An introduction to brain networks

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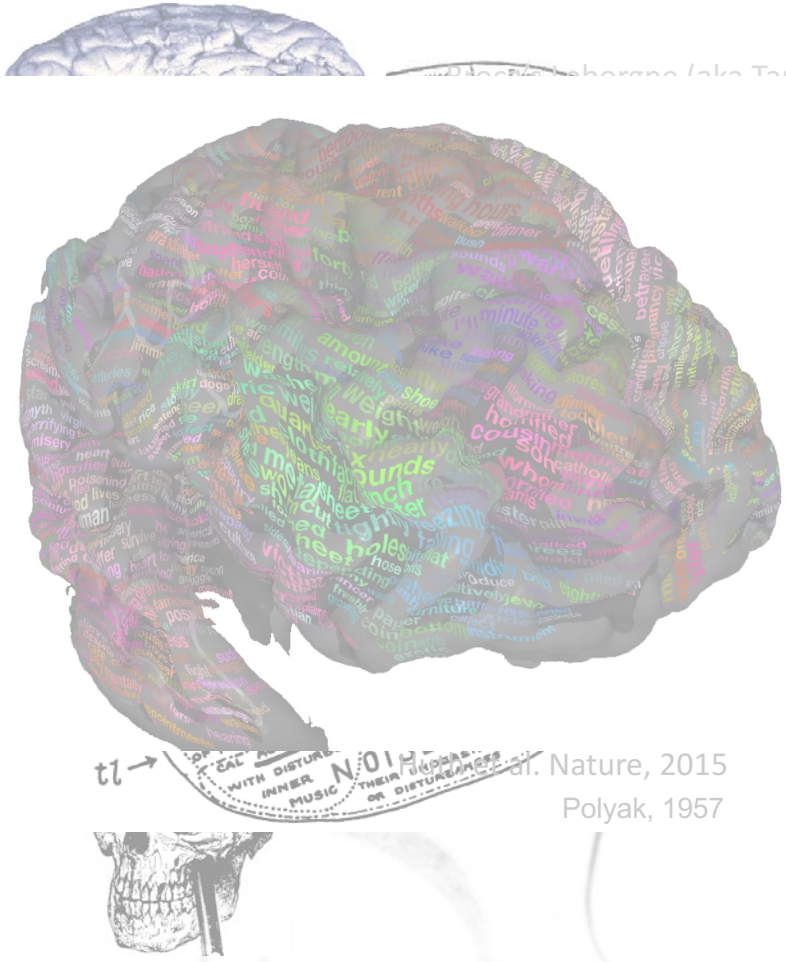
Laboratory for Brain & Mental Health

Monash Institute of Cognitive and Clinical Neurosciences

two fundamental principles of brain organization

segregation



Huth et al. Nature, 2015

Polyak, 1957

integration

1999

1990-1992

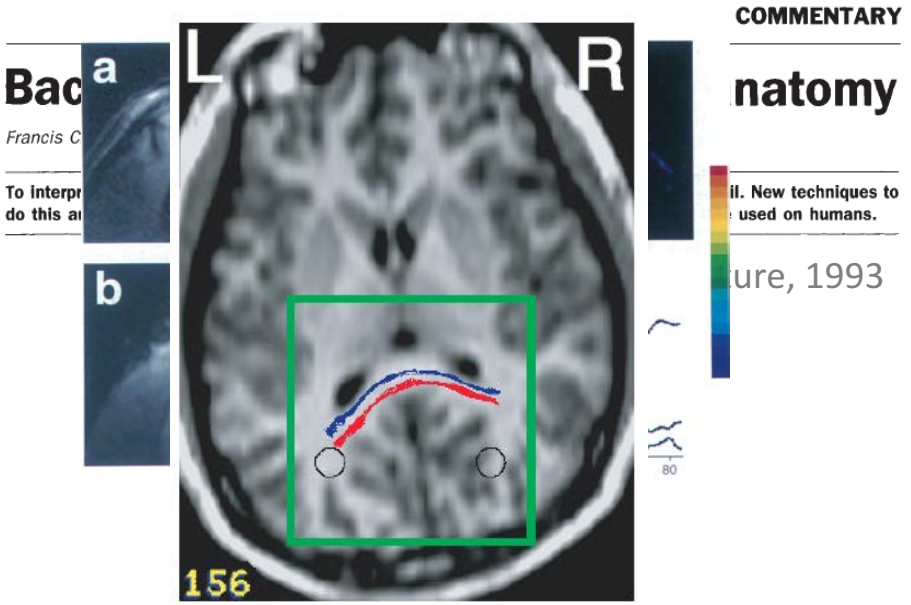
development of

discovery of BOLD

diffusion

contrast

tractography



ure, 1993

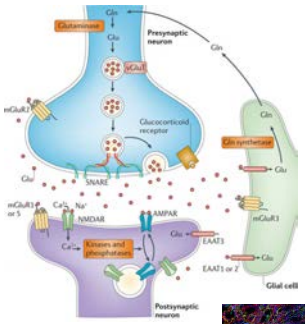
Conturo et al. PNAS, 1999

Felleman & Van Essen, Cereb Cortex, 1991

connectome:

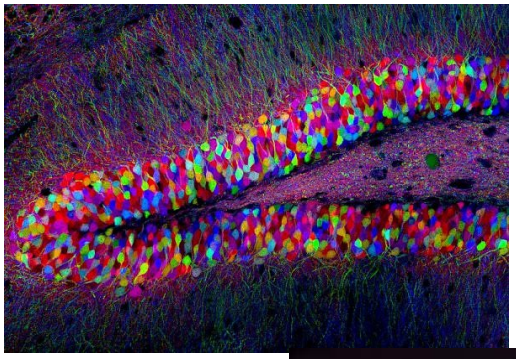
a comprehensive structural description of the network of elements and connections forming the human brain.

