CHALMERS | UNIVERSITY OF GOTHENBURG

Information and Computing in Nature: Philosophical Perspectives Conference
Polish Academy of Arts and Sciences in Krakow, Poland
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OPENING LECTURE

MECHANISMS OF COGNITION AND INTELLIGENCE IN NATURE

MODELS OF COGNITIVE INFORMATION PROCESSING BEYOND THE TURING MODEL OF COMPUTATION

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My background - from formal to natural languages

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

Thus we have

$$
\begin{aligned}
B = \sum_{J_C M_{J_C}} & (-1)^{\lambda_\nu+\lambda_\pi+L_C}\, \delta(J_\nu,\lambda_\nu)\, \delta(J_\pi,\lambda_\pi)\, \langle L_C M_{L_C} 00 | J_C M_{J_C} \rangle \\
\times & \sum_{L_C M_{L_C}} \langle (l_\nu L_\nu)\lambda_\nu\, (l_\pi L_\pi)\lambda_\pi; L_C | (l_\nu l_\pi) l_C\, (L_\nu L_\pi) L_C; L_C \rangle \qquad (54) \\
\times & \langle l\, m_l L_C M_{L_C} | L_C M_{L_C} \rangle\, (Y_{l_\nu} Y_{l_\pi})_{l_C}\, (Y_{L_\nu} Y_{L_\pi})_{L_C} (\chi^{S_\nu=0} \chi^{S_\pi=0})_{S_C=0}.
\end{aligned}
$$

The whole expression for A may be thereafter written as

$$
\begin{aligned}
A = \sum_{J_C M_{J_C}} & (-1)^{\lambda_\nu+\lambda_\pi+L_C}\, \delta(J_\nu,\lambda_\nu)\, \delta(J_\pi,\lambda_\pi)\, \langle L_C M_{L_C} 00 | J_C M_{J_C} \rangle \\
\times & \sum_{L_C M_{L_C}} \langle (l_\nu L_\nu)\lambda_\nu\, (l_\pi L_\pi)\lambda_\pi; L_C | (l_\nu l_\pi) l_C\, (L_\nu L_\pi) L_C; L_C \rangle \qquad (55) \\
\times & \langle l_C m_{l_C} L_C M_{L_C} | L_C M_{L_C} \rangle (Y_{l_\nu} Y_{l_\pi})_{l_C} (Y_{L_\nu} Y_{L_\pi})_{L_C} \\
\times & (\chi^{S_\nu=0} \chi^{S_\pi=0})_{S_C=0}\, R_{n_\nu l_\nu}\, R_{n_\pi l_\pi}\, R_{N_\nu L_\nu}\, R_{N_\pi L_\pi}.
\end{aligned}
$$

After Moshinsky-Talmi transformation $(N_\nu L_\nu; N_\pi L_\pi) \longrightarrow (n_C l_C; N_C L_C)$ it reads

$$
\begin{aligned}
A = \sum_{J_C M_{J_C}} & (-1)^{\lambda_\nu+\lambda_\pi+L_C}\, \delta(J_\nu,\lambda_\nu)\, \delta(J_\pi,\lambda_\pi)\, \langle L_C M_{L_C} 00 | J_C M_{J_C} \rangle \\
\times & \sum_{L_C M_{L_C}} \langle (l_\nu L_\nu)\lambda_\nu\, (l_\pi L_\pi)\lambda_\pi; L_C | (l_\nu l_\pi) l_C\, (L_\nu L_\pi) L_C; L_C \rangle \qquad (56) \\
\times & \langle l_C m_{l_C} L_C M_{L_C} | L_C M_{L_C} \rangle\, (Y_{l_\nu} Y_{l_\pi})_{l_C}\, R_{n_\nu l_\nu}\, R_{n_\pi l_\pi}\, (\chi^{S_\nu=0} \chi^{S_\pi=0})_{S_C=0} \\
\times & \sum_{n_C l_C N_C L_C} \langle n_C l_C N_C L_C; J_C | N_\nu L_\nu N_\pi L_\pi; J_C \rangle\, (Y_{l_C} Y_{L_C})_{L_C}\, R_{n_C l_C}\, R_{N_C L_C}.
\end{aligned}
$$

29

PhD in Computing, 2006
Computer Science,
Mälardalen University

Investigations into Information Semantics and Ethics of Computing

Gordana Dodig-Crnkovic

Current: Morphological Computing and Cognition

My background: Teaching

– Research Methods in Natural Sciences and Engineering
– Computing and Philosophy
– Computational Thinking and Writing Toolbox
– Formal Languages, Automata, and Theory of Computation
– Professional Ethics
– Emerging trends and Critical Topics in Interaction Design
– Human-centered design
– Research Ethics & Sustainable Development
– Transdisciplinary Research Methods

My background: Research

- Computing paradigms & Cognitive computing
- Computational knowledge generation
- Computational aspects of intelligence and cognition
- Theory of science/ philosophy of science;
- Philosophy of information
- Computing and philosophy and
- Ethics of emerging technologies
  (AI ethics, ethics of computing, information ethics, roboethics, ethics of autonomous cars, etc).

Information, Computation, Cognition

Agency-based Hierarchies of Levels

HUMBERTO MATURANA & FRANCISCO VARELA

'Everything said is said by an observer to an observer who could be him/herself ”

(Maturana and Varela, 1980; p. 8)

Through such self-observation, we interact with our own descriptions and can describe ourselves describing ourselves in an endless recursive process.

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, Dordecht: D. Reidel Publishing Co.

Information, computation, cognition. Agency-based hierarchies of levels

A short summary of the argument:

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

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

Information, computation, cognition. Agency-based hierarchies of levels

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

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

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

Information, computation, cognition.
Agency-based hierarchies of levels

5. Cognition consists of all (info-computational) processes necessary to keep a living agent's organizational integrity on all different levels of its existence.
   Cognition = info-computation
6. Cognition is equivalent to the (process of) life. *
   Its complexity increases with evolution.
   This complexification is a result of morphological computation.

*Maturana & Varela, Stewart

Information as a fabric of reality

"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.

