

Learning intelligent computing from living cells

Cognitive (semantic) information processing beyond the Turing model of computation

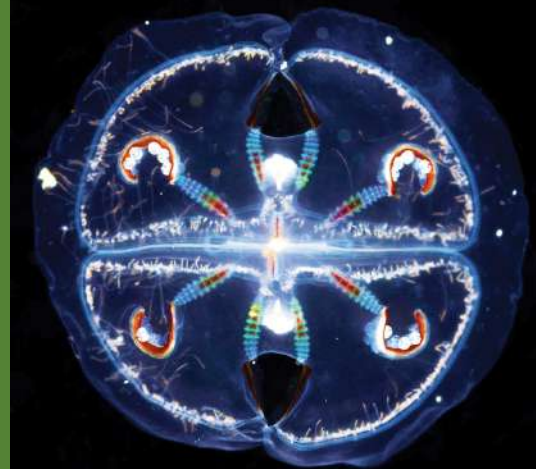
Gordana Dodig Crnkovic

Chalmers University of Technology, Gothenburg, Sweden

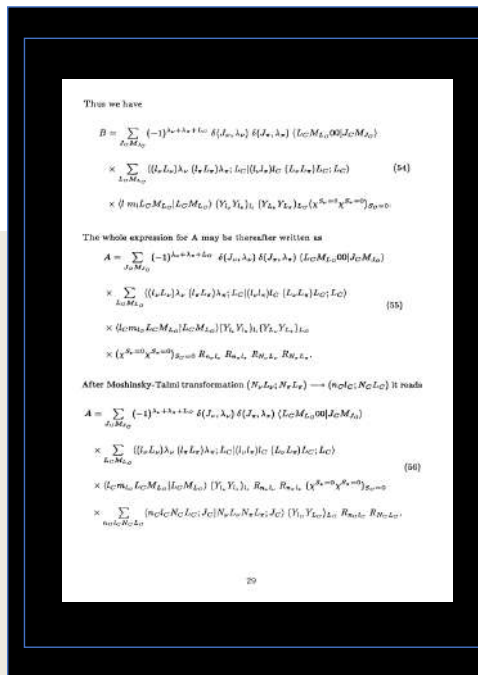
Mälardalen University, Västerås, Sweden

<https://gordana.se/>

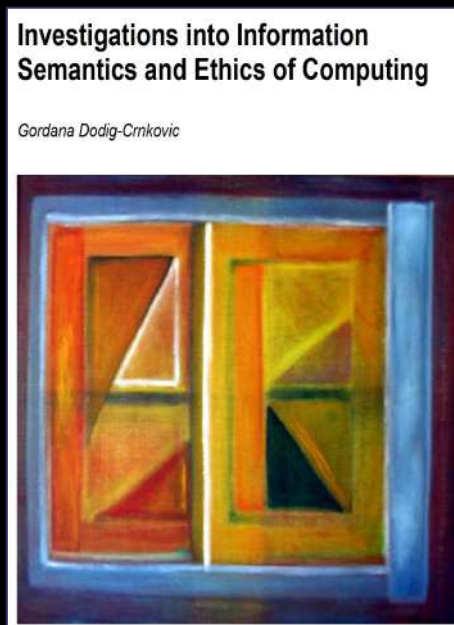
<https://www.linkedin.com/in/gordana-dodig-crnkovic/?originalSubdomain=se>



My background – From formal to natural languages



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



PhD in Computing, 2006
Computer Science,
Mälardalen University



Current: Morphological
Computing and Cognition
AI Ethics, Digital Ethics,
Digital Humanism

The context. Setting the expectations

This is a lecture that looks at a long - time perspective.

Even if it describes living systems in terms of computation, it is not transhumanism*, but instead, digital humanism.

In this era of artificial intelligence, it is searching the deepest roots of intelligence in the evolution of living beings.

"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

"Biology and computer science—life and computation—are related. I am confident that at their interface great discoveries await those who seek them."

Leonard Adleman. Computing with DNA. Scientific American, Aug. 1998

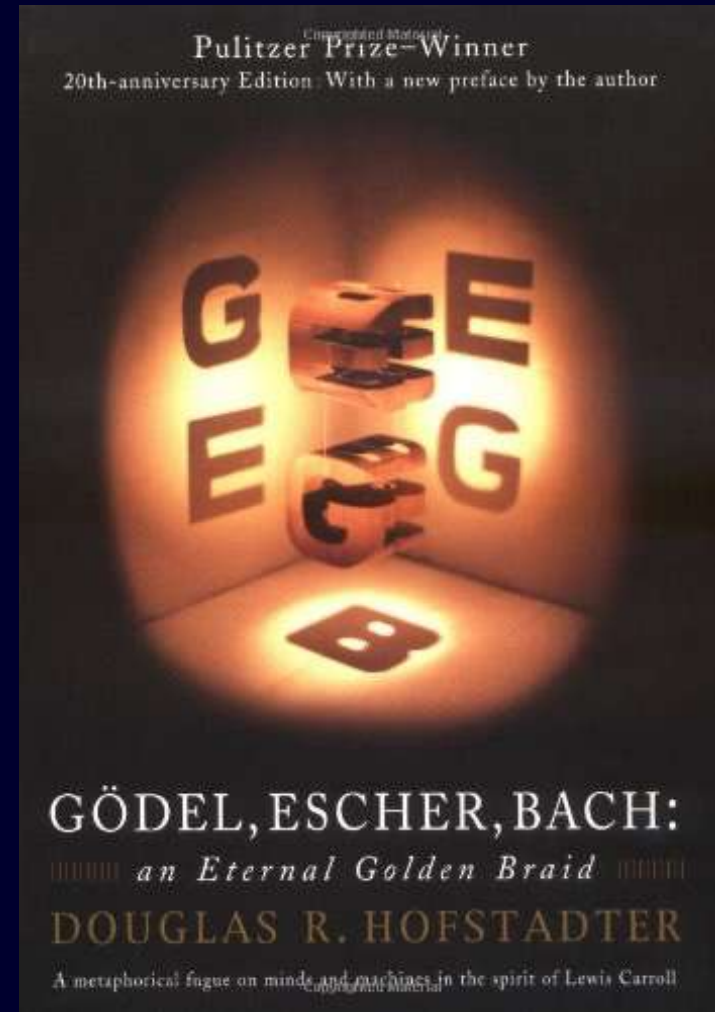
THE FRAMEWORK

THE FRAMEWORK

Information, Computation, Cognition

An Eternal Golden Braid

Agency-based Hierarchies of Levels



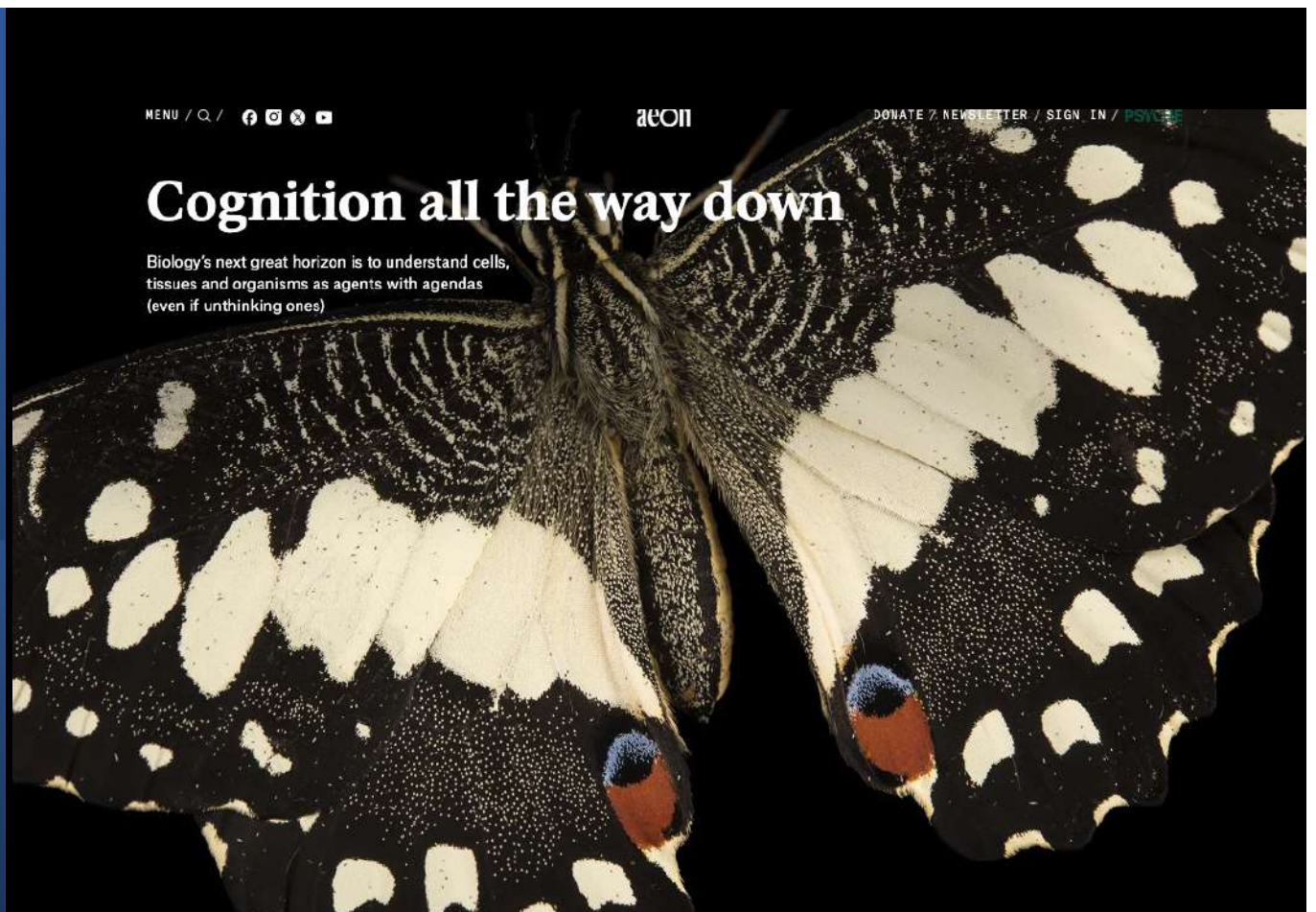
UNDERLYING PRINCIPLES: OBSERVER RELATIVITY AND AGENCY

'Everything said is said by an observer to an observer who could be him/herself (Maturana and Varela, 1980; p. 8)

MATURANA, H. and VARELA, F. J. (1980) *Autopoiesis and Cognition. The Realization of the Living*. Dordrecht, Holland/Boston, U.S.A./London, England. Reidel Publishing Co. Boston Studies in the Philosophy of science, 42.

Michael Levin

Fundamental ideas
about
biological basis of
cognition:
living cells as Darwin's
agential material



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Cognition all the way down

Biology's next great horizon is to understand cells, tissues and organisms as agents with agendas (even if unthinking ones)

Close-up detail of the *Papilio demoleus malapaensis*, the Emebutterfly. Photo by Joel Sartore/National Geographic

Michael Levin is the Vannevar Bush Chair and Distinguished Professor of Biology at Tufts University in Massachusetts, where he directs the Allen Discovery Center and the Tufts Center for Regenerative and Developmental Biology.

Daniel C Dennett is the Austin B Fletcher professor of philosophy and co-director of the Center for Cognitive Studies at Tufts University. He is the author of more than a dozen books, the latest of which is *From Bacteria to Bach and Back: The Evolution of Minds* (2017). He lives in Massachusetts.

Biologists like to think of themselves as properly scientific behaviourists, explaining and predicting the ways that proteins, organelles, cells, plants, animals and whole biota behave under various conditions, thanks to the smaller parts of which they are composed. They identify causal mechanisms that reliably execute various functions such as copying DNA, attacking antigens, photosynthesising, discerning temperature gradients, capturing prey, finding their way back to their nests and so forth, but they don't think that this acknowledgment of functions implicates them in any discredited teleology or imputation of reasons and purposes or understanding to the cells and other parts of the mechanisms they investigate.

But when cognitive science turned its back on behaviourism more than 50 years ago and

<https://aeon.co/essays/how-to-understand-cells-tissues-and-organisms-as-agents-with-agendas>

Observer relativity and agency of basic elements*

'Everything said is said by an observer to an observer who could be him/herself " (Maturana and Varela, 1980; p. 8)

Maturana, Humberto, and Francisco Varela (1980) Autopoiesis and Cognition: The Realization of the Living, Boston Studies in the Philosophy of Science [Cohen, Robert S., and Marx W. Wartofsky (eds.)], Vol. 42, Dordrecht: D. Reidel Publishing Co.

*Agency defines the concrete point of view instead of "God eye perspective".

Explicating observer's perspective (coordinates) does not mean subjectivity, but relativity. Theory of relativity as well as quantum mechanics are observer relative.

THE ARGUMENT IN A NUTSHELL

Proposition:

Every cell processes information (computes) and makes sense of it

A summary of the argument

1. Basic assumption: we are part of a **computing nature** that consists of **informational structures** with **computational processes**.
2. Information is a **structure** consisting of **differences in one system that cause differences in another system**.
In other words, **information is <observer>-relative**.
3. Computation is **information processing** (dynamics of information). It is a **physical process of morphological change in the informational structure which is the physical implementation of information**, as there is no information without physical implementation (Landauer, "Computation: A Fundamental Physical View").

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

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

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

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

Cognition = computation of information (info-computation)

7. In living beings, cognition is equivalent to the (process of) life.*

Its complexity increases with evolution. This complexification is a result of physical/morphological computation.

8. Every cell processes information (computes) and makes sense of information/data goal-directedly. Gut cells compute individually, and collectively as a tissue, organ, and part of an organism .**

* Maturana, H.; Varela, F. Autopoiesis and Cognition: The Realization of the Living; D. Reidel Pub. Co.: Dordrecht, The Netherlands, 1980; ISBN 9789027710154.

Stewart, J. Cognition = life: Implications for higher-level cognition. Behav. Process. 1996, 35, 311–326.

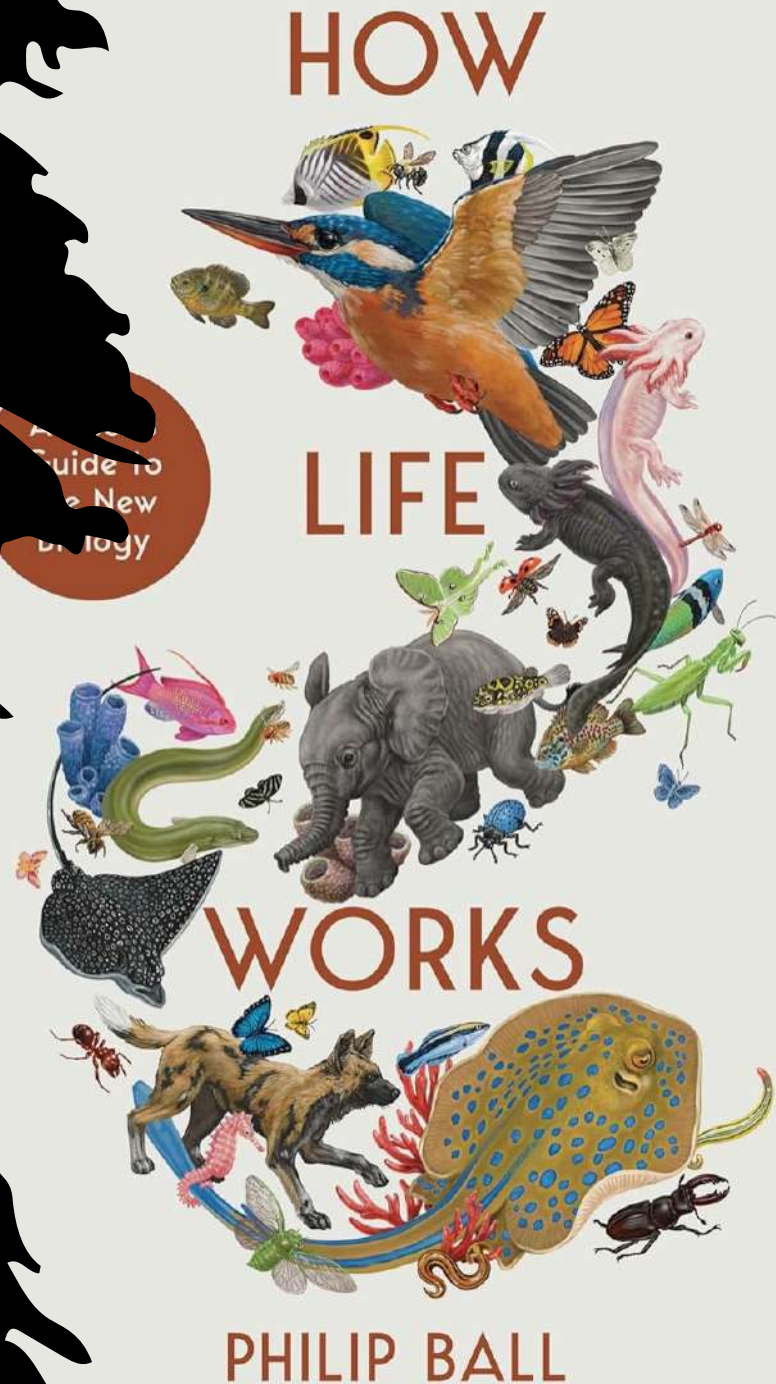
** Manicka, S., Levin, M. (2019) Modeling somatic computation with non-neural bioelectric networks. Sci Rep 9, 18612 <https://doi.org/10.1038/s41598-019-54859-8>

9. Evolution = Extended evolutionary synthesis, which considers that not only random mutations but also sequences of changes caused by laws of physics and chemistry (described as morphological computation) lead to the development of new structures which are exposed to natural selection
[Jablonka and Lamb, 2014][Noble, 2016] [Ginsburg and Jablonka, 2019] <https://extendedevolutionarysynthesis.com/about-the-ees>
Evolution is driven by cognitive agents. ***
10. Cognition, intelligence, and similar capacities of physical and biological systems come in degrees.

*** Manicka S, Levin M. (2019) The Cognitive Lens: a primer on conceptual tools for analyzing information processing in developmental and regenerative. morphogenesis. Phil. Trans. R. Soc. B 374: 20180369. <http://dx.doi.org/10.1098/rstb.2018.0369>

<https://encyclopedia.pub/entry/9878> Cognition-Based Evolution

BIOLOGY: A REVISED CENTRAL DOGMA



one of the finest and most versatile of current non-fiction writers'
JOHN CAREY, THE SUNDAY TIMES

A revised central dogma for the 21st century: All biology is cognitive information processing

Miller Jr, William B. ; Baluska, Frantisek; Reber, Reber, Arthur S.

Abstract

Crick's Central Dogma has been a foundational aspect of 20th century biology, describing an implicit relationship governing the flow of information in biological systems in biomolecular terms. Accumulating scientific discoveries support the need for a revised Central Dogma to support evolutionary biology's still-fledgling migration from a Neodarwinian canon.

A reformulated Central Dogma to meet contemporary biology is proposed: all biology is cognitive information processing.

