Department of Computer Engineering
and Industrial Automation

School of Electrical and
Computer Engineering

Unicamp

Natural Computing: A Panoramic View

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DCA/FEEC/Unicamp

IA013 – Introduction to Natural Computing

Campinas, SP, Brazil

Overview of the presentation

1. The natural world, the artificial world, and their intersections;
2. The power of computer simulation;
3. Epistemological issues to be addressed;
4. A taxonomy of natural computing;
5. Nature-inspired computation;
6. Nature-inspired computation: case studies;
7. Nature as computation;
8. Outlining an attainable future.

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Natural x Artificial

- **An anthropocentric definition:**
- **Natural: any part of the physical world which is not a product of intentional human design.**
- **Artificial: product of intentional human design.**

The natural world

The natural world

The natural world

The artificial world

The artificial world

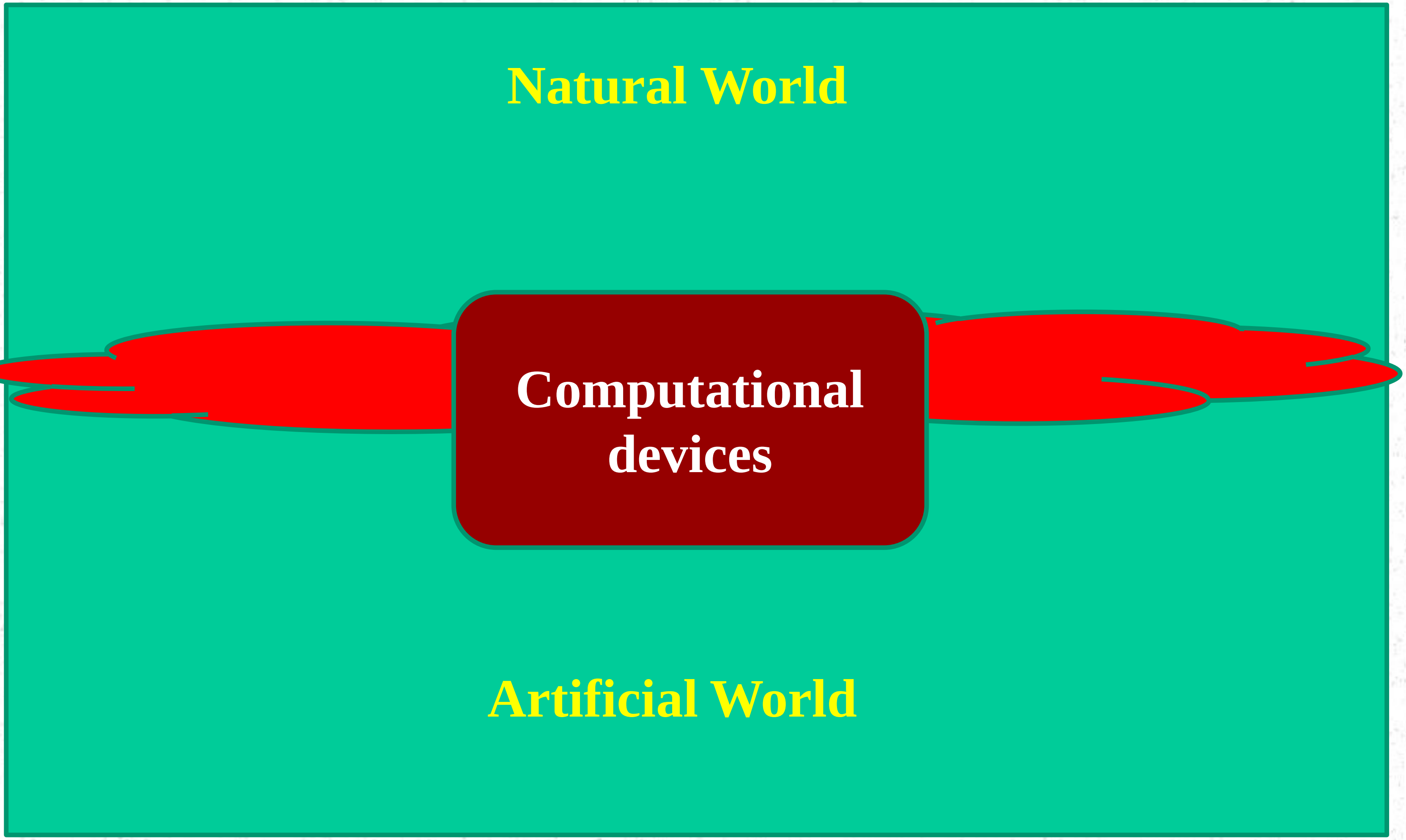
Their intersections

Their intersections

Their intersections

The Palm Islands, Dubai

Computational devices



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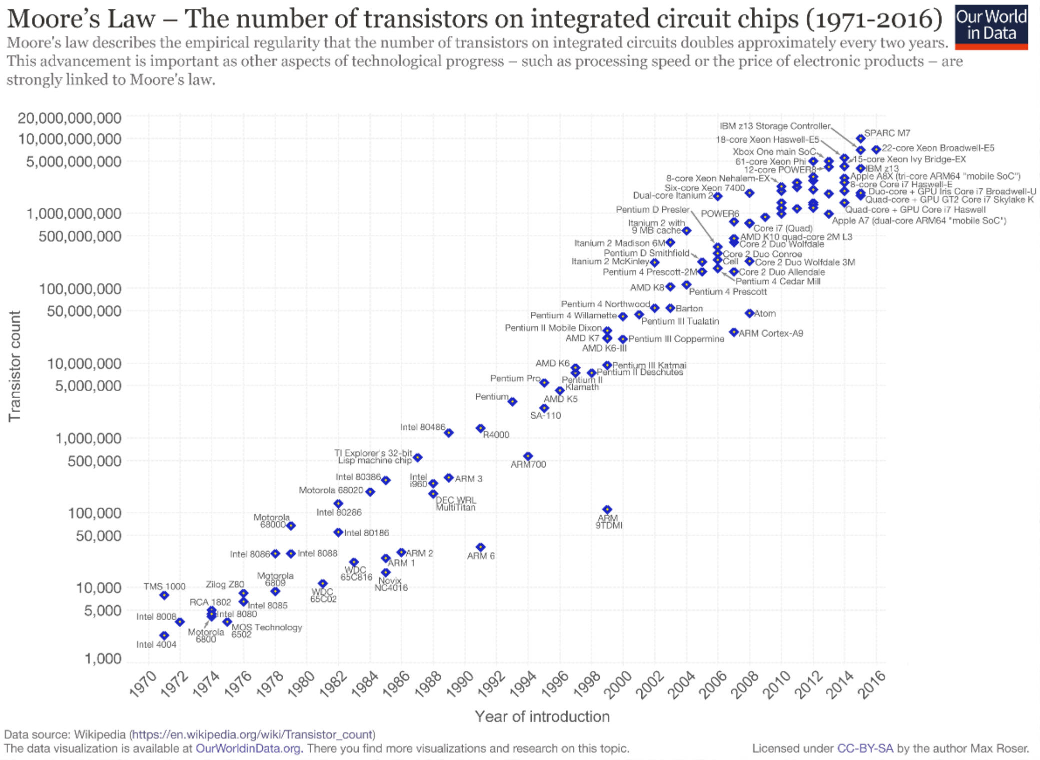
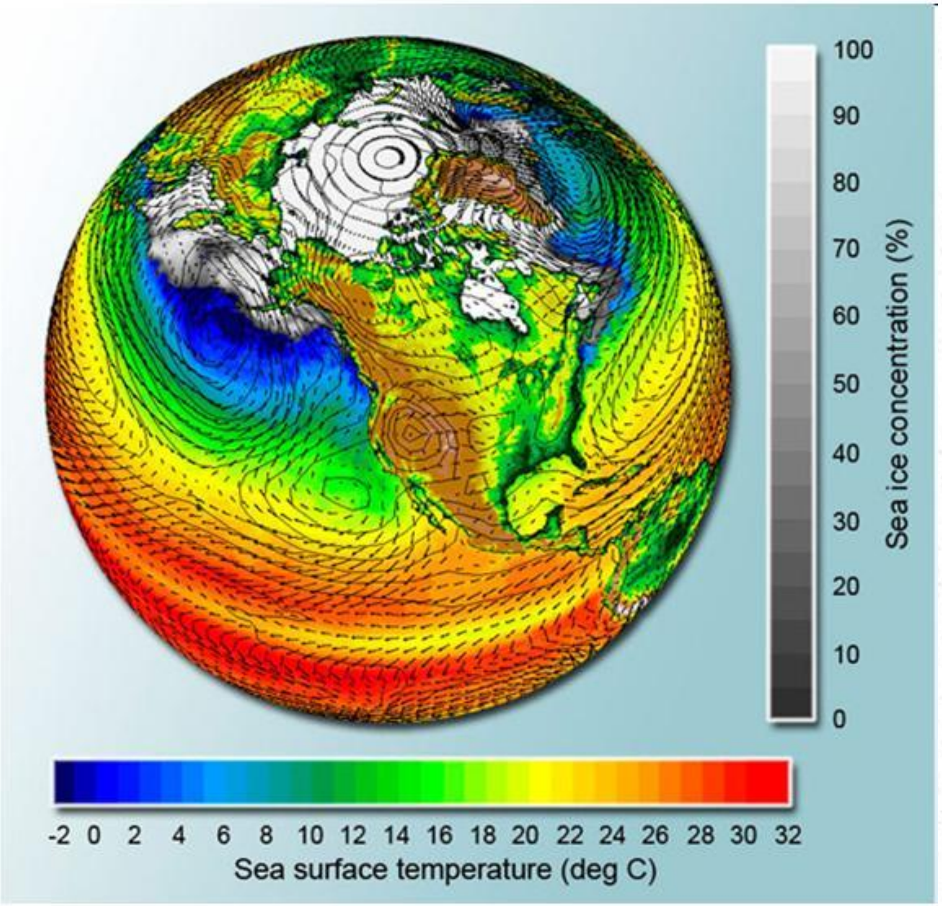
The power of computer simulation

- Digital computers are general purpose machines.
- The Moore's law:



Matrioshka – Russian doll

The power of computer simulation



Roy Spencer, former NASA scientist

The power of computer simulation

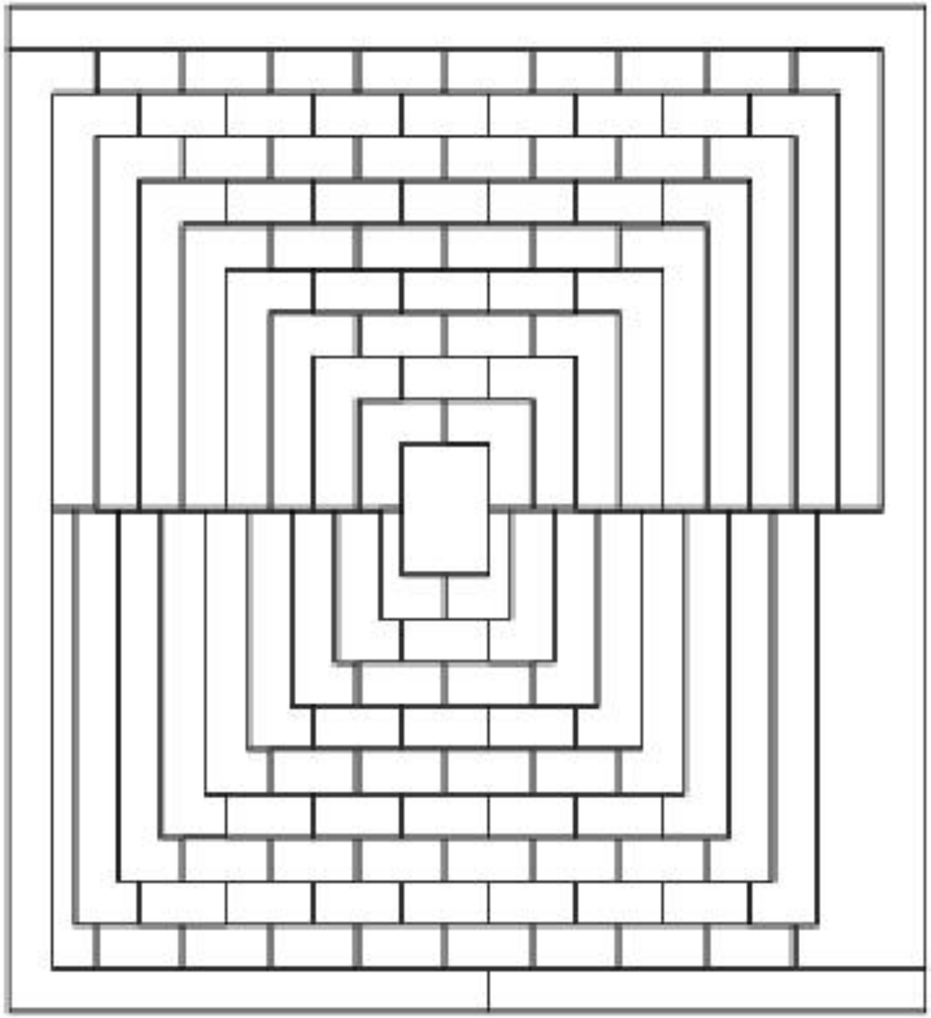
Artificial Terrain Generation
[vterrain.org – Virtual Terrain Project]