Sporns, Tononi, Kötter, PLoS Comp Biol, 2005



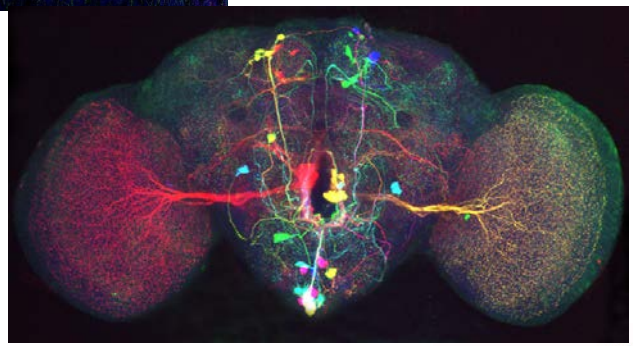
nanoscale

nm



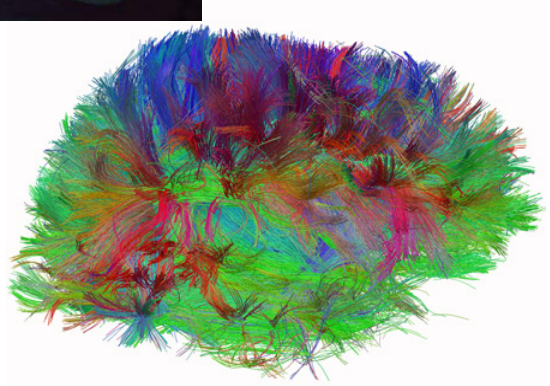
microscale

nm to μm



meso

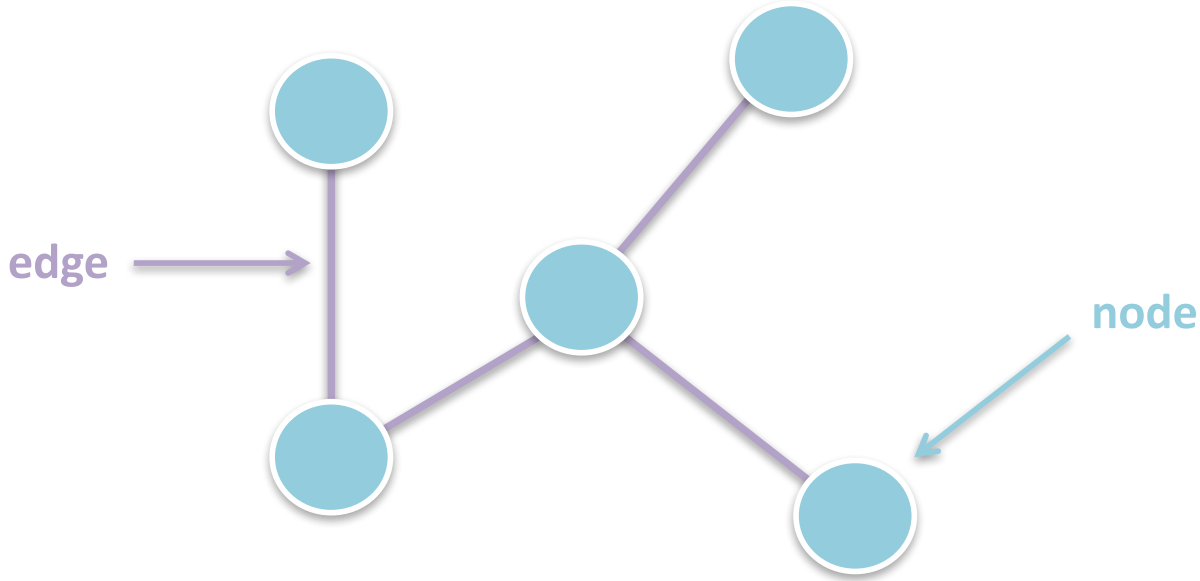
μm to mm



macroscale

mm to cm

modelling brain networks as graphs



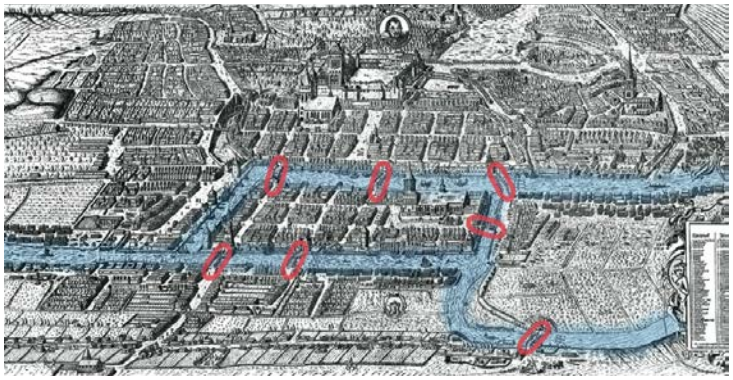
any network can be modelled as a graph of nodes connected by edges

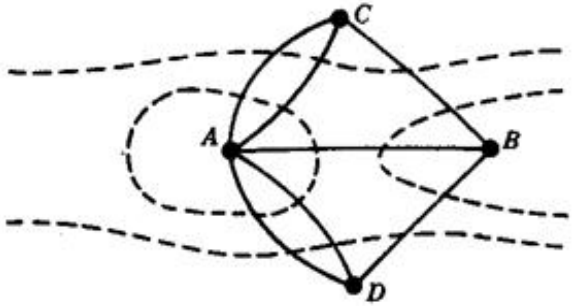
nodes represent fundamental processing units

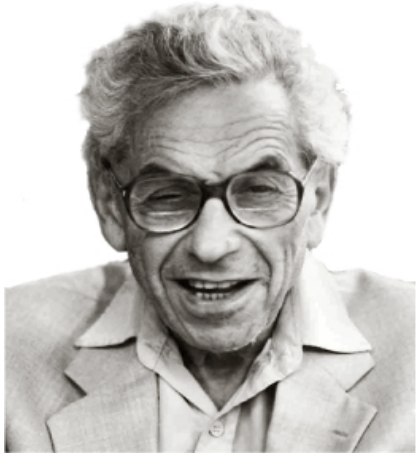
edges represent the interactions between nodes

a brief history of graph theory

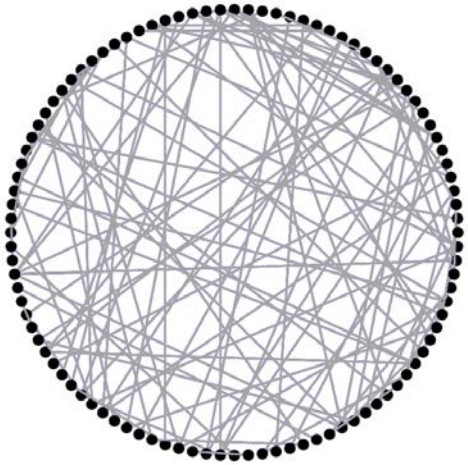
Leonhard Euler
(1707-1783)

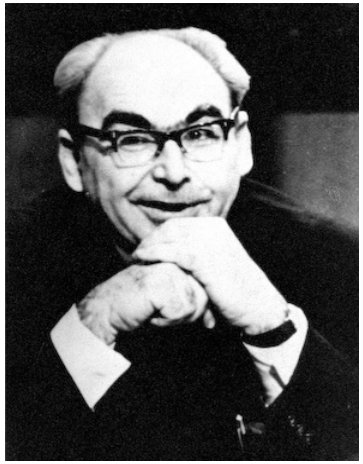






Paul Erdős
(1913-1996)



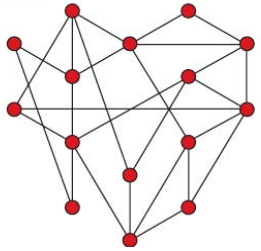


Alfréd Rényi
(1921-1970)

