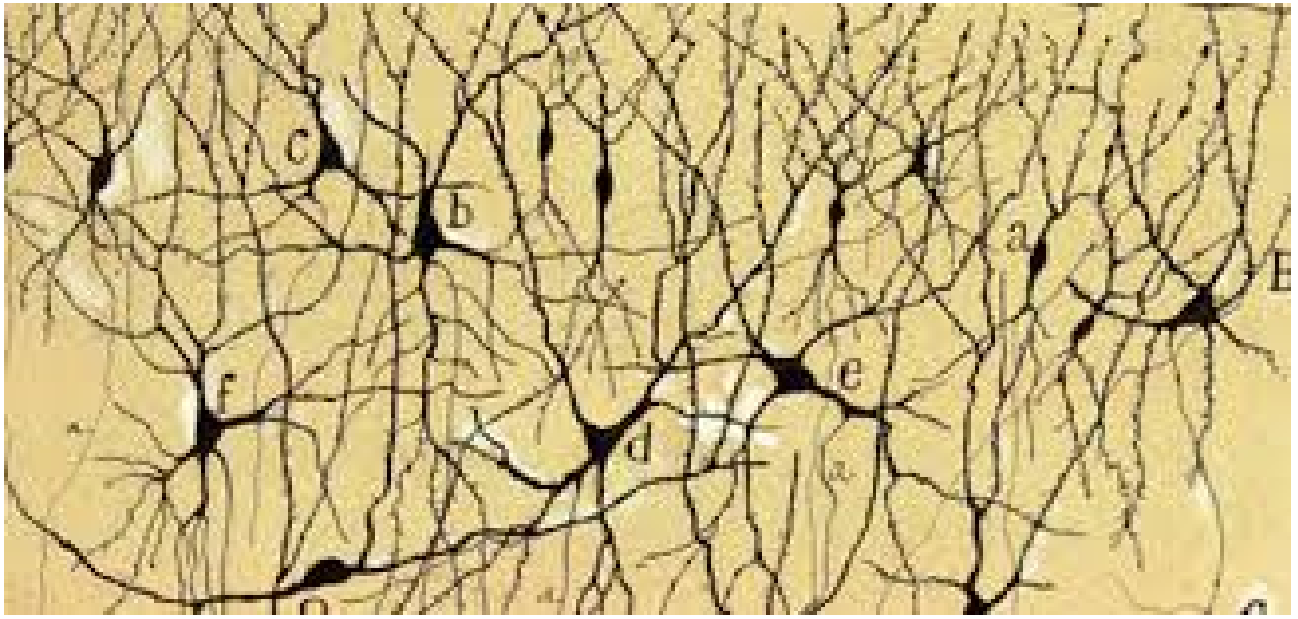
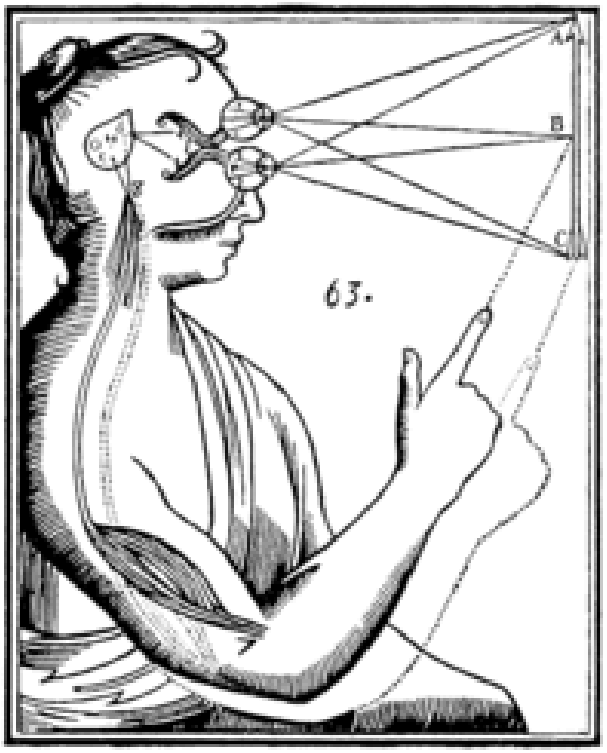
Network dynamics of neural systems



Samuel Johnson
Warwick Mathematics Institute, and
Centre for Complexity Science,
University of Warwick, UK



“[The] mechanism of our body is so constructed that simply by this gland's being moved in any way by the soul or by any other cause, it drives the surrounding spirits towards the pores of the brain, which direct them through the nerves to the muscles; and in this way the gland makes the spirits move the limbs.”

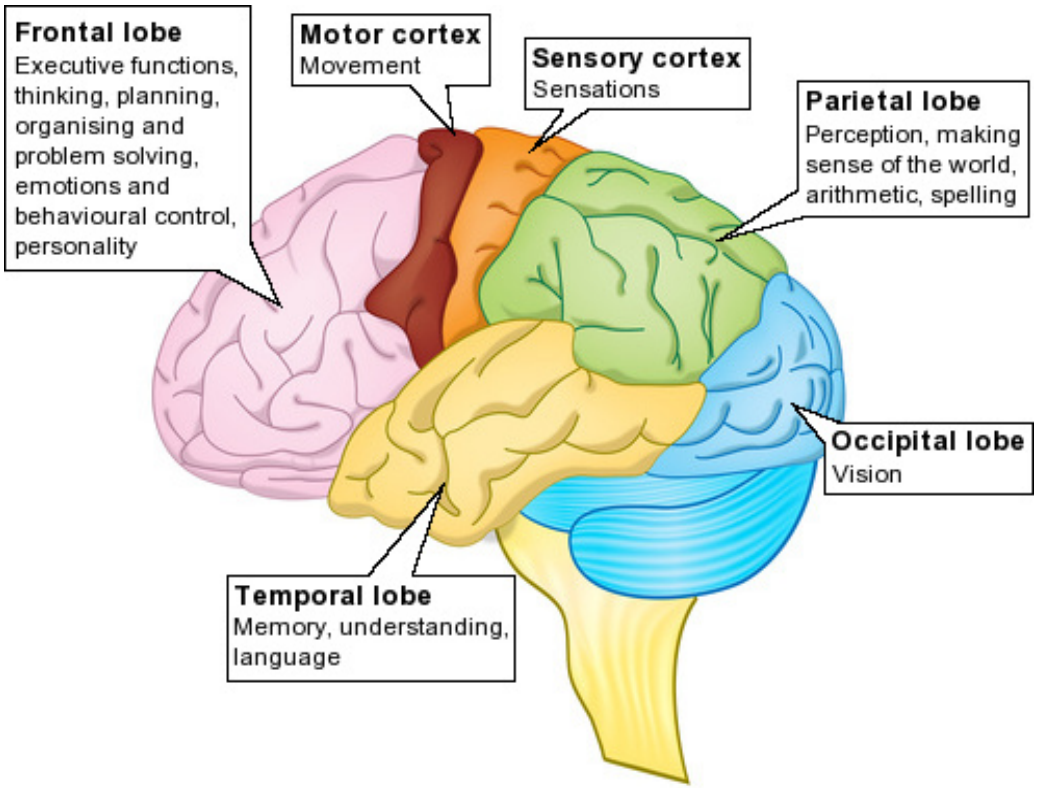
—René Descartes, Passions of the soul (1649)

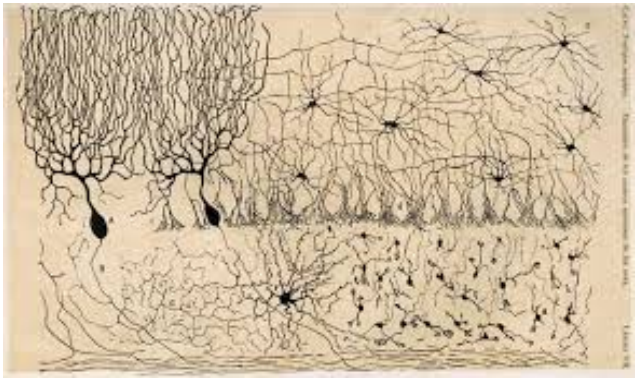
"Souls are immaterial subjects of mental properties. They have sensations and thoughts, desires and beliefs, and perform intentional actions. Souls are essential parts of human beings..."
—Richard Swinburne, The Evolution of the Soul (1997)

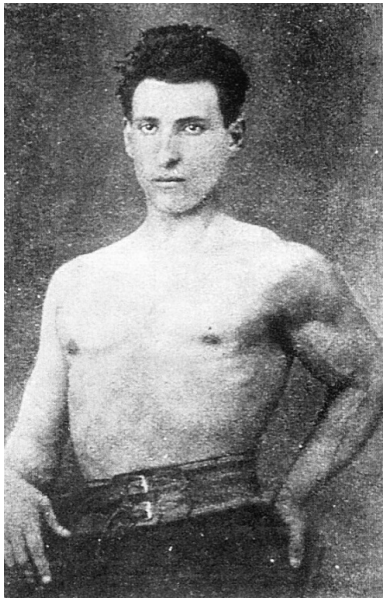
"[T]he most commonsensical solution to the biocentrism problem parallels an elaboration that naturally accommodates personality survival. Neither of these elaborations appears to require any basic change in the orthodox theory. But both require a relaxing of the idea that physical and mental events occur only when paired together."
—Henry P. Stapp, Compatibility of Contemporary Physical Theory with Personality Survival (2015)

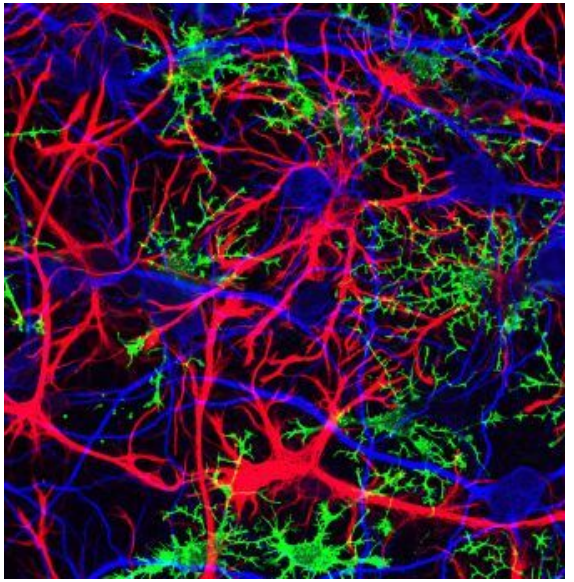
"Doctor, here is business enough for you."

