



Autonomous Agents, Cognition, and Intelligence

Agent-Based Models as Foundations for Describing Natural and Artificial Intelligence

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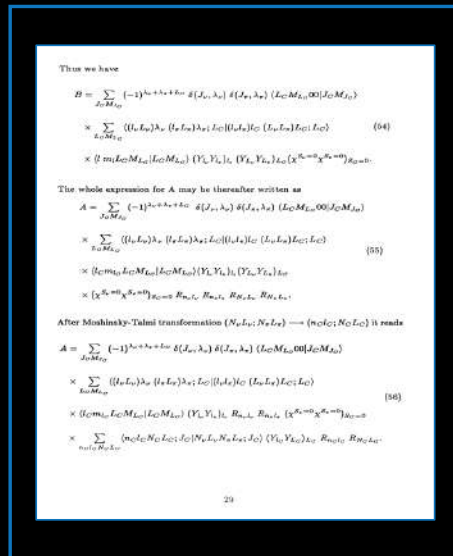
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A Background - From Formal To Natural Languages

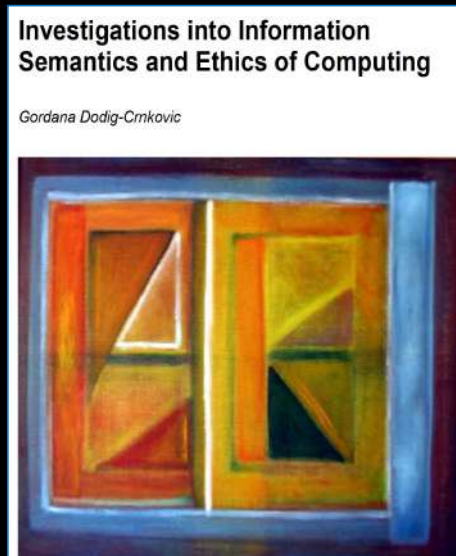
PHYSICS

PhD in Physics, 1988
On Alpha-decay, Department of Physics,
University of Zagreb



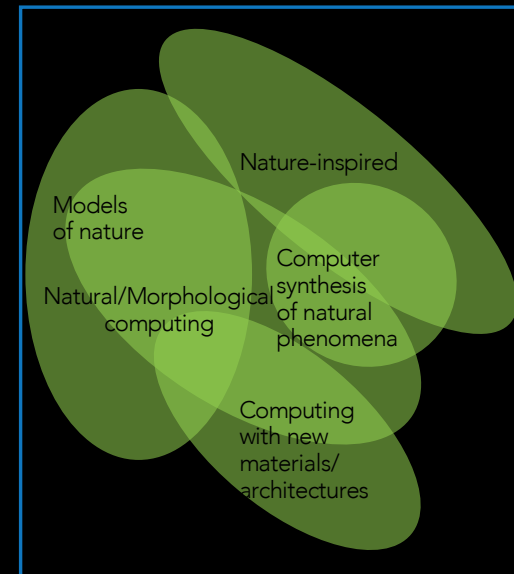
COMPUTING

PhD in Computing, 2006
Computer Science,
Mälardalen University



COGNITIVE SCIENCE

Current: Morphological
Computing and Cognition



The Framework – Relational Ontology Information, Computation, Cognition: Agency-based Hierarchies of Levels

Information=structure (being)