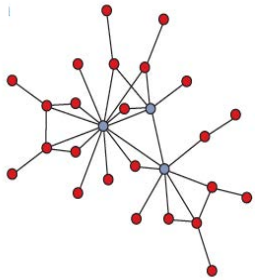
a brief history of graph theory

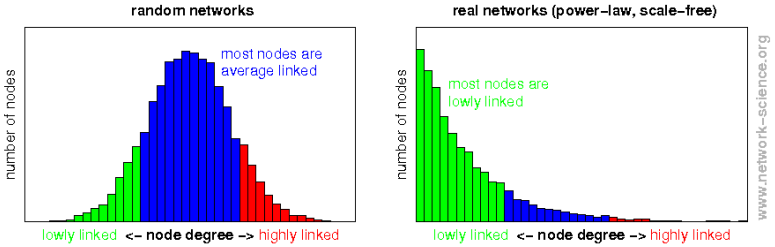
real networks have hubs

random



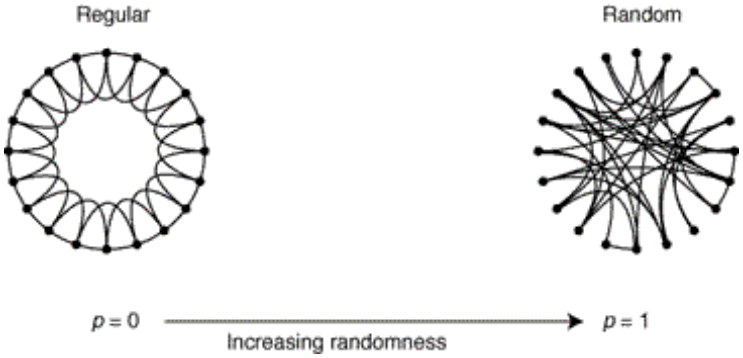
scale free

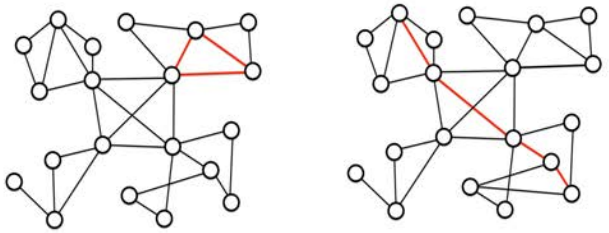




Barabasi & Albert, Science, 1999;
Barabasi & Oltvai, Nat Rev Genet, 2004

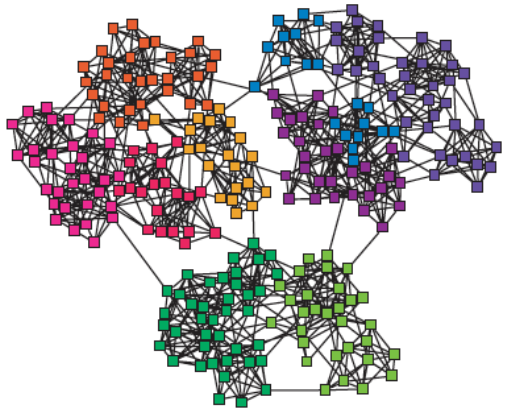
real networks are small-world

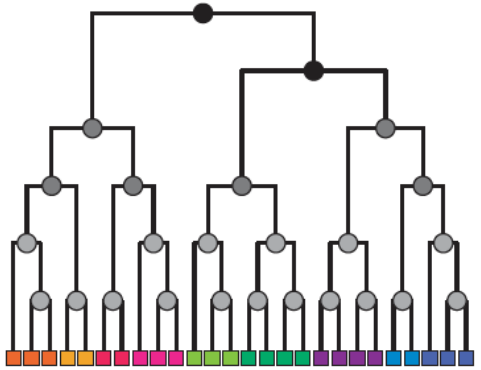




Watts and Strogatz, Nature, 1999

real networks are modular





Girvan & Newman, PNAS, 2004; Clauset, Moore & Newman, Nature, 2008

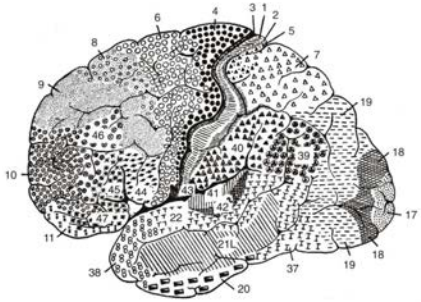
defining nodes

Brain nodes should have:

1. **Intrinsic consistency**
2. **Extrinsic differentiation**
3. **Spatially constrained**

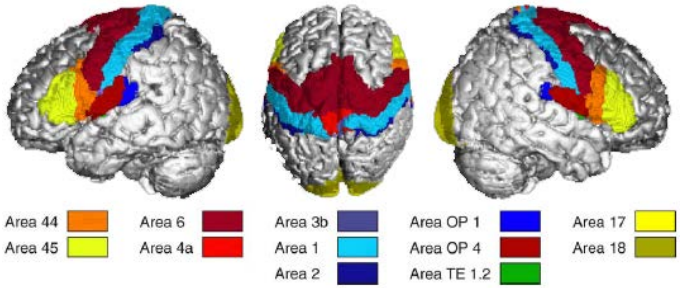
Fornito et al. NeuroImage, 2013

cytoarchitecture



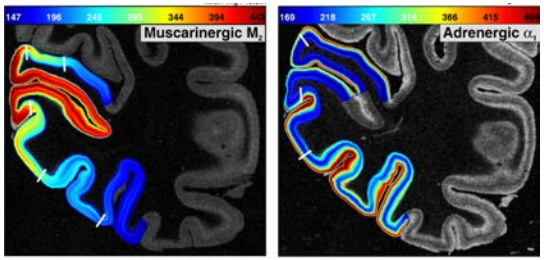
Brodmann, 1909

probabilistic



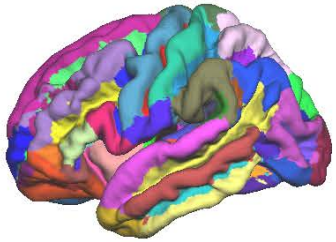
Eickhoff et al. NeuroImage, 2006

chemoarchitecture



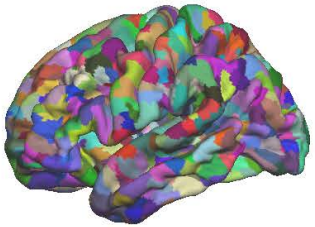
Eickhoff et al. NeuroImage, 2007

anatomical



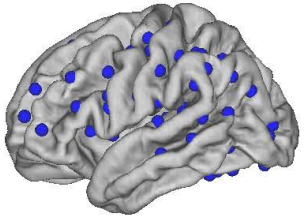
Tzuorio-Mazoyer, et al. NeuroImage, 2002
Desikan, et al. NeuroImage, 2006

random



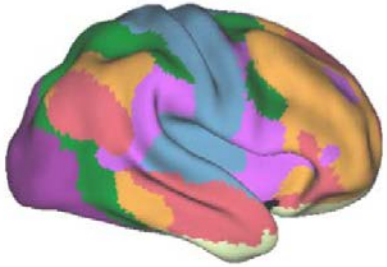
Hagmann, et al. PLoS One, 2007
Zalesky, et al. NeuroImage, 2010
Fornito et al. Font Sys Neurosci, 2010

functional



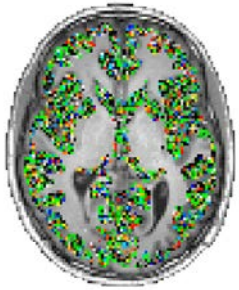
Dosenbach, et al. Science, 2010
Fornito et al. PNAS, 2012

data-driven



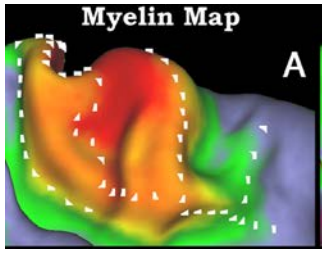
Yeo et al. J Neurophysiol, 2011
Craddock et al. Hum Brain Mapp, 2012
Power et al. Neuron, 2011

voxel-based



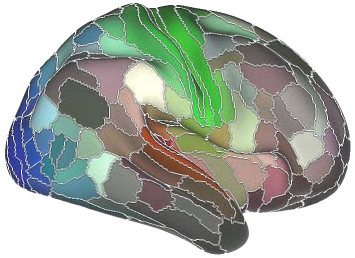
van den Heuvel et al. NeuroImage, 2009
Hayasaka & Laurienti, NeuroImage, 2010

myeloarchitecture



Glasser & Van Essen
J Neurosci 2011

multimodal



Glasser et al.
Nature, 2016

defining edges

Structural connectivity

The physical (anatomical) connections between brain regions

- Intrinsically directed
- Directionality cannot be resolved with MRI

Functional connectivity

A statistical dependence between spatially distinct neurophysiological signals

- Estimated at level of measured signals
- Can be directed or undirected

Effective connectivity

The influence that one neuronal system exerts over another

- Usually model-based
- Describes causal interactions at the neuronal level

Friston et al, 1994, Hum Brain Mapping; Fornito et al, 2015, Nat Rev Neurosci

defining edges

structural

electron microscopy

Bock et al. Nature, 2011
White et al. PTRS, 1986

tract-tracing

Oh et al. Nature, 2014
http://connectivity.brain-map.org

genetic labelling

Chiang et al. Curr Biol, 2011
www.flycircuit.tw

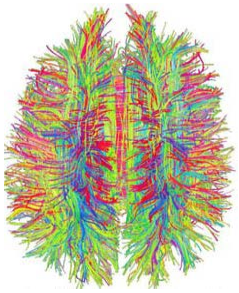
informatics

Modha & Singh PNAS, 2010
Shanahan et al. Fron Comp Neurosci,2013
http://cocomac.org

