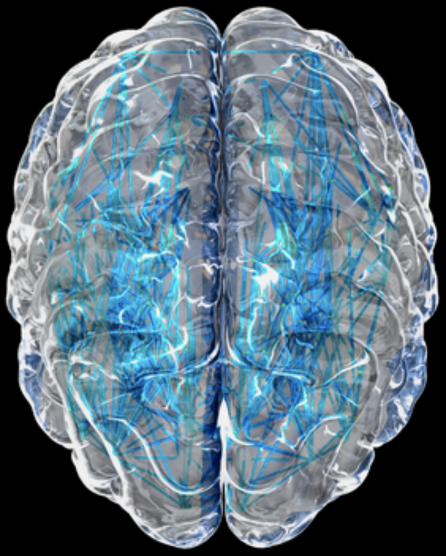
A Tutorial in Connectome Analysis (III): Topological and Spatial Features of Brain Networks



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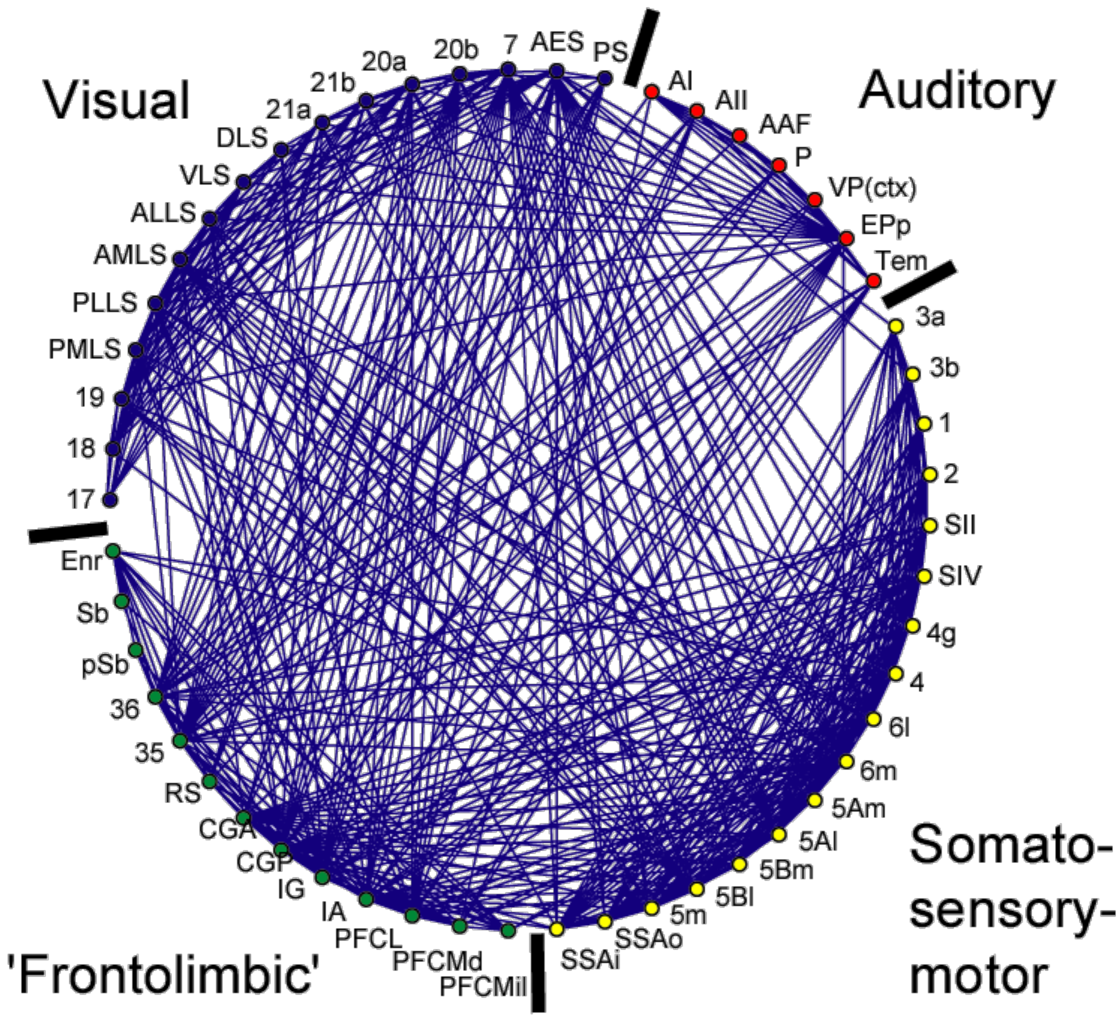
United Kingdom

http://www.dynamic-connectome.org

http://neuroinformatics.ncl.ac.uk/

@ConnectomeLab

Brain connectivity



Types of Brain Connectivity
Structural, functional, effective

Small-world
Neighborhood clustering
Characteristic path length

Spatial
preference for short connections but more long-distance connections than expected

Structure->Function
Network changes lead to cognitive deficits (Alzheimer's disease, IQ)

Hilgetag & Kaiser (2004) *Neuroinformatics* **2**: 353

Motifs

Motifs

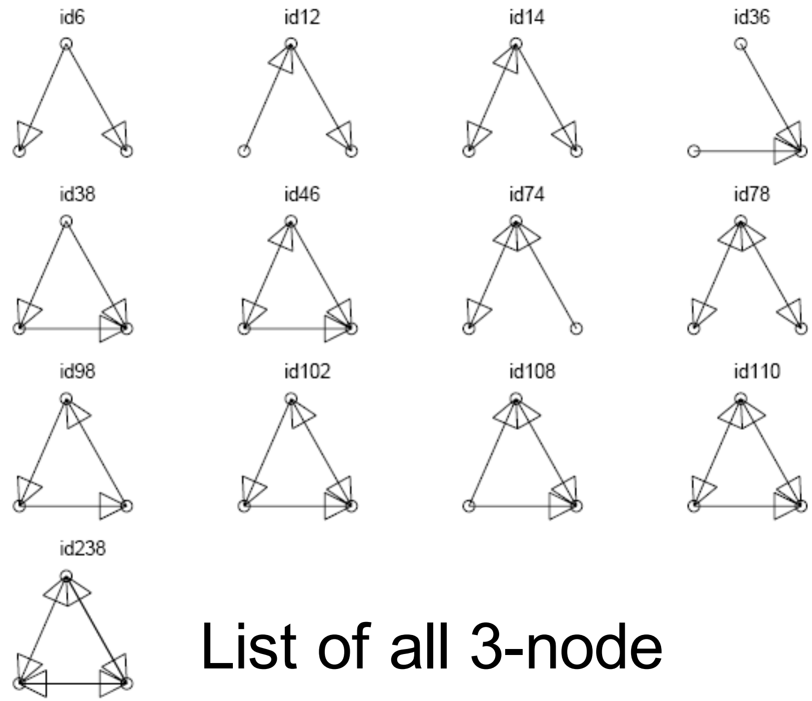
Idea: determine building blocks of networks.

Hope: structural building blocks correspond to functional units.

Pattern: possible connection configuration for a k-node subgraph

(see list of all 3-node configurations)

Motif: pattern that occurs significantly more often than for rewired benchmark networks
(same number of nodes and edges and same degree distribution)



List of all 3-node patterns

* Milo et al. (2002) Science;
http://www.weizmann.ac.il/mcb/UriAlon/groupNetworkMotifSW.html

Motif detection – algorithm

```
Network name: network_exmp.txt
Network type: Directed
Num of Nodes: 16 Num of Edges: 19
Num of Nodes with edges: 16
Maximal out degree (out-hub) : 3
Maximal in degree (in-hub) : 3
Roots num: 4 Leaves num: 4
Single Edges num: 19 Mutual Edges num: 0

Motif size searched  3
Total number of 3-node subgraphs : 21
Number of random networks generated : 100
Random networks generation method: Switches
Num of Switches range: 100.0-200.0,
      Success switches Ratio:0.652+0.01

The following motifs were found:

Criteria taken : Nreal Zscore > 2.00
                 Pval ignored (due to small number of random
networks)
                 Mfactor > 1.10
                 Uniqueness >= 4
```

Appearances in the real network

Random networks: mean+- SD

Uniqueness

Concentration $X10^{-3}$

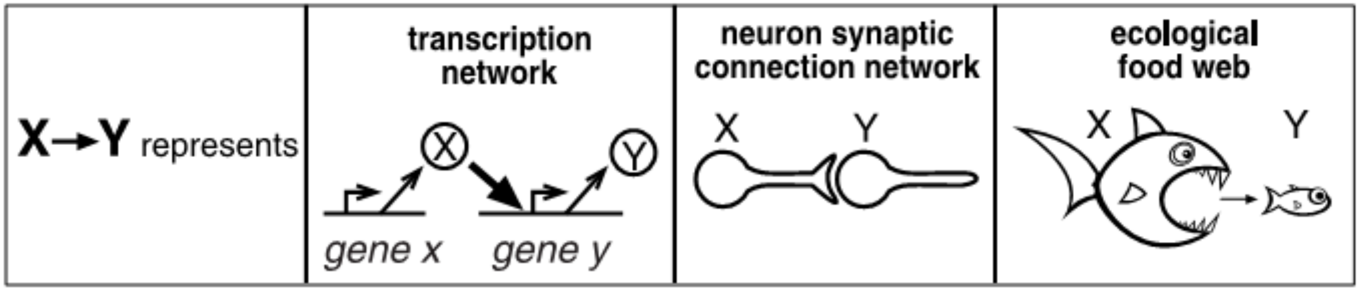
Full list includes 1 motifs

MOTIF ID	NREAL	NRAND STATS	NREAL ZSCORE	NREAL PVAL	UNIQ VAL	CREAL [MILI]
38	5	0.6+0.6	6.93	0.000	4	238.10

```
0 1 1
0 0 1
0 0 0
```

