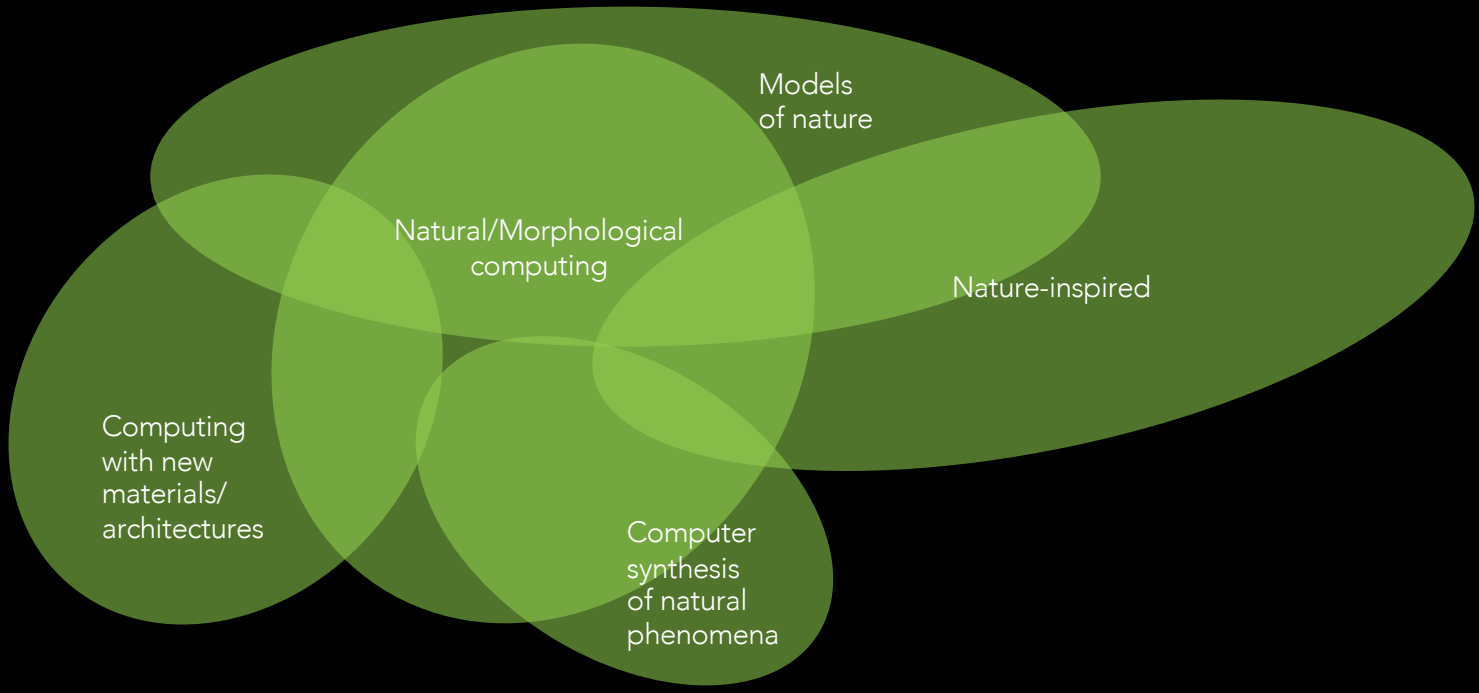
IS4SI 2019 Berkeley, 2019 06 04

Morphological, Natural, Analog, and other Unconventional Computing for Cognition and Intelligence



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Chalmers University of Technology and University of Gothenburg
& Mälardalen University, Sweden
http://www.gordana.se

Where is the I (sense of self) in AI?
Generating the meaning in information

The theme of the IS4SI 2019 invites for a discussion of intelligence, artificial intelligence, cognition and meaning.

Recent impressive success of machine learning for the capacities until recently considered exclusively human:

- speech recognition and speech generation
- conversational agents
- pattern recognition and classification
- self-driving cars

We know for sure that those computational devices do not have "sense of self".

But what is it that constitute meaning for an agent? What is agenthood for a human and for a machine? What would be the "I" of a machine?

"AI makes philosophy honest"

Even without AI, we do not know what "I" is, we do not know what intelligence is, we do not know what cognition is - in spite of extensive literature in philosophy, psychology, cognitive science and other brain sciences (cognitive neuroscience, developmental neuroscience, molecular and cellular neuroscience, neural engineering, neuroimaging, neurolinguistics, clinical neuroscience, systems neuroscience, and theoretical and computational neuroscience)

"AI makes Philosophy honest."

Daniel Dennett in a talk at the International Computers and Philosophy Conference, Laval, France in 2006

There is a two-way process going on: learning from sciences and humanities about cognition and intelligence and trying to generate cognitive and intelligent behavior in the artifacts.

See also: Daniel C. Dennett (2017) From Bacteria to Bach and Back: The Evolution of Minds. Norton. London, New York

In search of lost "I" in AI

Historical attempts: GOFAI and classical computationalism has shown their limitations. Based on symbolic computation and classical logic.

The development continued mostly in the direction of "narrow AI" that is solving one problem at the time – image recognition, speech recognition and generation etc.

More adequate and holistic modelling of cognition and intelligence in natural systems new insights made through EEEE- cognition (Embodied, Embedded, Enactive, Extended) cognition.

However, those developments are still not generally well known and we continue to discuss inadequacy of the classical cognitivism and GOFAI. Although (Scheutz, 2002) almost two decades ago pointed out new computational approaches beyond classical TM models, for a richer description of cognition and intelligence, many still continue to discuss the old computationalism.

A Two way learning process -

Learning from nature about cognition and intelligence and the development of new models of computation for applications to cognition and intelligence

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

— Ilya Prigogine. The End of Certainty: Time, Chaos and New Laws of Nature, 1997

"Developing formal tools capable of integrating this missing cipher—absential influence—into the fabric of the natural sciences is an enterprise that should be at the center of scientific and philosophical debate."

— Terrence W. Deacon, Incomplete Nature: How Mind Emerged from Matter

"In these times brimming with excitement, our 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."

— Lila Kari, Grzegorz Rozenberg, The Many Facets of Natural Computing. Communications of the ACM, October, Vol. 51 No. 10, Pages 72-83. 2008

Beyond Abstract Model of Computation/Calculation

Distributed, concurrent, resource-aware, embodied computing

The progress of computing depends on the development of hardware & software - algorithms, programming languages, compilers and interpreters, operating systems, virtual machines –all of which developed substantially since Turing time. Yet a lot of software development is still considered as applications of Turing Machine model.

Computability Theory is still based on Turing Machine model of computation.
This includes ("P = NP?") problem.

Research is always moving forward. Even the basic concepts such as space, time, mass, and energy evolve. It is time to move forward with the theoretical model of computation that will be more adequate for: distributed concurrent computing, resource aware (limited time, space, energy.

http://www.teuscher.ch/alanturing/index1.php?content=turing_day_home Turing day: Alan Turing, Life and Legacy. Lausanne EPFL, 2002

Intelligent Computing

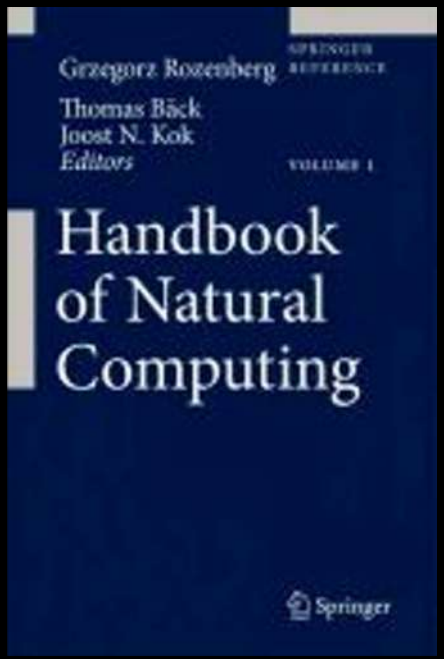
One of the ideals of computing ever since the time of Turing is *intelligent computing*, which would imply machine capable of not only executing mechanical procedure, but even intelligent problem solving. In a 1948 report, Turing suggested that the infant human cortex was an "unorganized machine".*

Thus the next goal after purely syntactic LCM (logical computing machine)** was a computer able to simulate behaviour of human *mathematician,* capable of intelligent insight.

*Webster CS. Alan Turing's unorganized machines and artificial neural networks: his remarkable early work and future possibilities. *Evolutionary Intelligence* 2012: 5; 35-43.

**B. Jack Copeland (2004) The Essential Turing: Seminal Writings in Computing, Logic, Philosophy, Artificial Intelligence, and Artificial Life plus The Secrets of Enigma 1st Edition

Beyond Conventional Computing: 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.

Natural Computing vs. Morphological Computing vs. Nonconventional Computing

Morphology studies shape, structure, pattern and material.

Structure and material are related. In the description of physical systems – material on one level of abstraction is a structure on the level below, (e.g. atom is a structure of protons, neutrons and electrons).

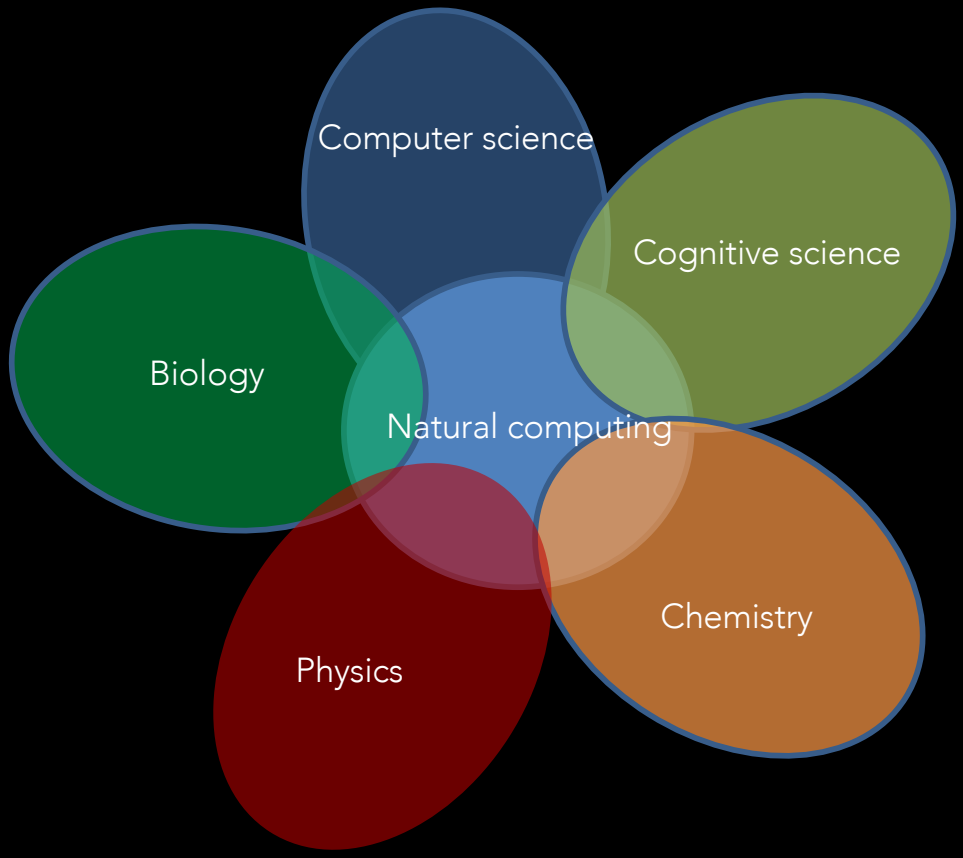
Morphology is described by data/information which describe a structure.

Dynamical processes on informational structure are morphological computation.

Morphological computing is a specific approach to natural computing which models nature in terms of structures and processes on those structures.

Nonconventional computing stands for all models and applications of computing that differs from the conventional ones. Natural computing, unconventional computing, cognitive computing are examples.

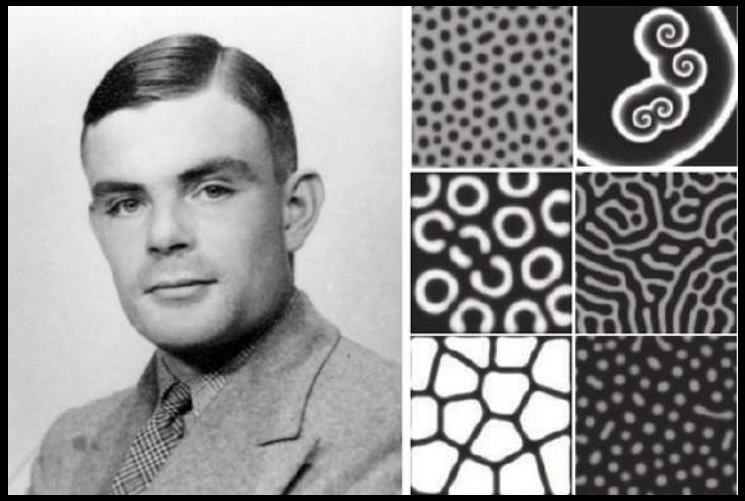
Transdisciplinarity of Natural Computing Research



Transdisciplinary character of knowledge field of natural computing

See also: Peter J. Denning. 2007. Computing is a natural science. Commun. ACM 50, 7 (July 2007), 13-18.
DOI: https://doi.org/10.1145/1272516.1272529

Turing beyond Turing Machine Model



2012 we celebrated 100th Turing birthday

Alan Turing was:

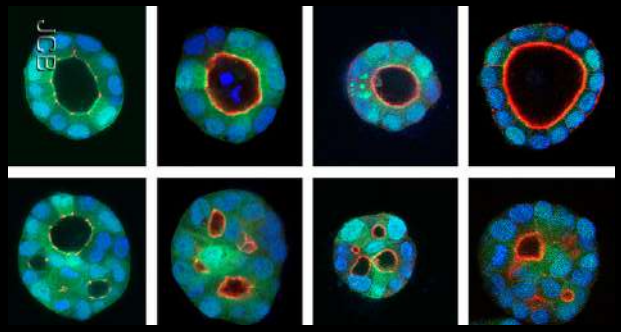
Mathematician

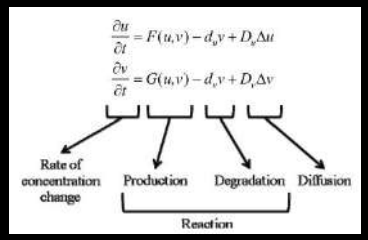
Originator of the "Logical Machine" (TM) computability theory

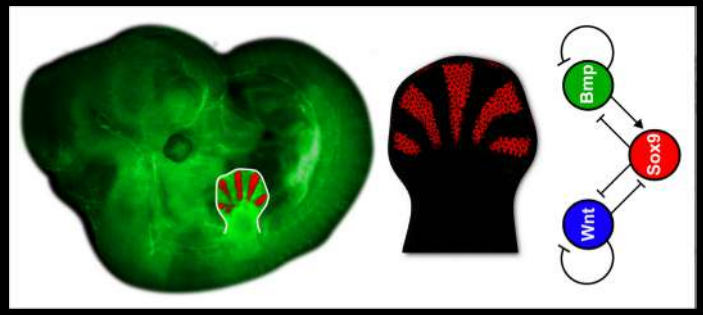
codebreaker

natural philosopher

visionary man before his time







Researchers confirm that a mathematical theory first proposed by Alan Turing in 1952 can explain the formation of fingers
https://www.crg.eu/en/news/crg-researchers-confirm-mathematical-theory-first-proposed-alan-turing-1952-can-explain-formation-fingers

http://www.cs.usfca.edu/www.AlanTuring.net/turing_archive/index.html Jack Copeland and Diane Proudfoot
http://www.turing.org.uk/turing The Alan Turing Home Page, Andrew Hodges

Barry Cooper: “The Bias of Mathematicians”

“Embodiment invalidating the `machine as data' and universality paradigm.”

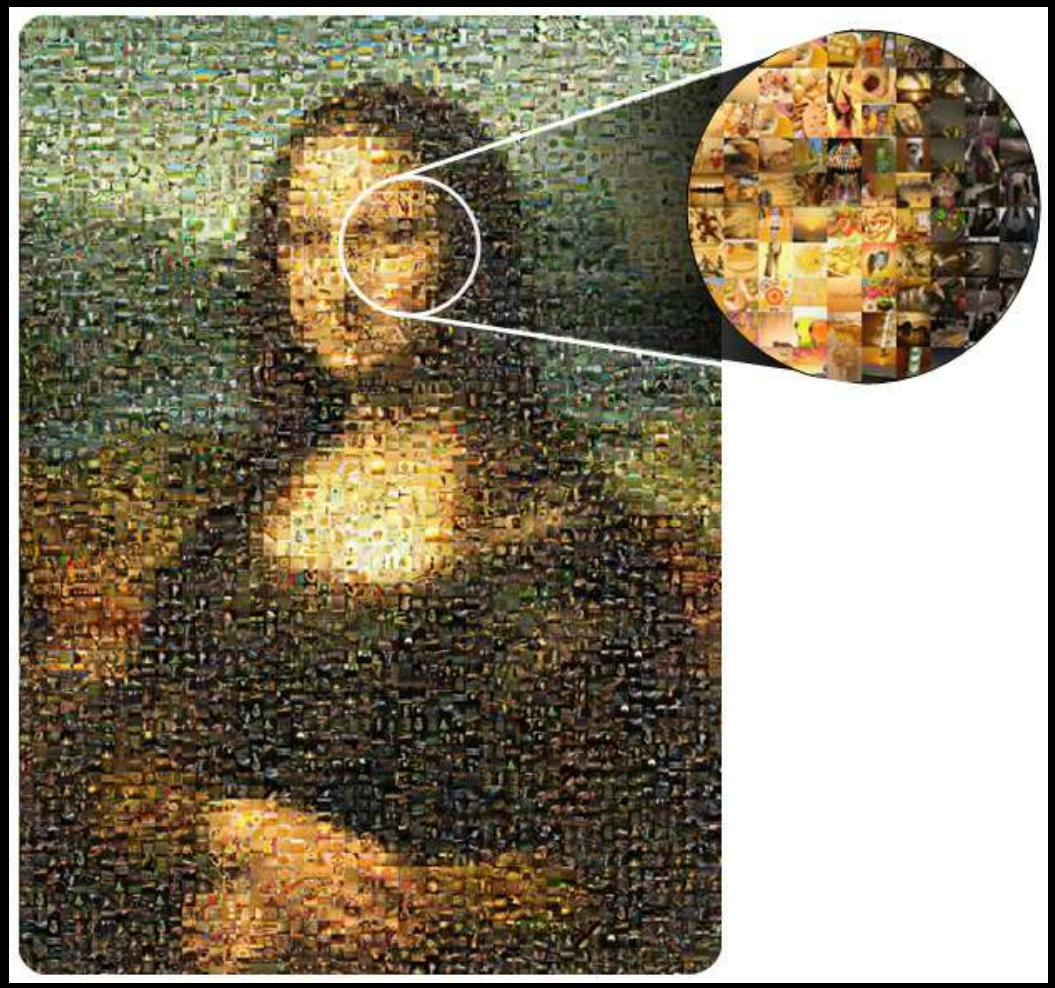
What is needed today is:

“A reaffirmation of experiment and evolving hardware, for both AI and extended computing generally.”