Computer Graphics & Visualization Group
Technische Universität München

The four color map theorem

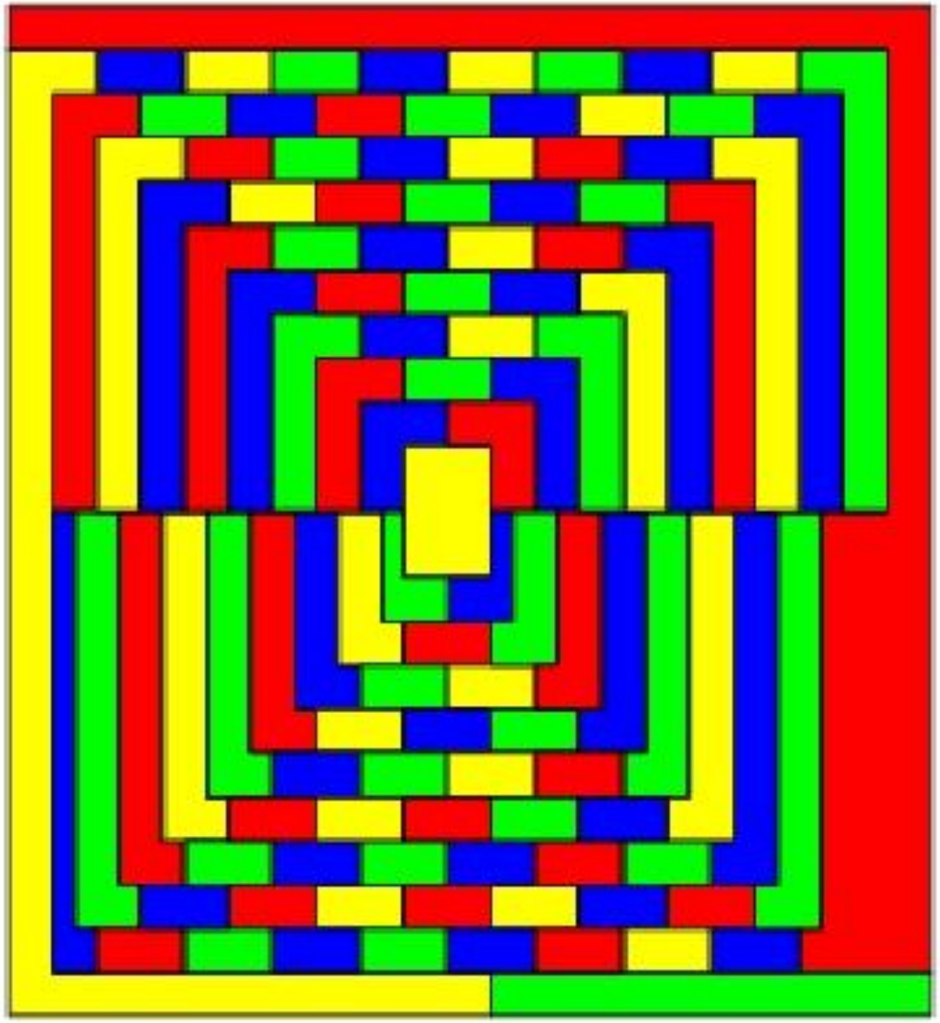
- Given any separation of a plane into contiguous regions, producing a figure called a map, no more than four colors are required to color the regions of the map so that no two adjacent regions have the same color.

The four color map theorem



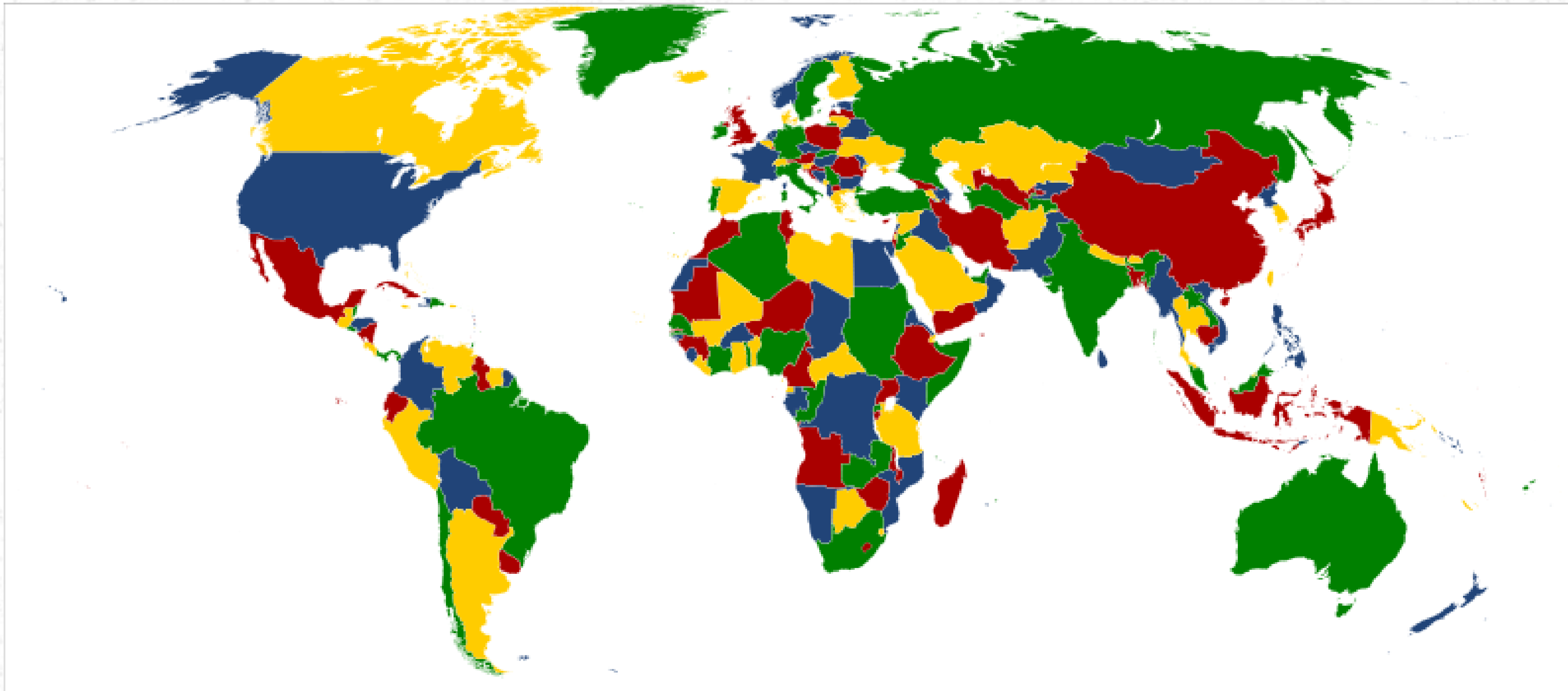
Source: Wikipedia

The four color map theorem



Source: Wikipedia

The four color map theorem



Source: Wikipedia

The four color map theorem

- The four color theorem was proven in 1976 by Kenneth Appel and Wolfgang Haken. It was the first major theorem to be proved using a computer.
- Until now, there is no demonstration of the theorem that does not use a computer.

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Epistemological issues to be addressed

- **A computer simulation can be used as a source of new knowledge?**
- **A computer simulation can tell us something that is not known?**
- **Notice that:**
  - **A simulation is no better than the assumptions built into it;**
  - **A computer can do only what it is programmed to do.**

Epistemological issues to be addressed

- Yes, definitely yes.

It is predominantly supported by the fact that even with full control over the premises, it can be very difficult to find out what they entail.

Herbert Simon (1916-2001)

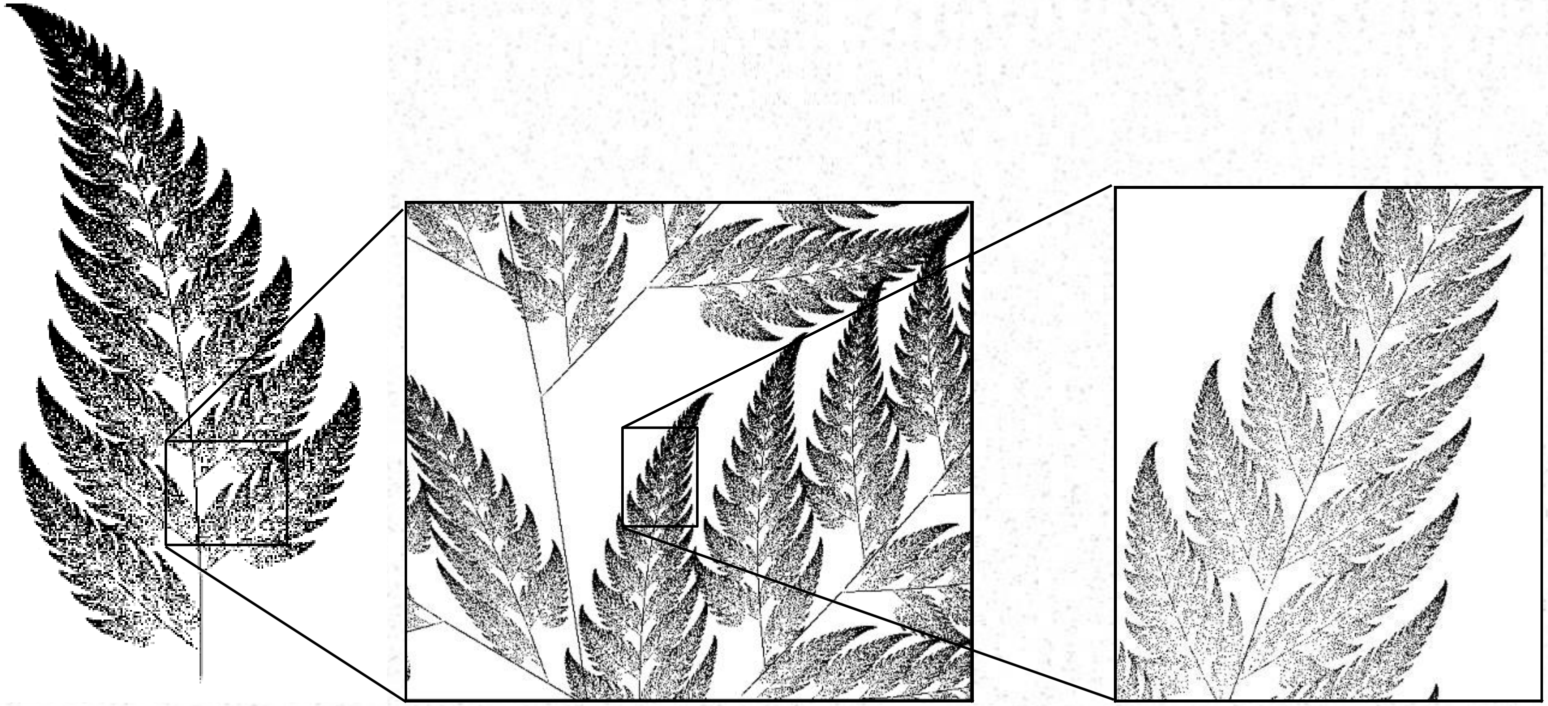
Simulation and Reality

Roger Penrose
(1931 -)

- **"In reasonably favourable circumstances, computer simulations can lead to hugely impressive imitations of reality, and the resulting visual representations may be almost indistinguishable from the real thing."**

Emulation of natural phenomena

Iterative function systems

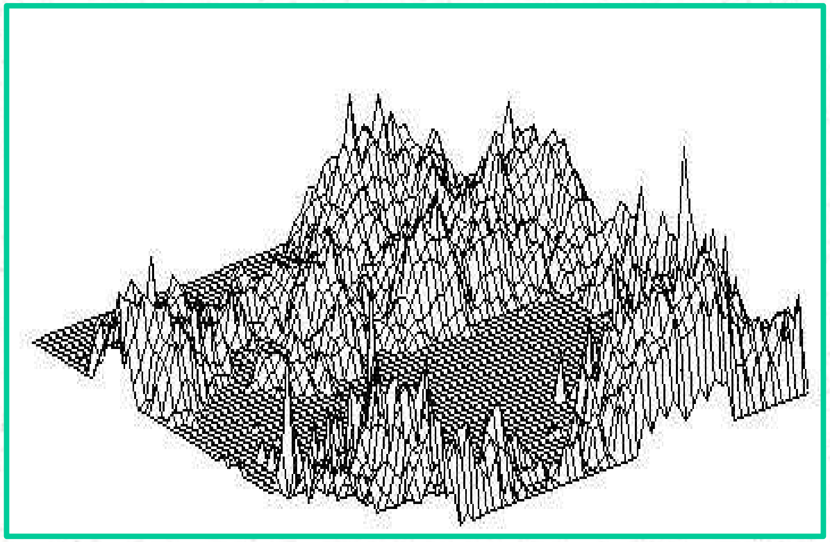


Emulation of natural phenomena

Lindenmayer systems

Emulation of natural phenomena

Brownian motion



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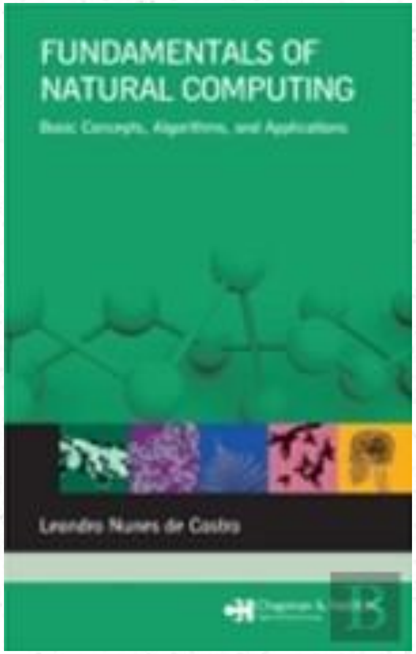
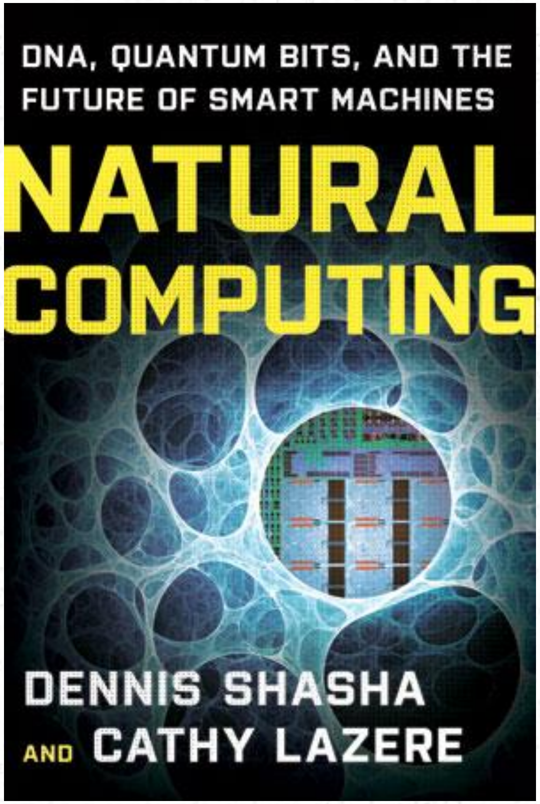
Natural computing