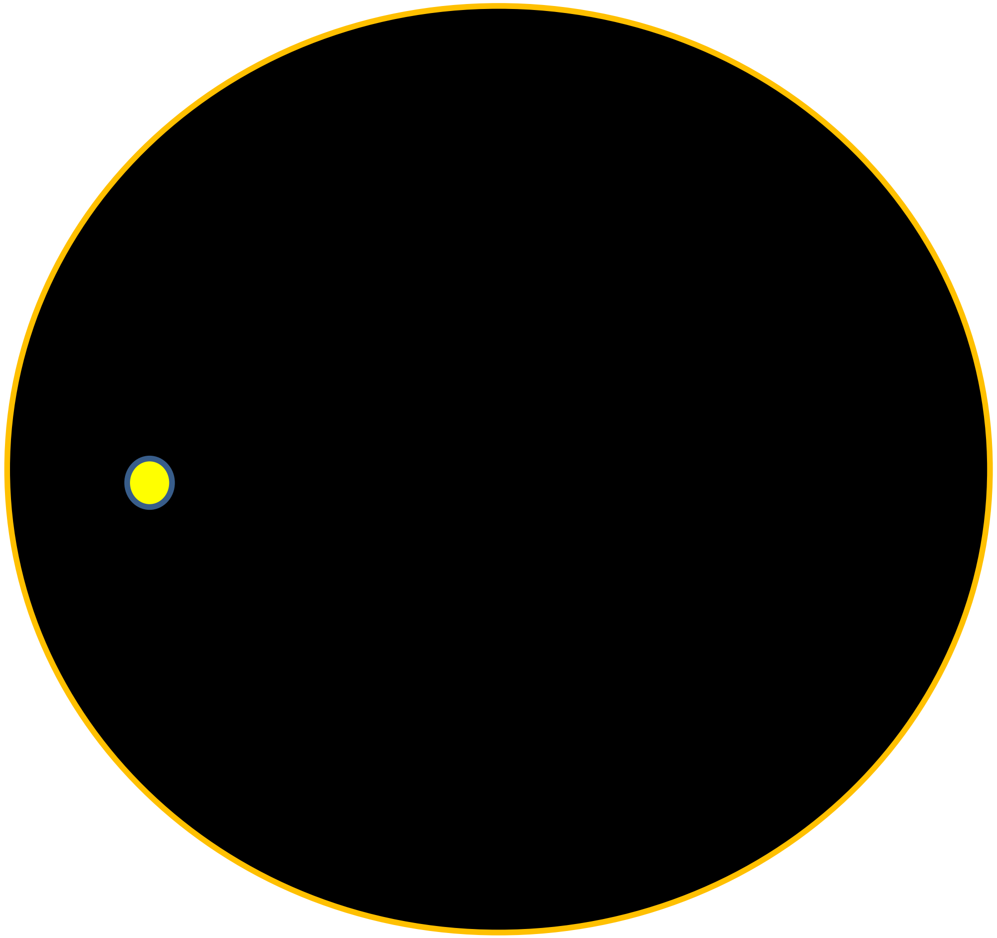
Hewitt, C. (2007). What Is Commitment? Physical, Organizational, and Social. In P. Noriega, J. Vazquez, Salceda, G. Boella, O. Boissier, & V. Dign (Eds.), Coordination, Organizations, Institutions, and Norms in Agent Systems II (pp. 293 –307). Berlin, Heidelberg: Springer Verlag.

*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

Information from data, an illustration

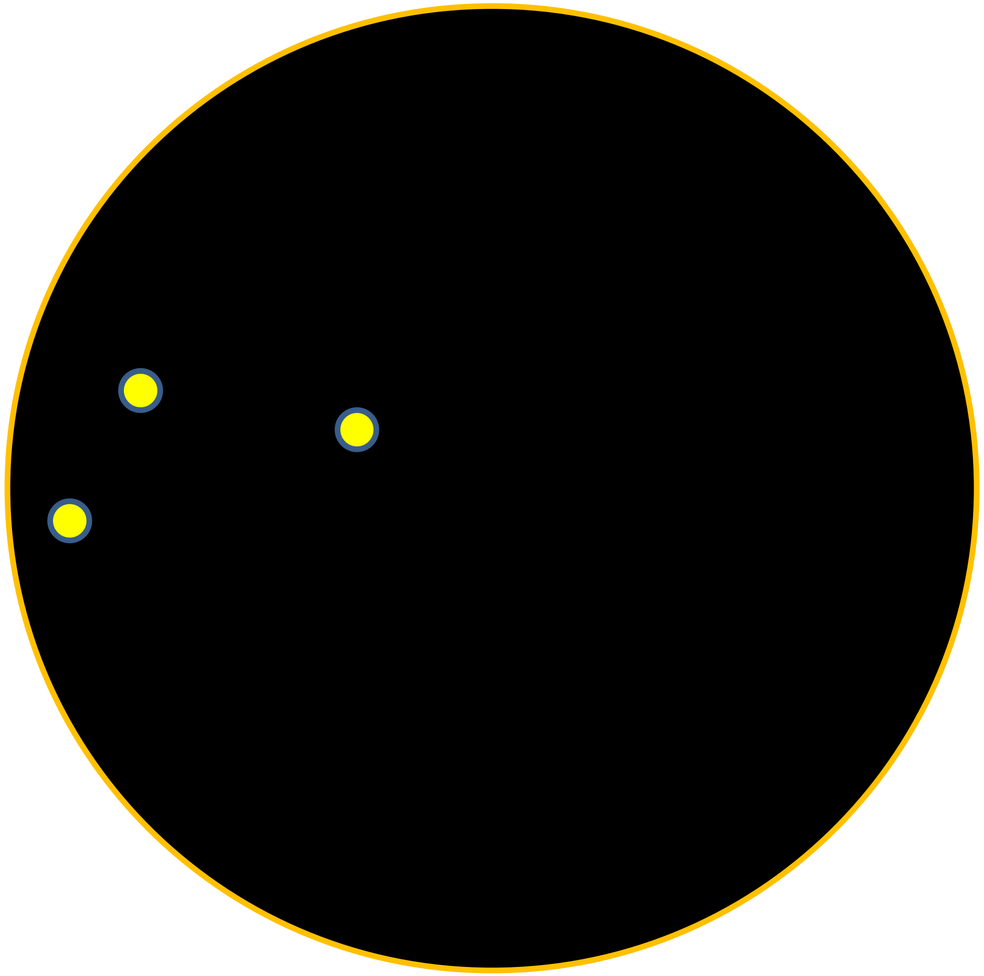
No differences for an agent

Information from data, an illustration



A difference that makes the difference
(For an agent who can see light)

Information from data, an illustration



A system of differences that constitutes the fabric of reality for an agent

Information structures as a fabric of reality

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.illc.uva.nl/HPI

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

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-betweenthings-at-the-bottom-of-things/

The relational definition of information

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.

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 – information dynamics.
In classical formulation: being and becoming.

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.

Reality as an informational structure with computational dynamics: Info-computationalism

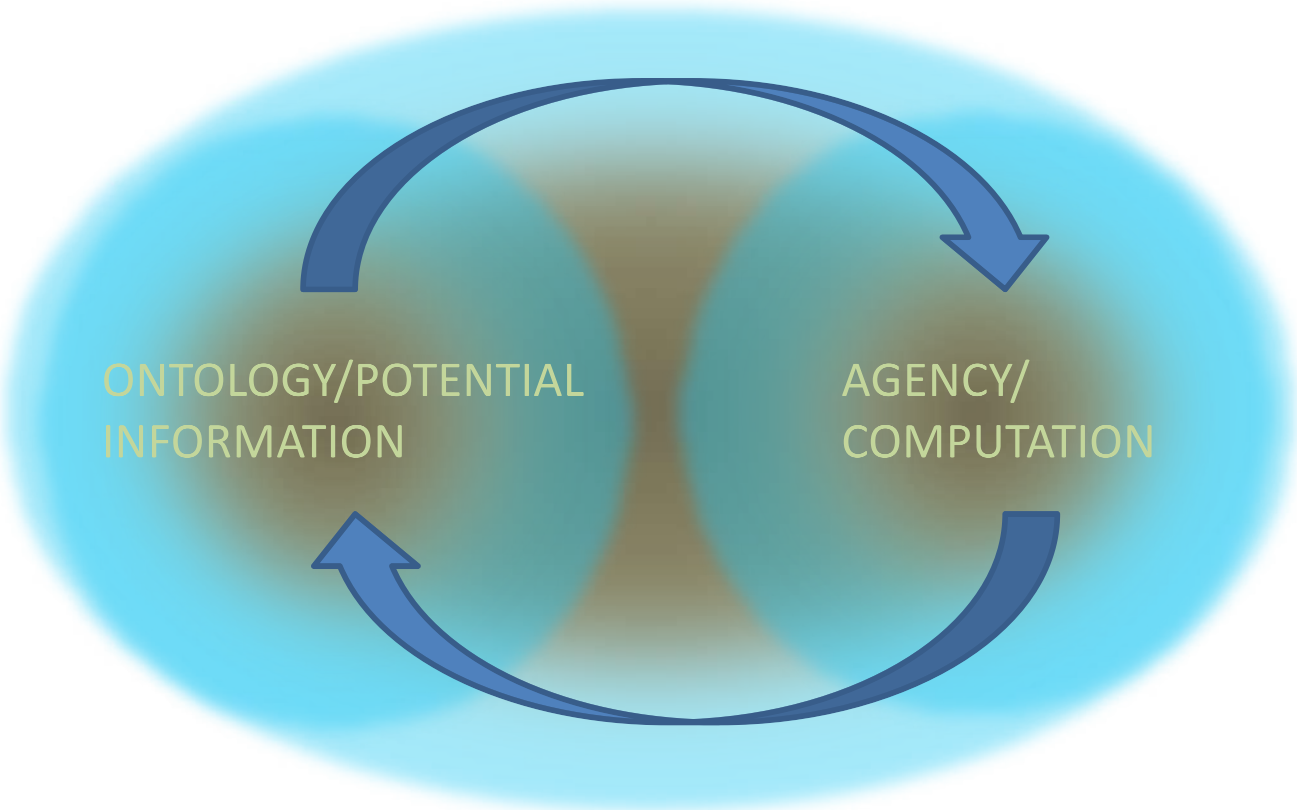
Information is defined as the difference in one physical system that makes the difference in another physical system.