Central to this contention is the recognition that **life is the self-referential state, instantiated within the cellular form**. Self-referential cells act to sustain themselves and to do so, cells must be in consistent harmony with their environment. That consonance is achieved by the continuous assimilation of environmental cues and stresses as information to self-referential observers. All received cellular information must be analyzed to be deployed as cellular problem-solving to maintain homeorhetic equilibrium*. However, the effective implementation of information is definitively a function of orderly information management. **Consequently, effective cellular problem-solving is information processing and management. The epicenter of that cellular information processing is its self-referential internal measurement. All further biological self-organization initiates from this obligate activity.**

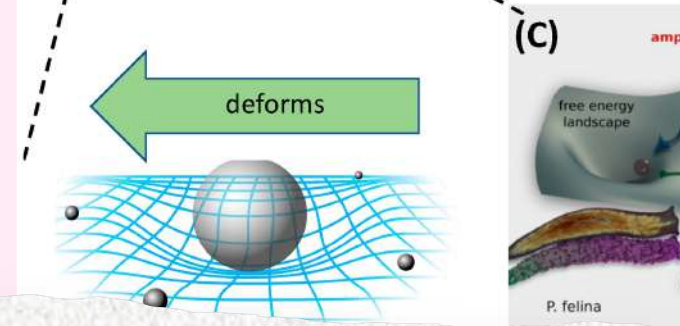
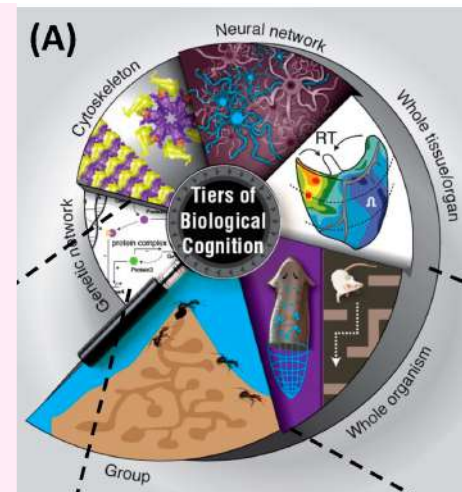
As the internal measurement by cells of information is self-referential by definition, self-reference is biological self-organization, underpinning 21st century Cognition -Based Biology.

PROGRESS IN BIOPHYSICS & MOLECULAR BIOLOGY Vol 182 Pp. 34-48 DOI 10.1016/j.pbiomolbio.2023.05.005
Published 2023

homeorhetic equipoise - Homeorhesis is a property of a dynamical system to return to a particular trajectory after an external perturbation or despite the continuous presence of random noise.



regeneration
behavior
gene
information
memory
mechanism
tissue
cell channel
cognition
control
Bioelectric
system
example
circuit
pattern
state
cancer
function
robot
morphology
time
change
GRNs
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GRNs
biology
form
work
type
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response
shape
Science
field
organism



INFORMATION COMPUTATION COGNITION

<https://www.google.com/url?sa=i&url=https%3A%2F%2Fdrmichaellevin.org%2F&psig=AOvVaw0lJD-kHKhoHVRXUxtSQ-AM&ust=1715005111239000&source=images&cd=vfe&opi=89978449&ved=0CBQQjhXqFwoTCKCGr6na9oUDFQAAAAAdAAAAABAJ>

https://www.mdpi.com/entropy/entropy-24-00819/article_deploy/html/images/entropy-24-00819-g001.png

Josh Bongard, University of Vermont. Xenobots. Book: how the body shapes the way we think

INFORMATION
COMPUTATION
COGNITION

Information as a fabric of reality for an agent

"Information is the difference that makes a difference."*

Gregory Bateson

It is the difference in the world that makes the difference for an agent.
Here the world includes agents themselves too.

"Information expresses the fact that a system is in a certain configuration that is correlated to the configuration of another system. Any physical system may contain information about another physical system."

Carl Hewitt

Bateson, G. (1972). *Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology* pp. 448–466). University Of Chicago Press.

Hewitt, C. (2007). What Is Commitment? Physical, Organizational, and Social. In P. Noriega, J. Vazquez, Salceda, G. Boella, O. Boissier, & V. Dign (Eds.), *Coordination, Organizations, Institutions, and Norms in Agent Systems II* (pp. 293 –307). Berlin, Heidelberg: Springer Verlag.

*Aaron Sloman has critical views on Bateson's formulation, in "What did Bateson mean when he wrote "information" is "a difference that makes a difference"?"

<https://www.cs.bham.ac.uk/research/projects/cogaff/misc/information-difference.html>

Informational structural realism (Floridi, Sayre) argues that information (for an agent) constitutes **the fabric of reality**:

Reality consists of informational structures organized on different levels of abstraction/resolution.

See also:

Van Benthem and Adriaans (2008) Philosophy of Information,
In Handbook of the Philosophy of science series. <http://www.ilc.uva.nl/HPI>

Ladyman J. and Ross D., with Spurrett D. and Collier J. (2007) Every Thing Must Go: Metaphysics Naturalized, Oxford UP

The relational definition of information for an agent

Combining definitions of Bateson:

“ Information is a difference that makes a difference.”

(Bateson, 1972)

and Hewitt:

“Information expresses the fact that a system is in a certain configuration that is correlated to the configuration of another system. Any physical system may contain information about another physical system.”

(Hewitt, 2007),

we get:

Information is defined as the difference in one physical system that makes the difference in another physical system.

Relational approaches in physics, from "It from bit" on

"What we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, all things physical are information-theoretic in origin and this **is a participatory universe.**"

John Archibald Wheeler, "Information, Physics, Quantum: The Search For Links" Proc. 3rd Int. Symp. Foundations Of Quantum Mechanics, Tokyo, 1989, Pp.354-368

Stephen Wolfram, A Project to Find the Fundamental Theory of Physics

<https://writings.stephenwolfram.com/2020/04/finally-we-may-have-a-path-to-the-fundamental-theory-of-physics-and-its-beautiful/>

Carlo Rovelli, Relational Quantum Mechanics

<https://plato.stanford.edu/entries/qm-relational/>

<https://www.scientificamerican.com/article/is-there-a-thing-or-a-relationship-between-things-at-the-bottom-of-things/>

INFORMATION
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Structure vs. process

For all living agents, information is the fabric of reality.

But: the knowledge of structures is only half a story.

The other half are changes/processes i.e. information dynamics.
In classical formulation: being (structure) and becoming (process).

Information processing will be taken as the most general definition of computation.*

This definition of computation has a profound consequence – if computation is the dynamics of informational structures of the universe, **the dynamics of the universe is a network of computational processes (natural computationalism)**.

Gordana Dodig-Crnkovic, Dynamics of Information as Natural Computation, Information 2011, 2(3), 460-477;
Selected Papers from FIS 2010 Beijing, 2011.

*Mark Burgin, Super-Recursive Algorithms, <https://link.springer.com/book/10.1007/b138114>

Computing Nature: Reality as an informational structure with computational dynamics

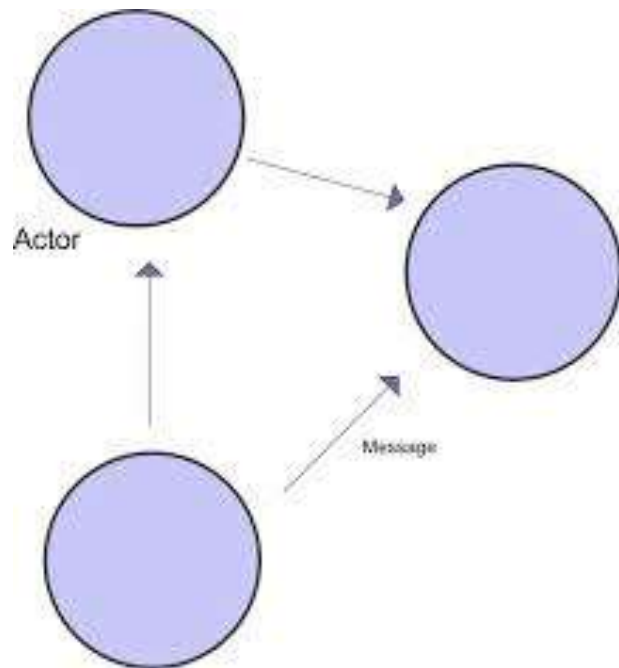
Information is defined as the difference in one physical system that makes the difference in another physical system.

This reflects the relational character of information and thus agent-dependency which calls for agent-based or actor models.

As a synthesis of [informational structural realism](#) and [natural computationalism](#), I propose [info-computational structuralism](#) that builds on two basic concepts: information (as a structure) and computation (as a dynamics of an informational structure) (Dodig-Crnkovic, 2011).

Information and computation are two basic and inseparable elements necessary for naturalizing <cognition>. (Dodig-Crnkovic, 2009)

Hewitt 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.

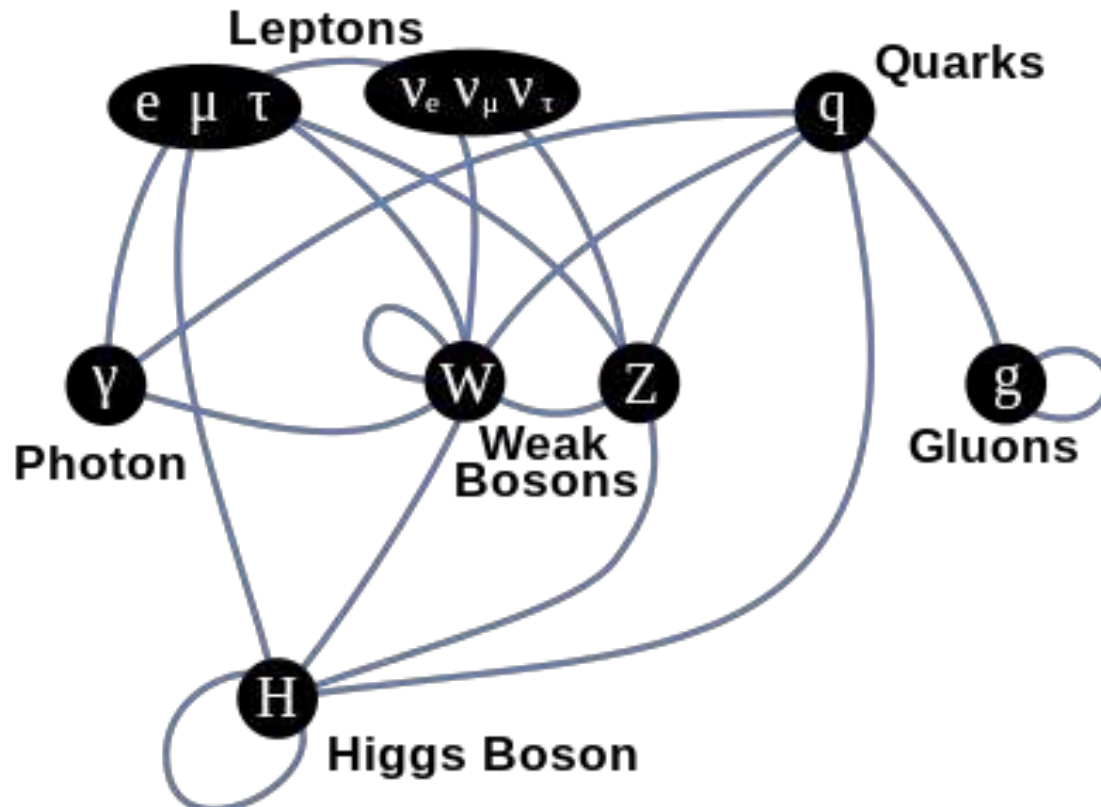
Hewitt Actor Model of concurrent distributed computation

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 become Agents only when they are able to process expressions for commitments including the following: Contracts, Announcements, Beliefs, Goals, Intentions, Plans, Policies, Procedures, Requests, and Queries.

In other words, Hewitt's Agents are human-like or if we broadly interpret the above capacities, life-like Actors.

Hewitt 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.

WHAT IS COMPUTATION?

The generality of the Turing machine model of computation was questioned on several grounds, by:

- Peter Wegner, through [interaction](#) (adaptivity of computational system) vs. algorithm as a fix procedure
- Mark Burgin, based [on more general definition of algorithm](#) that does not need to halt
- Yuri Gurevich: limitation of TM model as representing a [string-to-string computable function](#) (Unconstrained Church-Turing thesis cannot possibly be true, <https://arxiv.org/abs/1901.04911>)
- Barry Cooper: TM does not cover [higher order computation](#)
- Samson Abramsky – computing is about [behavior](#) in general
- ...

Unconstrained Church-Turing thesis cannot possibly be true - Yuri Gurevich

The Church-Turing thesis asserts that if a partial strings-to-strings function is effectively computable then it is computable by a Turing machine.

In the 1930s, when Church and Turing worked on their versions of the thesis, there was a robust notion of algorithm. These traditional algorithms are known also as classical or sequential. In the original thesis, effectively computable meant computable by an effective classical algorithm. Based on an earlier axiomatization of classical algorithms, the original thesis was proven in 2008.

Since the 1930s, the notion of algorithm has changed dramatically. New species of algorithms have been and are being introduced. We argue that the generalization of the original thesis, where effectively computable means computable by an effective algorithm of any species, cannot possibly be true.

TAXONOMY OF COMPUTATION

Burgin, M. and Dodig-Crnkovic, G., [A Taxonomy of Computation and Information Architecture](#). ECSA 2015 ASDS Workshop. In Proceedings of the 2015 European Conference on Software Architecture Workshops (ECSAW '15). ACM, New York, NY, USA. DOI=10.1145/2797433.2797440

INFORMATION
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Cognition

The dictionary definition (**human**-centric):

Cognition is the *mental* action or process of acquiring knowledge and understanding* through thought, experience, and the senses.

[*count noun*] a perception, sensation, idea, or intuition resulting from the process of cognition.

from Latin *cognitio(-)*, from *cognoscere* 'get to know'

<http://www.oxforddictionaries.com/definition/english/cognition>

from co- ("together") + **gnoscere* ("know, recognize, get acquainted with") <http://en.wiktionary.org/wiki/nosco#Latin>

We have, following Maturana & Varela and Steward

COGNITION = LIFE

*Mental = relating to the mind. Mind is a set of processes on which consciousness, perception, affectivity, emotions, judgment, thinking, and will are based.

Cognition

Cognition refers to the processes and mechanisms by which **living organisms extract, transform, store, retrieve, and apply information from their environment**. This encompasses several abilities including perception, attention, memory, language, problem-solving, executive function.

The simplest living organism is a single cell.

Cognition of a single cell is called **basal cognition**.

Perception: The collection of data about the environment through sensory inputs like sight, hearing, touch, taste, and smell.

Attention: The selective concentration on specific aspects of the environment or on specific tasks while ignoring other stimuli.

Memory: The retention and later recall of received information. This includes different categories like short-term memory, long-term memory, and working memory.

Language: The understanding and use of complex systems of symbols for communication, which can be verbal or nonverbal.

Problem-solving and decision-making: The application of information and reasoning to make choices, solve issues, and complete complex tasks.

Executive functions: Higher-order abilities that manage and control other cognitive abilities, assist in setting goals, planning for the future, and completing complex tasks.

These processes are central to an organism's ability to interact effectively with its environment and adapt to changes, contributing to survival and success.

Life as cognition. Autopoiesis as a self-reflective process

"Living systems are cognitive systems and **living is a process is a process of cognition**. This statement is valid for all organisms, with and without a nervous system."

Humberto Maturana, Biology of Cognition, 1970

Maturana and Varela (1980) define "autopoiesis" as follows: An autopoietic system is a system organized (defined as a unity) as a network of processes of production (transformation and destruction) of **components that** produces the components, such that:

- (i) through their interactions and transformations continuously they regenerate and realize the network of processes (relations) that produced them; and
- (ii) they constitute it (the system) as a concrete unity in the space in which they (the components) exist by specifying the topological domain of its realization as such a network.

Basal Cognition – Minimal Cognition Studies

Marc van Duijn, Fred Keijzer & Daan Franken (2006) Principles of Minimal Cognition. Casting Cognition as Sensorimotor Coordination. *Adaptive Behavior*, 14(2), 157-170

Lyon P, Keijzer F, Arendt D, Levin M. 2021 Reframing cognition: getting down to biological basics. *Phil. Trans. R. Soc. B.* 376: 20190750. <https://doi.org/10.1098/rstb.2019.0750>

Gershman et al. Reconsidering the evidence for learning in single cells (2021) *eLife*;10:e61907. DOI: <https://doi.org/10.7554/eLife.61907>

František Baluška & William B. Miller, Jr (2018) Senomic view of the cell: Senome versus Genome, *Communicative & Integrative Biology*, 11:3, 1-9, DOI: 10.1080/19420889.2018.1489184

To link to this article: <https://doi.org/10.1080/19420889.2018.1489184>

Manicka S, Levin M. 2019 The Cognitive Lens: a primer on conceptual tools for analysing information processing in developmental and regenerative morphogenesis. *Phil. Trans. R. Soc. B* 374: 20180369. <http://dx.doi.org/10.1098/rstb.2018.0369>

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For example, symbolic, language-form information processing characteristic of human languages, also exists on the level of chemical languages used by bacteria:

Mukherjee S, Bassler BL. Bacterial quorum sensing in complex and dynamically changing environments. *Nat Rev Microbiol.* 2019 Jun;17(6):371-382. doi: 10.1038/s41579-019-0186-5.

https://www.ted.com/talks/bonnie_bassler_how_bacteria_talk Bonnie Bassler on Bacterial quorum sensing

Ben-Jacob, E. (2006). *Bacterial Know-How: From Physics to Cybernetics.* , PHYSICAPLUS 7.

Ben Jacob, E., Shapira, Y. & Tauber, A.I. (2006). Seeking the foundations of cognition in bacteria: from Schrödinger's negative entropy to latent information. *Physica A.*

Ben-Jacob, E. (2009). Learning from bacteria about natural information processing. *Annals of the New York Academy of Sciences.*

Shapiro, J. A. (2007). Bacteria are small but not stupid: cognition, natural genetic engineering and socio-bacteriology. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 38.

Cellular Information Processing

“Cellular information processing could be understood in terms of morphogenesis and the ability of cell groups to model shape” [Friston et al. 2015] offers proof of principle that self-assembly is an emergent property of cells that share a common (genetic and epigenetic) model of organismal form. This allows the authors to interpret a system as “inferring the causes of its inputs—and acting to resolve uncertainty about those causes.” This novel perspective balances strategy with a focus on molecular pathways and bottom-up causation, with top-down constraints found in cybernetics and neuroscience. The driving force in this process is the minimization of surprise/prediction error. Friston et al. [68] find that by using a variational free energy approach to pattern formation and control in complex biological systems, the process of morphogenesis can be interpreted as Bayesian inference. (Dodig-Crnkovic, 2022)

Friston, K.; Levin, M.; Sengupta, B.; Pezzulo, G. (2015) Knowing one's place: A free-energy approach to pattern regulation. *J. R. Soc. Interface*, 12, 1383.

Dodig-Crnkovic, Gordana (2022) Cognition as Morphological/Morphogenetic Embodied Computation In Vivo, *Entropy* 24, no. 11: 1576. <https://doi.org/10.3390/e24111576>

The computational boundary of a "self"

Michael Levin proposes "a fundamental definition of an Individual based on the ability to pursue goals at an appropriate level of scale and organization and suggest a formalism for defining and comparing the cognitive capacities of highly diverse types of agents."

Any Self is demarcated by a computational surface – the spatio-temporal boundary of events that it can measure, model, and try to affect. This surface sets a functional boundary - a cognitive "light cone"* which defines the scale and limits of its cognition. "

Levin hypothesizes "that higher level goal-directed activity and agency, resulting in larger cognitive boundaries, evolve from the primal homeostatic drive of living things to reduce stress – the difference between current conditions and life-optimal conditions."

Levin, Michael (2019) The Computational Boundary of a "Self": Developmental Bioelectricity Drives Multicellularity and Scale-Free Cognition. *Front. Psychol.*, Volume 10 - 2019
<https://doi.org/10.3389/fpsyg.2019.02688>

"cognitive light cone" relates to "umwelt" in the semiotic theories of Jakob von Uexküll and Thomas A. Sebeok.

In search of adequate model of computation capable of implementing information dynamics in cognitive systems...

Turing Machine is a model of computation equivalent to an algorithm, thus sequential symbol manipulation, and it may be used for the description of different processes in living organisms.

We need computational models for the basic characteristics of life as the ability to differentiate and synthesize information, make a choice, adapt, evolve, and learn in an unpredictable world.

That requires computational mechanisms and models which are not sequential and predefined as a Turing machine but can run in parallel and have sensitivity to resources (space, time, energy).*

* Leslie Valiant argues that PAC learning describes how organisms evolve and learn:

L. Valiant. Probably Approximately Correct. Basic Books, 2013.

In search of adequate model of computation...

Computational approaches that are capable of modeling **adaptation, evolution, and learning** are found in the field of natural computation and computing nature.

Cognitive computing and cognitive robotics are attempts to **construct abiotic systems exhibiting cognitive characteristics**.

