



ShanghAI Lectures 2014

<http://shanghailectures.org> November 13

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

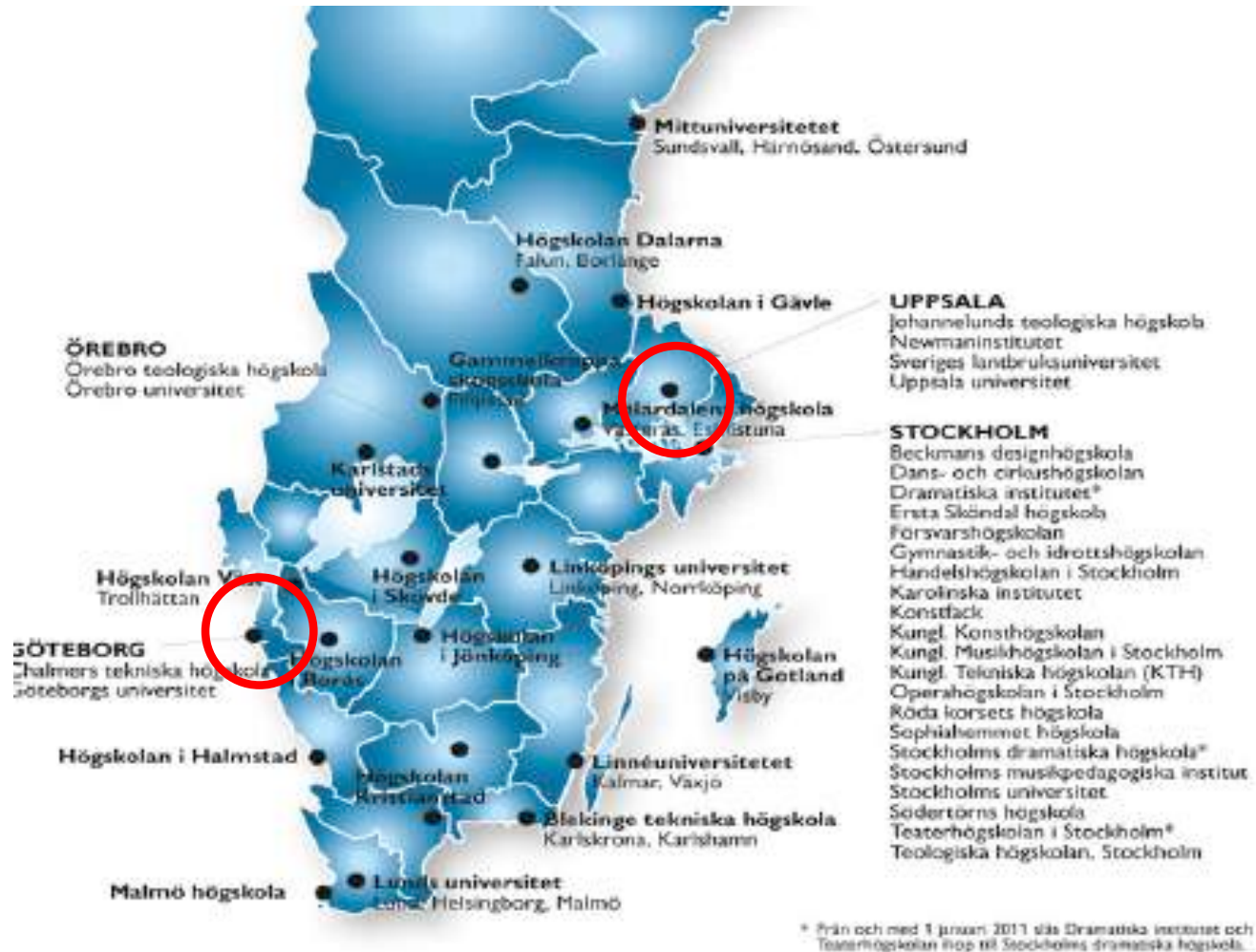
Morphologically computing physical world

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Chalmers University of Technology &
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Sweden



Butterfly morphogenesis –
Gabriel Kelemen

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Gordana Dodig Crnkovic - My background

Research

Computing Paradigms
Computational knowledge generation
Computational aspects of Intelligence and Cognition
Theory of Science/ Philosophy of Science
Information science (generation of information in cognitive systems)
Computing and Philosophy and
Ethics (Ethics of Computing, Information Ethics, Roboethics and Engineering Ethics).

<http://www.idt.mdh.se/personal/gdc/work/publications.html>

Teaching

Research Methods in Natural Sciences and Engineering
Computing and Philosophy
Computational Thinking and Writing Tool Box
Formal Languages, Automata Theory and Computation
Professional Ethics
Research Ethics and Sustainable Development

<http://www.idt.mdh.se/personal/gdc/work/publications.html>

PhD in Theoretical Physics from Zagreb University (1988)
PhD in Computing from Mälardalen University (2006)



Science in making

"I invite readers not on a visit to an archaeological museum, but rather on an adventure in science in making"

Ilja Prigogine in *The End of Certainty: Time, Chaos and New Laws of Nature*,
1997

Information concept – Claude Shannon

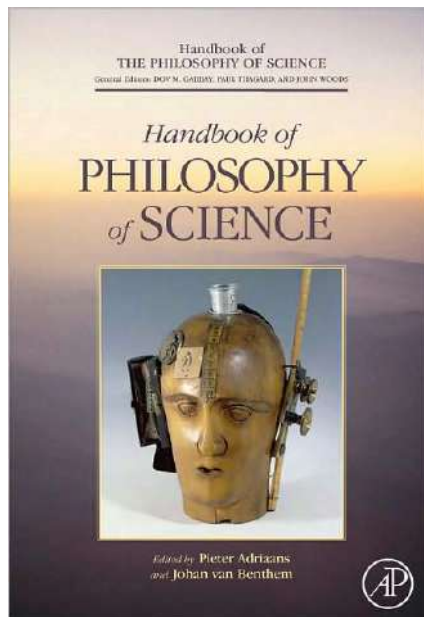
“The word “information” has been given different meanings by various writers in the general field of information theory. It is likely that at least a number of these will prove sufficiently useful in certain applications to deserve further study and permanent recognition.

It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general field. “

C Shannon, 1993, “The Lattice Theory of Information”



What is information?

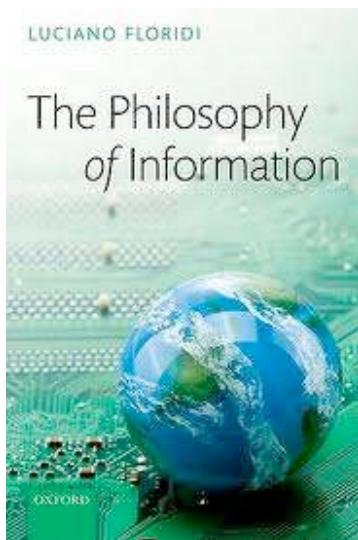


Pieter Adriaans, Johan van Benthem, Edts. (2008)
Philosophy of Information (Handbook of the Philosophy
of Science) Elsevier.

Information as the primary stuff of the universe

If **information is to replace matter/energy as the primary stuff of the universe**, as H von Baeyer (2003) suggests, it will provide a new basic unifying framework for modeling of reality in the twenty-first century.

L Floridi proposes **Informational Structural Realism** - a view of the world as the totality of informational objects dynamically interacting with each other.

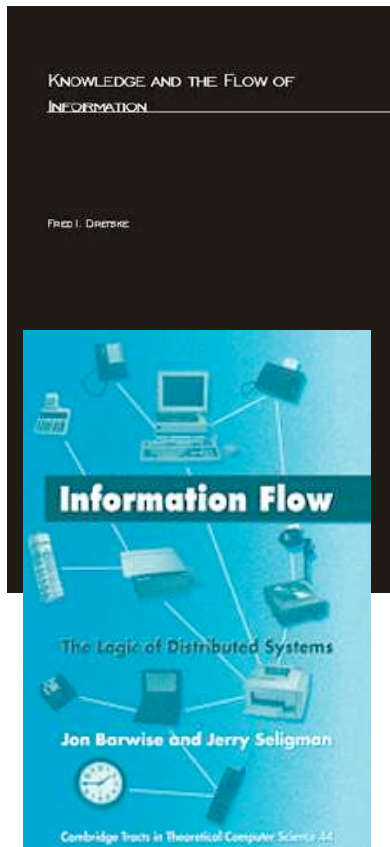


Von Baeyer, H. (2004) Information: The New Language of Science. Cambridge: Harvard University Press.

Floridi, L. (2008). A defence of informational structural realism. *Synthese*, 161(2), 219-253

Luciano Floridi (2011) *The philosophy of information*, Oxford University Press

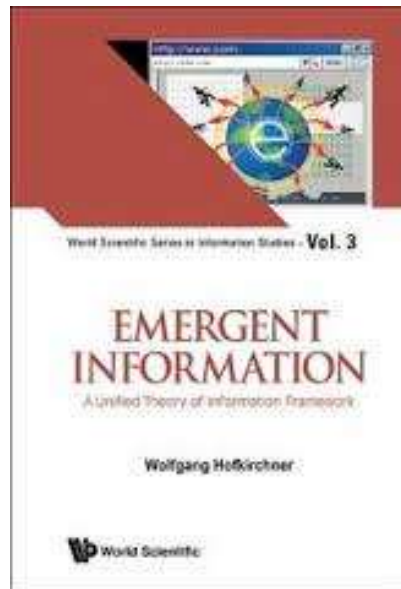
Information flow



- Traditionally, information was considered to be a **building block of knowledge and thus supposed to always be true**.
- The early developments of the field of dynamic of information such as seminal work of (Dretske, 1999) (**information flow** as linguistic regularities) and (Barwise & Seligman, 1997) (informational relation between **situations**)
- Described in the **Philosophy of Information handbook** (Benthem van & Adriaans, 2008), as well as (Burgin, 2010) or (Floridi, 2011).

Dretske, F. (1999). *Knowledge and the flow of information* (pp. 1-288). N. Y.: Cambridge Univ. Press.
Barwise, J., & Seligman, J. (1997). *Information flow: the logic of distributed systems*. Cambridge: Cambridge University Press.

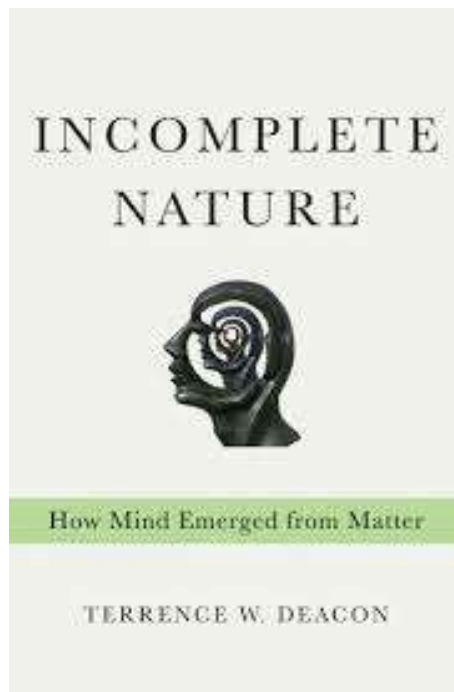
Emergent information



- **Informational dynamics may be characterized as processes of self-organization.** Whenever self-organizing systems relate to the environment, they create/generate information, called “emergent information”.
- The information generation is consisting of **cognition** (information generation of a self-organizing system vis-à-vis its environment); **communication** (the coupling of cognitive processes of at least two self-organizing systems) and **cooperation**. Cooperation feeds back to communication as communication does to cognition. That’s the basic dynamics of emergent information.