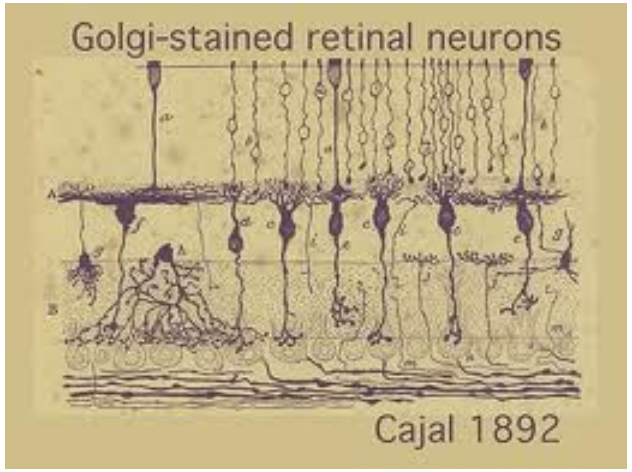
A moral man, Phineas Gage
Tamping powder down holes for his wage
Blew his special-made probe
Through his left frontal lobe
Now he drinks, swears, and flies in a rage.
— Anonymous



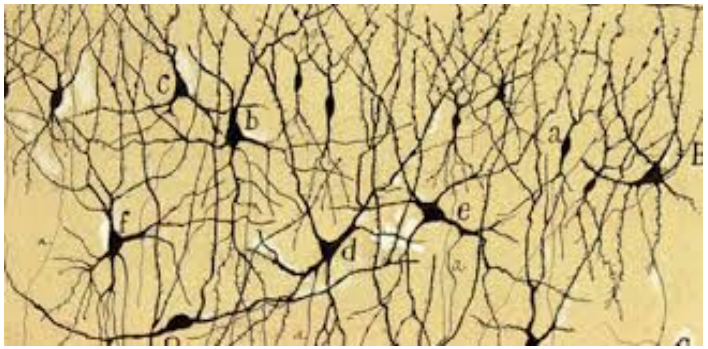


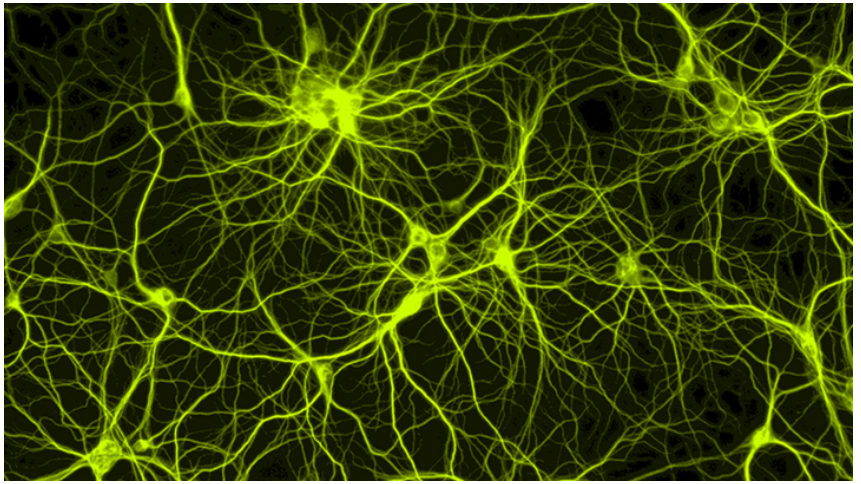


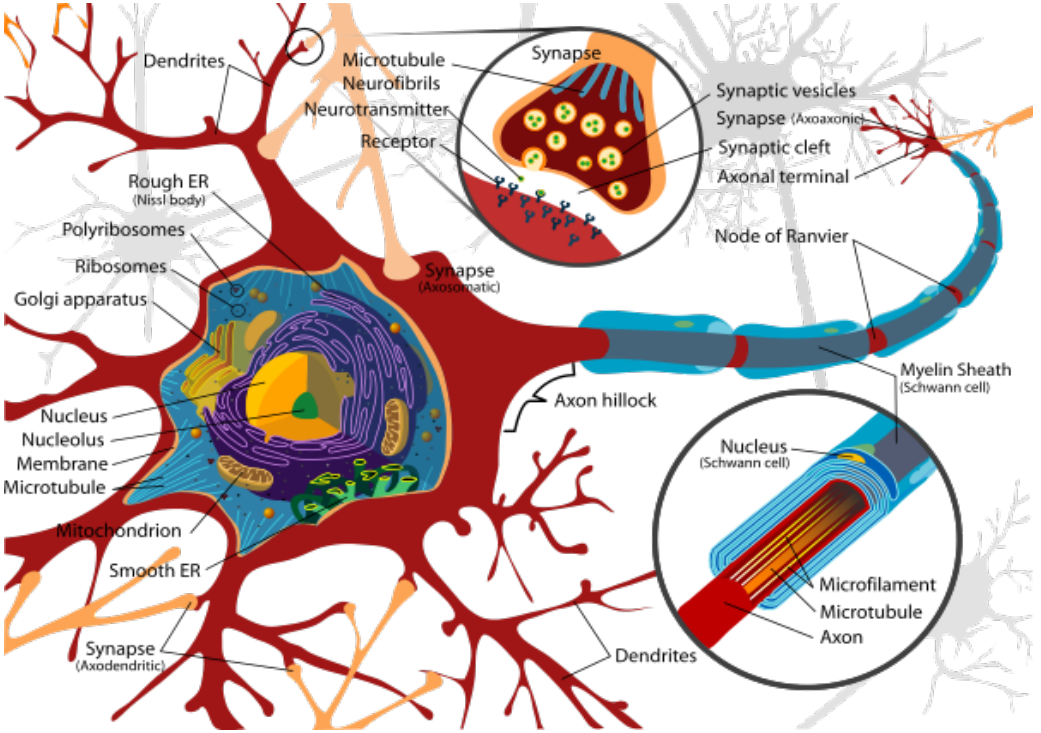


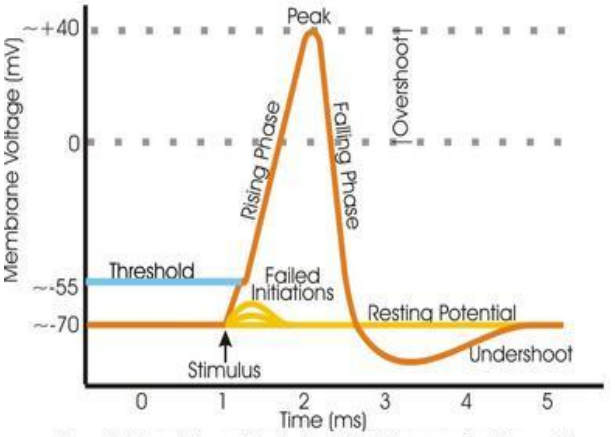


S. Ramón y Cajal

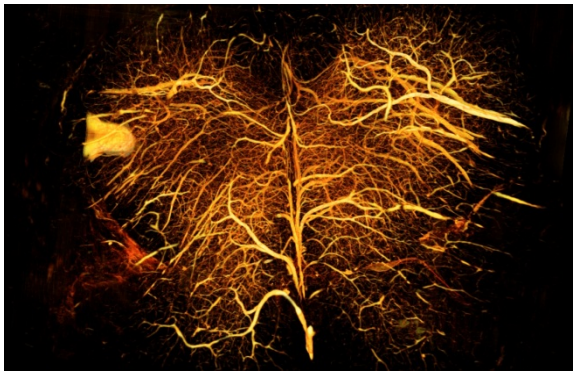






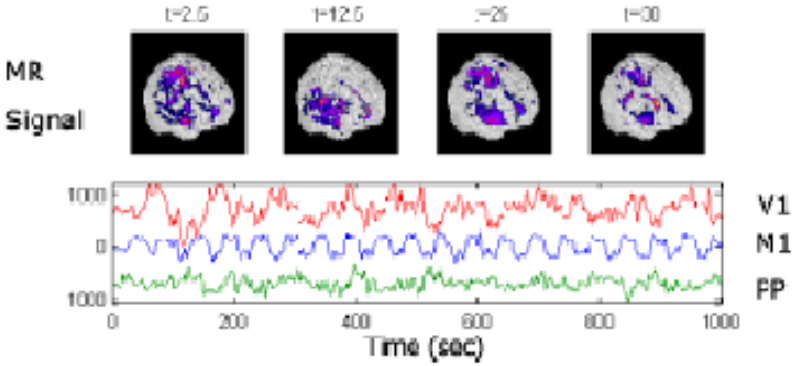


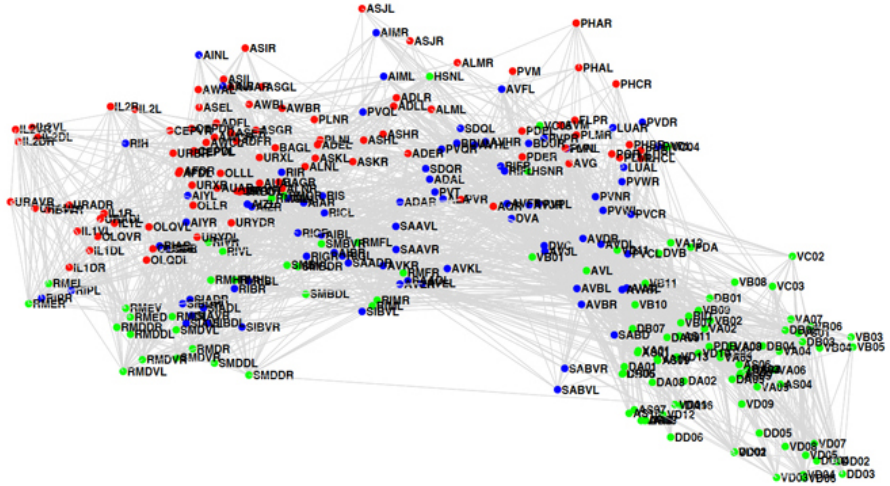
Action Potential



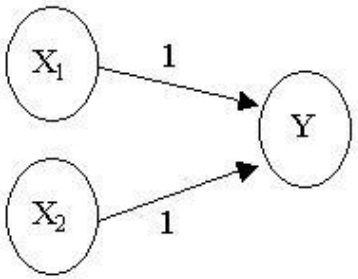
⇐ Structural

Functional ⇒

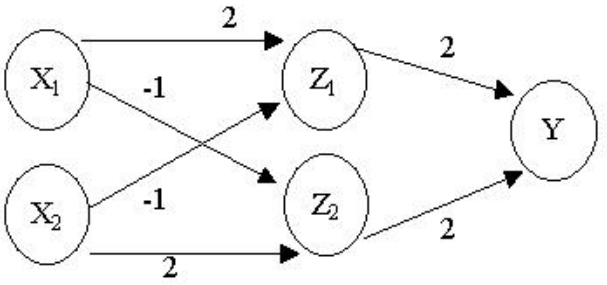




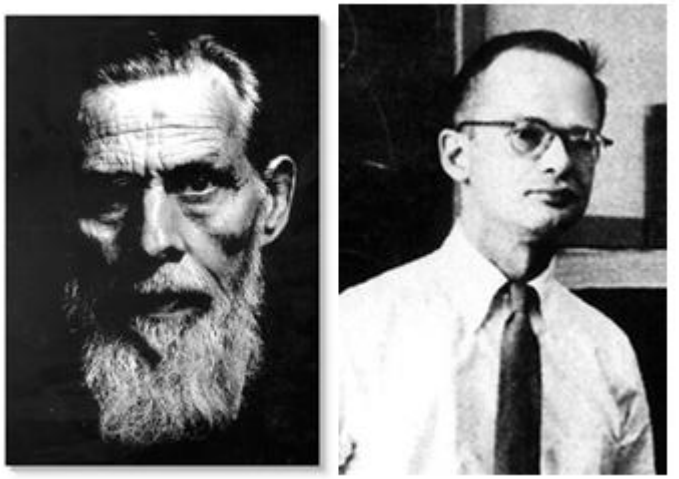
	# neurons	# synapses
C. elegans	302	~ 7,500
Fruit fly	10^5	10^7
