COMPUTING NATURE AND COMPUTATIONAL THINKING

Gordana Dodig Crnkovic
Mälardalen University, School of Innovation, Design and Engineering

http://www.mrtc.mdh.se/~gdc/work/presentations.html
Mälardalen University Sweden

Mälardalen University: 13 000 students, 900 employees, 3 campuses

Västerås: 138 709 inhabitants 2011
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

– Information - kunskap - vetenskap (in Swedish)

– Professional Ethics

http://www.idt.mdh.se/personal/gdc/work/courses.html
My Background: Research

– Computing Paradigms (Natural/Unconventional Computing and Info-Computationalism, Computational aspects of Science of Information/Foundations of Information; Social Computing);

– Computational knowledge generation, Computational aspects of Intelligence and Cognition; Theory of Science/ Philosophy of Science;

– Information science (generation of information in cognitive systems)

– Computing and Philosophy (Especially Info-computationalism) and


http://www.idt.mdh.se/personal/gdc/work/publications.html
Knowledge. Hinders to Knowledge

White spots on the map of knowledge – what we know that we do not know.

Knowledge – what we believe to know and seems to work well. Part of it are False believes that look like knowledge – what we believe we know, but we actually are wrong! Those are even more important and difficult to fix than things that we understand that we do not know. Those are typical hinders to new knowledge.

Questioning of the “self-evident” is necessary, but self-evident is by its nature something we seldom suspect…

(Fallibility of scientific knowledge – Popper: Knowledge is evolving.)
What is Universe? What is Knowledge? What is Science?

Based on an enormous boost of distributed cognition and extended mind of humanity we witness a major paradigm shift in our understanding of the universe and our place in it.

This big picture is important as it sets the framework for how we think.

That is why not only theory of particular sciences or specific phenomena but even philosophy of nature makes the difference. (And empirical data are as well known theory-laden, even by implicit theory)

http://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy_NASA
Three Major Paradigm Shifts in Understanding of the Universe

Mytho-poetic, God-governed, unpredictable Universe
Mechanistic Universe, ideally predictable
Info-Computational Human-Centric Universe (in some domains predictable, in some domains statistically predictable, and yet others unpredictable)

Computing Nature and Nature Based Computation

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

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!

http://www.youtube.com/watch?v=56qR0iX5A4o
http://en.wikipedia.org/wiki/Natural_computing
Computing Nature and Nature Inspired Computation: How Real?

If it looks like a duck, if it walks like a duck and it quacks like a duck, is it a duck?
(If it looks like computation is it computation?)
The Universe as a Computer – Natural Computationalism

We are all living inside a gigantic computer. No, not The Matrix: the Universe.

Every process, every change that takes place in the Universe, may be considered as a kind of computation.

K Zuse, N Wiener, E Fredkin, S Wolfram, G Chaitin, S Lloyd, G ’t Hooft, C Seife, D Deutsch, CF von Weizsäcker, JA Wheeler, among others

String formation – Andrei Linde
http://physics.stanford.edu/linde

http://www.idt.mdh.se/personal/gdc/work/Pancomputationalism.mht
Models of Computation. Turing Machine Limits. 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, p. 223 Self-Modifying Systems in Biology and Cognitive Science)

The challenge to deal with \textit{computability in the real world/physical computing} (such as computing on continuous data, biological computing/organic computing, quantum computing, or generally \textit{natural computing}) has brought \textit{new understanding of computation}.\textit{ 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.}
The Wildfire Spread of Computational Ideas

"Everyone knows that computational and information technology has spread like wildfire throughout academic and intellectual life. But the spread of computational ideas has been just as impressive. Biologists not only model life forms on computers; they treat the gene, and even whole organisms, as information systems. Philosophy, artificial intelligence, and cognitive science don't just construct computational models of mind; they take cognition to be computation, at the deepest levels. …
The Wildfire Spread of Computational Ideas

… Physicists don't just talk about the information carried by a subatomic particle; they propose to unify the foundations of quantum mechanics with notions of information. Similarly for linguists, artists, anthropologists, critics, etc. Throughout the university, people are using computational and information notions -- such as information, digitality, algorithm, formal, symbol, virtual machine, abstraction, implementation, etc. -- as fundamental concepts in terms of which to formulate their theoretical claims."

Brian Cantwell Smith, The Wildfire Spread of Computational Ideas, 2003
“The word “information” has been given different meanings by various writers in the general field of information theory. It is likely that at least a number of these will prove sufficiently useful in certain applications to deserve further study and permanent recognition. It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general field. “


Dodig-Crnkovic G., Ab Ovo. Information: Between the Anvil and Hammer – Orphean Theme, oil on canvas
What is Information?