Wolfgang Hofkirchner (2011) Emergent Information: A Unified Theory of Information Framework, World Scientific

Three forms of information



- Deacon (2011) distinguishes between the following three forms of information:
- *Information 1* (Shannon) (data, pattern, signal) (data communication) [syntax]
- *Information 2* (Shannon + Boltzmann) (intentionality, aboutness, reference, representation, relation to object or referent) [semantics]
- *Information 3* ((Shannon + Boltzmann) + Darwin) (function, interpretation, use, pragmatic consequence) [pragmatics]

Three forms of information

Deacon's three types of information correspond to three types of:

Formative mechanisms:

[Mass-energetic [Self-organization [Self-preservation (semiotic)]]]

Emergent dynamics:

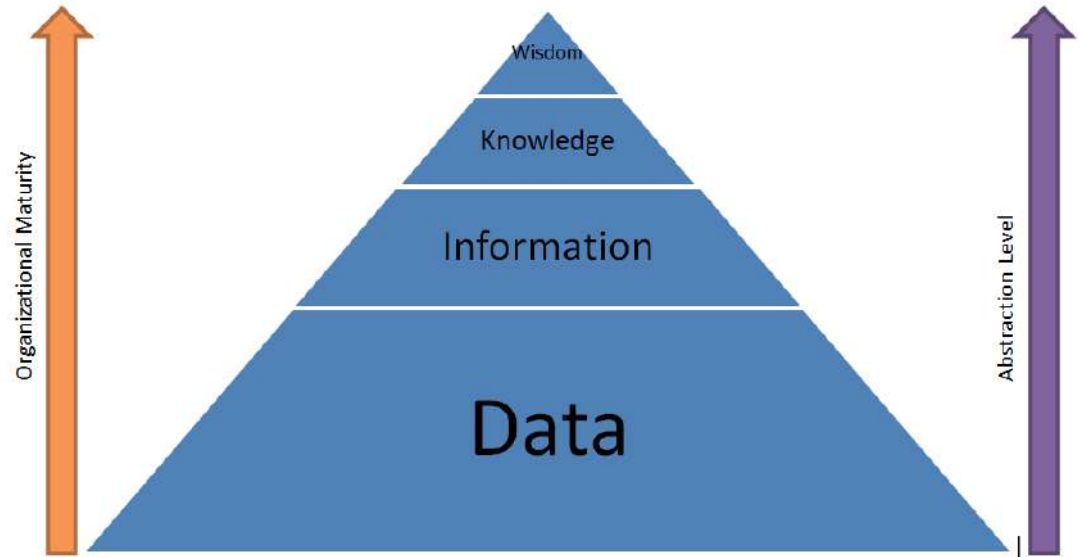
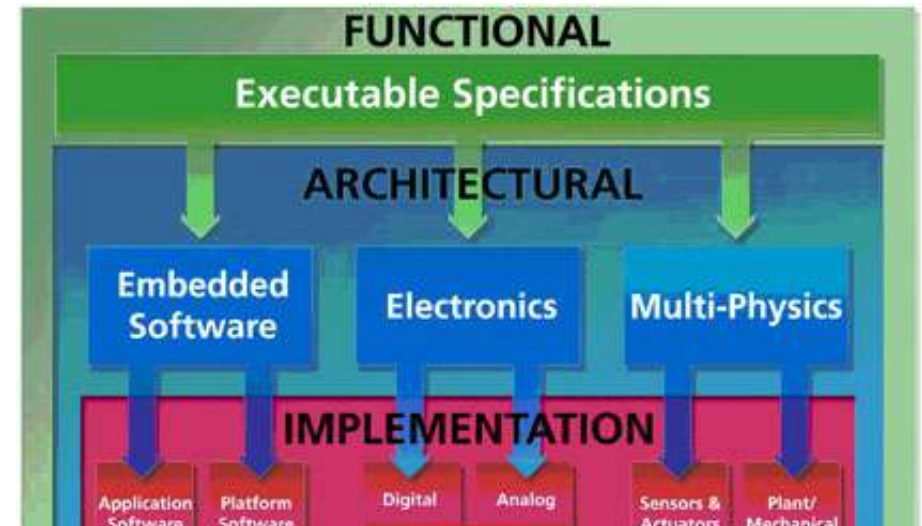
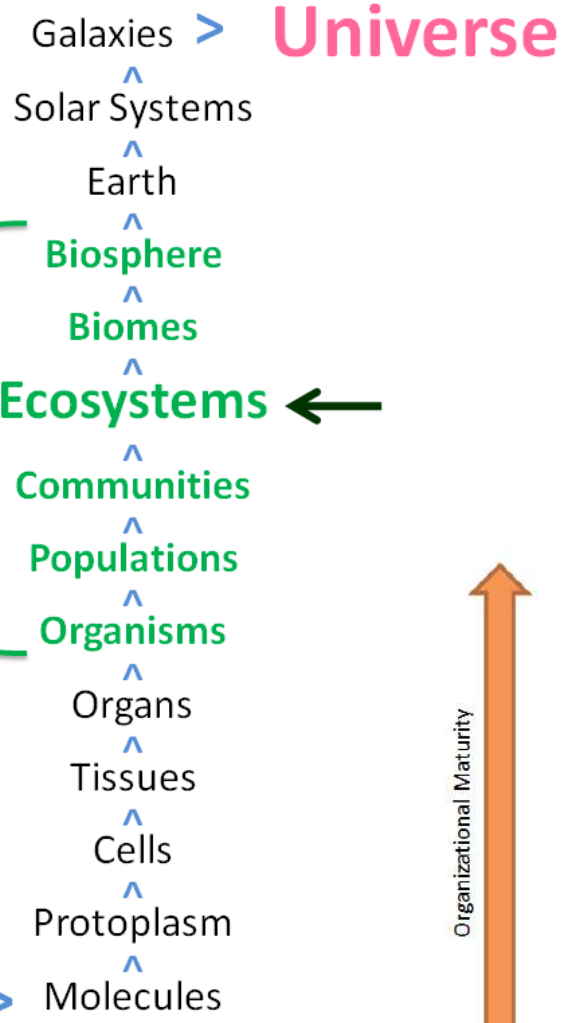
[Thermo- [Morpho- [Teleo-dynamics]]]

Aristotle's causes:

[Efficient cause [formal cause [final cause]]].

Levels of Description – Levels of Abstraction – Levels of Organization

Levels of Organization



Information and complexity

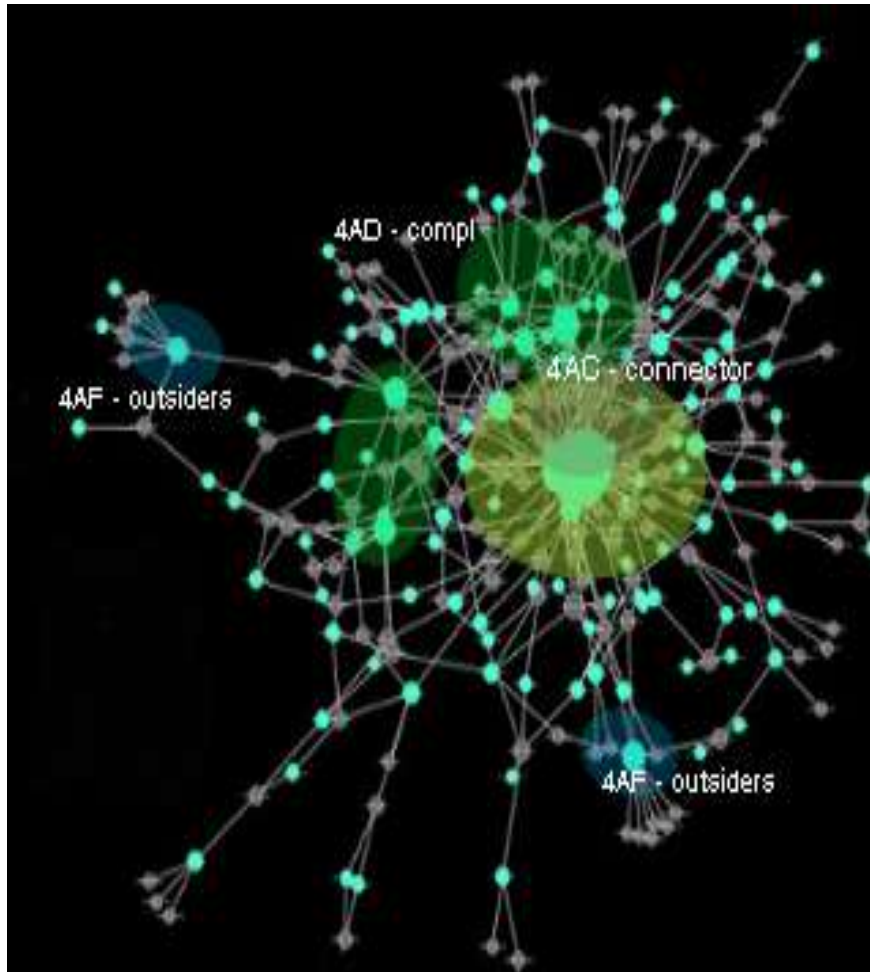
A complex system is a system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts.

Disorganized complexity is a result of a very large number of parts, and *organized* complexity is a matter of the subject system exhibiting *emergent* properties.

Complex systems are found between orderly systems with high information compressibility and low information content and random systems with low compressibility and high information content.

http://en.wikipedia.org/wiki/Complex_system

Complexity



In a complex system, what we see is dependent on where we are and what sort of interaction is used to study the system. (observer dependence)

Study of complex systems:

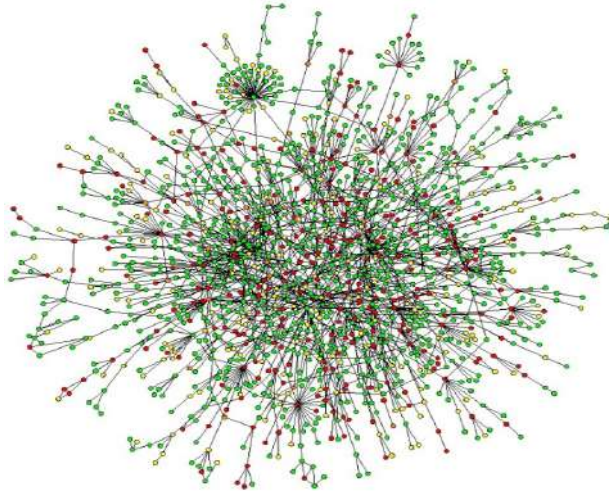
Generative Models

How does the complexity arise?

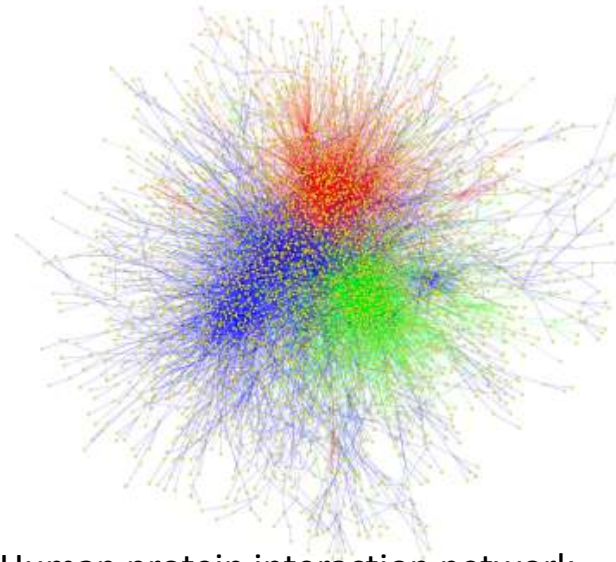
Evolution is the most well known generative mechanism.