Mouse	$7.1 \cdot 10^7$	10^{11}
Human	$8.6 \cdot 10^{10}$	10^{14}-10^{15}
Elephant	$2.57 \cdot 10^{11}$	?



AND Function



XOR Function



AL Hodgkin &
A Huxley (1952)

W McCulloch and W Pitts in 1943

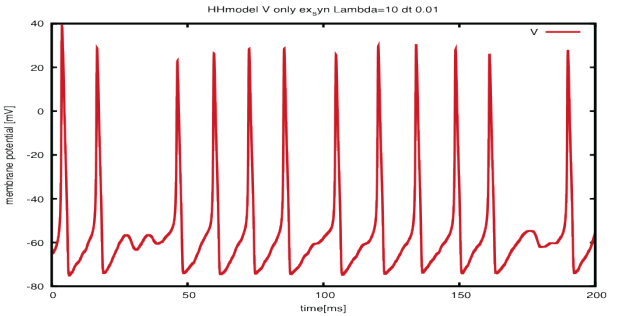
Hodgkin-Huxley model of electrical activity in the squid giant axon

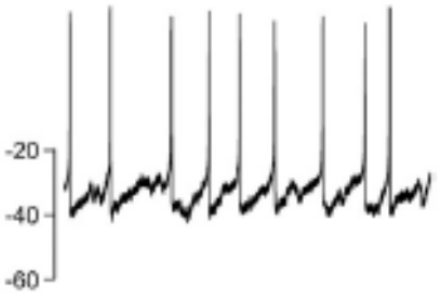
$$C_m \frac{dV}{dt} = -g_{Na} m^3 h (V - V_{Na}) - g_K n^4 (V - V_K) - g_L (V - V_L) + I_a(t)$$

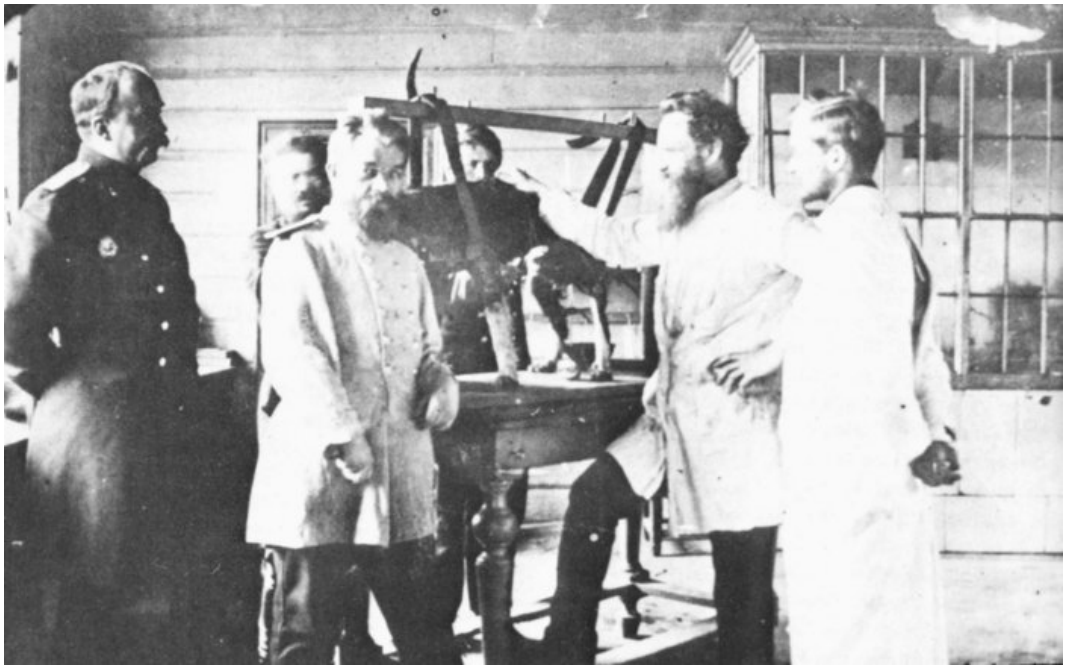
$$\frac{dm}{dt} = \frac{m_\infty(V) - m}{\tau_m(V)}$$

$$\frac{dh}{dt} = \frac{h_\infty(V) - h}{\tau_h(V)}$$

$$\frac{dn}{dt} = \frac{n_\infty(V) - n}{\tau_n(V)}$$





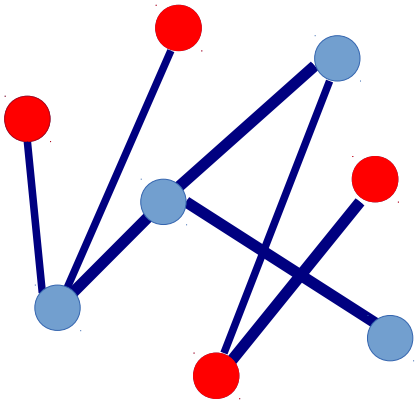


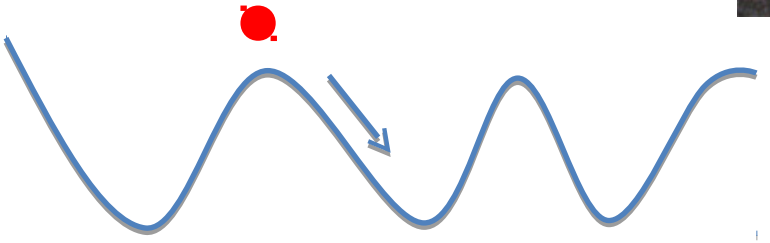
IP Pavlov

"Cells that fire together, wire together"