“The validating of a route to creation of new information through interaction and emergence. “

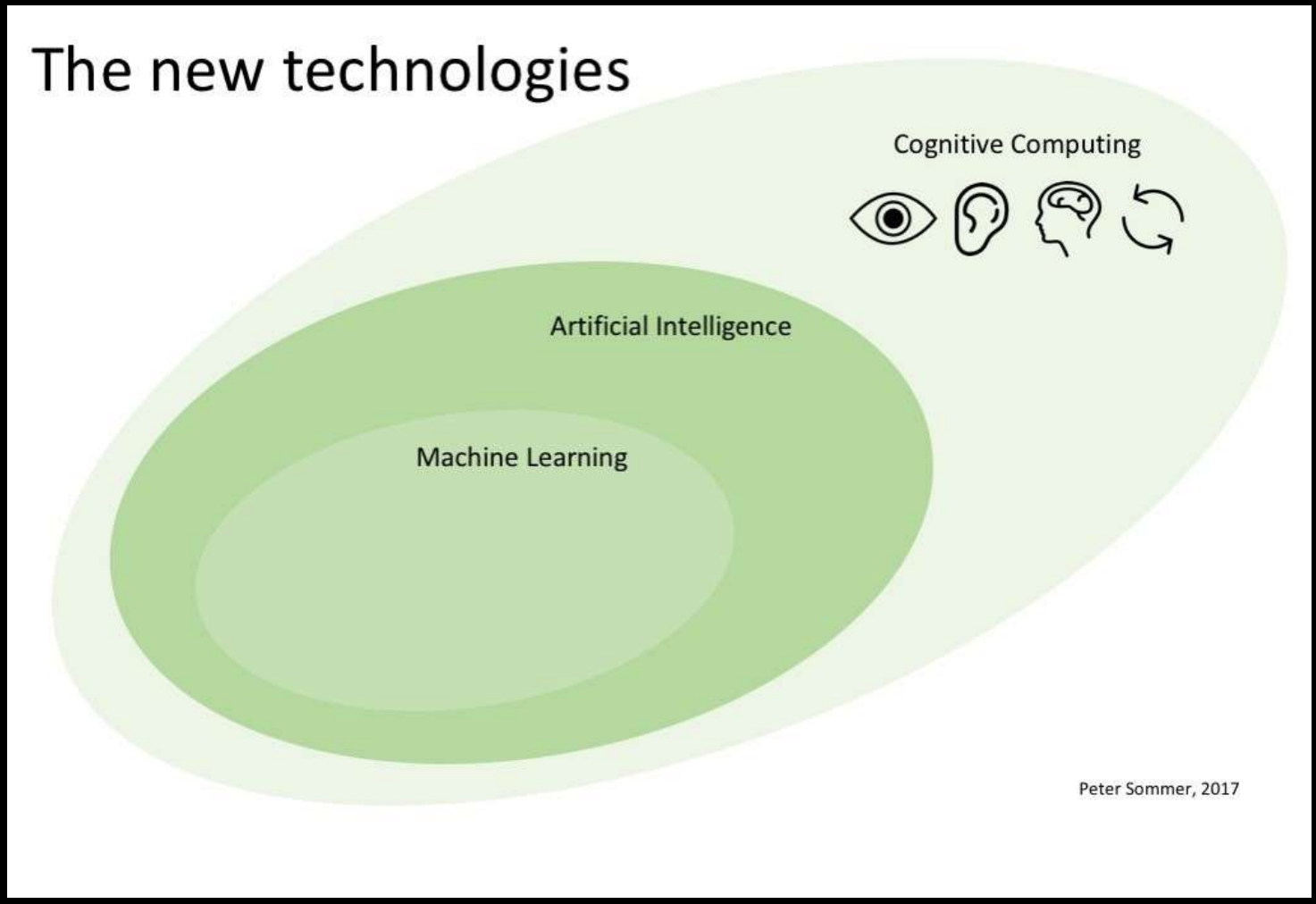
S. B. Cooper, “Turing’s Titanic Machine?,” Communications of the ACM, vol. 55, no. 3, pp. 74–83, 2012

Turing Machines and a Modelling of Complex Systems



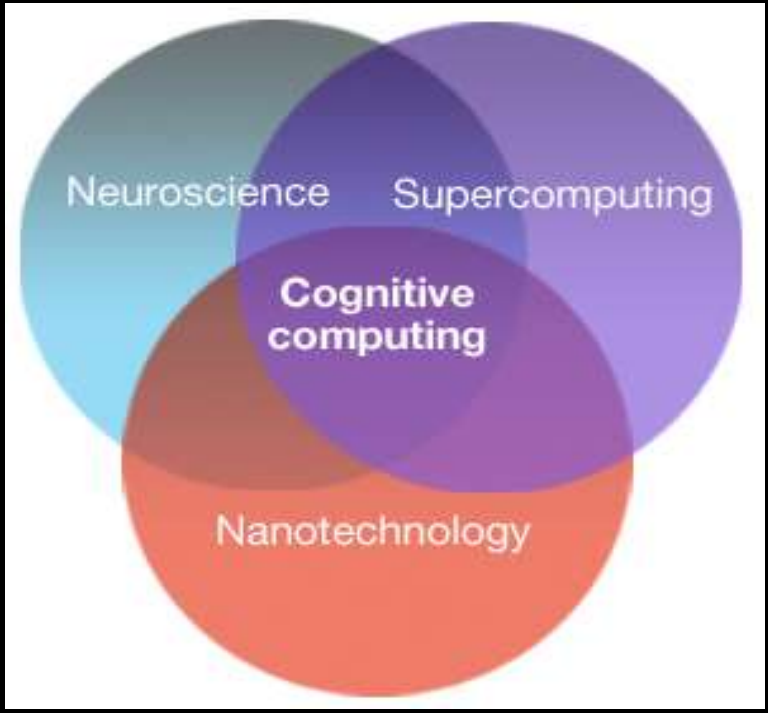
Simplified, one can say: anything can be used to model anything else – in some way. The question is how meaningful (or applicable or adequate) the model is.

Artificial Intelligence, Machine Learning and Cognitive Computing



https://www.ibm.com/blogs/nordic-msp/artificial-intelligence-machine-learning-cognitive-computing/

Unconventional computing: Cognitive Computing



Cognitive Informatics (CI) is a discipline across computer science, information science, cognitive science, brain science, intelligence science, knowledge science and cognitive linguistics, which investigates into the internal information processing mechanisms and processes of the brain, the underlying abstract intelligence theories and denotational mathematics, and their engineering applications in cognitive computing and computational intelligence.

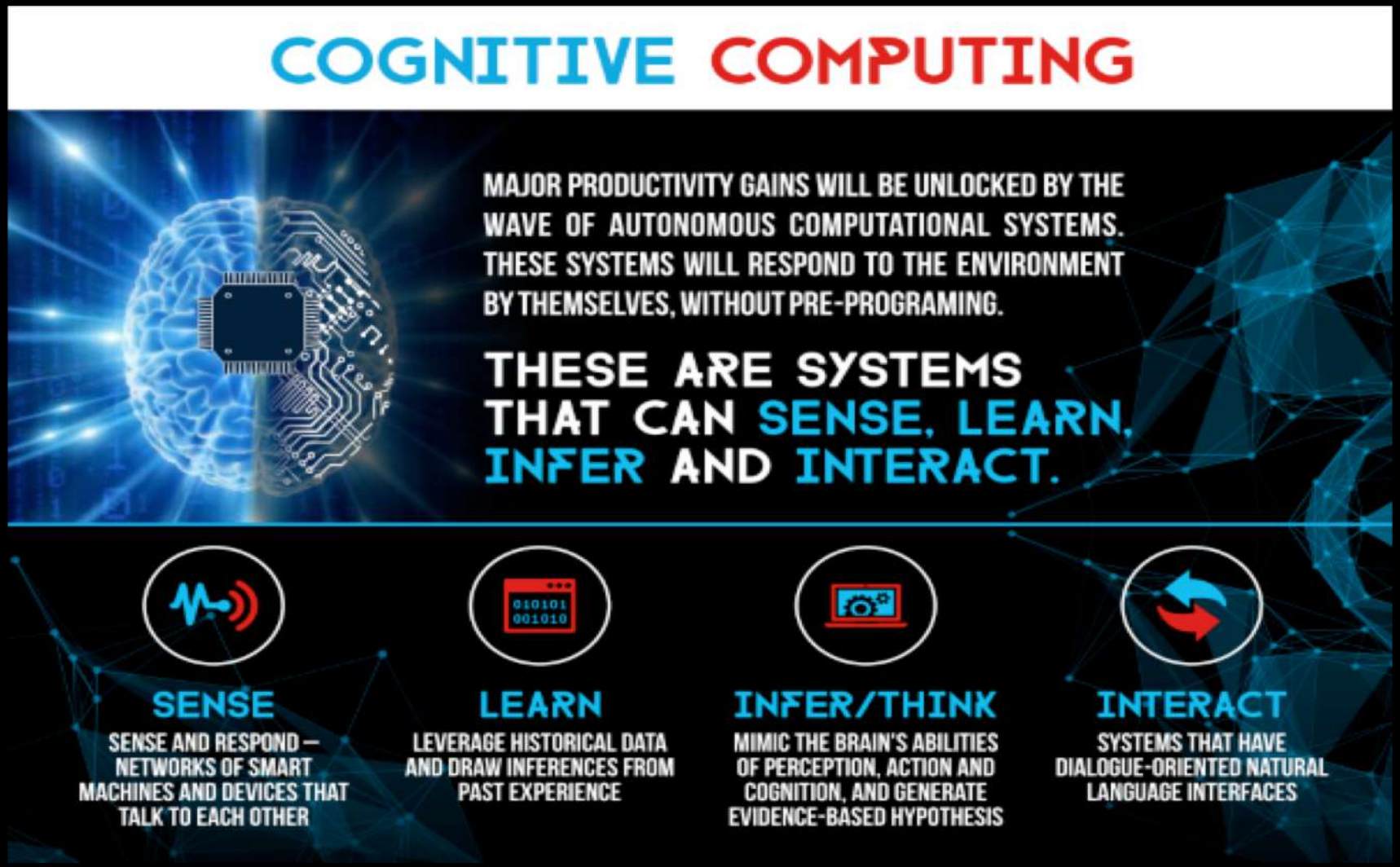
Cognitive Computing (CC) is a novel paradigm of intelligent computing theories and methodologies based on Cognitive Informatics that implements computational intelligence by autonomous inferences and perceptions mimicking the mechanisms of the brain.

http://www.ucalgary.ca/icic/ The International Institute of Cognitive Informatics and Cognitive Computing

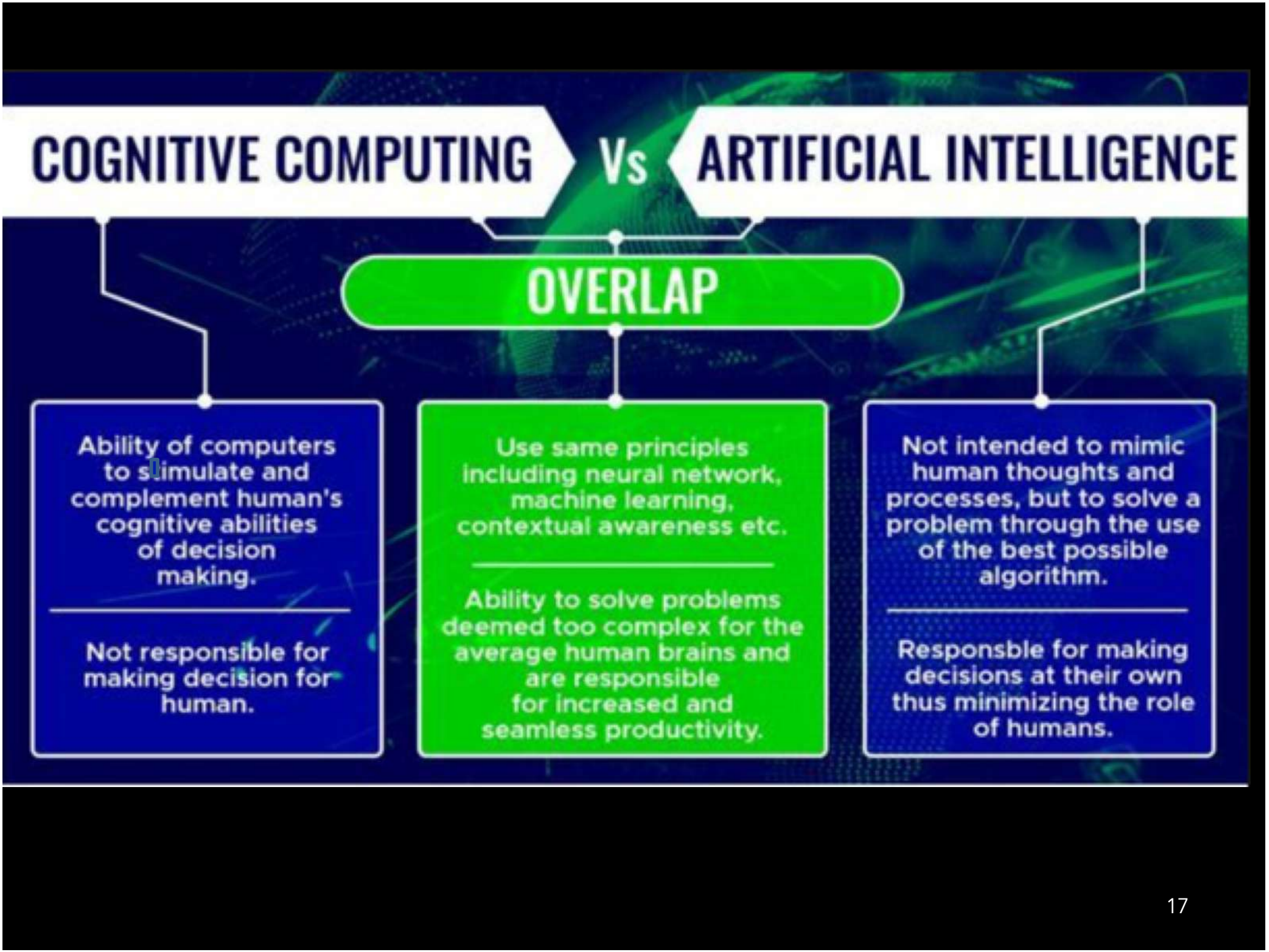
http://www.kurzweilai.net/ibm-unveils-cognitive-computing-chips-combining-digital-neurons-and-synapses

Machine Cognition

Machines that sense, learn, reason/think and interact with us in natural language



http://www.enterrasolutions.com/media/Wipro-Cognitive-Computing-2.png


COGNITIVE COMPUTING
Vs
ARTIFICIAL INTELLIGENCE
OVERLAP
Ability of computers to stimulate and complement human's cognitive abilities of decision making.
Not responsible for making decision for human.
Use same principles including neural network, machine learning, contextual awareness etc.
Ability to solve problems deemed too complex for the average human brains and are responsible for increased and seamless productivity.
Not intended to mimic human thoughts and processes, but to solve a problem through the use of the best possible algorithm.
Responsble for making decisions at their own thus minimizing the role of humans.

Info-computational framework for cognition and intelligence – in search for an "I" of an agent

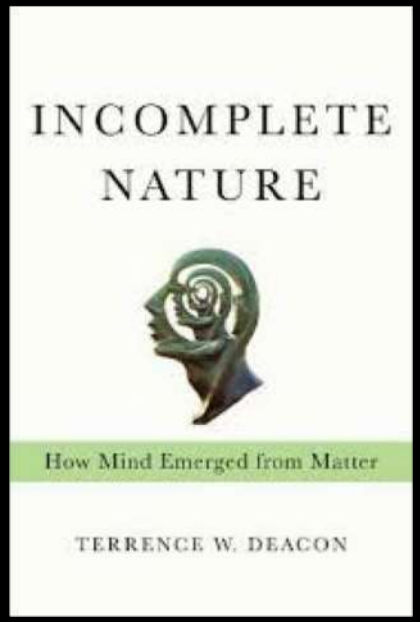
The open question about levels of abstraction is analyzed within the framework of info-computational constructivism, with natural phenomena modeled as computational processes on informational structures.