Complexity generated from simple elements with simple rules (CA)

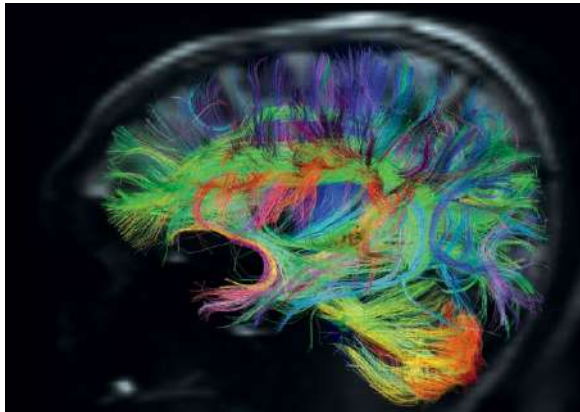
Network models of complex systems



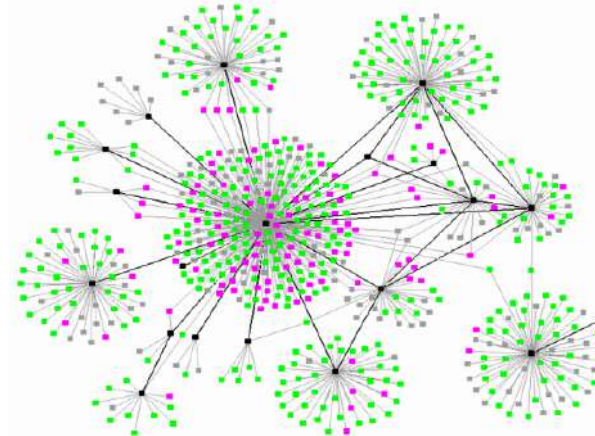
Protein network in yeast cells



Human protein interaction network



Human connectome



Social network



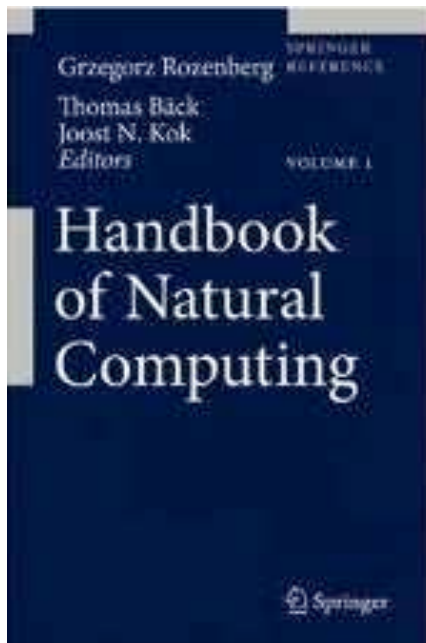
Computation as information processing

With information as the primary stuff of the universe (informational structural realism), the most general view of **computation is as dynamics of information (information processes)**.

This results in a dual-aspect universe: **informational structure with computational dynamics**. (Info-Computationalism, Dodig Crnkovic)

Information and computation are closely related – no computation without information, and no information without computation (dynamics).

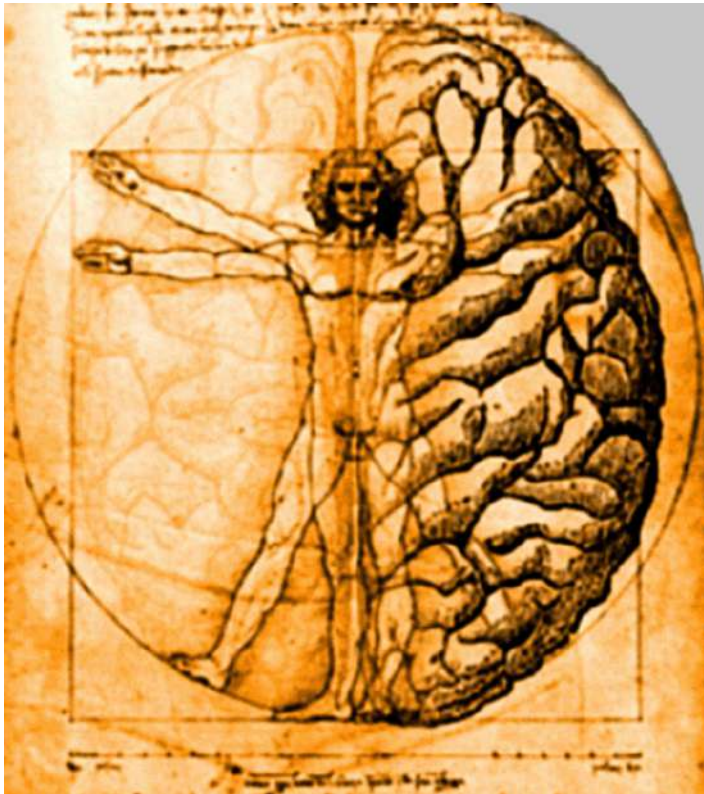
Beyond Conventional Computing Machinery: Natural Computing



- According to the Handbook of Natural Computing, natural computing is **“the field of research that investigates both human-designed computing inspired by nature and computing taking place in nature.”**
- It includes among others areas of cellular automata and neural computation, evolutionary computation, molecular computation, quantum computation, nature-inspired algorithms and alternative models of computation.

Grzegorz Rozenberg, Joost N. Kok, Thomas Bäck (2102) Handbook of Natural Computing, Springer.

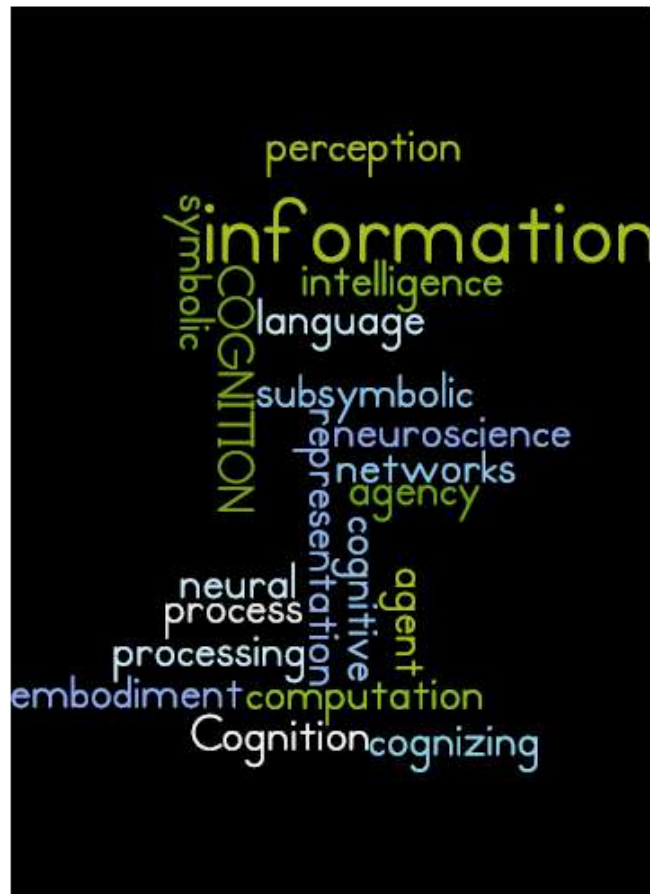
Cognition as processing of information



100 billions of neurons connected with tiny "wires" in total longer more than two times the earth circumference. This intricate and apparently messy neural circuit that is responsible for our cognition and behavior.

<http://www.istc.cnr.it/group/locen>

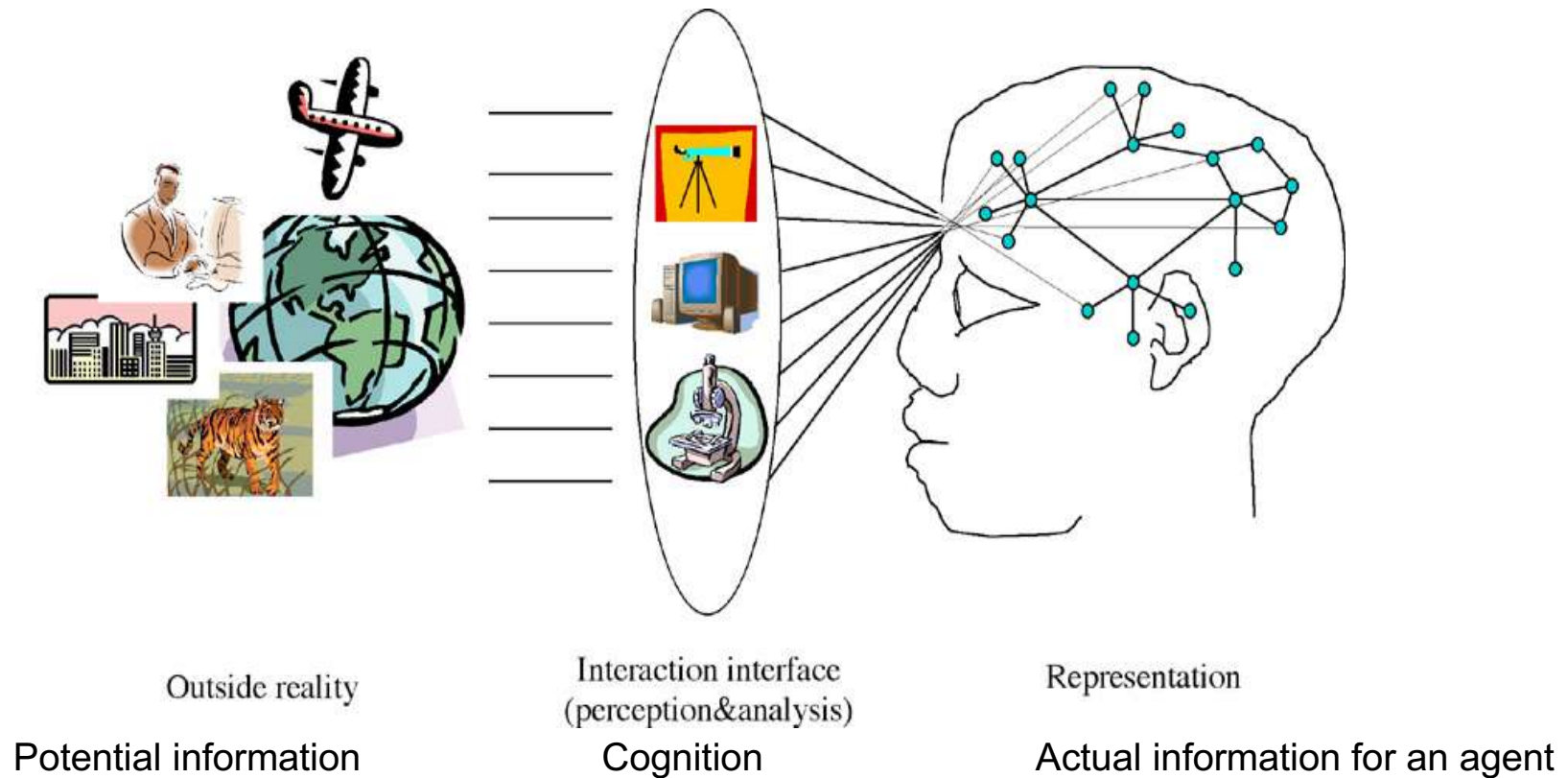
What is Cognition?