DO Hebb

Amari-Hopfield Model



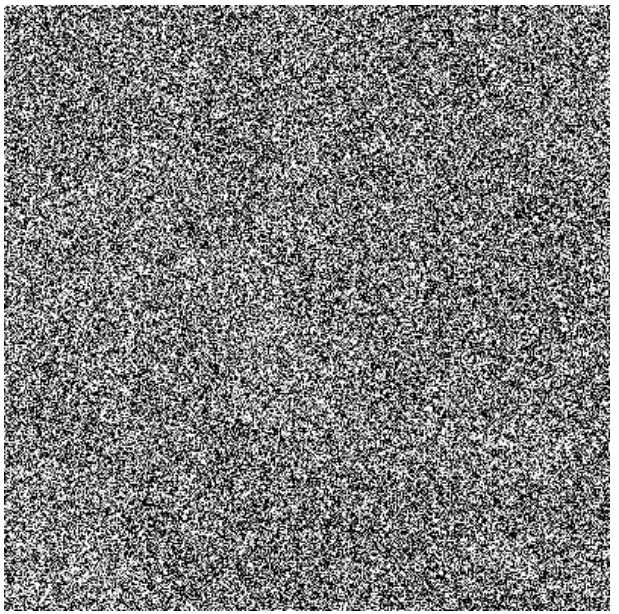


$$\xi_i^{\nu} = \pm 1$$

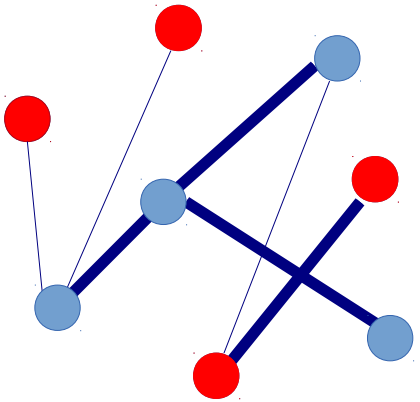
$$\omega_{ij} = \frac{1}{N}\sum_{\nu=1}^{P} \xi_i^{\nu}\xi_j^{\nu}$$

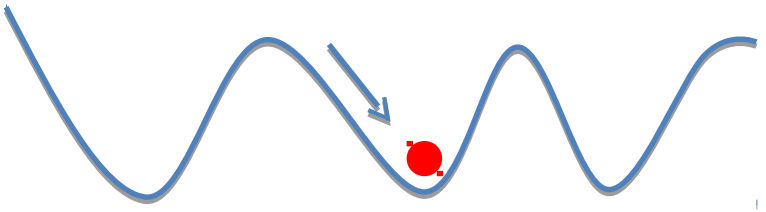
$$P(s_i = +1) = \frac{1}{2}\tanh\left(\frac{h_i - \theta_i}{T}\right) + \frac{1}{2}$$

$$m^{\nu} = N^{-1}\sum_i s_i \xi_i^{\upsilon}$$



Amari-Hopfield Model





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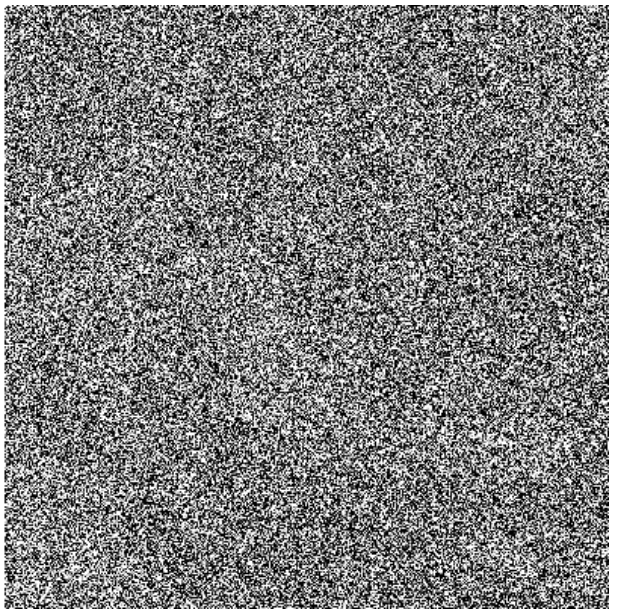
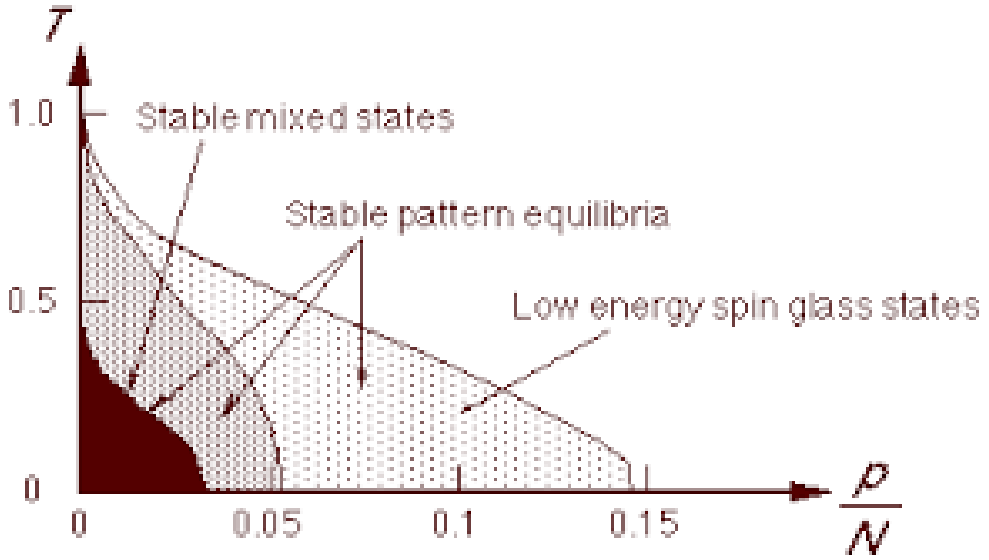
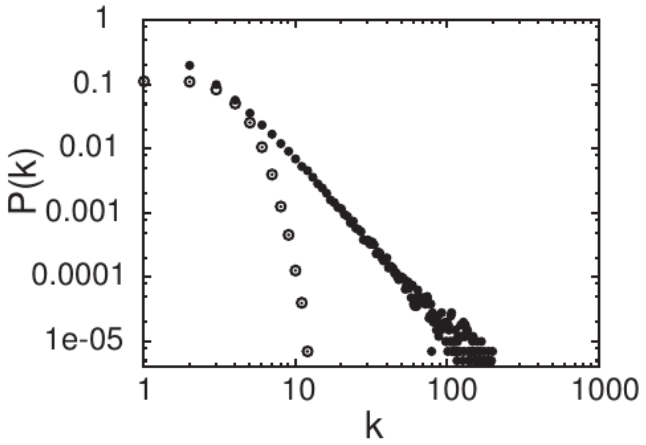
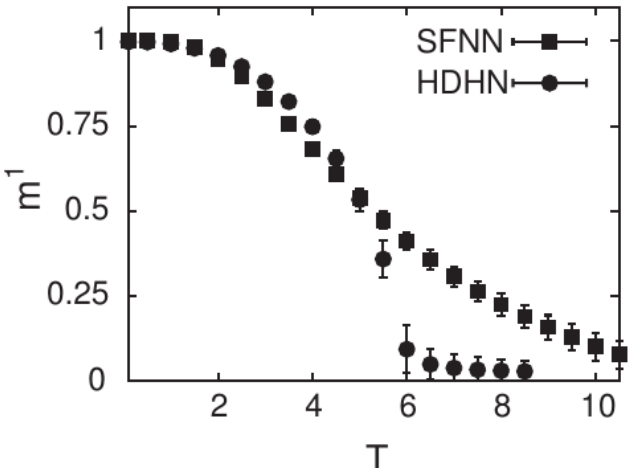


Amari-Hopfield Model



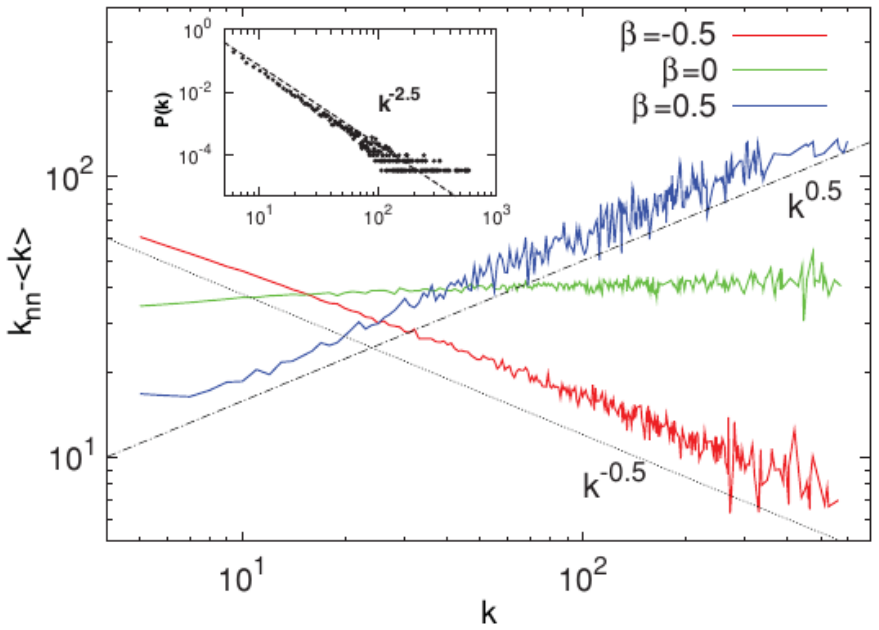
$$T_c = \frac{\langle k^2 \rangle}{\langle k \rangle}$$