A special issue of the Journal of Logic, Language and Information (Volume 12 No 4 2003) is dedicated to the different facets of information.

A *Handbook on the Philosophy of Information* (Van Benthem, Adriaans) is in preparation as one volume *Handbook of the philosophy of science*.

http://www.illc.uva.nl/HPI/
Information as The Primary Stuff of the Universe – Informationalism

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

L Floridi proposes Informational Structural Realism - a view of the world as the totality of informational objects dynamically interacting with each other (Synthese Vol.161, Number 2, 219 253, A defence of informational structural realism).
Information as a Fabric of Reality

According to Gregory Bateson, Information is the difference that makes a difference.

Informational structural Realism (Vedral, Goyal, Floridi, Sayre) argues that information is the fabric of reality.

Daniel C. Dennett and John Haugeland see information as means of unification:
“It is tempting to suppose that some concept of information could serve eventually to unify mind, matter, and meaning in a single theory.”

Computation as Information Processing

With information as the primary stuff of the universe, the most general view of computation is as time-dependent behavior (dynamics) of information.

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

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

As we can observe, structures in the world constantly change.

The knowledge of structures is half a story. The other half is understanding processes, dynamics.

In a classical formulation: being and becoming.
Computing Nature. Dual-Aspect Info-computational Metaphysics

Metaphysics (First Philosophy) is a study of first principles, classification of all entities that exist/can exist, the nature of their properties, and the nature of change.
Info-computationalism (ICON*)

Information and computation are two interrelated and mutually defining phenomena – there is no computation without information (computation understood as information processing), and vice versa, there is no information without computation (information as a result of computational processes).

Being interconnected, information is studied as a structure, while computation presents a process on an informational structure.

In order to learn about foundations of information, we must also study computation.

* The ICON is the simplest type of sign, since it is a pattern that physically resembles what it `stands for'. (Charles Sanders Peirce)
Critics of the evolutionary approach mention the impossibility of “blind chance” to produce such highly complex structures as intelligent living organisms. Monkeys typing Shakespeare are often used as illustration (an interesting account is given by Gell-Man in his *Quark and the Jaguar*.)

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


http://www.liacs.nl/~rozenber/bolognae.pdf
http://www.csd.uwo.ca/~lila/biocomp.html
How does nature compute?
– Learning from Nature *

“It always bothers me that, according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space, and no matter how tiny a region of time …

So I have often made the hypothesis that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequer board with all its apparent complexities.”

Richard Feynman “The Character of Physical Law”

* 2008 Midwest NKS Conference, Indiana University — Bloomington, IN
Computing Nature

http://www.cs.indiana.edu/~dgerman/2008midwestNKSconference/
What is Computation? (How) Does Nature Compute?

Continuum-discrete controversy is bridged by the same dual-aspect approach (Info-Computationalism).

This counters the argument against computational mind which claims that computational mind must be discrete.

It is also an answer to the critique that the universe might not be computational as it might not be entirely digital.

Computation as information processing can be both continuous and discrete.
Unified Info-Computational Theory

Semantics (meaning) is essential; information has both declarative and non-declarative forms (e.g. biology), each of them with specific functions for an agent. We must be able to understand computational mechanisms of knowledge production.

This approach is agent-centered which allows for pluralism: logical, epistemological and ethical. It is supported by research results from physics, biology, neuroscience and philosophy of mind, among others.
Unity of Sciences in the Info-computationalist Framework

This framework enables understanding mechanisms of science on both object level and meta-levels.

Object level: describing different phenomena within sciences such as biology, physics, chemistry, etc. as manifestation of same sort of informational-computational processes.

Meta levels in a sense of understanding scientific theories of different sciences translated into the same info-computationalist language.
Unity of Sciences in the Info-computationalist Framework

One more level of understanding is provided by the insight into mechanisms of cognition, within the same framework. If we are searching for a path of unification, it should go via common language and conceptual apparatus, and Info-Computationalism is providing both.
Reality: Blind Men And An Elephant

It’s a Fan!

It’s a Wall!

It’s a Rope!

It’s a Spear!

It’s a Snake!

It’s a Tree!
There is a difference between the world in itself, noumenon ("Ding an sich") and the phenomenon - the world as it appears for an observer ("Erscheinung").