PLI

Axer, et al. NeuroImage, 2011

DWI



Hagmann et al. PLoS One, 2007

functional

electrophysiology

Yu et al. Cereb Cortex, 2008

ECoG

Bastos et al. Neuron, 2015
Brovelli, et al. PNAS, 2004

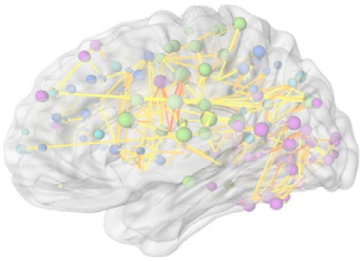
calcium imaging

Ahrens et al. Nat Methods, 2013

M/EEG

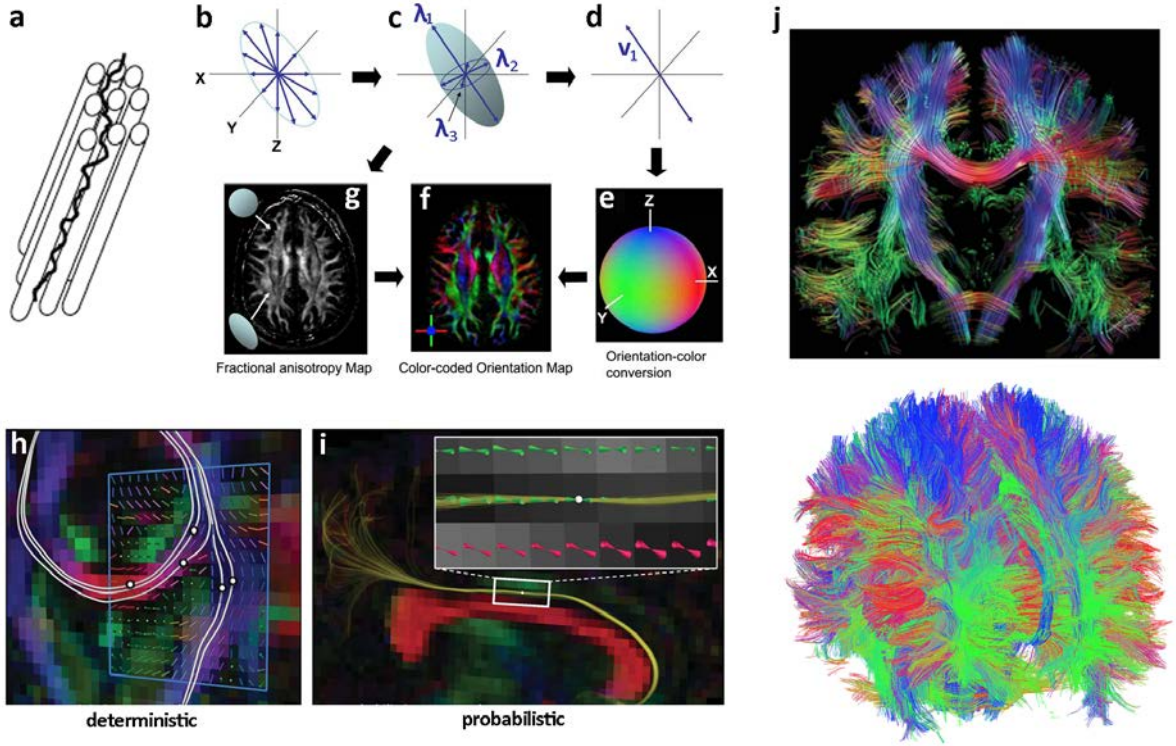
Engel et al. Neuron, 2013

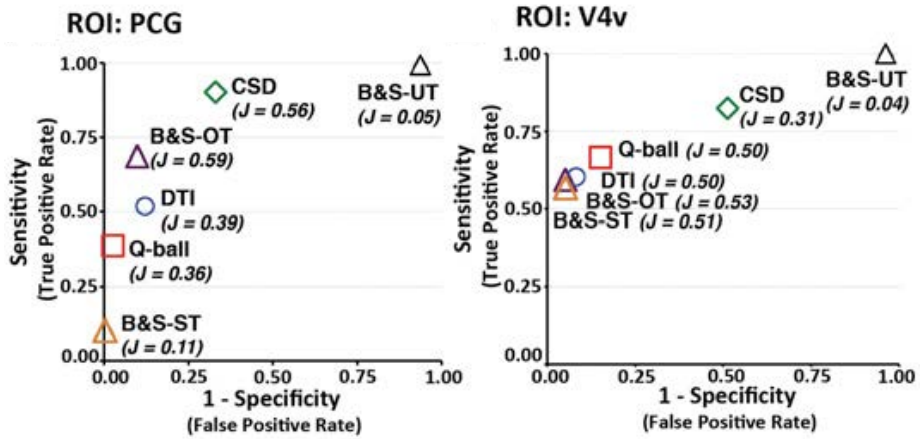
fMRI



Smith et al. NeuroImage, 2011

mapping structural connectivity in humans with DWI





Johansen-Berg & Rushworth, Ann Rev Neurosci, 2014; Mori & Zhang, Neuron, 2008; Tournier et al. Magn Res Med, 2011; Isenberg, 2011; Thomas, et al. PNAS, 2014

measuring connection weights with diffusion MRI

connection weights typically estimated as:
number of connecting streamlines
average tract FA or other diffusivity index

but:

Neuroimage 73 (2013) 239–254

Contents lists available at SciVerse ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Comments and Controversies

White matter integrity, fiber count, and other fallacies: The do's and don'ts of diffusion MRI

Derek K. Jones[a,b,*], Thomas R. Knösche[c], Robert Turner[c]

[a] Cardiff University Brain Research Imaging Centre (CUBRIC), School of Psychology, Cardiff University, Park Place, Cardiff, CF10 3AT, UK
[b] Neuroscience and Mental Health Research Institute, Cardiff University, Cardiff, CF10 3AT, UK
[c] Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstrasse 1A, 04013 Leipzig, Germany

emerging approaches include:
axon diameter & density (Assaf et al. NeuroImage, 2013)
track density imaging (Calamante, et al. NeuroImage, 2011)
myelin content (Deoni et al. Magn Res Med, 2008)

defining edges

structural

electron microscopy

Bock et al. Nature, 2011
White et al. PTRS, 1986

tract-tracing

Oh et al. Nature, 2014
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genetic labelling

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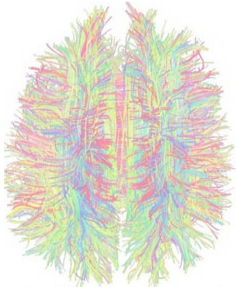

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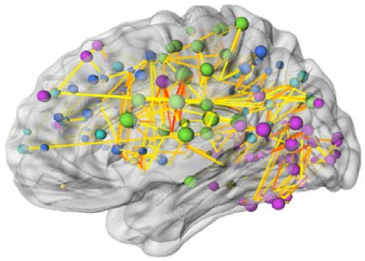
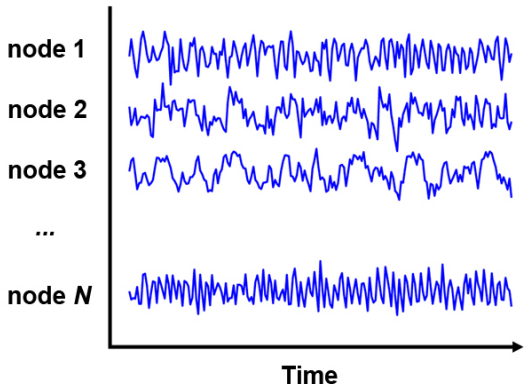
fMRI