Info-computationalism is a synthesis of informational structuralism (nature is informational structure for an agent) (Floridi, Sayre) and natural computationalism/pancomputationalism (nature computes its future states from its earlier states) (Zuse, Fredkin, Wolfram, Chaitin, Lloyd)

Whatever exists for an agent comes in a form of information.

Information stands for matter-energy structures of the physical world.

Computing Nature – Levels of organization



Deacon distinguishes between the three forms of information:

Information 1 (Shannon) (data, pattern, signal) (data communication) [what it exhibits—syntax]

Information 2 (Shannon + Boltzmann) (intentionality, aboutness, reference, representation, relation to object or referent) [what it conveys—semantics]

Information 3 ((Shannon + Boltzmann) + Darwin) (function, interpretation, use, pragmatic consequence) [what it's for—pragmatics]

In terms of dynamical processes it ciórresponds to
Thermo- [Morpho- [Teleo-dynamics]]]

Mass-energetic [self-organization [self-preservation (semiotic)]]] levels

and corresponding Aristotle's causes [Efficient [Formal [Final cause]]]

Ehresmann, Andrée C. (2012) "MENS, an Info-Computational Model for (Neuro-)cognitive Systems Capable of Creativity." Entropy 14, no. 9: 1703-1716. https://www.mdpi.com/1099-4300/14/9/1703

Info-computational framework

The world presents potential information for an agent. Information is relational.

Computation is in general information processing. Suitable model for computation within info-computational framework is Hewitt's Actor model.

Hewit's actors can be seen as agents.

Info-computationalism is a kind of physicalism where physical matter is represented by information, and information processing is physical computation.

Life as info-computational generative process of cognition at different levels of organization

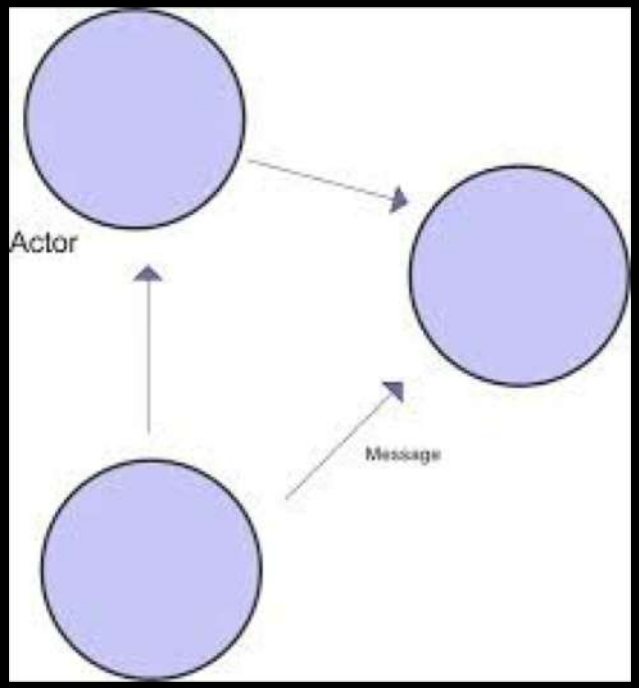
An agent is an entity capable of acting on its own behalf.

It can be seen as an "actor" in the Actor model of computation in which "actors" are the basic elements of concurrent computation exchanging messages, capable of making local decisions and creating new actors.

Computation is thus distributed in space where computational units communicate asynchronously and the entire computation is not in any well-defined state.

(An actor can have information about other actors that it has received in a message about what it was like when the message was sent.) (Hewitt, 2012)

Actor model of concurrent distributed computation



"In the Actor Model [Hewitt, Bishop and Steiger 1973; Hewitt 2010], computation is conceived as distributed in space, where computational devices communicate asynchronously and the entire computation is not in any well-defined state.

(An Actor can have information about other Actors that it has received in a message about what it was like when the message was sent.) Turing's Model is a special case of the Actor Model."
(Hewitt, 2012)

Hewitt's "computational devices" are conceived as computational agents – informational structures capable of acting on their own behalf.

Actor model of concurrent distributed computation

Actors are the universal primitives of concurrent distributed digital computation. In response to a message that it receives, an Actor can make local decisions, create more Actors, send more messages, and designate how to respond to the next message received.

For Hewitt Actors rise to the level of "Agenthood " when they competently process expressions

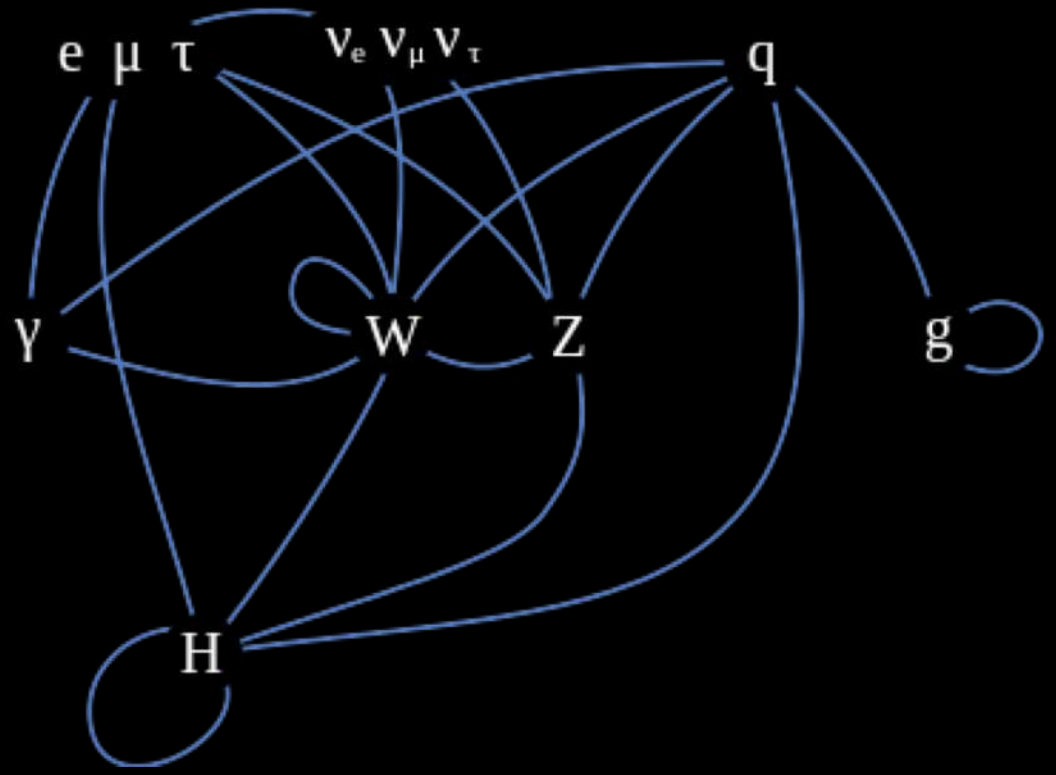
for commitments including the following:

Contracts, Announcements, Beliefs, Goals, Intentions, Plans,

Policies, Procedures, Requests, Queries.

In other words, his agents are human-like.

Actor model of concurrent distributed computation



Unlike other models of computation that are based on mathematical logic, set theory, algebra, etc. the Actor model is based on physics, especially quantum physics and relativistic physics. (Hewitt, 2006)

Summary of interactions between particles described by the Standard Model.

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

Living Agents

A living agent is a special kind of actor that can reproduce and that is capable of undergoing at least one thermodynamic work cycle. (Kauffman, 2000)

This definition differs from the common belief that (living) agency requires beliefs and desires, unless we ascribe some primitive form of <belief> and <desire> even to a very simple living agents such as bacteria. The fact is that they act on some kind of <anticipation> and according to some <preferences> which might be automatic in a sense that they directly derive from the organisms morphology. Even the simplest living beings act on their own behalf.

Living Agents

Although a detailed physical account of the agents capacity to perform work cycles and so persist in the world is central for understanding of life/cognition, as (Kauffman, 2000) (Deacon, 2007) have argued in detail, this work is primarily interested of the info-computational aspects of life.

Info-computational approach takes information an computation to be the two basic building block concepts, corresponding to structure and process, being and becoming.

Given that there is no information without physical implementation (Landauer, 1991), computation as the dynamics of information is the *execution of physical laws under given constraints.*

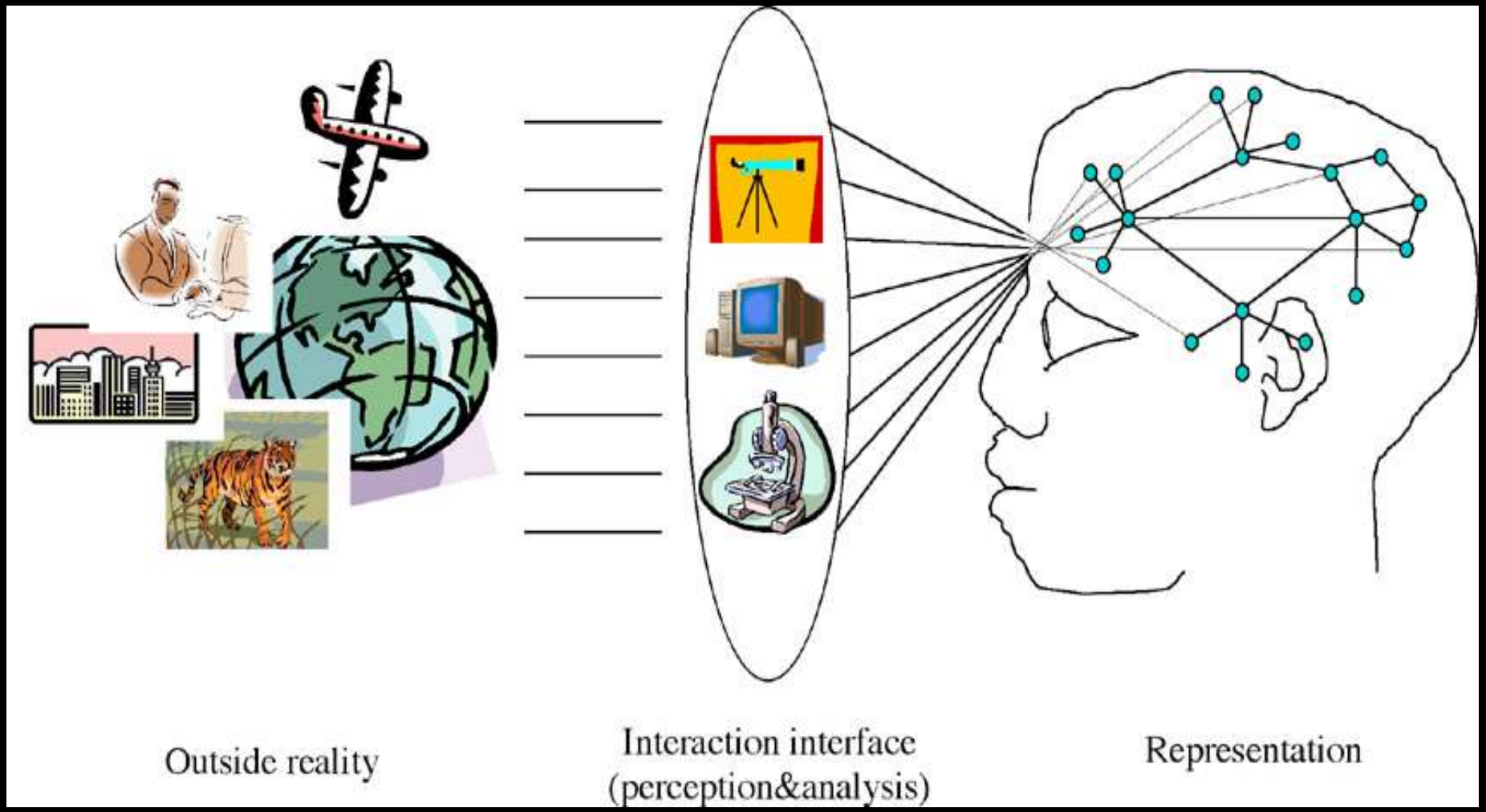
Living Agents

Kauffman's concept of agency (also adopted by Deacon) suggests the possibility that life can be derived from physics. That is not the same as to claim that life can be reduced to physics which is obviously false.

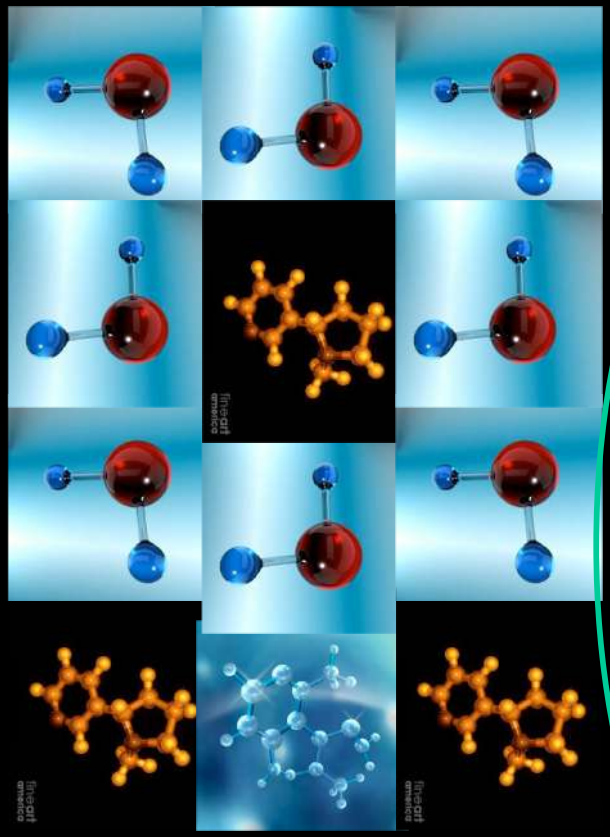
However, in deriving life from physics one may expect that both our understanding of life as well as physics will change.

We witness the emergence of information physics (Goyal, 2012) (Chiribella, G.; D'Ariano, G.M.; Perinotti, 2012) as a possible reformulation of physics that may bring physics and life/cognition closer to each other. This development smoothly connects to info-computational understanding of nature (Dodig-Crnkovic & Giovagnoli, 2013).

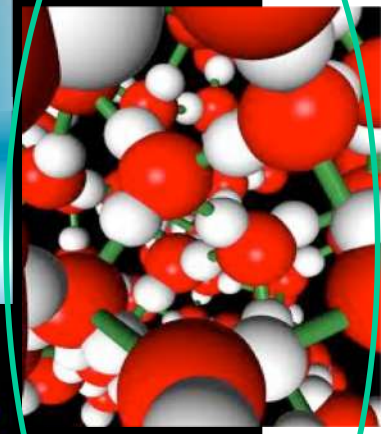
World as information for an agent



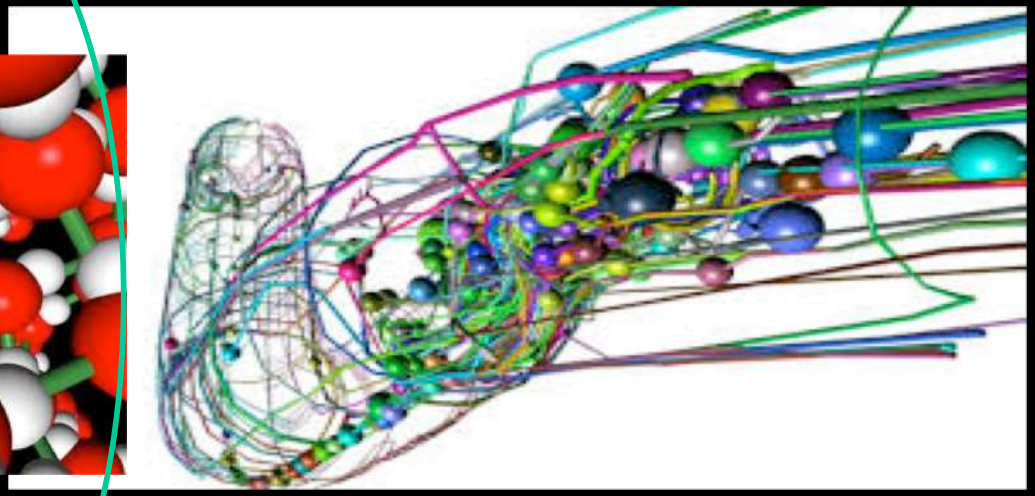
Agency-based hierarchies of levels. World as information for an agent



Potential information
Outside reality for C-elegans



Interaction interface
for C-elegans



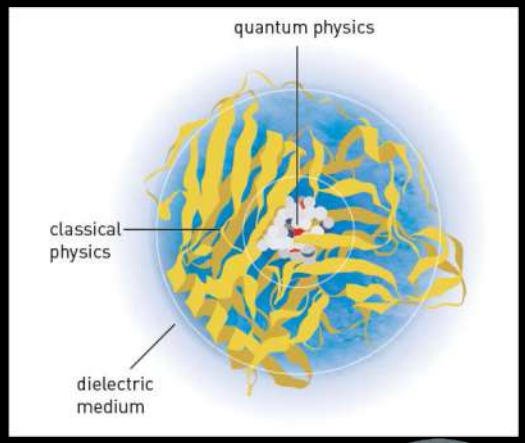
Actual Information C-elegans

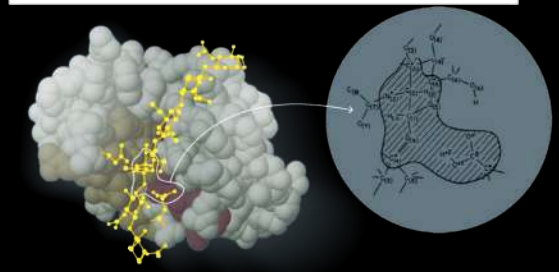
C. Elegans has 302 neurons (humans have 100 billion). The pattern of connections between neurons has been mapped out decades ago using electron microscopy, but knowledge of the connections is not sufficient to understand (or replicate) the information processor they represent, for some connections are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

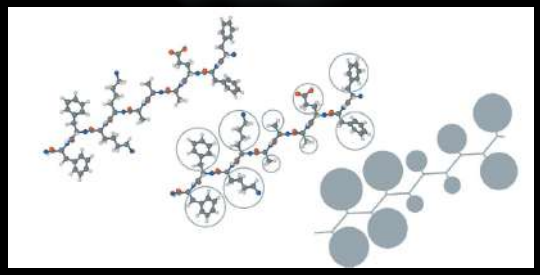
http://www.33rdsquare.com/2013/07/david-dalrymple-update-on-project.html

An illustration: Agent-dependent multiscale modeling of complex chemical system

Observer-centric model – enhanced resolution where observation is made – where chemical reaction takes place







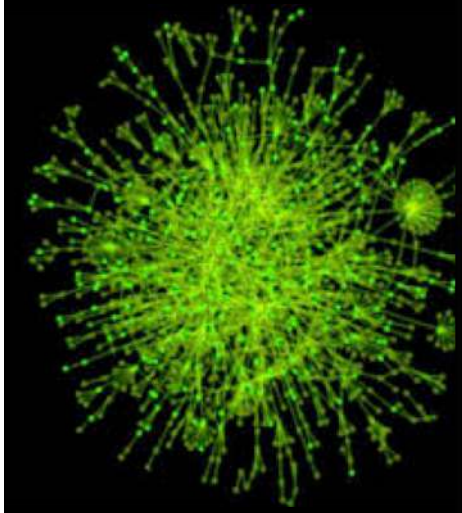
The Nobel Prize in Chemistry 2013 "for the development of multiscale models for complex chemical systems" ...
Karplus, Levitt and Warshel **managed to make Newton's classical physics work side-by-side with the fundamentally different quantum physics.** The strength of classical physics was that calculations were simple and could be used to model large molecules but no way to simulate chemical reactions for which chemists use quantum physics. Such calculations require enormous computing power.