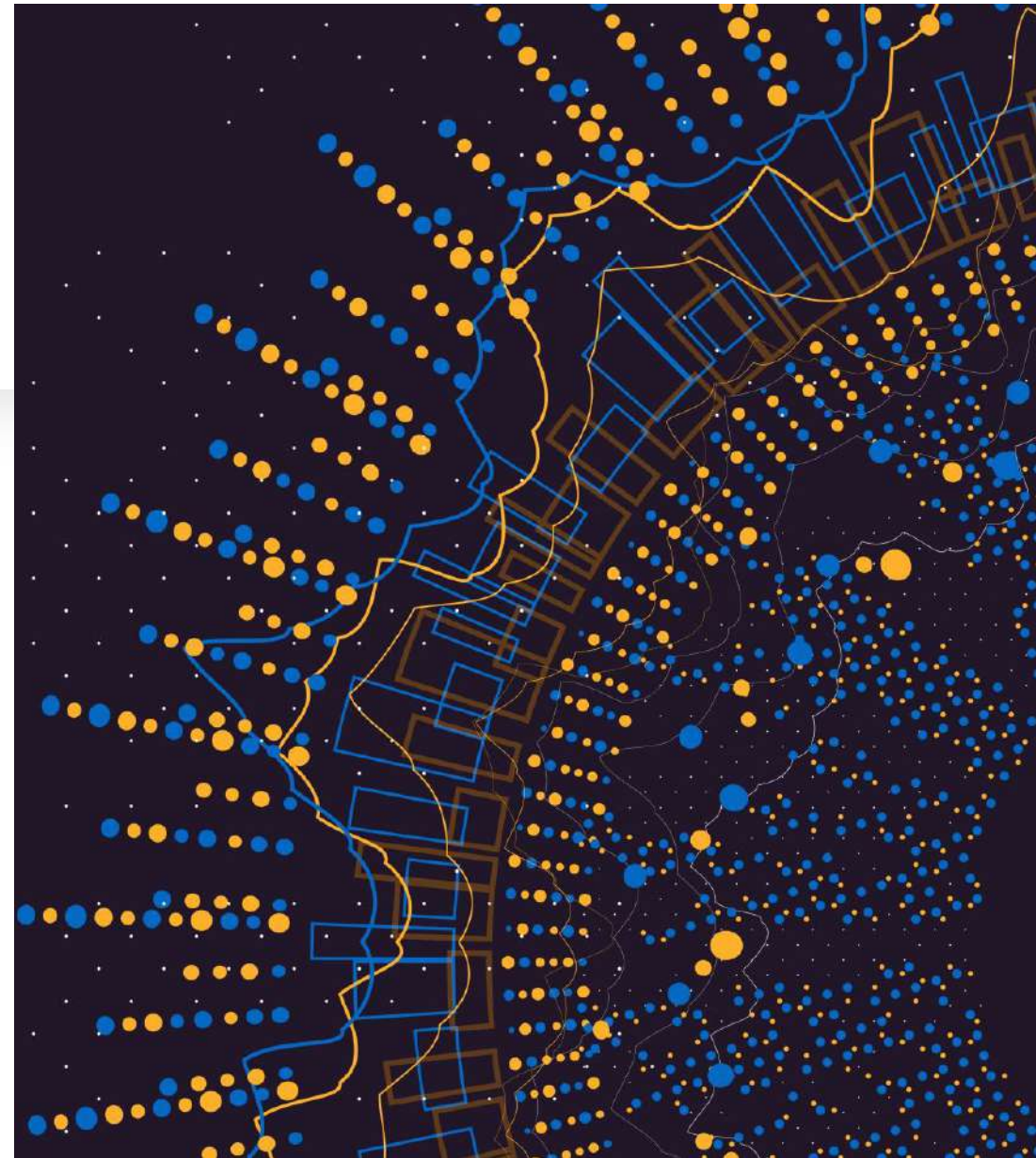
Computation=change (becoming)

Cognition = adaptive information processing performed by an **agent**, who perceives, interprets, and responds in a goal-directed way

Types of agency in nature

- Minimal agency = capability of acting
- Reactive Agency
- Autonomous and Goal-Oriented Agency
- Reflective and Intentional Agency

* Agency in the sense of S. Kauffman and T. Deacon





Overview

How Agent-Based Systems
Can be used to Model
Intelligence

- Framework: relational ontology
- Agent-based models from physics to chemistry, biology, cognitive systems, social networks, ecologies
- Cognitive systems and intelligence (problem solving ability) – rooted in the material properties of the substrate
- Agents exist on a diversity of levels of organization in nature
- Agent-based computational models
- Some believe that mind cannot be modeled computationally. Depends on which computational models are used!
- René Magritte: This Is Not a Pipe, “Ceci n'est pas une pipe”

Agent-Based Models

Key Idea

- Agent-based models represent systems using "agents" that interact and exchange information.

Minsky's "Society of Mind" (1986)

- Intelligence is the collective behavior of simple processes called agents.
- Flexibility in assigning agents various roles and processes.

Michael Levin & Daniel Dennett (2020)

- "Cognition all the way down"
- All intelligences are collective intelligences.