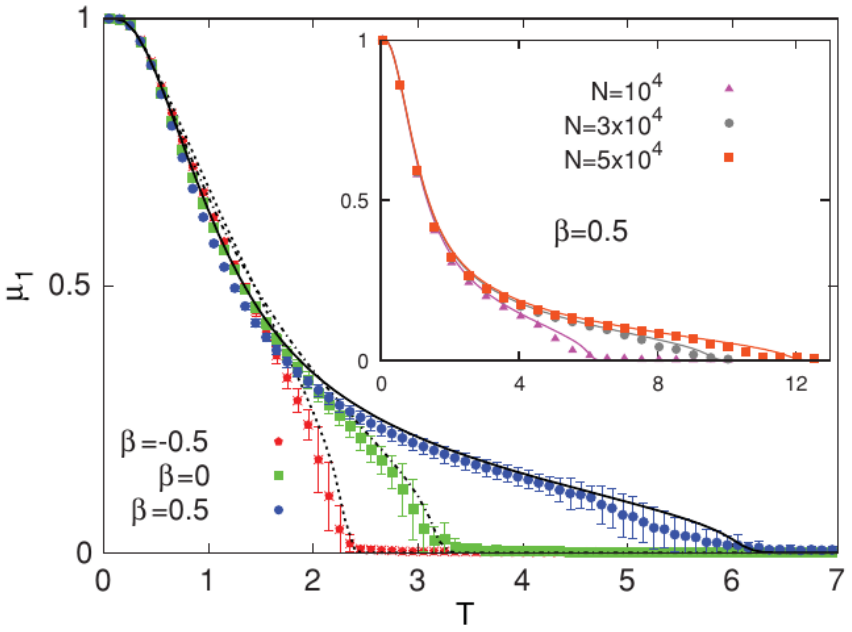




J.J. Torres et al. / Neurocomputing 58–60 (2004)

Assortativity



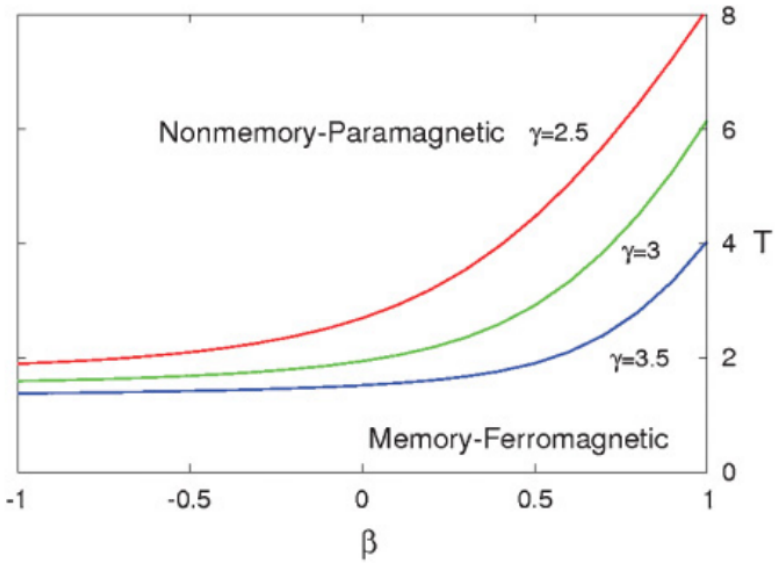


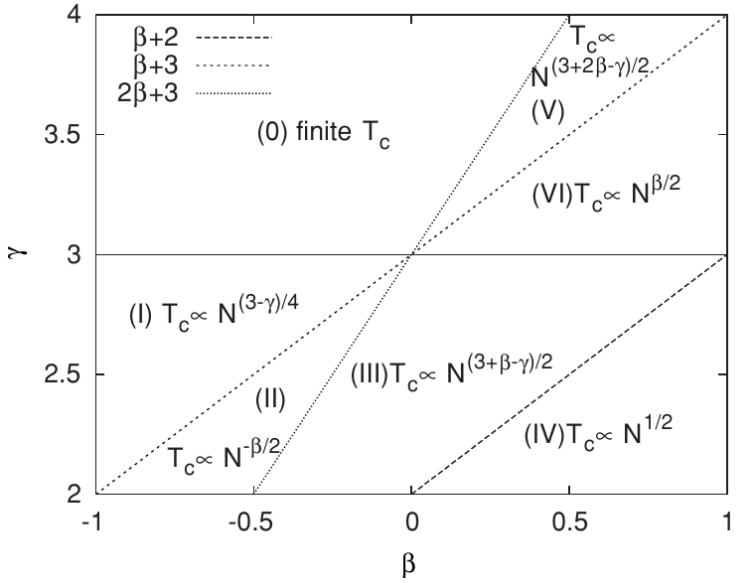
PHYSICAL REVIEW E **83**, 036114 (2011)

Enhancing neural-network performance via assortativity

Sebastiano de Franciscis,* Samuel Johnson,† and Joaquín J. Torres‡

Assortativity





PRL **104,** 108702 (2010) PHYSICAL REVIEW LETTERS week ending 12 MARCH 2010

Entropic Origin of Disassortativity in Complex Networks

Samuel Johnson, Joaquín J. Torres, J. Marro, and Miguel A. Muñoz

Evolving networks

PHYSICAL REVIEW E **79**, 050104(R) (2009)

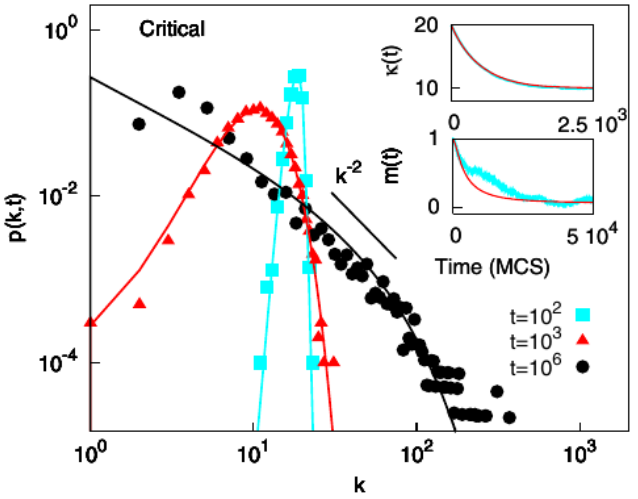
Nonlinear preferential rewiring in fixed-size networks as a diffusion process

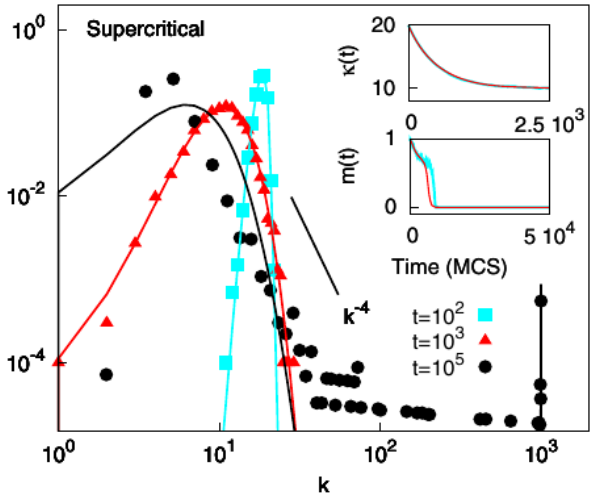
Samuel Johnson, Joaquín J. Torres, and Joaquín Marro

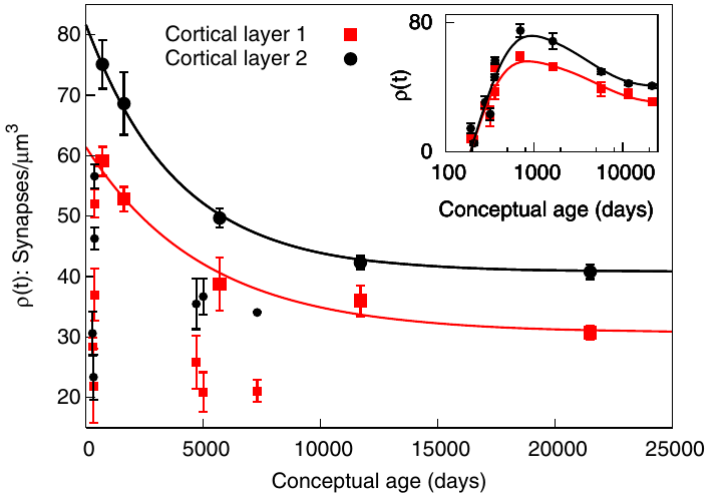
Evolving networks and the development of neural systems

