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Morphological Computing as Logic Underlying Cognition in Human, Animal, and Intelligent Machine

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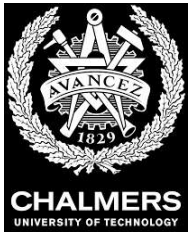
Affiliations

School of Innovation, Design and Engineering

Division of Computer Science and Software Engineering

Research groups:
Artificial Intelligence and Intelligent Systems
Ubiquitous Computing



Department of Computer Science and Engineering

Computer Science and Software Engineering Division

Research groups:
Interaction Design and Software Engineering
Critical Robotics

Research background

Physics, Computer science, Philosophy, Cognitive science

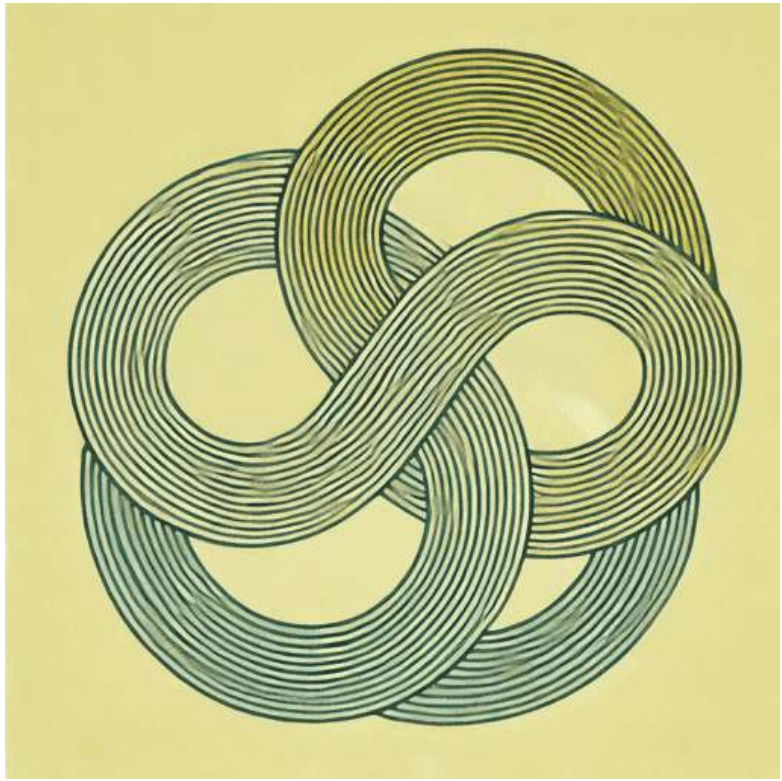
Logic

1. Logic is the systematic study of principles and rules of reasoning.

2. The term "logic" can refer to the framework of principles, rules, or “mechanics” of reasoning as applied, for example in modelling.

We will focus on identification of “derivation rules” from the properties of the “epistemic substrate” on which they apply, on different levels of abstraction.