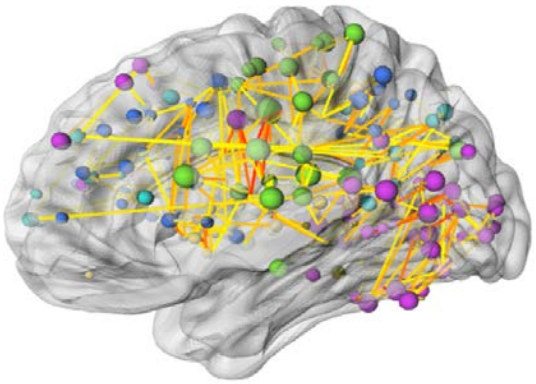
Fornito et al. NeuroImage, 2013
Smith et al. NeuroImage, 2011

mapping functional connectivity with fMRI

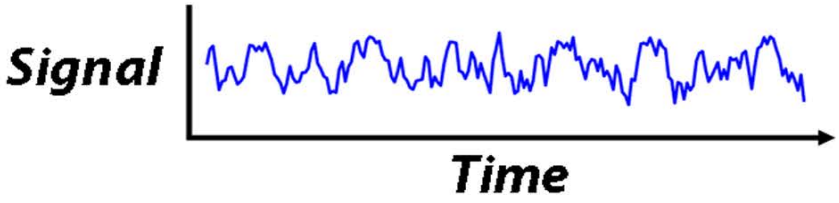


statistical dependence

correlation
partial correlation
mutual information
...
etc

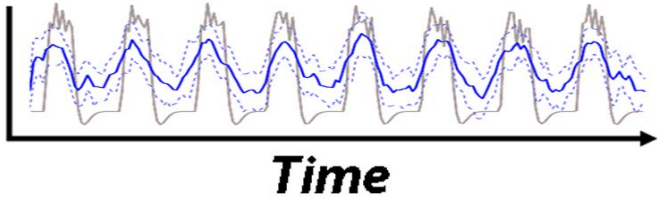


rest



Fox & Raichle, Nat Rev Neurosci, 2002
Achard et al. J Neurosci, 2005
Smith et al. NeuroImage, 2011

task

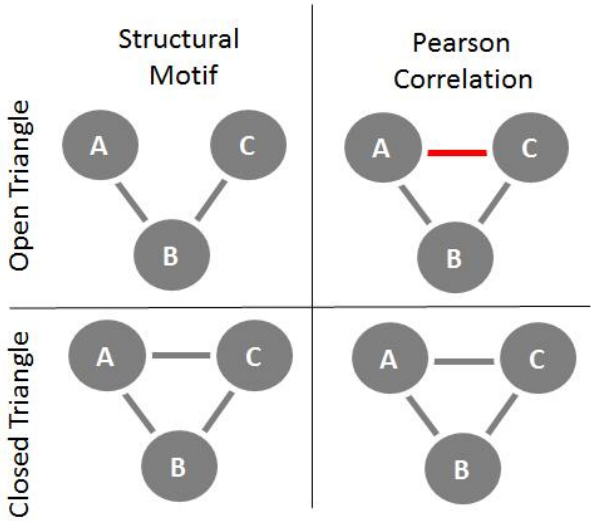


Fornito et al. PNAS, 2012
Fornito et al. Biol Psychiatry, 2012
Cole et al. Nat Neurosci, 2013