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).

(Dodig-Crnkovic & Giovagnoli, 2013) Information and computation are two basic and inseparable elements necessary for naturalizing <cognition>. (Dodig-Crnkovic, 2009)

Computing nature. Dual-aspect info-computational metaphysics



Metaphysics (First Philosophy) is a study of first principles, classification of all entities hat exists/can exist , the nature of their properties, and the nature of change.

The last concept from the triad: Information, Computation, Cognition

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.

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.

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.

It is important to notice:
Computationalism is not what it used to be…

… that is, the thesis that persons are Turing machines.

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 mechanistic and predefined as a Turing machine and that are sensitive to resources (space, time, energy).*

* PAC Probably Approximately Correct – Leslie Valiant

Computationalism is not what it used to be …

… that is the thesis that persons are Turing machines.

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.

Turing computation: “Turing on Super-Turing and adaptivity” according to Hava Siegelmann

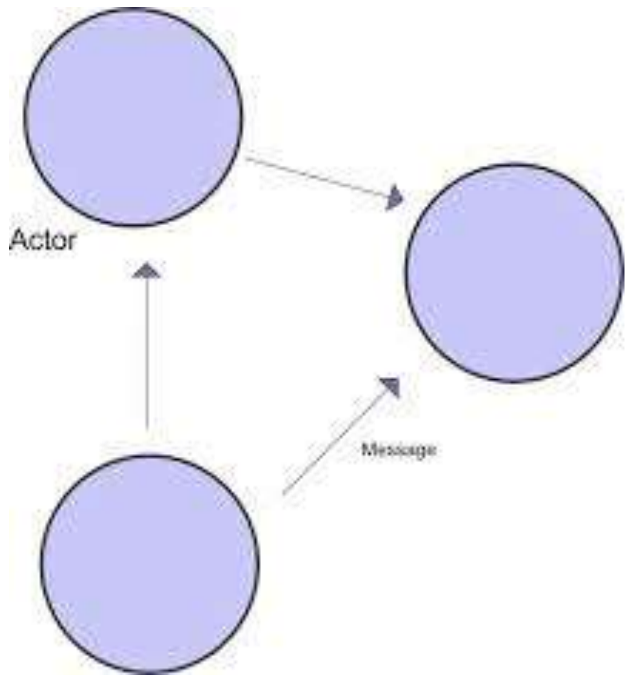
“Biological processes are often compared to computation and modeled on the Universal Turing Machine. While many systems or aspects of systems can be well described in this manner, Turing computation can only compute what it has been programmed for. (…)

Yet, adaptation, choice and learning are all hallmarks of living organisms. This suggests that there must be a different form of computation capable of this sort of calculation. (…)

Super-Turing model is both capable of modeling adaptive computation, and furthermore, a possible answer to the computational model searched for by Turing himself.”

Hava T. Siegelmann, Turing on Super-Turing and adaptivity, Progress in Biophysics and Molecular Biology, http://www.sciencedirect.com/science/article/pii/S0079610713000278

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.

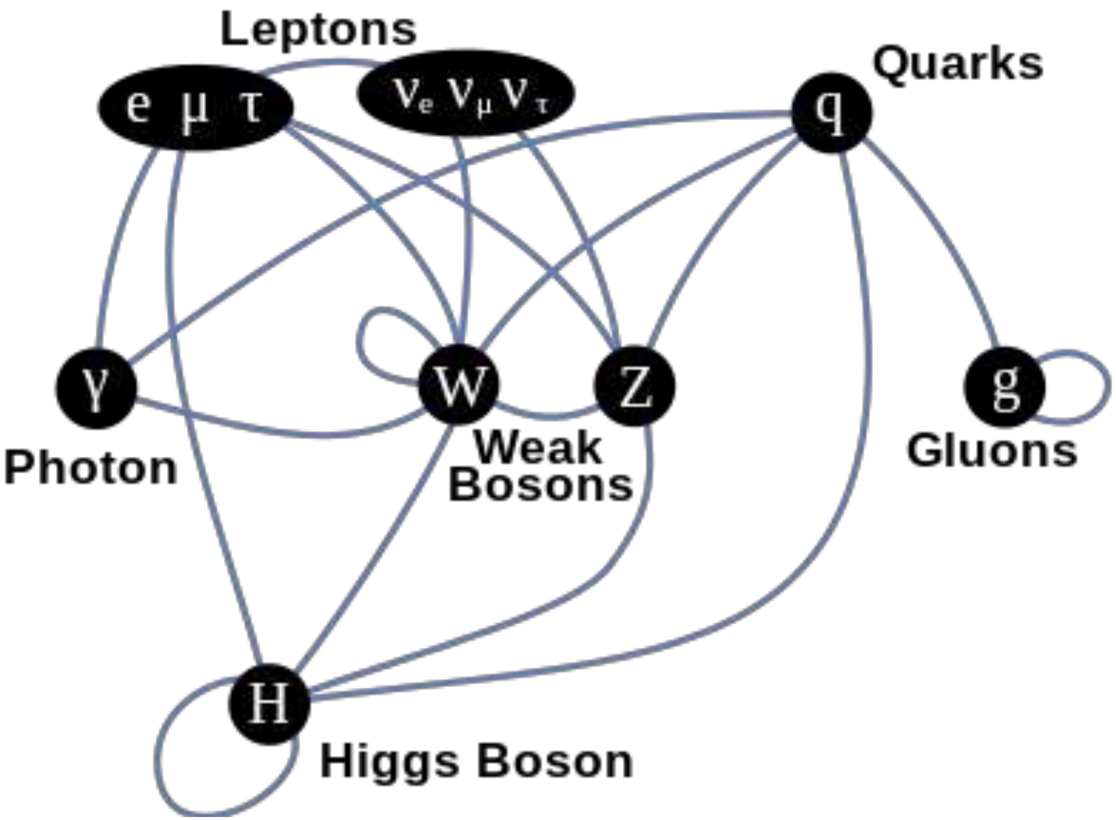
Actor model of concurrent distributed computation

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 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.

Actor model of concurrent distributed computation

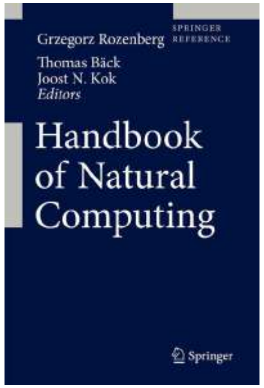


Summary of interactions between particles described by the Standard Model.

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)

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

Computing nature and nature-inspired computation



In 1623, Galileo in his book *The Assayer - Il 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*.