Epistemology,
Cognitive Science,
Logic: An Eternal Golden Loop



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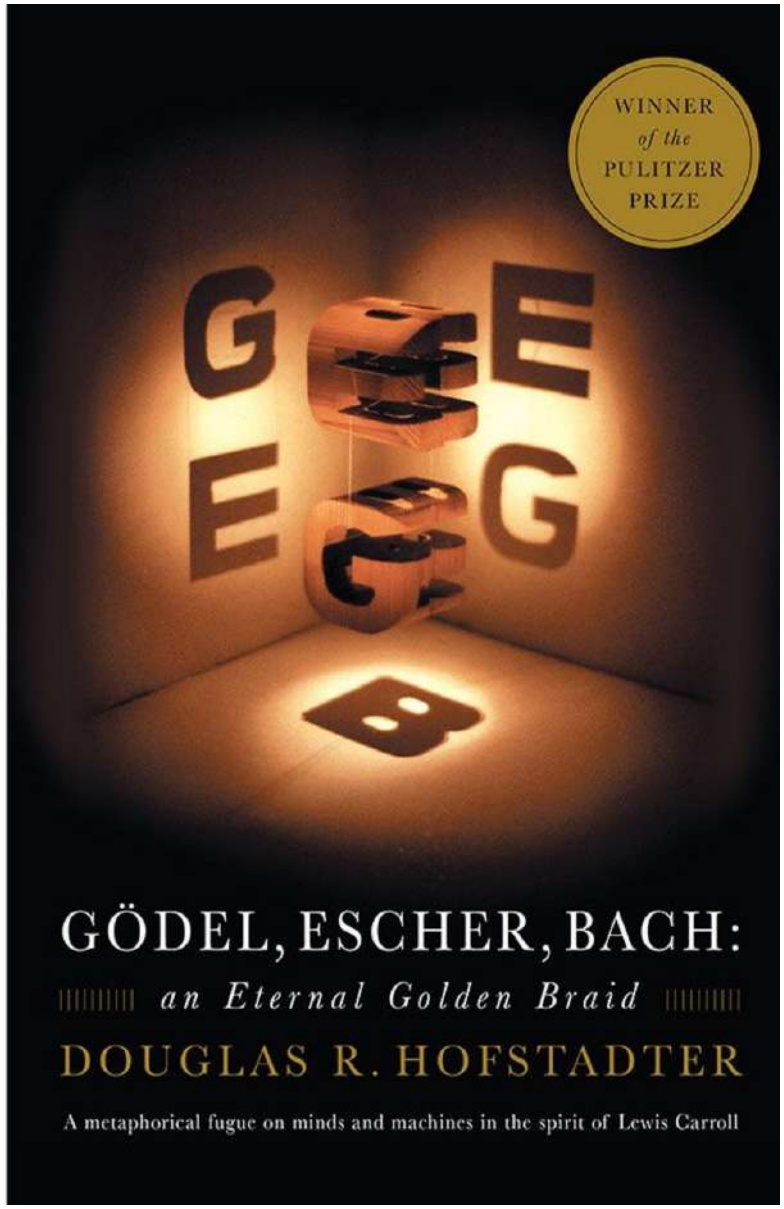


https://www.amazon.se/G%C3%B6del-Escher-Bach-Eternal-Golden/dp/0465026567

Epistemology: the study of knowledge
Logic: the study of reasoning (information transformations)
Cognitive science: the study of knowledge production from data, information and existing knowledge

Rationality, Logic, Interaction, and Naturalization of Logic

Epistemology, Cognitive Science, and Logic form an info-computational system. Information is inherently relational.

The "International Workshop on Logic, Rationality and Interaction" https://golori.org/ (2007-2025) explores new interfaces like epistemic studies of rational behavior in games, social software, and the role of interaction in natural language.

These new perspectives on logic, rationality, and interactions between agents attracted a new set of disciplines into the scope of logic such as linguistics, games, economics, and the social sciences.

This has led to a shift from a human-centric perspective to a cognitive and intelligent agent-centric perspective.

Logic Naturalized

John Dewey in “Essays in experimental logic”provided an early **account of** logic based on the natural sciences (Dewey 1916).

This aligns with Quine’s view that epistemology, ontology, and other philosophical branches, should be informed by sciences (Quine 1969). He specifically argued against the existence of an a priori epistemology or philosophy, implying that there is no a priori logic either. Epistemology, according to Quine, is a part of psychology (cognitive science) and thus of natural science.

Jan Woleński in the articles "Logic in the Light of Cognitive Science", and “Naturalism and Genesis of Logic” builds on the experiential character of knowledge that can be understood phylogenetically which allows us to investigate the genesis of logic through the lenses of evolutionary theory, (Woleński 2012)(Woleński 2012).

