Modelling Interacting Networks in the Brain

Philippe De Wilde

Department of Computer Science
Heriot-Watt University
Edinburgh

SICSA Stirling 17-6-2010

Outline

McCulloch and Pitts, 1948

- “For every [millisecond] there is therefore one proposition ... such that knowledge of its truth or falsity describes the neuron completely ...”
- “... all the significant relations within a nervous net can be expressed as propositional relations which only involve truth values.”
- -> Perceptrons (Minsky and Papert, 1969)
- -> RAM networks (Aleksander, 1977)

Bishop, 1995

- “... a network which has a feedforward architecture in which each hidden unit generates a nonlinear function of the weighted sum of its inputs.”
- “... a neural network model can be regarded simply as a particular choice for the set of functions...”
- “ ... biological realism would impose entirely unnecessary constraints.”
- -> Bayesian inference

Murray, 1987

- “The incoming excitatory and inhibitory pulse stream inputs to the neuron are integrated to give a postsynaptic potential that varies smoothly from 0 to 5V. ... The resultant periodic waveform is then converted to a series of voltage spikes.”
- -> Smith

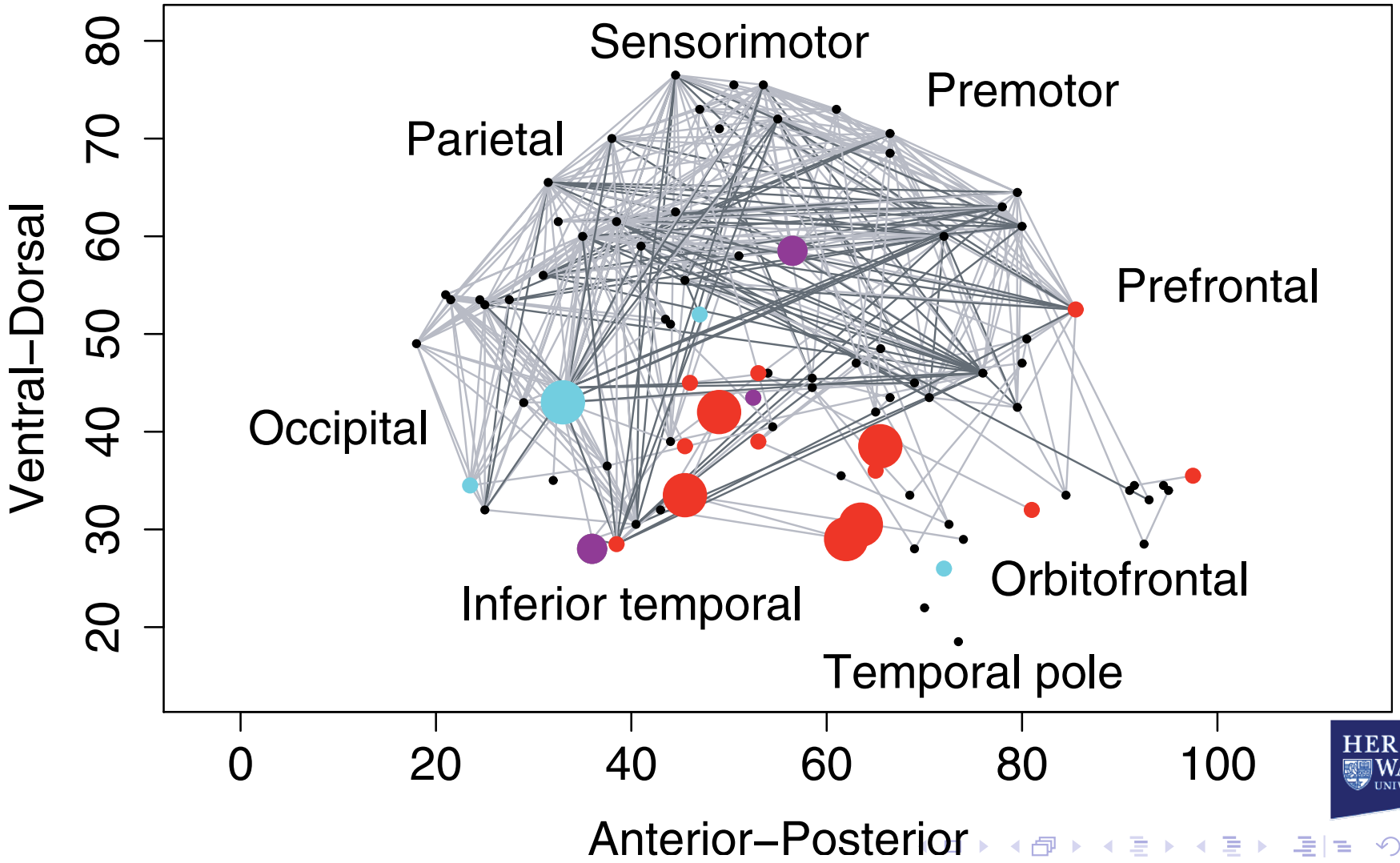
Paun, 2000

- "The objects evolve by means of spiking rules, which are of the form $E/a^c \rightarrow a; d$, where E is a regular expression over a and c, d are natural numbers, $c \geq 1, d \geq 0$. The meaning is that a neuron containing k spikes such that $a^k \in L(E), k \geq c$, can consume c spikes and produce one spike, after a delay of d steps. This spike is sent to all neurons to which a synapse exists outgoing from the neuron where the rule was applied."
- -> Frisco

Minsky, 1988

- “The nerve cells in an animal’s brain can’t always move aside to make room for extra ones. So those new layers might indeed have to be located elsewhere, attached by bundles of connection wires. Indeed, no aspect of the brain’s anatomy is more striking that its huge masses of connection bundles.”
- -> small world models of the brain

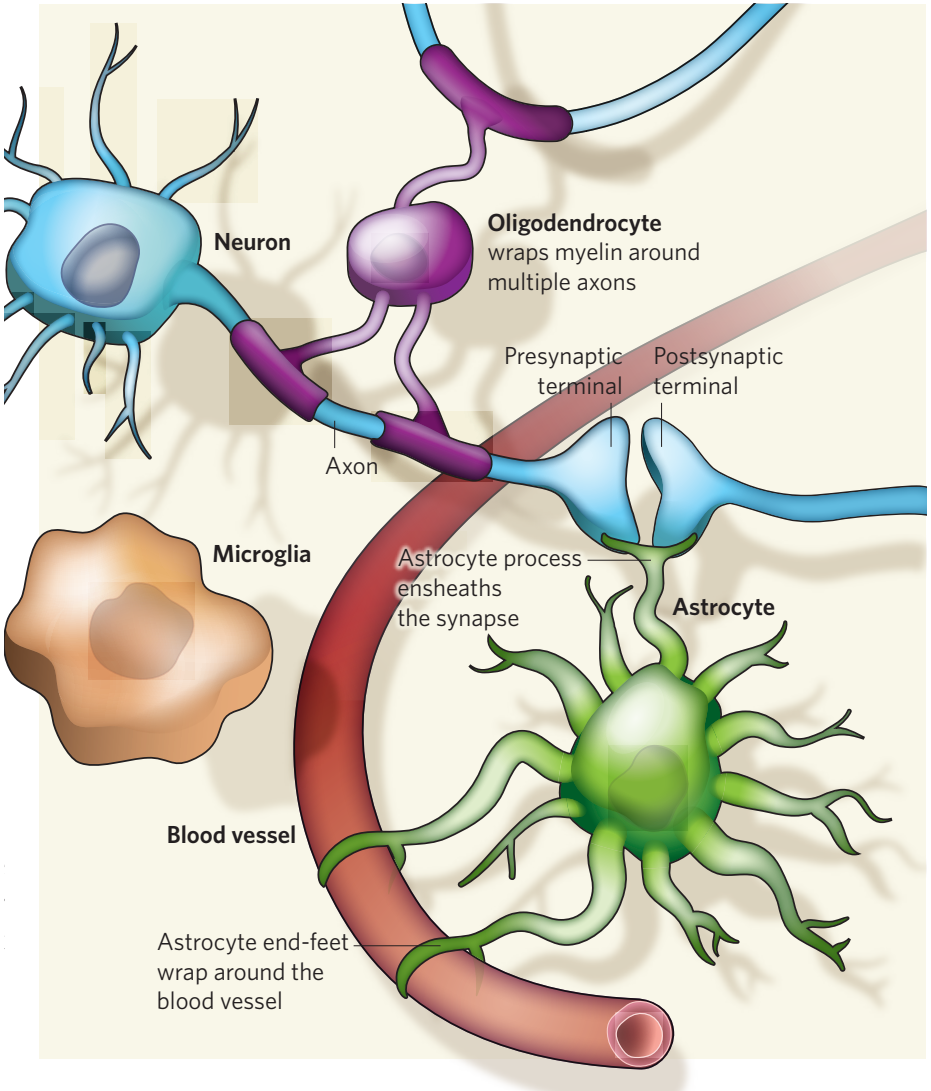
Healthy old person's default brain network [Achard and Bullmore, 2007]