Motif Adjacency Matrix

Motif detection – results



Network	Nodes	Edges	N_{real}	$N_{rand} \pm SD$	Z score	N_{real}	$N_{rand} \pm SD$	Z score	N_{real}	$N_{rand} \pm SD$	Z score
Gene regulation (transcription)				X → Y → Z, X → Z	**Feed-forward loop**		X → Z, X → W, Y → Z, Y → W	**Bi-fan**			
E. coli	424	519	40	7 ± 3	10	203	47 ± 12	13			
*S. cerevisiae**	685	1,052	70	11 ± 4	14	1812	300 ± 40	41			
Neurons				X → Y → Z, X → Z	**Feed-forward loop**		X → Z, X → W, Y → Z, Y → W	**Bi-fan**		X → Y, X → Z, Y → W, Z → W	**Bi-parallel**
C. elegans†	252	509	125	90 ± 10	3.7	127	55 ± 13	5.3	227	35 ± 10	20

Milo et al. Science, 2002

Motif detection – problems

Advantages:

- Identify special network patterns which *might* represent functional modules

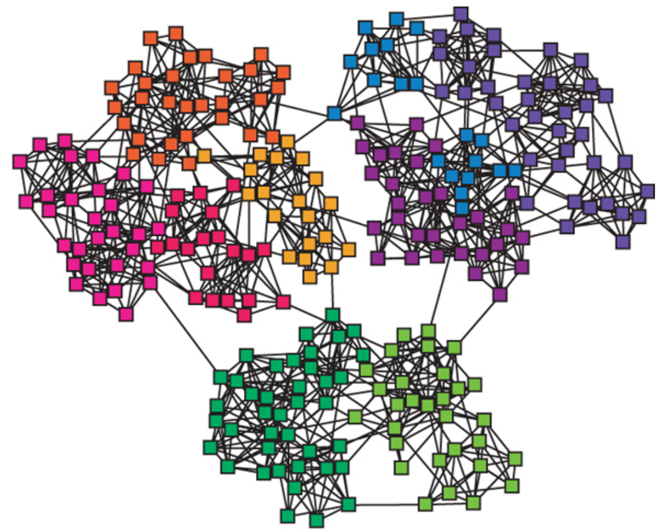
Disadvantages:

- Slow for large networks and
  unfeasible for large (e.g. 5-node) motifs
  (#patterns: 3-node – 13; 4-node – 199; 5-node: 9364; 6-node - 1,530,843)
- Rewired benchmark networks do not retain *clusters*;
  most patterns become insignificant for clustered benchmark networks*

* Kaiser (2011) Neuroimage

Clusters (or Modules or Communities)

Clusters



Clusters: nodes within a cluster tend to connect to nodes in the same cluster but are less likely to connect to nodes in other clusters

Quantitative measure: modularity Q
(Newman & Girvan, Physical Review E, 2004)

important terms:

hierarchical (cluster, sub-cluster, …)

overlapping or *non-overlapping*
(one node can only be member of one cluster)

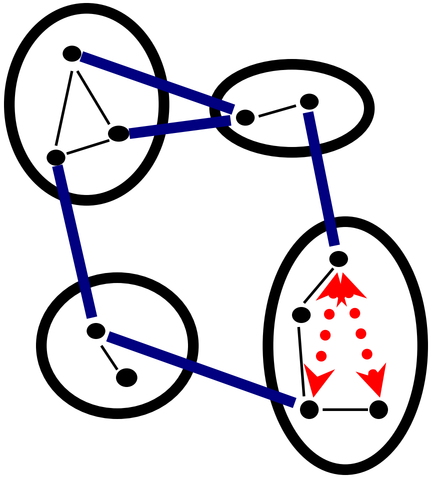
predefined number of clusters
(e.g. k-means algorithm)

Potential time problem for large networks, $O(k^N)$
Hundreds of algorithms for cluster detection!

Cluster detection – example

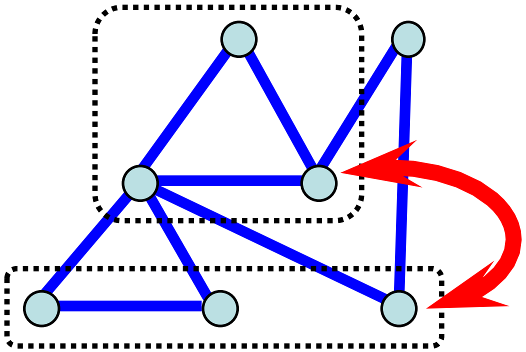
Non-hierarchical, overlapping

Genetic algorithm



- Have as few as possible connections ***between*** them
- Have as few as possible absent connections ***within*** them

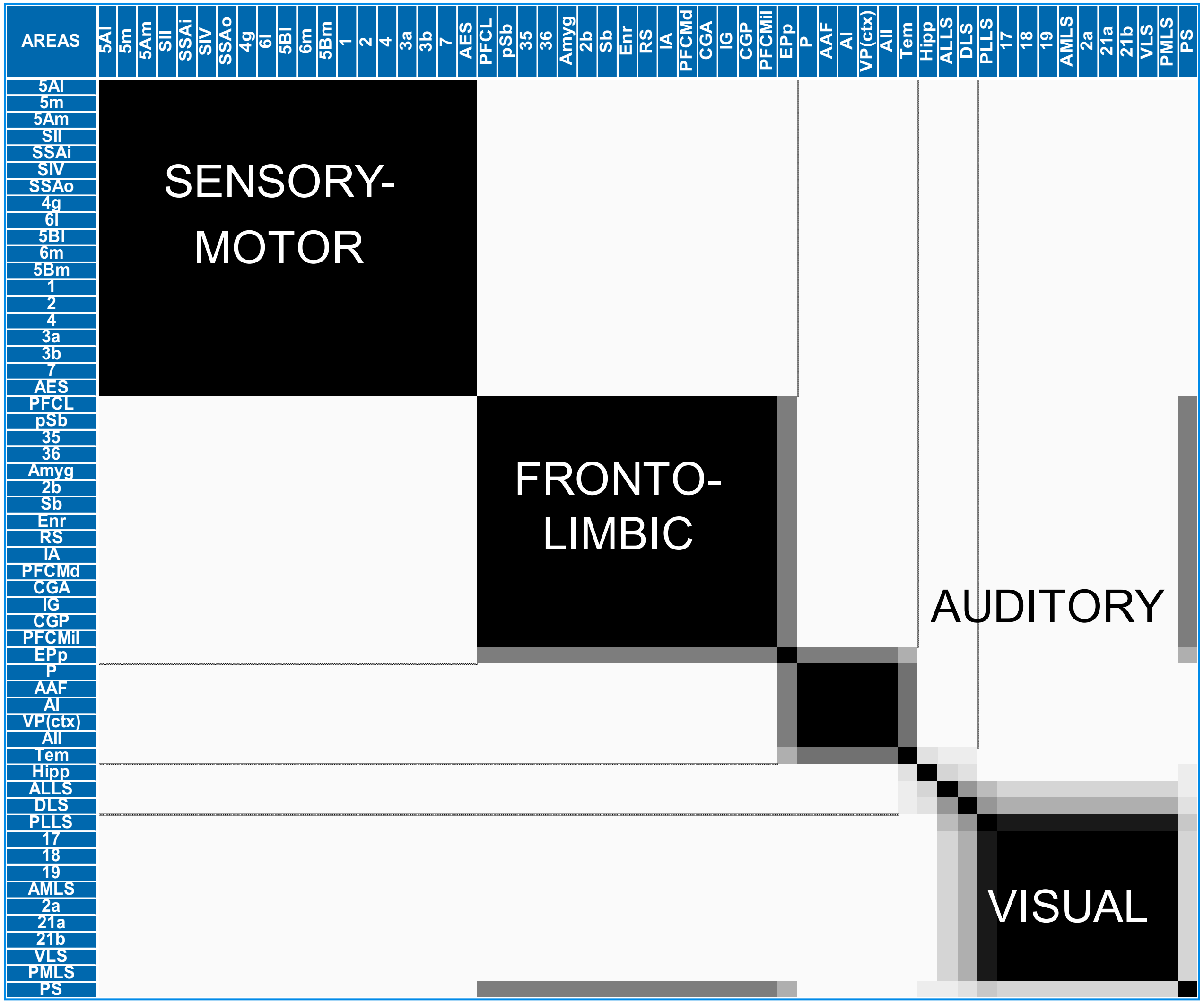
Procedure



- Random starting configurations
- Evolution:
  - Mutation : Area relocation
  - Evaluation : Cost function
  - Selection : Threshold
- Validation

Hilgetag et al. (2000) Phil. Trans. Roy. Soc. Lond. B.

Cluster detection



Example:

Cat cortical network

Black:

same cluster

Graylevel:

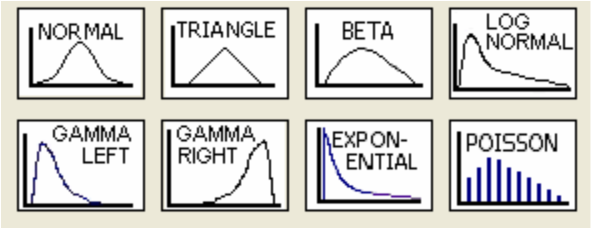
Ambiguous cases

Hilgetag et al. (2000) Phil Trans R Soc 355: 91

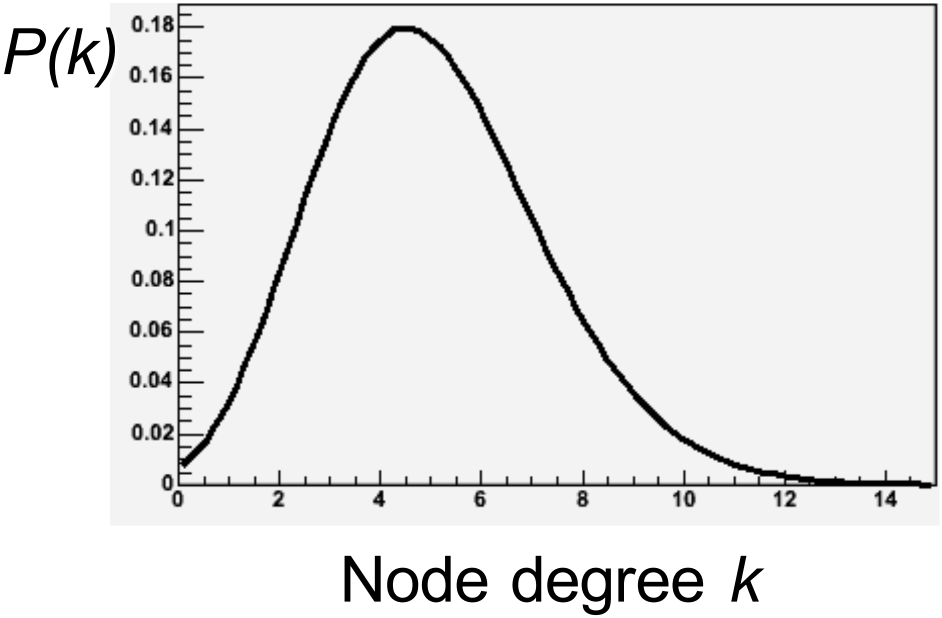
Random graphs

Preliminary: Degree distributions

Degree distributions



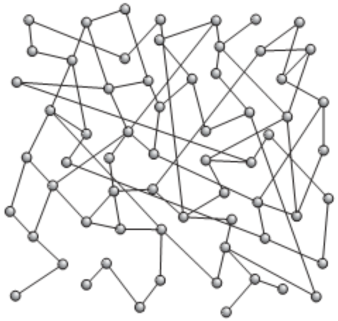
Theoretical (known properties):
P(k) is the probability that a node with *k* edges exists in the network (probability distribution)