Computational & Intelligent Models- Increasingly Important

Not only in practical applications like transportation, manufacturing, retail, finance, etc. but also in fundamental science:

2013 Chemistry Nobel Prize for computational „Multiscale models of complex chemical systems“- Martin Karplus, Michael Levitt and Arieh Warshel

2024 Chemistry Nobel Prize for the use of AI to predict the structure of proteins (Demis Hassabis & John Jumper) and computational protein design (David Baker)

2024 Physics Nobel Prize for the use of physics to find patterns in information that enable machine learning with artificial neural networks.

The feeling that computation has nothing to do with mind is quickly becoming a minority view.

Hierarchies of Information, Computation, and Cognition

Core Concept

- Nature as a network of information-processing agents, from physical particles to ecosystems.

Hierarchy of Levels (Dodig-Crnkovic 2016)

- Information structures → Information exchange → Computation → Cognition

Terrence Deacon's Levels of Natural Information (From the book "Incomplete Nature: How Mind Emerged from Matter" (2011))

- From simple data patterns to complex biological functions.

Active Matter as the Basis for Agency, Self-organization, Autopoiesis

Active Matter

- Matter is not only passive (like in Newtonian mechanics), it is intrinsically active!
Physical systems perform computations through interactions (e.g., subatomic particles, molecules, etc.).

Self-Organization and Autopoiesis

- Systems have the ability to maintain and produce themselves, a key feature of natural computation. New models: Constructor theory –David Deutsch and Chiara Marletto & Assembly theory –Lee Cronin and Sara Walker.

Hewitt Actor Model of Distributed Concurrent Computation (2010)

- Elementary particles and molecules are viewed as computational agents exchanging messages. Unlike the Turing Machine which is a mathematical construct, this method is physics-inspired.