Penrose, 1989

- "... there is an essential non-algorithmic ingredient to thought processes."
- "... something of significance is actually calculated before the one-graviton level is reached."
- -> quantum computing

A Low-level View [Allen and Barres, 2009]



Three Types of Nodes

- Neurons: integrate-and-fire neuron with noisy membrane potential. State: membrane potential, -100 mV to 0 mV. Dynamics modelled by several stochastic ordinary differential equations per neuron
- Astrocytes: control synapse function and vascular tone. State: Ca^{2+} concentration, 10 μmol to 100 μmol, not directly measured.
- Capillary junctions: non-Bernoulli flow of erythrocytes. State: diameter of upstream capillary (or arteriole), 5 μm to 500 μm.

Three Types of Nodes

- Neurons: integrate-and-fire neuron with noisy membrane potential. State: membrane potential, -100 mV to 0 mV. Dynamics modelled by several stochastic ordinary differential equations per neuron
- Astrocytes: control synapse function and vascular tone. State: Ca^{2+} concentration, 10 μmol to 100 μmol, not directly measured.
- Capillary junctions: non-Bernoulli flow of erythrocytes. State: diameter of upstream capillary (or arteriole), 5 μm to 500 μm.

Three Types of Nodes

- Neurons: integrate-and-fire neuron with noisy membrane potential. State: membrane potential, -100 mV to 0 mV. Dynamics modelled by several stochastic ordinary differential equations per neuron
- Astrocytes: control synapse function and vascular tone. State: Ca^{2+} concentration, 10 μmol to 100 μmol, not directly measured.
- Capillary junctions: non-Bernoulli flow of erythrocytes. State: diameter of upstream capillary (or arteriole), 5 μm to 500 μm.

Three Types of Networks

- N Neurons: random directed graph with out-degree ΘN, $\Theta \in [0.05, 0.9]$.
- Astrocytes: random directed graph with edge probability inversely proportional with distance between astrocytes.
- Microvascular: a single binary tree.

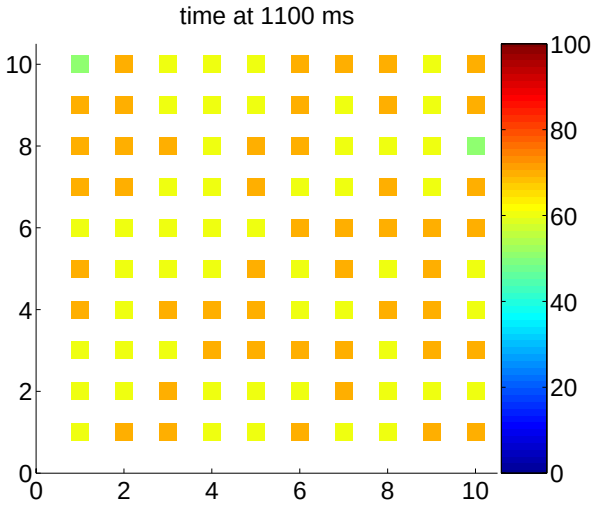
Three Types of Networks

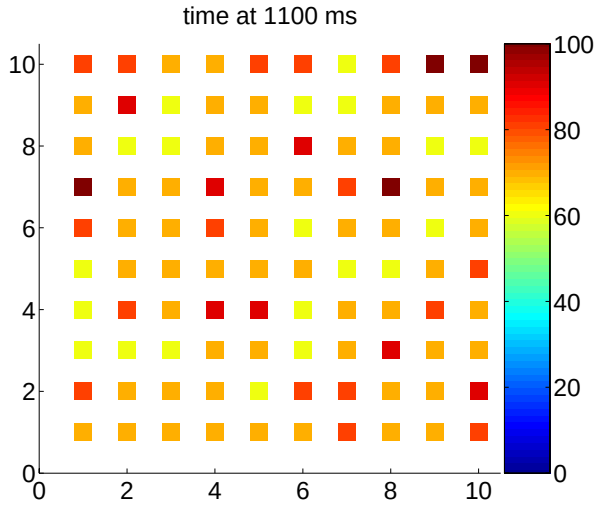
- N Neurons: random directed graph with out-degree ΘN, $\Theta \in [0.05, 0.9]$.
- Astrocytes: random directed graph with edge probability inversely proportional with distance between astrocytes.
- Microvascular: a single binary tree.