Model for natural computing

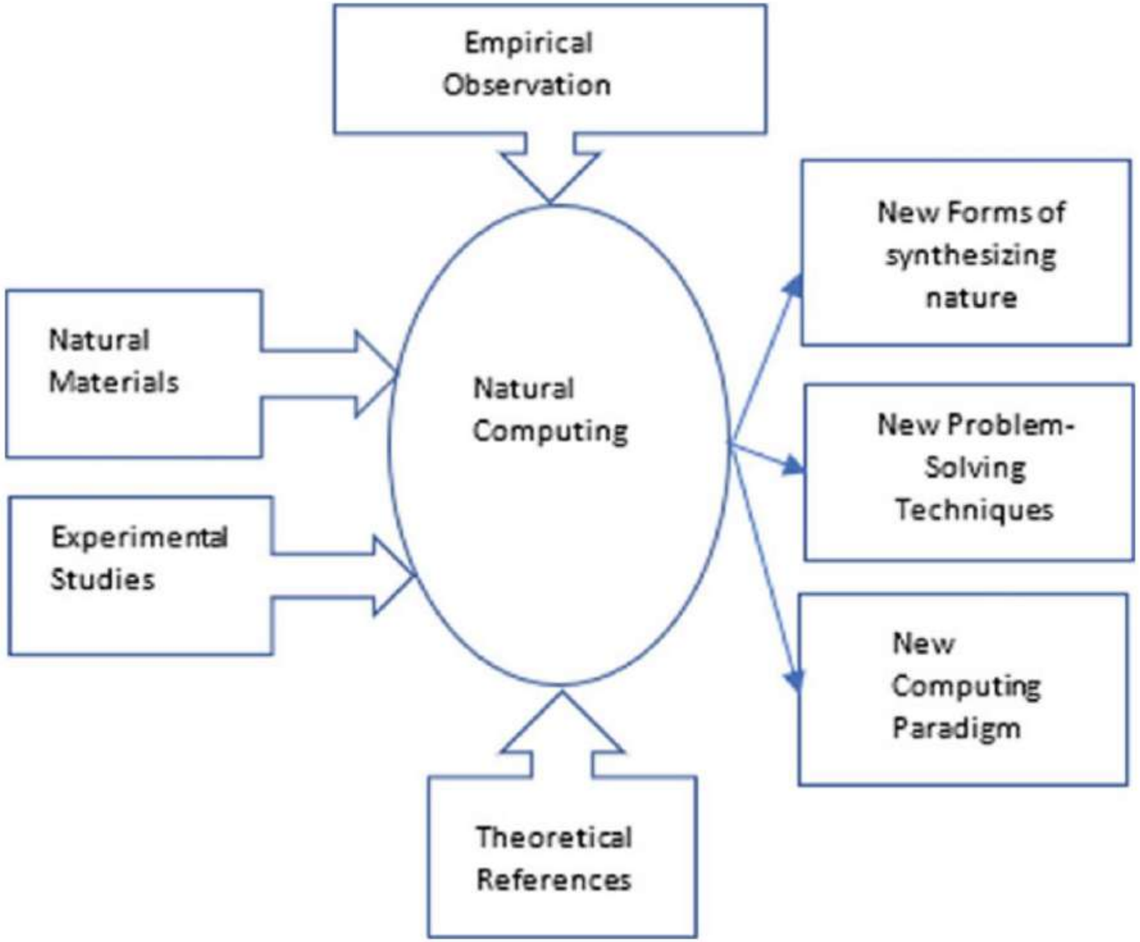


Fig. 1. Model for natural computing

https://link.springer.com/chapter/10.1007/978-981-15-1420-3_202 A Study on Natural Computing: A Review, Rashmi Pathak and Shyam Sunder Gupta

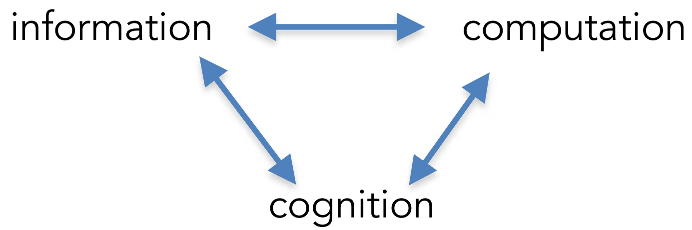
Models of Computation Beyond the Turing Machine

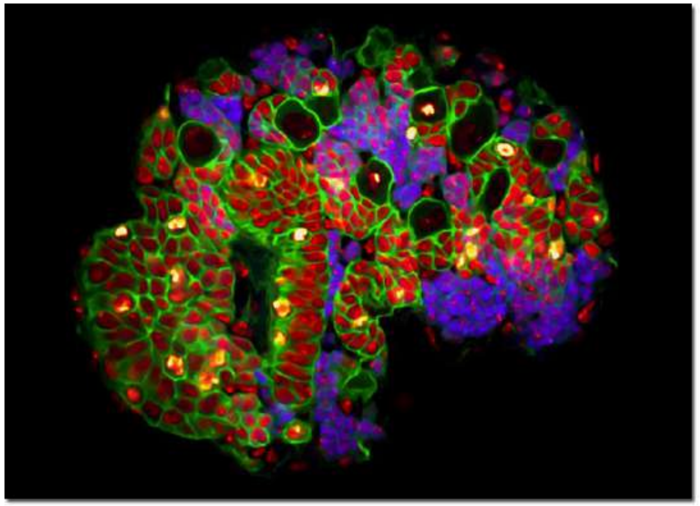
With the advent of computer networks, which are the main paradigm of computing today, the model of a computer in isolation*, represented by a Turing Machine, has become insufficient.

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).

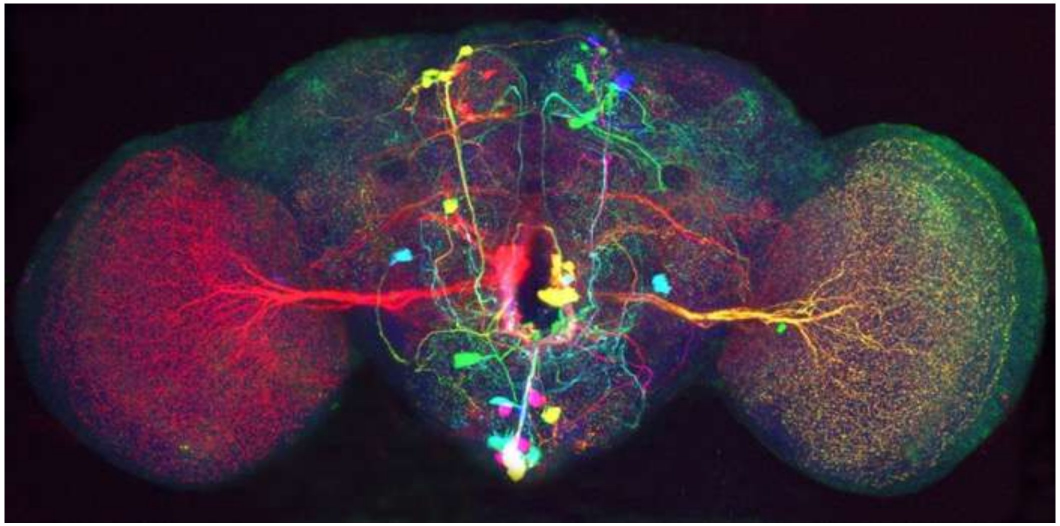
*This view of a system in isolation is inherited from physics. I. Prigogine strongly emphasized the importance of the environment/context especially essential for living beings.
Prigogine, Ilya; Stengers, Isabelle (1984). Order out of Chaos: Man's new dialogue with nature. Flamingo