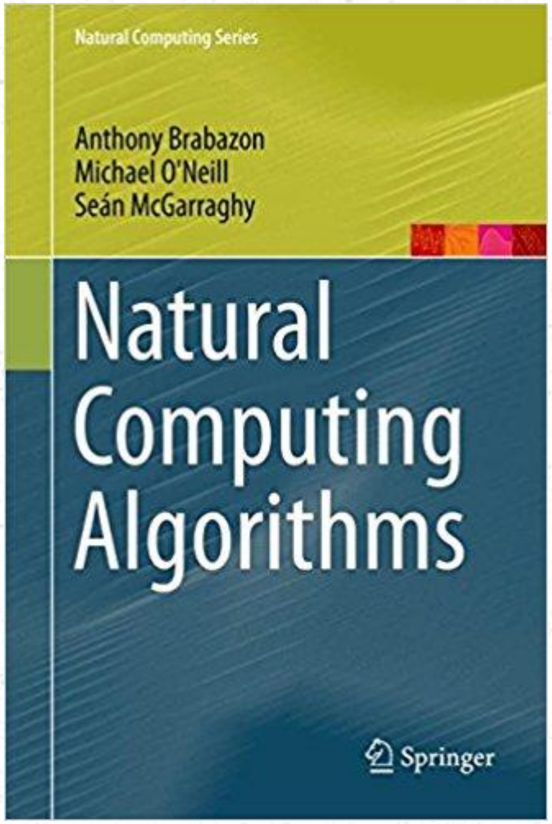
- de Castro, L. N. (2006) *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*, Chapman & Hall/CRC.
- de Castro, L. N. (2010) *Computação Natural – Uma Jornada Ilustrada*, Editora Livraria da Física.

Natural computing



- Shasha, D. & Lazere, C. "Natural Computing: DNA, Quantum Bits, and the Future of Smart Machines", W. W. Norton & Company, 2010.

Natural computing



Brabazon, A.; O'Neill, M. & McGarraghy, S. "Natural Computing Algorithms", Springer, 2015.

Natural computing

- Further readings:

  - de Castro, L. N. “Fundamentals of natural computing: An overview”, Physics of Life Reviews, vol. 4, no. 1, pp. 1–36, 2007.

  - Johnson, C. “Teaching natural computation”, IEEE Computational Intelligence Magazine, vol. 4, no. 1, pp. 24–30, 2009.

  - Kari, L. & Rozenberg, G. “The many facets of natural computing”, Communications of the ACM, vol. 51, pp. 72–83, 2008.

  - Rozenberg, G.; Bäck, T. & Kok, J. N. (Eds.) “Handbook of Natural Computing”, Springer, 2012.

Natural computing

- Journals:
  - Natural Computing

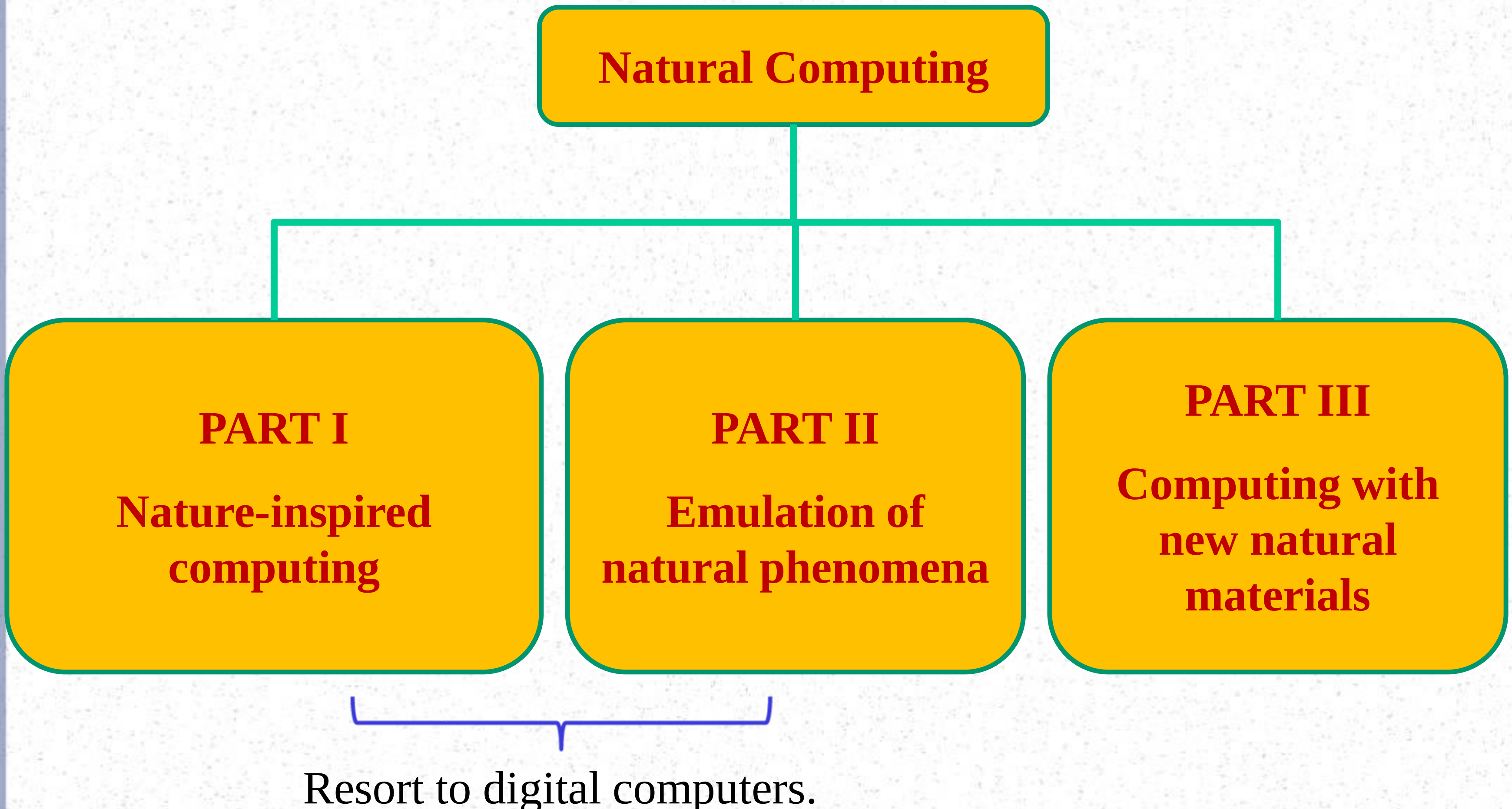
  - International Journal of Natural Computing Research

Natural computing

- Natural computing is a terminology introduced to encompass three classes of methods:

1. Those that take inspiration from nature for the development of novel problem-solving techniques;
2. Those that are based on the use of computers to emulate natural phenomena; and
3. Those that employ natural materials (e.g., molecules) to compute.

Natural computing



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Why to search inspiration on Nature?

- **Nature as a source of useful metaphors for Computer Engineering: What makes a natural process a valid inspiration in the synthesis of a new and well-succeeded algorithm?**

- **When an algorithm can be qualified as being nature-inspired?**

Degree of inspiration

- **Strong inspiration: Nature as an immediate solution tool.**
- **Weak inspiration: Nature as a metaphor and as a source of creativity.**
- **Nature-inspired algorithms can often be traced to the use of computer simulations to investigate Nature.**

Nature-inspired algorithms

- Generally conceived from interdisciplinary partnerships;
- Usually classified as heuristics or meta-heuristics;
- Have become popular over the last 50 years because they are able to provide high performance solutions to problems that can not be solved by exact or dedicated algorithms.

When a problem is hard to solve?

- **When the problem is NP-hard and we are looking for the solution of medium to large-size instances;**
- **When the problem has been formulated recently and so there was not enough time to develop a dedicated solution, exploiting its peculiarities.**

Source of inspiration no. 1

- Theory of evolution by natural selection:
  - The exploratory power of (1) reproduction with inheritance, (2) mutation, and (3) selection;
  - Natural selection is the key to the existence of all the biological problem-solving mechanisms we find in Nature.

Source of inspiration no. 1

Theodosius Dobzhansky

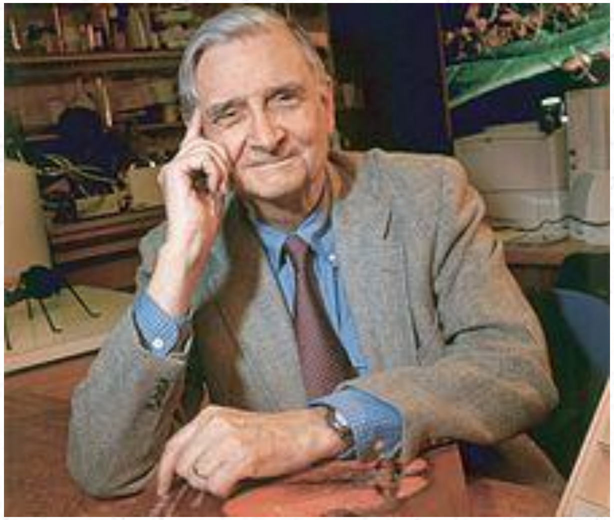
- **Dobzhansky, T. 1973. "Nothing in biology makes sense except in the light of evolution" The American Biology Teacher 35: (March): 125-129.**

Source of inspiration no. 1

- How to measure the success of a living organism?
- Should we do that by the longevity of the individual?
- Should we do that by the longevity of the species?
- Should we do that by the longevity of the gene?
- Or should we do that by the efficiency of energy usage?

Source of inspiration no. 1

Edward Osborne Wilson



- **The hallmark of life is this: a struggle among an immense variety of organisms weighting next to nothing for a vanishingly small amount of energy.**

Source of inspiration no. 2

- **Complexity and emergence**
  - **Emergence behavior is the appearance of some high level function as a result of the interactions of some collection of independent elements.**

El-Hani, C.N. & Emmeche, C. "On some theoretical grounds for an organism-centered biology: Property emergence, supervenience, and downward causation", Theory in Biosciences, vol. 119, nos. 3-4, pp. 234-275, 2000.

Source of inspiration no. 2

- Main purpose: to develop algorithms which are relatively simple to code, yet capable of achieving complex emergent behavior.
- Collective intelligence: the structure of networks of contacts between agents affects group performance in problem-solving situations.

Godoy, A. & Von Zuben, F.J. "Topology of social networks and efficiency of collective intelligence methods", Proceeding of the Fifteenth Annual Conference on Genetic and Evolutionary Computation Conference Companion, pp. 1415-1422, 2013.

Source of inspiration no. 3

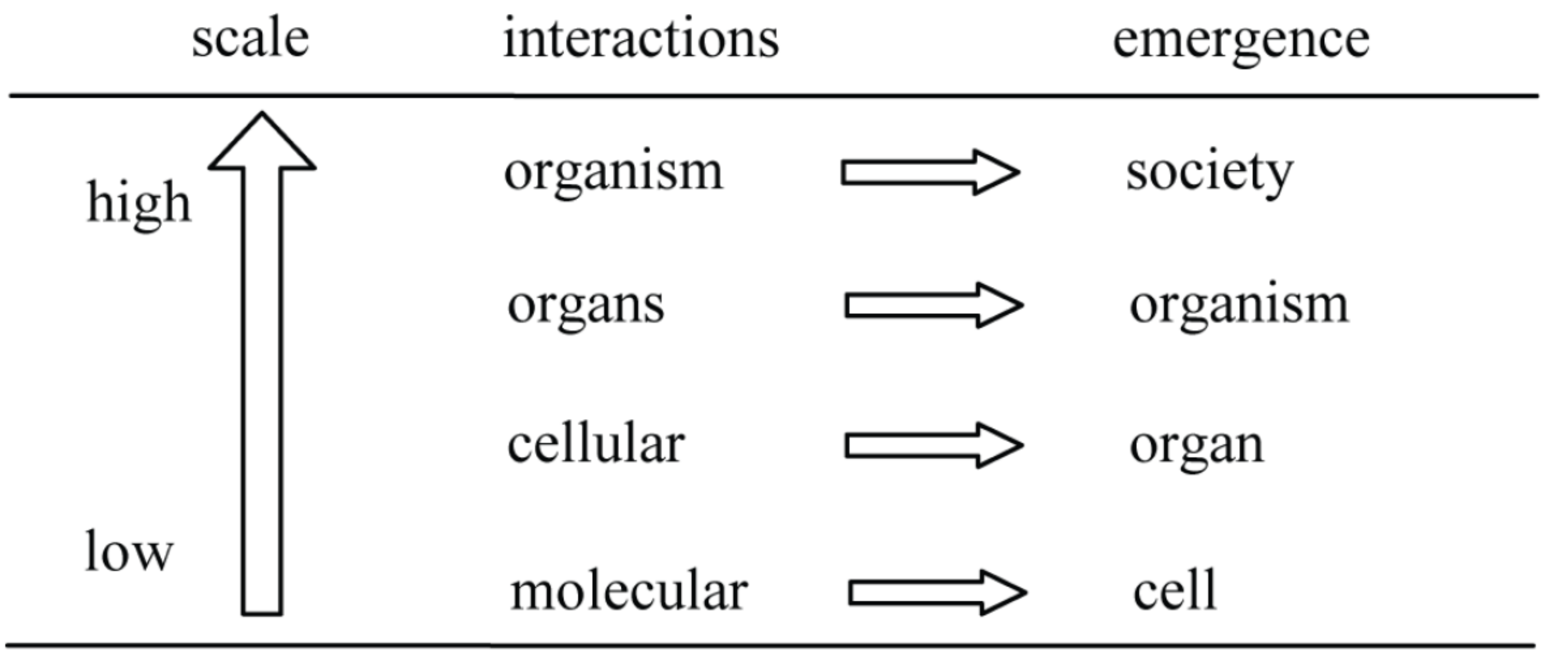
- Spatio-temporal phenomena
  - nonlinear dynamical systems with spatially distributed degrees of freedom
  - Lattices or networks of large number of dynamical systems
  - Two ingredientes: local dynamics + interactions.