Samuel Johnson, J Marro and Joaquín J Torres

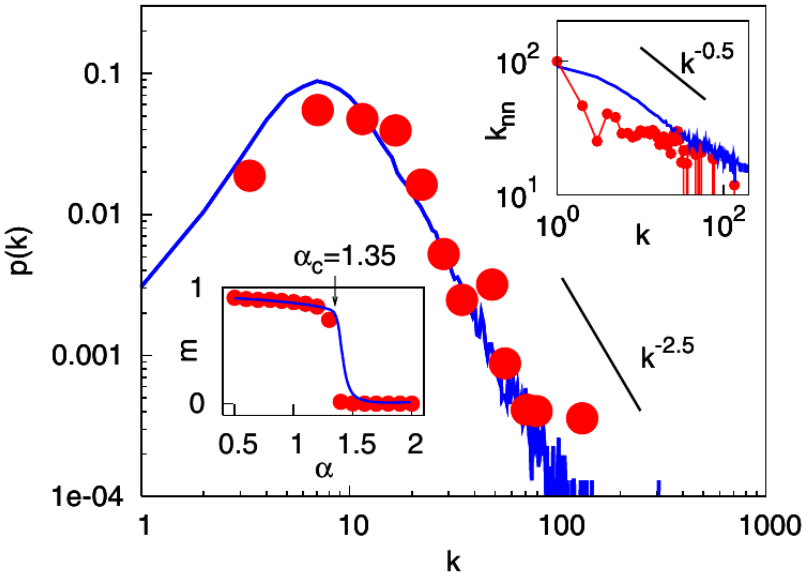
Evolving networks

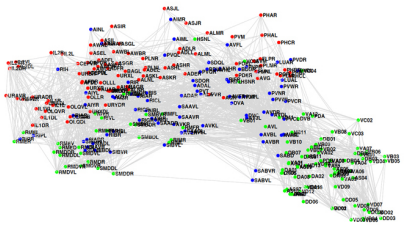






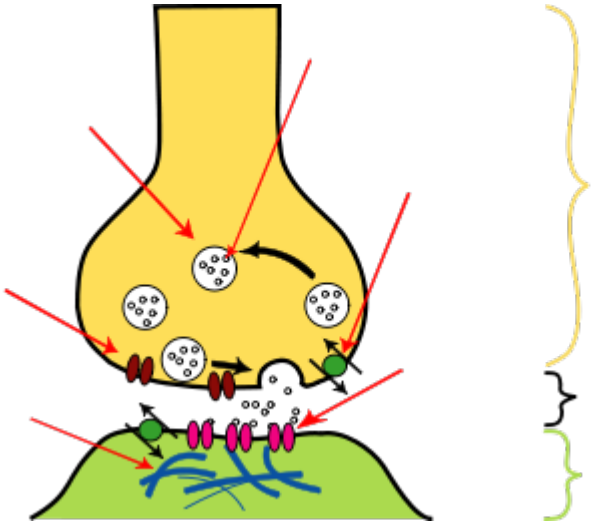
Evolving networks

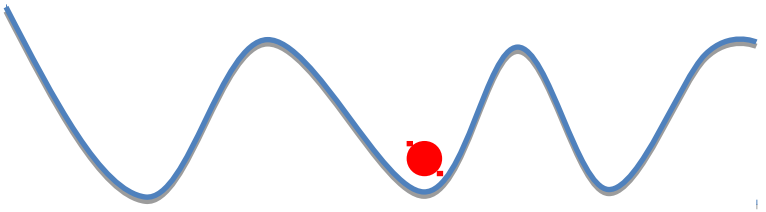


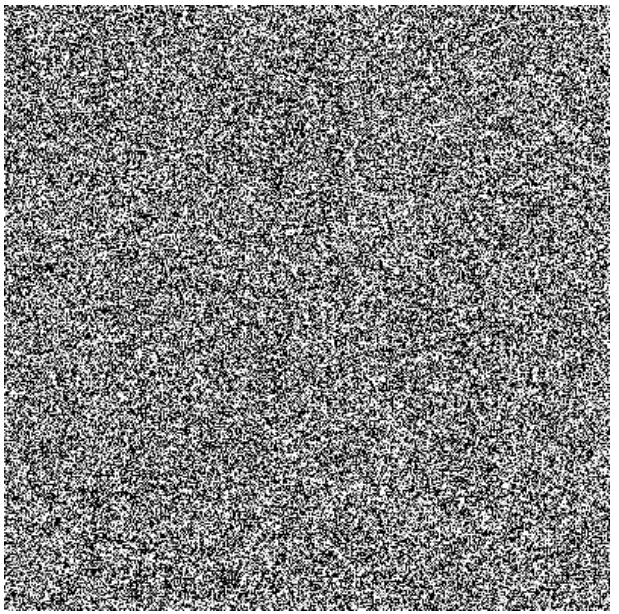


	Experiment	Simulation	Theory	Configuration
C	0.28	0.28	0.23	0.15
l	2.46	2.19	1.86	1.96
r	−0.163	−0.207	−0.305	−0.101

Computation at the Edge of Chaos

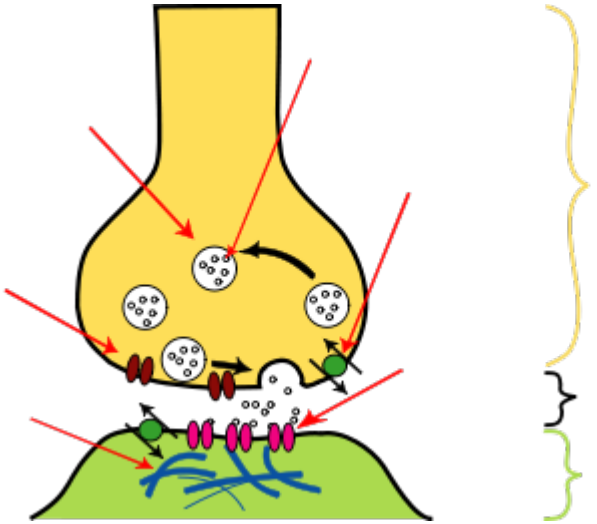


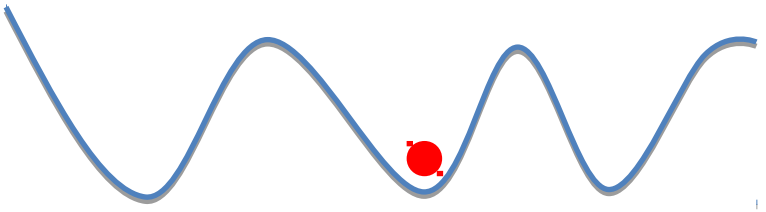


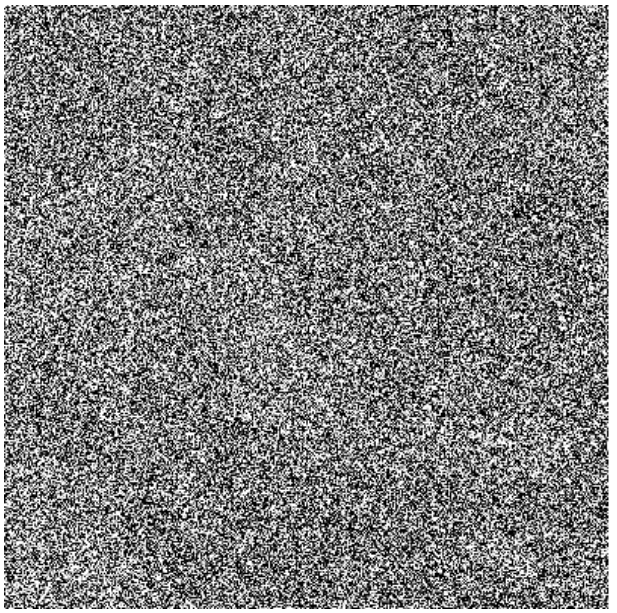


SJ, J Marro & JJ Tores, *EPL* (2008)