- Process of perceiving, reasoning, decision making and thinking.
- Body's & brain's way of processing information to create meaning / make sense for an agent.
- Cognition = Life (Maturana & Varela, 1980)

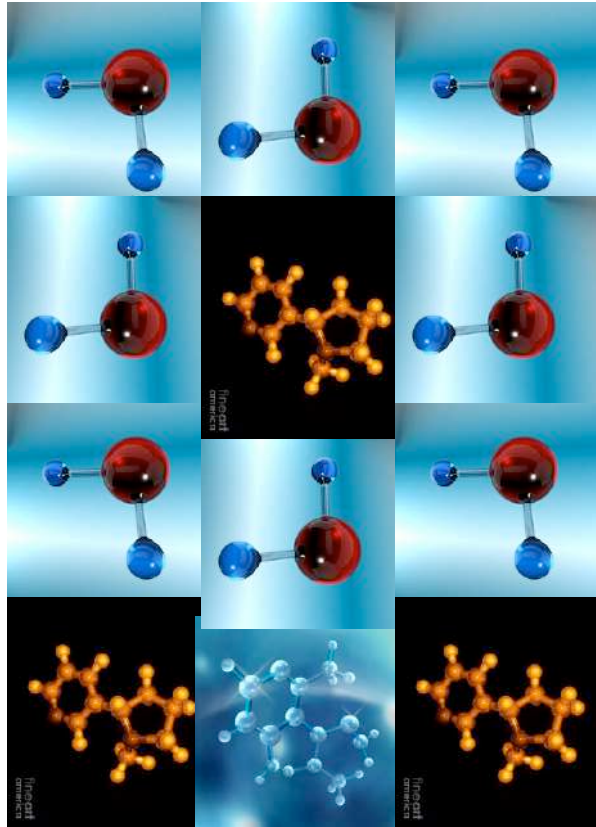
Maturana, H. & Varela, F., 1980. Autopoiesis and cognition: the realization of the living, Dordrecht Holland: D. Reidel Pub. Co.

Cognition: Agency-based hierarchies of levels. World as information for an agent

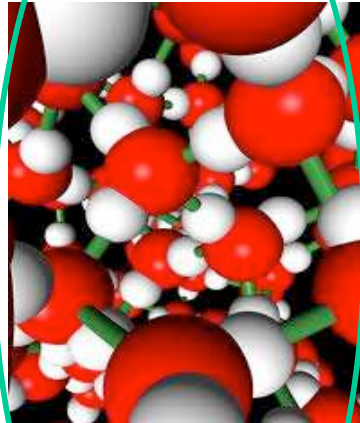


From: <http://www.alexekurakin.org>

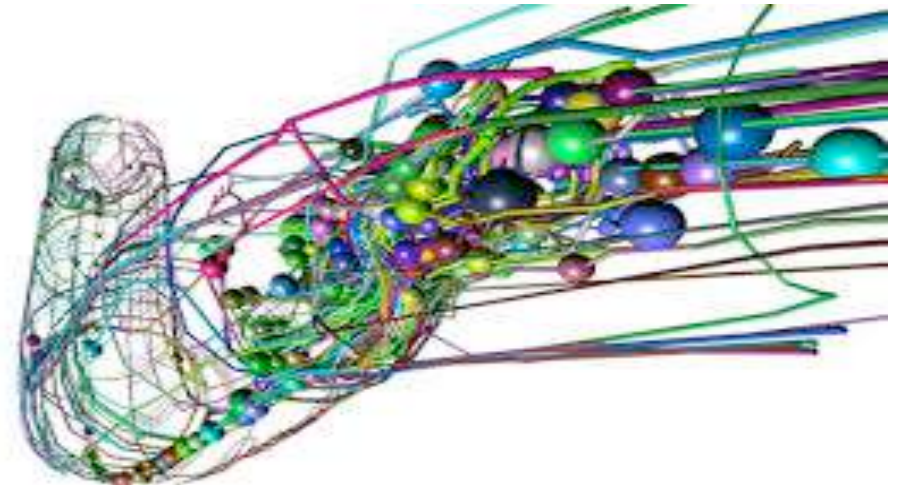
**Cognition: Agency-based hierarchies of levels.
World as information for an agent**



Potential information
Outside reality for C-elegans



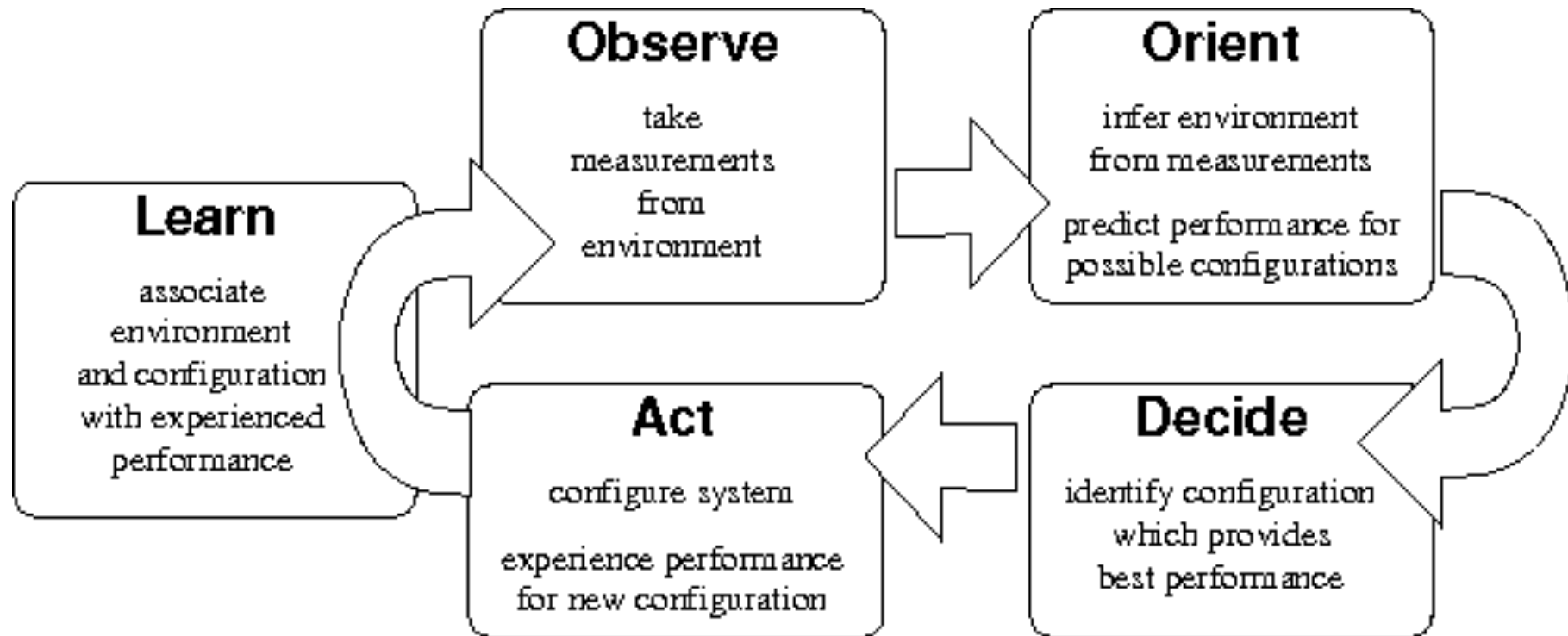
Interaction interface for C-elegans
Cognition



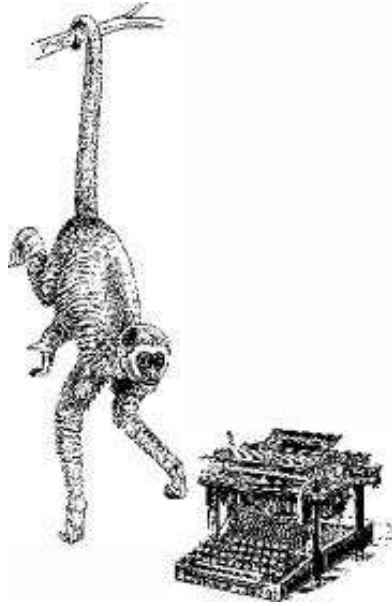
Actual Information C-elegans

C. Elegans has 302 neurons (humans have 100 billion). The pattern of connections between neurons has been mapped out decades ago using electron microscopy, but knowledge of the connections is not sufficient to understand (or replicate) the information processor they represent, for some connections are **inhibitory** while others are **excitatory**.

Technological Application: Cognitive Network Technology



How does nature compute? Self-organization + evolution (via auto-poiesis)



Critics of the evolutionary approach mention the impossibility of “blind chance” to produce such highly complex structures as intelligent living organisms. Proverbial monkeys typing Shakespeare are often used as illustration (an interesting account is given by Gell-Man in his *Quark and the Jaguar*.)



Chaitin and Bennet: Typing monkeys’ argument does not take into account physical laws of the universe, which dramatically limit what can be typed. Moreover, the universe is not a typewriter, but a computer, so a monkey types random input into a computer. The computer interprets the strings as programs.

Naturalizing knowledge

- Knowledge* may be studied as a natural phenomenon -- that the subject matter of epistemology is not our concept of knowledge, but the knowledge itself. (Feldman, Kornblith, Stich -Naturalized epistemology)
- *The stimulation of his sensory receptors is all the evidence anybody has had to go on, ultimately, in arriving at his picture of the world. **Why not just see how this construction really proceeds?** Why not settle for psychology?* ("Epistemology Naturalized", Quine 1969; emphasis mine)
- Why not settle for **info-computing**?

- *knowledge *that* as well as knowledge *how*

Info-computing of knowledge

In the info-computational framework knowledge is a result of the structuring of input data:

data → information → knowledge

by an interactive computational process going on in the nervous system* during the adaptive interplay of an agent with the environment, which clearly increases its ability to cope with the dynamical changing of the world.

Hebbian learning

http://en.wikipedia.org/wiki/Hebbian_theory

*Process of learning through physical computation happens even in organisms without nervous system such as bacteria – bacterial cognition.



Naturalist understanding of cognition

- A great conceptual advantage of cognition as a subject of study is that **all living organisms possess some cognition**, in some degree. (Maturana and Varela, 1980)
- Maturana's and Varela's' understanding of cognition is most suitable as the basis for a computationalist account of the naturalized evolutionary epistemology.

See also: Dodig-Crnkovic, G. Where do New Ideas Come From? How do they Emerge? Epistemology as Computation (Information Processing) in *Randomness & Complexity, from Leibniz to Chaitin*, C. Calude ed. 2007



Cognition as re-structuring in an agent through interaction with the environment

Info-computationalist project is defining cognition as information processing phenomenon, closely related to the development of multilevel dynamical computational models and simulations of cognizing systems, with important consequences for the development of artificial intelligence and artificial life.

Natural computation opens possibilities to implement embodied cognition into artificial agents, and perform experiments on simulated agents and ecosystems.