Source of inspiration no. 3

- Ecosystems are highly complex and dynamic environments composed of a high number of interdependent variables defined in space and time.
- Biogeographic Computation (BC) is a research field in the realm of Natural Computing aimed at understanding ecosystems computing.

Pasti, R., de Castro, L.N. & Von Zuben, F.J. “Ecosystems Computing: Introduction to Biogeographic Computation”, International Journal of Natural Computing Research, vol. 2, no. 4, pp. 47-67, 2011.

Source of inspiration no. 3



Cohen, I.R. & Harel, D. “Explaining a complex living system: Dynamics, multi-scaling and emergence”, Journal of the Royal Society Interface, vol. 4, no. 13, pp. 175–182, 2007.

Biogeographic computation

- Keywords:
  - Adaptation
  - Speciation
  - Geographical processes (e.g. dispersion, isolation)
  - Ecological processes
  - Evolutionary processes
- Computer simulation:
  - Artificial ecosystems
  - Diversity maintenance
  - Automatic control of the number of species (sub-populations)

Source of inspiration no. 4

- **Organic computing**
  - **Computer systems are being characterized by ever-growing complexity and a pronounced distributed organization.**
  - **So, it is necessary to develop decentralized architectures and efficient management.**
  - **The goal of organic computing is to develop new concepts and tools to manage such systems, looking for adaptability, self-organization (and other self-x properties), and manageability.**

Müller-Schloer, C.; Schmeck, H. & Ungerer, T. (Eds.) "Organic computing: a paradigm shift for complex systems", Springer, 2011.

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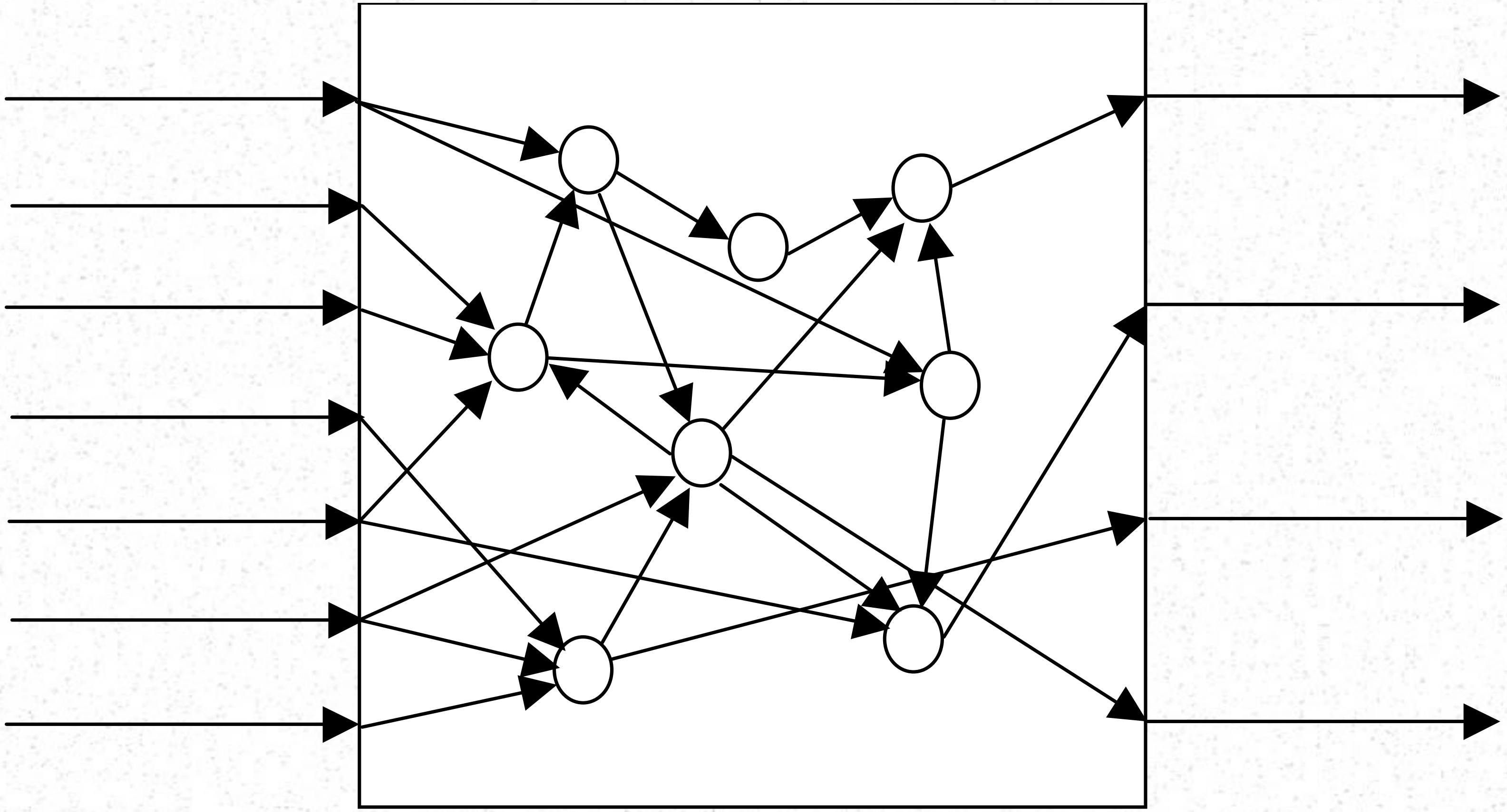
Nature-inspired computation

- In the next slides, we will see some examples of learning and optimization algorithms inspired by natural phenomena.
- It will be very easy to capture the similarities between the events in nature and the corresponding events in the virtual world of a computer simulation.
- Besides, it will be possible to perceive that the same problem can be solved employing completely distinct paradigms.

Case Study 1

Artificial neural networks



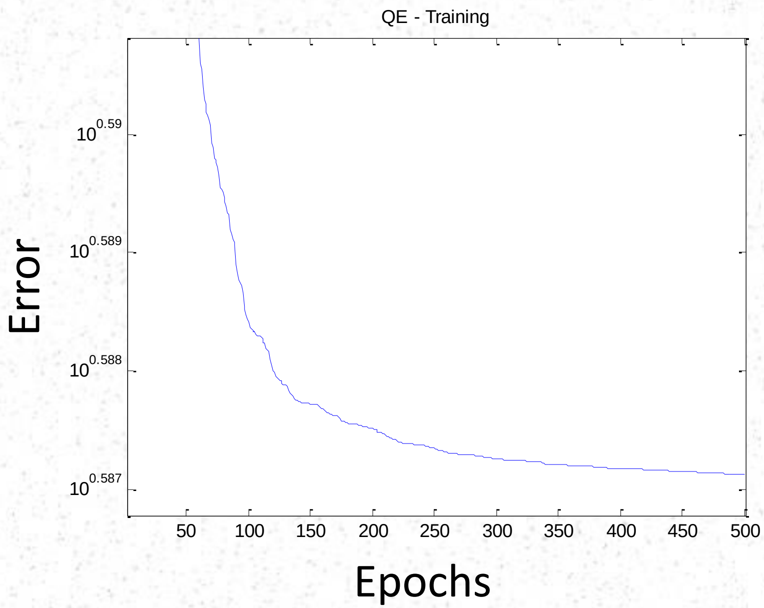
Pictorial view of a neurocomputer

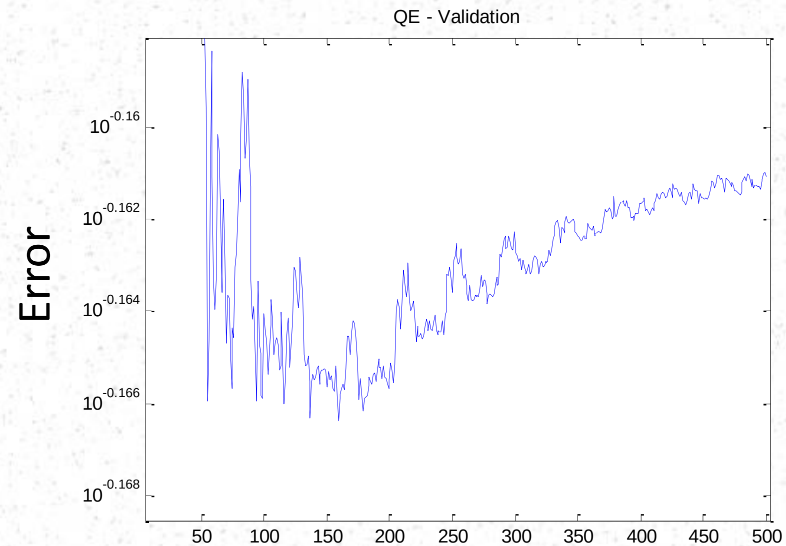
Artificial neural networks

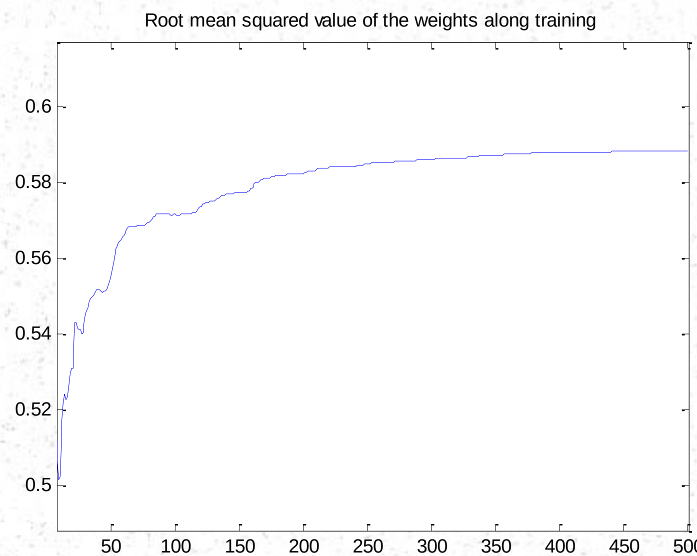
- Multidimensional mapping (supervised learning)
- Self-organization (unsupervised learning)
- Nonlinear dynamics

Artificial neural networks

Learning from data







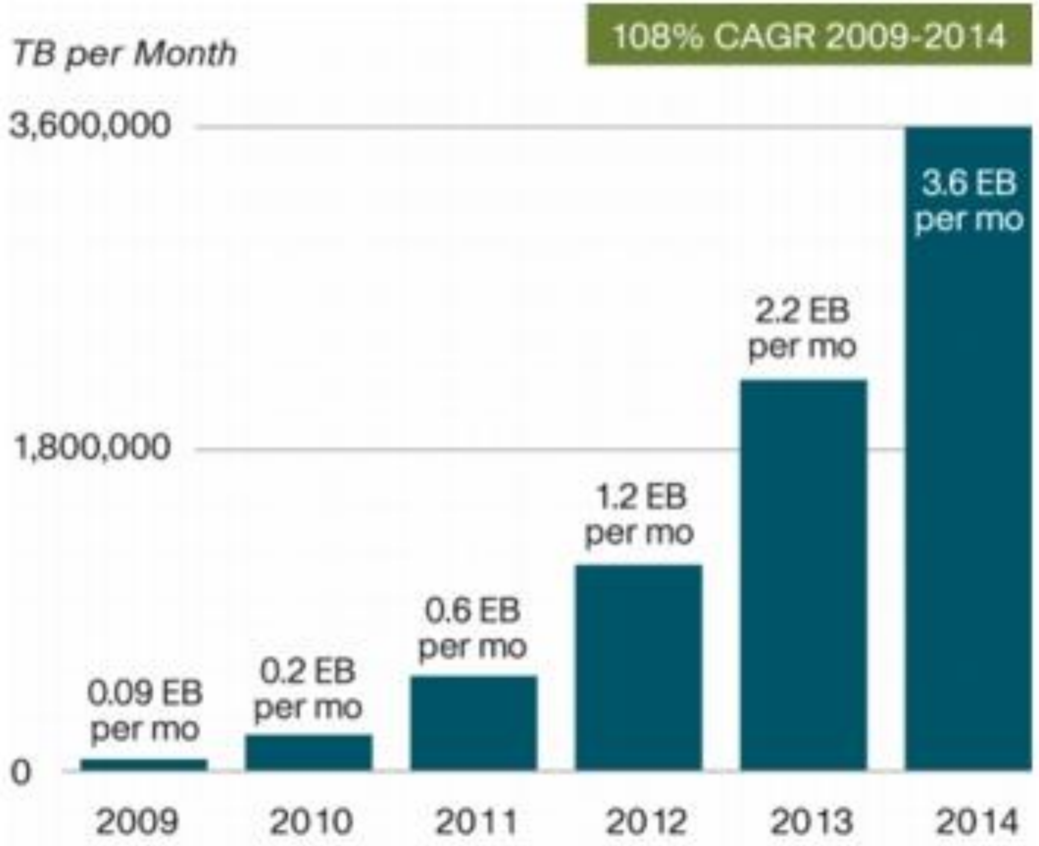
Why should machines have to learn?