As **cognition comes in degrees**, it is meaningful to talk about the cognitive capabilities of artifacts, even though those are not meant to assure the continuation of existence ("the survival") of artificial cognitive agents, which was the evolutionary role of cognition in biotic systems.

Models of Computation Beyond the Turing Machine

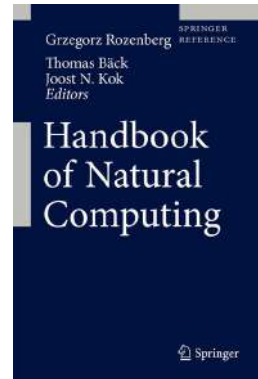
With the advent of computer networks, which are the main paradigm of computing today, [the model of a computer in isolation*](#), represented by a Turing Machine, has become insufficient.

The basic difference between an isolated computing box and a network of computational processes (nature itself is understood as a computational mechanism) is [the interactivity of computation](#). The most general computational paradigm is interactive computing (Wegner, Goldin).

*This view of a system in isolation is inherited from physics. I. [Prigogine strongly emphasized the importance of the environment/context especially essential for living beings](#).

Prigogine, Ilya; Stengers, Isabelle (1984). Order out of Chaos: Man's new dialogue with nature. Flamingo

Computing nature and nature-inspired computation



In 1623, Galileo in his book *The Assayer - II Saggiatore*, claimed that the language of nature's book is mathematics and that the way to understand nature is through mathematics. Generalizing "mathematics" to "computation" we may agree with Galileo – the great book of nature is an e-book.

Peter J. Denning. 2007. Computing is a natural science. *Commun. ACM* 50, 7 (July 2007), 13-18.
DOI=10.1145/1272516.1272529
<http://doi.acm.org/10.1145/1272516.1272529>

<http://www.youtube.com/watch?v=JA5QoTMvsiE&feature=related> Mandelbrot fractals

Natural computation includes:

Computation Inspired by nature:

Evolutionary computation

Neural networks

Artificial immune systems

Swarm intelligence

Simulation and emulation of nature:

Fractal geometry

Artificial life

Computing with natural materials:

DNA computing

Quantum computing

Journals: Natural Computing and IEEE Transactions on Evolutionary Computation, Unconventional computing, etc.

THE MANY FACETS OF NATURAL COMPUTING

A closer look at nature from the point of view of information processing can and will change what we mean by computation.

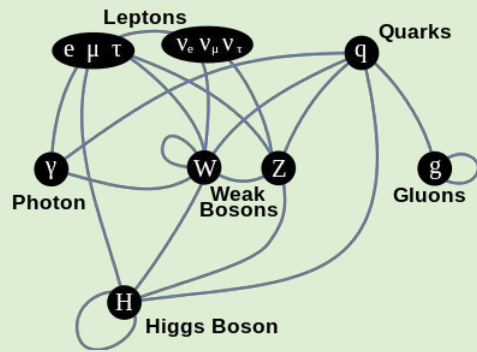
it is indeed believed that one of the possible contributions of computer science to biology could be the development of a suitable language to accurately and succinctly describe, and reason about, biological concepts and phenomena.



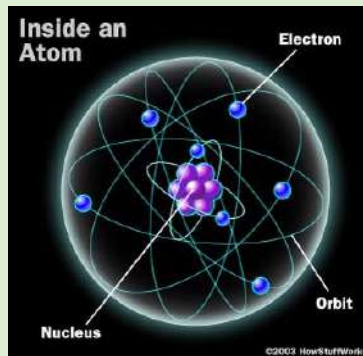
As the natural sciences are rapidly absorbing ideas of information processing, and the meaning of computation is changing as it embraces concepts from the natural sciences, we have the rare privilege to take part in several such metamorphoses.

<https://www.csd.uwo.ca/~lkari/Natural-Computing-Review.pdf>

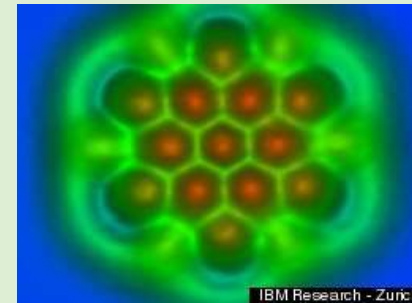
Computing Nature and Nature Inspired Computation



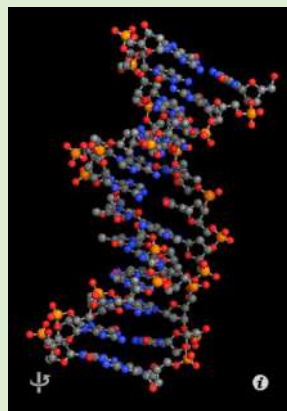
Subatomic particles



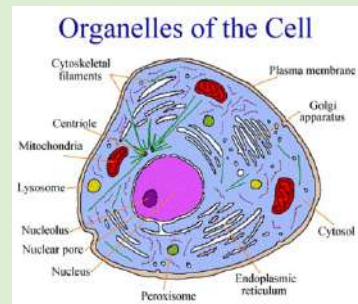
Atoms



This image, by IBM scientists using an atomic force microscope, shows a nanographene molecule with carbon-carbon bonds



DNA molecule



Unicellular organism



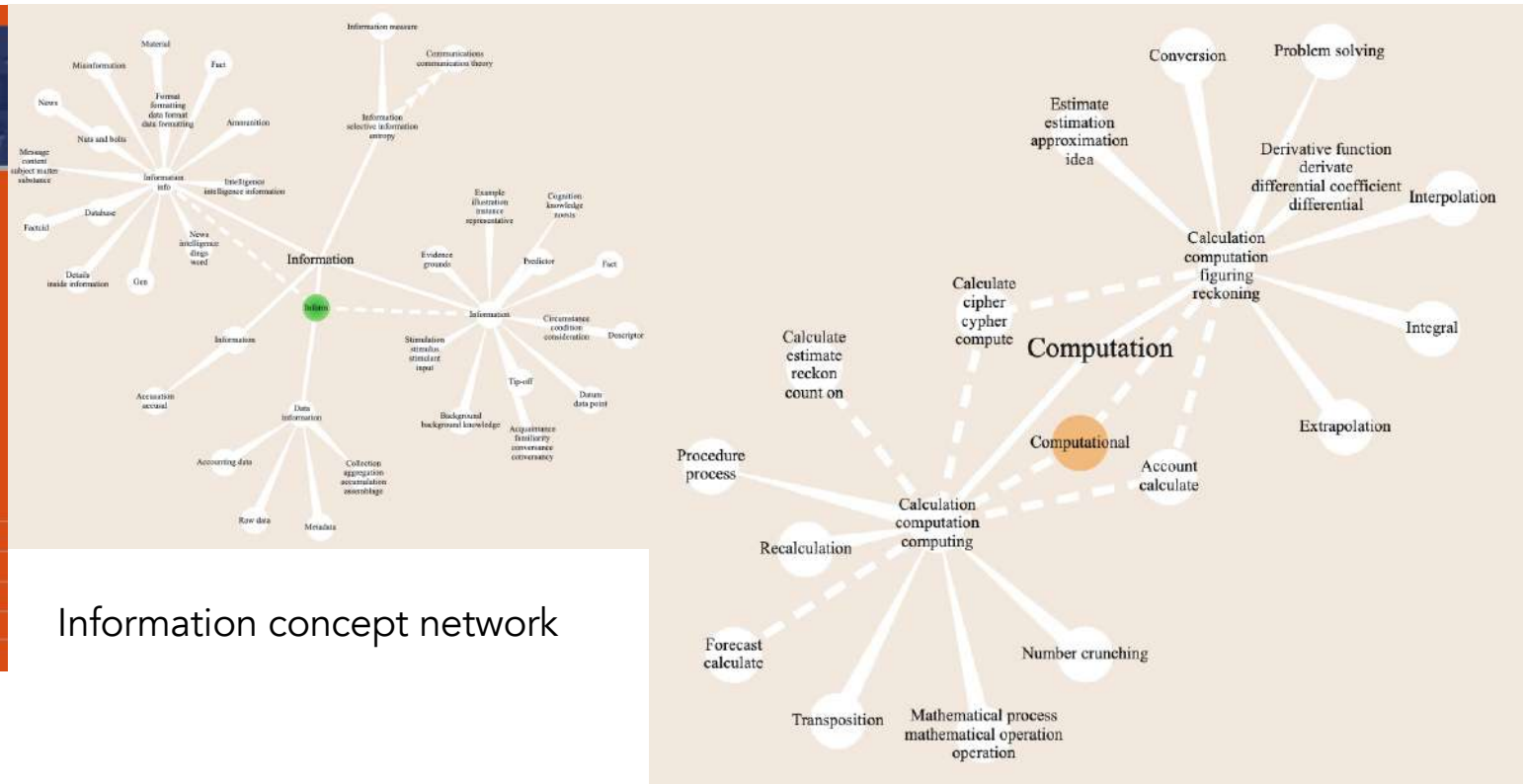
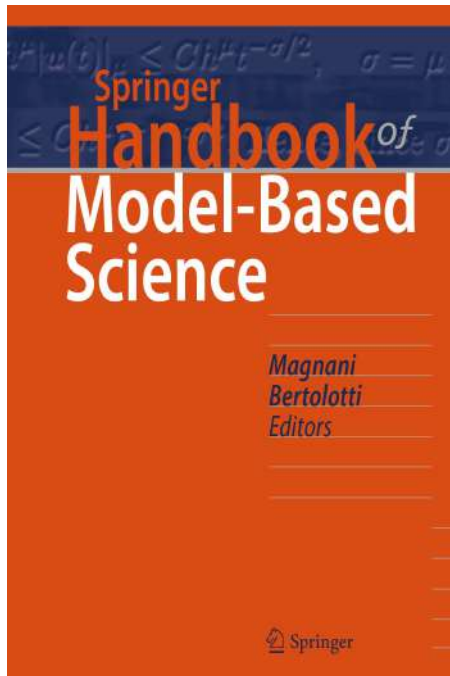
Bacterial colony a multi-cellular "organism"

Bacteria collectively "collects latent information from the environment and from other organisms, process the information, develop common knowledge, and thus learn from past experience" (Ben-Jacob, 2009)

Peter J. Denning. 2007. Computing is a natural science. Commun. ACM 50, 7 (July 2007), 13-18. DOI=10.1145/1272516.1272529 <http://doi.acm.org/10.1145/1272516.1272529>

http://www.ted.com/talks/bonnie_bassler_on_how_bacteria_communicate

Computational aspects of model-based reasoning



Information concept network

Computation concept network

Dodig-Crnkovic, G., Cicchetti, A. (2017). Computational Aspects of Model-Based Reasoning. In: Magnani, L., Bertolotti, T. (eds) Springer Handbook of Model-Based Science. Springer Handbooks. Springer, Cham. https://doi.org/10.1007/978-3-319-30526-4_32

Discussion about the Conceptual Basis of the Computing Nature Framework

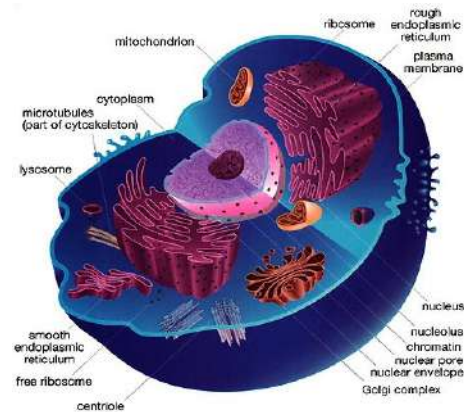
Dodig-Crnkovic, G. & Miłkowski, M. (2023) "[Discussion on the Relationship between Computation, Information, Cognition, and Their Embodiment.](https://doi.org/10.3390/e25020310)" Entropy, 25(2), 310. MDPI AG. Retrieved from <http://dx.doi.org/10.3390/e25020310>

Is computational nature an overgeneralization?

Does it make sense to think in terms of parallels:

information	computation
structure	process
being	becoming
space/time	matter/energy

Computing Cells: Self-generating Systems



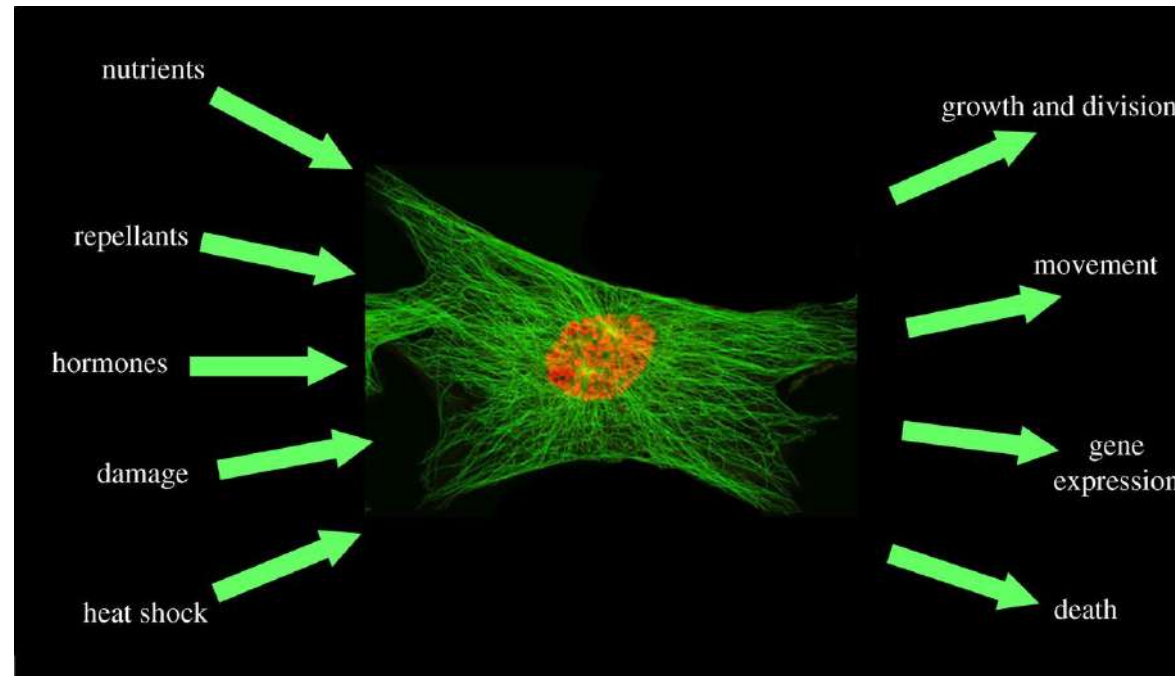
Complex biological systems must be modeled as self-referential, self-organizing "component-systems" (George Kampis) which are self-generating and whose behavior, though computational in a general sense, goes far beyond Turing machine model.

"a component system is a computer which, when executing its operations (software) builds a new hardware.... [W]e have a computer that re-wires itself in a hardware-software interplay: the hardware defines the software, and the software defines new hardware. Then the circle starts again." Kampis (1991) p. 223

Kampis (1991) *Self-Modifying Systems in Biology and Cognitive Science. A New Framework For Dynamics, Information, and Complexity*, Pergamon Press

Dodig Crnkovic, G. (2011). Significance of Models of Computation from Turing Model to Natural Computation. *Minds and Machines*, (R. Turner and A. Eden guest eds.) Volume 21, Issue 2, p.301.

Natural Cognition & Intelligence. Basic Level of Cells Processing Information



<http://rsfs.royalsocietypublishing.org/content/4/3/20130070>

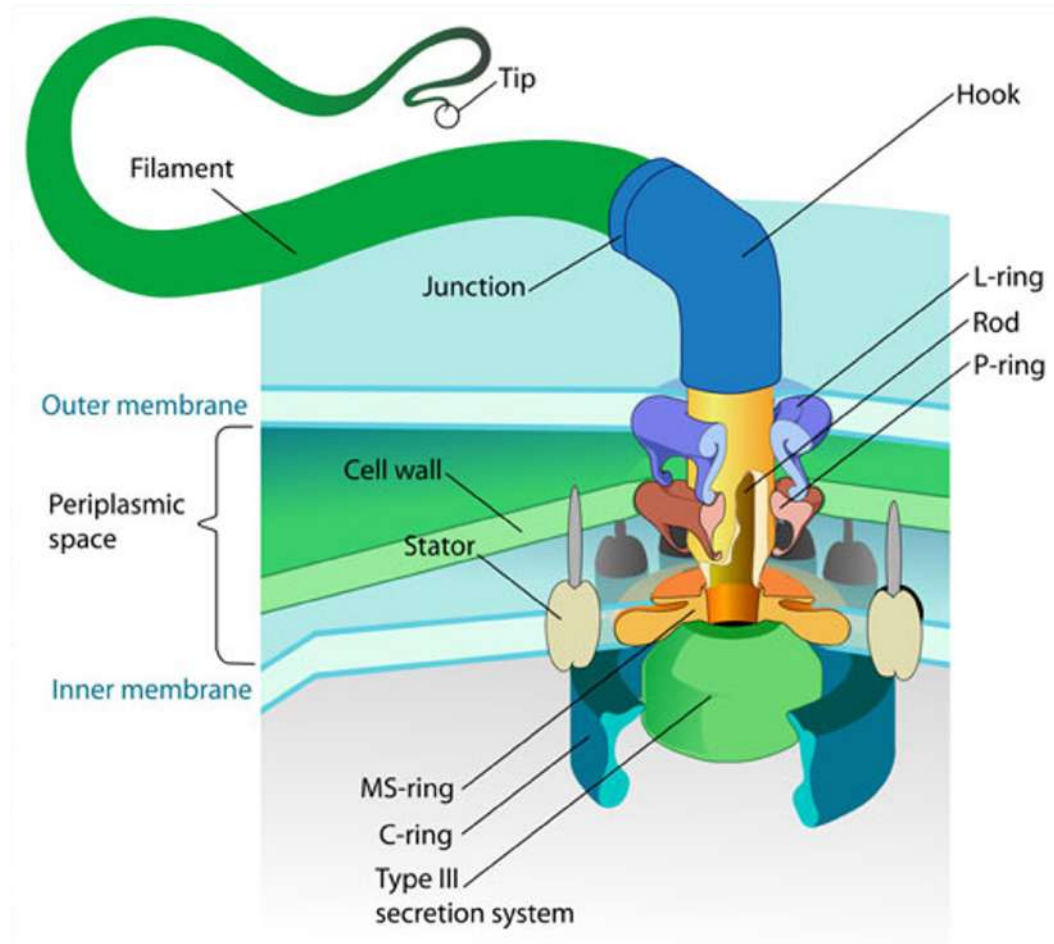
<https://www.youtube.com/watch?v=wJyUtbn0O5Y&list=PLXPeXawEy4EcPnecIV1FaZA6bgVDujLzm&index=7> Harvard University
XVIVO animation showing inner world of a cell

<http://www.youtube.com/watch?v=NJxobgkPEAo&feature=related> From RNA to Protein Synthesis
<http://www.youtube.com/watch?v=3aVT2DTbtA8&feature=related> Replication, Transcription, and Translation

“even the most primitive living organisms are minimally “cognitive”

J. Stewart (1996). Cognition = Life : Implications for higher-level cognition. *Behavioural Processes* 35: 311-326.

Some (Very Mechanistic) Details of a Molecular Machinery in Bacteria (Unicellular Organism)



<https://www.youtube.com/watch?v=cwDRZGj2nnY> The Bacterial Flagellar Motor
https://www.youtube.com/watch?v=X_tYrnv_o6A Body's Molecular Machines

Single-celled *Lacrymaria olor* Hunts Down Another Cell

Lacrymaria olor is a single-celled organism, its name means "tears of a swan". It has a "neck" and a "mouth".

Lacrymaria olor beats the hair-like cilia around its 'head' and extends its neck up to 8 times its body length.

