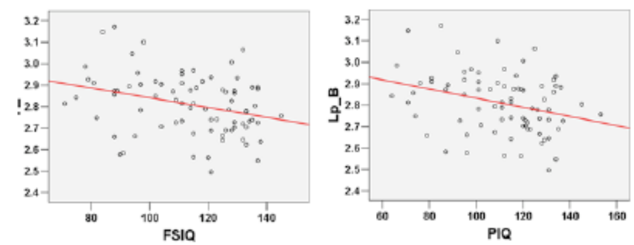
Kaiser & Hilgetag (2006) *PLoS Comp Biol*

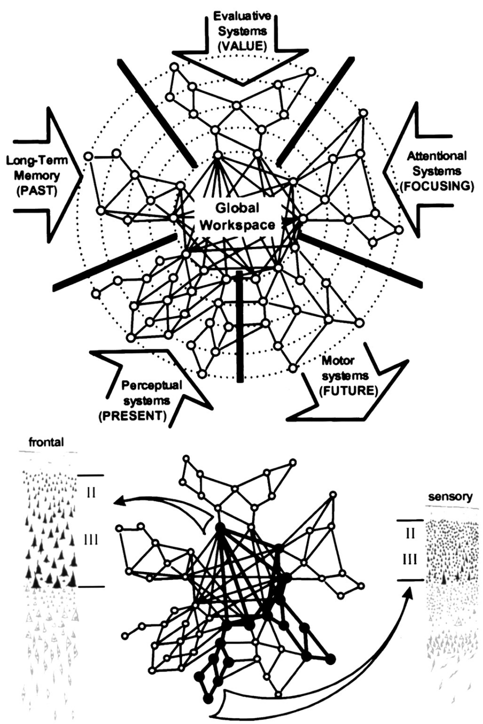
Expensive, long-range integrative connections may be “worth it” for extra cognitive capacity



- Greater efficiency (or shorter path length) of human brain networks is correlated with higher IQ

Van den Heuvel et al (2009) *J Neurosci*; Li et al (2009) *PLoS Comp Biol;* Bassett et al (2010) *PLos Comp Biol*;



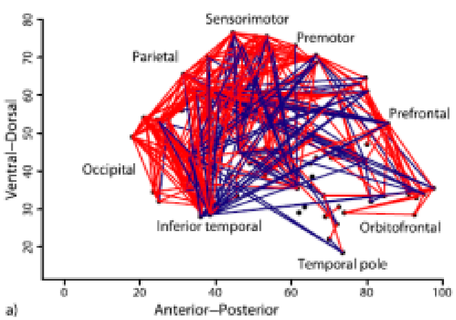


- Global (neuronal) workspace theory predicts integrative networks will be required for conscious, effortful processing

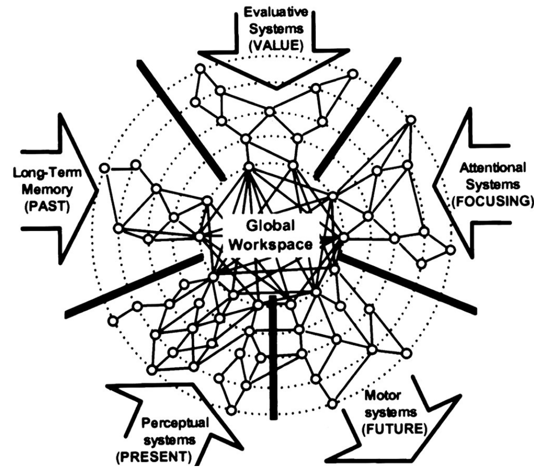
Dehaene et al (1998) *Proc Natl Acad Sci*

Baars (1993) *A cognitive theory of consciousness*

Cartoon interpretation of economical small-world architecture in terms of cognitive processes



High efficiency
Short path length
(Higher cost)



Integrated processes

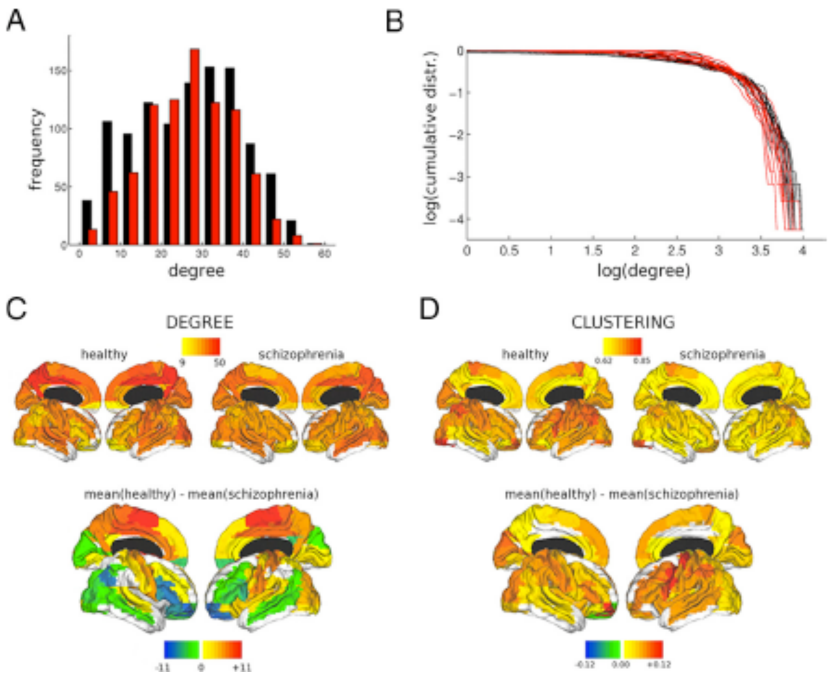
General – eg "executive"
Isotropic (IQ)
Distributed
Conscious
Effortful