In simulations of how a drug couples to its target protein in the body, the computer performs quantum theoretical calculations on those atoms in the target protein that interact with the drug. The rest of the large protein is simulated using less demanding classical physics.

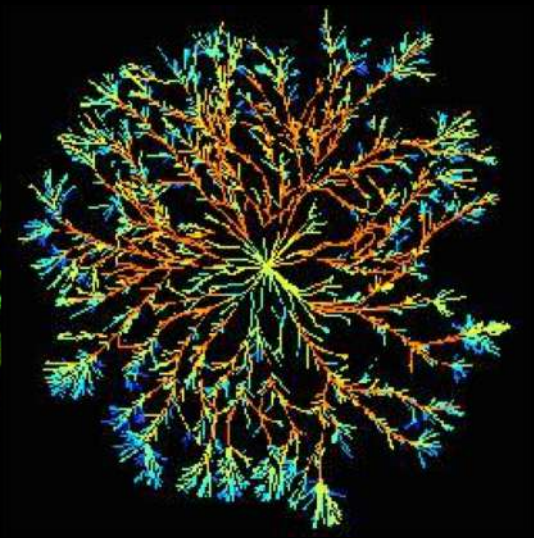
Today the computer is just as important a tool for chemists as the test tube. Simulations are so realistic that they accurately enough predict the outcome of traditional experiments.

http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2013/advanced-chemistryprize2013.pdf

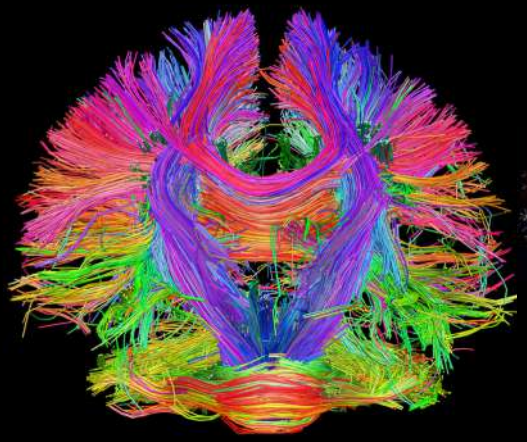
Information processing in life-networks



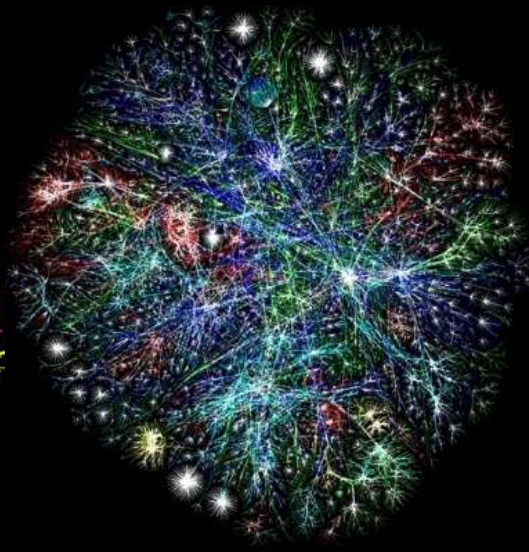
A map of protein–protein interactions in yeast cell



Bacteria Network Ben-Jacob
Bacteria display various multicellular behaviors: emitting, receiving and processing a large vocabulary of chemical symbols



Human brain connectome

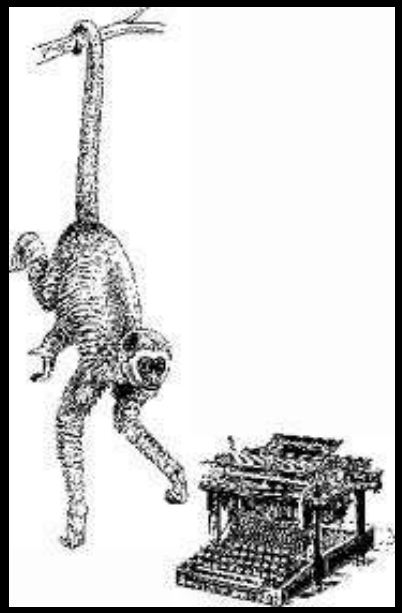


Internet map

http://www.nature.com/nrg/journal/v5/n2/fig_tab/nrg1272_F2.html
http://microbes-mind.net/ben-jacob/ https://en.wikipedia.org/wiki/ Eshel_Ben-Jacob
http://eldar.cz/cognition/complexEshel Ben Jacob Learning from Bacteria about Social Networks
http://www.nature.com/news/neuroscience-making-connections-1.10260
http://www.humanconnectomeproject.org
https://en.wikipedia.org/wiki/Opte_Project

How Does Nature Compute?

Evolution through Morphological Computing, Self-Organization and Selection



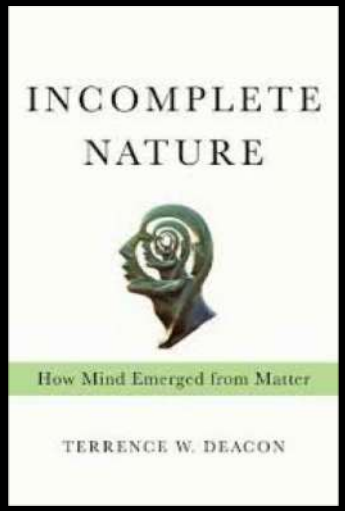
Critics of the evolutionary approach mention the impossibility of "blind chance" to produce such highly complex structures as intelligent living organisms. Proverbial monkeys typing Shakespeare are often used as illustration (an interesting account is given by Gell-Man in his Quark and the Jaguar.)

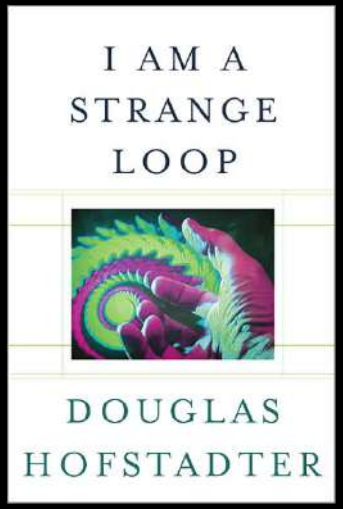
Chaitin and Bennet: Typing monkeys' argument does not take into account physical laws of the universe, which dramatically limit what can be typed. Moreover, the universe is not a typewriter, but a computer, so a monkey types random input into a computer. The computer interprets the strings as programs.

Eva Jablonka and Marion J. Lamb (2019) Evolution in Four Dimensions. Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life (EXTENDED EVOLUTIONARY SYNTHESIS)

A crucial moment in the development of the sense of self in an agent – sensing capabilities and nervous system

- **Neural precursors in sponges**: Although sponge cells do not show synaptic transmission, they do communicate with each other via calcium waves and other impulses, which mediate some simple actions such as whole-body contraction
- **Radiata.** Jellyfish, comb jellies, and related animals have diffuse nerve nets rather than a central nervous system. In most jellyfish the nerve net is spread more or less evenly across the body
- **Bilateria.** The fundamental bilaterian body form is a tube with a gut cavity, and a nerve cord (or two parallel nerve cords), with an enlargement (a "ganglion") for each body segment, with an especially large ganglion at the front, called the "brain".





What the nervous system brings is the self-reflective capability – a model of a body inside a body - a self-representation.

http://www.scholarpedia.org/article/Nervous_system

Summary

Connecting data to intelligent agency is done by modelling cognitive systems (natural and artifactual) as information processors, equipped with physical information sensors and physical actuators acting upon information.

Assumptions

1. Nature can be modelled as a network of networks of computational processes on several levels of abstraction (organization) (computing nature)
2. There is no information without physical implementation (Landauer)
3. Dynamics of natural information = physical /natural/morphological computation
4. Cognition/Intelligence = natural/morphological computation in cognitive agents
5. Intelligence = problem solving ability for both living organisms and artifacts. Its basic precondition is ability to learn (biological or machine learning)

Summary

Implications

1. <Cognition> and <intelligence> are abilities of all living beings and they come in degrees

2. Cognition and intelligence are both EEEE (Embodied, Embedded, Enactive, Extended)

3. For living organisms COGNITION=LIFE.
   For artifacts COGNITION = ARTIFACTUAL SURROGATE OF LIFE

4. All cognizing systems (organisms and artifacts) are essentially dependent on information exchange with the surrounding

Summary

Implications

5. Biological cognition and intelligence can only be understood in the context of evolution.

6. Evolution in the computing nature is the result of morphological computation on several levels of organization

7. ”I” as a sense of self in living organism comes from the self reflective subset that relates the inner state of the organism with the state of the environment. For intelligent artifacts the surrogate of the sense of self can be engineered.

* *That results in genetic, epigenetic, behavioural, and symbolic variation
Eva Jablonka and Marion J. Lamb (2019) Evolution in Four Dimensions. Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life (EXTENDED EVOLUTIONARY SYNTHESIS)

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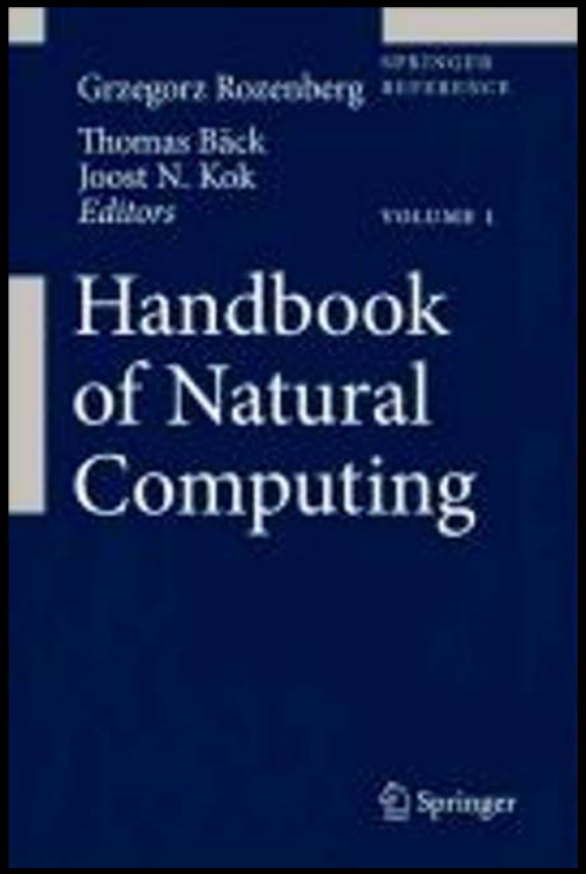

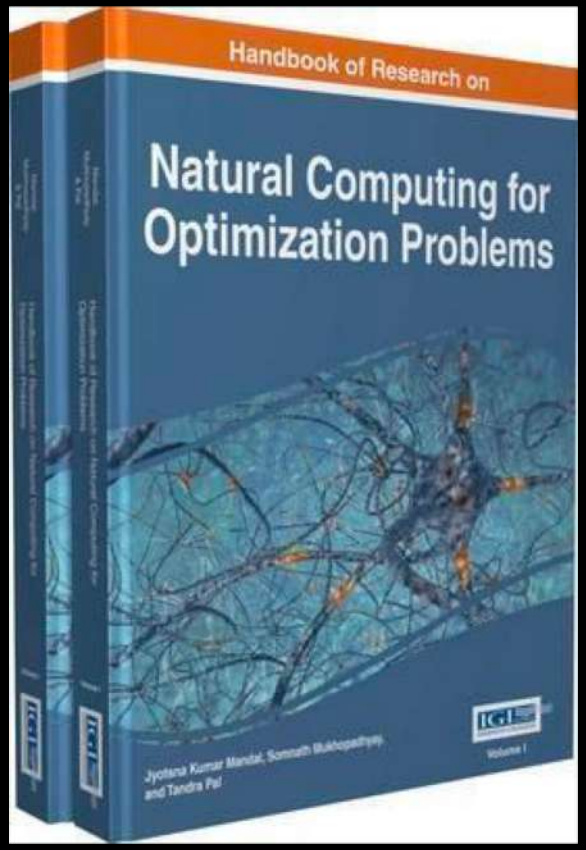

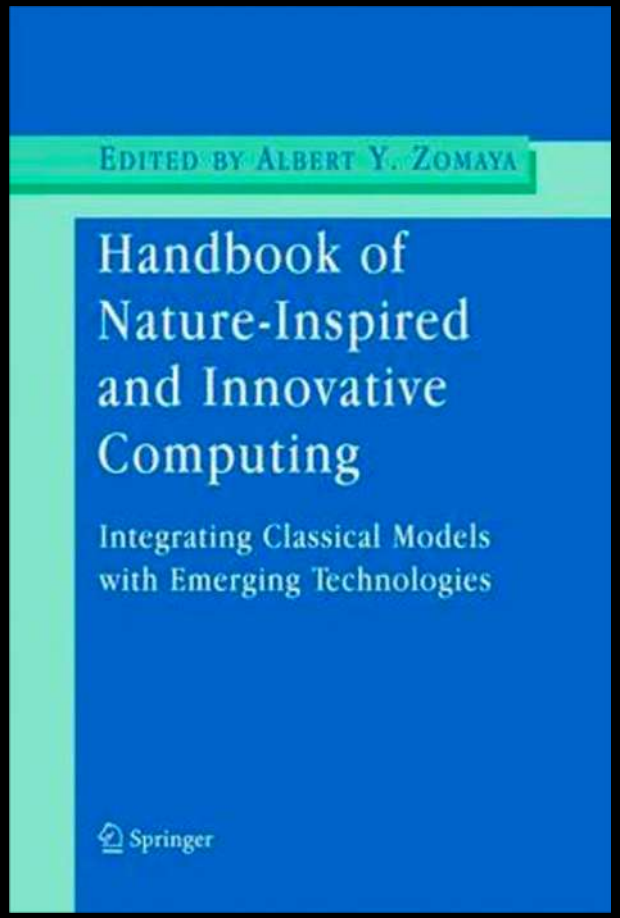

Artificial immune systems; Deep Learning; Evolutionary computing; Genetic algorithms; Neural Networks; Quantum Cryptography; Swarm Intelligence

https://www.igi-global.com/book/handbook-research-natural-computing-optimization/142105

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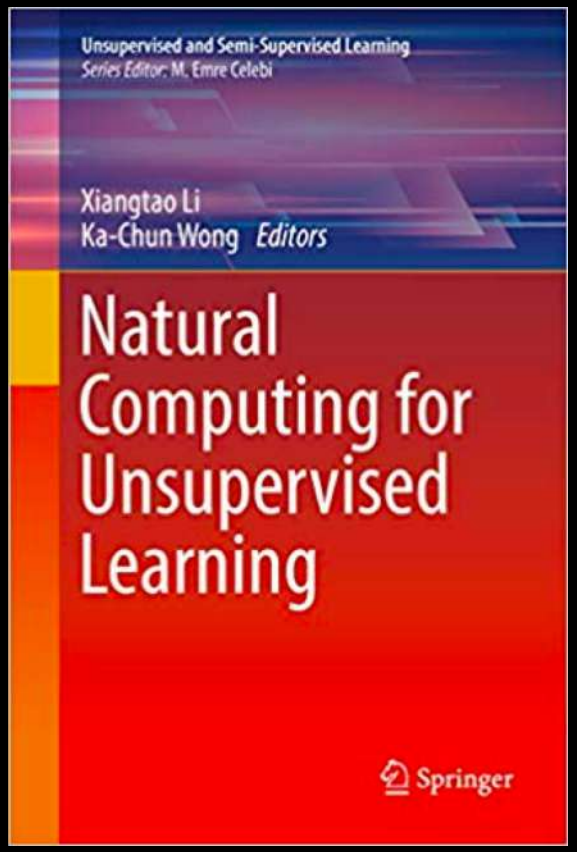