- Alternative question:

Why not design machines to perform as desired in the first place?

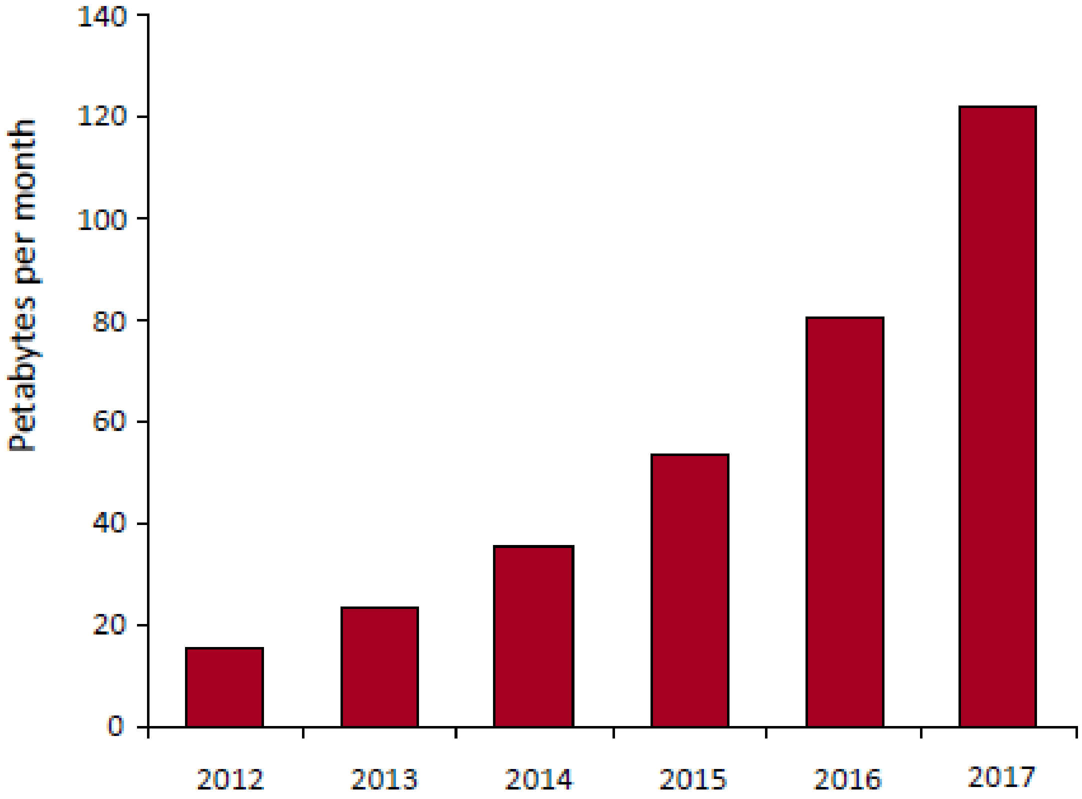
1. Learning from data: Some tasks cannot be defined well except by example; that is, we might be able to specify input/output pairs but not a concise relationship between inputs and desired outputs.
2. Data mining: Hidden among large piles of data may be present important relationships and correlations.

Learning from Data



Source: Cisco VNI Mobile, 2010

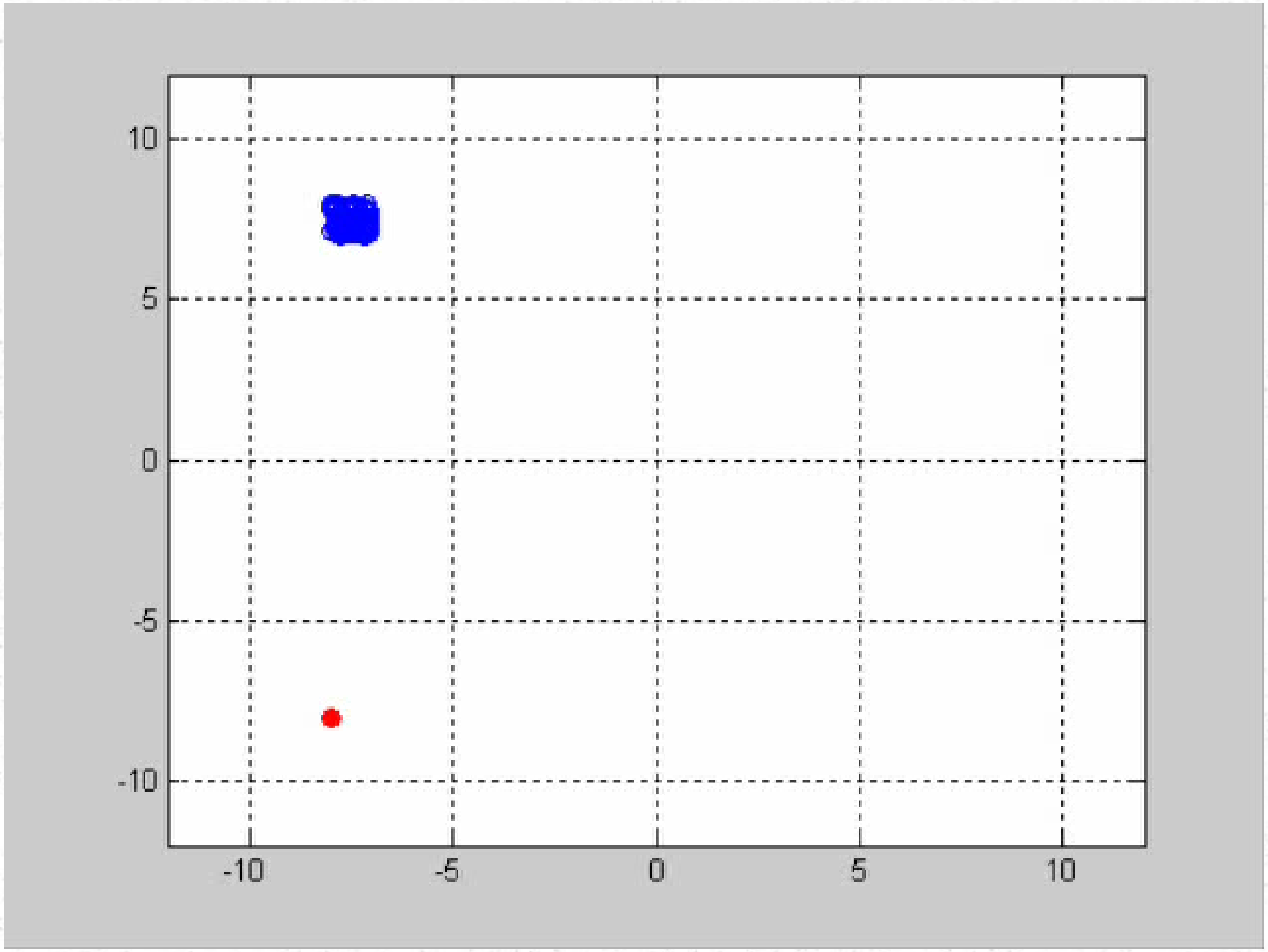
Learning from Data



Forecast Mobile Data Traffic Growth in Canada
http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf09444.html

Case Study 2

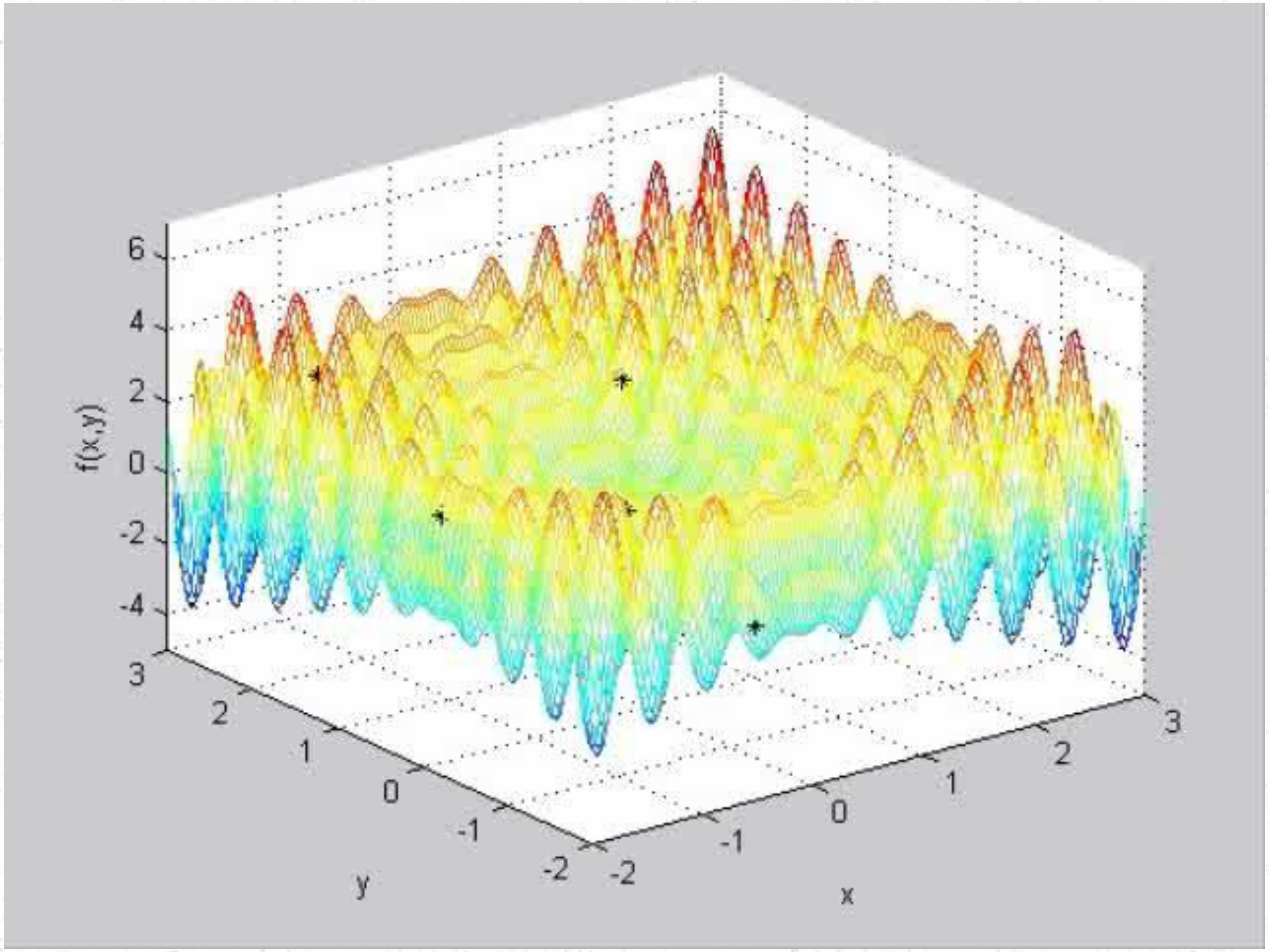
Particle swarm optimization



There is a video associated with this slide.

Case Study 3

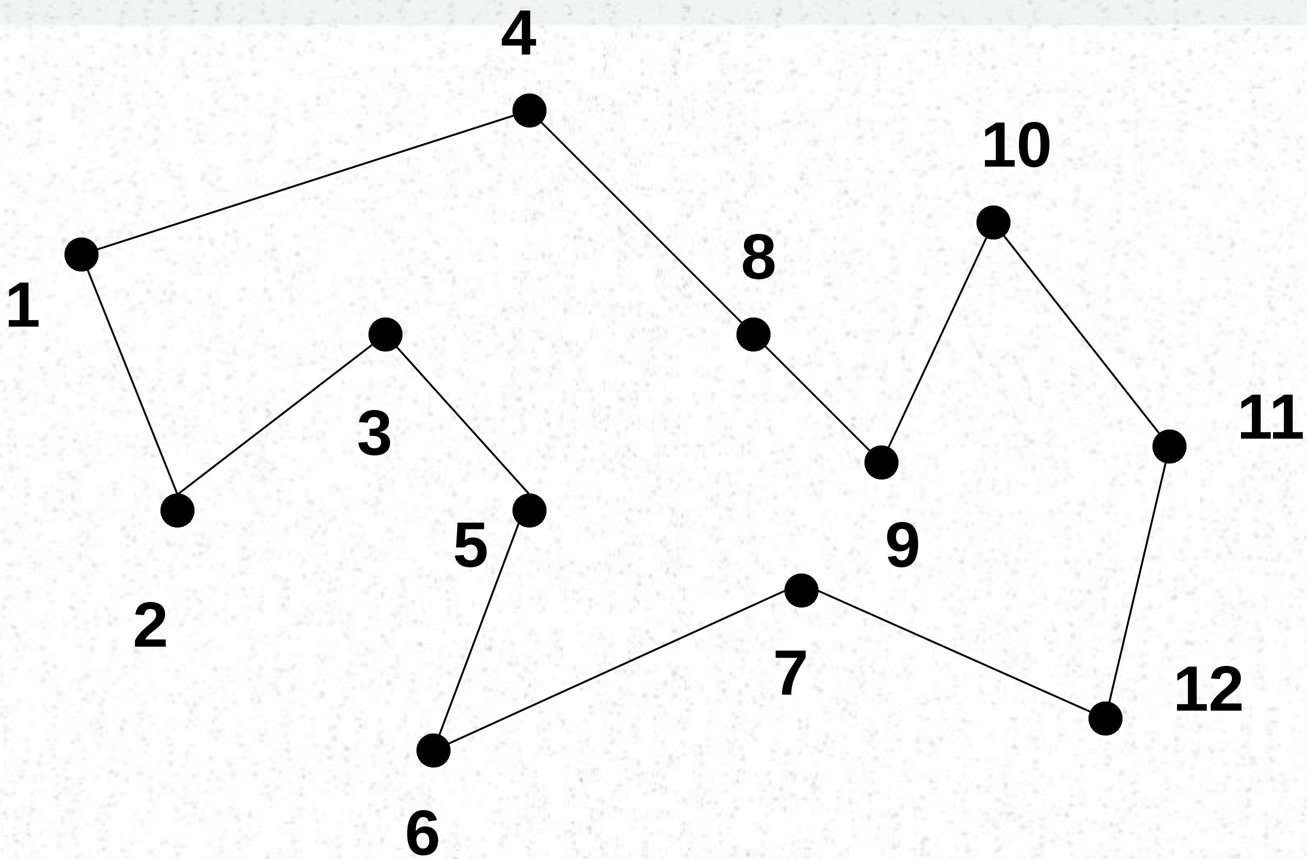
Artificial immune network for continuous optimization



There is a video associated with this slide.