<https://www.youtube.com/watch?v=sq6Y54mxjOg>

<https://www.cell.com/cms/10.1016/j.cub.2019.09.034/attachment/e5e40ae4-8751-4336-acc5-318c3897f558/mmc2.mp4>



[https://www.cell.com/current-biology/fulltext/S0960-9822\(19\)31196-0?returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0960982219311960%3Fshowall%3Dtrue](https://www.cell.com/current-biology/fulltext/S0960-9822(19)31196-0?returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0960982219311960%3Fshowall%3Dtrue)
Coupled Active Systems Encode an Emergent Hunting Behavior in the Unicellular Predator *Lacrymaria olor*

Microorganismic cognition

Microorganisms have sensors and actuators, and use chemical signaling and transfer of genetic information as a basis for adaptation and learning.



<http://phys.org/news/2009-11-conquer-social-network-cells.html>



<http://www.hhmi.org/research/global-mapping-genetic-networks> A functional network for a yeast cell



Eshel Ben Jacob
bacterial colony

Bacteria sense,
adapt and
communicate
by "chemical
language"

https://en.wikipedia.org/wiki/Ben-Jacob%27s_bacteria



<http://www.cellcognition.org/>
The cell cognition project

Basal Cognition



living world. Is a nervous system needed? If so, why? If not, why not? A new two-part theme issue of Phil Trans B on the emerging field of 'Basal Cognition', edited by Pamela Lyon, Fred Keijzer, Detlev Arendt and Michael Levin, explores these questions.

Part 1: <https://royalsocietypublishing.org/toc/rstb/2021/376/1820>

Part 2: <https://royalsocietypublishing.org/toc/rstb/2021/376/1821>

Plant cognition

Plants do not have nervous system, but they have information-processing systems as a basis for adaptation, and learning. Plants selectively adapt to the resources in the environment which are available for their survival and reproduction.

Exogenous signals

Light (quality, quantity, duration, direction)

Mechanical, constant (substrate, support)
Mechanical, variable (wind, herbivores)

Atmospheric humidity
Other plants proximity
Temperature
Nutrients
Water
CO₂
Pathogenes
Gravity

Endogenous signals

Growth regulators (cytokinin, ethylene, gibberellin, auxin, abscisic acid, brassinosteroids)

Mechanical, growth related tissue compression and tension

Defence signals
Jasmonic acid
Salicylic acid

Developmental regulators (mobile RNA)

Metabolites (sugars, glutamate)



Signal processing and transduction in plant cells: the end of the beginning?
S. Gilroy and A. Trewavas (2001)
Nature Reviews Molecular Cell Biology 2, 307-314

Dynamics of Long-distance Signaling via Plant Vascular Tissues
Notaguchi Michitaka, Okamoto Satoru (2015) Frontiers in Plant Science. Vol. 6 No. 00161
<http://journal.frontiersin.org/article/10.3389/fpls.2015.00161/full>

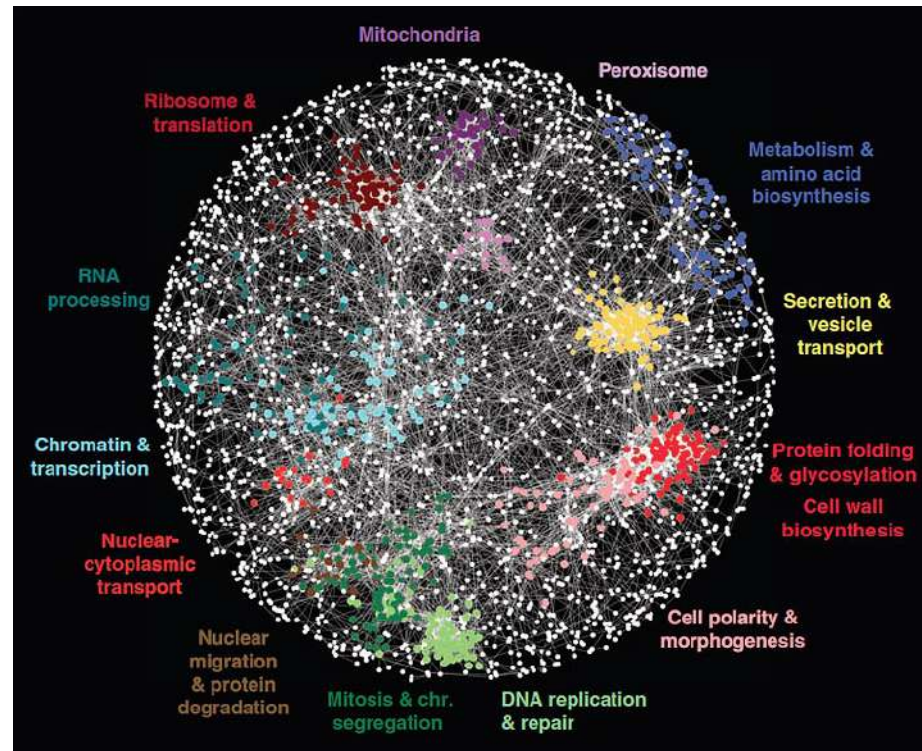
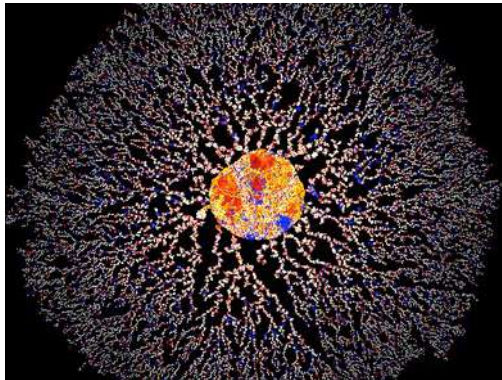
Plants: Adaptive behavior, root-brains, and minimal cognition.
Garzon, Paco; Keijzer, Fred (2011). " Adaptive Behavior. 19 (3): 155–171.

Plant behaviour and communication.
Karban, Richard (2008). " Ecology Letters. 11 (7): 727–739.
doi:10.1111/j.1461-0248.2008.01183.x. PMID 18400016.

Animal cognition

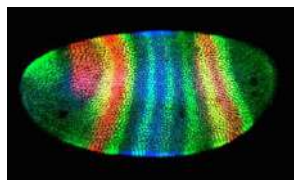
Rudimentary forms of language

<http://www.cellcognition.org/> The cell cognition
https://en.wikipedia.org/wiki/Molecular_cellular_cognition

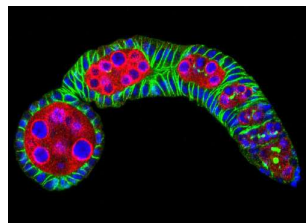


<http://phys.org/news/2009-11-conquer-social-network-cells.html>

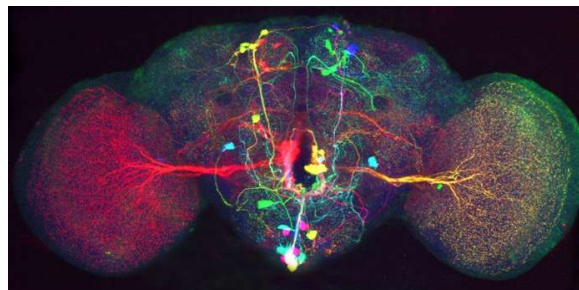
http://www.visualcomplexity.com/vc/images/122_big01.jpg Protein network



Fruit fly embryo



Fruit fly larva

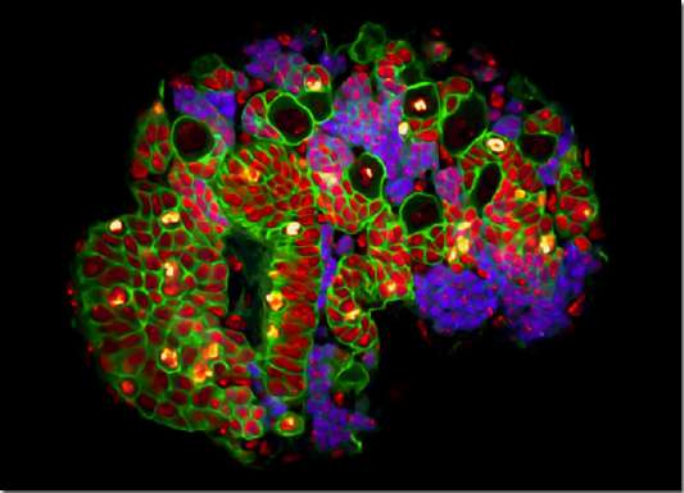
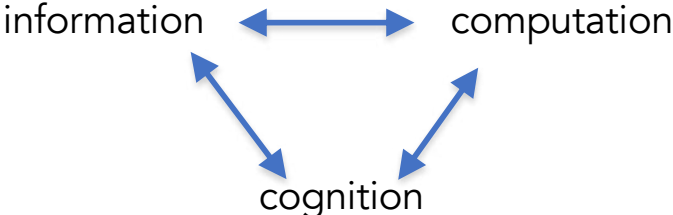


Fruit fly brain neurons

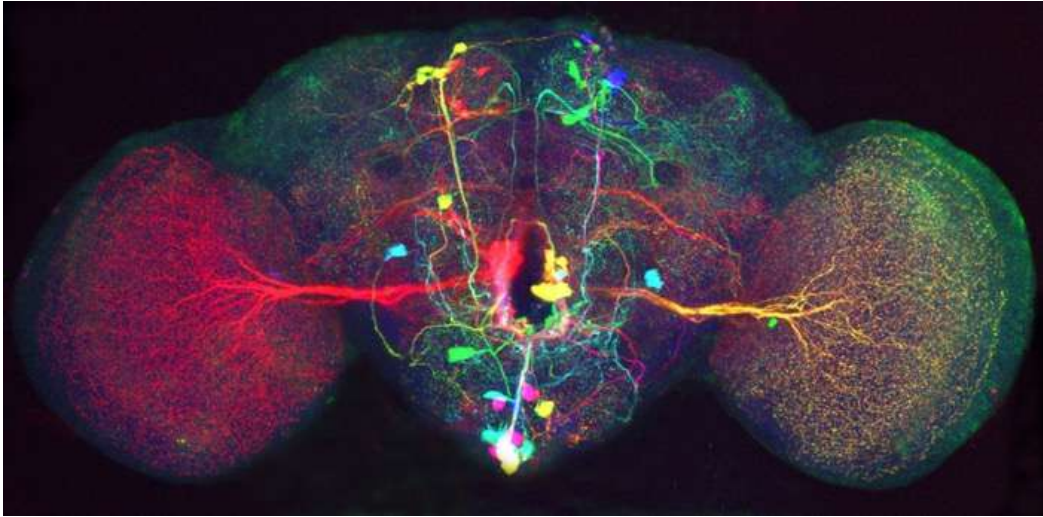


Fruit fly head

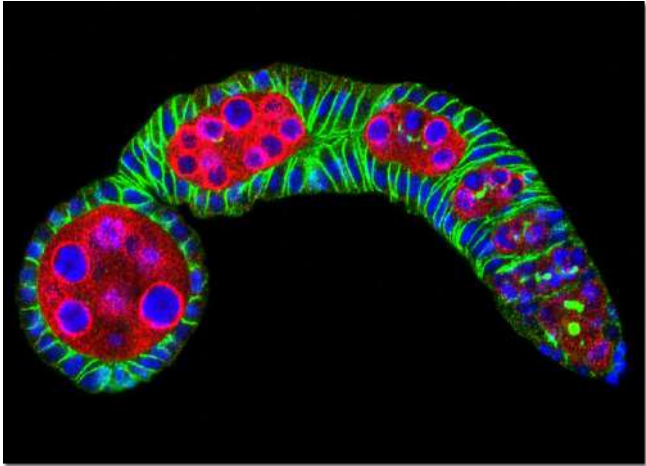
Modeling information, computation, and cognition from an agent's perspective.



Fruit fly brain micrograph



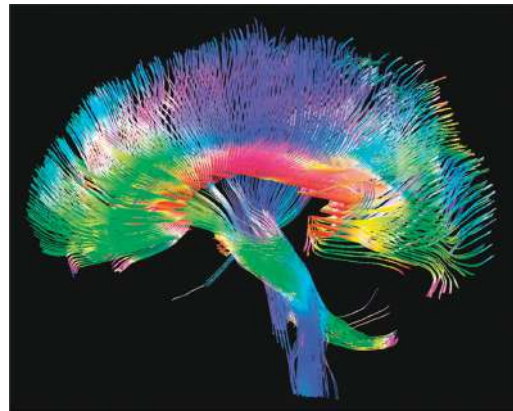
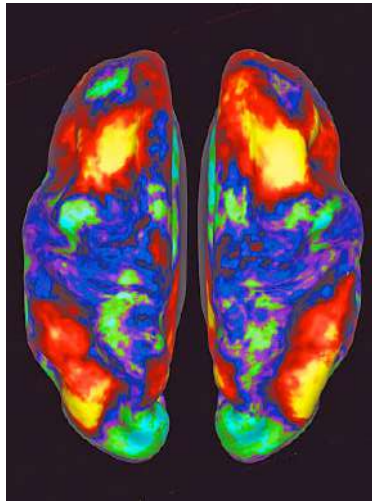
Fruit fly brain neurons



Fruit fly larva

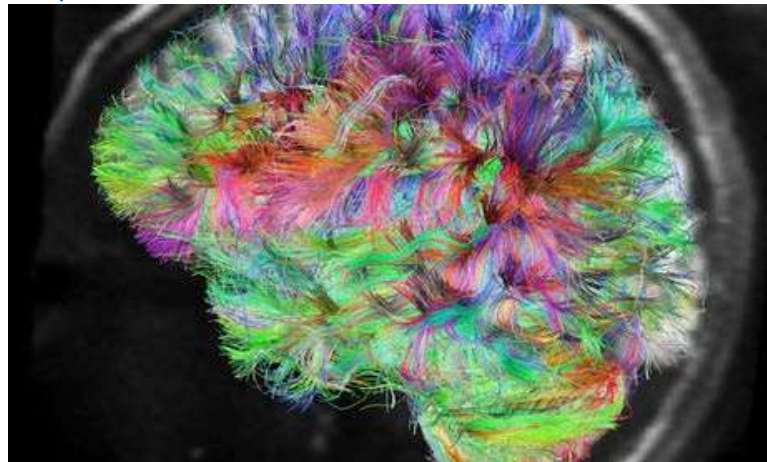
Information, computation, cognition

Agency/Interaction-based Hierarchies of Levels



Human connectome

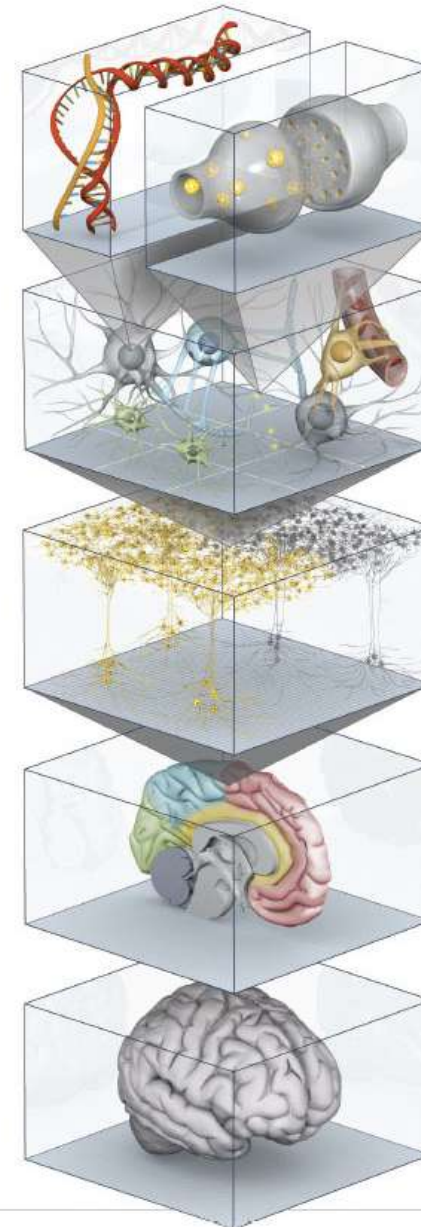
<http://outlook.wustl.edu/2013/jun/human-connectome-project>



<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.

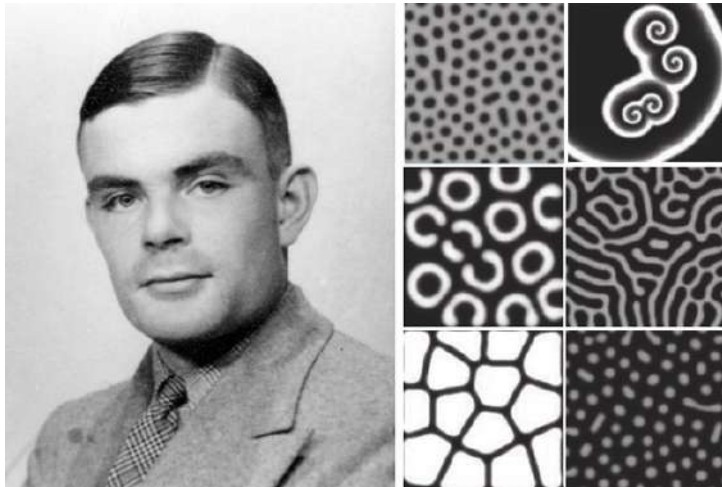
Regions

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.

Turing Beyond Turing Machine Model- Morphogenesis



2012 we celebrated 100th Turing birthday

Alan Turing was:

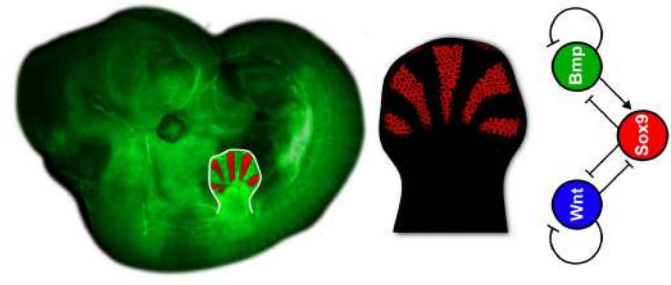
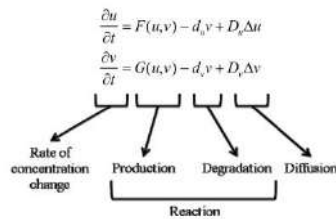
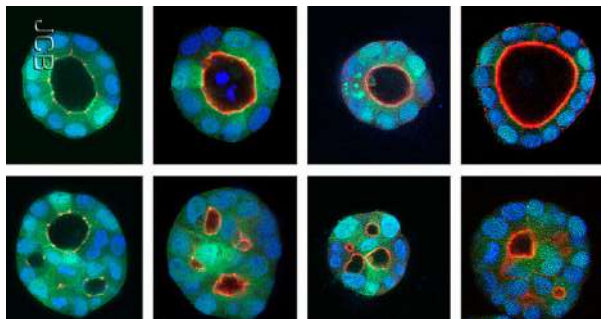
Mathematician

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

Codebreaker

Natural philosopher

Visionary man before his time

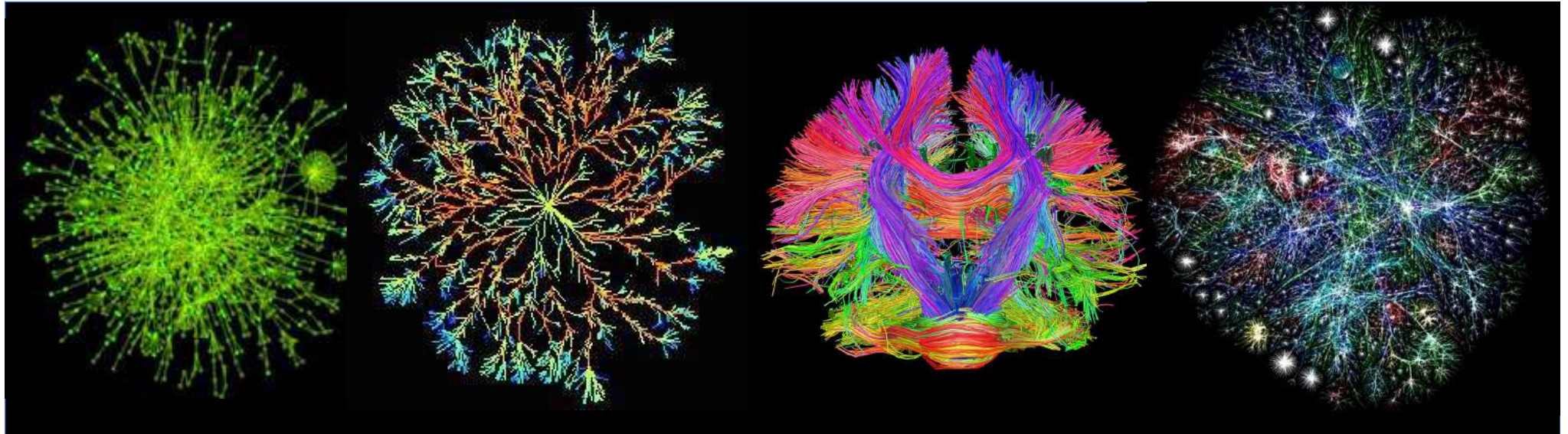


Researchers confirm that a mathematical theory first proposed by Alan Turing in 1952 can explain the formation of fingers
<https://www.crg.eu/en/news/crg-researchers-confirm-mathematical-theory-first-proposed-alan-turing-1952-can-explain-formation-fingers>

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

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

FINALLY: IN WHAT SENSE CAN WE SAY THAT GUTS COMPUTE?