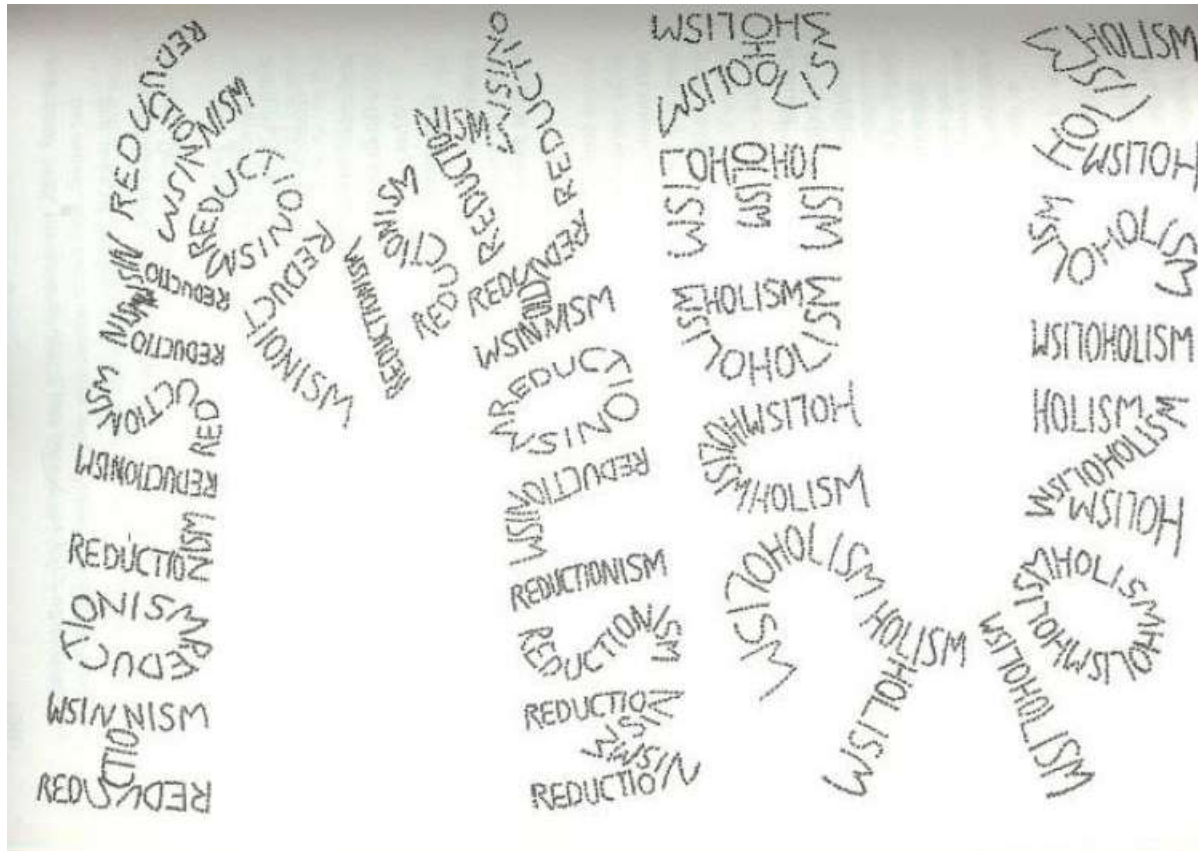


Digital vs. analog, discrete vs. continuous and symbolic vs. sub symbolic information

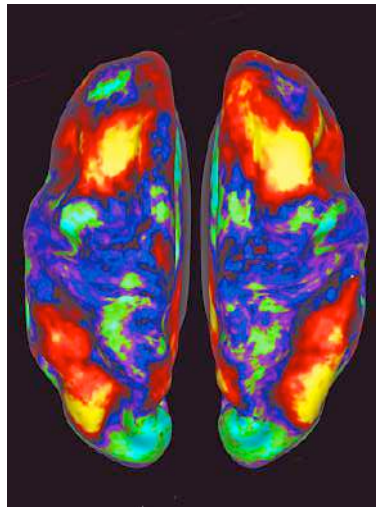
- “**Symbolic simulation** is thus a two-stage affair: first the mapping of inference structure of the theory onto hardware states which defines symbolic computation; second, the mapping of inference structure of the theory onto hardware states which (under appropriate conditions) qualifies the processing as a symbolic simulation.
- Analog simulation, in contrast, is defined by a single mapping from causal relations among elements of the simulation to causal relations among elements of the simulated phenomenon.”

R. Trenholme, “Analog Simulation,” *Philosophy of Science*, vol. 61, no. 1, pp. 115–131, 1994.

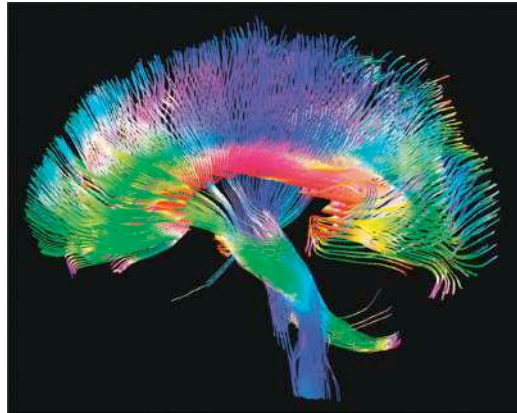
Symbolic vs. sub-symbolic computation (information processing)



Douglas Hofstadter in his dialogue “Prelude...Ant fugue” in Godel, Escher, Bach.

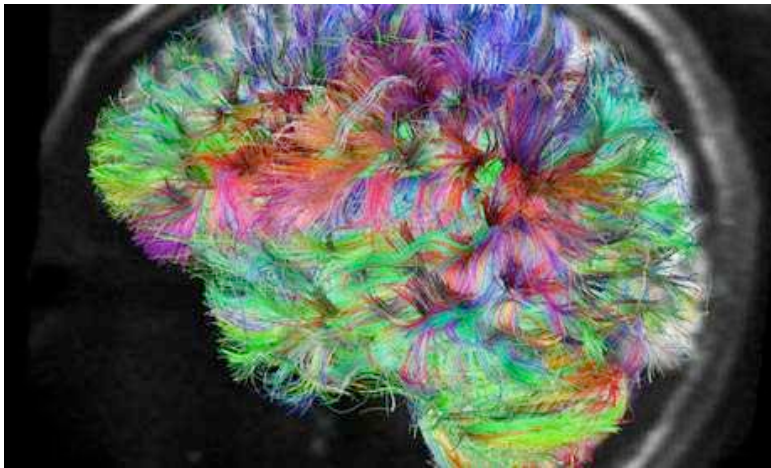


Natural information processing



Human connectome

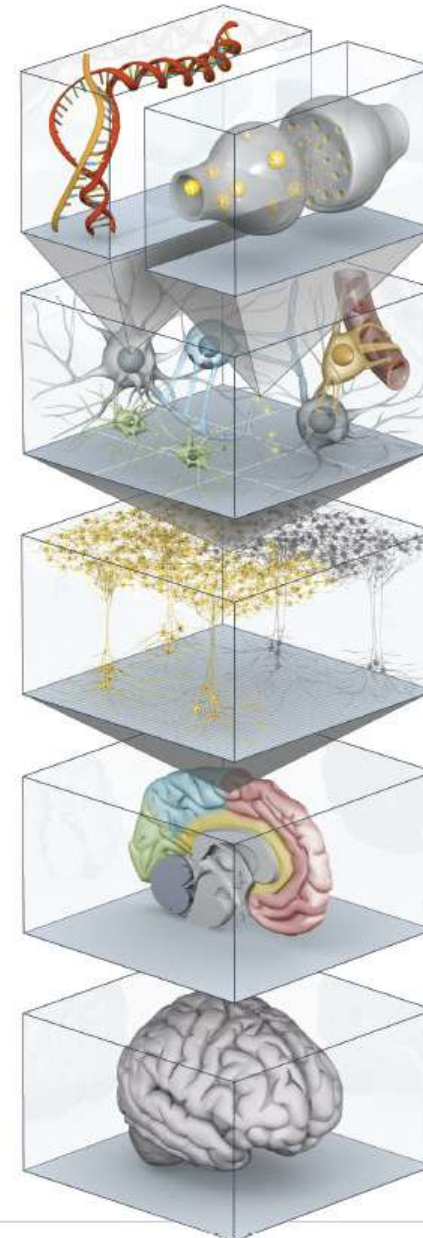
<http://outlook.wustl.edu/2013/jun/human-connectome-project>



<http://www.nature.com/scientificamerican/journal/v306/n6/pdf/scientificamerican0612-50.pdf> The Human Brain Project

Deconstructing the Brain

The Human Brain Project intends to create a computer simulation of the 89 billion neurons inside our skull and the 100 trillion connections that wire those cells together. A meticulous virtual copy of the human brain would potentially enable basic research on brain cells and circuits or computer-based drug trials. The project, which is seeking €1 billion in funding from the European Union, would model each level of brain function, from chemical and electrical signaling up to the cognitive traits that underlie intelligent behaviors.



Molecular

A century of research, beginning with the first inspection of a brain cell under a microscope, would translate into a digital facsimile that combines component molecular parts to assemble a cell that demonstrates the essential properties of a neuron—the transmission of electrical and chemical signals.

Cellular

A brain-in-a-box simulation will have to capture every detail of neurons and nonneuronal glial cells, including the exact geometric shapes of the dendrites and axons that receive and send information.

Circuits

A model of the neural connections between different brain areas and among neighboring cells may furnish clues to the origins of complex brain diseases such as autism and schizophrenia.

Regions

Major neural substructures—the amygdala (emotions), the hippocampus (memory), the frontal lobes (executive control)—can be inspected alone or as they interact with one another.

Whole Organ

An in silico brain might substitute for the actual organ. By removing the computer code for a "gene," the virtual system can, for instance, mimic the effects of a mutation, as scientists do today by "knocking out" a gene in mice. The tool would avoid the lengthy breeding process and could simulate a multitude of experimental conditions.

Henry Markram (2012) The Human Brain Project, *Scientific American* 306, 50 – 55

Info-computationalism, in a nutshell

- Nature can be described as a complex informational structure for a cognizing agent.
- Computation is information dynamics (information processing)
- Computation is constrained and governed by the laws of physics on the fundamental level (morphology).

Morphogenetic/morphological computing. From raw data to semantic information

- Turing proposed diffusion-reaction model of morphogenesis as the explanation of the development of biological patterns (spots and stripes on animal skin).
- Morphogenesis is a process of morphological computing. Physical process – though not computational in the traditional sense, presents natural (unconventional), morphological computation. Essential element in this process is **the interplay between the informational structure and the computational process - information self-structuring and information integration, both synchronic and diachronic, going on in different time and space scales in physical bodies.**

Morphogenetic/morphological computing. From raw data to semantic information

- Info-computational naturalism describes nature as informational structure – a succession of levels of organization of information.
- Morphological computing on that informational structure leads to new informational structures via processes of self-organization of information.
- Evolution itself is a process of morphological computation on a long-term scale. It proceeds through the process of autopoiesis, in the interplay between living organisms and the environment.