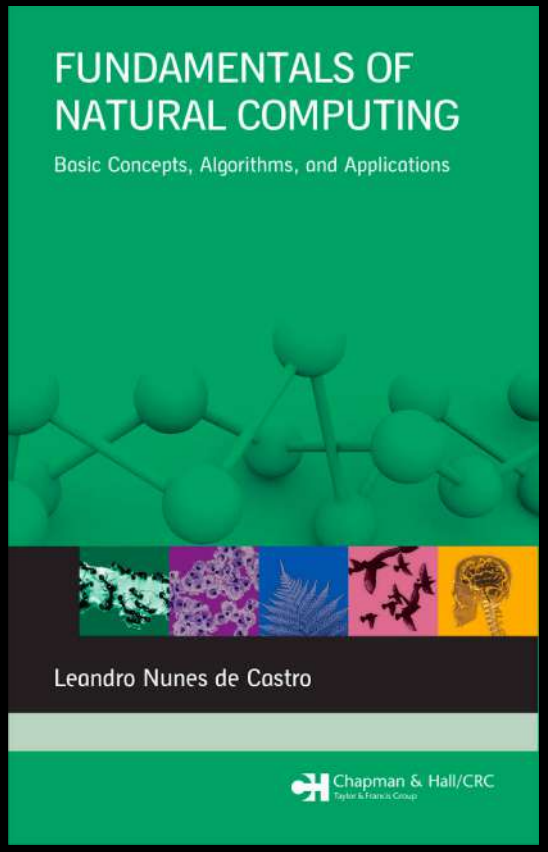

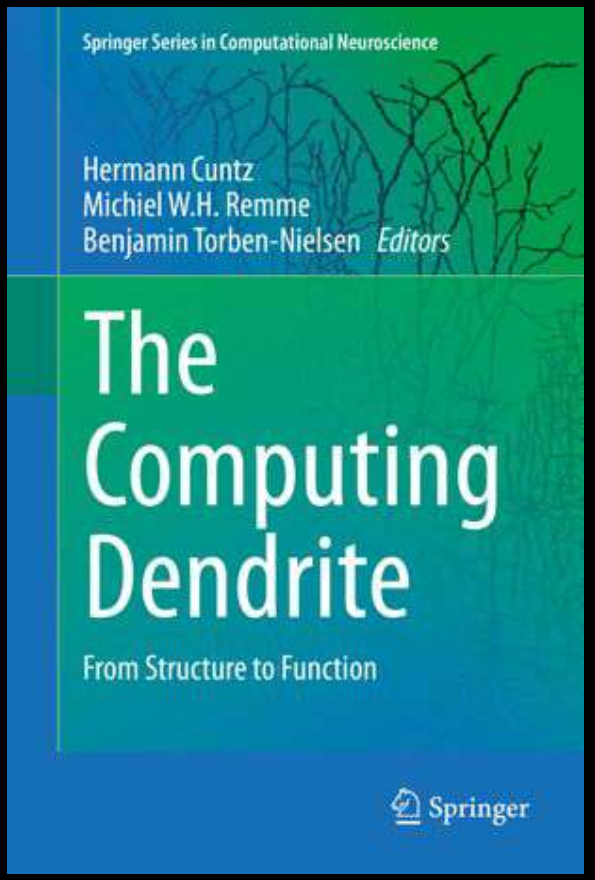

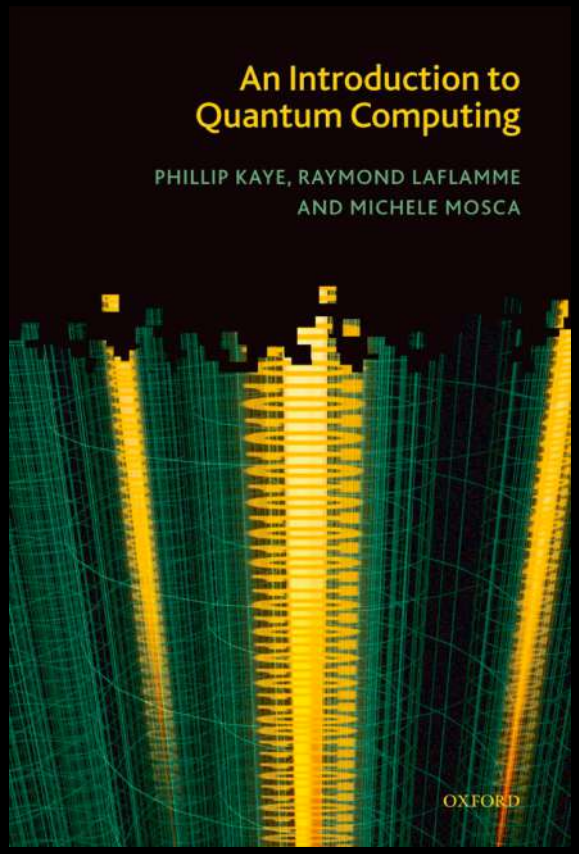
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PHILLIP KAYE, RAYMOND LAFLAMME
AND MICHELE MOSCA
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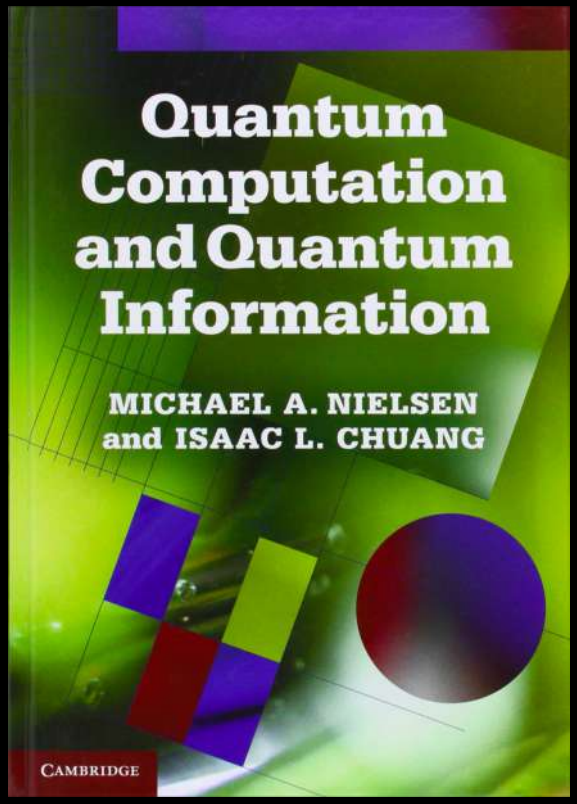
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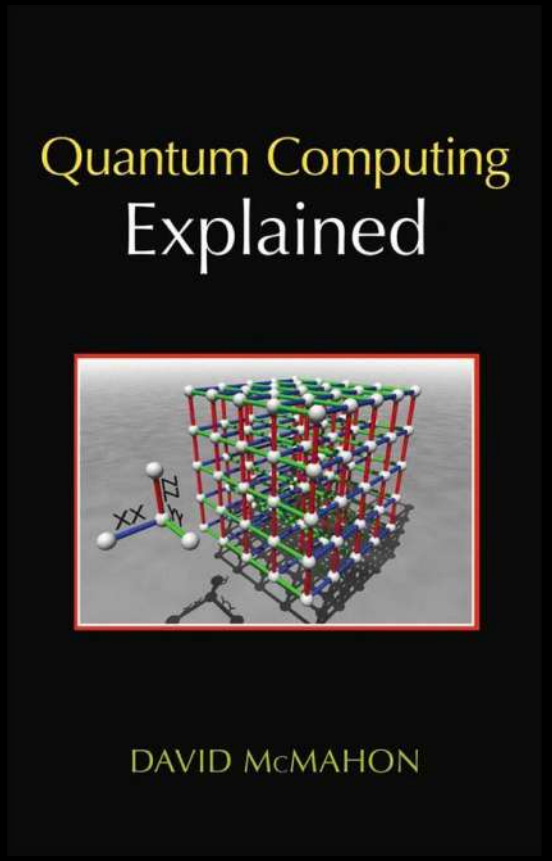
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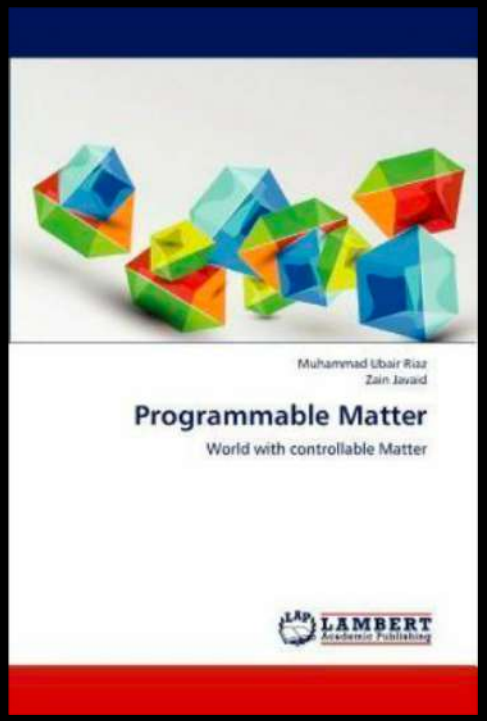
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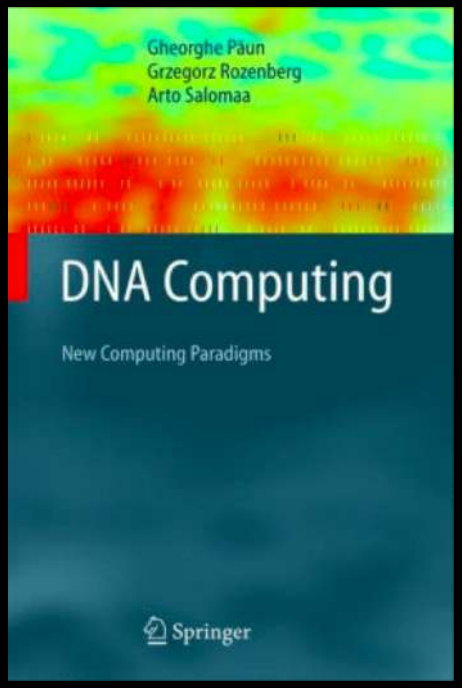
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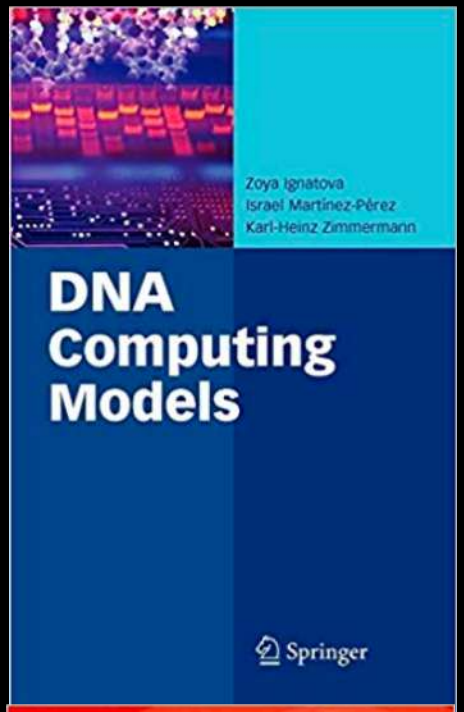
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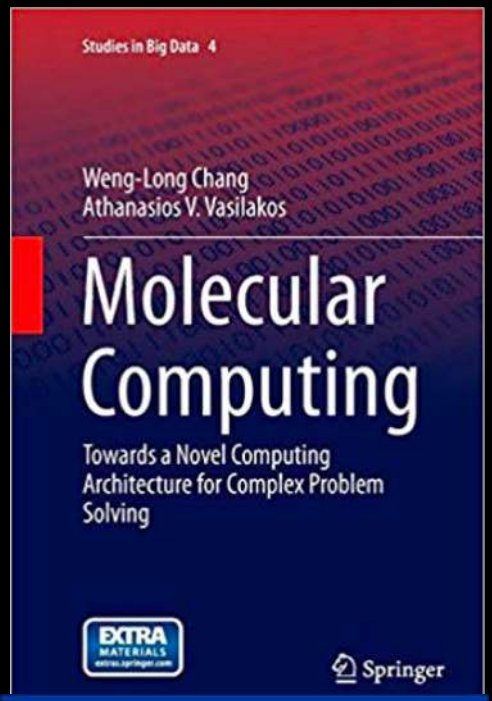
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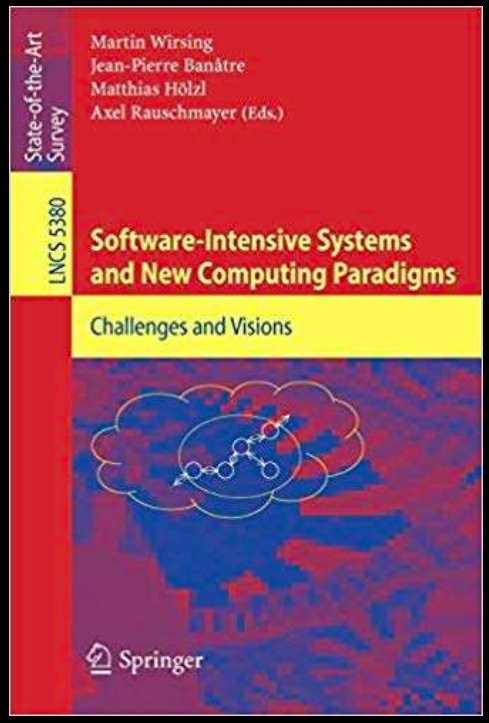
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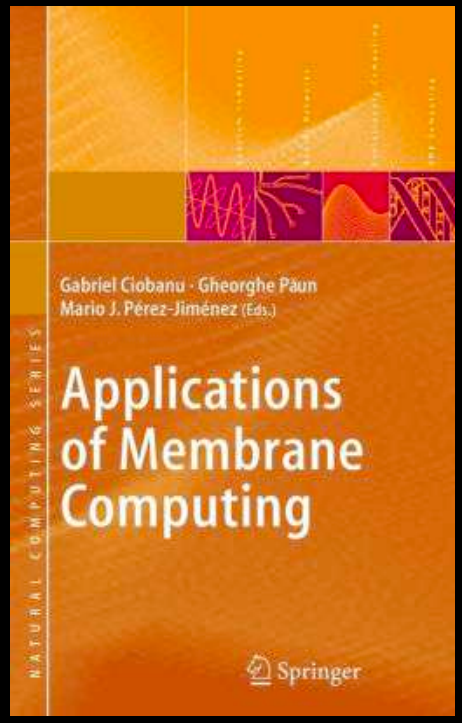
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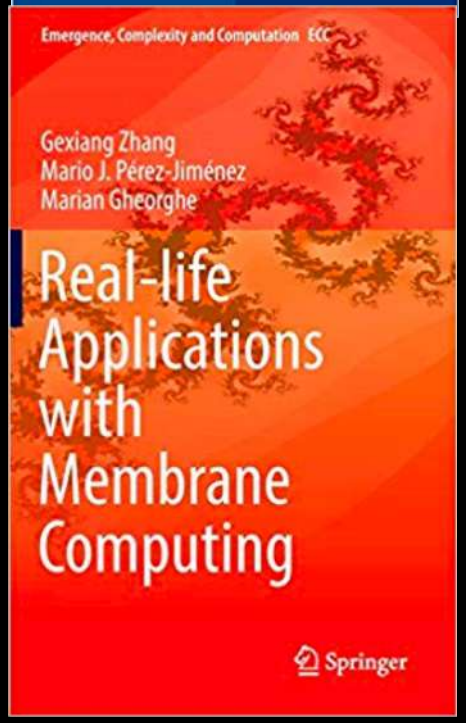
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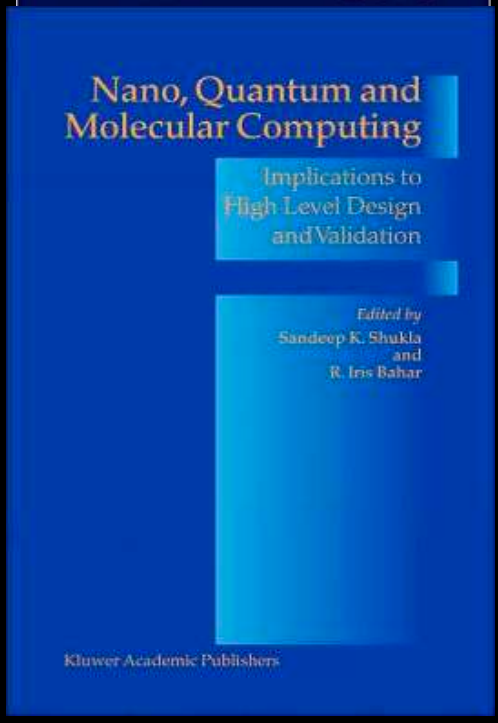
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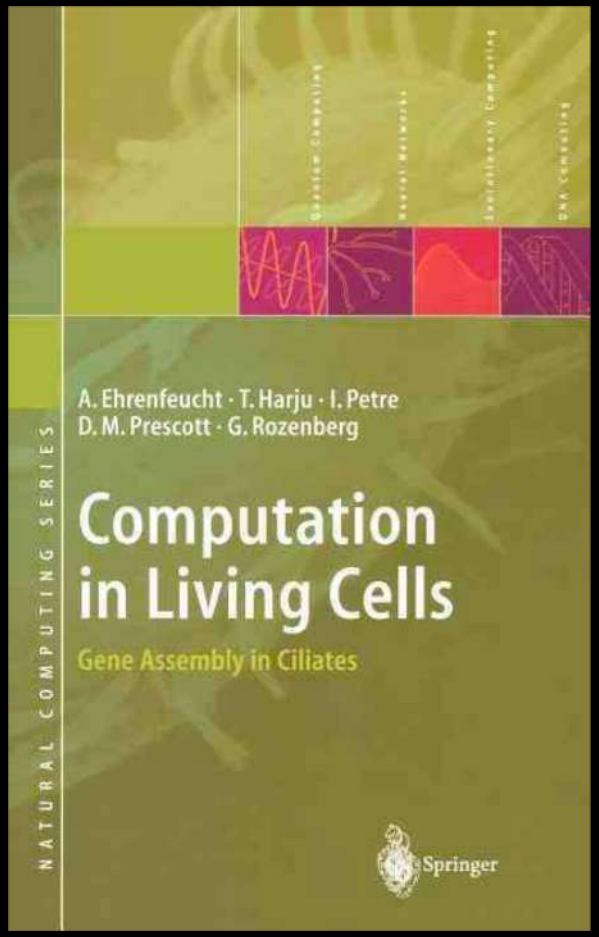