In the computing universe, guts naturally compute.
Here is how.

On the macroscopic level:

- The gut does have a complex system of nerves and neurotransmitters that communicate with the brain, known as the gut-brain axis.
- This system helps regulate many processes in the body.
- This communication network is so intricate and important that it's sometimes referred to as the body's "second brain." This "second brain," the enteric nervous system, consists of sheaths of neurons embedded in the walls of the long tube of our gut. The enteric nervous system can control digestive processes, such as the mixing and propulsion of food through the stomach and intestines, without input from the brain.

IN WHAT SENSE CAN WE SAY THAT GUTS COMPUTE?

On the macroscopic level, cont.:

- There's also growing evidence that the bacteria in our gut (the gut microbiota) can influence our brain and behavior, including mood and mental health.
- This bi-directional communication between the gut and the brain happens via various routes, including neural pathways, hormones, and the immune system.

So, while the gut and gut don't "compute" in the traditional sense, they do have a sophisticated system for processing information and communicating with the brain. They play a crucial role in maintaining homeostasis and contributing to the overall functioning of the body.

- And yes, we have "gut feeling"

CONCLUSIONS

We highlighted several topics of importance for the development of new understanding of computation: **natural computation (physical computation), interactivity, concurrency and distributedness** as fundamental for computational modeling of information processing systems such as living organisms and their networks.

The new developments in modeling are needed to support this generalized framework for cognitive architectures. In such a way, we will achieve a **better understanding of computation as information processing mechanisms of cognition and intelligence on different levels of organization in nature.**

CONCLUSIONS

In words of Lila Kari and Grzegorz Rozenberg

“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.

Let us step up to this challenge. Let us befriend our fellow the biologist, our fellow the chemist, our fellow the physicist, and let us together explore this

new world. Let us, as computers in the future will, embrace uncertainty. Let us dare to ask afresh: “What is computation?”, “What is complexity?”, “What are the axioms that define life?”

Let us relax our hardened ways of thinking and, with deference to our scientific forebears, let us begin anew.”

<https://www.csd.uwo.ca/~lkari/Natural-Computing-Review.pdf> The Many Facets of Natural Computing

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- <http://www.ucalgary.ca/icic/> The International Institute of Cognitive Informatics and Cognitive Computing (ICIC)
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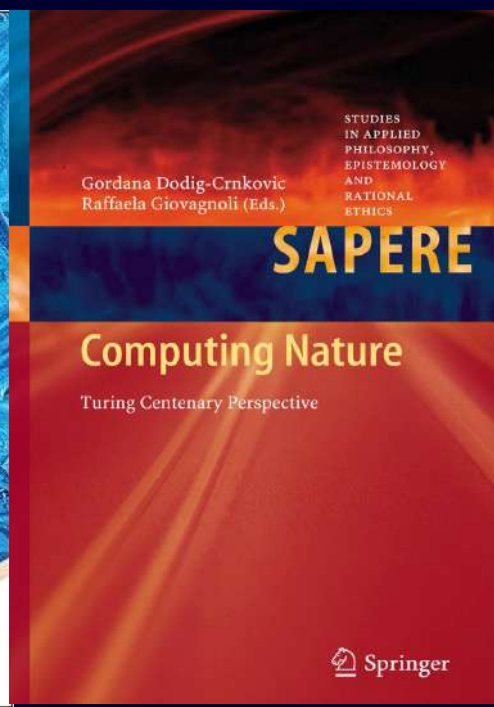
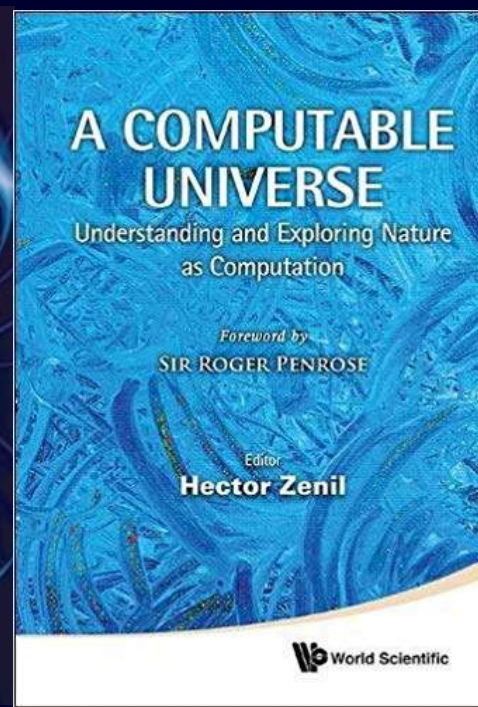
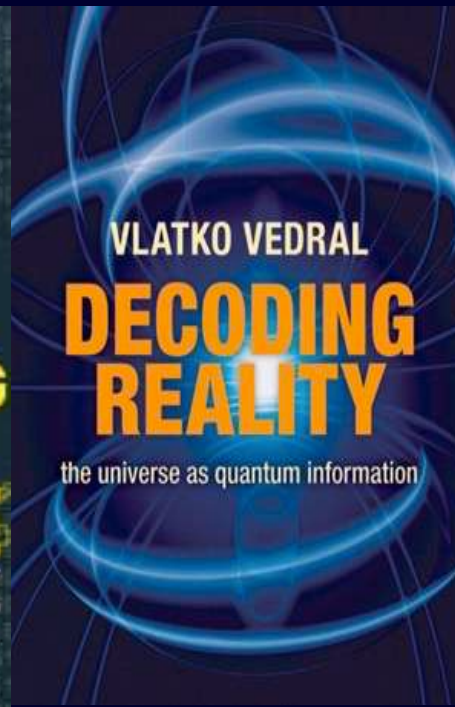
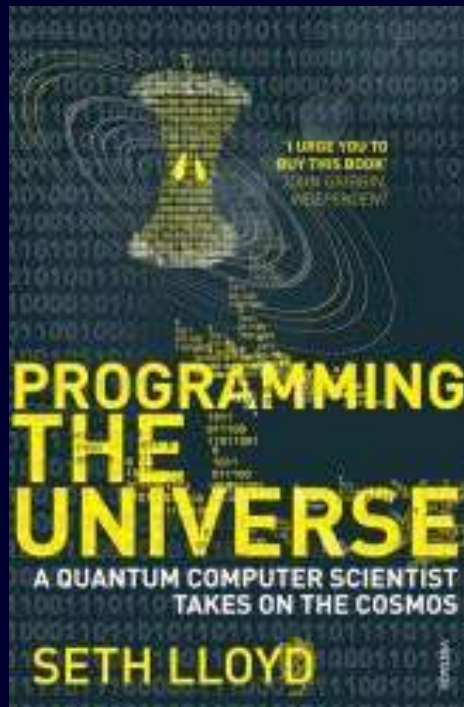
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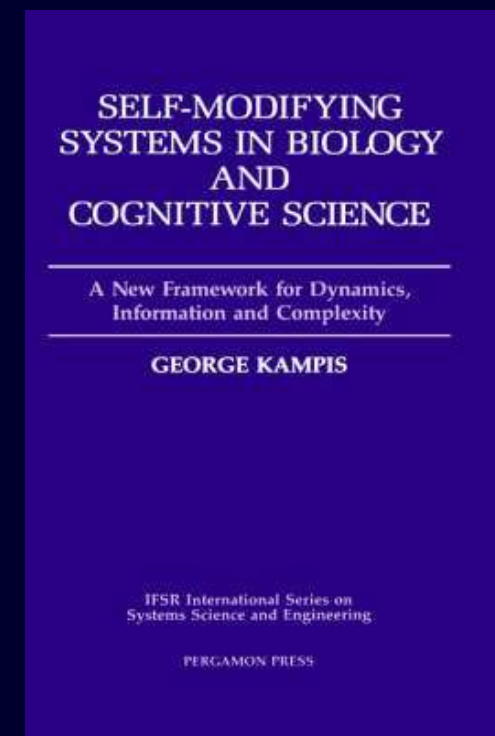
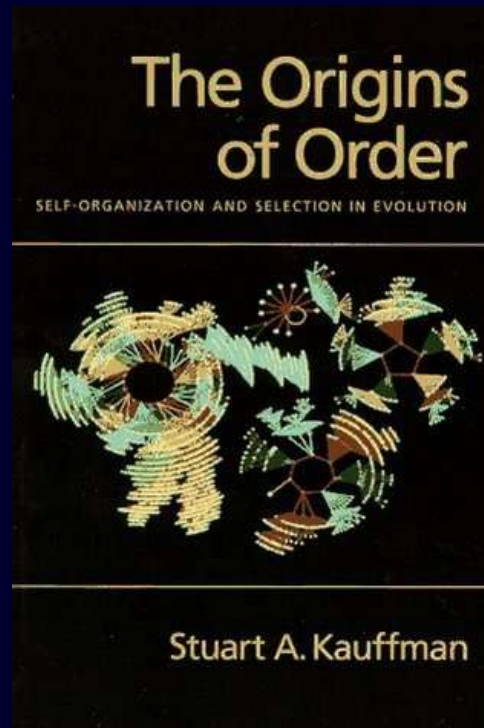
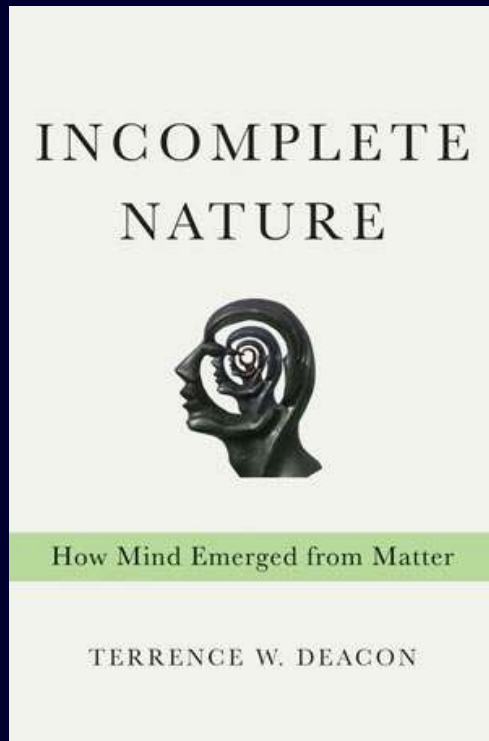
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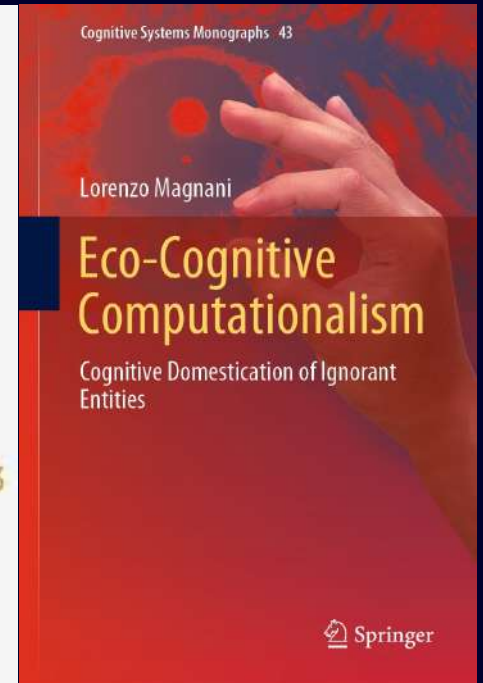
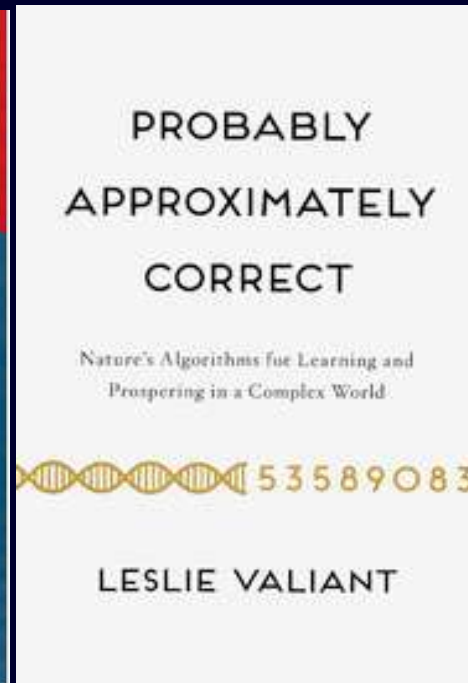
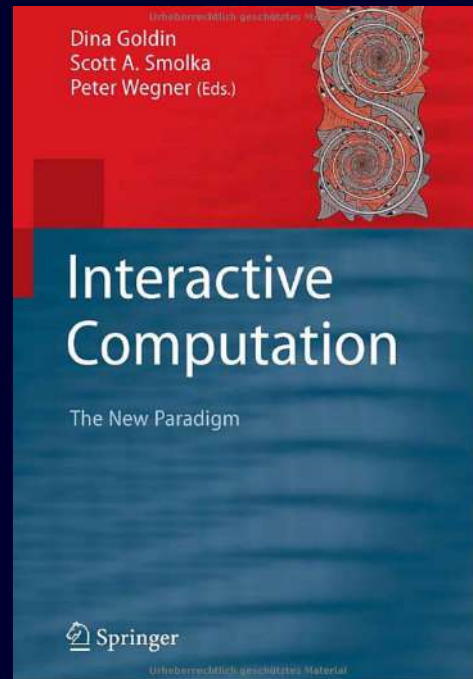
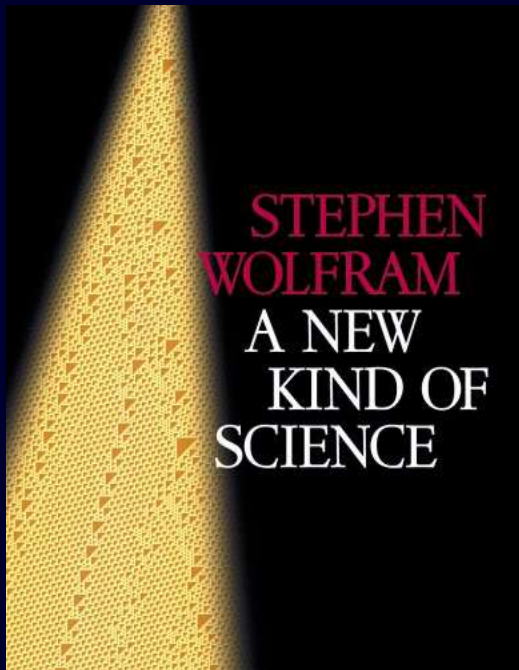
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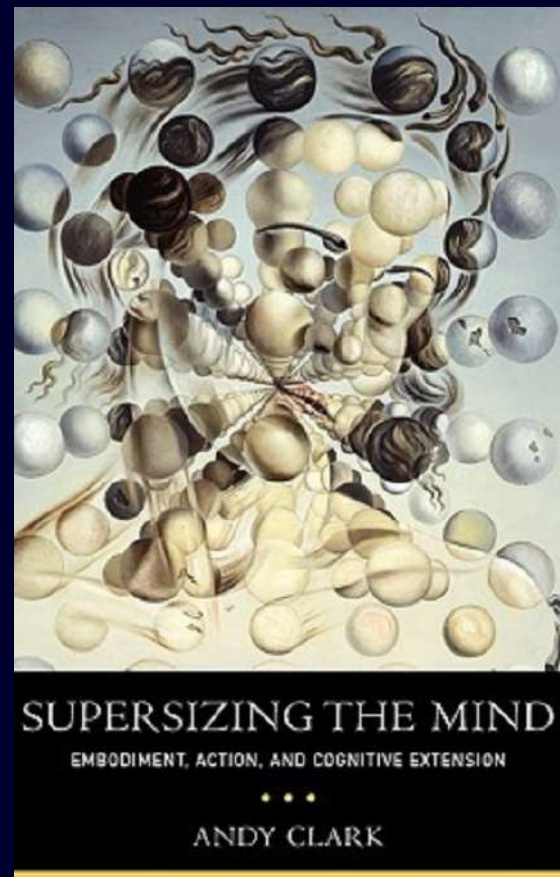
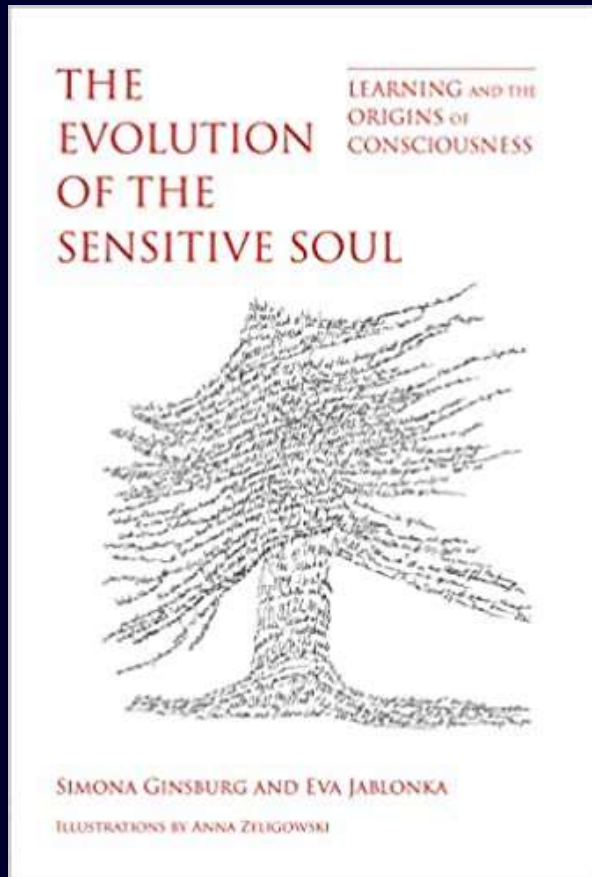
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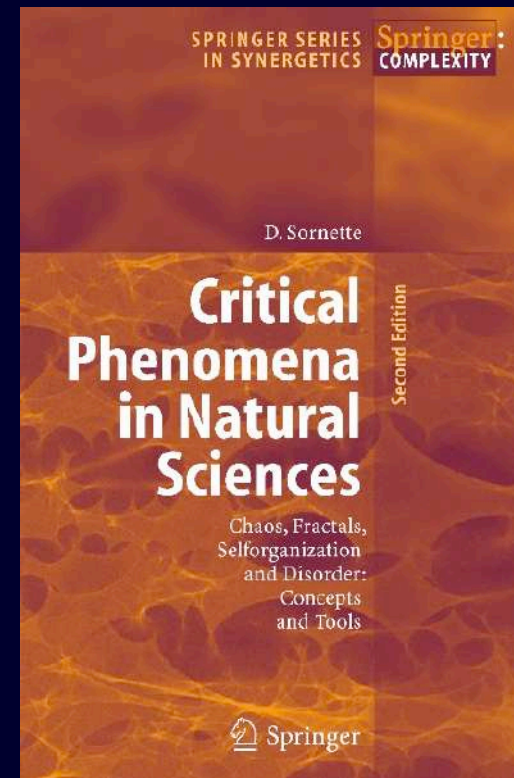
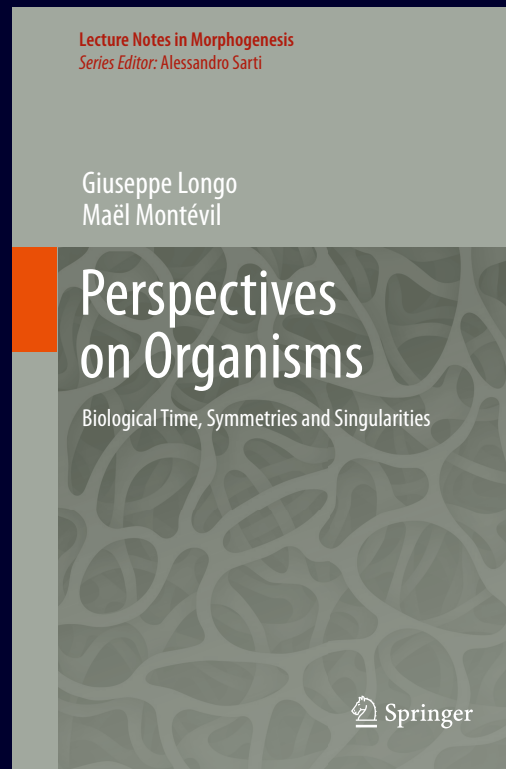
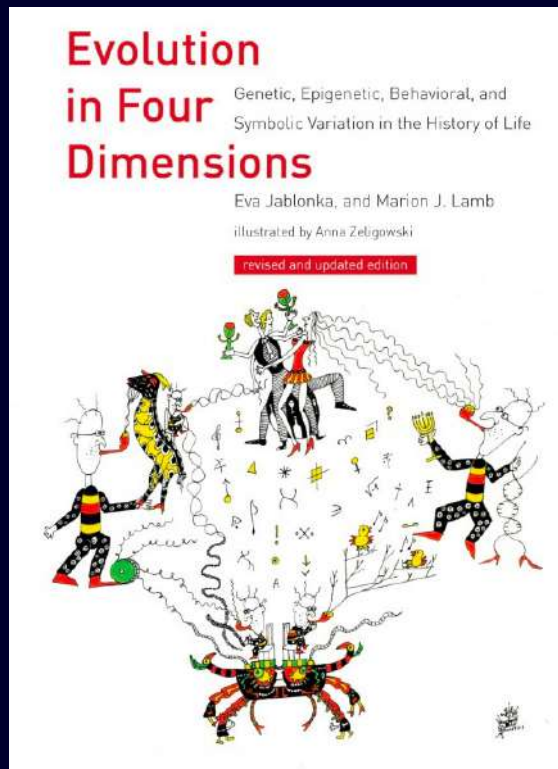
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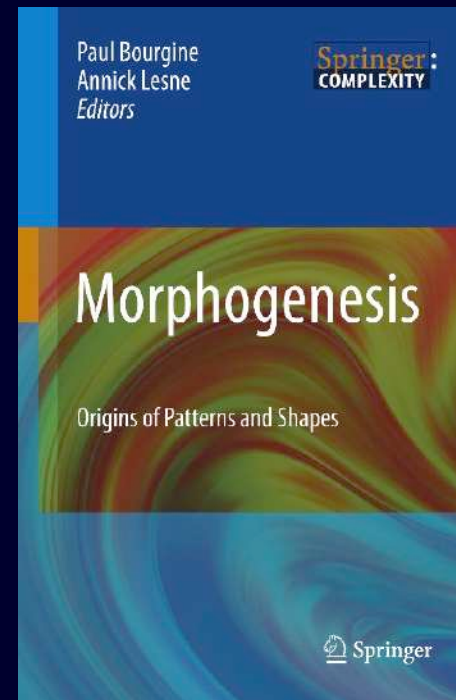
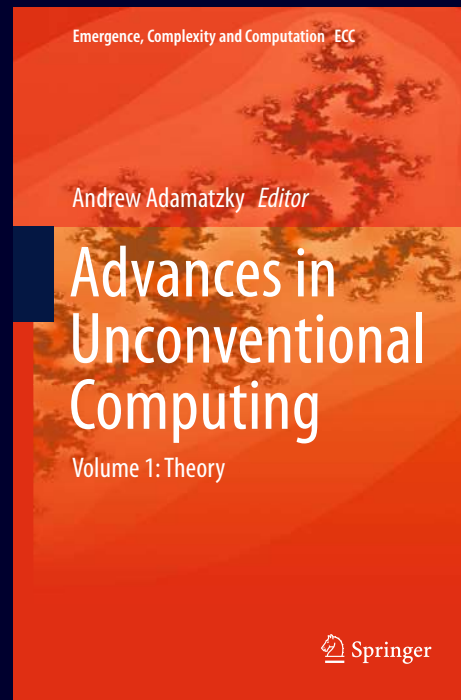
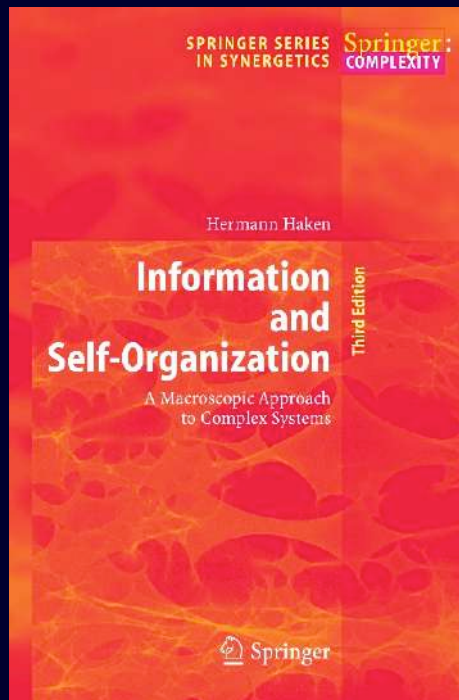
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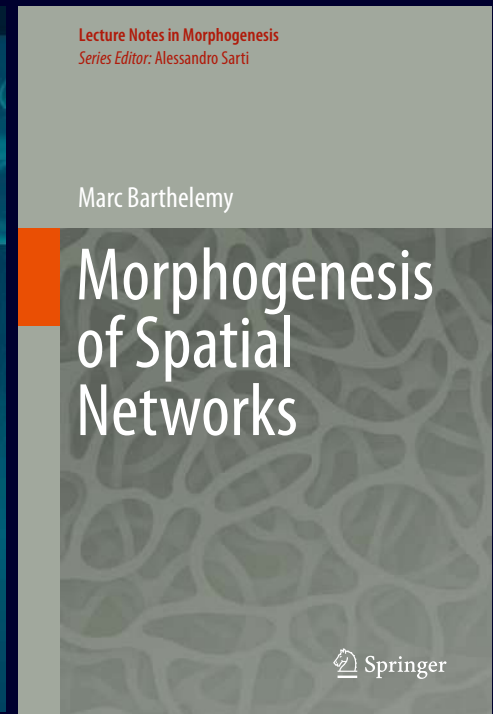
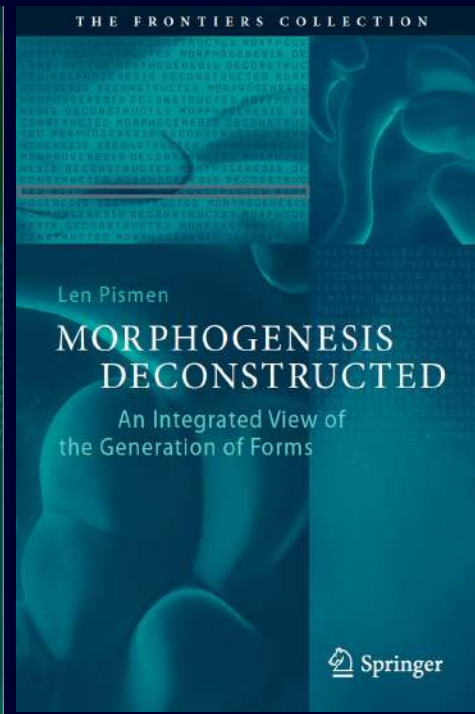
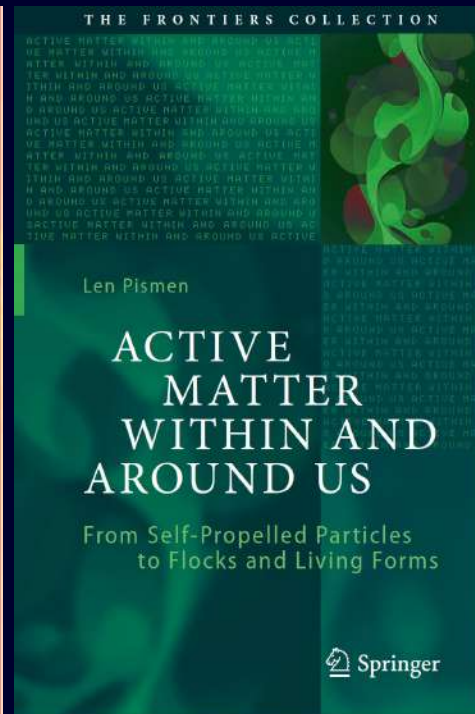
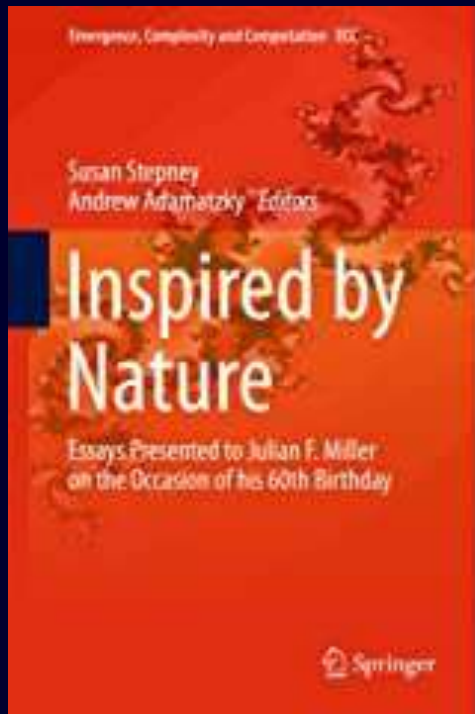
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Natural/Unconventional/Morphological Computing