Degree distribution

Numerical (real-world network):
use the number of occurrences of a node (histogram)

Random graphs



- often called Erdős–Rényi* random graphs

- Generation:
  For each potential edge
  (adjacency matrix element outside the diagonal),
  establish an edge
  (set that element of the adjacency matrix to 1)
  with probability *p*

$$A = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

*Erdős, P.; Rényi, A. (1959). Publicationes Mathematicae 6: 290–297.

Properties of random graphs

- Edge density = *p*
- Binomial *degree distribution* (histogram of node degrees)

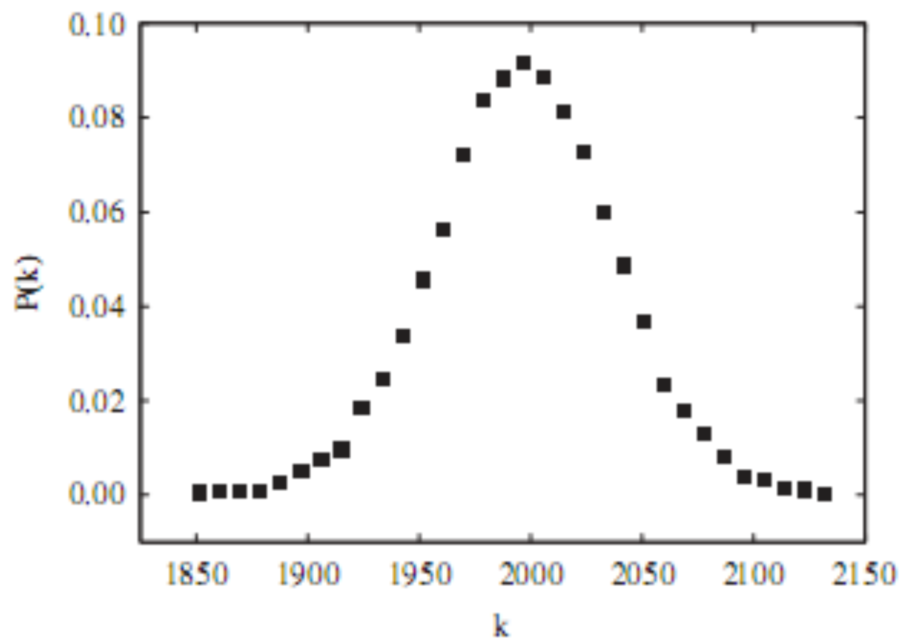
$$P(k) = \binom{n-1}{k} p^k (1-p)^{n-1-k}$$

Can be approximated as Poisson distribution

$$f(k;\lambda) = \frac{e^{-\lambda}\lambda^k}{k!} \qquad \lambda = n * p$$

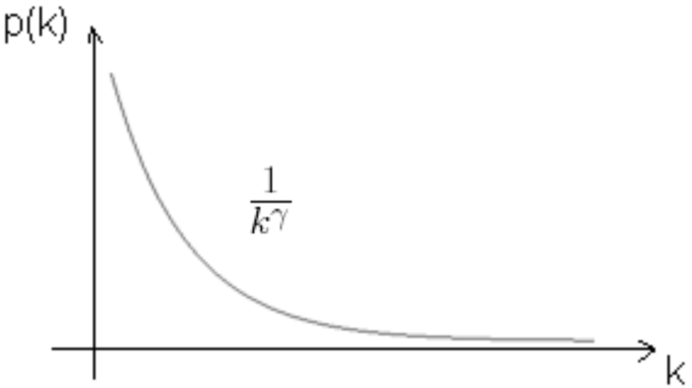
-> exponential *tail*

(networks are therefore sometimes called *exponential networks*)



Scale-free networks

Power-law degree distribution

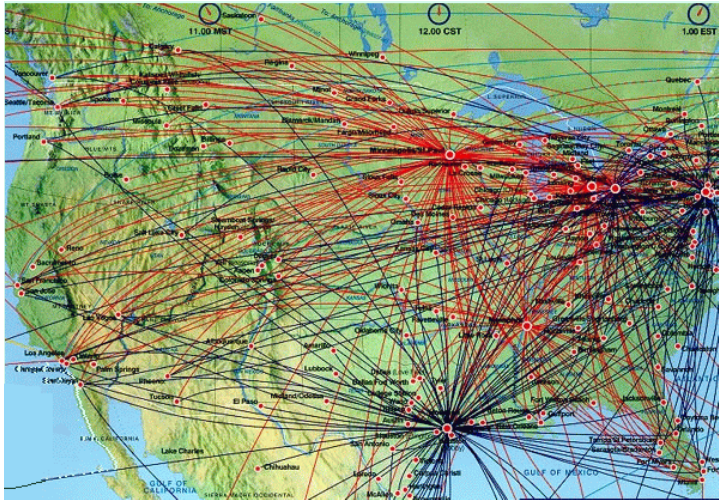


Barabasi & Albert, Science, 1999

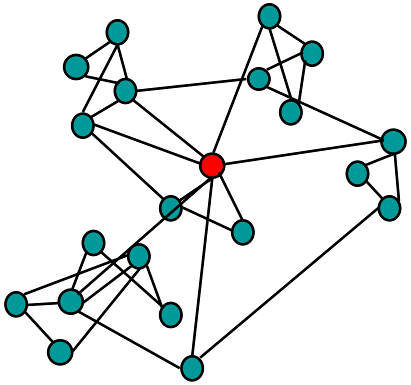
Power-law function:

f(x) = x^{-a} = $1/x^a$

Scale-free = no characteristic scale



Airline network

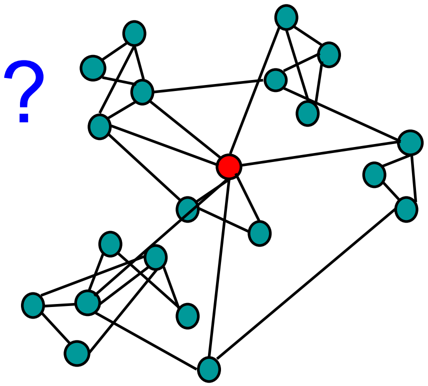


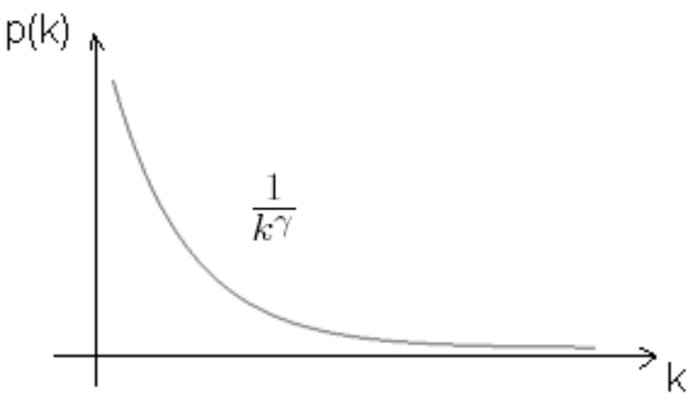
Hub =

highly-connected node

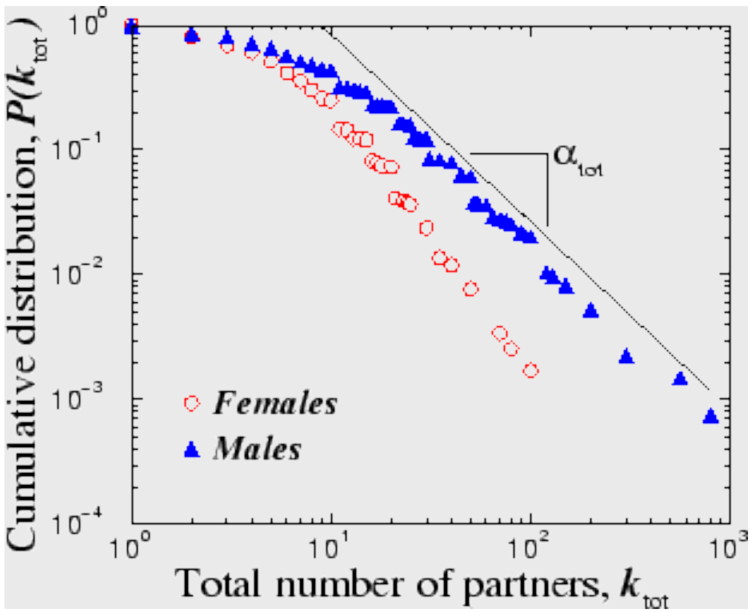
(potentially important for the network)

Is your network scale-free?