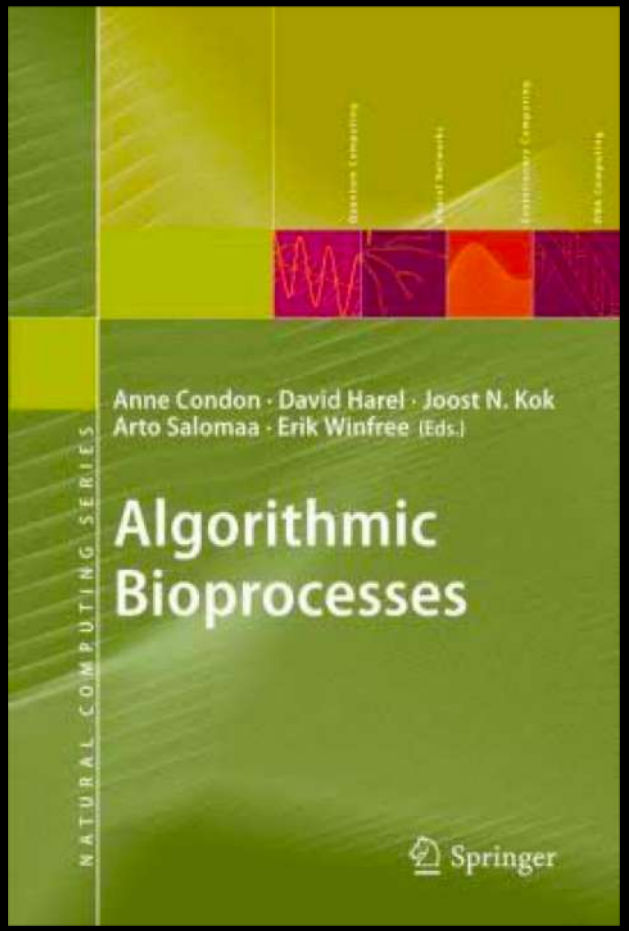

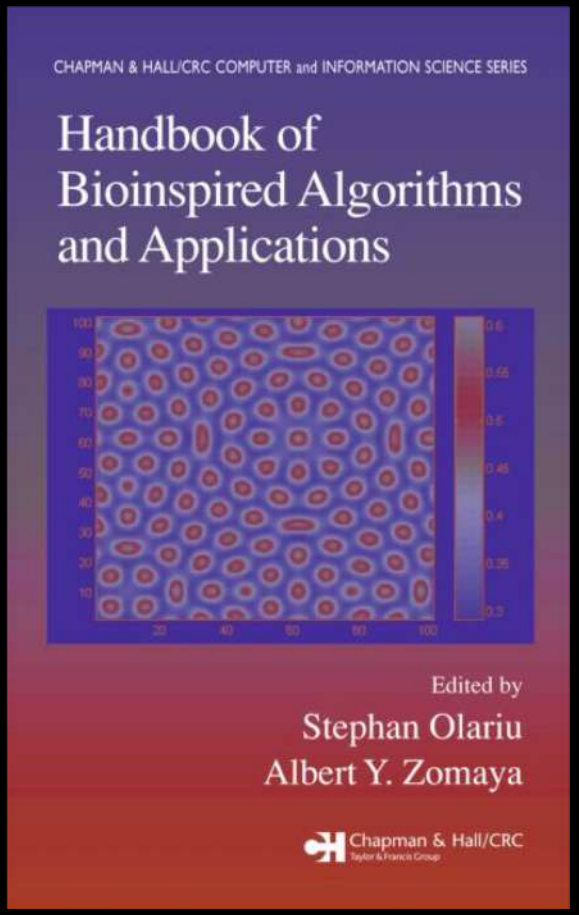

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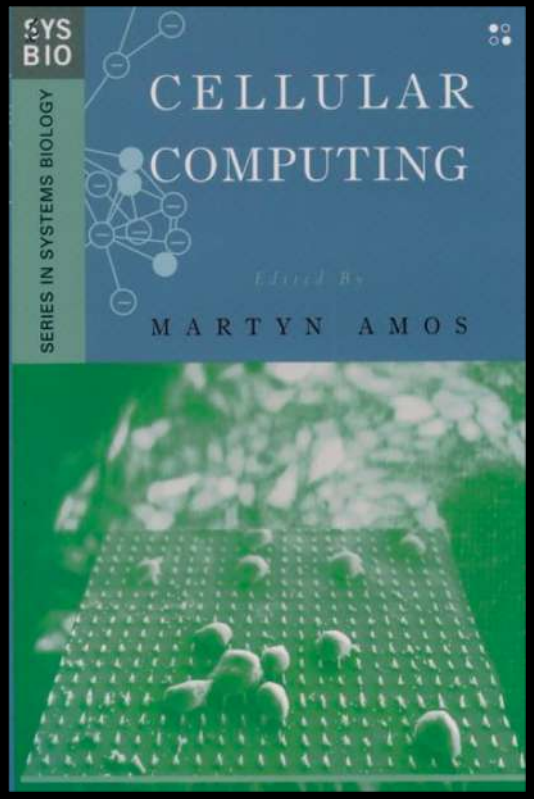

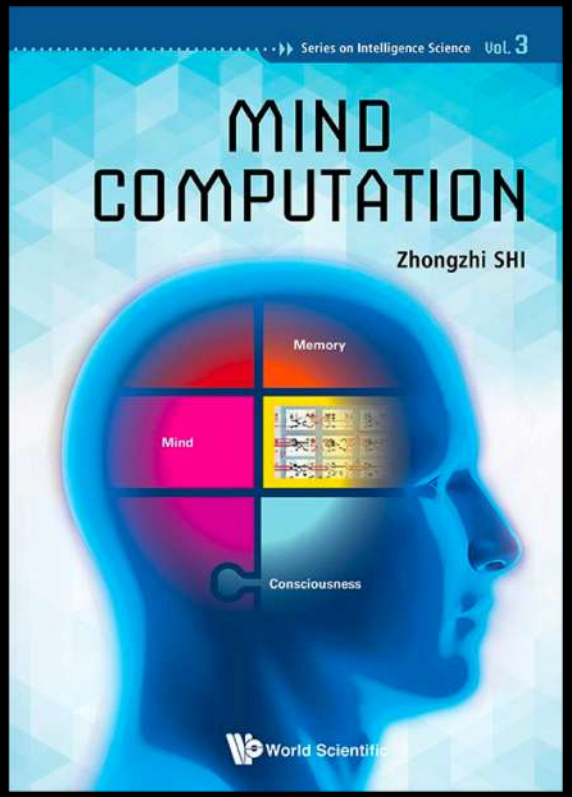

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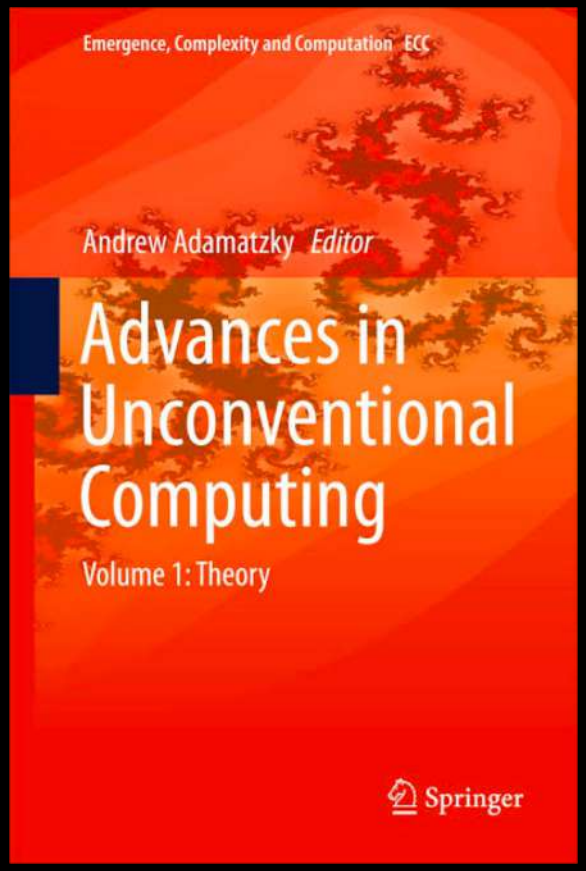

The unconventional computing is a niche for interdisciplinary science, cross-bred of computer science, physics, mathematics, chemistry, electronic engineering, biology, material science and nanotechnology. The aims of this book are to uncover and exploit principles and mechanisms of information processing in and functional properties of physical, chemical and living systems to develop efficient algorithms, design optimal architectures and manufacture working prototypes of future and emergent computing devices.

This first volume presents theoretical foundations of the future and emergent computing paradigms and architectures. The topics covered are computability, (non-)universality and complexity of computation; physics of computation, analog and quantum computing; reversible and asynchronous devices; cellular automata and other mathematical machines; P-systems and cellular computing; infinity and spatial computation; chemical and reservoir computing.

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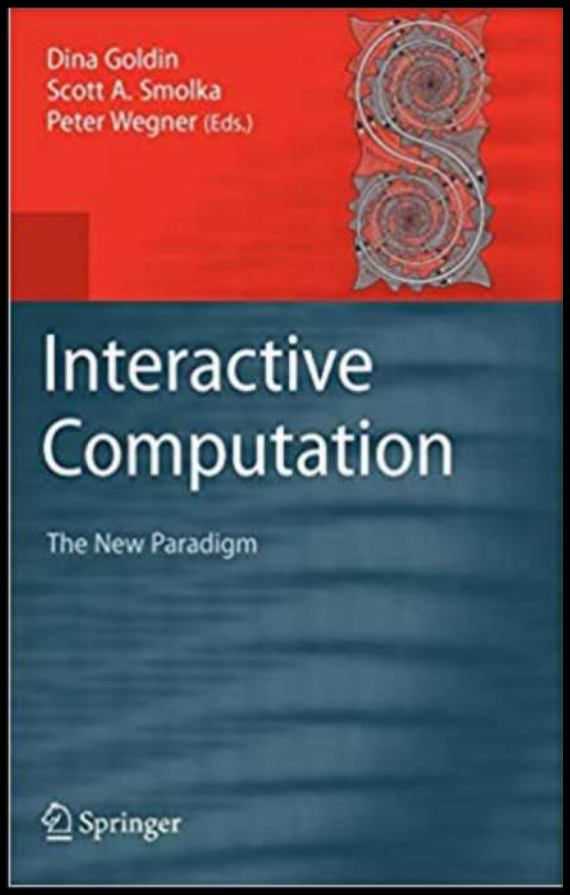

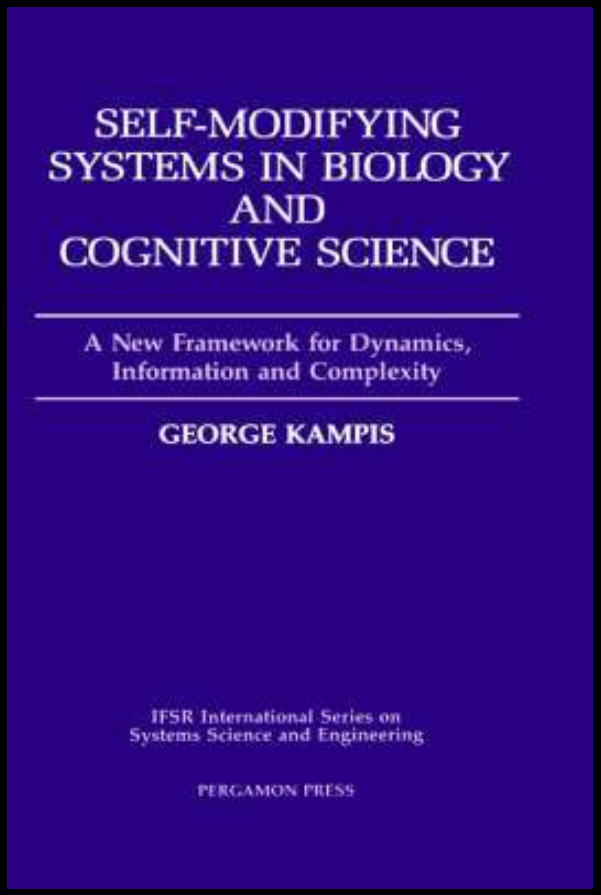

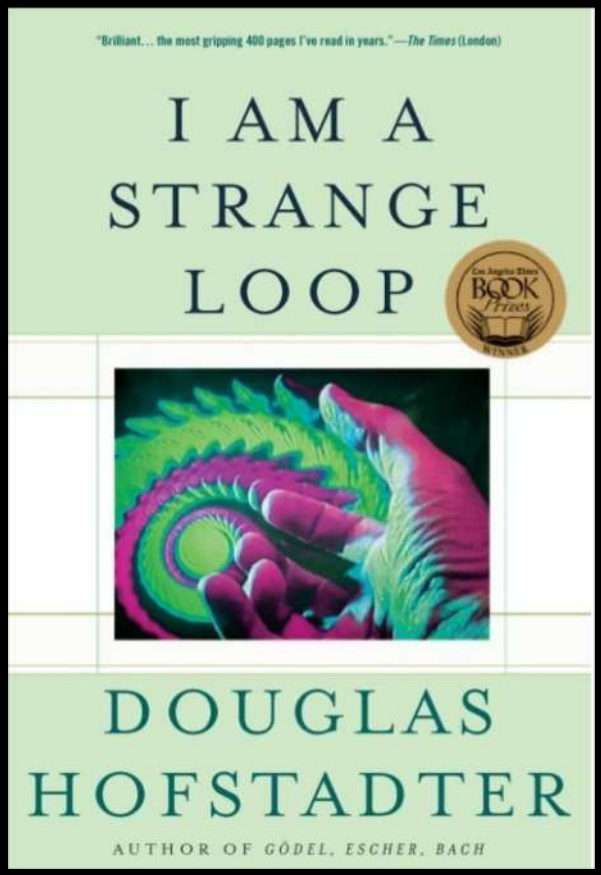

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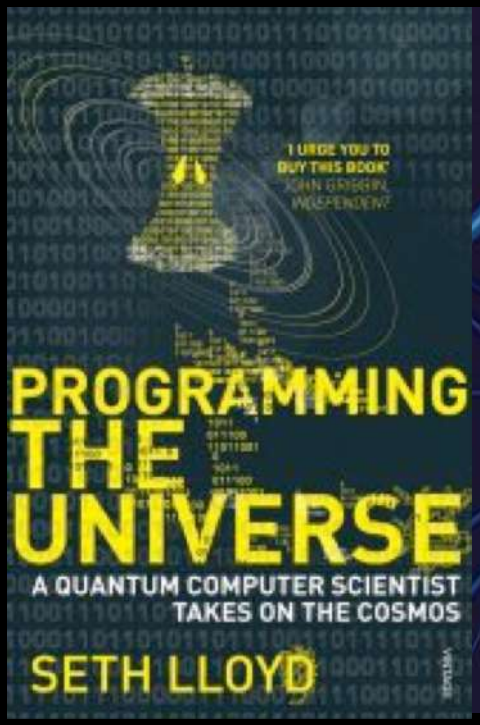