Case Study 4

The Travelling Salesperson Problem



Each candidate solution is a permutation

1 2 3 5 6 7 12 11 10 9 8 4

The Travelling Salesperson Problem

- Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?
- The only known exact algorithm asks for testing all the permutations, looking for the one with the shortest path. $\rightarrow$ Exhaustive search

The Travelling Salesperson Problem

- It is an NP-hard problem in combinatorial optimization.
- Being *N* the number of cities, the cardinality of the search space is given by:

$$\frac{(N-1)!}{2}$$

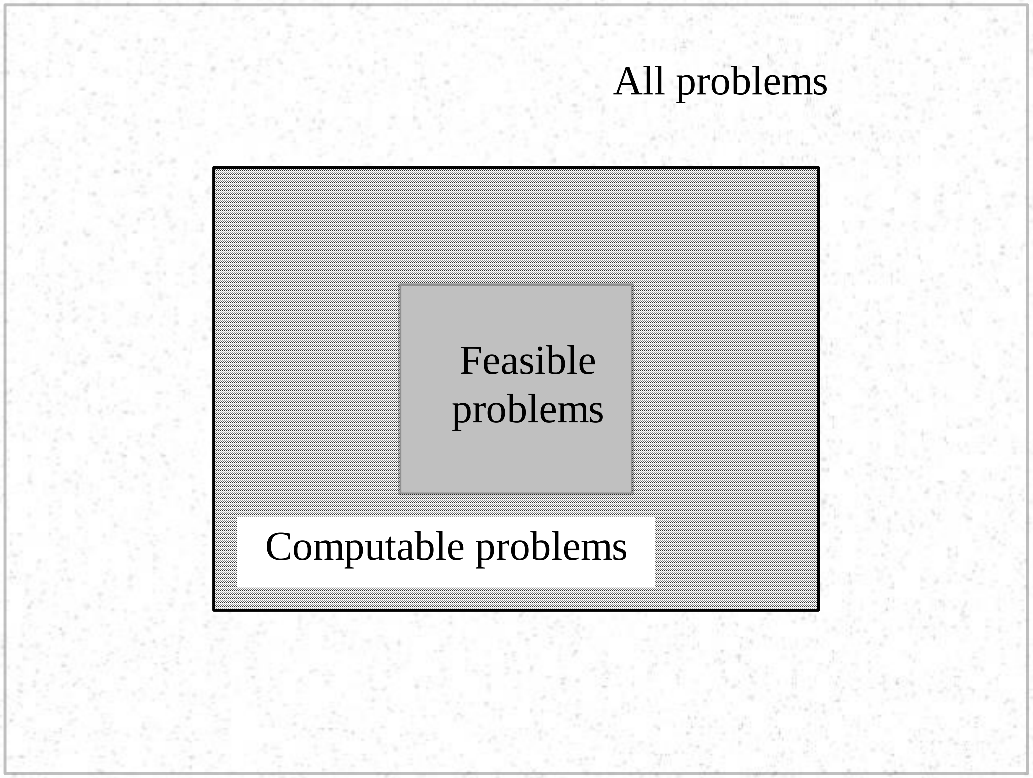
The Travelling Salesperson Problem

- Problem with 8 cities:
- (8-1)!/2 = 2520 possibilities → Easy to solve!

- Problem with com 20 cities:
- (20-1)!/2 = 60,822,550,204,416,000 possibilities → Not so easy!

- Typical problem with 100 cities:
- (100–1)!/2 = 4.5×10^{155} possibilities!!!
- 1.5×10^{135} years of processing in a 10THz machine;
- Estimated age of the universe = 13.7×10^{9} years.

The Travelling Salesperson Problem



The TSP is fully characterized as a problem in the hatched area.

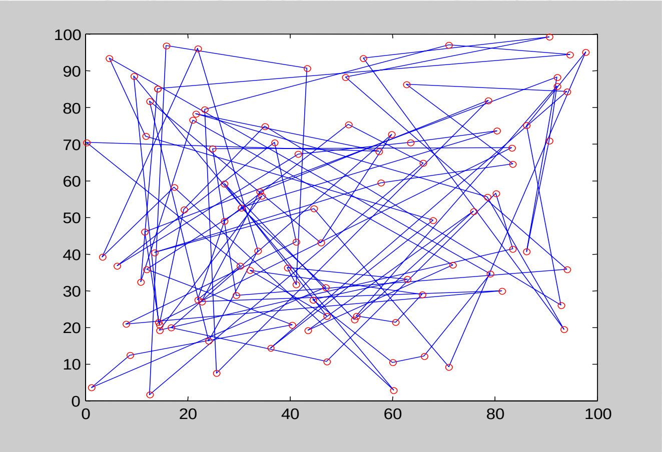
The Travelling Salesperson Problem

- Warning:
  - The TSP is certainly not the best example of a problem to be treated by natural computation.
  - Given a heuristics to solve TSP, you can visualize its pros and cons.
  - Researchers have had enough time to improve heuristics to solve TSP, looking at specificities of the problem and not (solely) at natural inspiration.

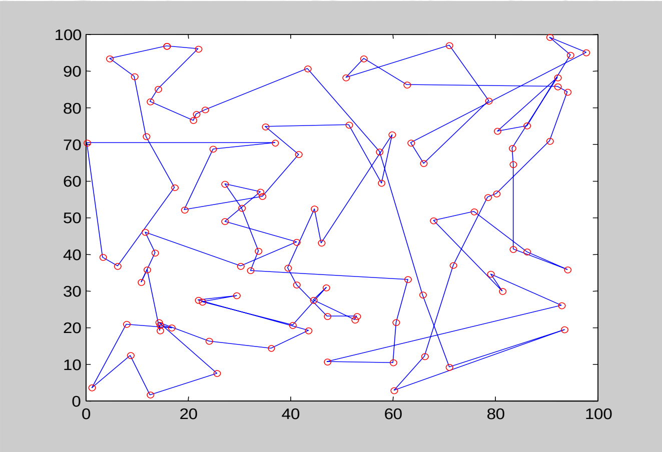
Case Study 4.1

The Travelling Salesperson Problem – Option no. 1

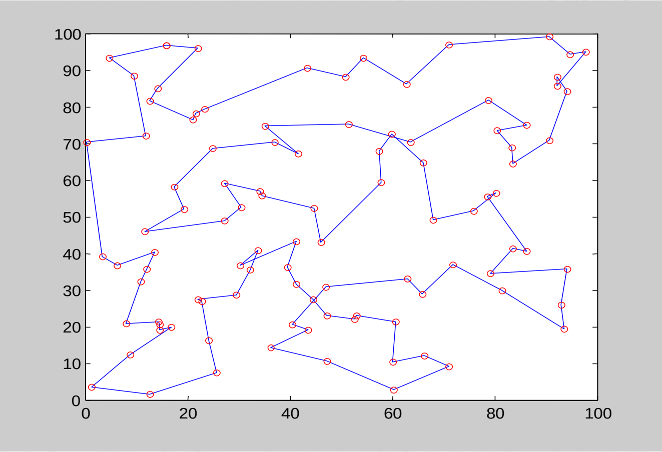
Best individual at the initial population