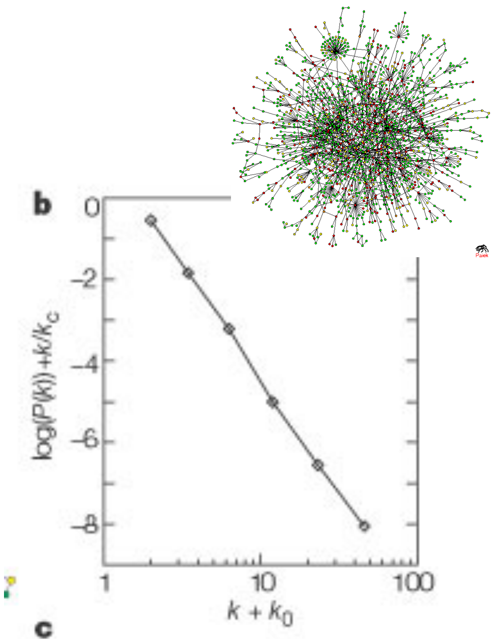
Log-log plot

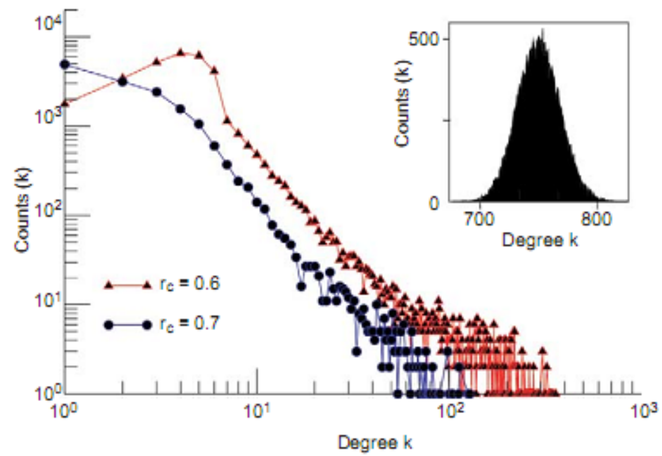


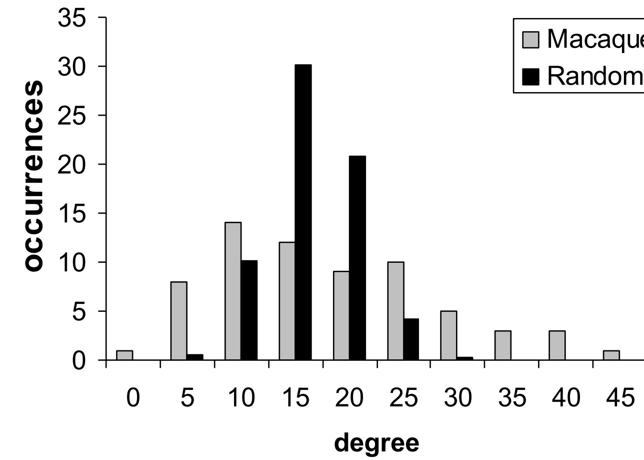
Barabasi & Albert, Science, 1999

Liljeros, Nature, 2001

Examples for biological scale-free networks







Protein-protein interaction network

Jeong et al., Nature, 2001

Correlation network between cortical tissue (fMRI voxels)

Eguiluz et al., Phys Rev Lett, 2005
Sporns et al., Trends Cogn Sci, 2004

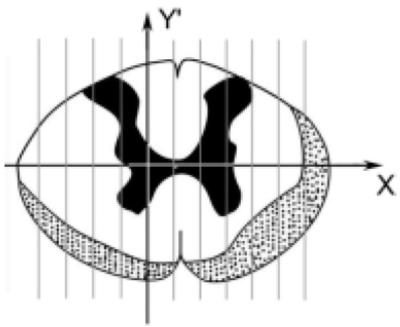
Cortical fibre tract network?

Kaiser et al., Eur J Neurosci, 2007

Robustness

Neural robustness against network damage (lesions)

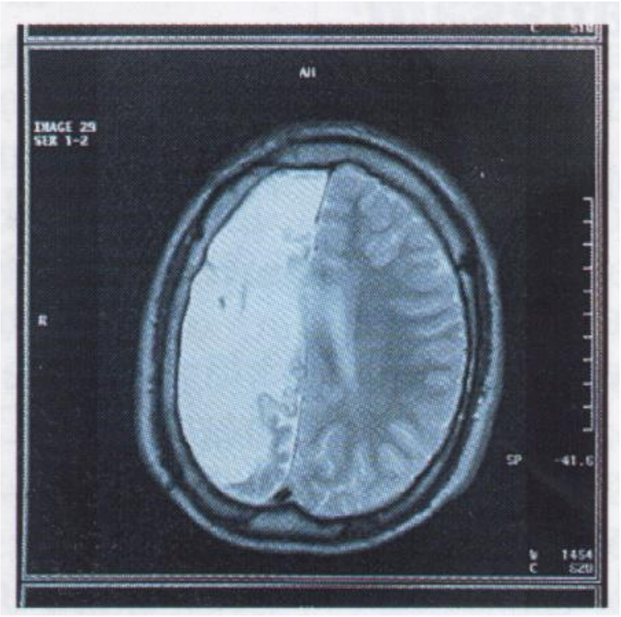
Rats: Spinal chord injury



large recovery possible with as few as 5% of remaining intact fibers

You et al., 2003

Human: Compensation for loss of one hemisphere at age 11

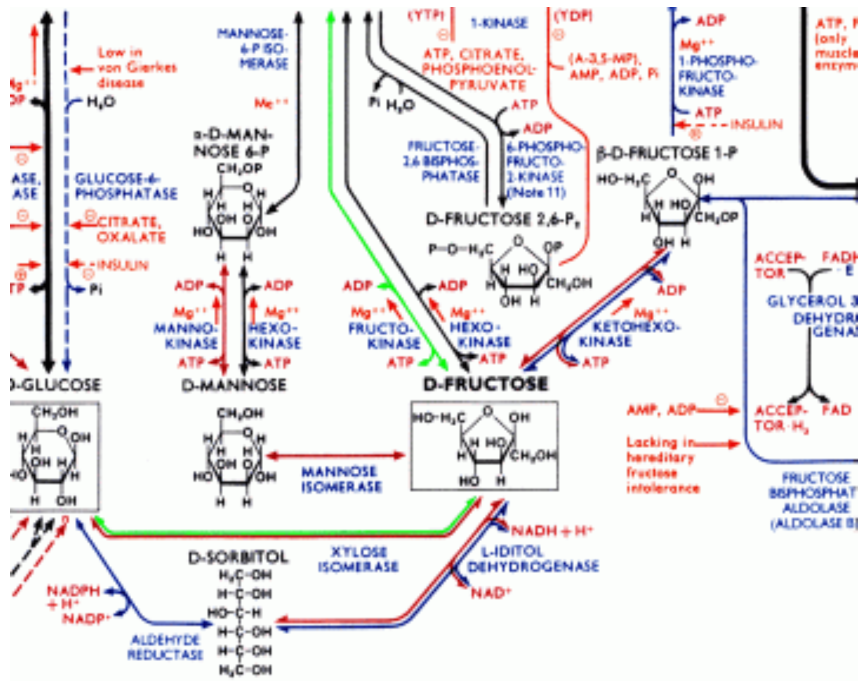


Cellular robustness against damage (gene knockouts)

- Mutations can be compensated by gene copies or alternative pathways*:

  ~70% of single-gene knockouts are non-lethal

- The metabolism can adjust to changes in the environment (e.g. switch between aerob and anaerob metabolism)



* **A. Wagner. Robustness against mutations in genetic networks of yeast.** ***Nature Genetics*****,** 24**, 355-361 (2000).**

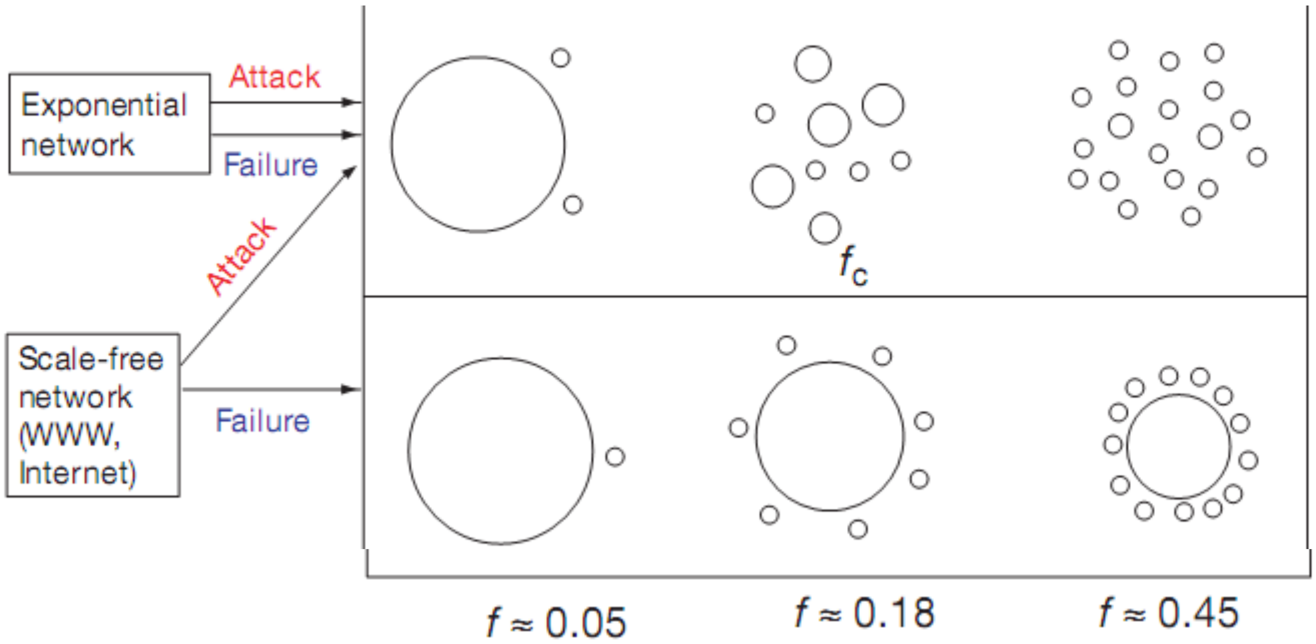
Measures of structural integrity

How is the global topology of the network affected?