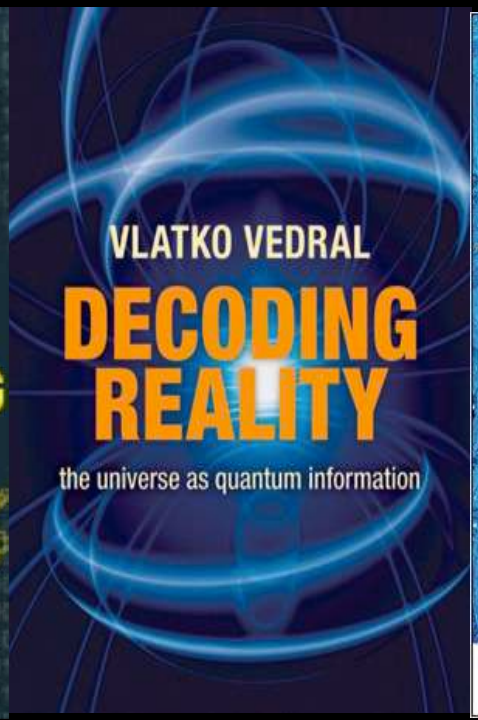

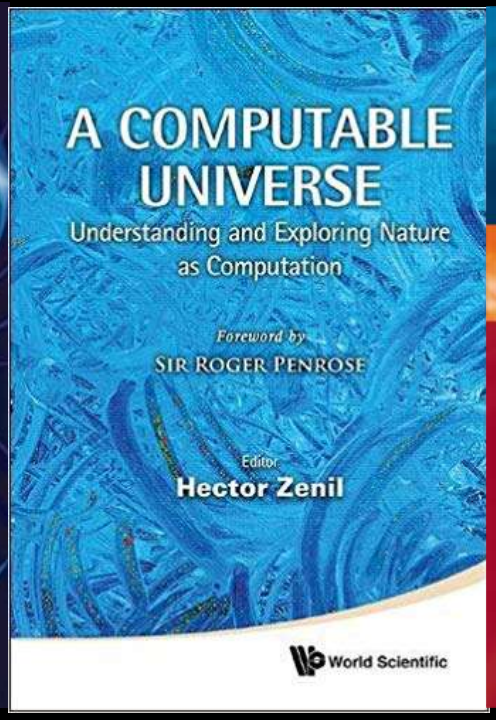

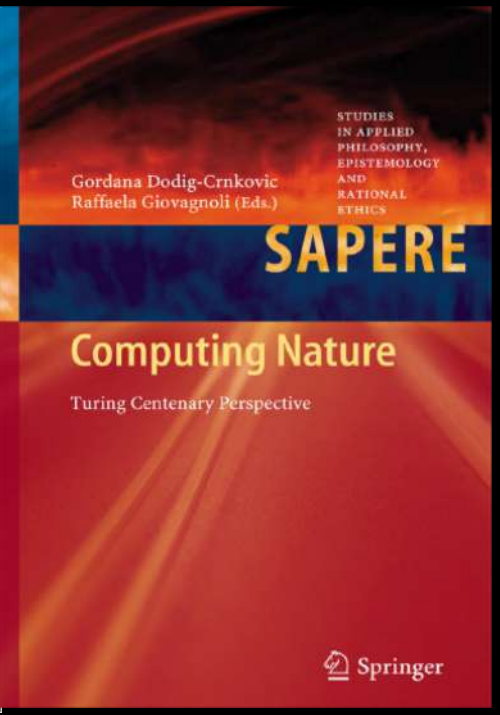

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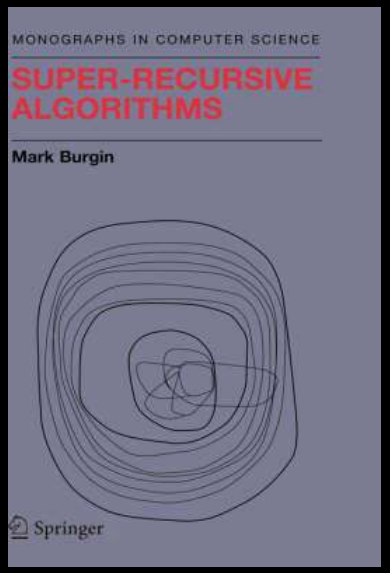

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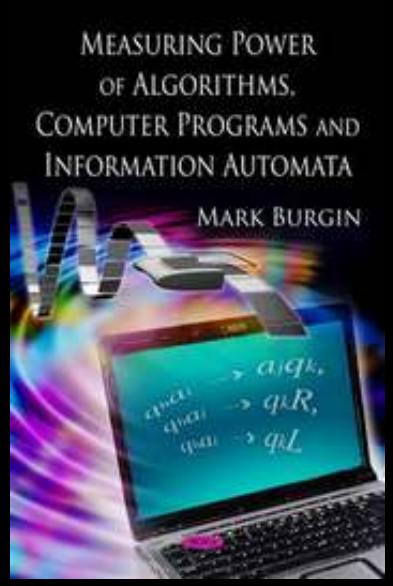
Mark Burgin, 2010



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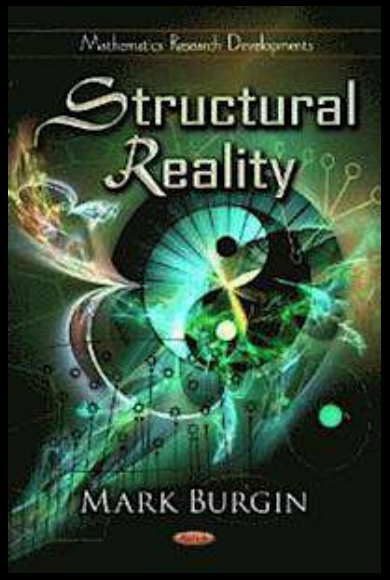

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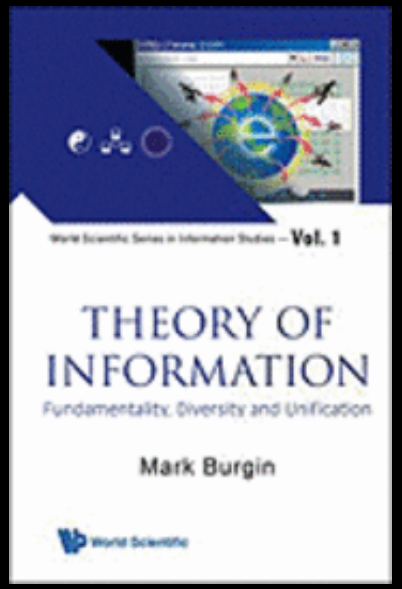
Mark Burgin, 2013



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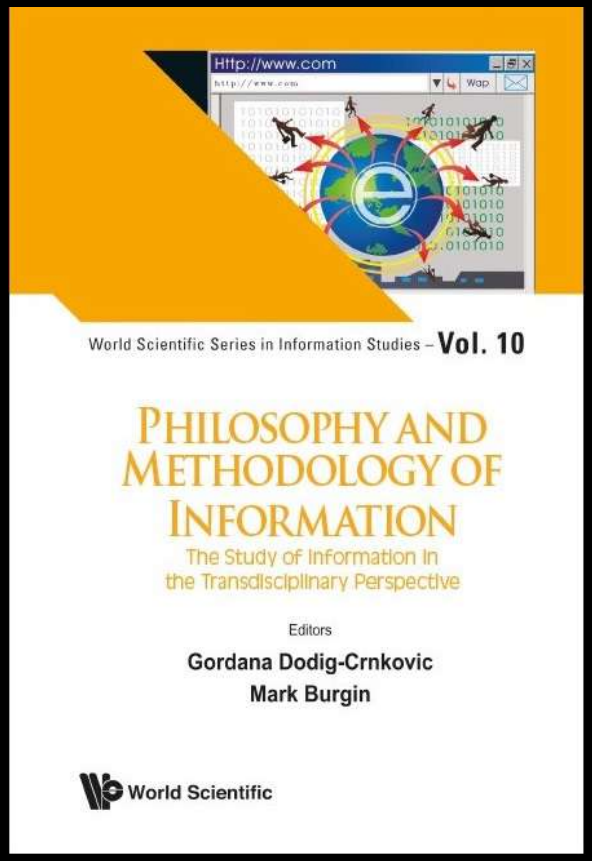

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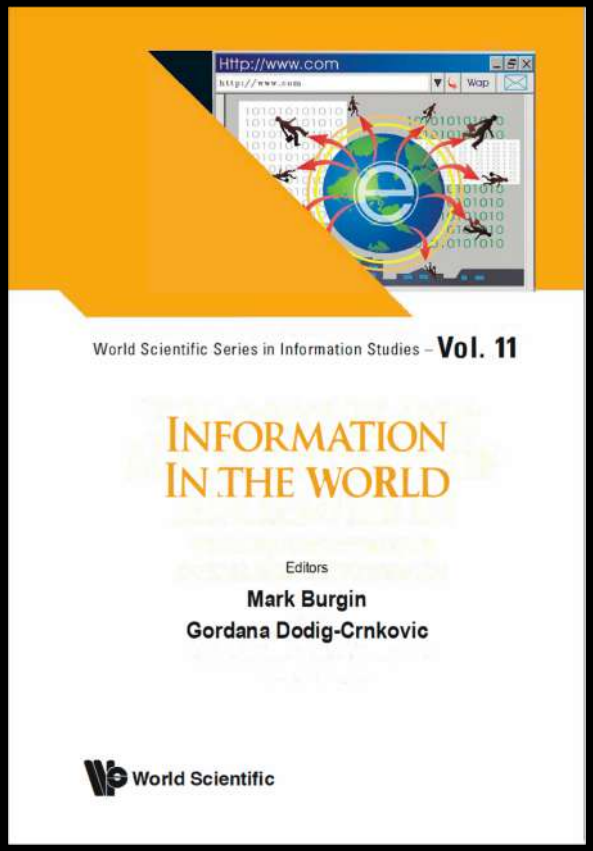

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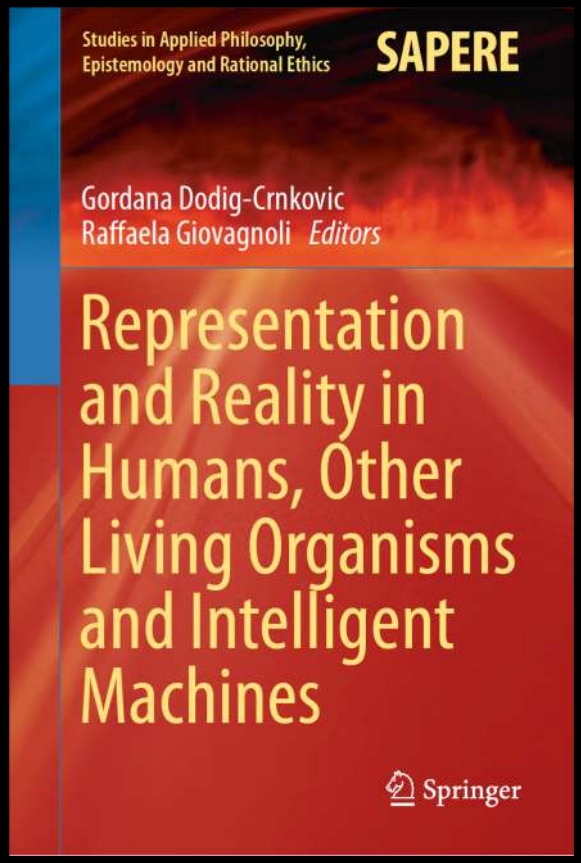

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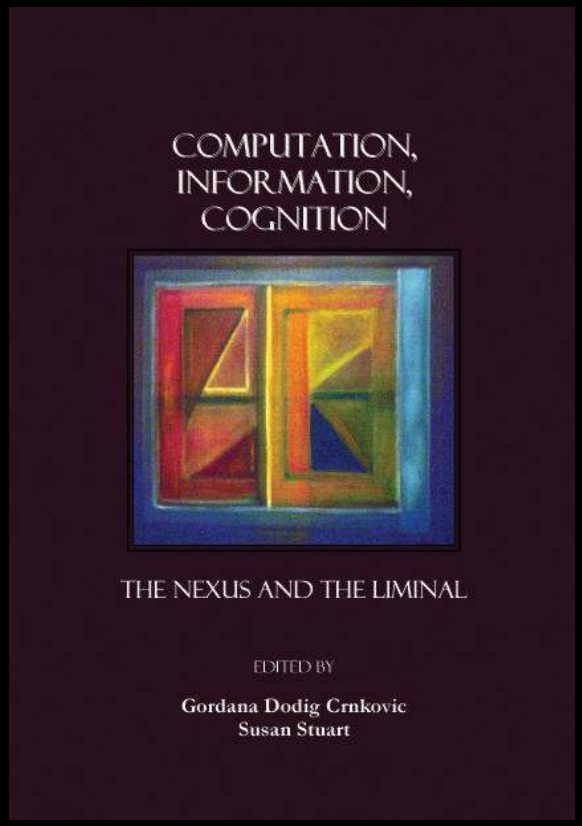

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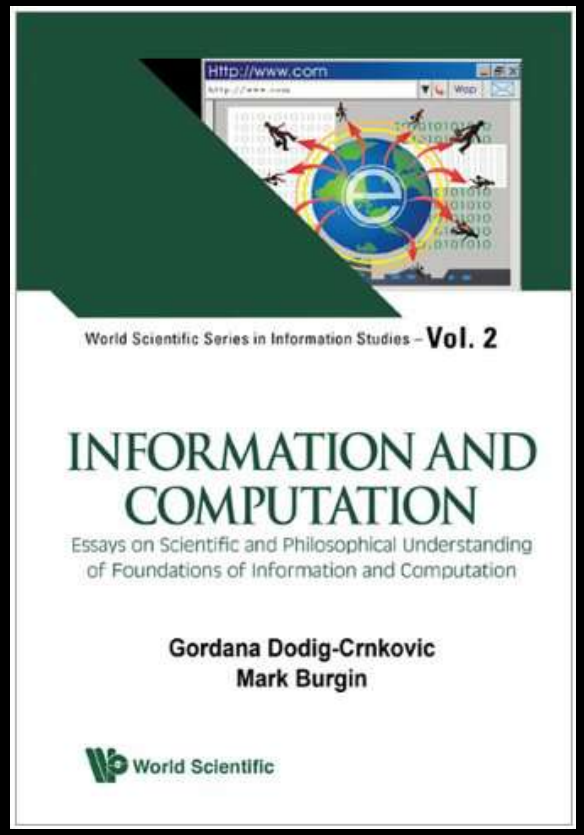

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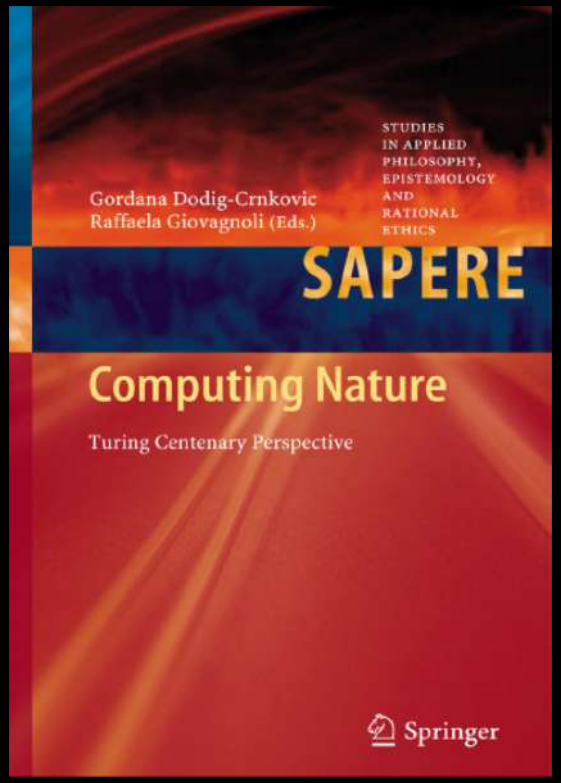

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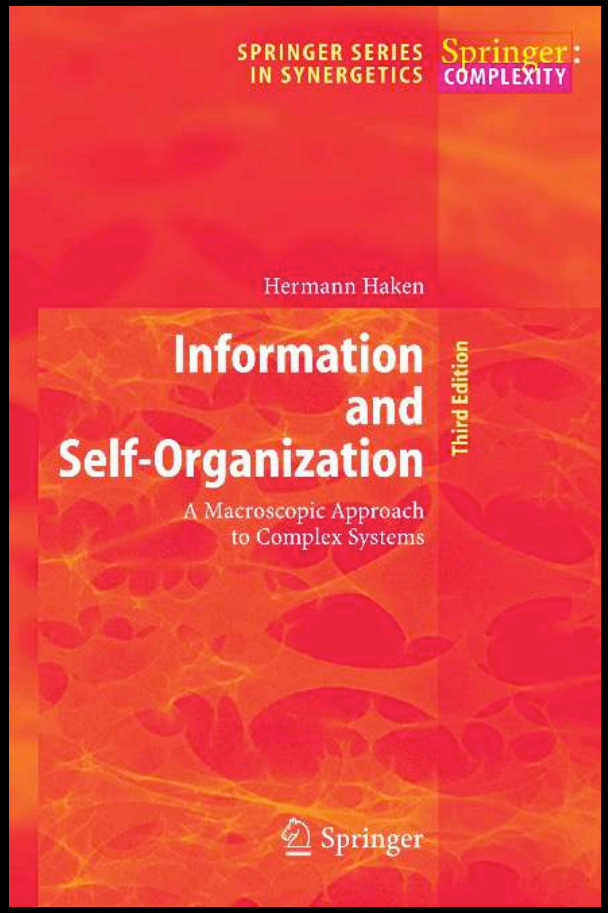