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

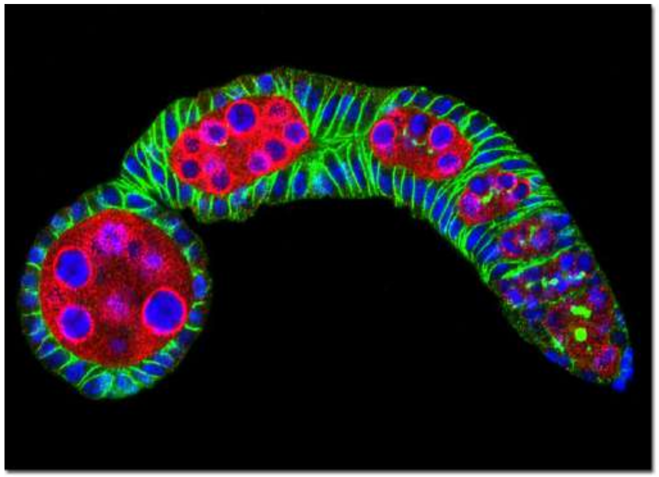




Fruit fly brain micrograph

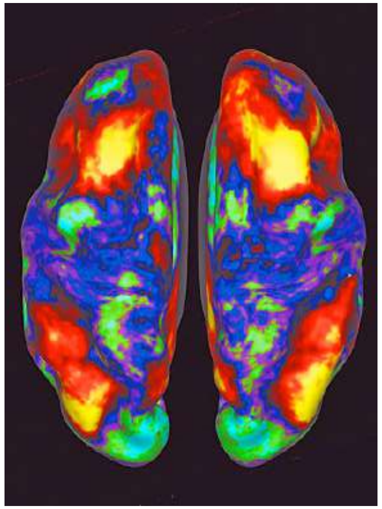


Fruit fly brain neurons

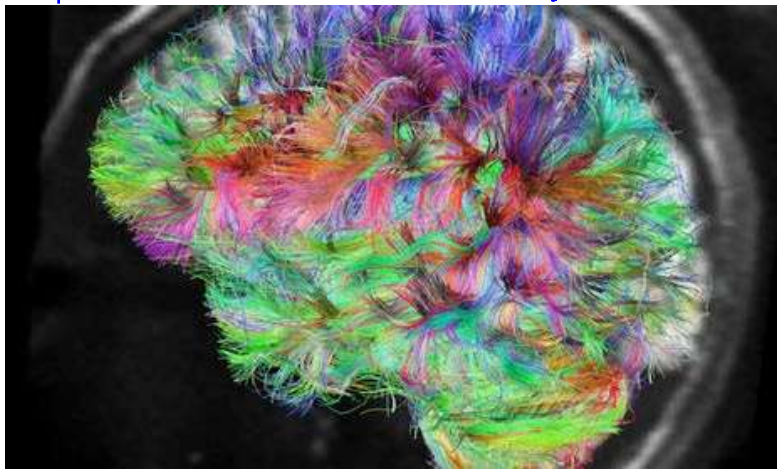


Fruit fly larva

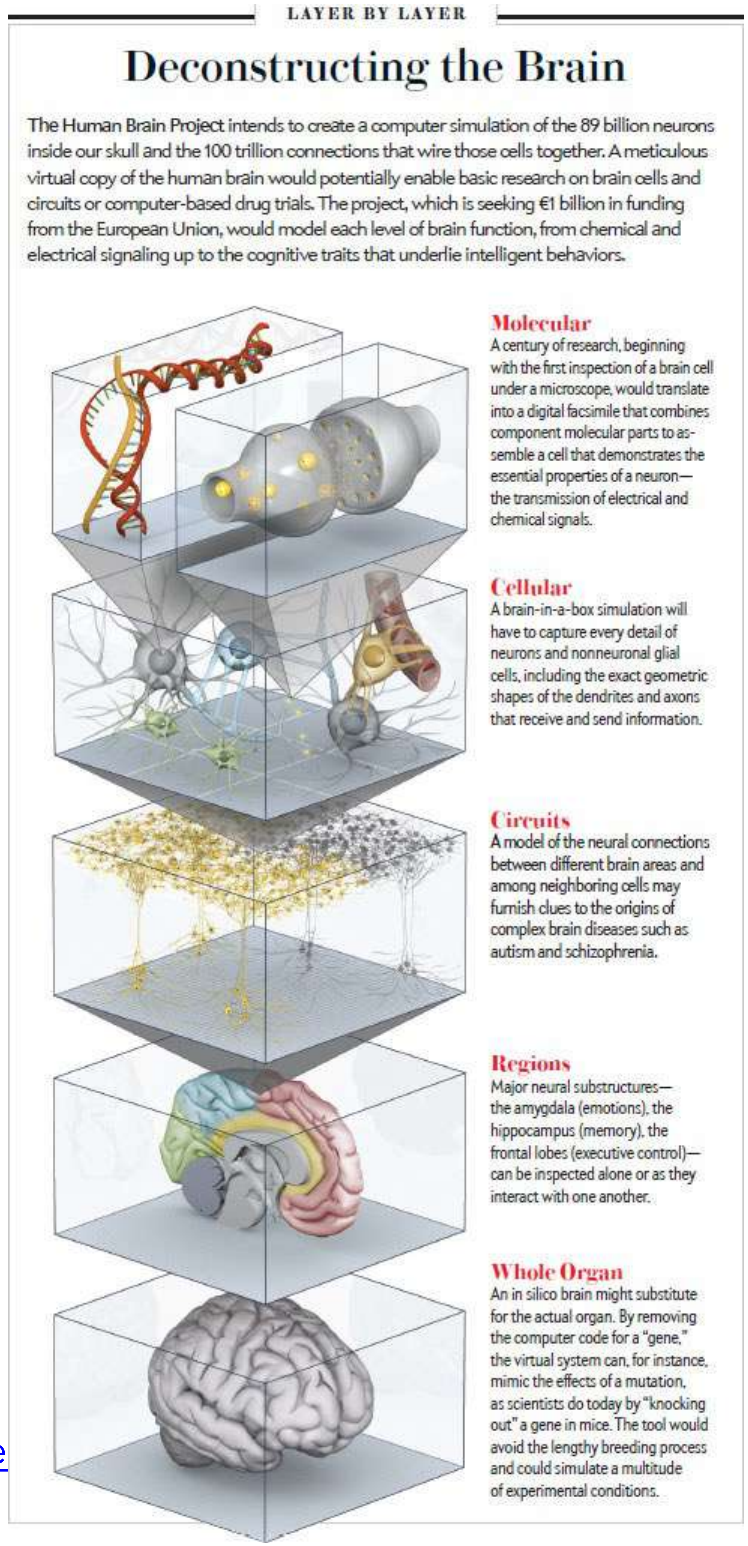
Information, computation, cognition Agency/Interaction-based Hierarchies of Levels



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



LAYER BY LAYER

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.

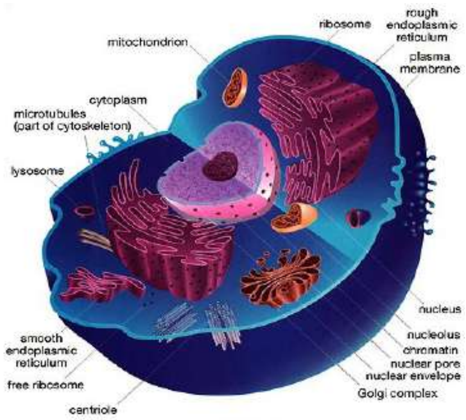
Cellular
A brain-in-a-box simulation will have to capture every detail of neurons and nonneuronal glial cells, including the exact geometric shapes of the dendrites and axons that receive and send information.