Idea: Changes in *structural* properties might indicate *functional* changes (like lower performance of the system)

Structural measure		Potential functional impact
↑ All-pairs shortest path		longer transmission time
		Alzheimer
↓ Reachability	↑ Fragmentation	occurrence of isolated parts (components)
↓ Clustering coefficient		less interaction within modules
		Schizophrenia

Example: fragmentation



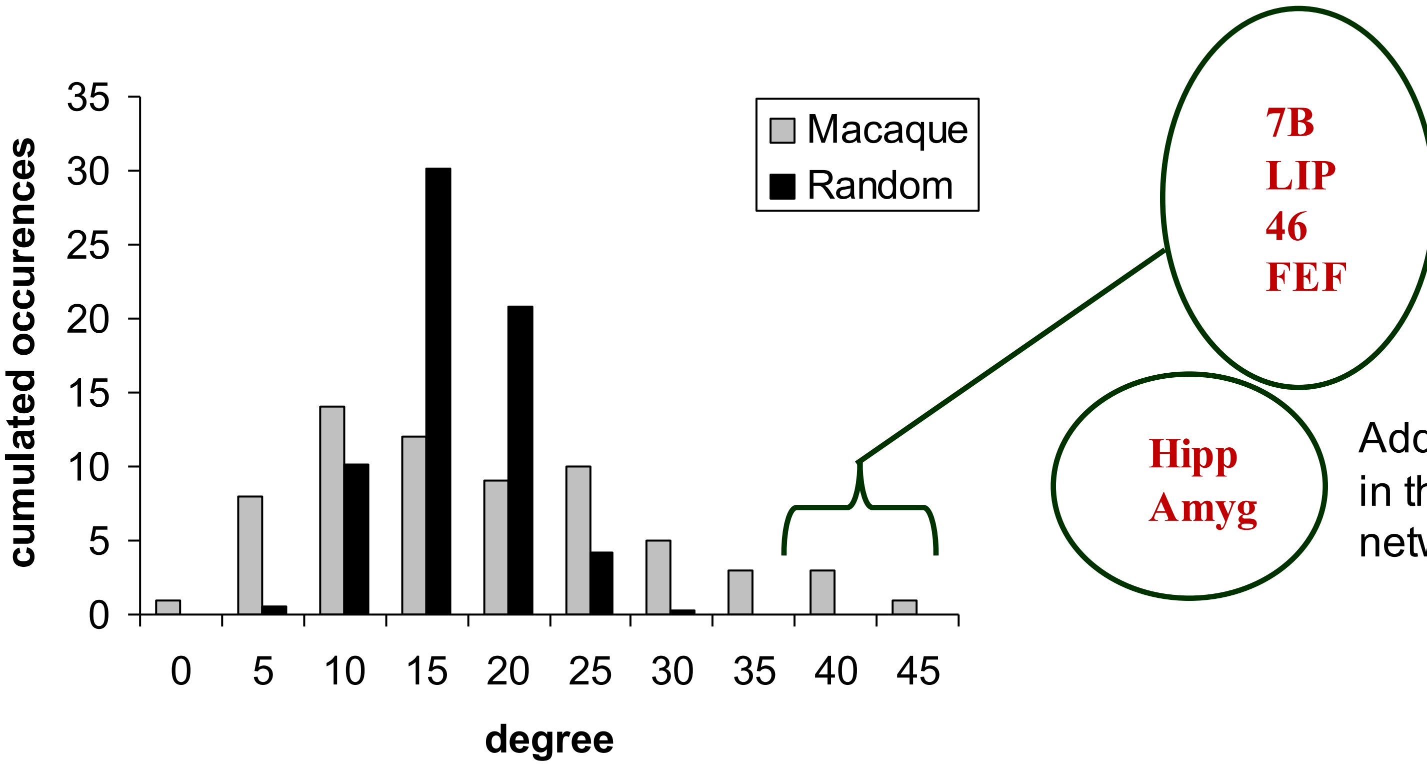
f: fraction of removed nodes

f_c: fraction where the network breaks into small fragments

Albert R, Jeong H, Barabasi AL (2000) Nature 406: 378–382

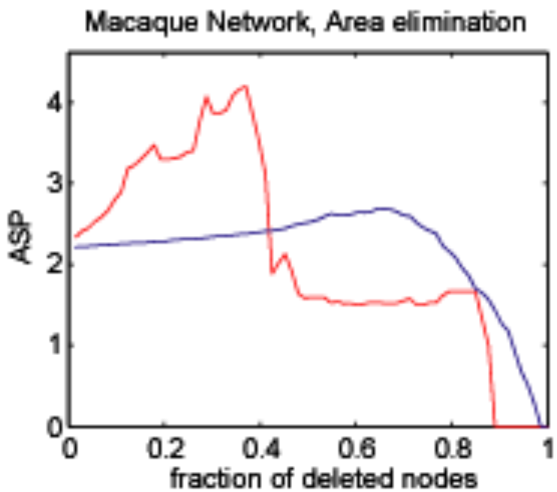
Example: simulated brain lesions

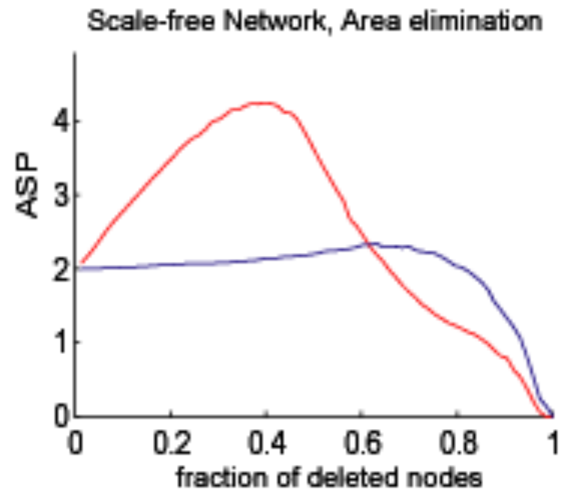
Is the brain similar to a scale-free network?

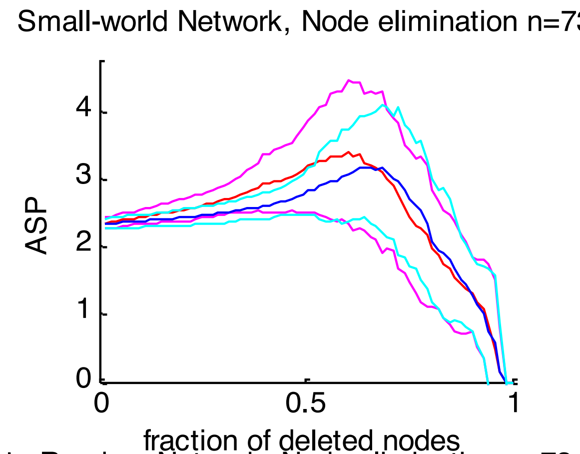


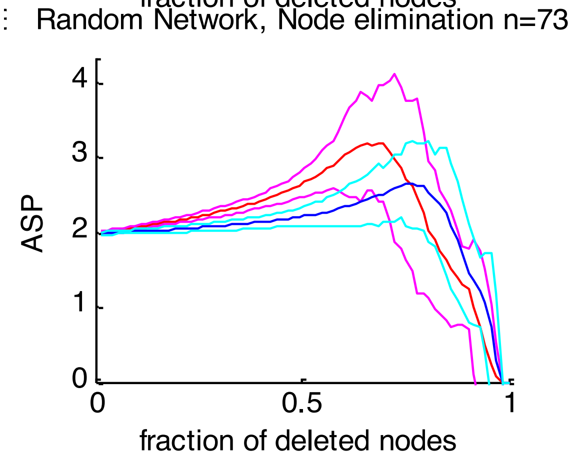
Additional hubs in the extended network of the cat