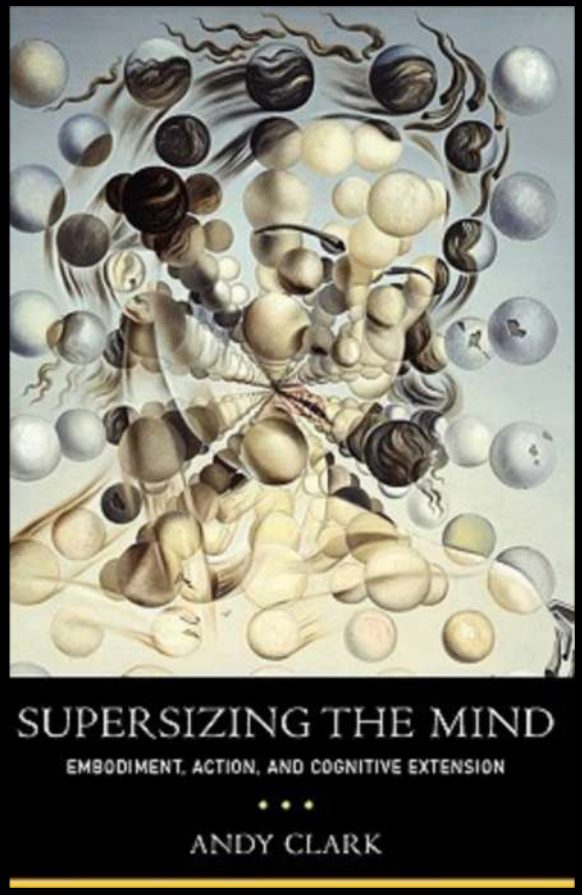

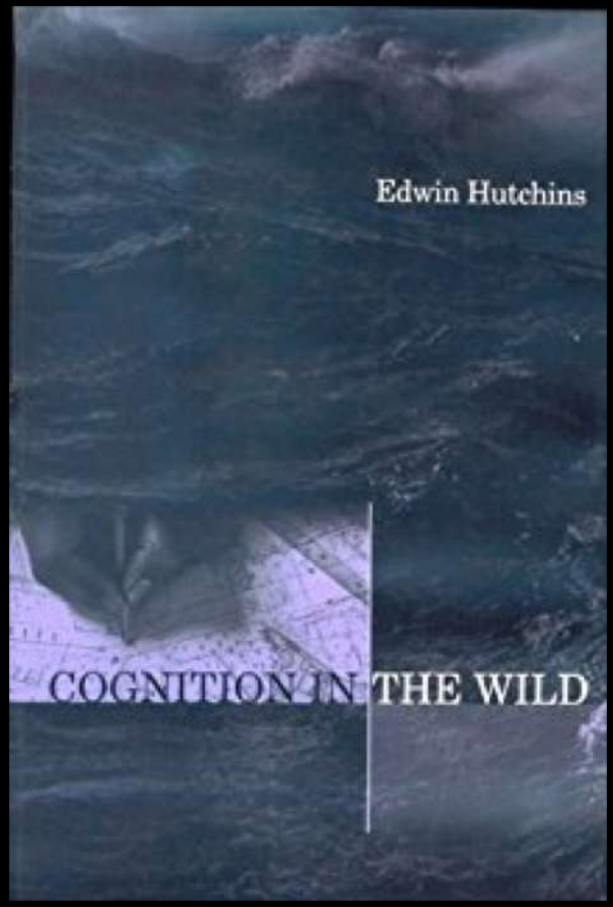

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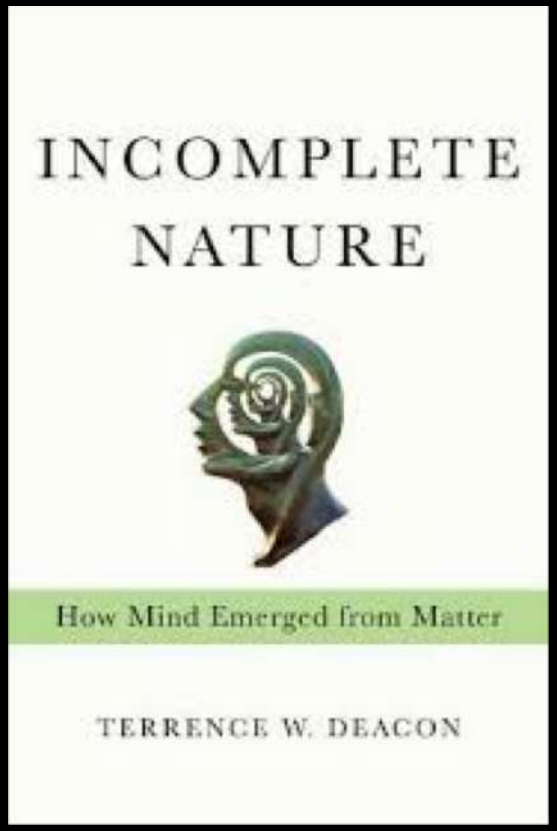

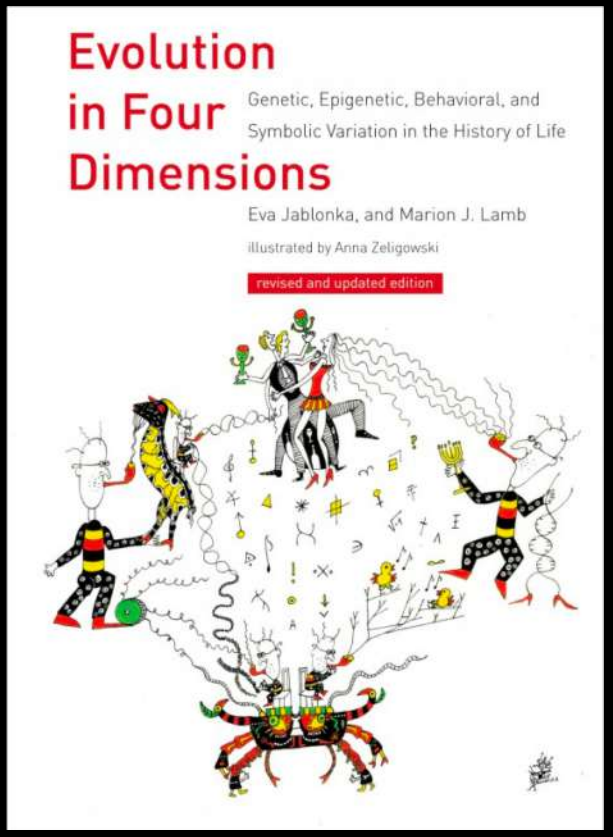

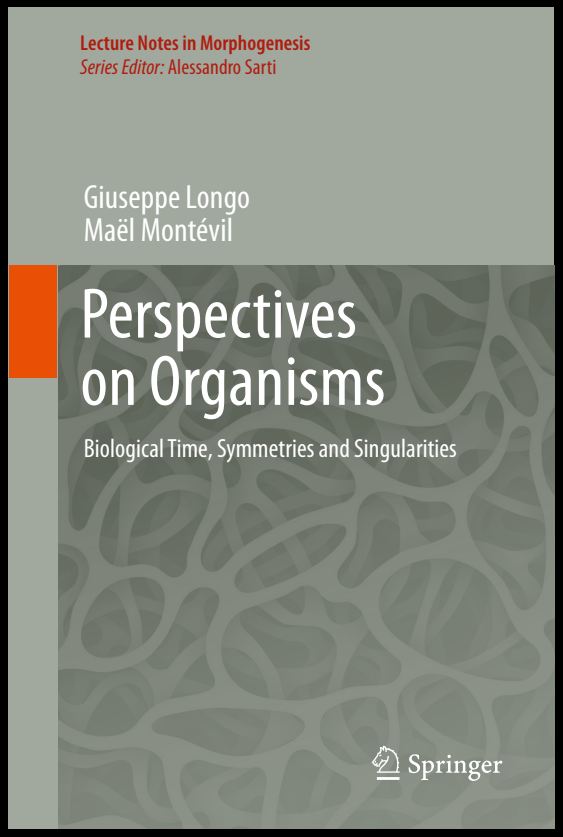

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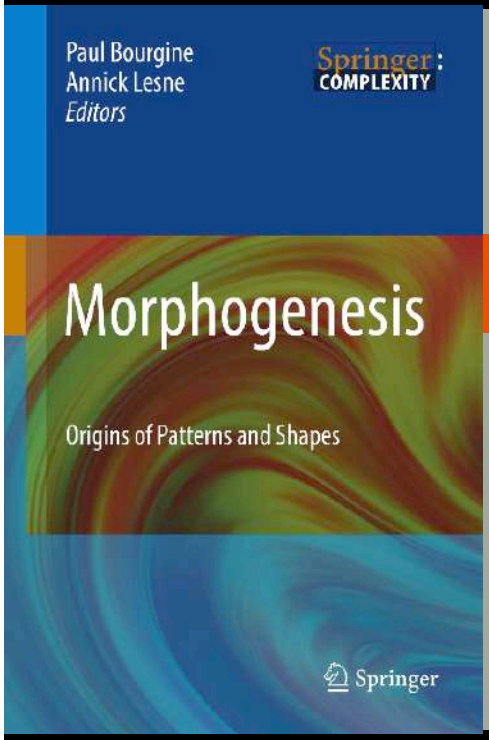

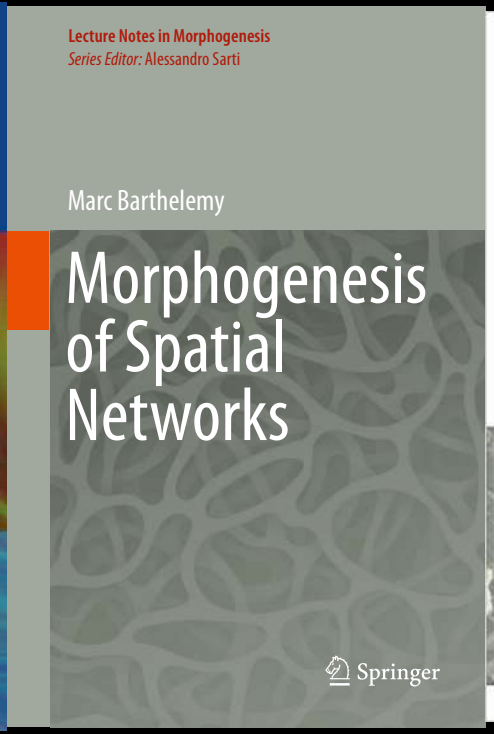

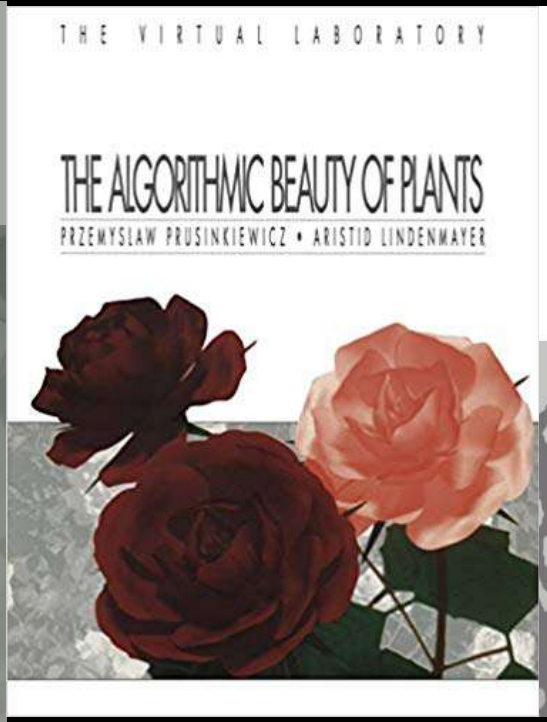

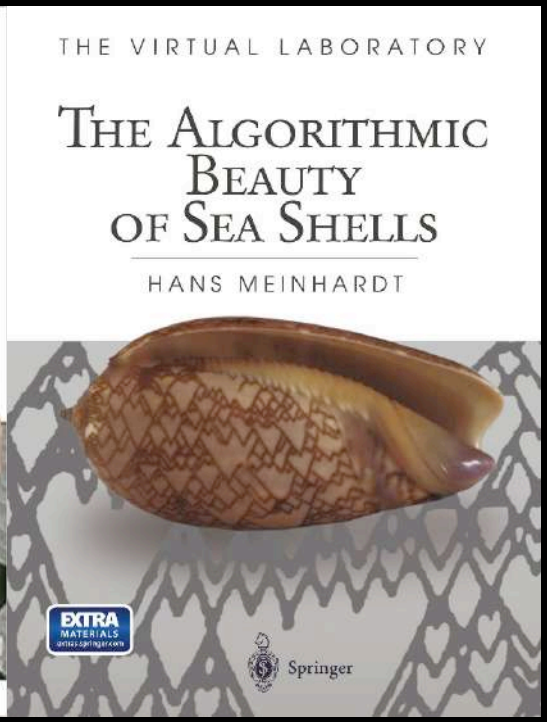

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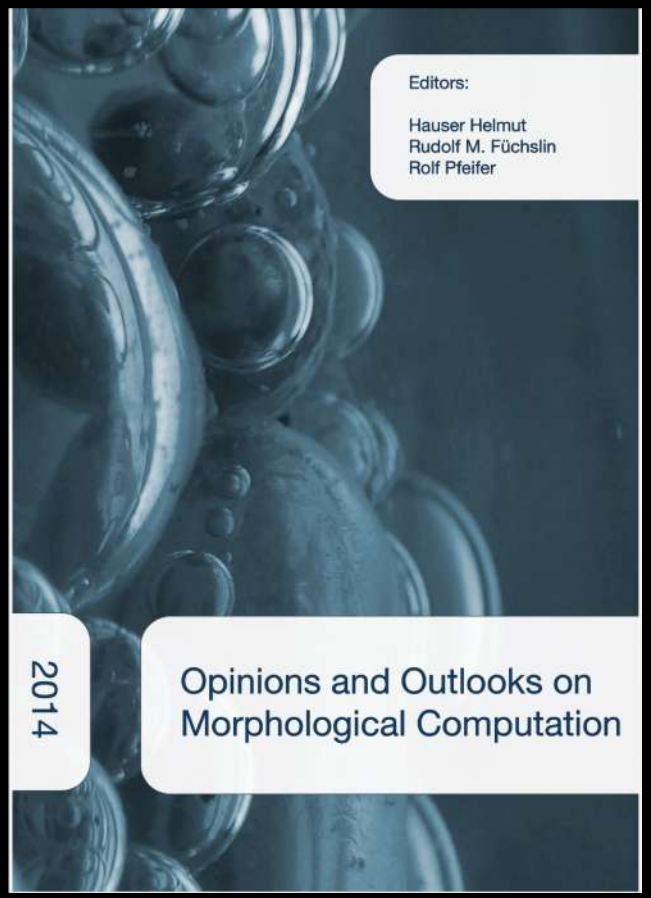

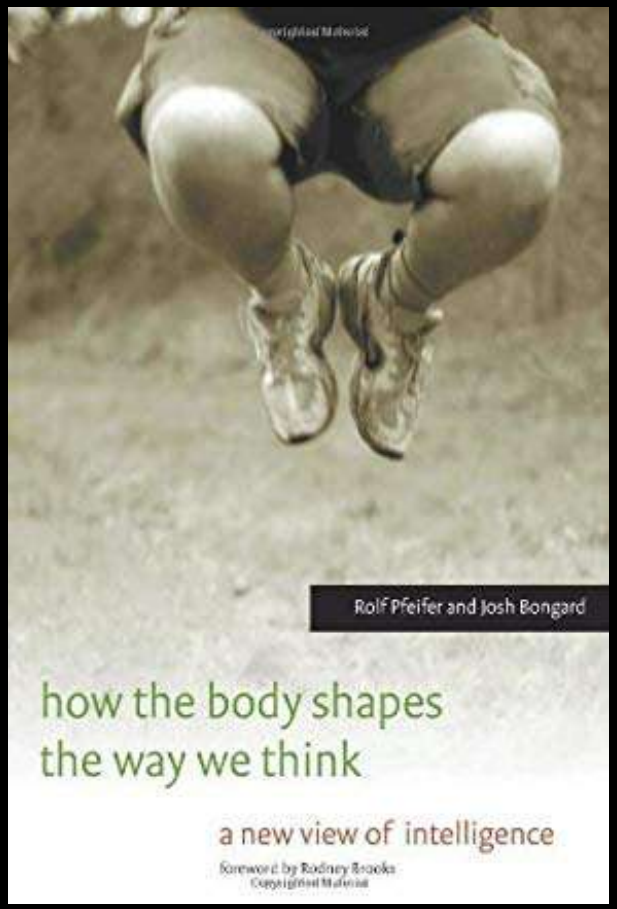

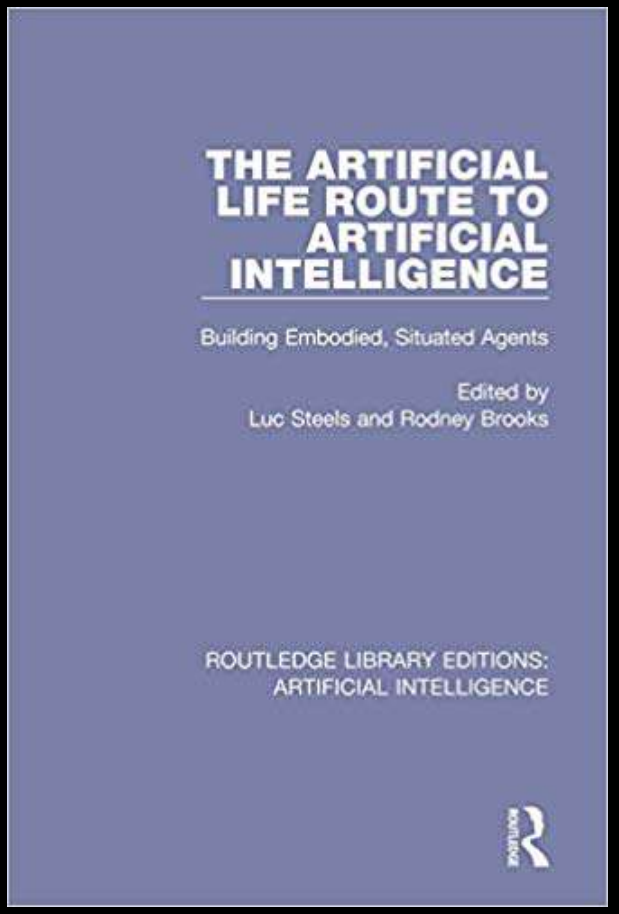

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Events organized on this topic

Embodied Cognition: Constructivist and Computationalist Perspectives
IACAP 2016, Ferrara. http://www.iacap.org/conferences/iacap-2016/symposium-robert-lowe-gordana-dodig-crnkovic-embodied-cognition-constructivist-and-computationalist-perspectives/
Co-organized with: Robert Lowe, Alexander Almér, Rickard von Haugwitz

Morphological Computing and Cognitive Agency
@Gothenburg summit of International Society for the Study of Information, is4si
http://is4si-2017.org/
Co-organized with: Robert Lowe, Alexander Almér

Foundations of Cyberphysical Computation: Morphological and Embodied Computing, Theory and Applications, Marcus Wallenberg Symposium. May 7th-9th, 2018
https://sites.google.com/view/morphologicalcomputing
Co-organized with: Robert Lowe

Workshop on Software Engineering for Cognitive Services. https://www.se4cog2018.com
27/5–3/6 @ICSE 2018 Gothenburg https://sites.google.com/view/se4cog2018
Co-organized with: Rao Mikkilineni