Morphological Computation: Connecting <Body>, <Brain>, and <Environment>

soft robotics / self-assembly systems and molecular robotics/
self-assembly systems at all scales / embodied robotics /
reservoir computing / physical reservoir computing/ real neural systems
systems medicine / functional architecture / organization /
process management / computation based on spatio-temporal dynamics/
information theoretical approach to embodiment mechatronics /
amorphous computing / molecular computing

<http://morphcomp.org>

<http://www.eucognition.org/index.php?page=theoretical-scheme> Tutorial on Embodiment: R Pfeifer

A mathematical model for Info-computationalism - A. C. Ehresmann



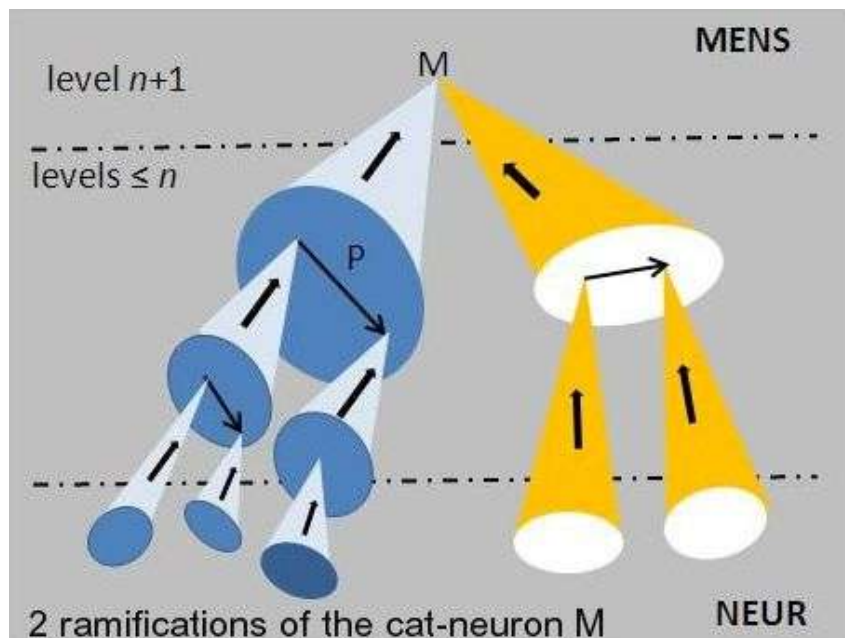
Open peer commentary on the article “Info-computational Constructivism and Cognition” by Gordana Dodig-Crnkovic.

Ehresmann proposes a mathematical approach to the framework developed by Dodig-Crnkovic. Based on the Property of natural computation, called **the multiplicity principle** development of increasingly complex cognitive processes and knowledge is described.

“**Local dynamics are classically computable**, a consequence of the MP is that **the global dynamics is not**, thus raising the problem of developing more elaborate computation models.”

<http://www.idt.mdh.se/~gdc/work/Constructivist%20Foundations%209%282%29.pdf>

An Info-Computational Model for (Neuro-)cognitive Systems Capable of Creativity - Andrée C. Ehresmann



Ehresmann’s model is based on a Dynamic Category Theory, accounting for the functioning of the neural, cognitive and mental systems **at different levels of description and across different timescales.**

Andrée C. Ehresmann <http://www.mdpi.com/1099-4300/14/9/1703>

Information, computation, cognition. Agency-based Hierarchies of Levels

Short summary of the argument:

1. Information constitutes a **structure** consisting of **differences in one system that cause the differences in another system**. In other words, **information is <observer>*-relative**.
2. Computation is **information processing** (dynamics of information). It is **physical process of morphological change in the informational structure** (physical implementation of information, as there is no information without physical implementation.)

*<> brackets indicate that the term is used in a broader sense than usually.

Information, computation, cognition. Agency-based Hierarchies of Levels

3. Both information and computation appear **on many different levels of organisation**/abstraction/resolution/granularity of matter/energy in space/time.
4. Of all agents (entities capable of acting on their own behalf) only **living agents** have the **ability to actively make choices so to increase the probability of their own continuing existence**. This ability of living agents to act autonomously on its own behalf is based on the use of energy/matter and information from the environment.

Information, computation, cognition. Agency-based Hierarchies of Levels

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

Cognition = info-computation

6. **Cognition is equivalent with the (process of) life.***

Its complexity increases with evolution.

This complexification is a result of morphological computation.

* Maturana, H. & Varela, F., 1980. Autopoiesis and cognition: the realization of the living, Dordrecht Holland: D. Reidel Pub. Co.

Conclusions

Info-computationalism bring new more general ideas of:

- **Information** (difference that makes a difference for an agent)
- **Computation** (information dynamics)
- **Cognition** as life (all structures and processes that constitute life)
- studied at different levels of organisation/ abstraction/ granularity (spatial scale)
- And different time scales, taken synchronously/asynchronously

Conclusions

Topics of importance for the development of new understanding of cognition as info-computation and its evolution in the physical world:

- Natural computation/Morphological computation as generalized model of computation (*natural information processing*)
- *Interactivity* as fundamental for computational modelling of concurrent distributed information processing systems such as living organisms and their networks

Some open questions

- Self organization of information in physical agents (and their networks) able to re-structure themselves through interactions with the environment as a result of morphological/morphogenetic computation.
 - On different spatial scales
 - On different temporal scales
- Meta-morphogenesis (Aaron Sloman)
- Abiogenesis – origins of life
- Robotic applications
- Nano-technology applications
- We need the details of the computational behavior on different levels of organization and on different time scales.

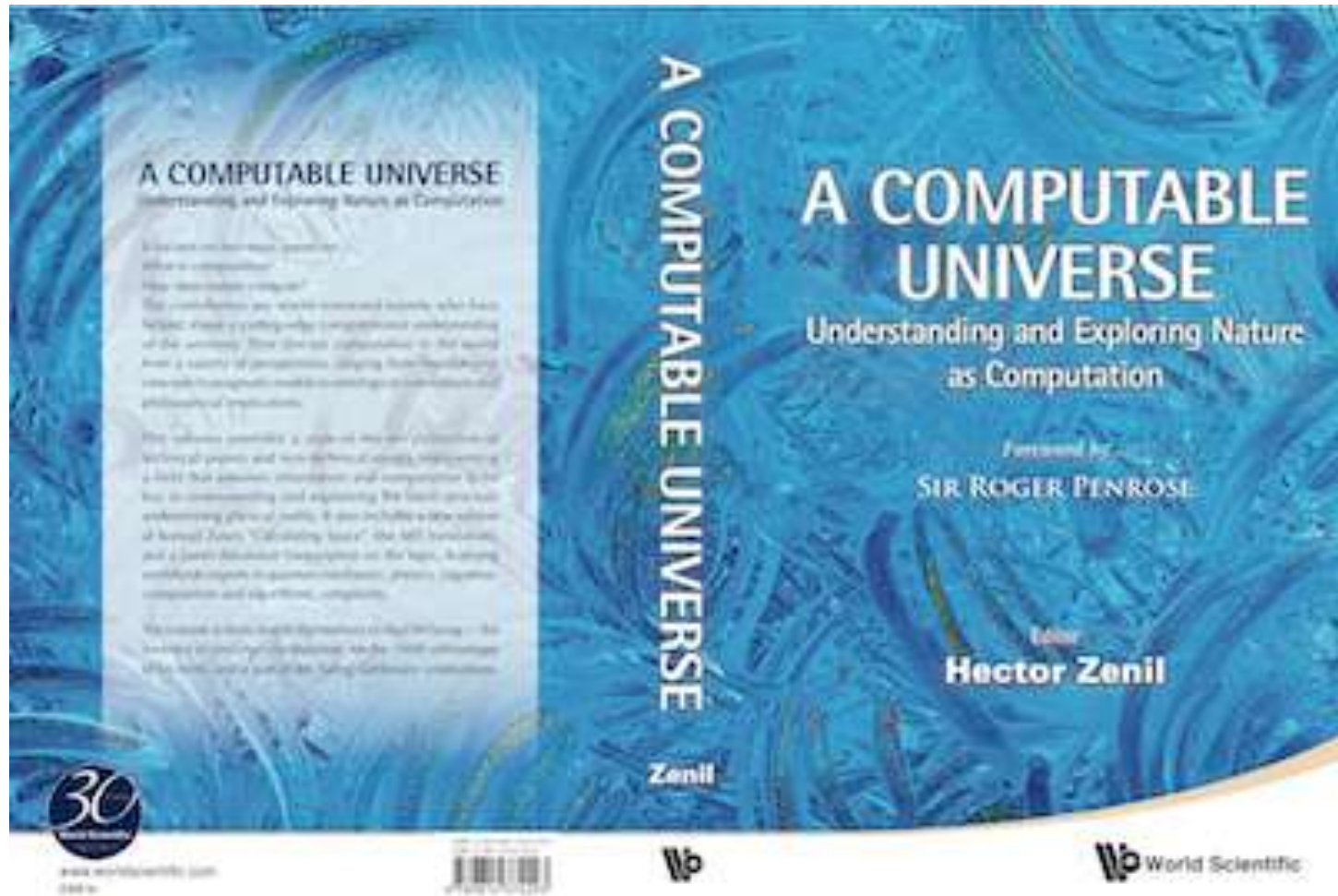


“(O)ur task is nothing less than to discover a new, broader, notion of computation, and **to understand the world around us *in terms of information processing.***”

G. Rozenberg and L. Kari, “The many facets of natural computing,” *Communications of the ACM*, vol. 51, pp. 72–83, 2008.



A computable universe





SPECIAL JOURNAL ISSUES

Information: The Physics of Information (2014)

Guest Editors: H. Zenil and G. Dodig-Crnkovic

http://www.mdpi.com/journal/information/special_issues/physics-information

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Entropy: Natural/ Unconventional Computing

(selection of papers from the Symposium at AISB/IACAP)

Guest Editors: G. Dodig-Crnkovic and R. Giovagnoli

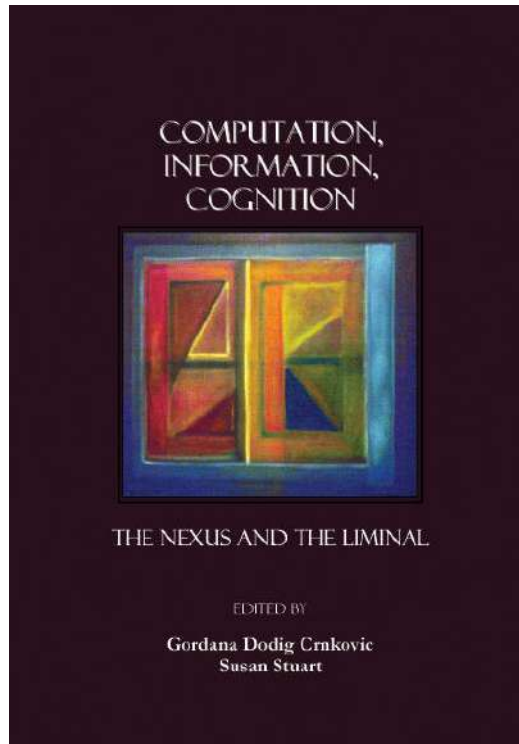
http://www.mdpi.com/journal/entropy/special_issues/unconvent_computing

Information: Information and Energy/Matter

Guest Editor: G. Dodig-

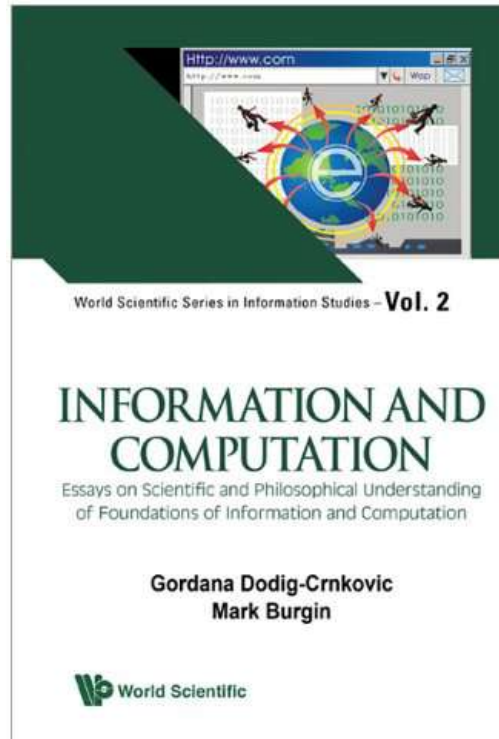
Crnkovic http://www.mdpi.com/journal/information/special_issues/matter