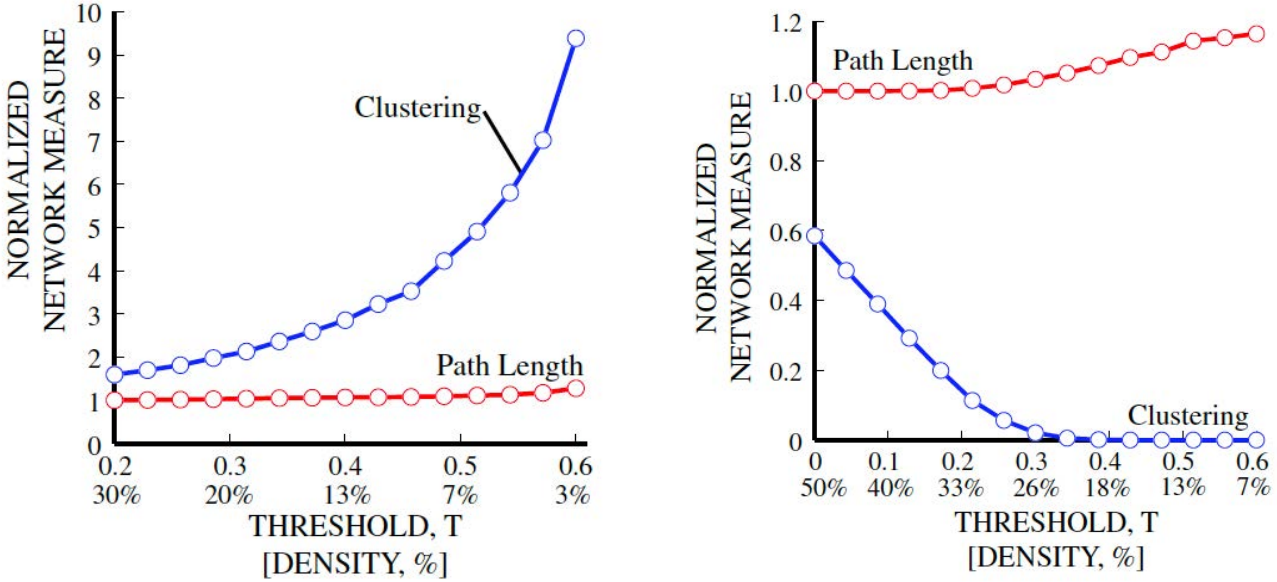
dynamics

Zalesky et al. PNAS, 2014
Hutchison, et al. NeuroImage, 2013

topological biases of common functional connectivity measures



Fornito, Zalesky & Bullmore, 2016, *Fundamentals of Brain Network Analysis*



Zalesky, Fornito, Bullmore, NeuroImage, 2012

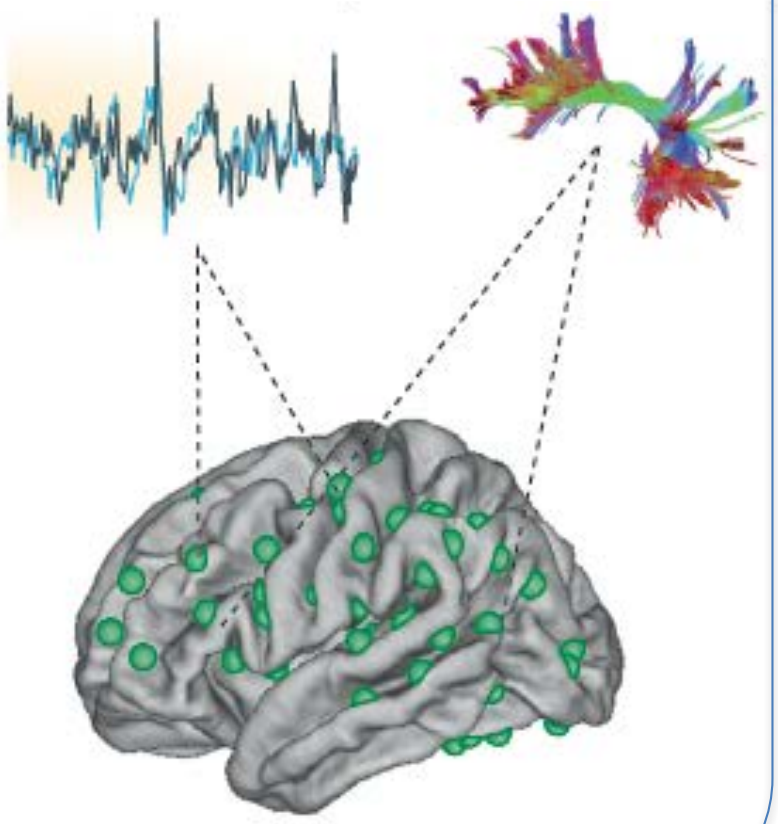
from data to graph

define nodes & edges

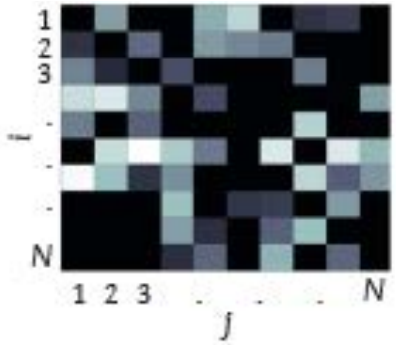
build graph

functional connectivity

structural connectivity



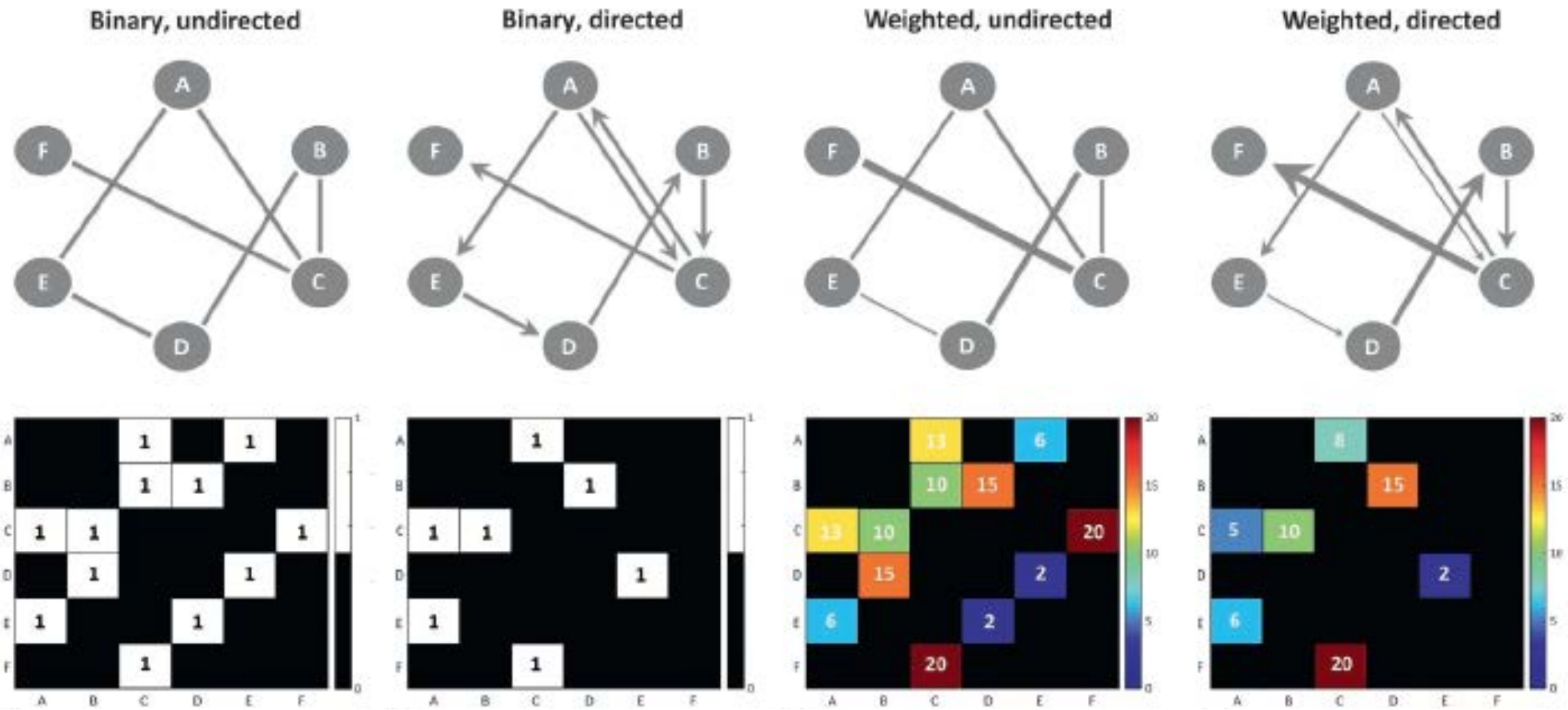
adjacency matrix



brain graph

Fornito, Zalesky, & Breakspear. 2015, Nat Rev Neurosci

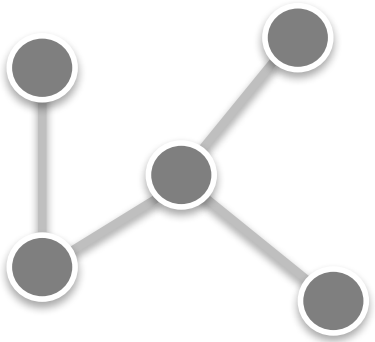
matrices and graphs are formally equivalent



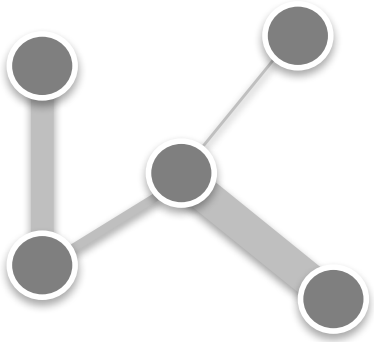
Fornito, Zalesky & Bullmore, 2016, *Fundamentals of Brain Network Analysis*

which graph best represents the brain?