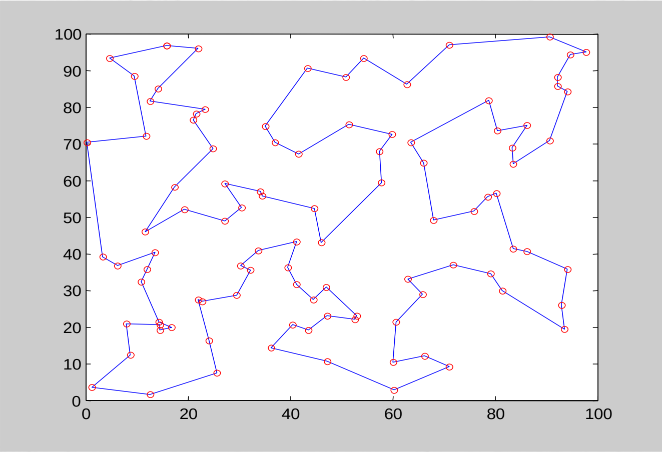
Best individual after 500 generations



Best individual after 2000 generations

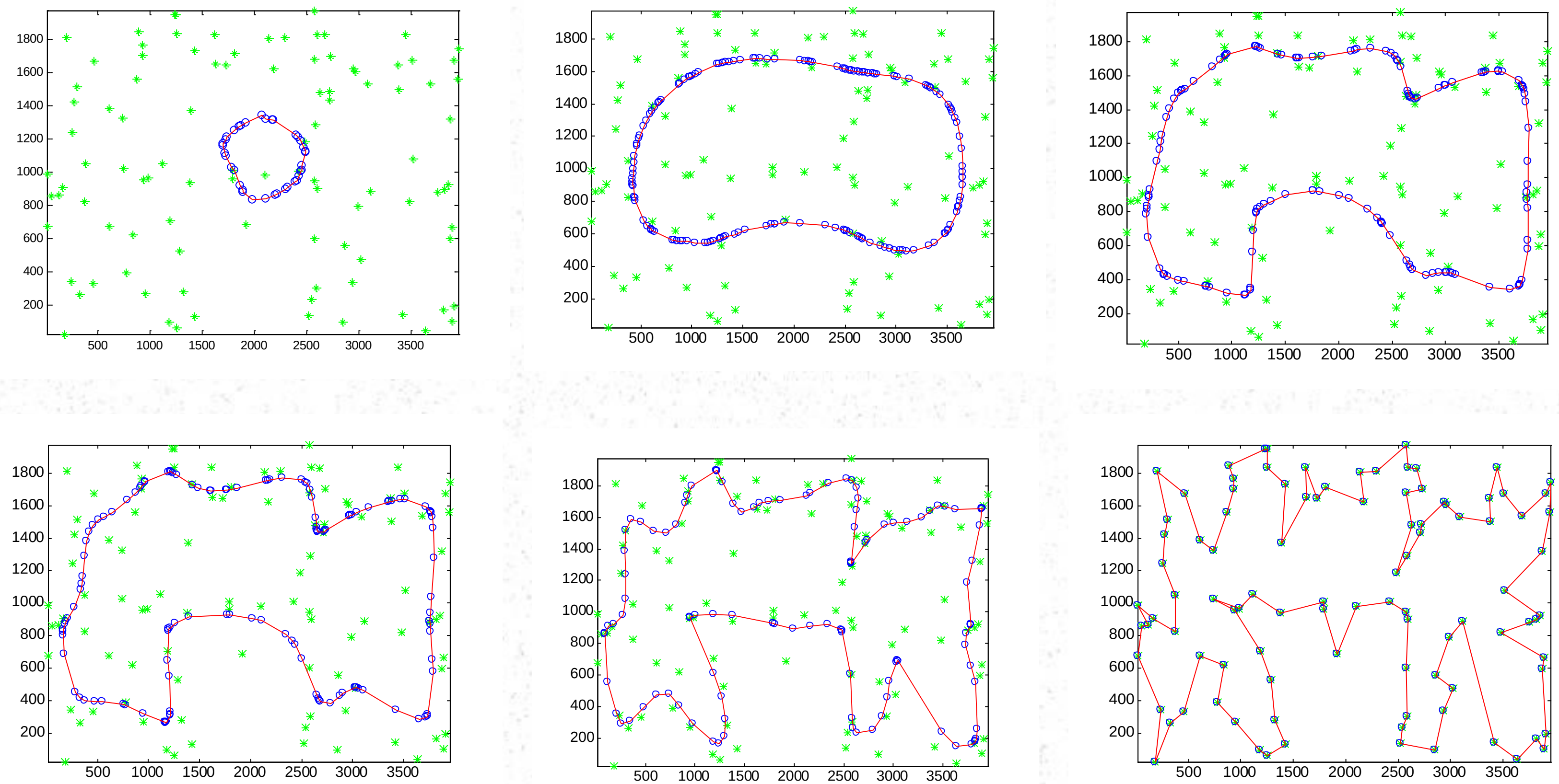


Best individual after 4000 generations



Case Study 4.2

The Travelling Salesperson Problem – Option no. 2

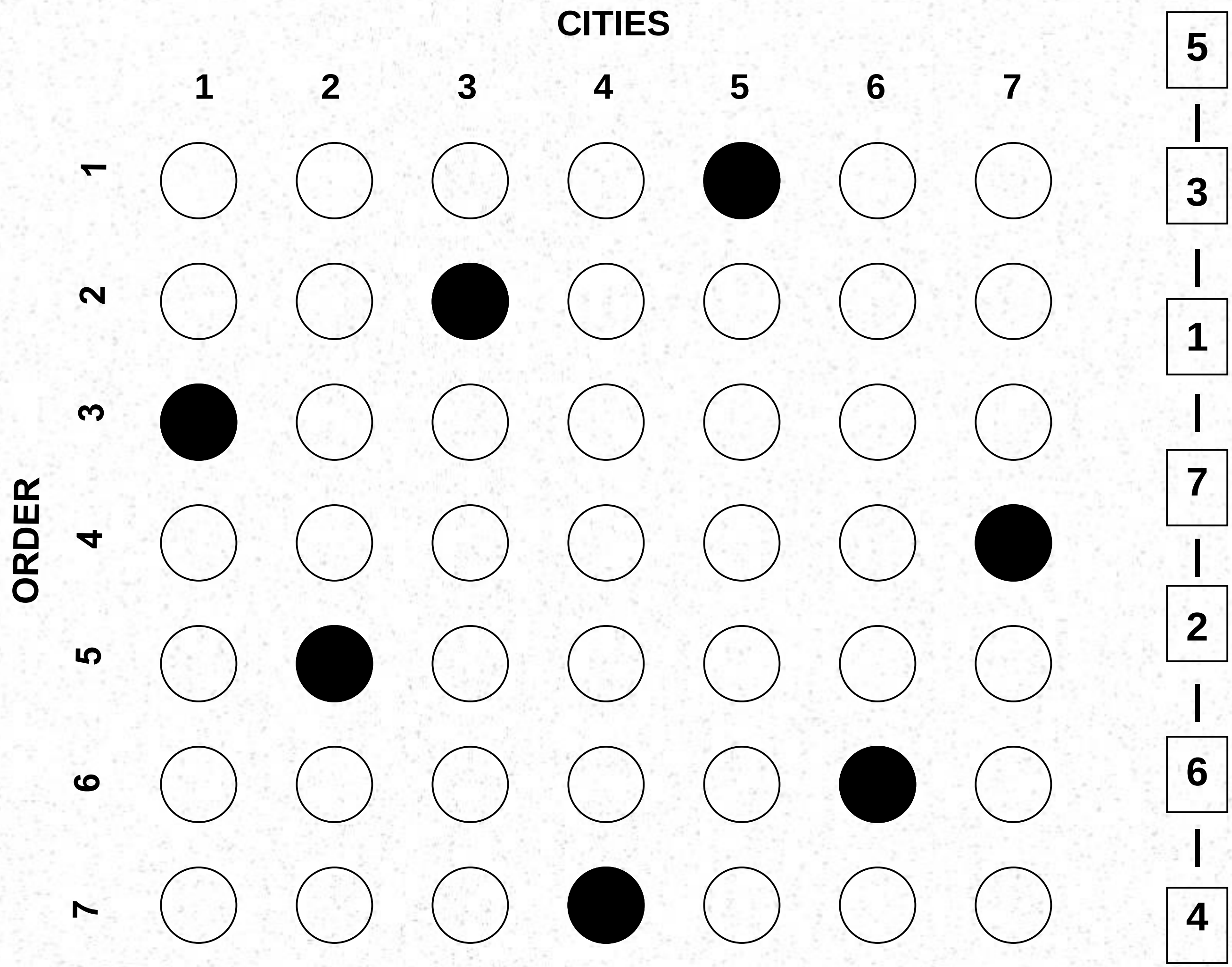


Self-organizing neural network
with a dynamic topology

Case Study 4.3

The Travelling Salesperson Problem – Option no. 3

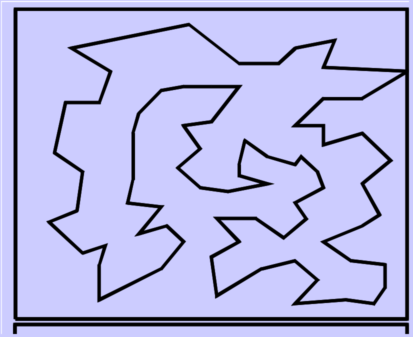
Recurrent neural network –
Nonlinear relaxation dynamics