These two concepts are distinct but connected in Kant's philosophy.
Info-computationalism (ICON) Applied

Info-computationalism aims at connecting non-living and living nature in a unified natural philosophy.

Among others observer is integrated in the scientific epistemology. That means that we need to understand how an observing agent interacts with the system and what knowledge might be constructed from that kind of interaction.

The knowledge generated by different kinds of agents will be different even though it is about the same physical world.
Naturalized epistemology is an idea that *knowledge may be studied as a natural phenomenon*: the subject matter of epistemology (theory of knowledge) is not our concept of knowledge, but the knowledge itself. (Feldman, Kornblith)

“If the stimulation of his sensory receptors is all the evidence anybody has had to go on, ultimately, in arriving at his picture of the world. Why not just see how this construction really proceeds? Why not settle for psychology? “

("Epistemology Naturalized", Quine 1969; emphasis mine)

I will re-phrase the question to be: *Why not settle for info-computation?*
The variation on the theme Naturalized Epistemology, becomes as follows:

*If the stimulation of her sensory receptors is all the evidence anybody has had to go on, ultimately, in arriving at her picture of the world. Why not just see how this construction really proceeds? Why not settle for the study how informational structures of the world induce informational structures in an agent via computational processes?*
Naturalist Understanding of Cognition

According to Maturana and Varela (1980) even the simplest organisms possess cognition and their meaning-production apparatus is contained in their metabolism. Of course, there are also non-metabolic interactions with the environment, such as locomotion, that also generate meaning for an organism by changing its environment and providing new input data.

Maturana and Varela’s understanding that all living organisms have some cognition, in some degree, is the most suitable basis for the computationalist account of the naturalized evolutionary epistemology.
Info-computational Account of Knowledge Generation

Natural computing is a new paradigm of computing beyond the Turing Machine and applies to all physical processes including those going on in our brains.

To develop models of natural computers, scientists must study topics not usually associated with computing, including organic chemistry, molecular biology, bioengineering, and smart materials.
At the physical level, living beings are open complex computational systems in a regime on the edge of chaos, characterized by maximal informational content. Complexity is found between orderly systems with high information compressibility and low information content and random systems with low compressibility and high information content. (Flake)
The essential feature of cognizing living organisms is their ability to manage complexity, and to handle complicated environmental conditions with a variety of responses which are results of adaptation, variation, selection, learning, and/or reasoning. (Gell-Mann)
As a result of evolution, increasingly complex living organisms arise that are able to survive and adapt to their environment. It means they are able to register inputs (data) from the environment, to structure those into information, and in more developed organisms into knowledge.

The evolutionary advantage of using structured, component-based approaches is improving response-time and efficiency of cognitive processes of an organism.

*This restructuring is morphological computing*
Cognition as Restructuring of an Agent in the Interaction with the Environment

Naturalized knowledge generation recognizes the body as our basic cognitive instrument.

All cognition is embodied cognition, in both microorganisms and humans (Gärdenfors, Stuart).

In more complex cognitive agents, knowledge is built upon not only reaction to input information, but also on intentional choices, dependent on value systems stored and organized in agents memory.
Cognition as Restructuring of an Agent in the Interaction with the Environment

Information and computation (communication) are fundamental, as information and its processing are basic structural and dynamic elements which characterize structuring of input data (data → information → knowledge) by an interactive computational process going on in the agent during the adaptive interplay with the environment.
Natural Computing in Cognizing Agents

- Agent-centered (information and computation is in the agent)

- Agent is a cognizing biological organism or an autonomous adaptive intelligent machine

- Interaction with the physical world and other agents is essential

- Kind of physicalism with information as a stuff

- Agents are parts of different cognitive communities

- Self-organization is a fundamental mechanism for information processing and thus cognition

- Circularity (recursiveness, self-reflexiveness) is central for biological organisms
Morphogenesis means the creation of form and it is used to describe the creation of shape during animal development.

(In biology it is one of the four fundamental interrelated classes of events that characterize all of development: Patterning - Regulation of timing - Cell differentiation - Morphogenesis: The processes that generate tissue organization and shape).