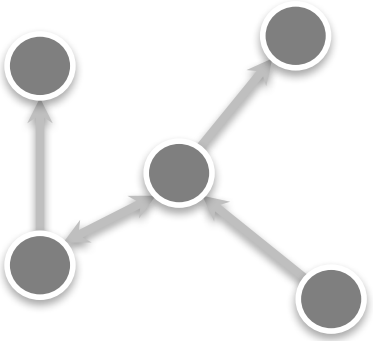
binary



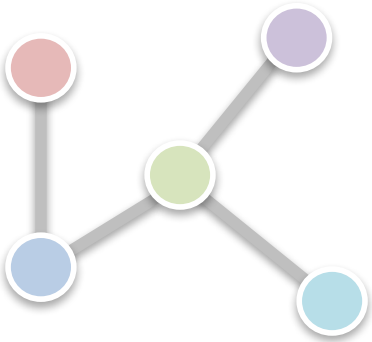
weighted



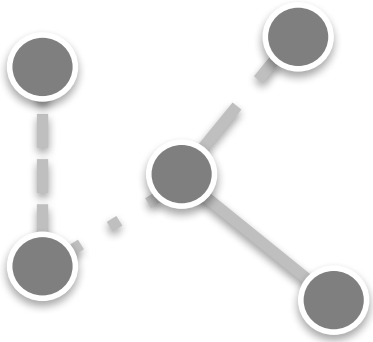
directed



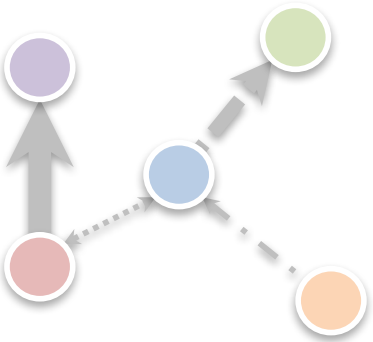
heterogeneous nodes



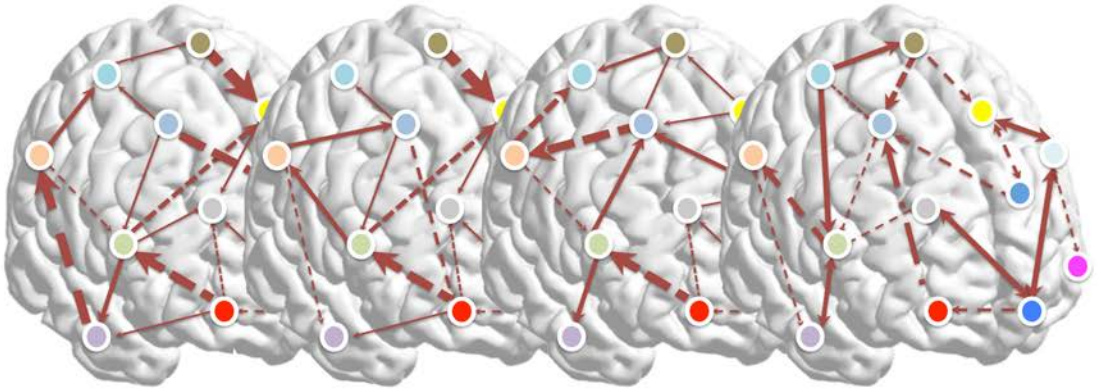
heterogeneous edges



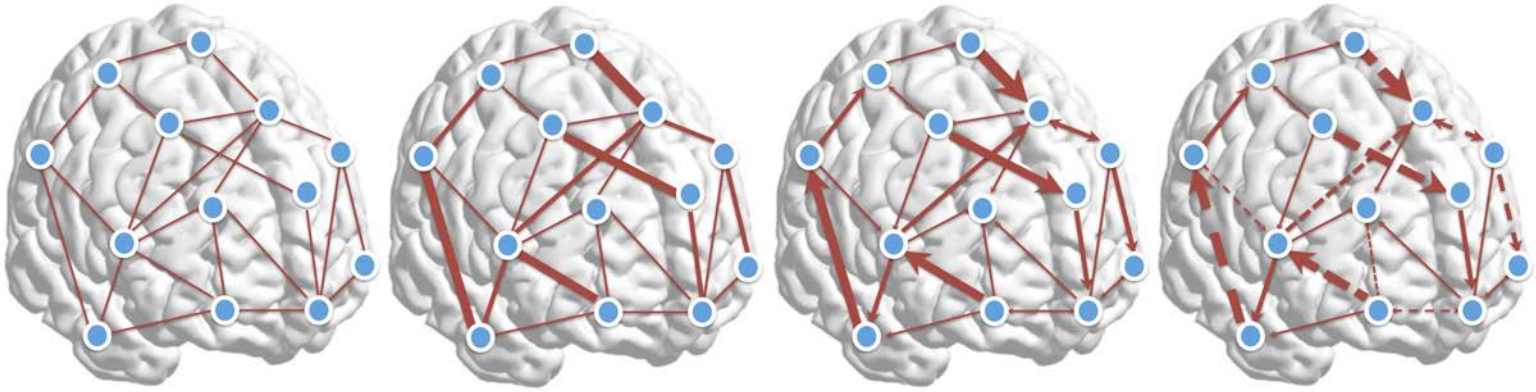
hybrid



which graph best represents the brain?



time (milliseconds to years)



nodes	homogeneous	homogeneous	homogeneous	homogeneous
edges	homogeneous	homogeneous	homogeneous	heterogeneous
weight	binary	weighted	weighted	weighted
directionality	undirected	undirected	directed	directed
method	all	all	electron microscopy tract-tracing most functional imaging	electron microscopy tract-tracing + some functional imaging

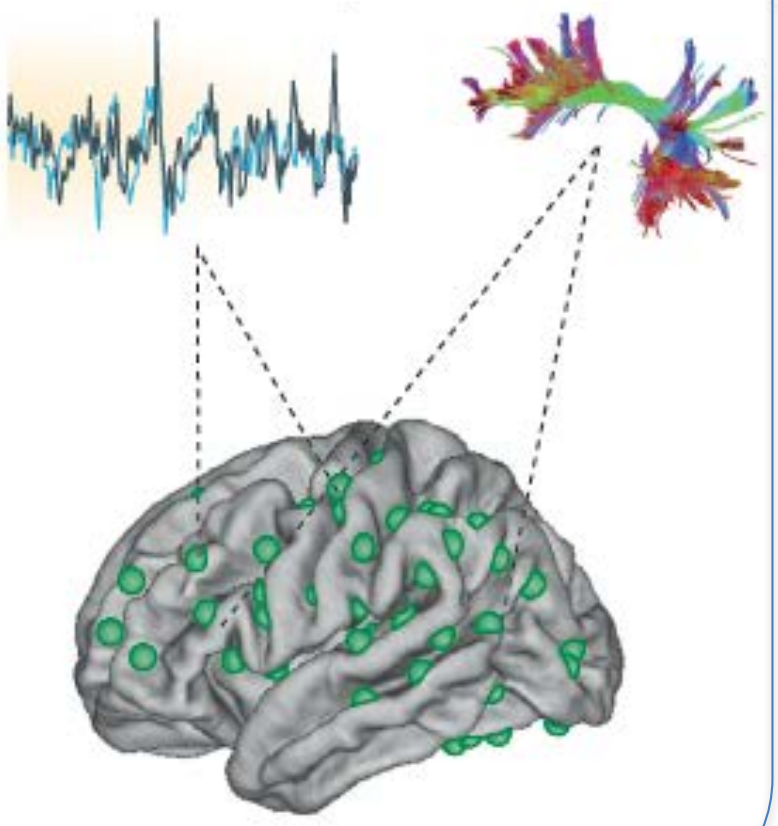
Fornito, Zalesky, & Breakspear. 2013, NeuroImage; Fornito, Zalesky, Bullmore, 2016, *Fundamentals of Brain Network Analysis*