Natural/Unconventional/Morphological Computing

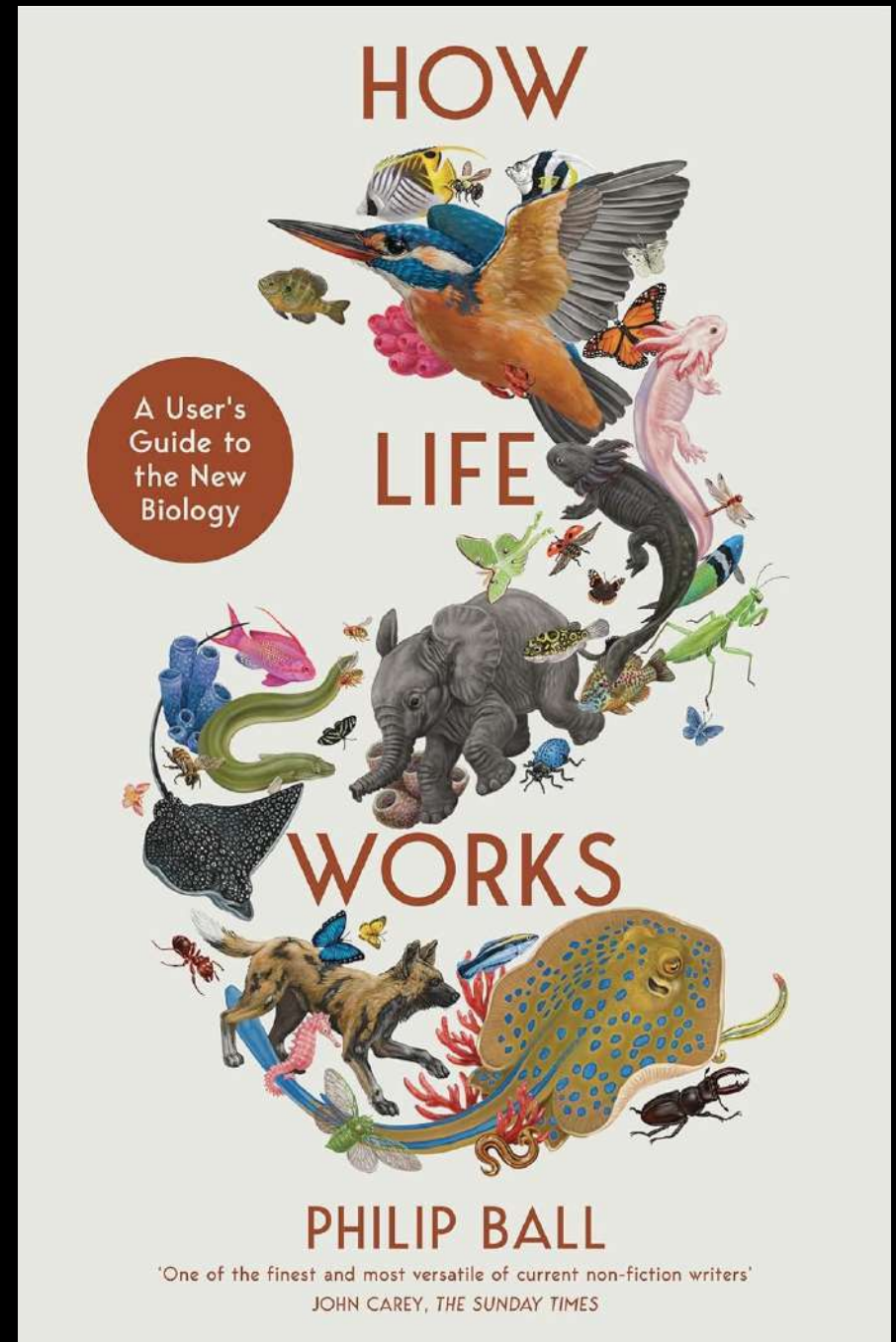


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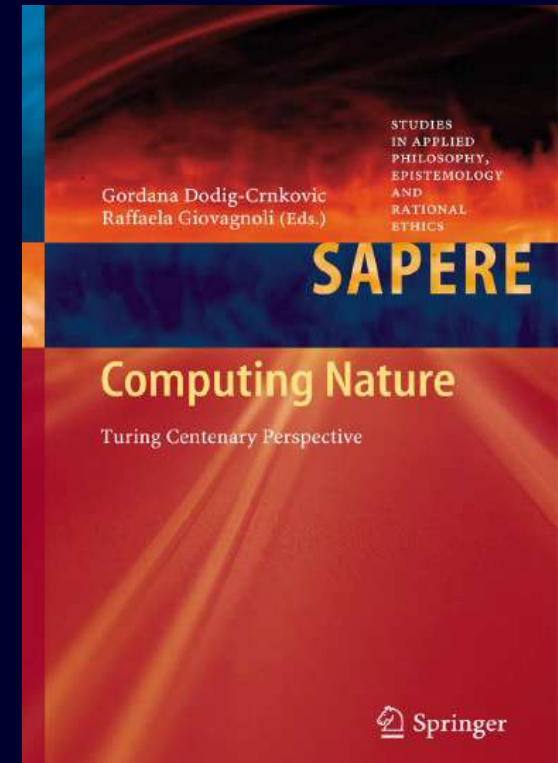
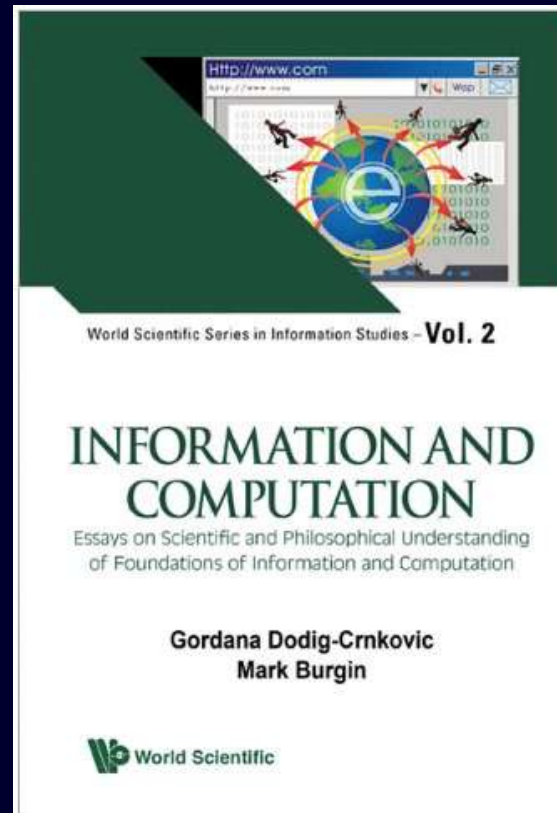
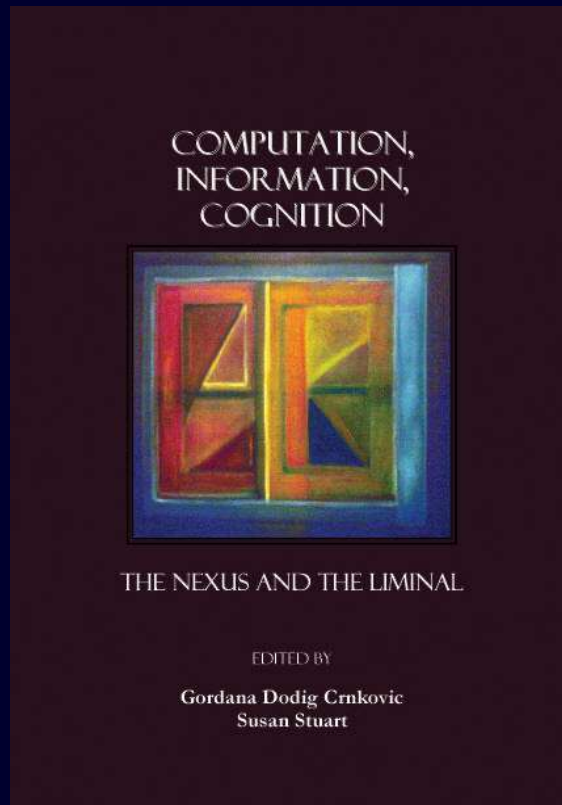
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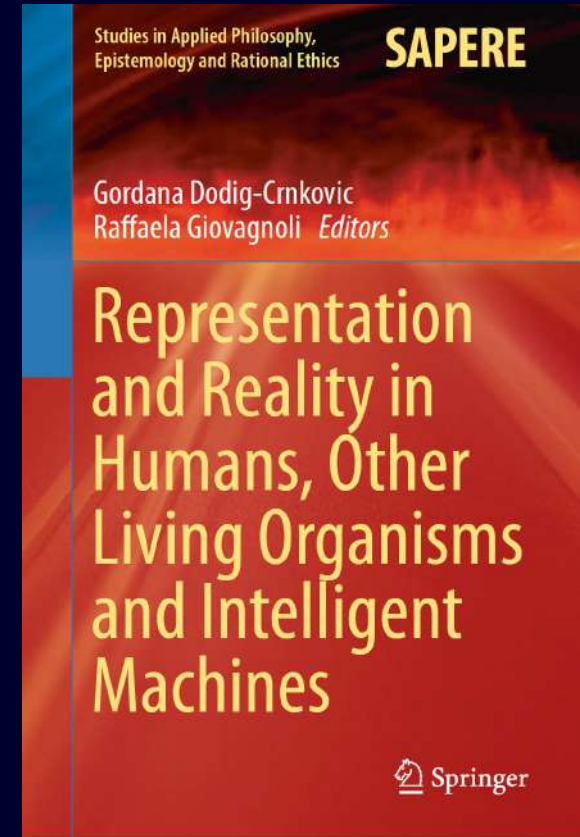
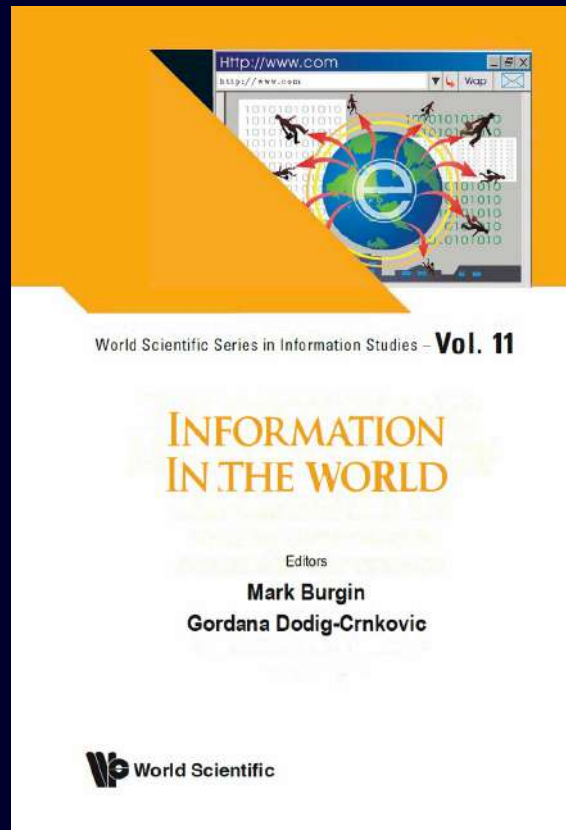
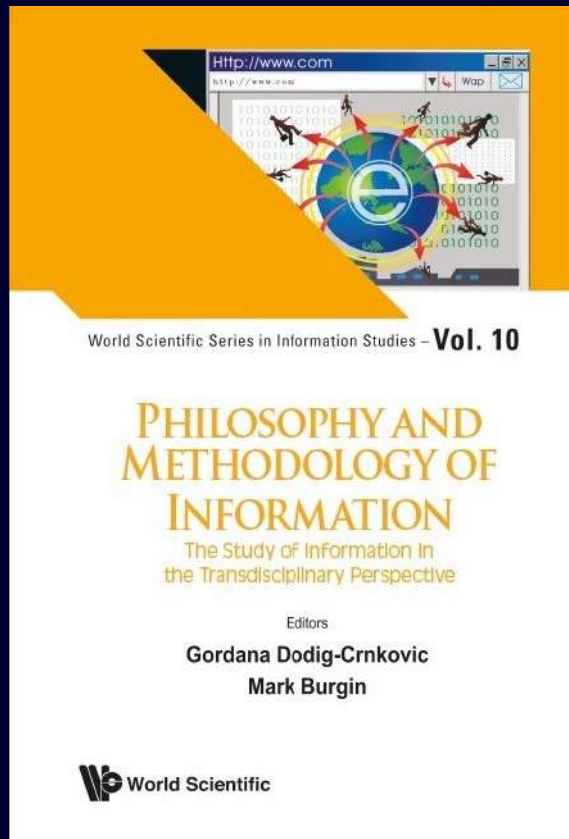
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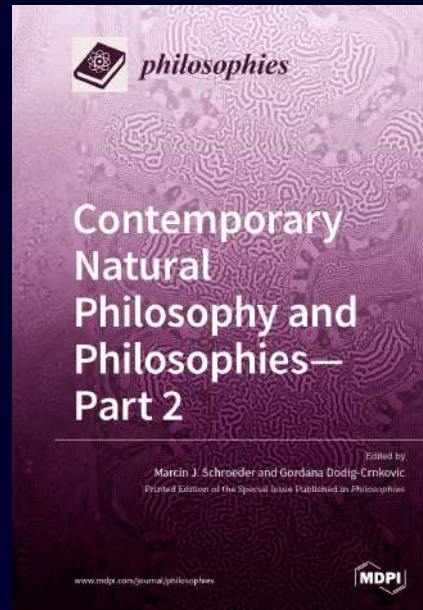
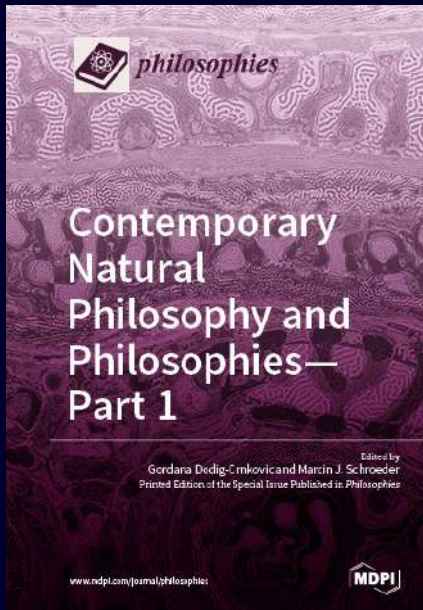


