Dynamic of Information as Natural Computation

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12,000 students and around 900 employees, of which 67 are professors
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

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

http://www.idt.mdh.se/personal/gdc/work/courses.html
My background: research

– Computing Paradigms, info-computationalism
– Info-computational knowledge generation
– Info-computational aspects of Intelligence and Cognition
– Theory of Science/ Philosophy of Science;
– Information science (generation of information in cognitive systems)
– Computing and Philosophy and

http://www.idt.mdh.se/personal/gdc/work/publications.html
"I invite readers not on a visit to an archaeological museum, but rather on an adventure in science in making"

Information is everywhere – whether it’s digital information in our devices, analogue content in books, or biological data encoded in our cells. But how do they compare in terms of storage amount? How have our means of storing information grown over the decades? And do you know what a zettabyte or a yottabyte is?

BBC - Future - Technology - Byte-sized graphic guide to data storage
MEGABYTES

1 MEGABYTE = APPROXIMATELY 1,000 KILOBYTES
(ACTUALLY 1,024 KB)

0.004 M
Apple I
RAM in Apple’s first computer, 1976

0.004
Oyster card
London public transport

0.02
Punched paper tape
largest feasible reel

0.02
Tandy 200 computer
amount of RAM, 1984

0.02
Word document
single page

0.7
Audio cassette
90 min

256 MB
Kindle
first generation

1.5
War & Peace
Kindle ebook

5
William Shakespeare
complete works

20
10,000 pages of text
about 20 novels

66
Mosquito genome
DNA for malaria mosquito

9
Blu-Ray
1 sec at HDTV quality

1.5
3.5” Floppy disk

1 ebook
average size

Million 10^6 M (mega)
Billion (Milliard) $10^9$ G (giga)
Billion (Milliard) $10^9$ G (giga)

- **Facebook**: 365 billion photos and videos stored per sec, 2012
- **Kindle Touch**: 4 billion
- **iPhone 5 total storage**: 32 GB
- **4K digital cinema**:
  - 2.3 min normal frame rate
  - 4.6 min high frame rate
- **Wikipedia**: 4.6 billion all current articles without edit history
- **DVD dual-layer**: 8.5 GB
- **YouTube videos uploaded per min**: 29.2 GB
- **Large Hadron Collider data produced per min**: 28.5 GB
- **Mad Men one episode**: 25.4 GB
- **Human sperm DNA created per men, per sec**: 1.760 GB
- **The Hobbit 4K digital cinema high frame rate**: 778 GB
- **Eggs per woman at birth - about 450**: 343 GB
- **Wolfgang Amadeus Mozart complete works as MP3**: 20 GB
- **Blu-ray max disc capacity**: 128 GB
Trillion (Billion) $10^{12}$ T (tera)

20,000 TB
Google data processed per day, 2008

304
Human eye
light receptors per sq mm

47
DNA in audio hair cells

42 TB
Amazon.com database

2,220
Synthetic DNA data storage capacity 1 gram

651
Eagle's eye
light receptors per sq mm

2,000
All US academic research libraries printed collection

120
Internet traffic for all of 1993

274 TB
Facebook photos and videos stored per day, 2012

900
Mobile internet traffic per month, 2005

1,800
Emails sent globally per day, 2002
Quadrillion $10^{15}$ P (peta)

1. **Radio programming**
   - 3.5 petabytes globally in 2002

2. **Internet traffic**
   - 22.8 petabytes globally in 2002

3. **Climate data archive**
   - 6 petabytes of data, including repeats

4. **YouTube video uploaded in 2012**
   - 15.4 petabytes

5. **Supercomputer storage capacity**
   - 40 petabytes

6. **Human nose neurons**
   - 45.7 petabytes

7. **Telephone calls globally per day, 2002**
   - 47.4 petabytes

8. **Facebook photos and videos stored in 2012**
   - 100 petabytes

9. **Human sperm created per man per day**
   - 152 petabytes

10. **Human male ejaculation**
    - 211 petabytes

11. **Large Hadron Collider data produced per year**
    - 15 petabytes

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**Note:**

1 petabyte = approximately 1,000,000,000 megabytes (actually 1,099,511,627,776 bytes).
Quintillion (Trillion) $10^{18}$ E (exa)
ZETTABYTES
1 ZETTABYTE = APPROXIMATELY 1,000,000,000,000,000,000 MEGABYTES
(ACTUALLY 1,125,899,906,842,620 MB)

Sextillion $10^{21}$ Z (zetta)
Septillion (Quadrillion) $10^{24}$ Y (yotta)

Notes:
Figures are based on decimal not binary file sizes.
So 1 megabyte = 1000 kilobytes, not 1024 kilobytes.