Logic Naturalized

John Woods in his *Errors of Reasoning: Naturalizing the Logic of Inference* (Woods 2013) argues for the necessity of naturalizing logic.

Lorenzo Magnani as well points out the urgent need for naturalizing logic (Magnani 2018).

Paul Thagard shows how knowledge about real mechanisms contributes to "generalization, inference to the best explanation, causal inference, and reasoning with probabilities" (Thagard 2021).

The work of Joseph Brenner is also along the lines of natural logic, or in his words, Logic in Reality, (Brenner 2008)(Brenner 2012). Related work on naturalization by Terrence Deacon can also be seen as a proposal on the logic of (informational) nature (Deacon 2011). (move from language to information)

All mentioned proposals concern h u m a n - l e v e l l o g i c .
Moving from language to information enables involving sub-human agents.

Agent-based logic of Gabbay and Wood

Dov M. Gabbay and John Woods introduce the concept of "**A Practical Logic of Cognitive Systems**" (Gabbay and Woods 2003). **Practical logic** is rooted in **pragmatics**, which has historically been a branch of the **theory of signs** involving *non-trivial and irreducible references to **agents** – entities that receive and interpret messages.*

The authors define a cognitive agent as a being capable of **perception, memory, belief, desire, reflection, deliberation, decision, and inference**.

The practical logic offers a description of reasoning of **a practical cognitive system,** a cognitive agent that is an individual.

For them "logic is a principled account of certain aspects of practical reasoning", thus intrinsically pragmatic.

“Logical Dynamics of Information and Interaction” Johan van Benthem

In his book "Logical Dynamics of Information and Interaction" Johan van Benthem highlights that **practical logic is part of a pragmatic theory addressing the necessary aspects of** practical cognitive agency *at both linguistic and sublinguistic levels*, (Benthem 2011).

For this, “a suitably flexible notion of information is necessary”. Benthem emphasizes that his approach to practical logic, shares similarities with the "dynamic turn" in logic research.

Focus on the intersection of cognitive science and experimental studies of *the* ***underlying psychological and neurological realities of*** *human information processing and cognition.*

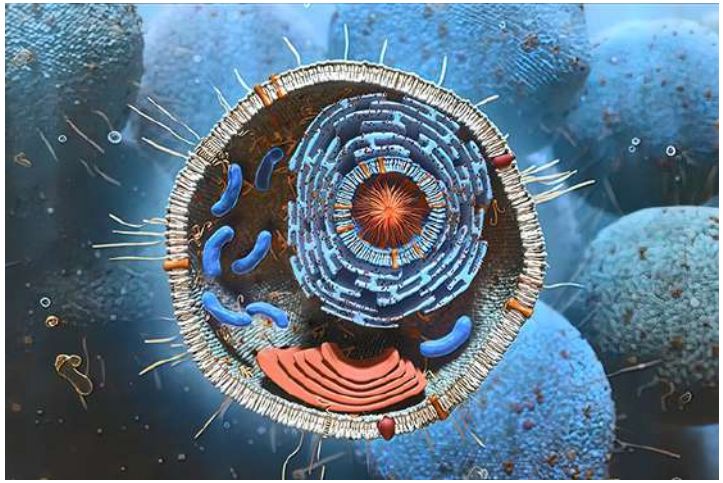
See also:
http://www.gordana.se/work/PRESENTATIONS-files/20220114-WLD-Logic%20of%20cognitive%20systems%20from%20single%20cells%20up.pdf
LOGIC OF COGNITIVE SYSTEMS FROM SINGLE CELL UP
UNESCO WORLD LOGIC DAY 2022: “COMPUTING NATURE - NEW TRENDS” ROUND TABLE

Logics “in the Wild”

“Chemistry is the logic of Biological Phenomena” (Garrett and Grisham 2023), claim based on the insight that biomolecules are informational carriers that provide structure and generative rules for biological cells.

In a more detailed computational approach, (Foulon et al. 2019) present a language for molecular computation.