Computation at the Edge of Chaos

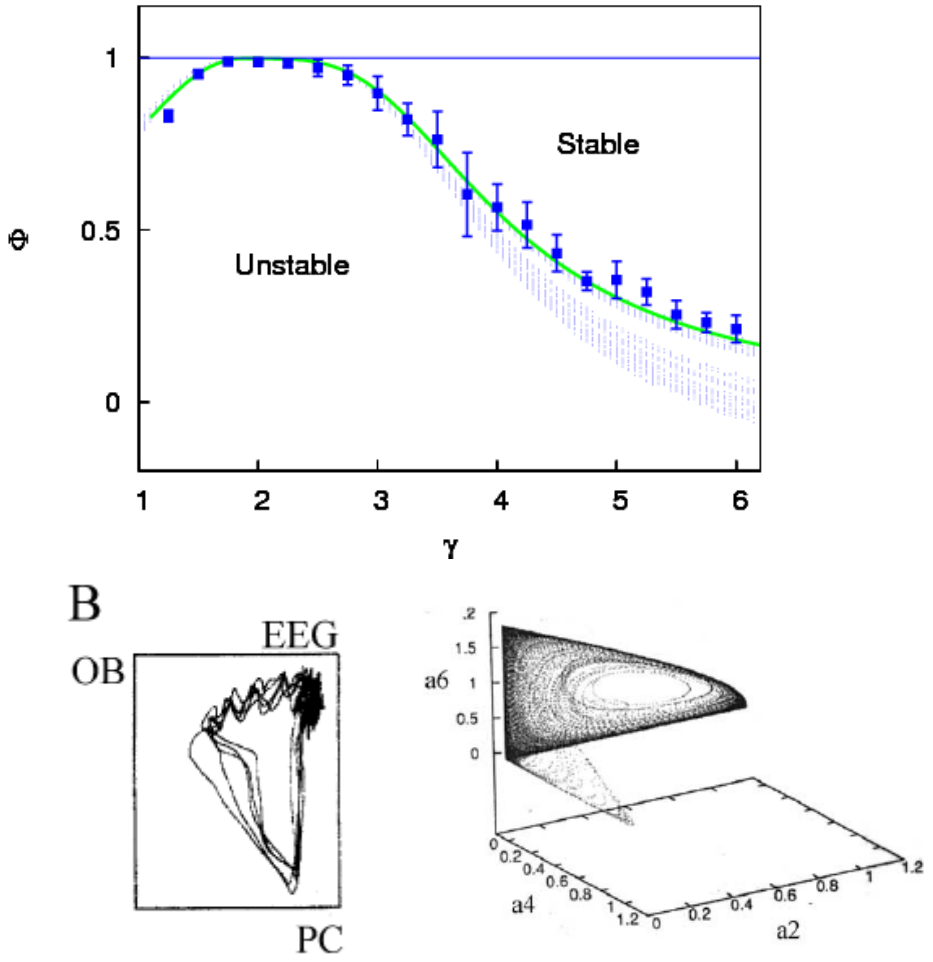




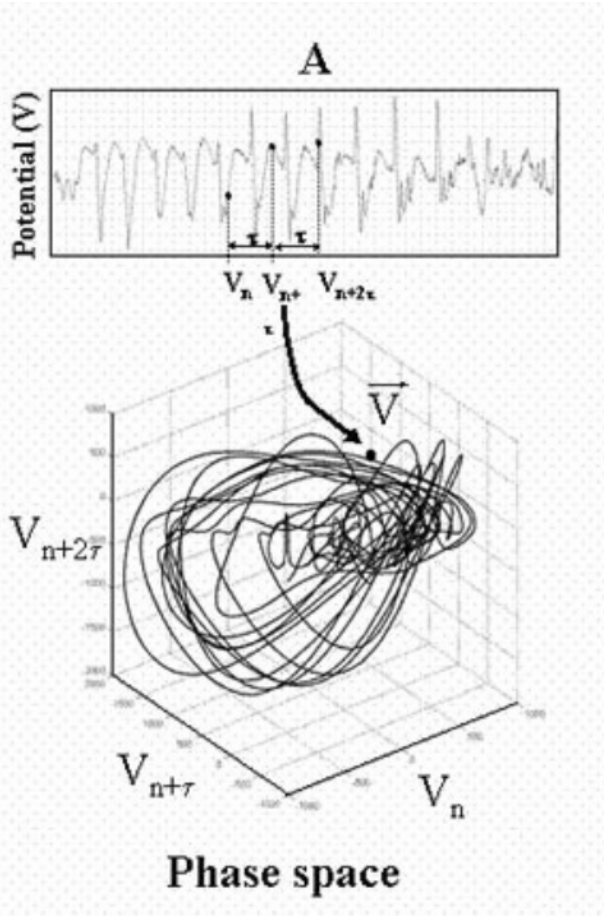


SJ, J Marro & JJ Tores, *EPL* (2008)

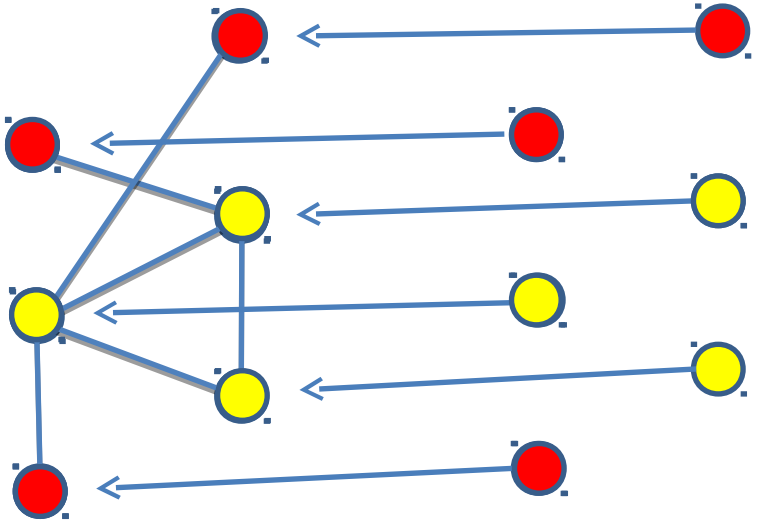
Computation at the Edge of Chaos



H Korn & P Faure, *C. R. Biologies* (2003)

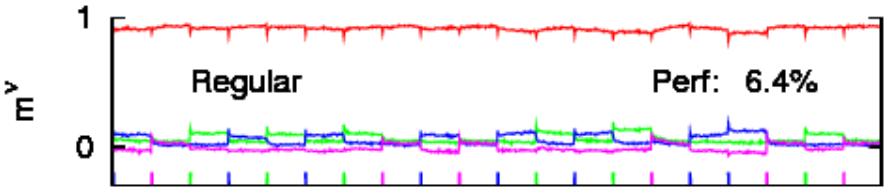


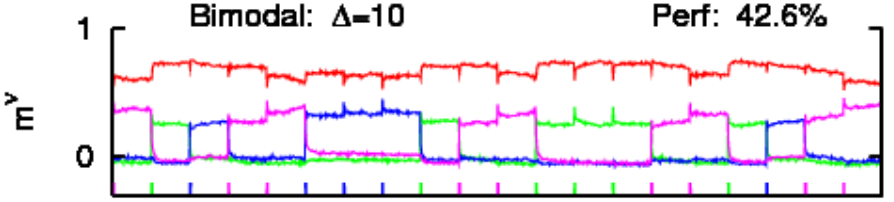
M L Van Quyen, *Biol Res* (2003)

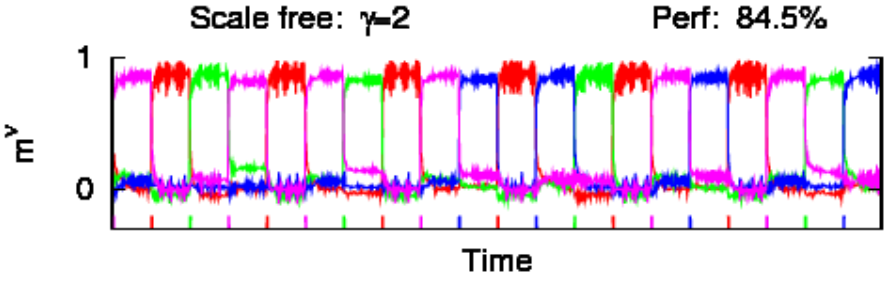


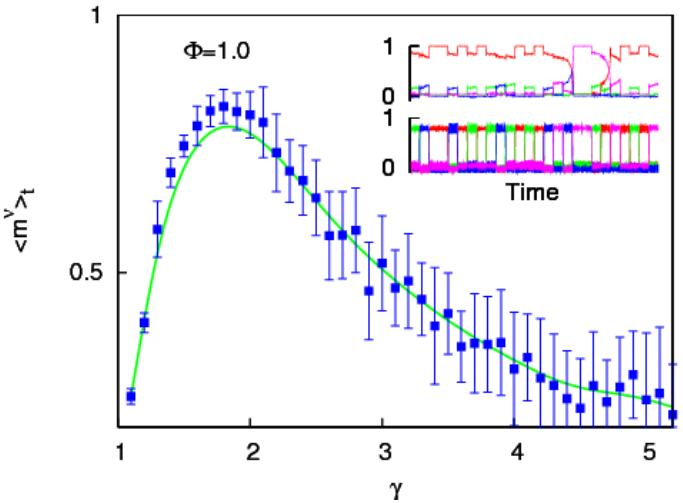
Network

Sensory neurons





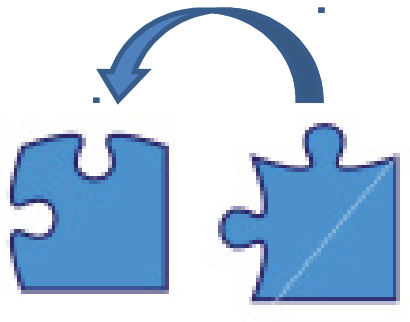




Short-term memory

Long-term potentiation (LTP) and depression (LTD): time scales of minutes. Good for long-term memory.

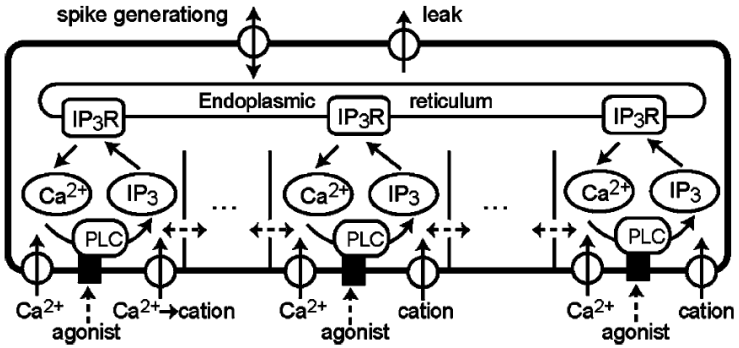
Sensory memory:
timescale of seconds.



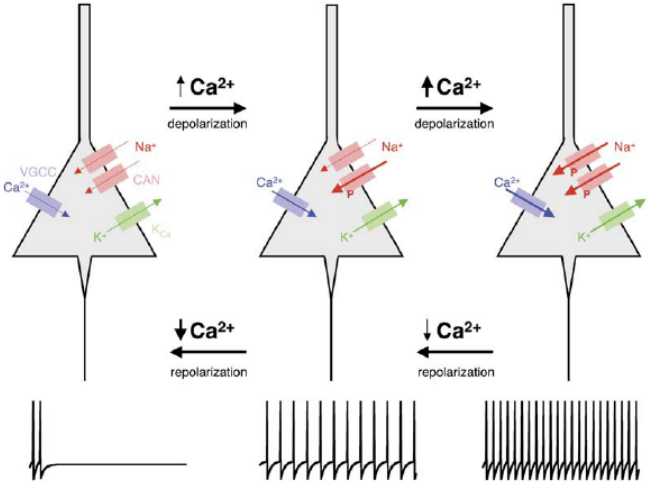
Working memory:
the brain's RAM

How can we remember new things so quickly?

Cellular bistability?



