Another Challenge for the Roadmap
Biological Complexity as a Theoretical Issue

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Telecom Italia background

- Telecom Italia on the frontier between biology and information science
  - **Neurobit**: control of a Khepera robot by “neurons on a chip”
  - **I-Learning**: technology supported mental rehearsal. Brain mechanisms underlying “mental” and “motor imagery”
  - **PACE**: creation of “programmable artificial cells”
  - **DELIS**: Biologically-inspired models for computation and telecommunications
  - **JADE**: a platform for agent-based simulations
This presentation

• Focus: the **theory of biological complexity**
• **The scaling problem** – a critical issue for NeuroIT
• **Key concepts**
• Use **key concepts** to describe **state of art**
  – What we know
  – What we don’t know
• The need for a **theory of biological complexity**
• **Implications for NeuroIT**
• **A modest proposal**
A provocation...

Intuition, insight and learning are no longer exclusive possessions of human beings: any large high-speed computer can be programmed to exhibit them also

H.A. Simon & Allan Newell, (1958)
The scaling problem

- Natural cognitive systems involve multi-level interactions between large numbers of heterogeneous agents operating at each level.
- Classical AI was unable to ‘scale up’ from small single-level models to larger, multi-level models.
- New AI (neural networks, evolutionary computing, evolutionary robotics etc.) has not been more successful than classical AI.
- To reach the goals of NeuroIT we have to resolve the ‘scaling problem’.
- This requires a theory of biological complexity.
The Gene-Brain Hierarchy

- The brain is organized at **many different levels**
  - From gene networks to large-scale modules
- Each level involves complex interactions between **large numbers of dishomogeneous** agents (molecules, genes, neurons, small neuronal networks etc.)
- Each level has **emergent properties** which contribute to the dynamics of the next level
- Large-scale **Artificial cognitive systems** will have to model multiple levels in the hierarchy
Algorithmic and ‘design’ complexity

• Cognitive systems can be described in terms of
  – **Algorithmic complexity**: the length of the shortest possible program capable of generating the system
  – **Design complexity**: the time required to build/evolve/train the system; the way this time scales with the size of the system

• Natural cognitive systems have
  – **High algorithmic complexity**: they are complicated to describe
  – **Low design complexity**: they can evolve/adapt (relatively) rapidly

Low design complexity is a requirement for artificial cognitive systems
Current scientific knowledge

• Growing knowledge about individual levels in the hierarchy
  – Molecular and genetic foundations of neural/synaptic function
  – Mechanics of neurons and small neuronal networks
  – Brain anatomy and functionality
  – Basic mechanisms of ontogeny
  – Psychological knowledge
    • Critical role of embodiment
• Very little knowledge about the relationships between levels
  – Emergence of higher level phenomena (e.g. patterns of gene expression, cognition) from lower level interactions (e.g. gene networks, neuronal networks)
Engineering models /1

- Current systems model:
  - Single levels in hierarchy
    - Artificial Neural networks
    - Evolutionary computing
    - Evolutionary robotics
    - Agent-based computing
    - Swarm computing…
  - Are very small
    - Artificial genomes $O(10^4 \text{ bit})$
    - ANNs : $O(10^3 \text{ neurons})$

Even the genome of E.Coli has $O(10^6) \text{ bp}$
The genome of H. Sapiens has $O(10^9) \text{ bp}$
The human brain contains $O(10^9) \text{ neurons}$
Engineering models /2

• **Constraints** on what it is possible to design appear to be very rigid
  – Many problems (e.g. training a feed-forward ANN) are NP-complete
• We do not know how to design/train systems with:
  – Large numbers of units
  – Dishomogeneous units
  – Multiple levels
• Current systems have **high design complexity** and low **algorithmic complexity**
• They are thus **fundamentally different** from natural cognitive systems
A theory of biological complexity

• Building large-scale cognitive systems requires a theory of biological complexity

• Diachronic theory
  – How do natural cognitive systems achieve low design complexity in
    • Evolution
    • Development (ontogenesis)
    • Learning

• Synchronic theory
  – How can we predict the dynamics of systems with multiple layers of dishomogeneous agents (high algorithmic complexity)
Current complexity theory

- Current complexity theory describes **abiotic systems** (e.g. cellular automata)
  - Interactions between large numbers of **homogeneous agents**
  - **Low algorithmic complexity**: agents and populations are easy to describe
  - **High design complexity**: it is hard to design a population to produce a required behavior
- The theory does not provide an adequate basis to understand/design complex artificial systems
- A useful theory of biological complexity will require important steps forward with respect to current complexity theory
Goals for a theory of biological complexity

- Develop strategies to achieve rapid evolution, ontogenesis and learning
  - Example: ‘grammars’ for protein evolution
- Predict the dynamics of interactions between large numbers of dishomogeneous agents
- Validate models computer simulations
- Apply the models to the construction of artificial cognitive systems
- Identify intractable problems (problems we will never be able to resolve)
  - Hypothesis: adaptation to arbitrary environments is an intractable problem
Research strategies

• Make better use of **existing biological knowledge**
  – Behavior of neuronal networks
  – Evolutionary theory
• Integrate knowledge from **under-exploited disciplines**, for example:
  – Paleontology (evolution as a historical process)
    • Role of structural and historical constraints in biological evolution
    • Multilevel theories of biological evolution (group selection, interaction between cooperation and competition)
  – Molecular theories of morphogenesis
  – Role of neuro-modulators in cognition
• Create mathematical models that are **directly applicable to engineering goals**
Implications for NeuroIT

• The current roadmap is formulated in terms of technological outcomes and their applications
• Two key projects require the construction of systems which are orders of magnitude larger than current models
  – Factor 10: a growing body and a growing brain
  – The Constructed Brain: simulating an entire brain
• These projects are unlikely to be feasible without new design strategies
• An adequate theory of biological complexity can make a useful contribution to the development of such strategies
A modest proposal

- Create a new multidisciplinary project, specifically dedicated to the development of a theory of biological complexity
- The new project should be complementary to the other areas of work already identified in the roadmap
- The project should
  - Use specific knowledge developed within other projects
  - Contribute mathematical models and tools which are directly applicable within these projects
Thank you for your attention

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