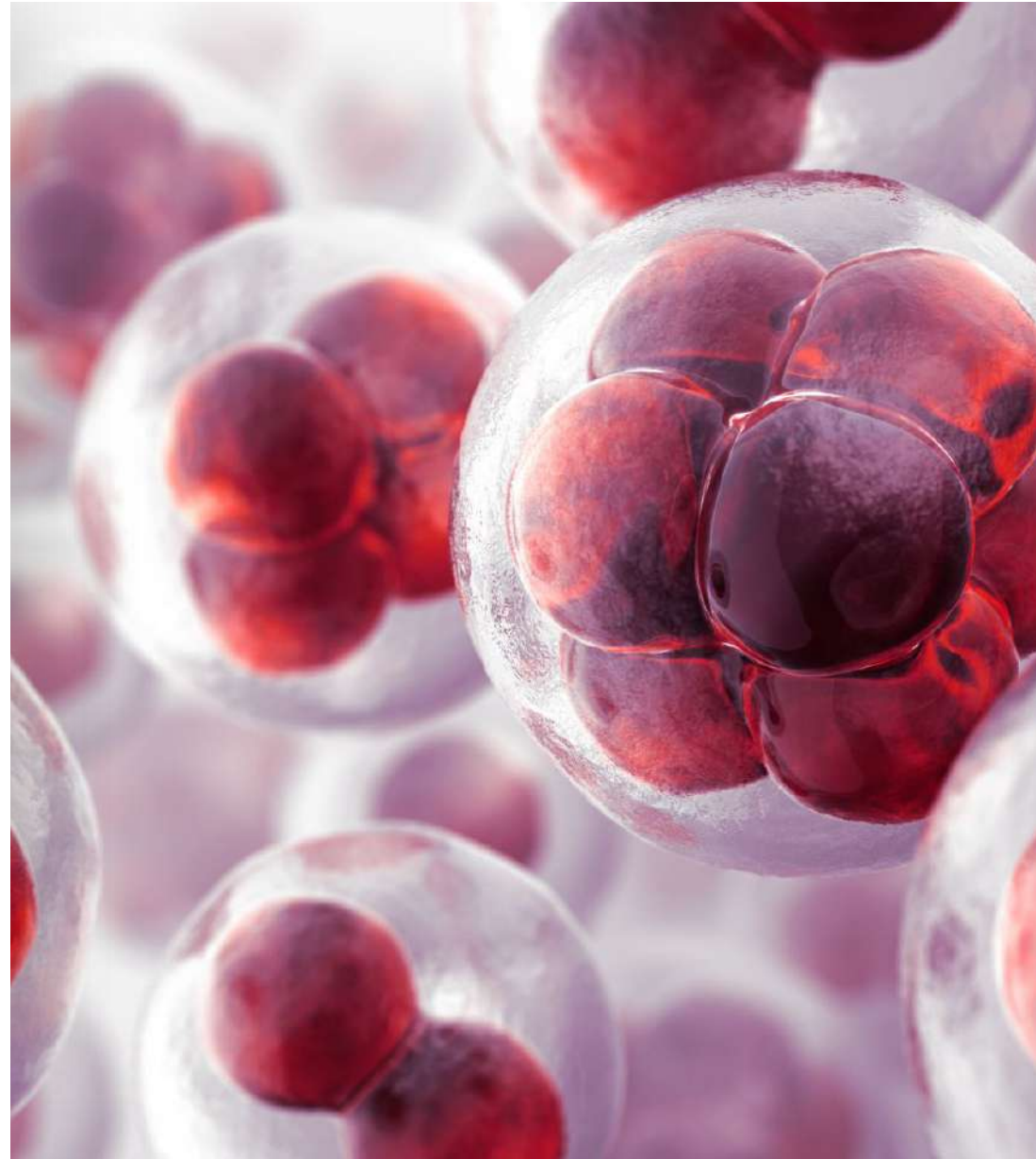
Cognition at the Cellular Level

Cognition in Simple Organisms

- Even bacteria show proto-cognitive abilities, processing information and adapting to their environment.

Autopoiesis as Cognition

- Self-maintenance and regeneration processes are foundational forms of cognition in all life forms.
- Humberto Maturana and Francisco Varela (1980) "Autopoiesis and cognition: the realization of the living"
- John Stewart (1996) "Cognition = Life"



Organismic Cognition and Evolution

Cognition as a Driver of Biological Development

- Cognition arises from interactions at various biological levels, driving evolution and development.
- Extended Evolutionary Synthesis – changes are not random but results of goal-directed agency of living beings.

Info-Computational Approach

- A unified model linking physical, chemical, and biological processes.

Emergence of Intelligence

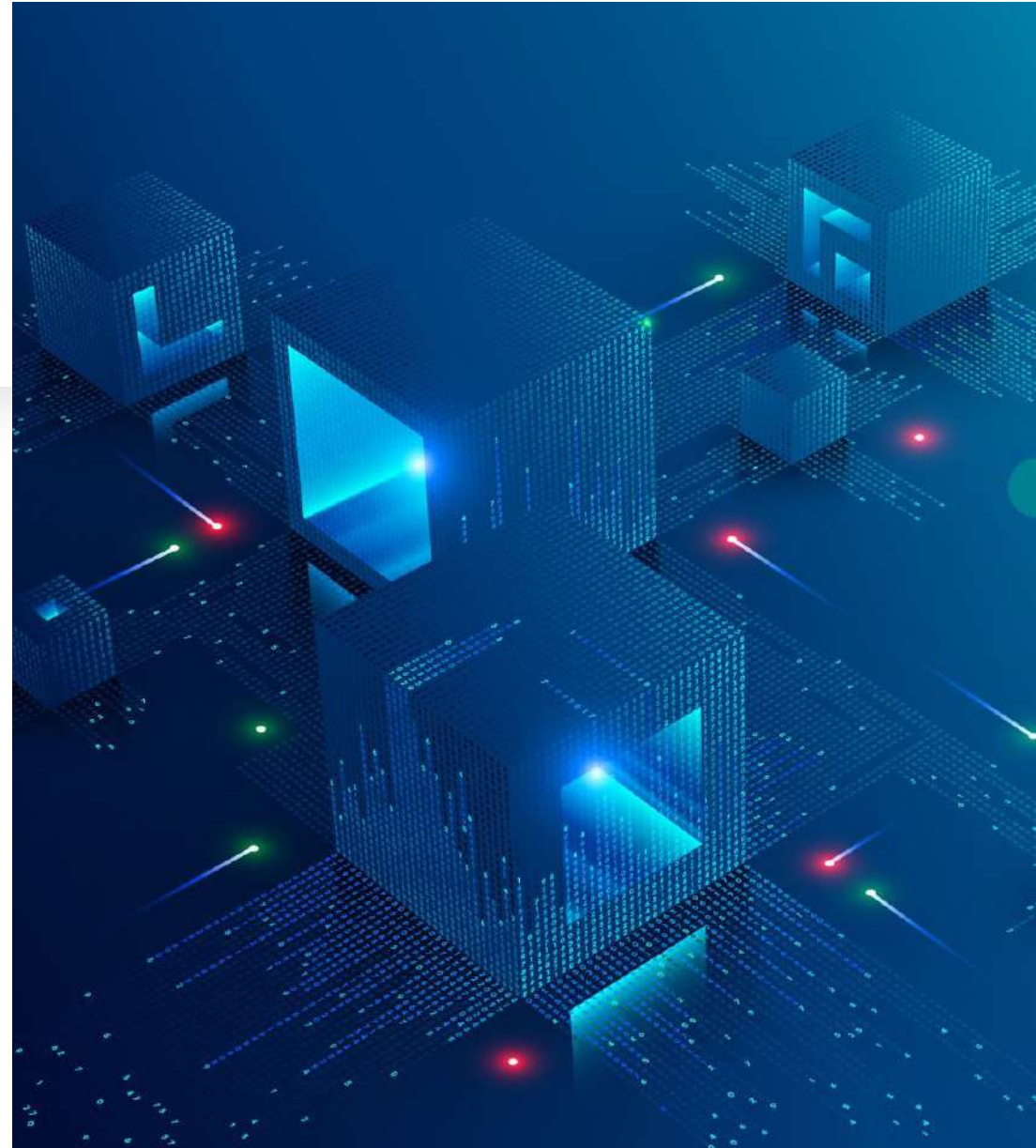
- Intelligent behaviors emerge from agent interactions at different levels of complexity.