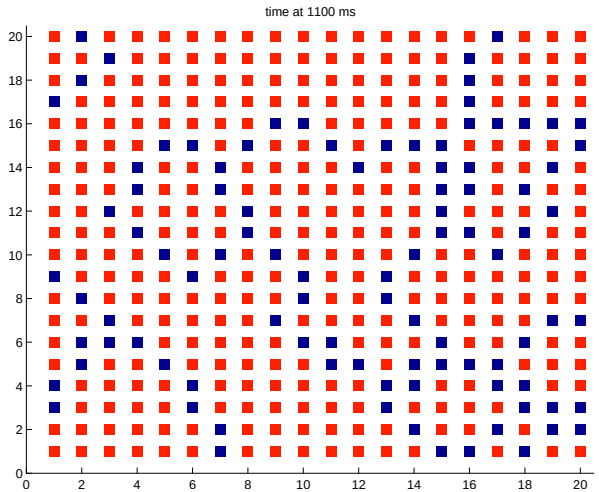
Three Types of Networks

- N Neurons: random directed graph with out-degree ΘN, $\Theta \in [0.05, 0.9]$.
- Astrocytes: random directed graph with edge probability inversely proportional with distance between astrocytes.
- Microvascular: a single binary tree.

Example: Firing Patterns of Neurons and Astrocytes







With astrocytes, more neurons fire at higher frequency.

Summary

- Computer Science has inspired brain models.
- There are three networks in the brain: neurons, astrocytes, and capillaries.

- Next
  - Blue Brain, using Blue Gene
  - neuroeconomics
  - systems biology -> systems neuroscience
  - stroke: software for revalidation
  - dementia: software for care

Further Reading and Picture Credits I

- Chris M. Bishop.
  Neural Networks for Pattern Recognition.
  OUP, 1995.
- Pierluigi Frisco.
  Computing with Cells: Advances in Membrane Computing.
  OUP, 2009.
- Marvin Minsky.
  The Society of Mind.
  Picador, 1988.
- Marvin Minsky and Seymour Papert.
  Perceptrons: An Introduction to Computational Geometry.
  MIT Press, 1969.

Further Reading and Picture Credits II


Roger Penrose.
The Emperor's New Mind: Concerning Computers, Minds and the Laws of Physics.
OUP, 1989.


Sophie Achard and Ed Bullmore.
Efficiency and Cost of Economical Brain Functional Networks.
PLoS Comput. Biol. 3(2):e17, 2007.


Nicola Allen and Ben Barres.
Glia - more than just brain glue.
Nature 457(5 Feb):675–677, 2009.

Further Reading and Picture Credits III


Warren S. McCulloch and Walter Pitts.
The Statistical Organization of Nervous Activity.
Biometrics, 4(2):91–99, 1948.


A.F. Murray and A.V.W. Smith.
Asynchronous Arithmetic for VLSI Neural Systems.
Electronics Letters, 23(12):642–643, 1987.


O. Ibarra, A. Paun, G. Paun, A. Rodriguez-Paton, P. Sosik, and S. Woodworth.
Normal forms for spiking neural P systems.
Theoretical Computer Science, 372(2-3):196–217, 2007.

Further Reading and Picture Credits IV

S. Shahid, J. Walker, and L. S. Smith.
A New Spike Detection Algorithm for Extracellular Neural Recordings.
IEEE Trans. on Biomedical Engineering, 57(4):853–866, 2010.

Xi Shen and Philippe De Wilde.
Long-term neuronal behavior caused by two synaptic modification mechanisms.
Neurocomputing, 70(7–9):1482–1488, 2007.

Xi Shen and Philippe De Wilde.
Robustness and regularity of oscillations in neuronal populations.
BioSystems, 88(1–2):127–136, 2007.

Further Reading and Picture Credits V


Xi Shen, Xiaobin Lin and Philippe De Wilde.
Oscillations and spiking pairs: behavior of a neuronal model with STDP learning.
Neural Computation, 20(8):2037–2069, 2008.


Manissa Wilson and Igor Aleksander.
Pattern-recognition properties of RAM/ROM arrays.
Electronics Letters, 13(9):253–254, 1977.