However we model of four types of development by morphological computation of an informational structure (data representation) governed by (local) physical laws.

http://www.scholarpedia.org/article/Morphogenesis
Morphogenesis as Computation (Information Processing) - Turing's Reaction-Diffusion Model of Morphogenesis

“Patterns resulting from the sole interplay between reaction and diffusion are probably involved in certain stages of morphogenesis in biological systems, as initially proposed by Alan Turing. Self-organization phenomena of this type can only develop in nonlinear systems (i.e. involving positive and negative feedback loops) maintained far from equilibrium.” Dulos, E., Boissonade, J., Perraud, J. J. Rudovics, B., Kepper, P. (1996) Chemical morphogenesis: Turing patterns in an experimental chemical system, Acta Biotheoretica, Volume: 44, Issue: 3, pp. 249 -261

http://cgjennings.ca/toybox/turingmorph
Morphological Computation in Robotics
Connecting Body, Brain, And Environment

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

CENTRAL IDEAS

Levels of Description – Levels of Abstraction – Levels of Organization

http://www.youtube.com/watch?v=73-GtI7YCsl&feature=related
Atoms to Universe *Zoom OuT* (1.41)

http://www.youtube.com/watch?v=ae9Kwfzh4T8&feature=related
A Measure of Everything (2.21)

http://www.youtube.com/watch?v=b0lxbzgwW7l&feature=related
Size Of The Universe (2.11)
Complexity

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

http://www.youtube.com/watch?v=C2vglCfQawE Game of life producing complex behavior

Generative Models

How does the complexity arize?
Evolution is the most well known generative model.

Network models: Networks understanding networks

http://www.youtube.com/watch?v=ni_A2bAkUww&feature=relmfu
Complexity from Simplicity

http://www.youtube.com/watch?v=gQgoNitl1g
Emergence - Complexity from Simplicity, Order from Chaos (1 of 2) (4.54)

http://www.youtube.com/watch?v=ONiWmzrmfuY&NR=1
Murray Gell-Mann On Emergence (1.30)

http://www.youtube.com/watch?v=Lk6QU94xAb8
Fractals - The Colors Of Infinity (53:45)

http://www.youtube.com/watch?v=u_CaCie8R4U&feature=related
Patterns in Nature (3.04)
Generative Models: From The Origins Up in Complexity

http://www.youtube.com/watch?v=U6QYDdgP9eg&NR=1
The Origin of Life - Abiogenesis (10)

http://www.youtube.com/watch?v=rtmbcfb_rdc&p=0696457CAFD6D7C9
The Origin of the Genetic Code (9.37)

http://www.youtube.com/watch?v=6RbPQG9WTZM&feature=related
The Origin of the Brain (9.29)

http://www.youtube.com/watch?v=NEEXK3A57Hk
The Origin of Intelligence (5.15)
Modelling of Complexity

http://www.youtube.com/watch?v=7WNUQspHyoA
Complexity & Chaos Emergence & Complexity (5.43)

Linear systems – decomposibility -
Modelled by Analysis – Top-down – Global (Reductionism)

Non-linear systems – behave as a WHOLE –
Modelled by Synthesis - Bottom-up, Distributed)) Holism, System approaches

Complex behavior can emerge from SIMPLE GENERATORS!
Self-Organization

http://www.youtube.com/watch?v=SkvpEfAPXn4&feature=fvwrel
Robots with a mind of their own (1.38)

http://www.youtube.com/watch?v=QdQBH 5Aabs&feature=related
Self-replicating Kinematic Cellular Automata (0.06)

http://www.youtube.com/watch?v=KPP-4-LEHXQ
Self Organization of vertical magnetic dipoles floating on water (2.53)

Self-star properties in organic systems:
Complex Adaptive Systems

http://www.youtube.com/watch?v=TCOmBVrnDeA&feature=related
Complex adaptive systems (1.02)

http://www.youtube.com/watch?v=bnKhzRpXPvM&feature=related
A New Frontier: Systems Biology (12.55)

http://www.youtube.com/watch?v=KO7BIrHVQU0&playnext=1&list=PL04270148FBDF86A6
Cities and Countries Part Two: Cultural Systems (4:45)

http://www.youtube.com/watch?v=t2JHbhYyoJc
Eunice E. Santos receives 2010 IEEE Computer Society Technical Achievement Award (1.38)
Agent-based Models

An agent-based model (ABM) is a computational model for simulating the actions and interactions of autonomous individuals in a network, to assess their effects on the system as a whole. It combines elements of game theory, complex systems, emergence, computational sociology, multi agent systems, and evolutionary programming. Monte Carlo Methods are used to introduce randomness.

http://en.wikipedia.org/wiki/Agent-based_model
Agent-based Models

The basic notion of agent based models is founded upon something that most modern science ignores: the study of complexity and emergence.