from data to graph

define nodes & edges

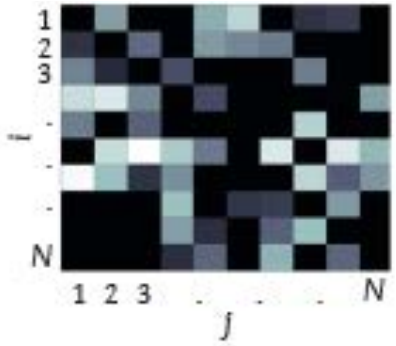
functional connectivity

structural connectivity



build graph

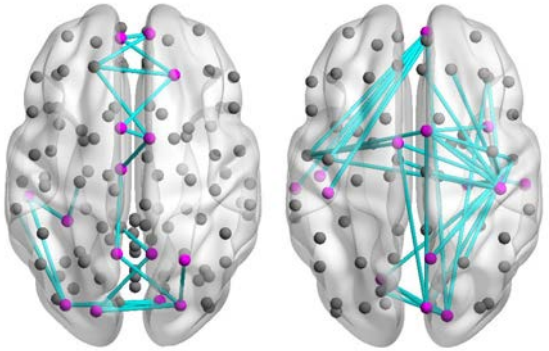
adjacency matrix



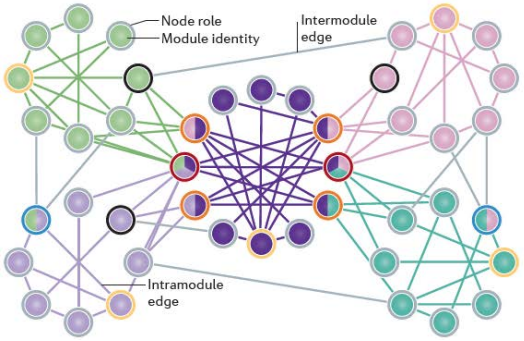
brain graph

network analysis

connectivity



topology



Fornito, Zalesky, & Breakspear. 2015, Nat Rev Neurosci

from data to graph

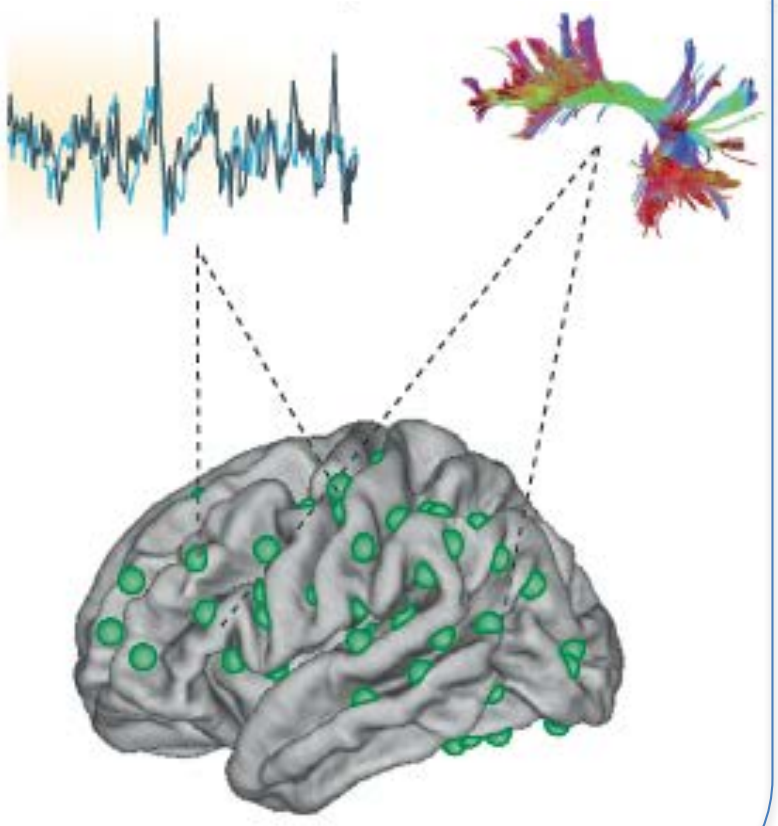
define nodes & edges

build graph

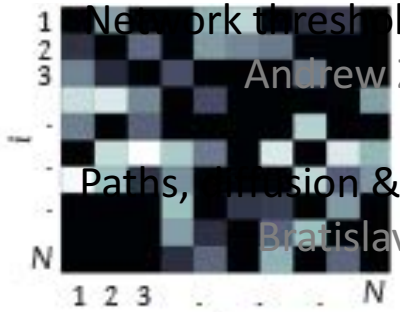
network analysis

functional connectivity

structural connectivity



adjacency matrix



Network thresholding & statistics

Andrew Zalesky

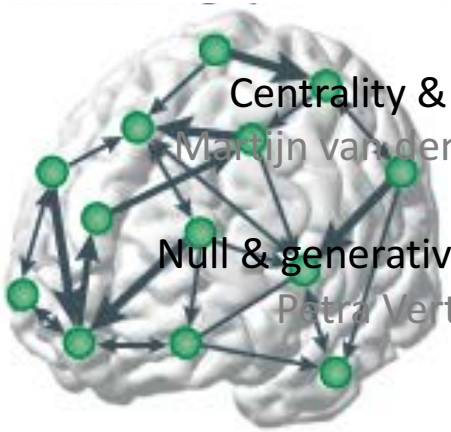
Paths, diffusion & communication

Bratislav Misic

Modularity (static & dynamic)

Sarah Muldoon

brain graph



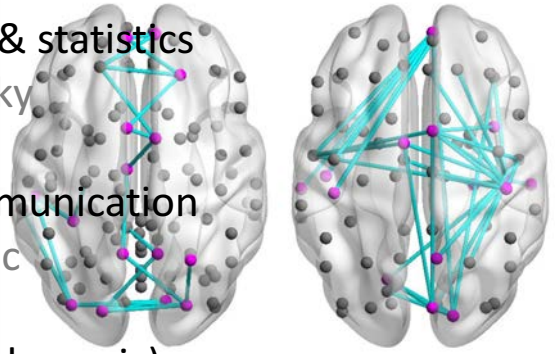
Centrality & hubs

Martijn van den Heuvel

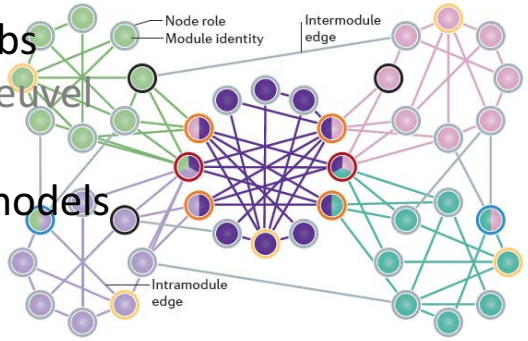
Null & generative models

Petra Vertes

connectivity



topology



Fornito, Zalesky, & Breakspear. 2015, Nat Rev Neurosci

summary

Graphs provide useful models of brain networks
A unified framework for representing multiscale organization

There are different methods for defining brain nodes and edges
Each has pros and cons; constrains interpretation of findings

Brain networks can be directed/undirected and weighted/unweighted
Node/edge heterogeneity and dynamics can also be accomodated

Brain networks can be analysed at the level of connectivity or topology
Effects can be mapped at individual edges, nodes, or globally

resources

graph theory/network science

Newman (2010) Networks: An introduction.

Newman (2003) SIAM Rev.

Albert & Barabasi (2002) Rev Modern Physics

graph theory and the brain

Sporns (2011) Networks of the brain.

Sporns (2012) Discovering the human connectome.

Bullmore & Sporns (2009) Nat Rev Neurosci.

Bullmore & Bassett (2011) Annu Rev Clin Psychol.

Fornito, Zalesky & Breakspear (2013) NeuroImage.

software

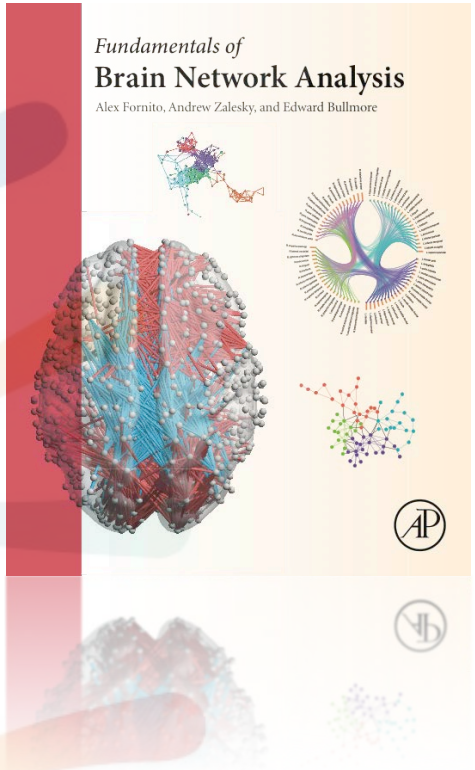
Brain connectivity toolbox:
https://sites.google.com/site/bctnet/

Graph analysis toolbox:
https://www.nitrc.org/projects/gat/

Network-based statistic:
http://www.nitrc.org/projects/nbs/

Task-related functional connectivity (cPPI):
http://www.nitrc.org/projects/cppi_toolbox/

Network visualization
http://immersive.erc.monash.edu.au/neuromarvl/



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http://amzn.to/1MLgMhU

Elsevier
http://bit.ly/1Hp29OZ

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An open-access journal for network neuroscience at all levels, from molecular to macroscales

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