Sequential removal of brain areas









randomly = irrespective of degree

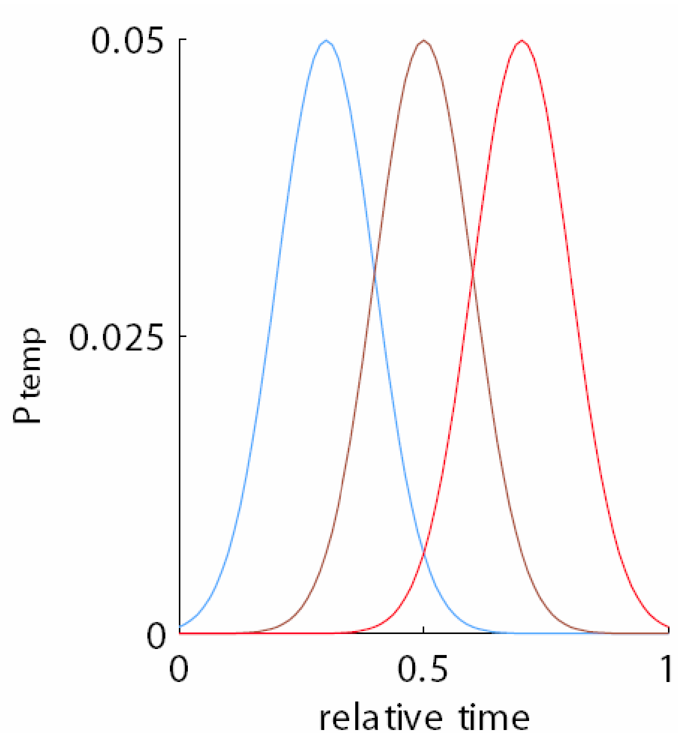
targeted = highly-connected nodes first

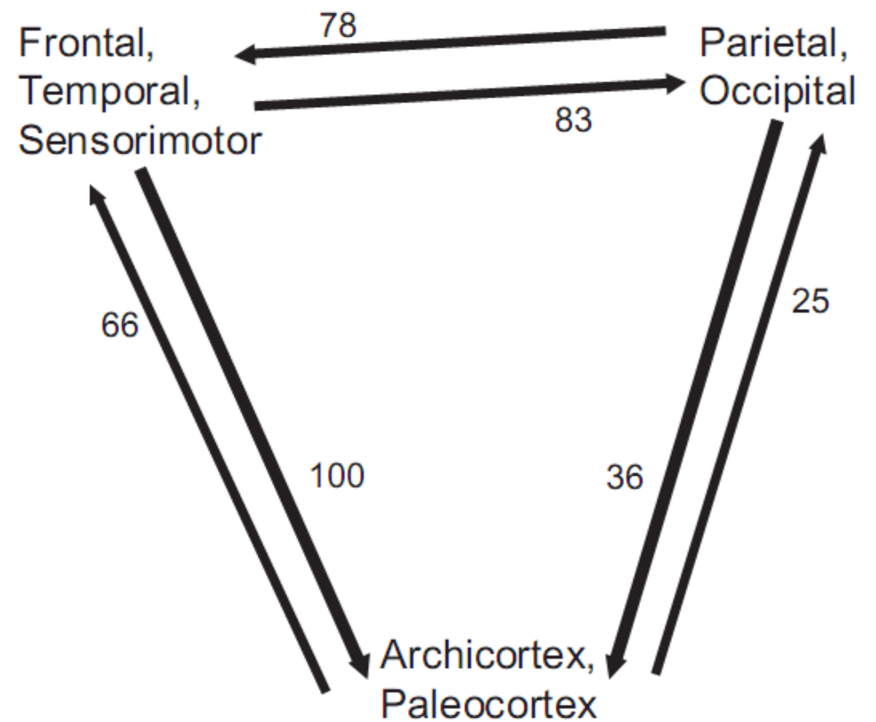
Kaiser et al. (2007) *European Journal of Neuroscience* 25:3185-3192

Where do ‘hubs’ come from?

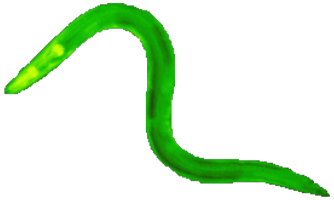
Not from preferential attachment…

During individual development, early-established nodes have more time to establish connections:

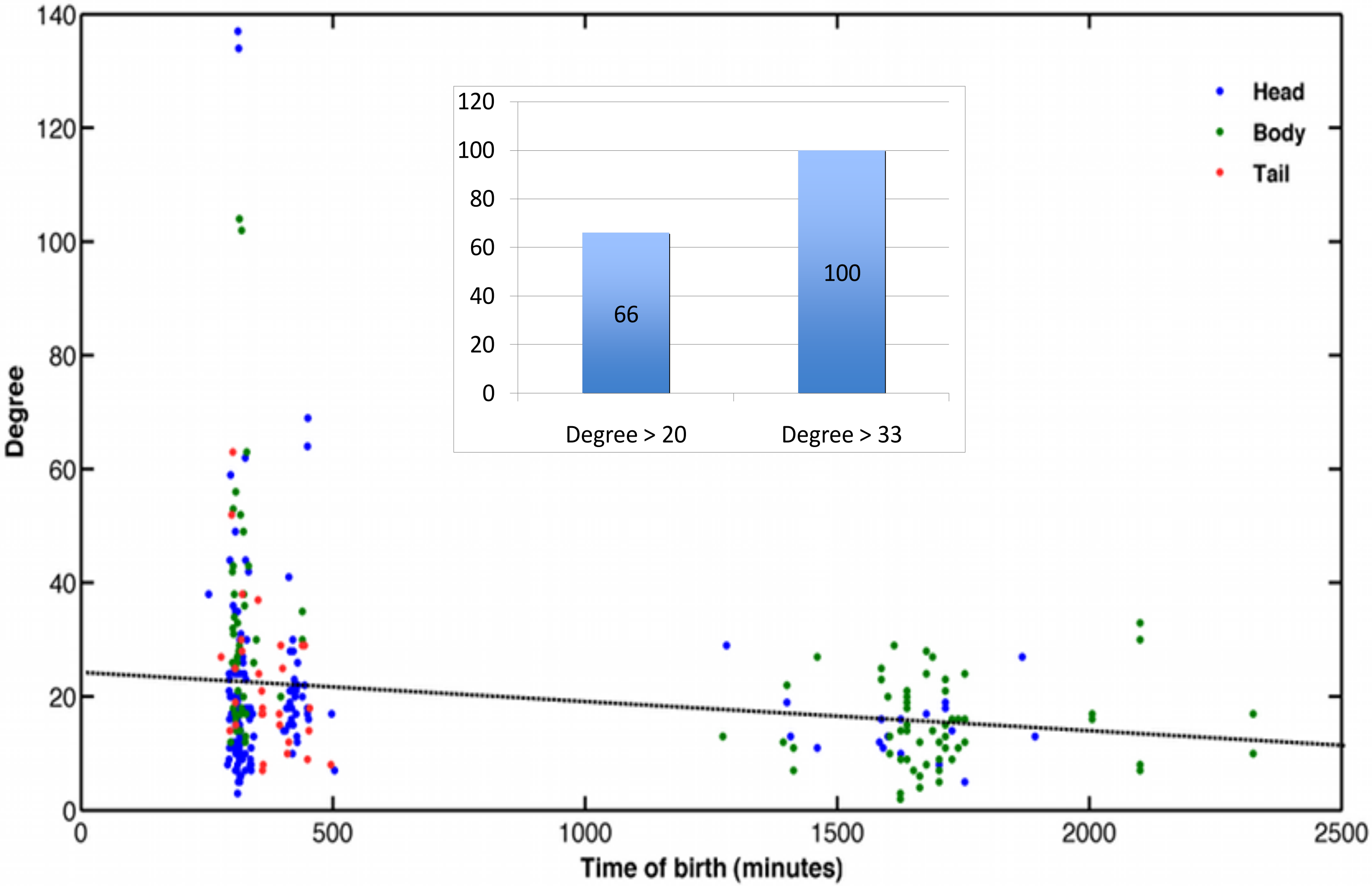




C. elegans network development: Varier & Kaiser (2011) PLoS Comput Biol
Nisbach & Kaiser (2007) *Eur Phys J B*
Kaiser et al. (2007) *European Journal of Neuroscience* 25:3185-3192

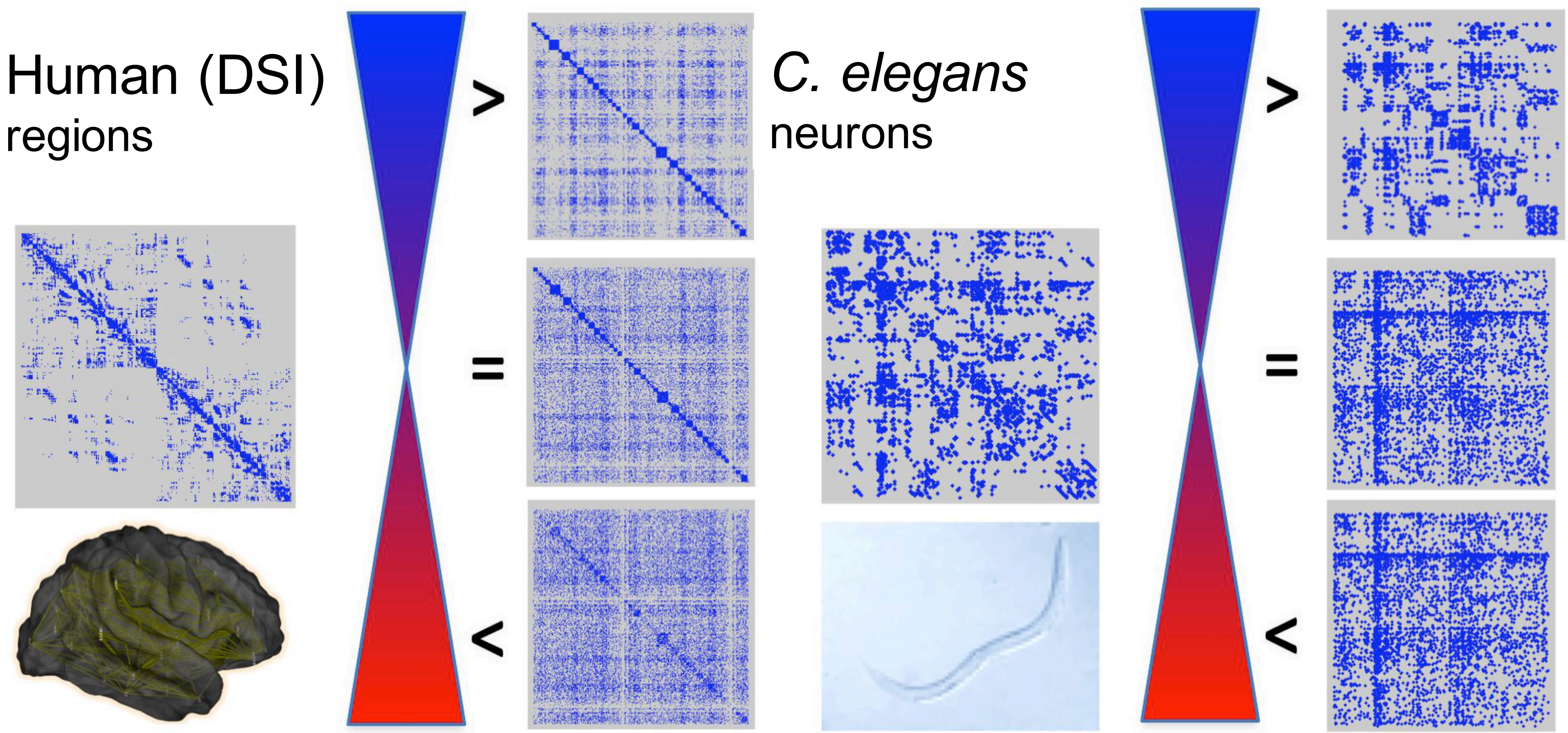


Hub neurons start early (old-gets-richer model)