Readings on Computing Nature



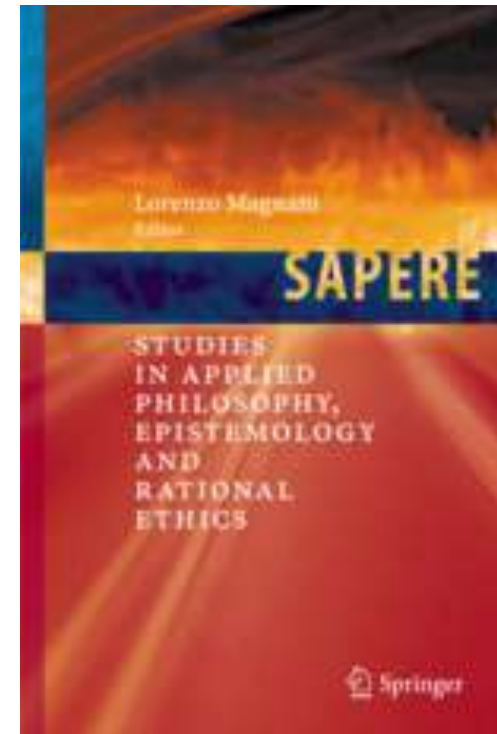
Computation, Information, Cognition

Editor(s): Gordana Dodig Crnkovic and Susan Stuart,
Cambridge Scholars Publishing, 2007



Information and Computation

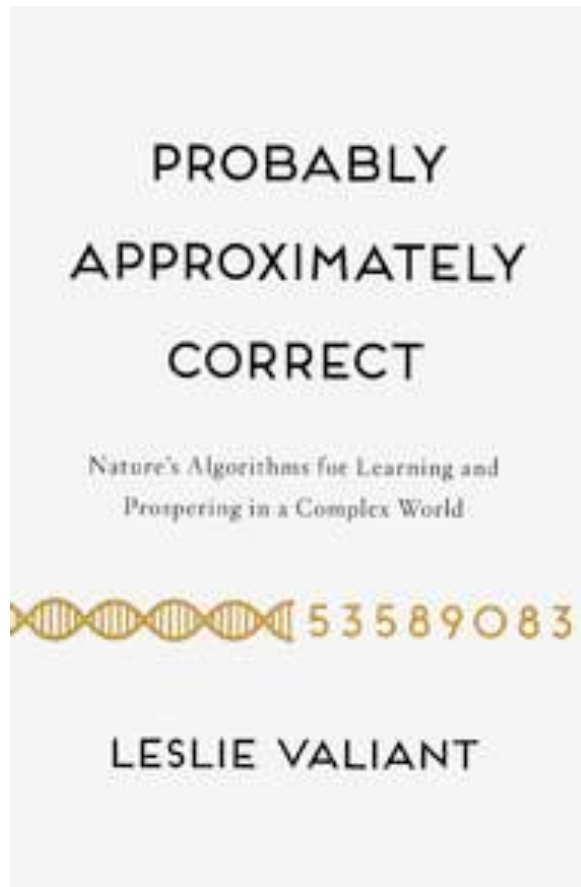
Editor(s): Gordana Dodig Crnkovic and Mark
Burgin, World Scientific, 2011



Computing Nature

Editor(s): Gordana Dodig Crnkovic and
Raffaella Giovagnoli, Springer, 2013

Two new books

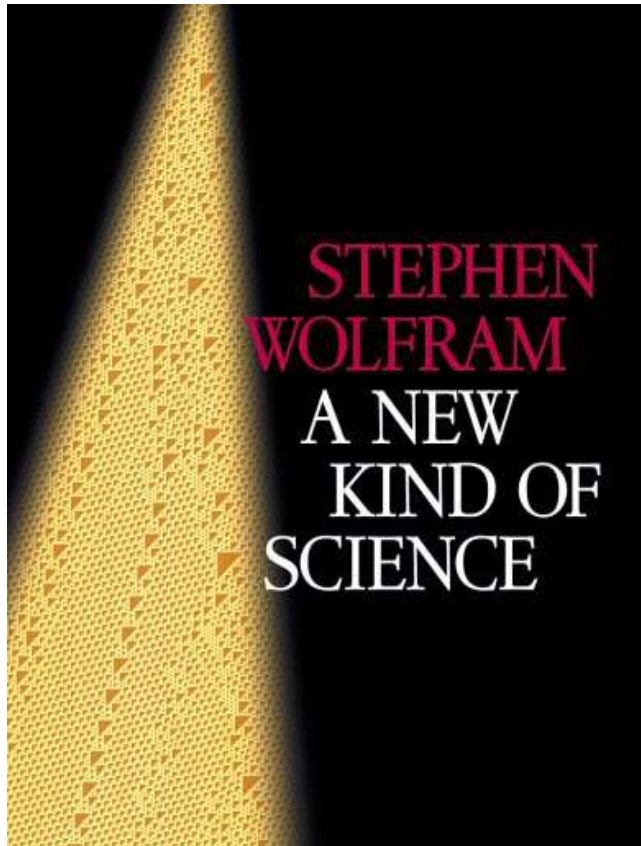


Life, computation, evolution & cognition. Written by a computer scientist.



Physical Computation & Cognition. Written by a philosopher.

Generative computing - A new computational paradigm
- cellular automata



A New Kind of Science

Book available at:

<http://www.wolframscience.com>

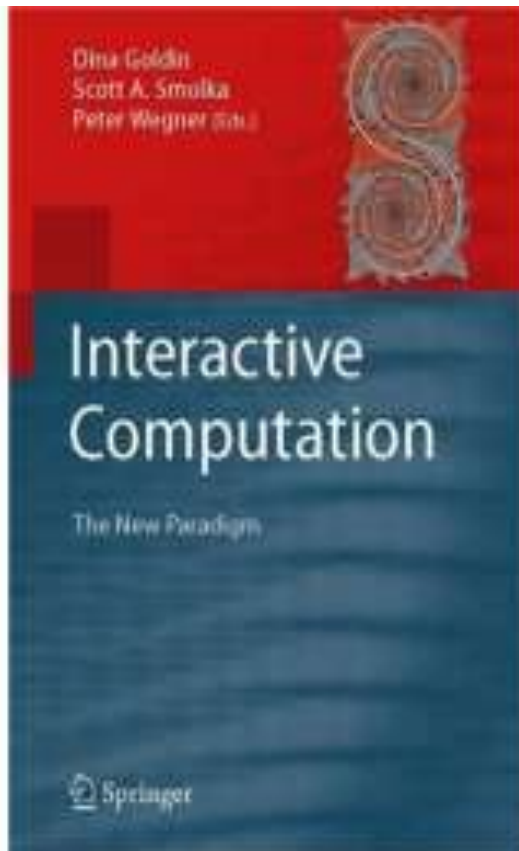
Based on cellular automata, complexity emerging from repeating very simple rules

See also

<http://www.youtube.com/watch?v=eC14GonZnU>

A New Kind of Science - Stephen Wolfram

Interactive Computation - A New Paradigm of Computation



Interactive Computation: the New Paradigm
Springer-Verlag in September 2006

Dina Goldin, Scott Smolka, Peter Wegner, eds.

Dina Goldin, Peter Wegner

*The Interactive Nature of Computing:
Refuting the Strong Church - Turing Thesis*

Minds and Machines

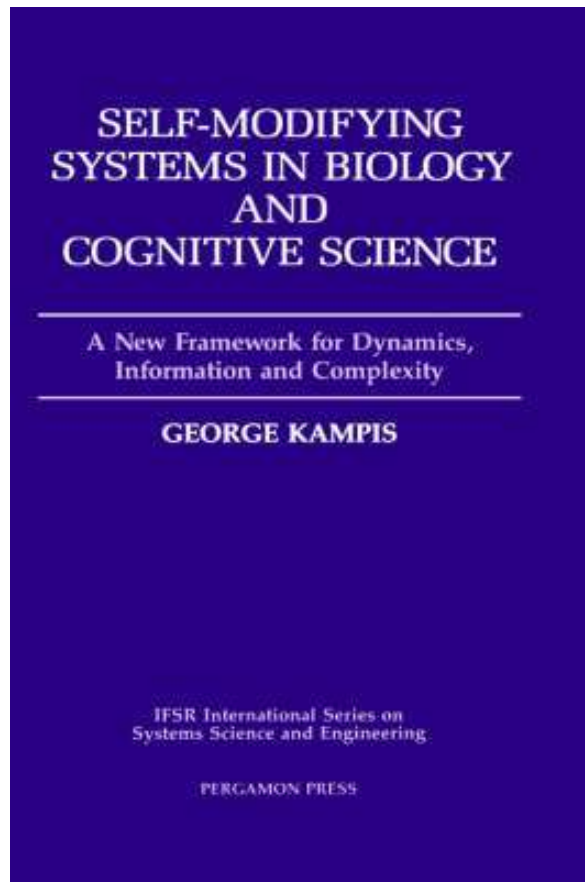
Volume 18 , Issue 1 (March 2008) p 17 - 38

<http://www.cs.brown.edu/people/pw/strong-cct.pdf>

Biology as Reactivity

http://research.microsoft.com/pubs/144550/CACM_11.pdf

Self-modifying Systems in Biology and Cognitive Science

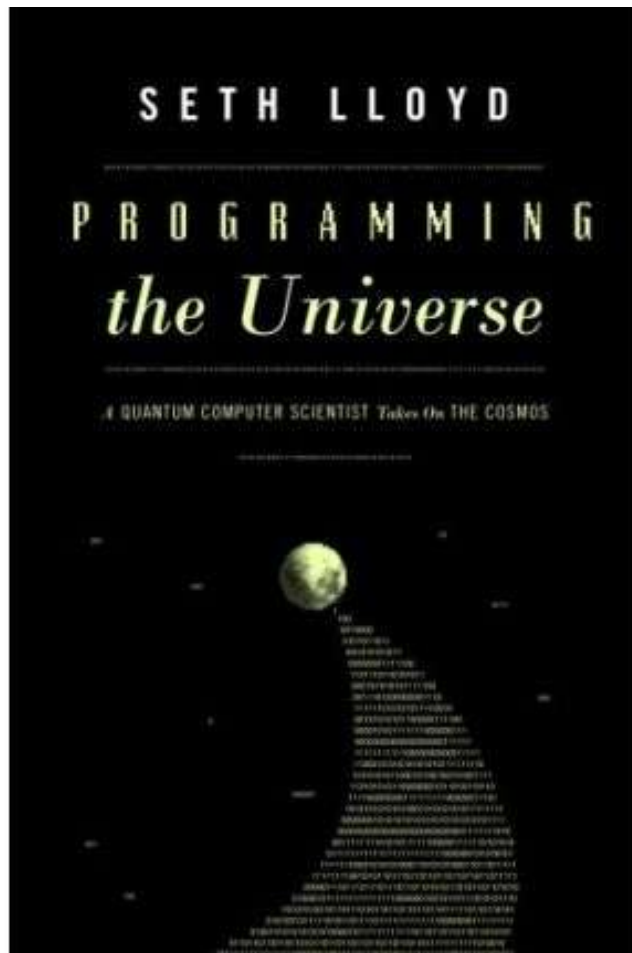


The topic of the book is the self-generation of information by the self-modification of systems. The author explains why biological and cognitive processes exhibit identity changes in the mathematical and logical sense. This concept is the basis of a new organizational principle which utilizes shifts of the internal semantic relations in systems.