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.

Computing cells: self-generating systems



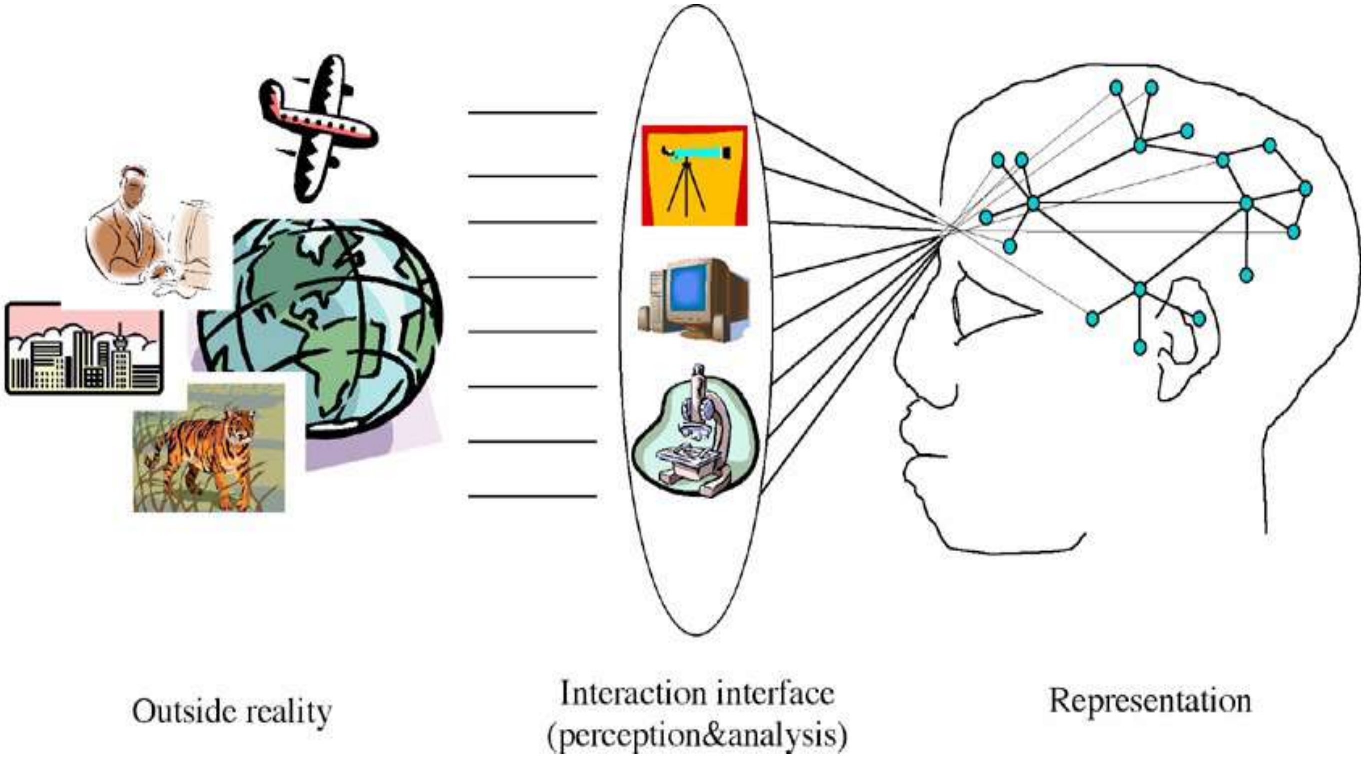
Complex biological systems must be modeled as self-referential, self-organizing "component-systems" (George Kampis) which are self-generating and whose behavior, though computational in a general sense, goes far beyond Turing machine model.

"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.

Cognition: Agency/Interaction-based hierarchies of levels. The world as information for an agent

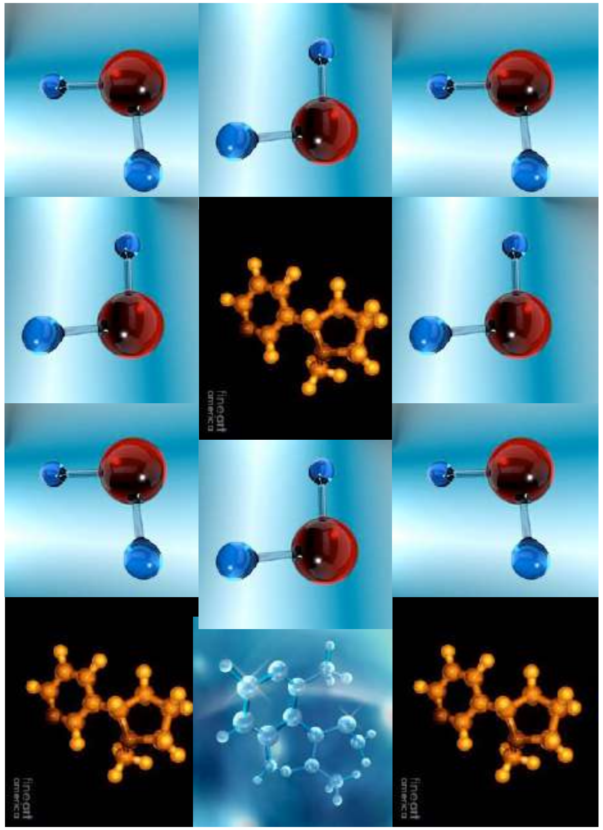


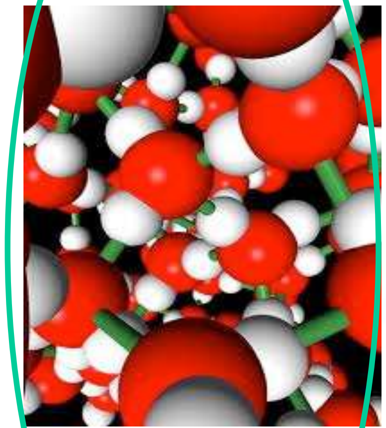
Potential information | Cognition | Actual information for an agent

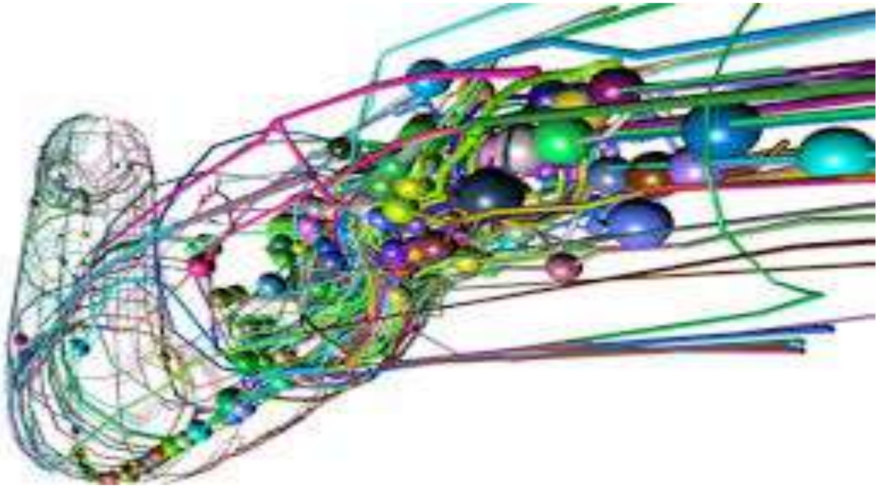
From: http://www.alexeikurakin.org

http://www.tbiomed.com/content/8/1/4 scale-invariance of self-organizational dynamics of energy/matter at all levels of organizational hierarchy

Agency/Interaction-based hierarchies of levels. The world as information for an agent







Actual Information C-elegans

Potential information
Outside reality for C-elegans

Interaction interface for C-elegans
Cognition

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

The reality for an agent – an observer-dependent reality

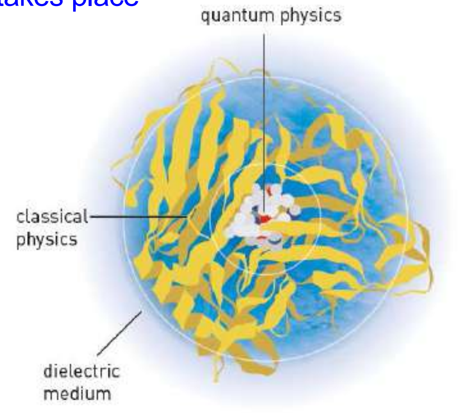
The reality for an agent is an informational structure with which the agent interacts. As systems capable of acting on their own behalf and making sense (use) of information, cognitive agents are of special interest with respect to <knowledge>* generation.