Varier & Kaiser (2011) *PLoS Computational Biology*

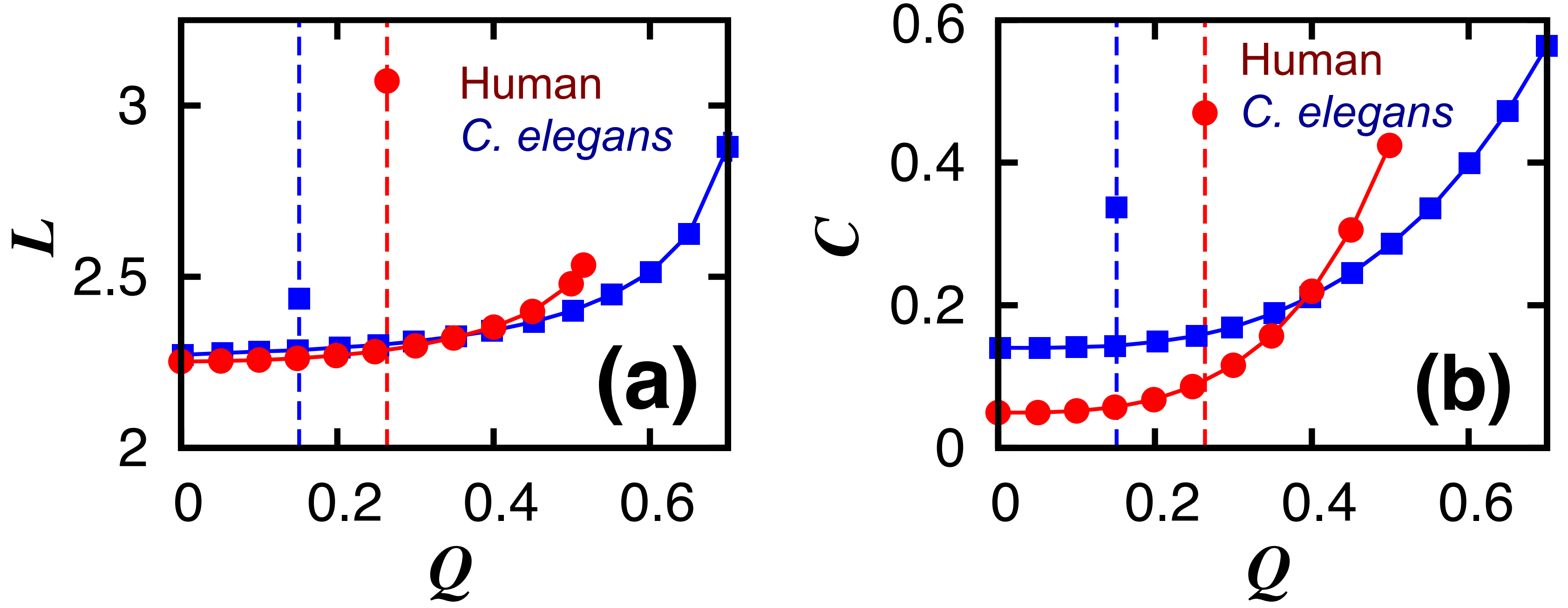
What is special about the modular organization of adult networks?



Increase or decrease of modularity *Q*

Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

Higher characteristic path length and higher clustering coefficient



Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

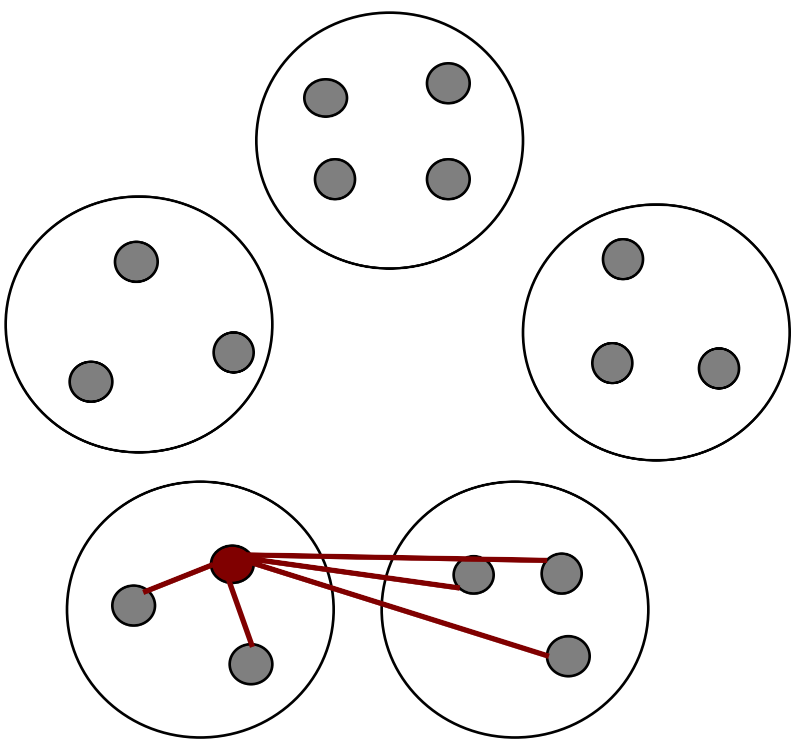
Lower dispersion *D*

For one node *i* : $D_i = R_i / R$

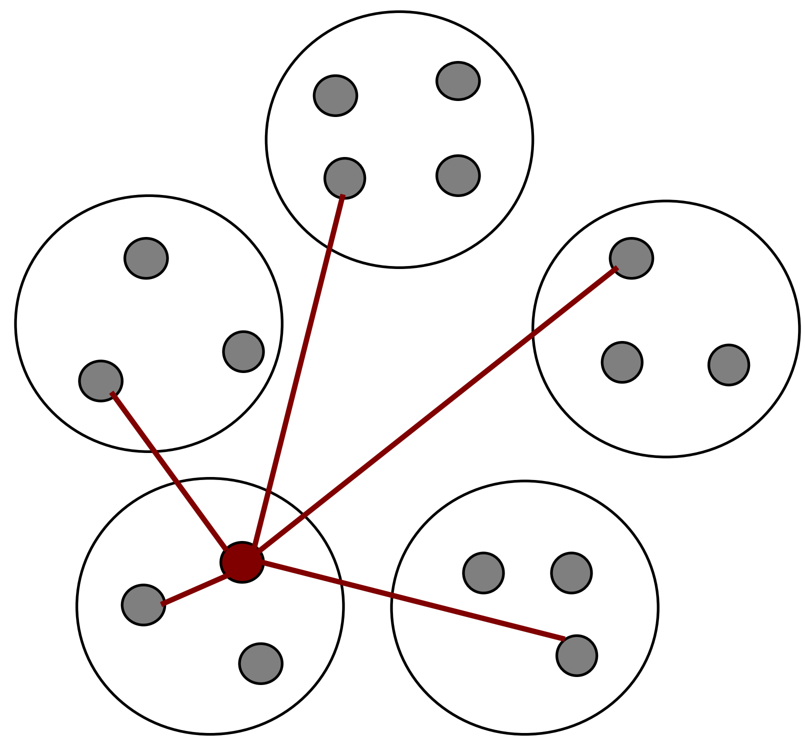
R_i the number of modules to which node i links to

R is the total number of modules (66 regions or 10 ganglia)

Low dispersion D = 2/5 = 0.4



High dispersion D = 5/5 = 1



Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

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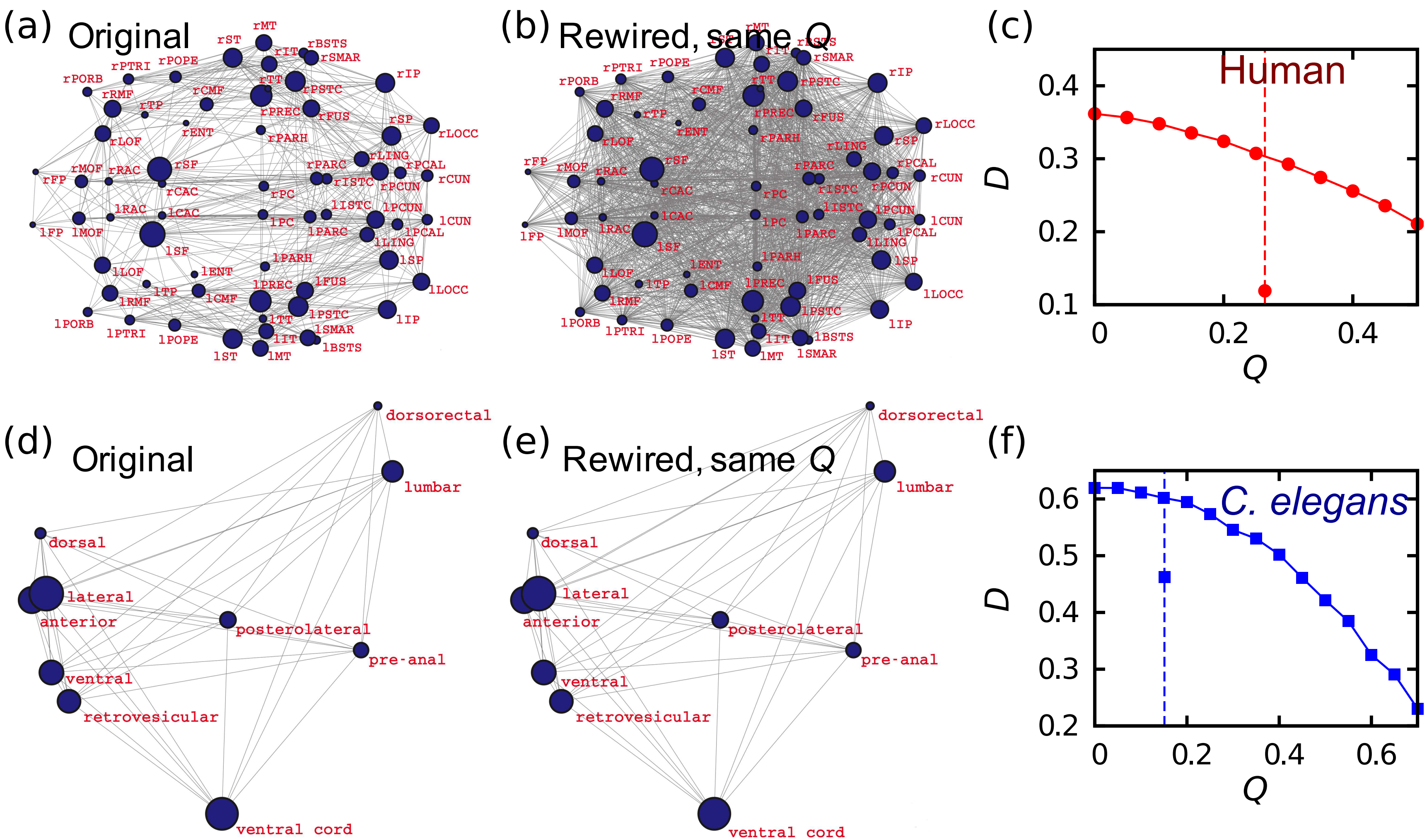


Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

Less information needed to grow the network

Algorithmic entropy: how much information is needed to encode for the network?