Most organic figures refer to genetic data and are based on multiplying DNA in single cell by number of cells. DNA in two cells is therefore counted twice, though cells within an organism are genetically exact or near-exact copies of one another.
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.

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


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

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

Luciano Floridi (2011) The philosophy of information, Oxford University Press
Traditionally, information was considered to be a building block of knowledge and thus supposed to always be true.

The early developments of the field of dynamic of information such as seminal work of (Dretske, 1999) (information flow as linguistic regularities) and (Barwise & Seligman, 1997) (informational relation between situations)

Described in the Philosophy of Information handbook (Benthem van & Adriaans, 2008), as well as (Burgin, 2010) or (Floridi, 2011).

Dretske formulated the strongly semantic view of information, that information must be true: ‘False information and mis-information are not kinds of information—any more than decoy ducks and rubber ducks are kinds of ducks.’ (Dretske, 1981, p. 55).

However, Burgin argues that false information is information too, in the same way as false statement is a statement and a fall impression is impression.

Interactions within information environments and their internal developments, etc.;

Information life cycles, from initial occurrence to final utilization and possible disappearance; and

Computation, both in the Turing-machine sense of algorithmic processing, and in the wider sense of information processing. “ (Floridi, 2002)

Logical dynamics of information
Johan van Benthem

- A recent study of information dynamics within a framework of logic is presented in Van Benthem’s book Logical Dynamics of Information and Interaction, developed as a theory of information-driven rational agency and intelligent interaction between information-processing agents.

- Van Benthem connects logic, philosophy, computer science, linguistics and game theory in a unified mathematical theory which provides dynamic logics for inference, observation and communication, with update of knowledge and revision of beliefs, changing of preferences and goals, group action and strategic interaction in games.

Emergent information
Wolfgang Hofkirchner

- Informational dynamics may be characterized as processes of self-organization. Whenever self-organizing systems relate to the environment, they create/generate information, called “emergent information”.

- The information generation is consisting of cognition (information generation of a self-organizing system vis-à-vis its environment); communication (the coupling of cognitive processes of at least two self-organizing systems) and cooperation. Cooperation feeds back to communication as communication does to cognition. That’s the basic dynamics of emergent information.

Three forms of information
Terrence Deacon

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

Deacon’s three types of information parallel his three
*formative mechanisms*:

- [Mass-energetic [Self-organization [Self-preservation
  (semiotic)]]]
- *Emergent dynamics*: [Thermo- [Morpho- [Teleo-dynamics]]]
- Corresponding *Aristotle’s causes*: [Efficient cause [formal
  cause [final cause]]].
Levels of Description – Levels of Abstraction – Levels of Organization

Levels of Organization

- Universe
  - Galaxy
  - Solar Systems
  - Earth
  - Biosphere
  - Biomes
  - Ecosystems
    - Communities
    - Populations
    - Organisms
      - Organs
      - Tissues
      - Cells
      - Protoplasm
    - Molecules
  - Atoms

Ecology

- Data
  - Information
  - Knowledge
  - Wisdom

Functional
- Executable Specifications
- Architectural
- Implementation
  - Embedded Software
  - Electronics
  - Multi-Physics
A complex system is a system composed of interconnected parts that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts.

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

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

http://en.wikipedia.org/wiki/Complex_system
In a complex system, what we see is dependent on where we are and what sort of interaction is used to study the system. (observer dependence)

Study of complex systems:

**Generative Models**

How does the complexity arise?

Evolution is the most well known generative mechanism.

Complexity generated from simple elements with simple rules (CA)

Network models of complex systems

Protein network in yeast cells

Human protein interaction network

Human connectome

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

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

Information and computation are closely related – no computation without information, and no information without computation (dynamics).
Beyond Conventional Computing
Machinery: Natural Computing

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

Cognition as processing of information

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

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

Biophysics of Computation: Information Processing in Single Neurons
What is Cognition?

