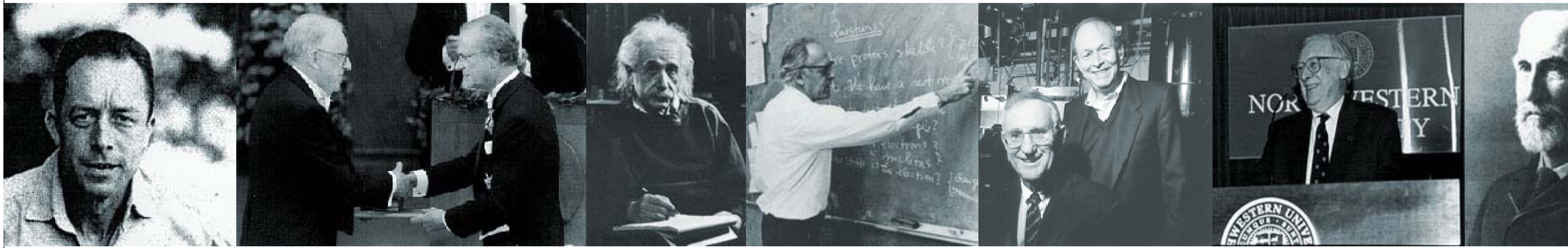
Another Challenge for the Roadmap
Biological Complexity as a Theoretical Issue



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Telecom Italia background

- Telecom Italia on the frontier between biology and information science
  - **Neurobit:** control of a Khepera robots 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

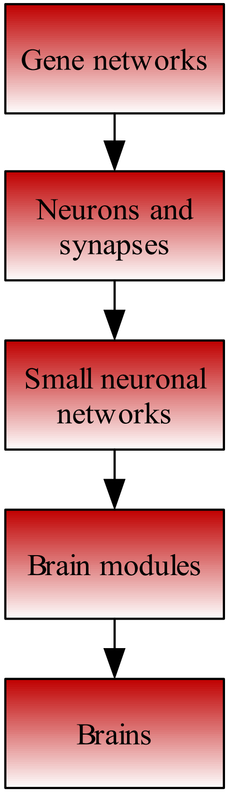
H.A. Simon & Allan Newell, (1958)

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 bit)
    - ANNs : **O**(10^3 neurons)

Even the genome of E.Coli has O(10^6) bp

The genome of H. Sapiens has O(10^9) bp

The human brain contains O(10^9) 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 compexity**
- 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 historica 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 fo 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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