If chemistry is the logic of biology, what is the logic of chemistry?



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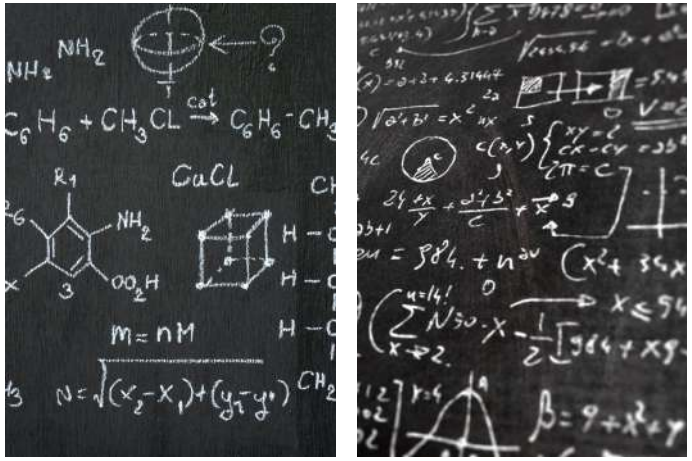

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Logics “in the Wild”

In search for the role of logic in knowledge production, decision-making, and agency in nature, we propose the following schema, in a recursive (circular) manner, starting with logic:

1. **Logic** is the intrinsic foundation of **mathematics**.
2. **Mathematics** is the intrinsic logic of **physics**.
3. **Physics** is the intrinsic logic of **chemistry**.
4. **Chemistry** is the intrinsic logic of **biology**.
5. **Biology** is the intrinsic logic of **cognition**.
6. **Cognition** is the intrinsic foundation of an agent’s **intrinsic logic**.
7. An agent’s **intrinsic logic** is the foundation of **extrinsic/externalized/shared logic**. Go to 1.

Connections between Morphology and Logic

- **Logic and Morphology**: The intrinsic structure of systems enables logical operations (or generation of new states/structures) and decision-making.

- **Evolutionary Perspective**: (Information processing) Mechanisms of Biological logic are evolving from unicellular organisms to human cognition.

Cognitive Logic Framework

- **Naturalized Logic**: Grounding human logic in the principles of physical, chemical, and biological computation.
- **Extended Evolutionary Synthesis (EES)**: Evolution as a process of learning and cognition.

Recursive Hierarchy of Logic

Hierarchy

Logic → Mathematics → Physics → Chemistry → Biology → Cognition →(Logic)

Insight: Logic emerges through interactions (defined [driven and constrained] by morphology) at each level.