Compressed adjacency matrix = genetic information

Decompression algorithm = gene expression, Turing morphogenetic fields etc.

Decompressed = adult brain connectivity

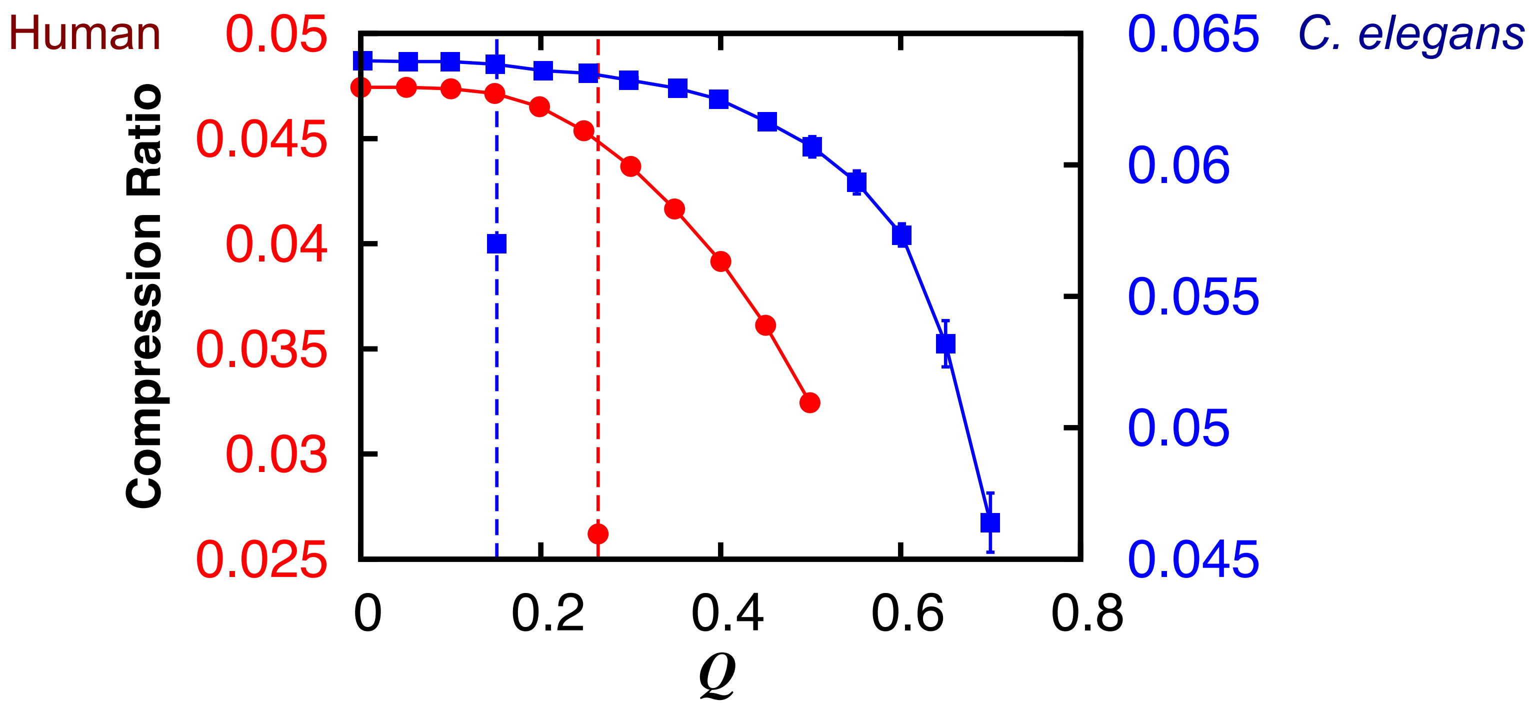
Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

Less information needed to grow the network

Algorithmic entropy: how much information is needed to encode for the network?

More information needed

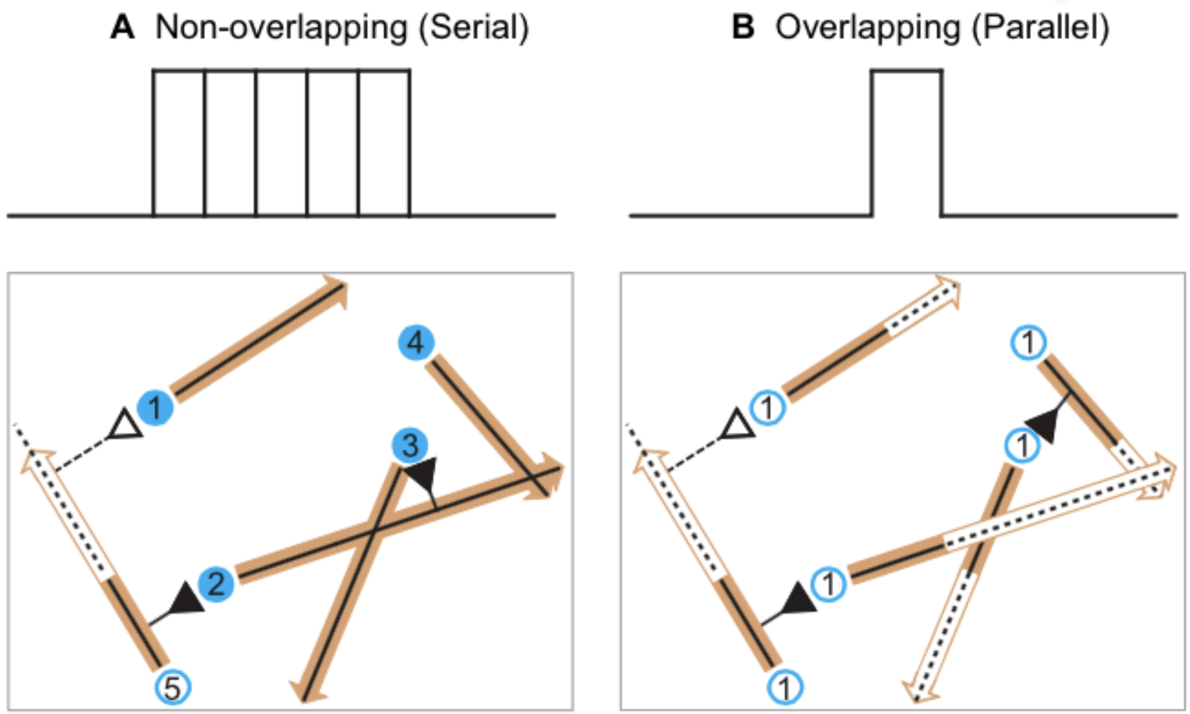
Less information needed



Compression ratio = size of compressed data / size of raw data

Kim & Kaiser (2014) *Phil. Trans. R. Soc. B*

Example growth rule: developmental time course - Axon growth time windows influence topology



Early starting neurons
- tend to become hubs
- have higher local efficiency
- have more long-distance connections

More bidirectional connections

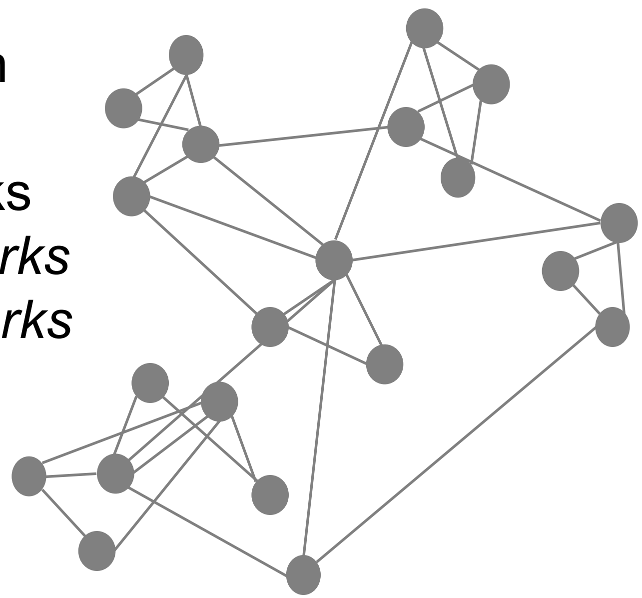
fewer long-distance connections

Model predictions are in agreement with *C. elegans* connectivity

Lim & Kaiser (2015) *Biological Cybernetics*

Summary

7. Macroscale:
- Degree distribution
  Random networks
  Scale-free networks
- *Small-world networks*
- *Hierarchical networks*



8. Robustness:
- Change of network properties after edge or node removal
- simulated brain lesions

6. Mesoscale:
- Motifs
- Clusters/Modules

9. Modular organisation

Preferential modularity: increased local clustering and global path length

➔ better local integration and global separation of processing

Lower algorithmic entropy: less information needed to encode connectivity

➔ fewer genes needed during brain development

Further readings

Luciano da Fontoura Costa

Costa et al. Characterization of Complex Networks
Advances in Physics, 2006

Ed Bullmore

Olaf Sporns

Bullmore & Sporns. Complex Brain Networks
Nature Reviews Neuroscience, 2009

Malcolm Young

Kaiser et al. Simulated Brain Lesions
(brain as scale-free network)
European Journal of Neuroscience, 2007

Alstott et al. Modeling the impact of lesions in the human brain
PLoS Computational Biology, 2009