Applications of Agent-Based Models

AI and Cognitive Robotics, distributed problem-solving where parallelism, scalability, and robustness make agent-based systems ideal for complex, dynamic environments.

This research has been developing past more than 20 years.

For example in October 2011 at EUCOG II meeting in Groningen, Netherlands the theme was "Autonomous Cognitive Systems in Real-World Environments"





Conclusions

Contributions

- Agent-based models offer a unifying framework to describe interactions, structure generation, and dynamics across physical, chemical, biological, cognitive, and social systems.
- We introduce levels of agency
- Agency is a driving force for the development of cognition and intelligence. They emerge through natural computation from active matter via self-organization, self-structuring, and adaptation.
- Applications in AI extend these principles to artificial systems, contributing to advancements in technology and increasing our understanding of intelligence.

Future Directions

- Continuous two-way learning process: from nature to artifacts and back. Lila Kari and Grzegorz Rozenberg (2008) "The Many Facets of Natural Computing"
- Understanding the role of agency in evolution
- Developing more advanced computational models
- Agent-based AI applications

Summary

Information, Computation, Cognition: Agency-based Hierarchies of Levels

Information constitutes a structure consisting of differences in one system that cause differences in another system. In other words, information is <observer>-relative.

Computation is information processing (dynamics of information). It is a physical process of morphological change in the informational structure which is the physical implementation of information, as there is no information without physical implementation (Landauer).