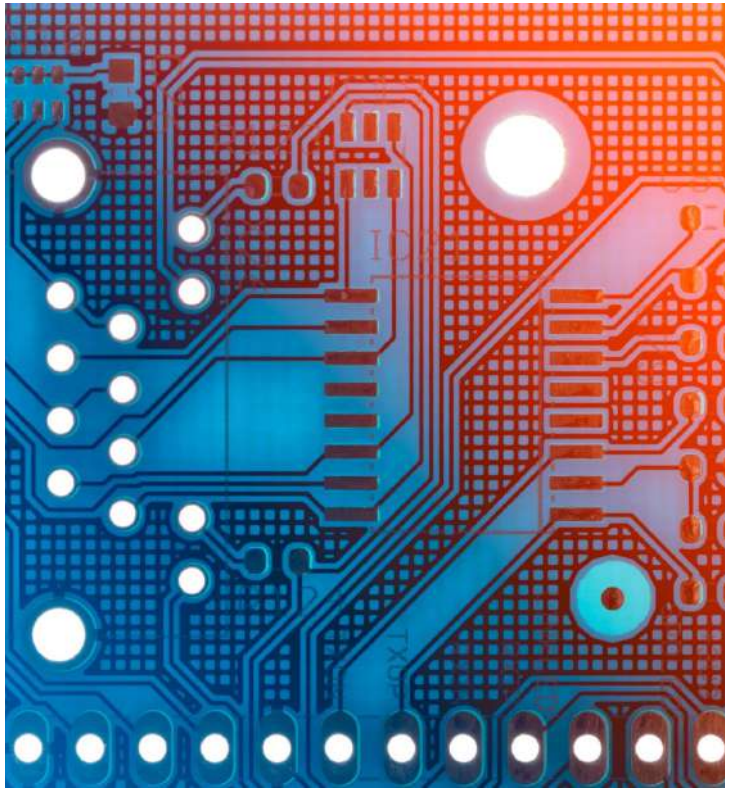
Info-Computational Framework Background

- **Key Idea**
  Cognition = Computation of Information

- View nature as a computational system, integrating non-living and living systems.

Morphological Computing

- Morphological computing connects physical, chemical, biological, and cognitive processes to information and logic.
- **Objective** is to explore how morphology defines cognitive abilities and processes in natural and artificial systems.



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Morphological Computing Overview

- Computation (information processing) unfolds in a (physical) form and structure following their intrinsic behaviors (natural computing)

- Biological organisms taking advantage of their body structures and shapes for efficient problem-solving.

Nature-inspired design

Bio-mimicry

Bio-mimetic

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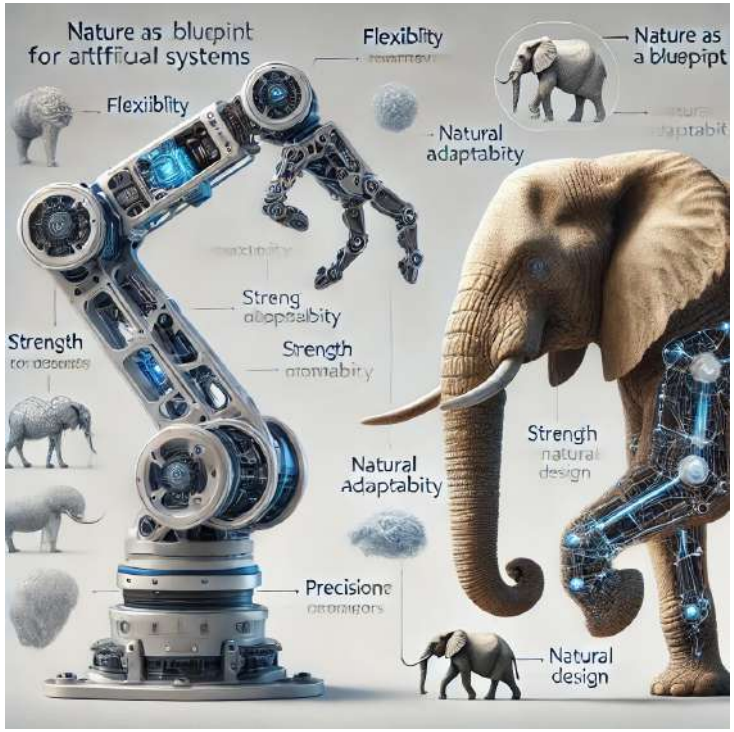
From Nature to Machines

- **Natural Computing**: Physical computing, intrinsic to all matter, Chemical computing, Biological computation in cells, tissues, and organisms, Cognitive computing, Social computing
- **Artificial Systems**: Mimicking natural principles in robotics and AI for better efficiency and adaptability.