ftp://wwwc3.lanl.gov/pub/users/joslyn/kamp_rev.pdf



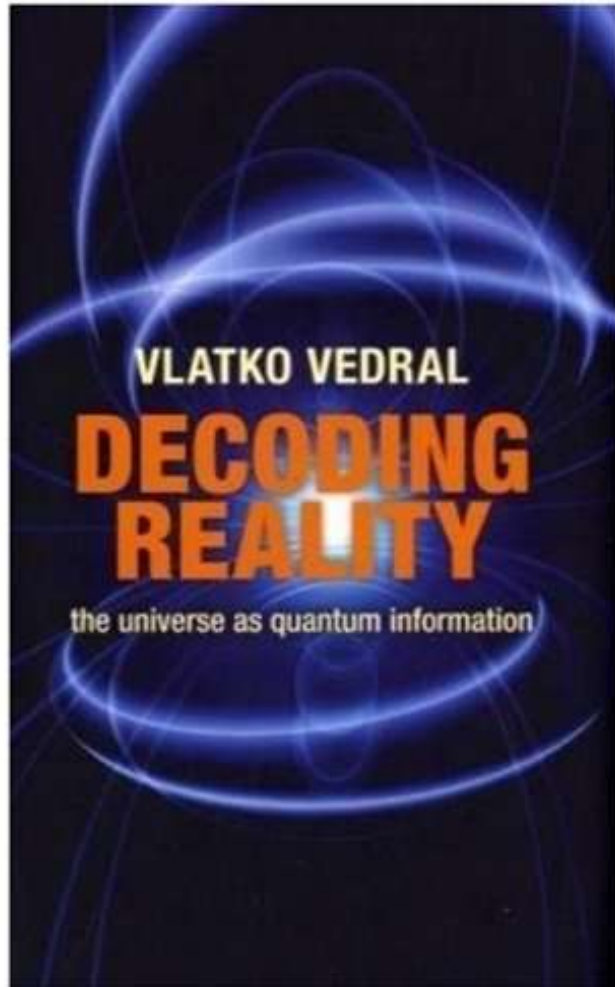
The Universe as quantum information



Programming the Universe: A Quantum Computer Scientist Takes on the Cosmos

by Seth Lloyd

The Universe as quantum information



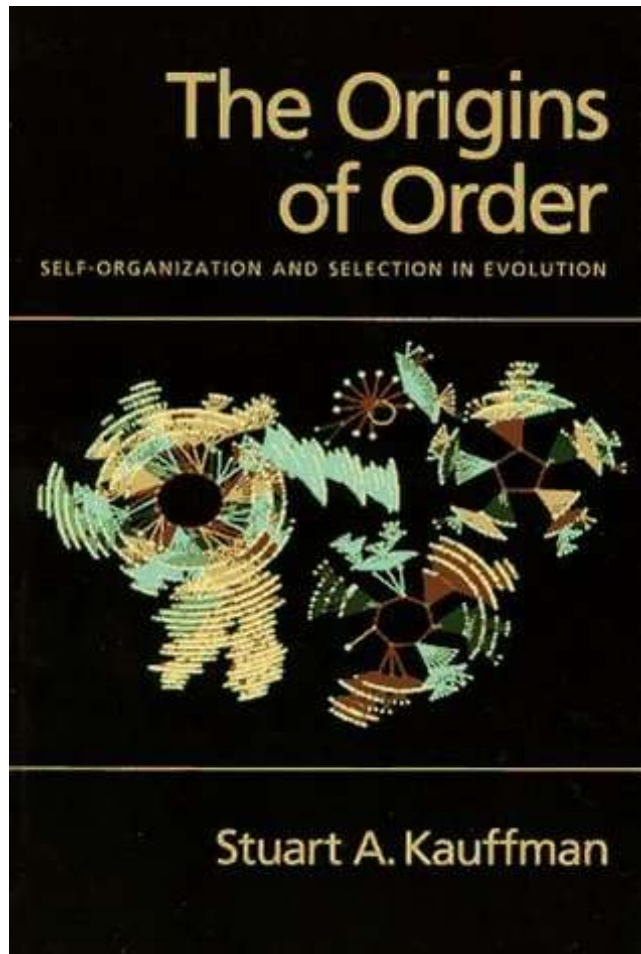
Decoding Reality

Vlatko Vedral

Reality = Information

Under Google books there are parts of this book available.

Self-Organization and Selection in Evolution

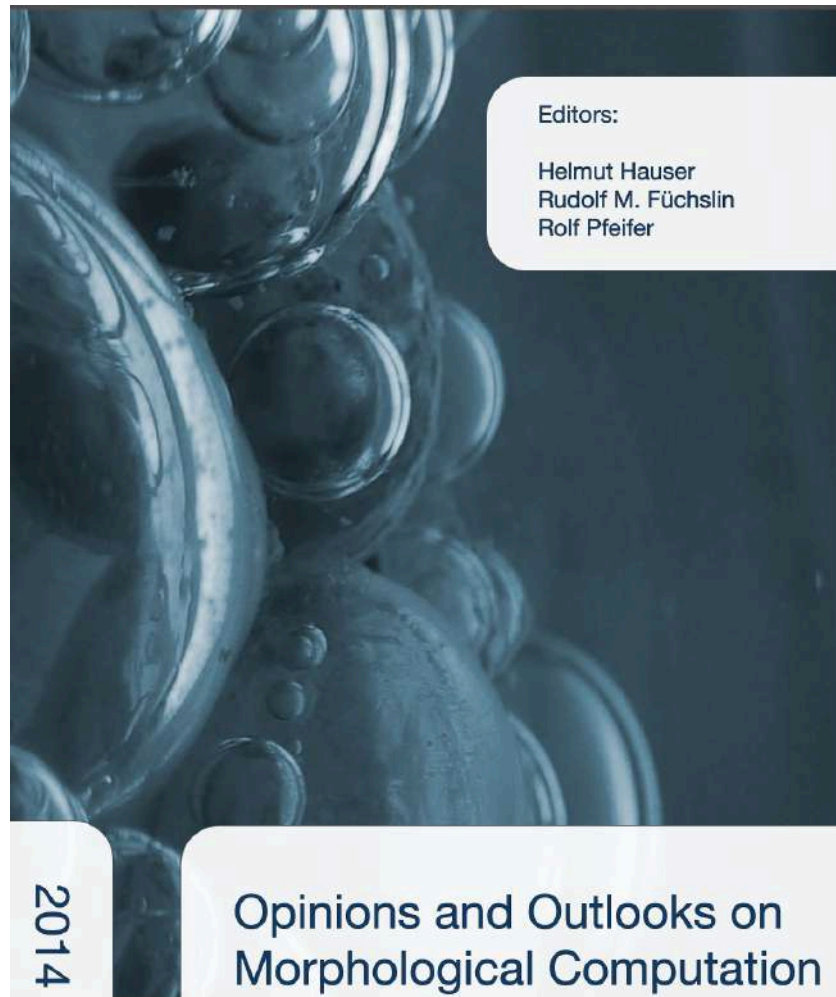


Stuart Kauffman argues that self-organization plays an important role in the emergence of life itself and may play as fundamental a role in shaping life's subsequent evolution as does the Darwinian process of natural selection.

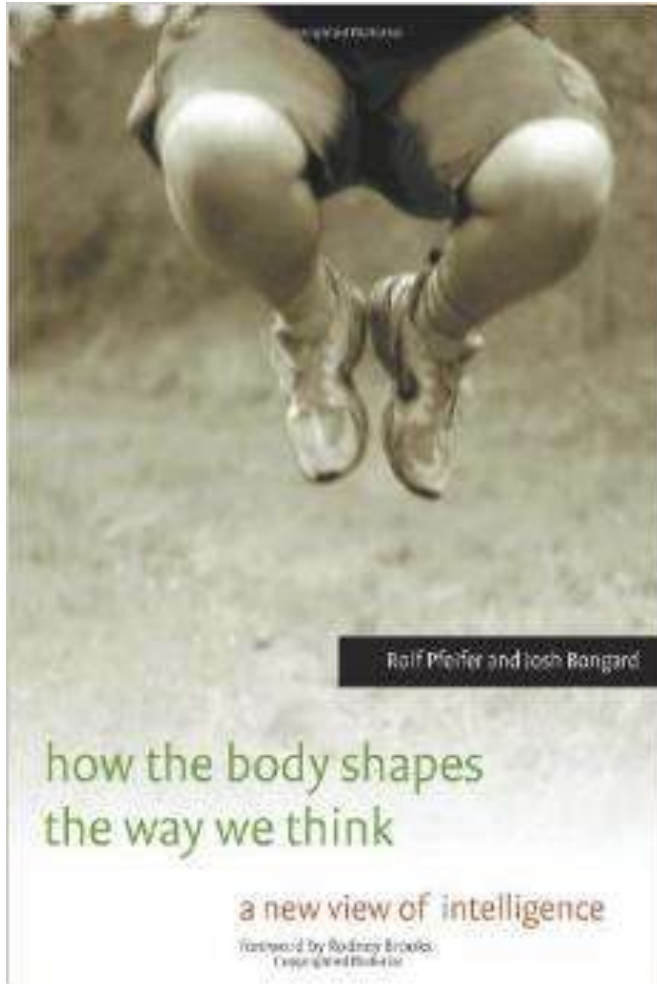
http://books.google.se/books/about/The_Origins_of_Order.html?id=IZcSpRJz0dgC&redir_esc=y



Connecting to the ShangAI Course Readings



**How the Body Shapes the Way We Think:
A New View of Intelligence**





How the Body Shapes the Way We Think:

A New View of Intelligence

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6.2 The Basics of Evolutionary Computation 184

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A New View of Intelligence

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Based on the Articles

- Dodig-Crnkovic, G. [Information, Computation, Cognition. Agency-based Hierarchies of Levels. In V. C. Müller \(Ed.\), Fundamental Issues of Artificial Intelligence \(Synthese Library\). Berlin: Springer. \(forthcoming\)](#)
- Dodig-Crnkovic, G. [Modeling Life as Cognitive Info-Computation, In: Computability in Europe 2014, Arnold Beckmann, Erzsébet Csuhaj-Varjú and Klaus Meer \(Eds.\) Proceedings of the 10th Computability in Europe 2014, Language, Life, Limits, Budapest, Hungary, June 23 - 27, 2014, LNCS, Springer](#)
- Dodig-Crnkovic, G. [Info-computational Constructivism and Cognition](#), *Constructivist Foundations* (2014), 9(2) pp. 223-231

Based on the Articles

- Dodig-Crnkovic G., [Dynamics of Information as Natural Computation](#), Information 2011, 2(3), 460-477; doi:10.3390/info2030460 Special issue: Selected Papers from FIS 2010 Beijing Conference, 2011.
http://www.mdpi.com/journal/information/special_issues/selectedpap_beijing
<http://www.mdpi.com/2078-2489/2/3/460/> See also:
http://livingbooksaboutlife.org/books/Energy_Connections
- Dodig-Crnkovic, G. [Information, Computation, Cognition. Agency-based Hierarchies of Levels](#). In V. C. Müller (Ed.), [Fundamental Issues of Artificial Intelligence \(Synthese Library\)](#). Berlin: Springer. (forthcoming)