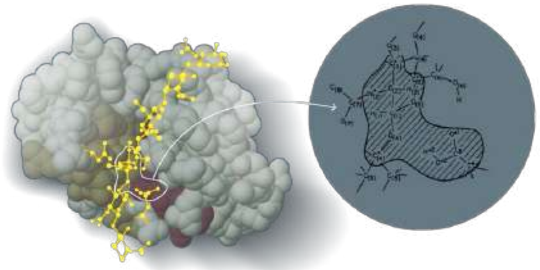
This relates to the idea of participatory universe, (Wheeler, 1990) "it from bit" as well as to endophysics or "physics from within" where an observer is being within the universe, unlike the "god-eye-perspective" from the outside of the universe. (Rössler, 1998)

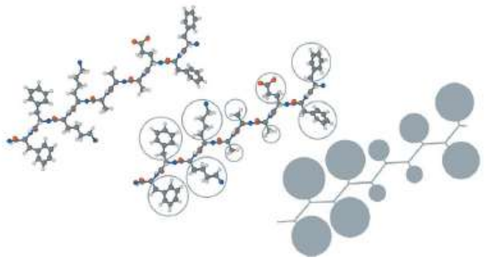
*<knowledge> for a very simple agent can be the ability to optimize gains and minimize risks. (Popper, 1999) p. 61 ascribes the ability to know to all living: "*Obviously, in the biological and evolutionary sense in which I speak of knowledge, not only animals and men have expectations and therefore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

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. 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.

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

Levels of organization of life/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.

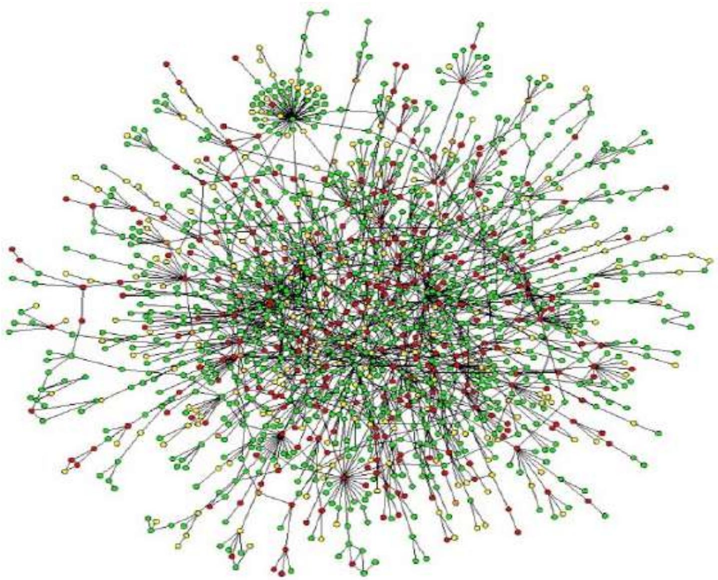
However, there are different types of <cognition> and we have good reasons to ascribe simpler kinds of <cognition> to other living beings.

Bacteria collectively "collects latent information from the

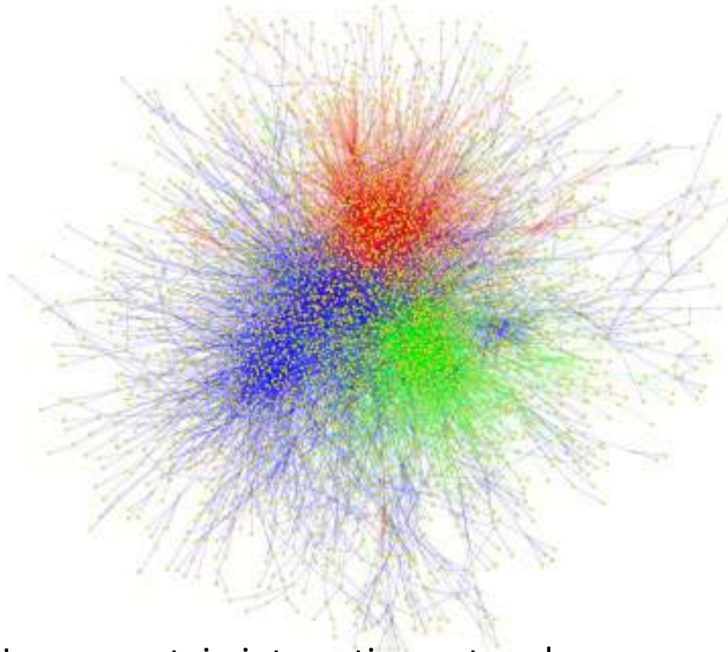
environment and from other organisms, process the information, develop common knowledge, and thus learn from past experience" (Ben-Jacob, 2008; Diggle et al., 2007)

Plants can be said to possess memory (in their bodily structures) and ability to learn (adapt, change their morphology) and can be argued to possess simple forms of cognition.

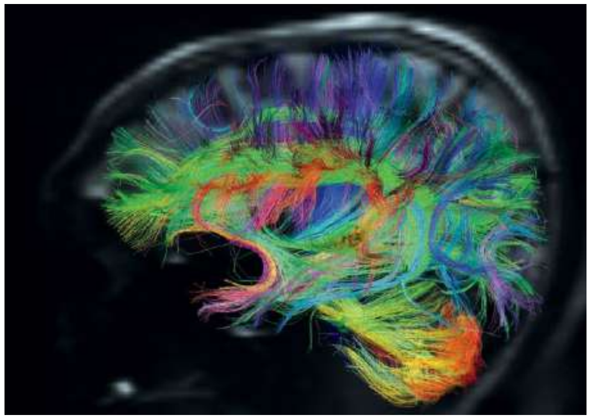
Agents/actors networks



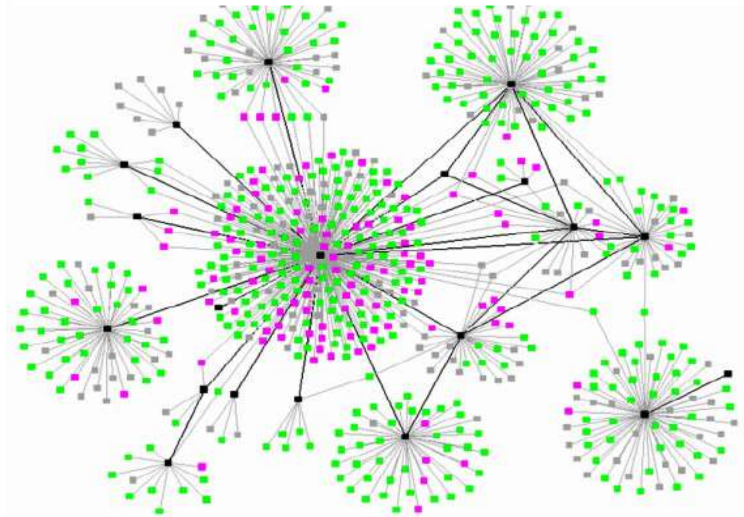
Protein network in yeast cells



Human protein interaction network



Human connectome



Social network

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.