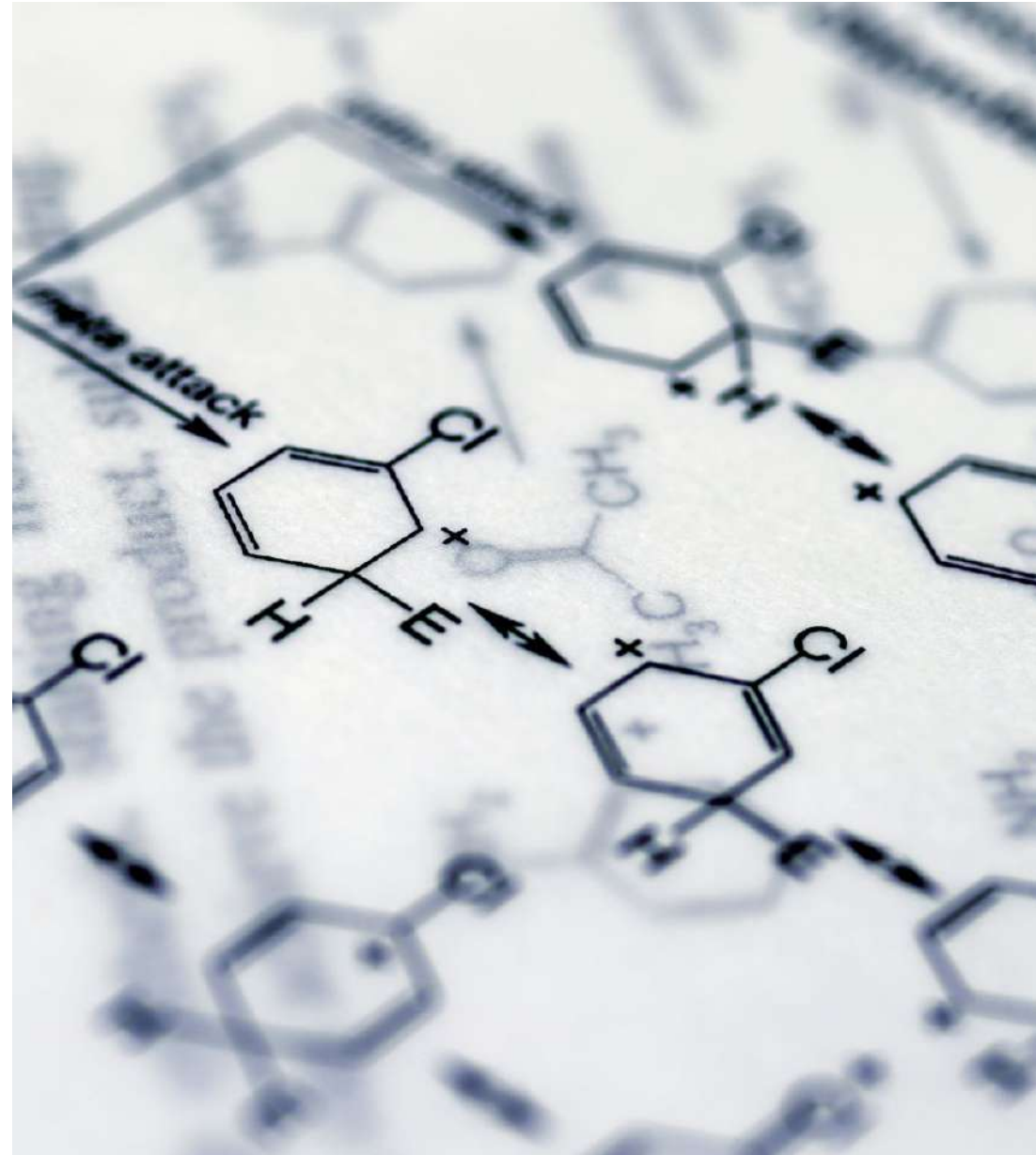


Information, Computation, Cognition: Agency-based Hierarchies of Levels

Both information and computation appear on a succession of levels of organization/abstraction/resolution/granularity of matter/energy in space/time.

Of all autonomous agents (entities capable of acting on their own behalf) only living agents have the ability to actively make choices so as to increase the probability of their own continuing existence /<survival>. This ability of living agents to act autonomously on their own behalf* is based on the use of energy and information from the environment.