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

Technological Application: Cognitive Network Technology

**Learn**
- associate environment and configuration with experienced performance

**Observe**
- take measurements from environment

**Act**
- configure system
- experience performance for new configuration

**Orient**
- infer environment from measurements
- predict performance for possible configurations

**Decide**
- identify configuration which provides best performance

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

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

- Naturalized epistemology (Feldman, Kornblith, Stich) is, in general, an idea that knowledge may be studied as a natural phenomenon -- that the subject matter of epistemology is not our concept of knowledge, but the knowledge itself.

- 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 computing?
Why not settle for computing when modeling knowledge?

In this framework knowledge is seen as a result of the structuring of input data:

\[
data \rightarrow \text{information} \rightarrow \text{knowledge}
\]

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

Hebbian learning

Naturalist understanding of cognition

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

See also: Dodig-Crnkovic, G. Where do New Ideas Come From? How do they Emerge? Epistemology as Computation (Information Processing) in Randomness & Complexity, from Leibniz to Chaitin, C. Calude ed. 2007
Cognition as re-structuring an agent through interaction with the environment

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

Natural computation opens possibilities to implement embodied cognition into artificial agents, and perform experiments on simulated eco-systems.
Digital vs. analog, discrete vs. continuous and symbolic vs. sub symbolic information

- “Symbolic simulation is thus a two-stage affair: first the mapping of inference structure of the theory onto hardware states which defines symbolic computation; second, the mapping of inference structure of the theory onto hardware states which (under appropriate conditions) qualifies the processing as a symbolic simulation.

- Analog simulation, in contrast, is defined by a single mapping from causal relations among elements of the simulation to causal relations among elements of the simulated phenomenon.”

Symbolic vs. sub-symbolic computation (information processing)

Douglas Hofstadter in his dialogue “Prelude…Ant fugue” in Godel, Escher, Bach.
Info-computationalism, in a nutshell

- Nature can be described as a complex informational structure for a cognizing agent.

- Computation is information dynamics (information processing)

- Computation is constrained and governed by the laws of physics on the fundamental level (morphology).
Morphogenetic/morphological computing. From raw data to semantic information

- Turing proposed diffusion-reaction model of morphogenesis as the explanation of the development of biological patterns (spots and stripes on animal skin).

- Morphogenesis is a process of morphological computing. Physical process – though not computational in the traditional sense, presents natural (unconventional), morphological computation. Essential element in this process is the interplay between the informational structure and the computational process - information self-structuring and information integration, both synchronic and diachronic, going on in different time and space scales in physical bodies.
Morphogenetic/morphological computing. From raw data to semantic information

- Info-computational naturalism describes nature as informational structure – a succession of levels of organization of information.

- Morphological computing on that informational structure leads to new informational structures via processes of self-organization of information.

- Evolution itself is a process of morphological computation on a long-term scale.
Ehresmann proposes a mathematical approach to the framework developed by Dodig-Crnkovic. Based on the Property of natural computation, called the multiplicity principle development of increasingly complex cognitive processes and knowledge is described. “Local dynamics are classically computable, a consequence of the MP is that the global dynamics is not, thus raising the problem of developing more elaborate computation models.”
The model, based on a ‘dynamic’ Category Theory, accounting for the functioning of the neural, cognitive and mental systems at different levels of description and across different timescales.
Conclusions

Topics of importance for the development of new understanding of computation as the dynamic of information and its role in the physical world:

- Natural computation as generalized model of computation (*natural information processing*)
- *Interactivity* as fundamental for computational modelling of concurrent distributed information processing systems such as living organisms and their networks
- It will be instructive to study processes of self organization of information in physical agents (and their networks) able to re-structure themselves through interactions with the environment as a result of morphological/morphogenetic computation.
“(O)ur task is nothing less than to discover a new, broader, notion of computation, and to understand the world around us in terms of information processing.”


In preparation: Information Journal, Special Issue "Physics of Information" , Hector Zenil and Gordana Dodig-Crnkovic, guest editors
A Computable Universe
Computation, Information, Cognition
Editor(s): Gordana Dodig Crnkovic and Susan Stuart, Cambridge Scholars Publishing, 2007

Information and Computation
Editor(s): Gordana Dodig Crnkovic and Mark Burgin, World Scientific, 2011
http://dx.doi.org/10.1007/978-3-642-37225-4

Computing Nature
Editor(s): Gordana Dodig Crnkovic and Raffaela Giovagnoli, Springer, 2013
p. 50
Based on the Articles