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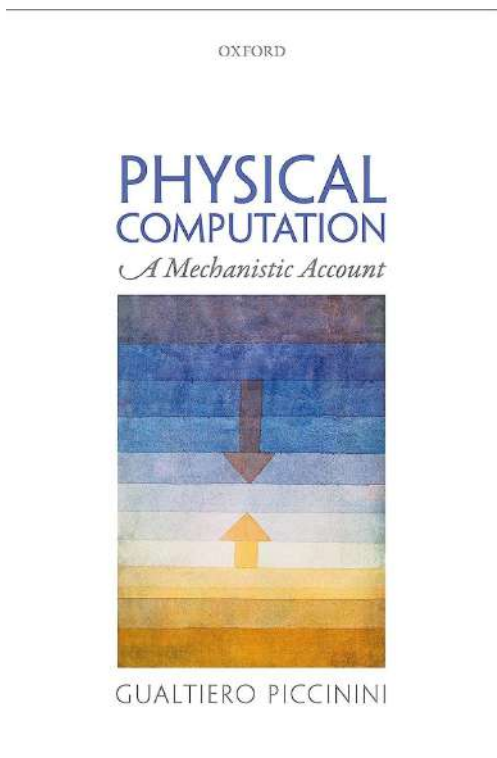
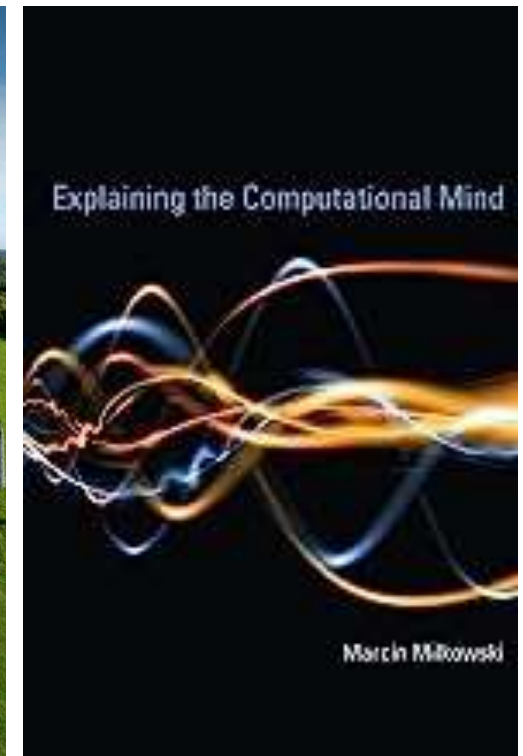
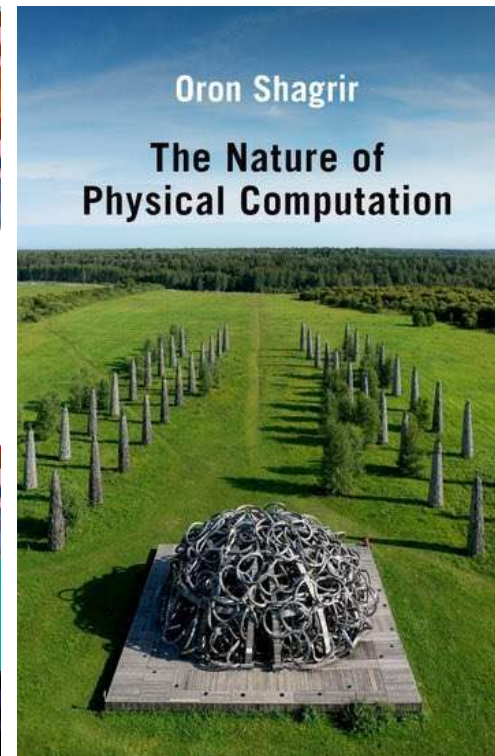
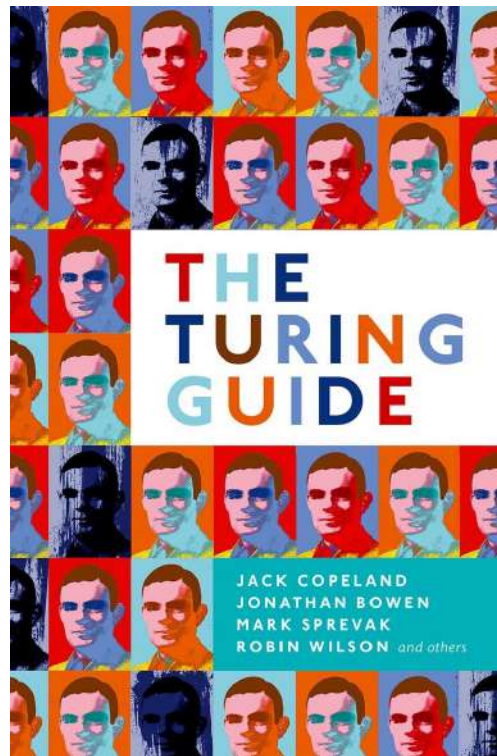
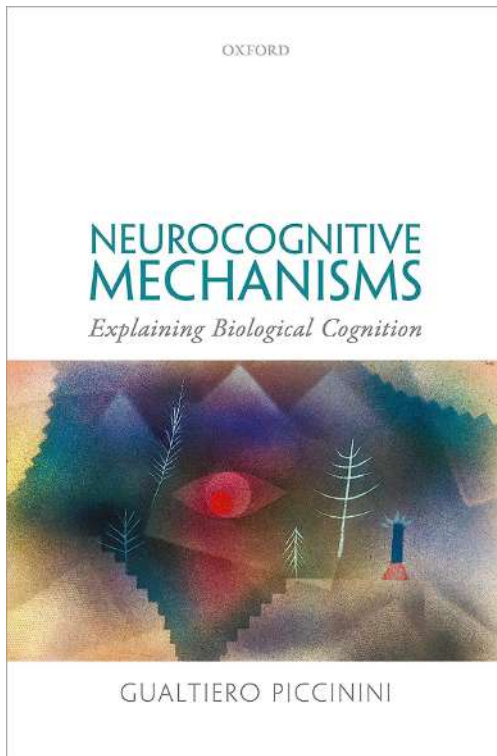
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BOOKS I RELATE TO WHEN
THINKING CRITICALLY
ABOUT INFO-
COMPUTATIONALISM
(COMPUTING NATURE)

COMPUTATIONAL TAXONOMIES



TAXONOMY OF COMPUTATION

In order to get an idea about how **complex** the notion of computation is, and that it often means different things to different people, we tried to systematically study computation from different points of view.

Burghin, M. and Dodig-Crnkovic, G., A Taxonomy of Computation and Information Architecture. ECSA 2015 ASDS Workshop. In Proceedings of the 2015 European Conference on Software Architecture Workshops (ECSAW '15). ACM, New York, NY, USA. DOI=10.1145/2797433.2797440

EXISTENTIAL TAXONOMY OF COMPUTATION

1. *Physical or embodied (object-based)* computations
2. *Abstract or structural (sign-based)* computations
3. *Cognitive or Mental (interpretant-based)* computations

The above constitutes *layered computational architecture* in cognitive agents. So we could also call it *architectural taxonomy of computation*.

EXISTENTIAL TAXONOMY OF COMPUTATION

1. *Physical or embodied (object-based)* computations

1.1 *Physical* computations (as quantum computing)

1.2 *Chemical* computations (as in chemical morphogenesis)

1.3 *Biological* computations (information processing in a cell)

2. *Abstract or structural (sign-based)* computations

2.1 *Subsymbolic* computations - data/signal processing

2.2 *Symbolic* computations - data structures processing

2.3 *Hybrid/mixed* subsymbolic and symbolic computations.

3. *Cognitive or Mental (interpretant-based)* computation

3.1 *Individual* (computational network of the brain)

3.2 *Group* (computational networks of individuals)

3.3 *Social* (computational networks of groups)

ORGANIZATIONAL TAXONOMY OF COMPUTATION

- *Centralized computations* - where computation is controlled by a single algorithm.
- *Distributed computations* - where there are separate algorithms that control computation in some neighbourhood that is represented by a node in the computational network.
- *Clustered computations* - where there are separate algorithms that control computation in clusters of neighbourhoods.

TEMPORAL TAXONOMY OF COMPUTATION

- *Sequential computations*, which are performed in linear time.
- *Parallel or branching computations*, in which separate steps (operations) are synchronized in time.
- *Concurrent computations*, which do not demand synchronization of separate steps (computations).

REPRESENTATIONAL TAXONOMY OF COMPUTATION

- *Discrete* computations, which include interval computations.
- *Continuous* computations, which include fuzzy continuous processes.
- *Hybrid/mixed* computations, which include discrete and continuous processes.

DOMAIN/DATA – BASED TAXONOMY OF COMPUTATION

- The domain of computation is *discrete* and data are *finite*. For instance, data are words in some alphabet.
- The domain of computation is *discrete* but data are *infinite*. For instance, data are ω -words in some alphabet. This includes interval computations because real numbers traditionally are represented as ω -words.
- The domain of computation is *continuous*.

OPERATIONAL TAXONOMY OF COMPUTATION

- Operations in computation are *discrete* and they transform *discrete* data elements. For instance, addition or multiplication of whole numbers.
- Operations in computation are *discrete* but they transform (operate with) *continuous* sets. For instance, addition or multiplication of all real numbers or of real functions.
- Operations in computation are *continuous*. For instance, integration of real functions. *Dynamical systems*.

PROCESS-ORIENTED TAXONOMY OF COMPUTATION

- The process of computation is *discrete*, i.e. it consists of separate steps in the *discrete* domain, and it transforms *discrete* data elements. For instance, computation of a Turing machine or a finite automaton.
- The process of computation is *discrete* but it employs *continuous* operations. An example is given by analogue computations.
- The process of computation is *continuous* but it employs *discrete* operations. For instance, computation of a limit Turing machine.
- The process of computation is *continuous* and it employs *continuous* operations. An example is given by computations in *dynamic* systems.

LEVEL-BASED TAXONOMY OF COMPUTATION

- At the top and the most abstract/general level, computation is perceived as *any transformation of information* and/or information representation.
- At the middle level, where computation is distinguished as a *discretized process of transformation* of information and/or information representation.
- At the bottom, least general level, computation is defined as a *discretized process of symbolic transformation* of information and/or symbolic information representation.

SPATIAL (PHYSICAL) LEVELS OF COMPUTATIONS

- *Macro-level* includes computations performed by mechanical calculators as well as electromechanical devices.
- *Micro-level* includes computations performed by integrated circuits.
- *Nano-level* includes computations performed by fundamental parts that are not bigger than a few nano meters.
- *Molecular level* includes computations performed by molecules.
- *Quantum level* includes computations performed by atoms and subatomic particles.

INFORMATION TRANSFORMATION VIEW OF COMPUTATION

We are building on our typology of models of **computation as information processing** (Burgin & Dodig-Crnkovic, 2013).

Future paths for the advancement of the field are expected both as a result of the development of *new computational models (complex computational architectures, concurrent distributed processing)* and **learning from nature how to better compute** using information transformation mechanisms of intrinsic computation.

As natural cognitive intelligent systems have developed abilities to deal with complexity by efficiently processing data and information, and on a higher level even knowledge (Burgin, 2005) (Burgin, Mikkilineni, Morana, 2015) we are trying to learn from nature how to compute in a more resilient and resource-effective way.

COMPUTATION AS INFORMATION TRANSFORMATION

As natural cognitive intelligent systems have developed **abilities to deal with complexity by efficiently processing data and information**, and on a higher level even knowledge (Burgin, 2005) (Burgin, Mikkilineni, Morana, 2015) we are trying to learn from nature how to compute in a more resilient and resource-effective way.

COMPUTATION AS INFORMATION TRANSFORMATION

If we want to further develop computational technologies to solve problems of huge data-processing and information-processing systems on global scale and in real time we should take into account *broader concept of computation than string-to-string mapping*.

One of the approaches going into this direction is *cognitive computing*, that is trying to *mimic human-level cognitive information processing* (“Probably Approximately Correct”- Leslie Valiant).

LIMITS OF COMPUTATION

Definition 2
 Turing machine
 $\Gamma = \{0, 1, \square\}$

1	1	0	0	1	0	1	\square	\square	\square
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$\triangleleft \rightarrow$
 internal states Q

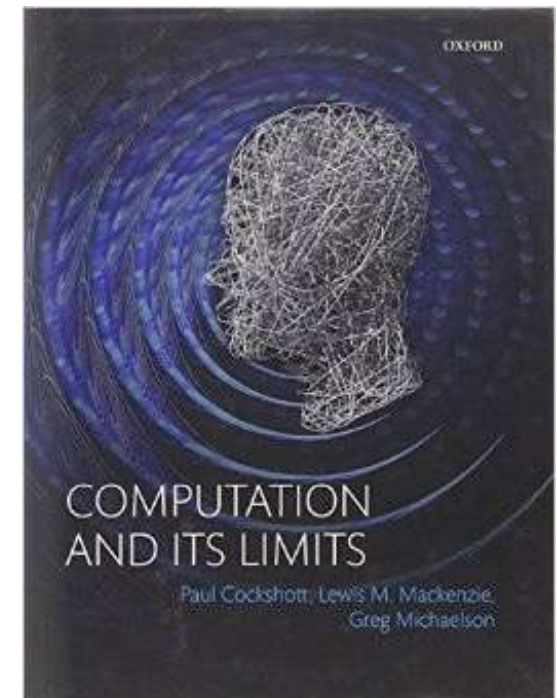
Definition
 $\delta: Q \times \Gamma \rightarrow Q \times \Gamma \times \{L, R\}$

$Q \times \Gamma$	0	1	\square
q	$(q', 1, R)$		

COMPUTATION AND ITS LIMITS

Paul Cockshott, Lewis M Mackenzie, and Gregory Michaelson,
Oxford University Press, 2012

- Computation is a controversial and debated topic
- An in-depth look at the limits to computing set by the laws of nature
- Includes a historical account of computing
- Highlights the computer/physics interaction
- A cross-disciplinary investigation of the relationship between computing and physical reality. It begins by exploring the mystery of why mathematics is so effective in science and seeks to explain this in terms of the **modeling of one part of physical reality by another**
- The authors investigate the extent to which the laws of nature and of logic constrain what we can compute. In the process, they examine formal computability, the thermodynamics of computation, and the promise of quantum computing.



WHAT IS COMPUTATION?

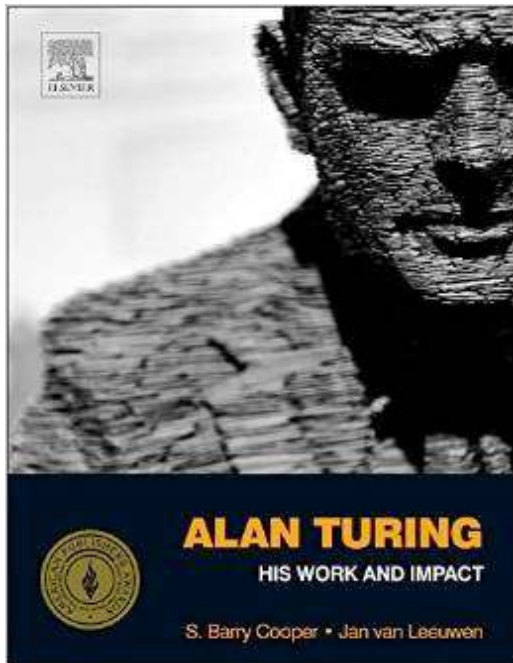
Cockshott et al. *Computation and its limits*,
Oxford University Press, 2012

Turing-Church thesis encompasses all algorithms. But:
“the key property of general-purpose computers is that they are general purpose. We can use them to deterministically model any physical system, of which they are not themselves a part, to an arbitrary degree of accuracy. Their logical limits arise when we try to get them to model a part of the world that includes themselves”. Cockshott et al.