- * Agency in the sense of S. Kauffman and T. Deacon



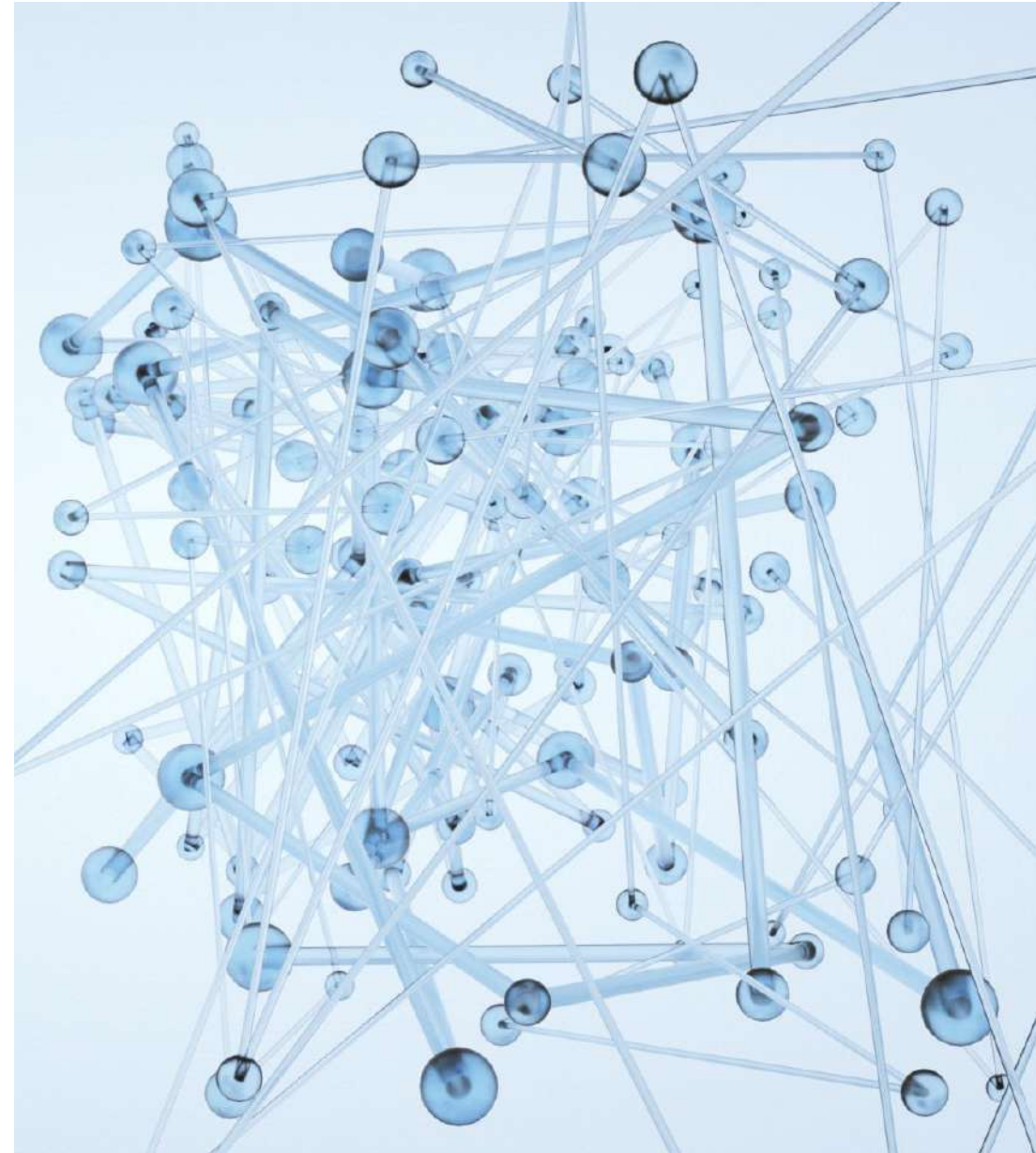
Information, Computation, Cognition: Agency-based Hierarchies of Levels

Cognition consists of all (info-computational) processes necessary to keep a living agent's organizational integrity on all different levels of its existence. Cognition = info-computation

Cognition is equivalent to the (process of) life.* Its complexity increases with evolution. This complexification is a result of morphological computation.

Cognition is both **embodied** and **distributed** information processing. It is a result of information processing in networks of agents.

*The original idea about cognition in living organisms:
Maturana & Varela, Stewart



Information, Computation, Cognition: Agency-based Hierarchies of Levels

Basal cognition exists already at the level of a single cell.

Levin unifies natural and artificial cognition into a continuum of possible cognitive architectures.

In AI technology, agents are expected to be the next frontier of generative AI

Levin M (2022) Technological Approach to Mind Everywhere: An Experimentally-Grounded Framework for Understanding Diverse Bodies and Minds. *Front. Syst. Neurosci.* 16:768201. doi: 10.3389/fnsys.2022.768201

Why agents are the next frontier of generative AI?
<https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/why-agents-are-the-next-frontier-of-generative-ai>



References

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