http://www.youtube.com/watch?v=2C2h-vfdYxQ&feature=related
Composite Agents (5.06)
Machines, Deterministic and Probabilistic

http://www.youtube.com/watch?v=PEDQoQuhkg&feature=related
Protein Synthesis (1.22)

http://www.youtube.com/watch?v=OtYz_3rkvPk&NR=1
Transcription (0.57)

http://www.youtube.com/watch?v=aCsBDNm9Mi
Babbage machine (1.57)

http://www.youtube.com/watch?v=40DkJ9vt5CI
Mechanical model of Turing Machine (2.43)

http://www.youtube.com/watch?v=M8ZEJTNW3OM&feature=related
Clockwork mechanism (8.50)

http://www.youtube.com/watch?v=YcqvJI8J6Lc&feature=fvwrel
IBM Nano (3.26)
The Blue Brain Project
AN EXAMPLE OF A NEW KIND OF SCIENCE

Henry Makram's lecture about the project (16:49)

http://www.youtube.com/watch?v=1fU4mK7ERfw
Henry Markram on the Blue Brain Project (14:54) Simulation-based research
Books in the New Computational Paradigm

A New Kind of Science

Book available at:
http://www.wolframscience.com

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

See also
http://www.youtube.com/watch?v= eC14GonZnU
A New Kind of Science - Stephen Wolfram
A New Paradigm of Computing – Interactive Computing

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

Dina Goldin, Scott Smolka, Peter Wegner, eds.

Dina Goldin, Peter Wegner
The Interactive Nature of Computing:
Refuting the Strong Church - Turing Thesis
Minds and Machines
Volume 18, Issue 1 (March 2008) p 17 - 38

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

Qualitative Complexity

Ecology, Cognitive Processes and the Re-Emergence of Structures in Post-Humanist Social Theory

By John Smith, Chris Jenks
Consciousness Computational Way

Mind as a self-referential system:

"In the end, we self-perceiving, self-inventing, locked-in mirages are little miracles of self-reference." Hofstadter
The Universe as Quantum Information

Reality = Information

Under Google books there are parts of this book available.
Computation, Information, Cognition

Editor(s): Gordana Dodig Crnkovic and Susan Stuart
Investigations into Science, Philosophy and Ethics of Information and Computing

Book (pdf) available at
Information and Computation

Editor(s): Gordana Dodig Crnkovic and Mark Burgin
World Scientific, 2011
Conclusion - New Paradigm of Knowledge Production

"Computational turn" – a new paradigm shift comparable with introduction of atomism in physical sciences.

Information and computation are the basis for all knowledge.

Cognition is information processing.

A new kind of science which includes life as natural computational phenomenon.
"Science is a dynamic process in which the assimilation of new phenomena, perspectives, and hypotheses into the scientific corpus takes place slowly. The apparent disunity of the sciences is the unavoidable consequence of this gradual integration process. Some thinkers label this dynamical circumstance a ‘crisis’.”
The Quest for Cognition in Plant Neurobiology (An example of computational thinking)

“Do plants compute? The blunt answer is “yes”. Plants compute insofar as they manipulate representational states. The *sine qua non* of representation-based competency is off-line adaptive behavior. Reactive behavior differs from truly cognitive one because it fails to meet the principle of dissociation (the states of a reactive system covary continuously with external states). Off-line competencies thus mark the borderline between reactive, noncognitive, cases of covariation and the cognitive case of intentional systems. Nocturnal reorientation in *Lavatera cretica leaves is not to be interpreted in reactive terms, since such a competency is not explained by means of online forms of covariation.” Francisco Calvo Garzón

http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2634130/
Why do We Need to Know About Computational Knowledge and Knowledge Production?

LEARNIG
LEARNING TO LEARN
LEARNING TO LEARN TO LEARN…
More on Computational Thinking


Henry Markram - The Blue Brain Project [http://www.youtube.com/watch?v=8iDR8Z-e_GU]
Paradigm Shift
Conclusion: Computing Nature: An Ongoing Paradigm Shift

Information/Computation as basic building blocks of understanding

Discrete/Continuum as two complementary levels of description

Natural interactive computing beyond Turing limit – *not only computing as it is but also computing as it may be*

Complex dynamic systems
Conclusion: Computing Nature: An Ongoing Paradigm Shift

Emergency (emergent property - a quality possessed by the whole but not by its parts)

Logical pluralism including paraconsistent logics

Philosophy informed by sciences and vice versa

Human-centric (agent-centric) models

Circularity and self-reflection (computing, cybernetics)

Ethics returns to researchers agenda (Science as a constructivist project – what is it we construct and why?)