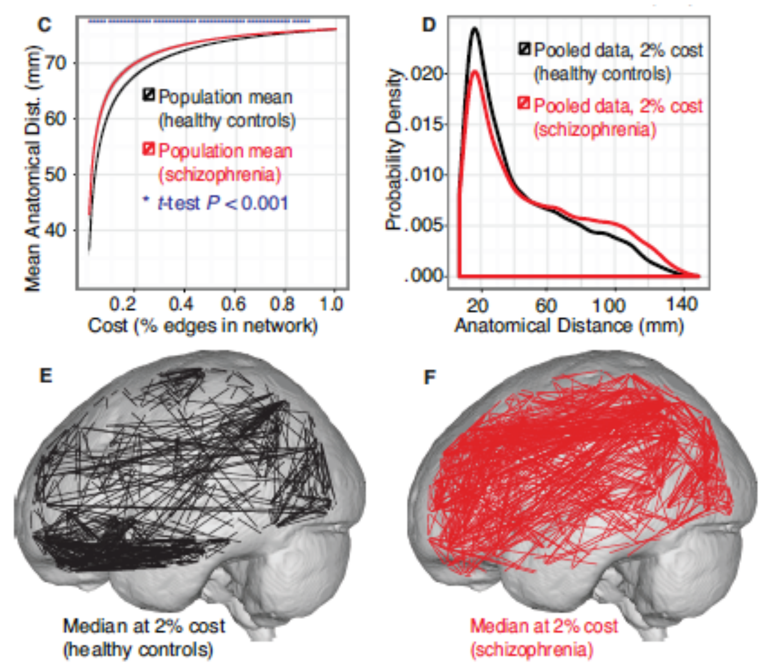
High clustering
Modularity
(Lower cost)

Segregated processes

Specialised – eg face vision
Encapsulated
Localised
Unconscious
Automatic

Disordered brain development may involve an abnormal trade-off between network cost and topology



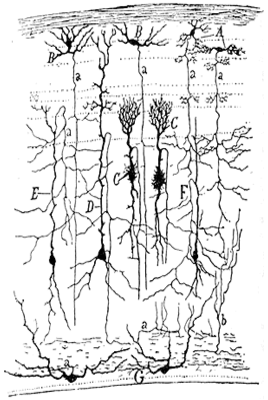


schizophrenia connectomes

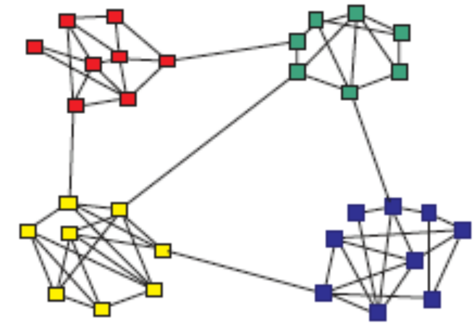
Topologically - less clustered, less modular and less hub-dominated: “subtle randomization”

Anatomically – less economically connected, a higher proportion of long distance edges

Lynall et al (2010) *J Neurosci*; Alexander-Bloch et al (2010) *Frontiers Sys Neurosci;* Rubinov et al (2009) *Hum Brain Mapp*



Conclusions



- About 200 years ago we began to understand the *anatomical* organization of brain networks; in the last 10 years or so we have also begun to understand the *topological* properties of brain networks

- Graph theoretical analysis is a way of simplifying complex systems that is generalizable to topological analysis of many scales and kinds of data and may provide a useful mathematical framework for modeling the connectome

- Hypothetically, brain networks "negotiate a trade-off" between minimization of connection costs and maximization of behaviourally advantageous topological properties, like efficiency

- Recent data suggest that cost-efficiency trade-offs in brain networks
  - are heritable
  - are renegotiated dynamically in response to changing cognitive demands (msec)
  - are relevant to normal and abnormal brain development (years)
  - can be modulated by drugs affecting cognitive performance