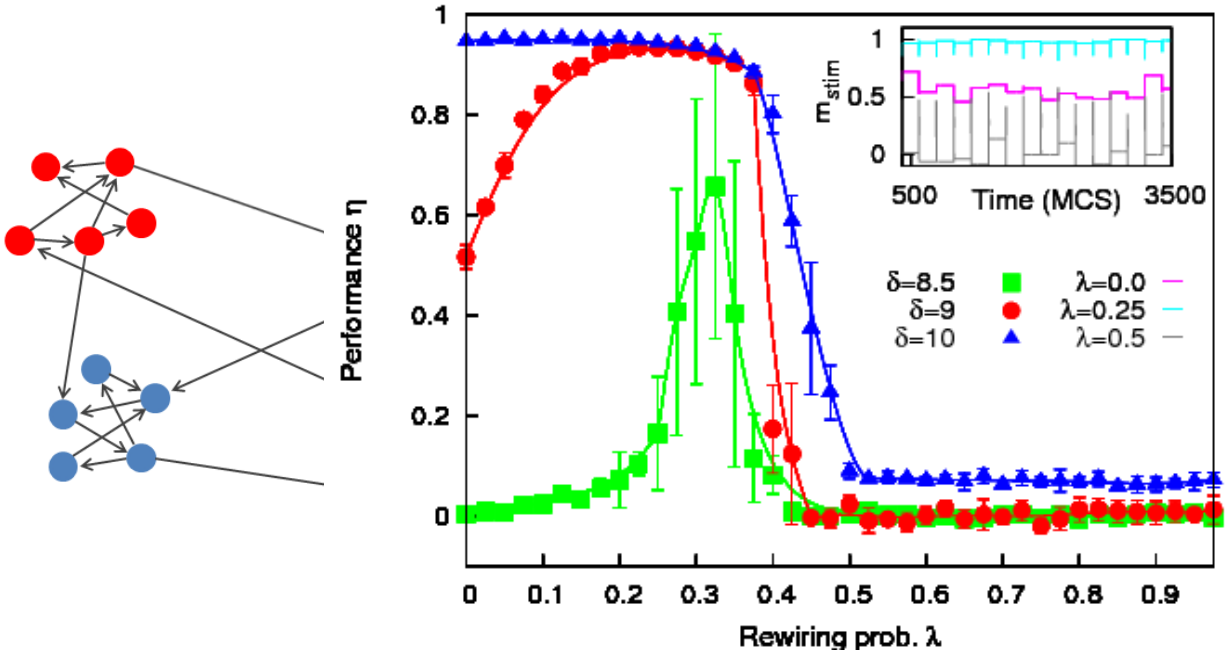
Terame & Fukai (2005)



Dodman & Siegelbaum (2006)

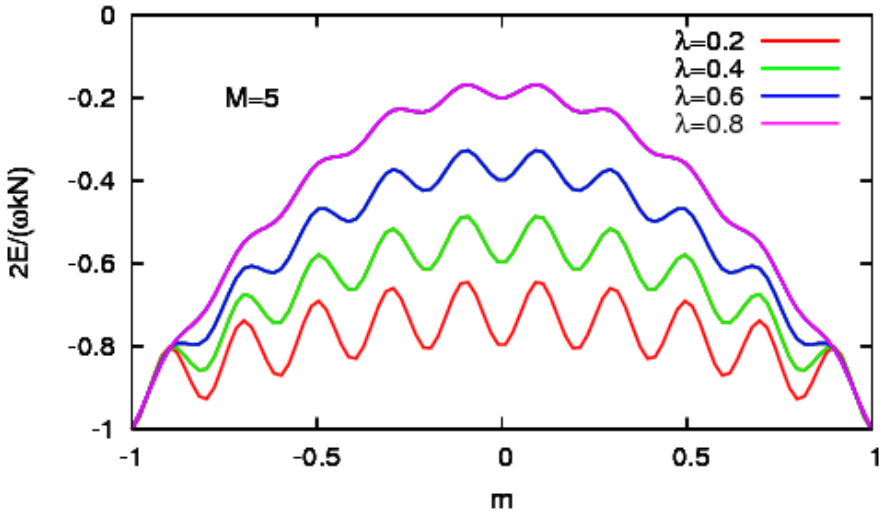
Problem: not very robust with notoriously noisy neurons

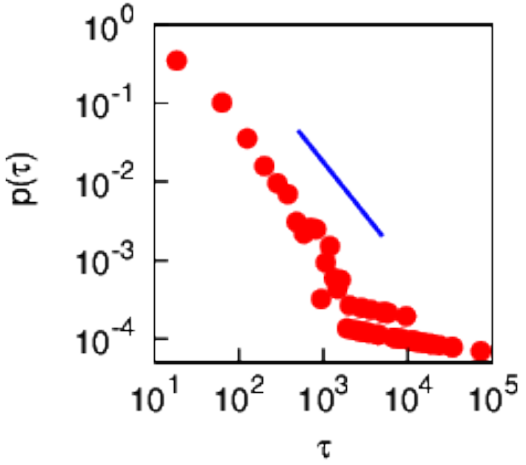
Cluster Reverberation?

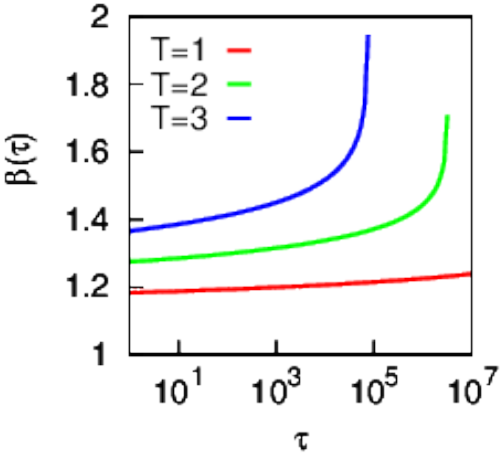


SJ, JJ Torres, & J Marro, *PLOS ONE* (2013)

Forgetting avalanches







$$\Delta E \simeq \frac{1}{4}\omega(n\langle k\rangle - \nu)$$

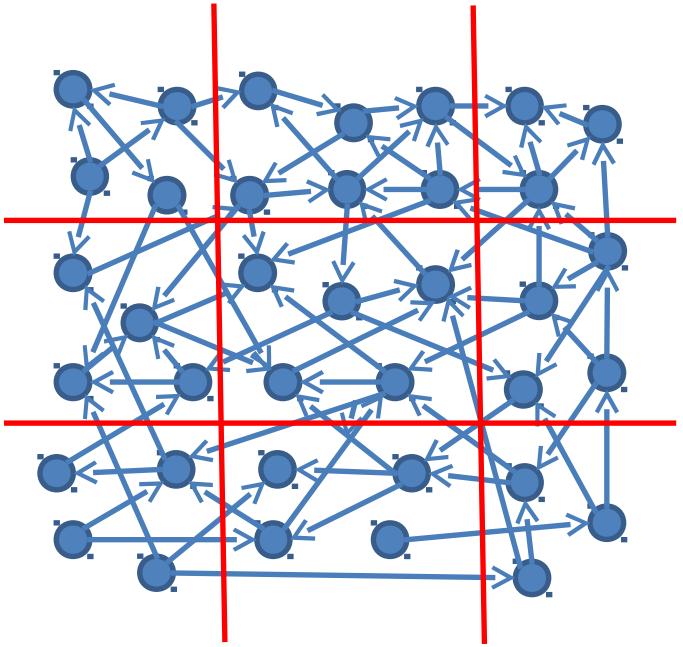
$$P(\nu) = \text{Poisson}$$

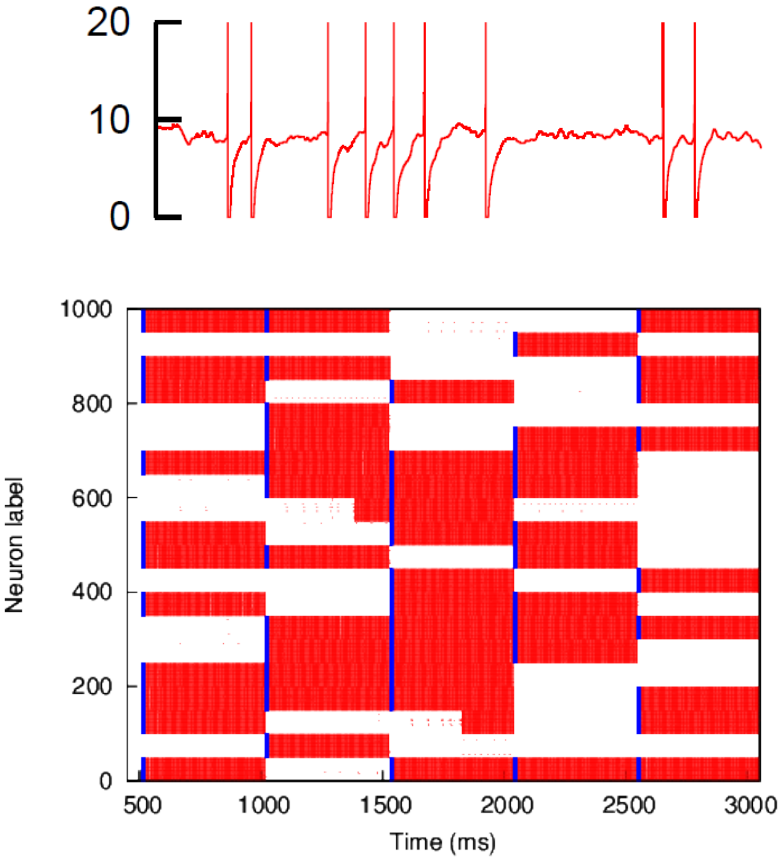
$$\tau \sim e^{\Delta E/T}$$

$$P(\tau) \sim \left(1 - \frac{4T}{\omega n\langle k\rangle}\ln\tau\right)^{-\frac{3}{2}} \tau^{-\beta(\tau)},$$

$$\beta(\tau) = 1 + \frac{4T}{\omega n\langle k\rangle}\left[1 + \ln\left(\frac{\lambda n\langle k\rangle}{1 - \frac{4T}{\omega n\langle k\rangle}\ln\tau}\right)\right]$$

It’s enough for the network to be clustered





…and LTP/LTD ⟹ modularity

Conclusions

- Simple neural-network models can provide insights into the mechanisms behind certain cognitive processes.
- Network topology is important.
- Our ignorance is still far greater than our knowledge.
- We really need to understand neural coding.

Joaquín J Torres

Thank you for your attention!

Joaquín Marro