Integrating the computer and the computed seems to be the crux of the problem where computing resources are finite, distributed and fluctuating as pointed out by Rao Mikkilineni

WHAT IS COMPUTATION?

TURING MACHINE MODEL AND BEYOND



Turing's Titanic Machine? Embodied and Disembodied Computing at the Turing Centenary, Barry Cooper

<https://dl.acm.org/doi/10.1145/2093548.2093569>

Ubiquity Symposium What is Computation? Computation is Process by Dennis J. Frailey

https://www.researchgate.net/publication/240319088_Ubiquity_symposium_'What_is_computation'

Turing's Revolution - Giovanni Sommaruga, Thomas Strahm

1. Turing and the History of Computability Theory

Conceptual Confluence in 1936: Post and Turing
Martin Davis, Wilfried Sieg

Algorithms: From Al-Khwarizmi to Turing and Beyond
Wolfgang Thomas

The Stored-Program Universal Computer: Did Zuse Anticipate Turing and von Neumann?

B. Jack Copeland, Giovanni Sommaruga

2. Generalizing Turing Computability Theory

Theses for Computation and Recursion on Concrete and Abstract Structures
Solomon Feferman

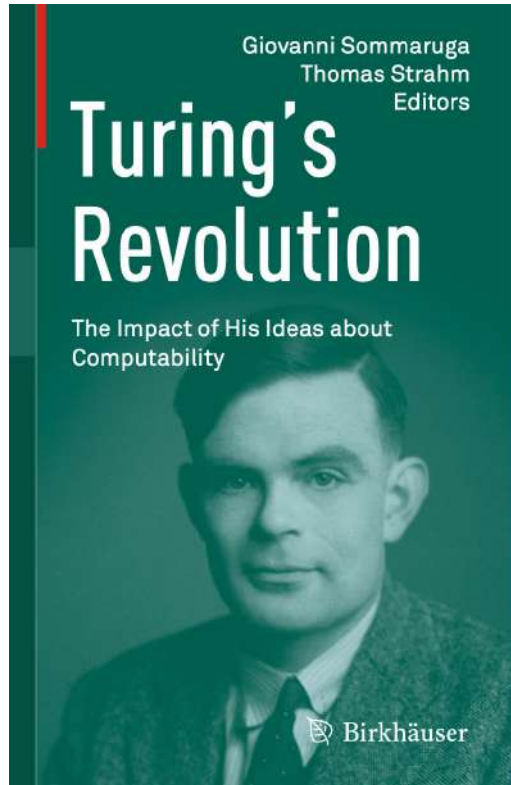
Generalizing Computability Theory to Abstract Algebras
J. V. Tucker, J. I. Zucker

Discrete Transfinite Computation
P. D. Welch

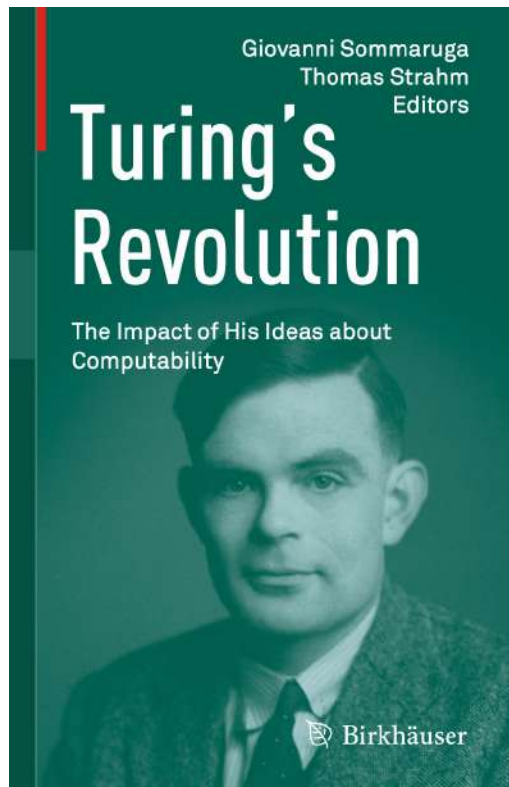
Semantics-to-Syntax Analyses of Algorithms
Yuri Gurevich

The Information Content of Typical Reals
George Barmpalias, Andy Lewis-Pye

Proof Theoretic Analysis by Iterated Reflection
L. D. Beklemishev



Turing's Revolution Giovanni Sommaruga, Thomas Strahm



3. Philosophical Reflections

Alan Turing and the Foundation of Computer Science
Juraj Hromkovič

Proving Things About the Informal
Stewart Shapiro

Why Turing's Thesis Is Not a Thesis
Robert Irving Soare

Incomputability Emergent, and Higher Type Computation

S. Barry Cooper

4. Correction to: The Stored-Program Universal Computer: Did Zuse Anticipate Turing and von Neumann?

B. Jack Copeland, Giovanni Sommaruga

THE REALITY FOR AN
AGENT.
AN OBSERVER-
DEPENDENT REALITY



An observer-dependent reality

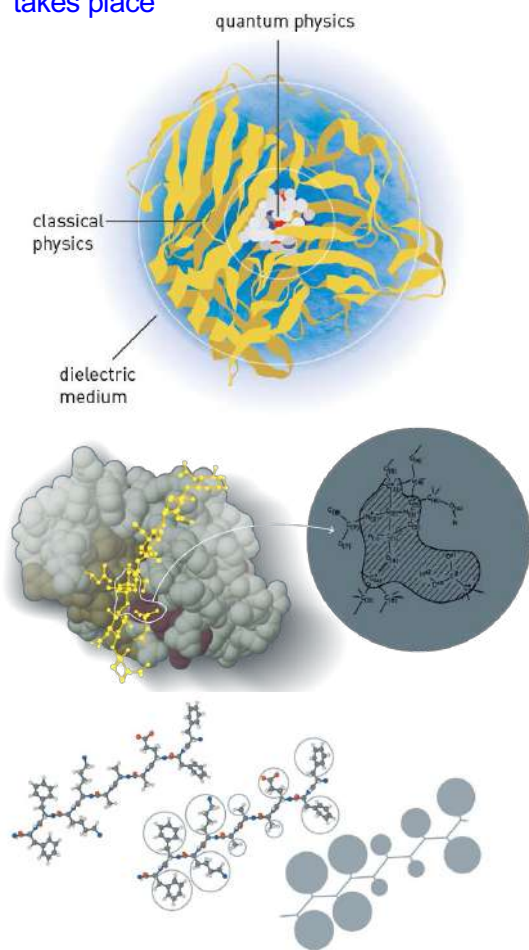
The reality for an agent is an informational structure with which the agent interacts. As systems capable of acting on their own behalf and making sense (use) of information, cognitive agents are of special interest with respect to <knowledge>* generation.

This relates to the idea of [participatory universe](#), (Wheeler, 1990) "it from bit" as well as to [endophysics](#) or "physics from within" where an observer is being within the universe, unlike the "god-eye-perspective" from the outside of the universe. (Rössler, 1998)

*<knowledge> for a very simple agent can be the ability to optimize gains and minimize risks. (Popper, 1999) p. 61 ascribes the ability to know to all living: "*Obviously, in the biological and evolutionary sense in which I speak of knowledge, not only animals and men have expectations and therefore (unconscious) knowledge, but also plants; and, indeed, all organisms.*"

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. But such calculations require enormous computing power.

Nobel Laureates in chemistry devised methods that use both classical and quantum physics.

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 predict the outcome of traditional experiments.

Levels of organization of life/cognition

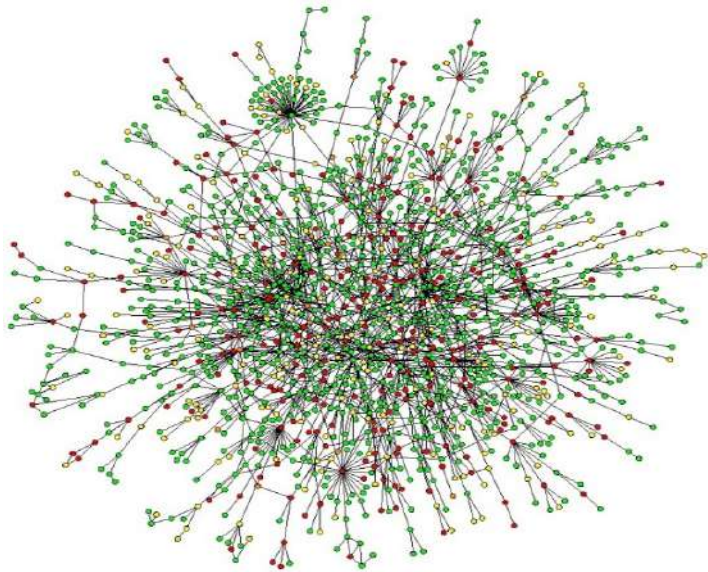
simpler kinds of <cognition> to other living beings.

Bacteria collectively "collects latent information from the environment and from other organisms, process the information, develop common knowledge, and thus learn from past experience" (Ben-Jacob, 2008; Diggle et al., 2007)

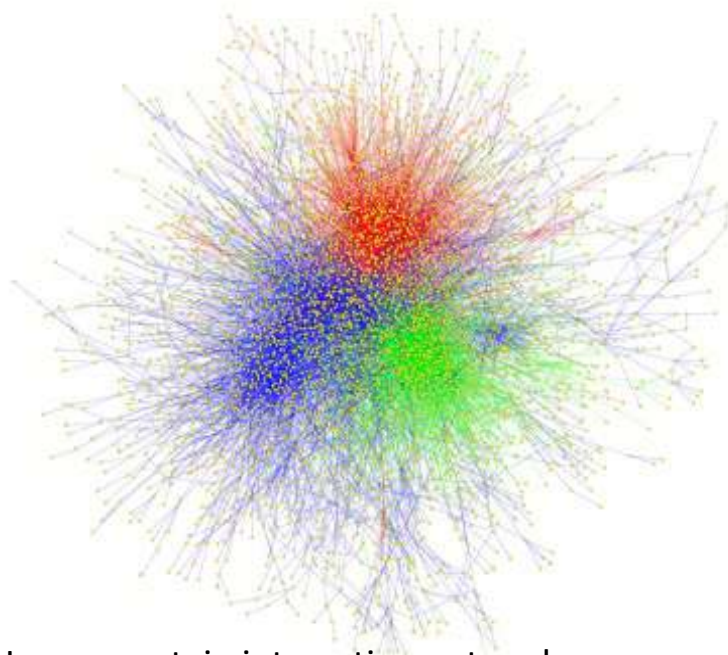
Plants can be said to possess simple forms of cognition. **The origin of <cognition> in first living agents is not well researched, as the idea still prevails that only humans possess cognition and knowledge.**

However, there are different types of <cognition> and we have good reasons to ascribe it to possess memory (in their bodily structures) and ability to learn (adapt, change their morphology) and can be argued to possess simple forms of cognition.

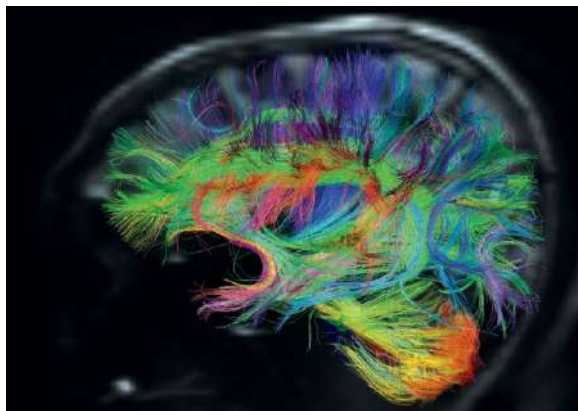
Agents/actors networks



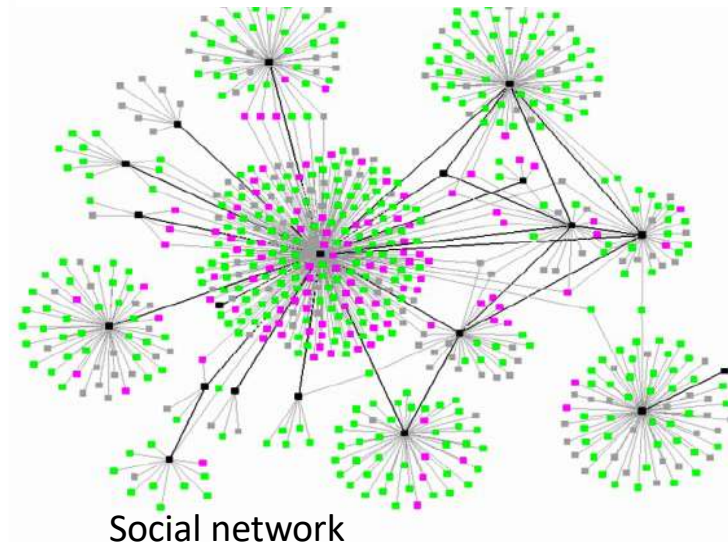
Protein network in yeast cells



Human protein interaction network

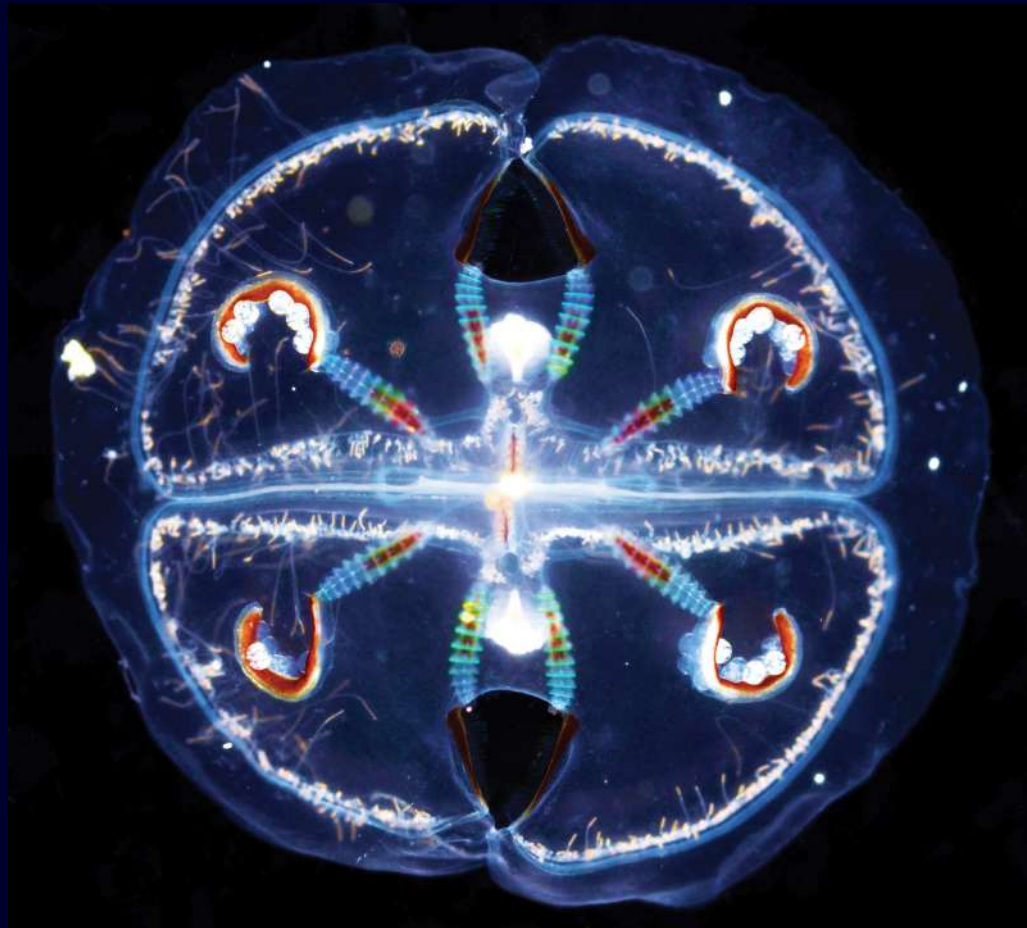


Human connectome



Social network

Living agents – basic levels of cognition



p. 109

<https://royalsocietypublishing.org/cms/asset/3b75e0de-6558-4b42-b874-e618151abc3c/rstb.2021.376.issue-1821.largecover.jpg>

Living agents – basic levels of cognition

A living agent is an entity acting on its own behalf, with autopoietic properties, that is capable of *undergoing at least one thermodynamic work cycle*. (S. 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 – basic levels of cognition

Although a **detailed physical account** of the agent's capacity to perform work cycles and so persist* in the world is central for the understanding of life/cognition, as (Kauffman, 2000) and (Deacon, 2007) have argued in detail, the **present argument is primarily focused on the info-computational aspects of life.**

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

*Contragrade processes (that require energy and do not spontaneously appear in nature) become possible by connecting with the orthograde (spontaneous) processes which provide a source of energy.

Living agents – basic levels of cognition

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 claiming 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.

COMPUTING
NATURE



Computing nature

The basic idea of computing nature is that all processes taking place in physical world can be described as computational processes – from the world of quantum mechanics to living organisms, their societies and ecologies. Emphasis is on regularities and typical behaviors. Even though we all have our subjective reasons why we move and how we do that, from the bird-eye-view movements of inhabitants in a city show striking regularities. In order to understand big picture and behavior of societies, we take computational approach based on data and information.

See the work of Albert-László Barabási who studies networks on different scales:

<http://www.barabasilab.com/pubs-talks.php>

Beyond Turing Machine Model, Computing Nature

The challenge to deal with *computability in the real world - physical computing (natural computing)* has brought new understanding of computation.

Natural computing has different criteria for success of a computation, halting problem is not a central issue, but instead the adequacy of the computational response in a network of interacting computational processes/devices.

COMPUTATIONAL ARCHITECTURE OF COGNITION

“(we) propose an *info-computational framework* to approach cognition in living organisms and in embodied cognitive agents of any kind:

the environment affords potential information which the agent can integrate into actual information and transform into knowledge by natural (intrinsic, physical) computation;

perception acts as an *information-processing and learning device*, through dynamical processes of self-organization of the agent.” [Dodig-Crnkovic, 61]

ARCHITECTURE OF COMPUTATION IN LIVING ORGANISMS

In nature the basic info-computational layer is grounded on physico-chemical, chemo-biological and bio-cognitive levels of information processing.

The dynamics of information differs on different levels of granularity of physical processes.

Computation performed by contemporary computing machines (designed computation) is distinctly different from the complex network of networks of computational processes in living organisms (cognitive computation).



The title "Every Cell Processes Information (Computes) and Makes Sense Of It" could be interpreted as a reflection of the complex capabilities of cells.

In a biological context, cells do indeed process information and respond to it. This can be seen in how cells interpret signals from their environment and respond appropriately. For instance, a cell can detect changes in nutrient availability and adjust its metabolism accordingly. Similarly, cells in your immune system can recognize foreign substances (like bacteria or viruses) and initiate a response to eliminate them.

However, it's important to note that the term "compute" is being used metaphorically here. Cells don't compute in the way a computer does, which is based on human-programmed algorithms. Instead, cells have evolved complex molecular networks that allow them to respond to their environment in a way that helps ensure their survival and the overall health of the organism.

Finally, "makes sense of it" is also an anthropomorphizing phrase when applied to cells. While cells react to signals, they don't "make sense" of information in the conscious way that a human mind does. They simply respond to biochemical signals according to their evolved structures and functions.

So, while the title could be a powerful way to communicate the complex capabilities of cells, it's essential to understand the nuances and limitations of these metaphoric descriptions.