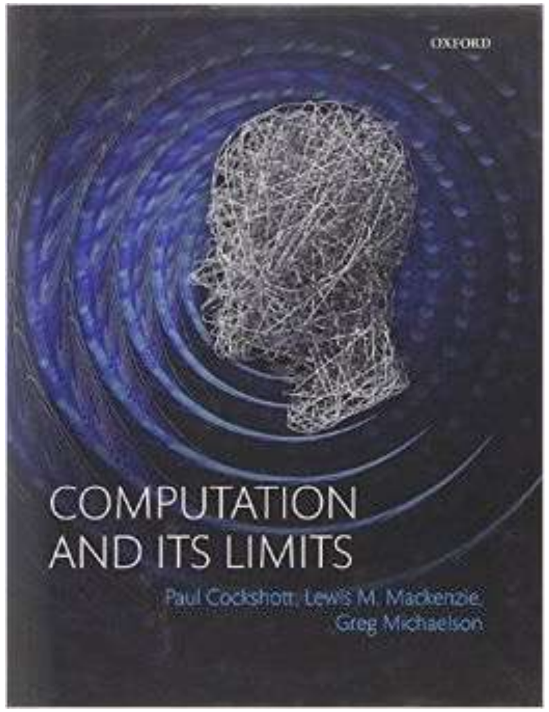
Natural computing has different criteria for success of a computation, halting problem is not a central issue, but instead the adequacy of the computational response in a network of interacting computational processes/devices.

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?

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*
- Barry Cooper*: TM does not cover higher order computation*
- Samson Abramsky – *computing is about behavior in general*
- …

WHAT IS COMPUTATION?

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

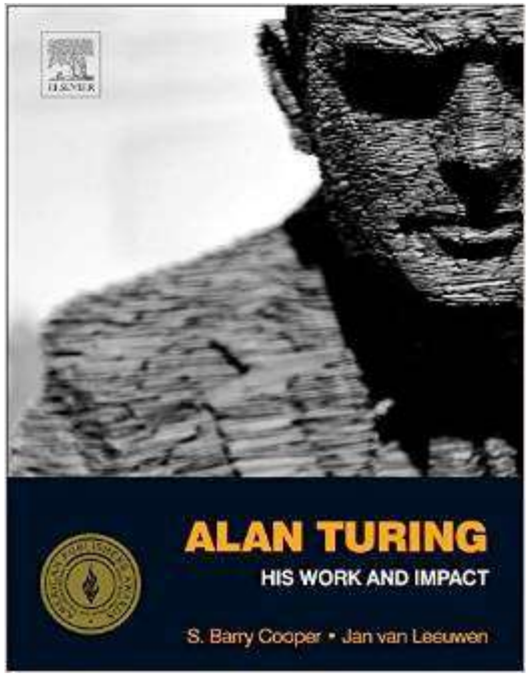
Turing-Church thesis encompasses all algorithms. But:

"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

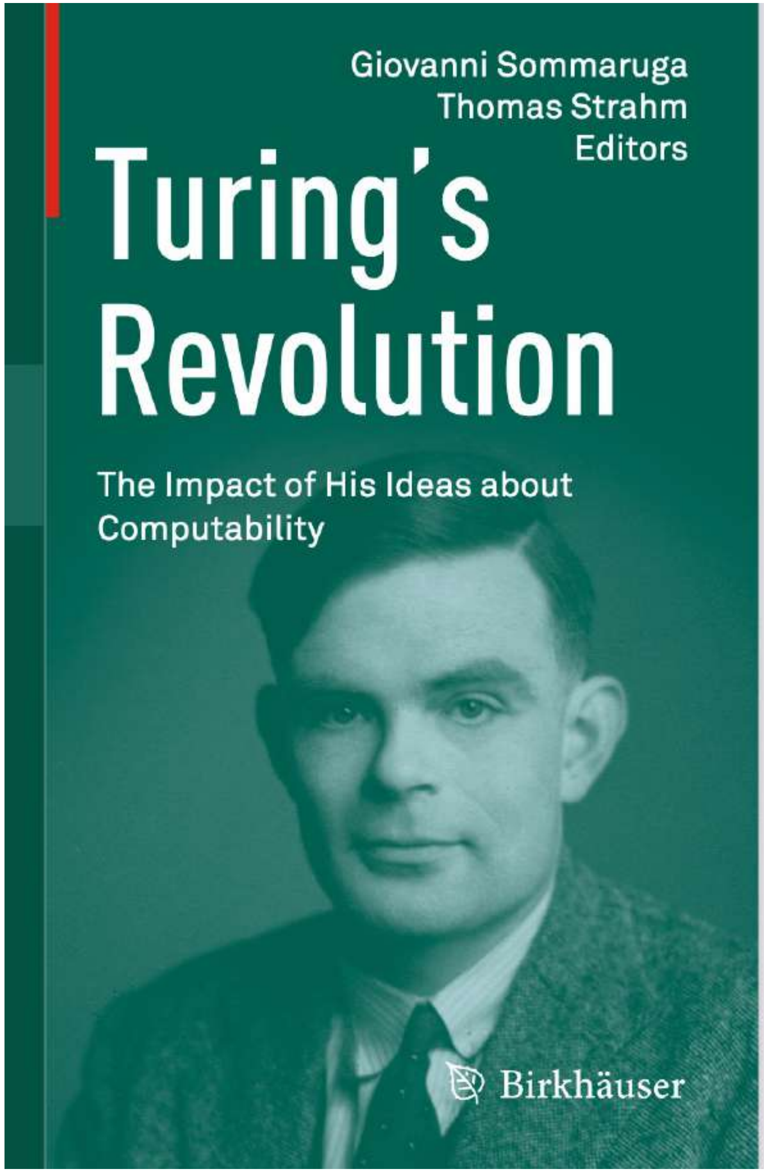
WHAT IS COMPUTATION?

TURING MACHINE MODEL AND BEYOND



https://dl.acm.org/doi/10.1145/2093548.2093569
Turing's Titanic Machine? Embodied and Disembodied Computing at the Turing Centenary, Barry Cooper

https://www.researchgate.net/publication/240319088_Ubiquity_symposium_'What_is_computation'
Ubiquity Symposium What is Computation? Computation is Process by Dennis J. Frailey



New Facets of "Algorithm"
Algorithms as Molecules in Large Organisms
Returning to Leibnizian Visions?

Generalizing Turing Computability Theory
Theses for Computation and Recursion on Concrete and Abstract Structures

Generalizing Computability Theory to Abstract Algebras

Discrete Transfinite Computation

Semantics-to-Syntax Analyses of Algorithms

Incomputability Emergent, and Higher Type Computation

COMPUTATIONAL TAXONOMIES

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.

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

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.

COMPUTATION AS INFORMATION TRANSFORMATION

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).

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).

SOME OPEN PROBLEMS

- How to connect and contextualize diverse views of information on different levels of granularity in nature?
- How exactly is physical computation (intrinsic/natural computation) connected with abstract computation and cognitive computation?
- How is computation realized in computational systems, in machines, and in living organisms?
- What can we learn from natural computational processes in cognitive systems that can be useful for engineered information systems and knowledge management, especially when it comes to managing complex systems and big data?
- How do we get connections between different theories in the research community of philosophy of information and computation?

CONCLUSION

We highlight 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.

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