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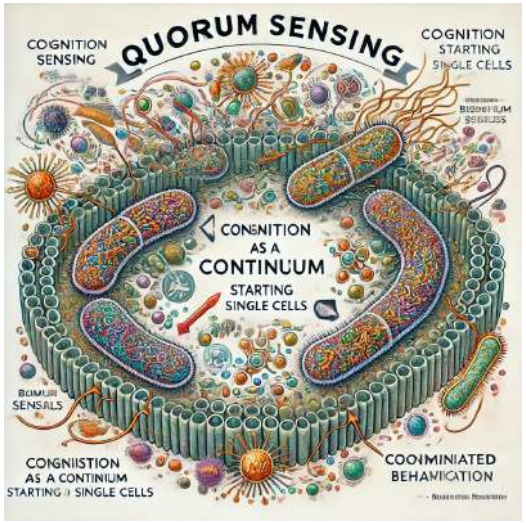
Bio-inspired Design
Bionics
Ecological Design

Basal and Pre-Neural Cognition

- **Basal cognition stands for** cognitive behaviours observed in single cells, including information processing, decision-making and memory.
- Cognition exists on a continuum, from bacteria to humans.
- Quorum sensing as a chemical "language."
- **Significance**: Demonstrates how simple systems achieve complex behaviors.



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Evolution as Learning

- Evolution involves learning processes influenced by cognition at various levels.
- Biological systems adapt through interactions with the environment.

Challenges and Open Questions

- Current Gaps
  - Mechanisms linking morphology to high-level cognition.
  - Transition from sub-symbolic to symbolic information processing.

- Future Directions

Bridging biological and artificial cognitive architectures.

Conclusion

Morphological computing integrates logic, information processing, and evolution across systems.

Future work

Further interdisciplinary research in info-computation and cognitive modelling is needed.

Acknowledgments

My research in this field was financed by Swedish Research Council project MORCOM@COGS.

Some observations

- There are interconnections between logic, epistemology, and sciences within the naturalist tradition.
- Scale-invariant, self-organizing dynamics exists across organizational scales of nature.
- Cognitive logic stems from the evolution of physical, chemical, and biological logic.

Some observations

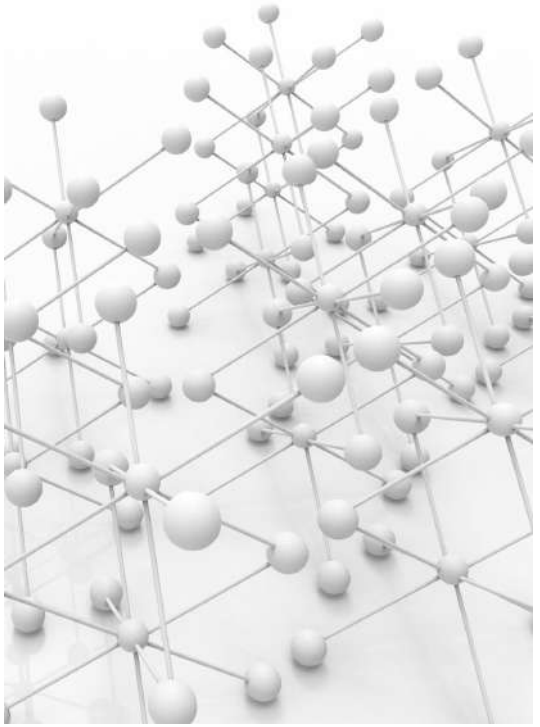
- The process of evolution and in particular its formulation as the Extended Evolutionary Synthesis of living agents is essential for understanding the emergence of human-level logic and the relationship between logic and information processing/ computational epistemology.

- Biological systems, such as humans and animals, use their body morphology to process information and solve problems more efficiently than purely symbolic-level computational approaches.

- Practical logic and logic in action are related concepts that emphasize the real-world applicability of logic, focusing on how logical reasoning and operations can be used to solve problems and make decisions in everyday life.

Applications

- Developing AI systems that use morphological computing principles to make more efficient use of computational resources and better resemble human cognitive abilities.
- Creating new cognitive models and theories that integrate morphological computing and logic to better understand human and animal cognition.
- Investigating how the morphology of biological systems can inform the design of new materials and devices for information processing and problem-solving.
- Designing robots with physical structures that can efficiently process information and solve problems by exploiting their body morphology.



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