Case Study 4.4

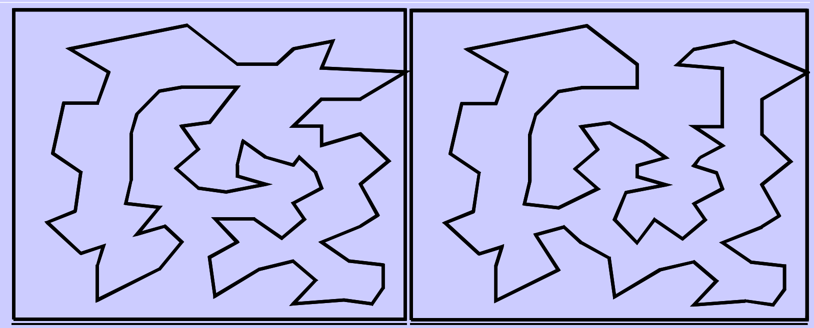
Multimodal optimization

TSP: 76 cities



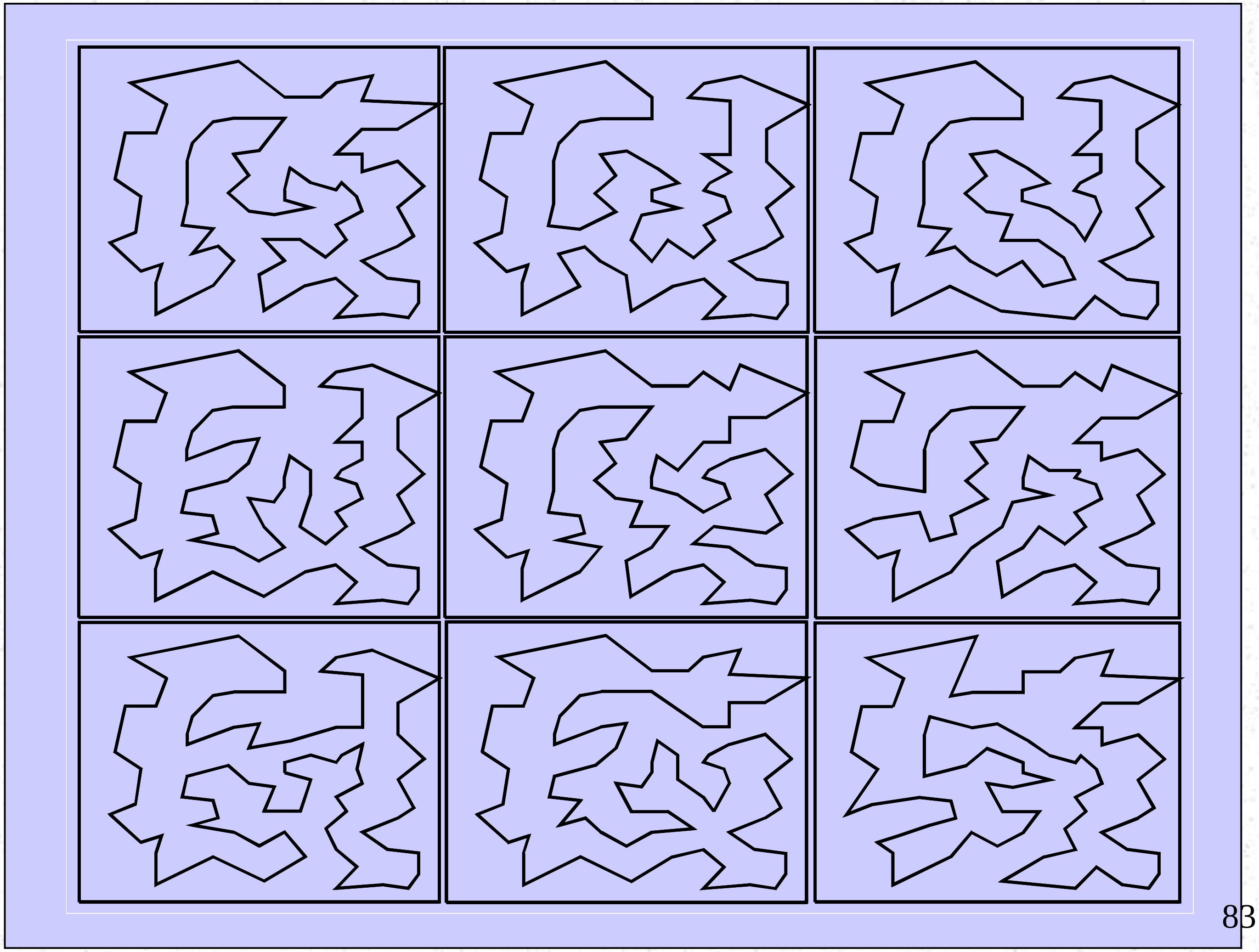
Multimodal optimization

TSP: 76 cities



Multimodal optimization

TSP: 76 cities



Multimodal optimization

Solution	Cost
1	538
2	541
3	542
4	543
5	544
6	546
7	548
8	552
9	553

Best solution

Acceptable solutions

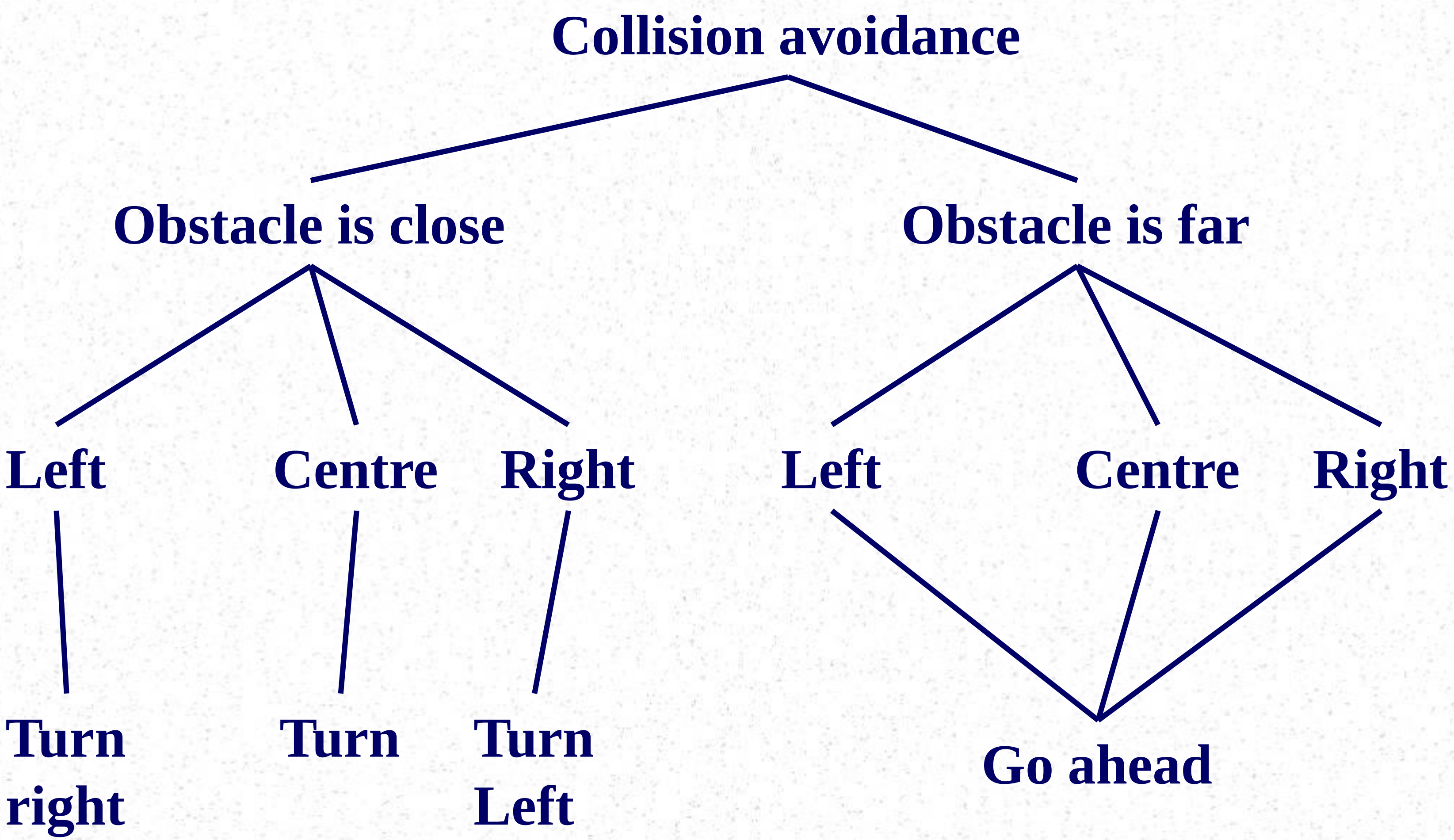
Case Study 5

Autonomous navigation of mobile robots

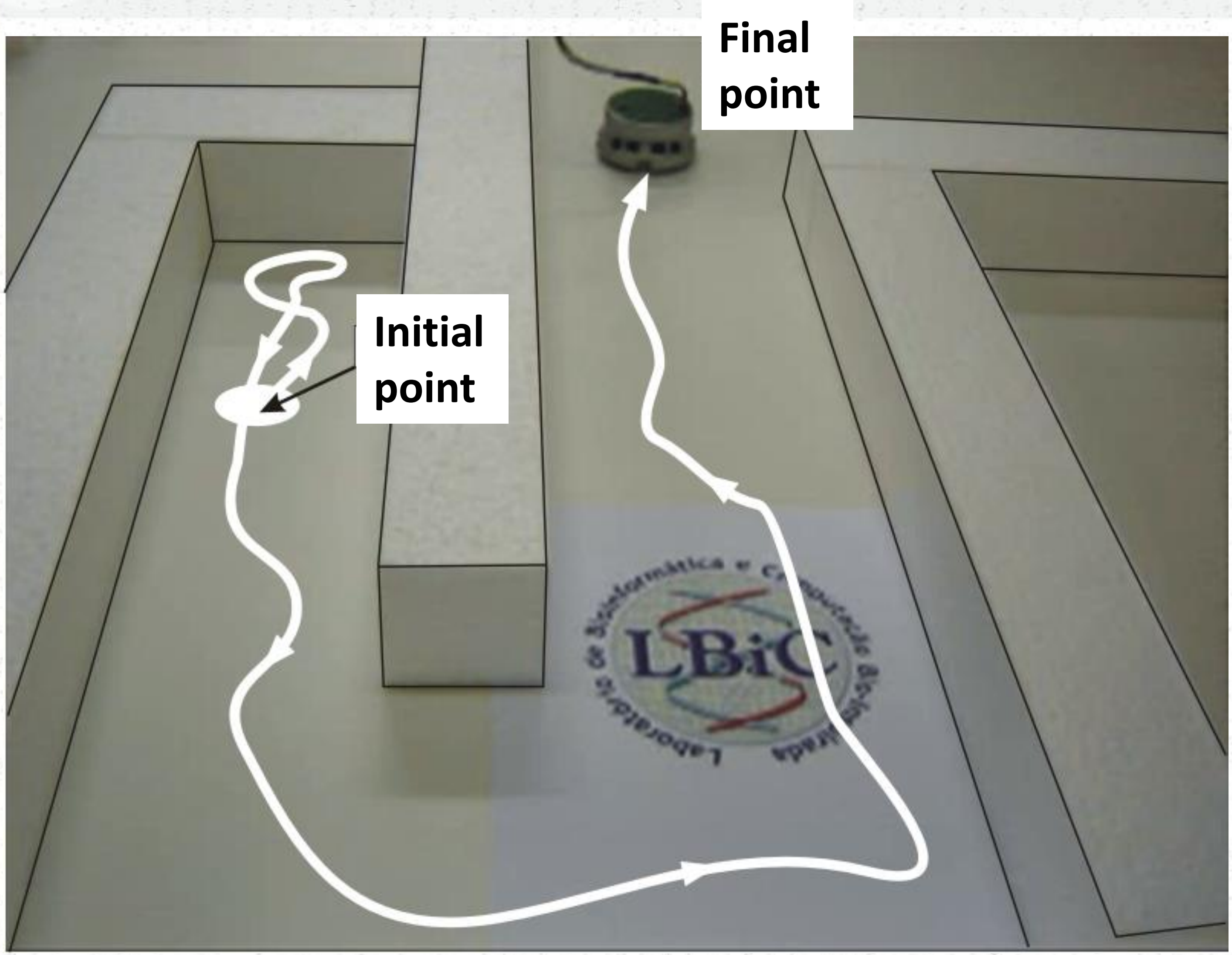
- Global path planning: devoted to the definition of an optimal path in a known environment. Would fail in an unknown environment and/or when facing dynamic and unforeseen obstacles.
- Local navigation planning: performs well in reacting to dynamic and unforeseen obstacles. Would be susceptible to local minima failures.

- That is why we should generally look for autonomous navigation.

Top-Down approach

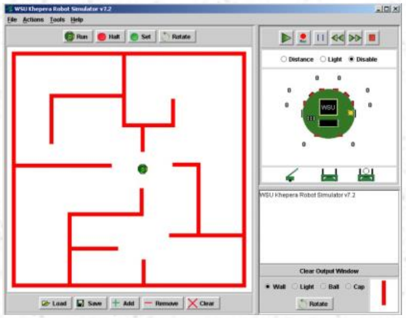


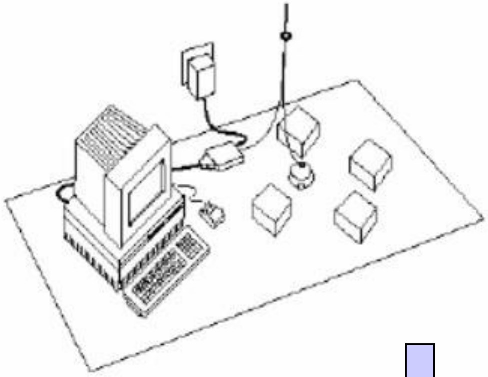
Limitation of the Top-Down Approach



Alley dilemma

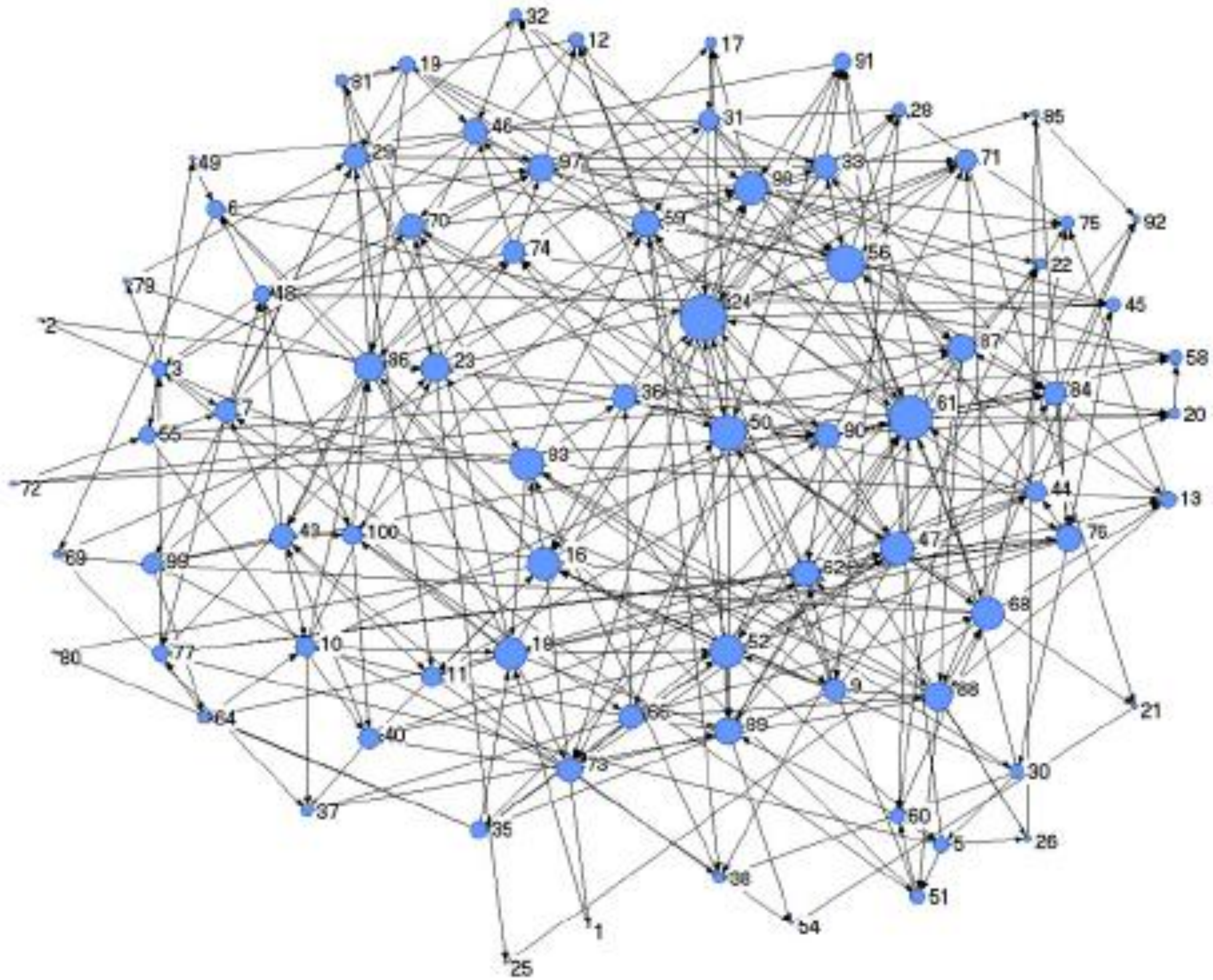
How to evolve a robot architecture + controller?



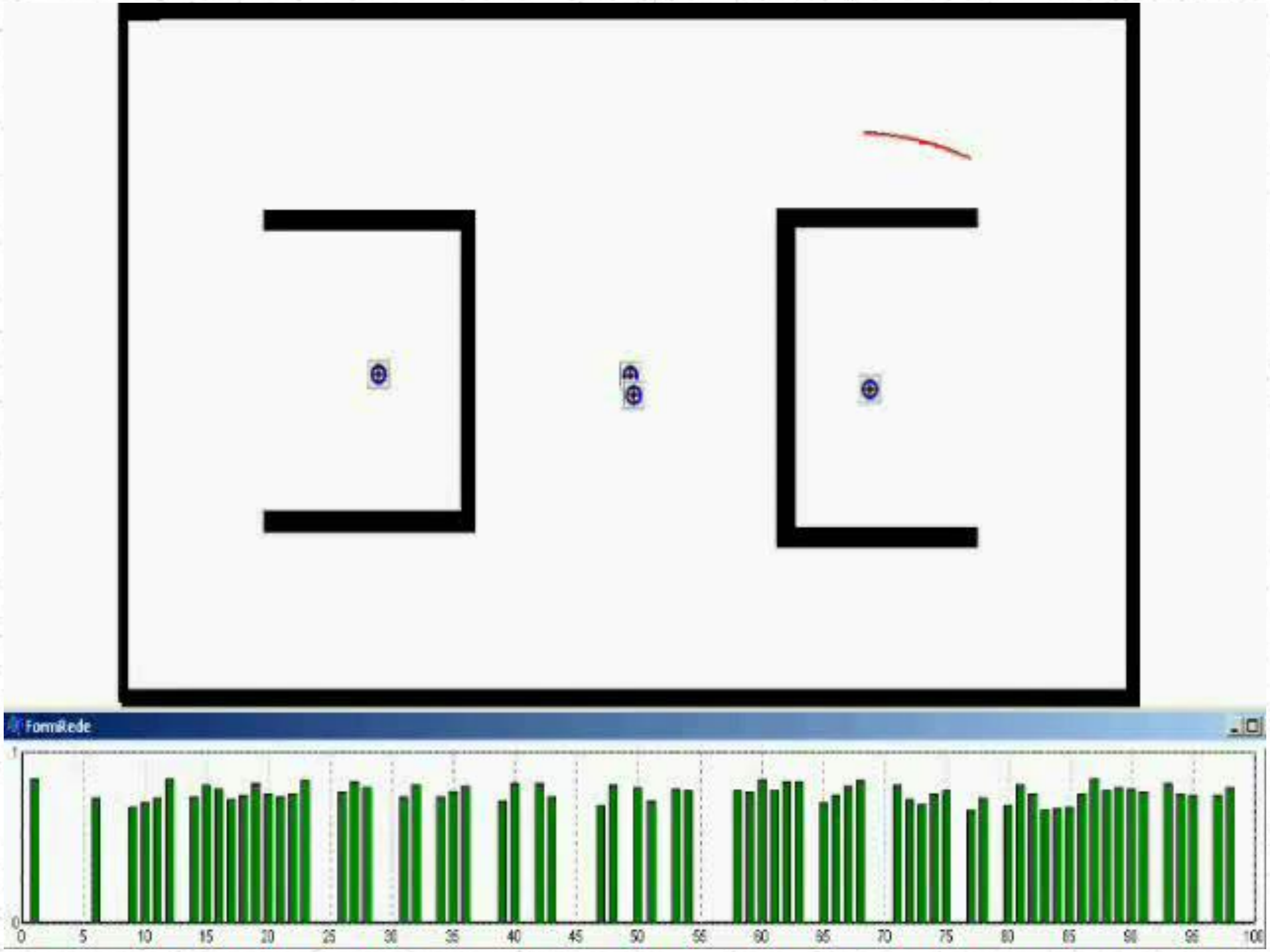


For Nonreactive tasks

Cazangi, R.R. (2008) “Synthesis of Autonomous Controllers for Mobile Robots by means of Bioinspired Computing, Ph.D. Thesis, Unicamp (in Portuguese).



Simulation Results



There is a video associated with this slide.

Real Experiment Results

There is a video associated with this slide.

Overview of the presentation

1. The natural world, the artificial world, and their intersections;
2. The power of computer simulation;
3. Epistemological issues to be addressed;
4. A taxonomy of natural computing;
5. Nature-inspired computation;
6. Nature-inspired computation: case studies;
7. Nature as computation;
8. Outlining an attainable future.

Nature as computation

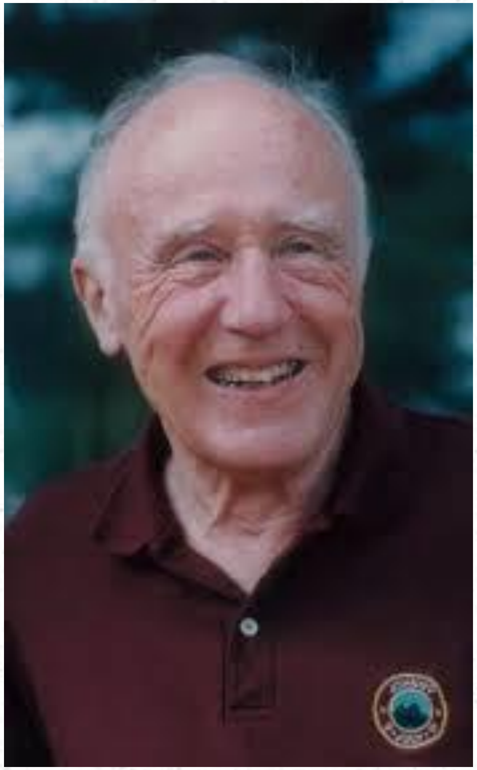
- **Some contemporary world views approach objects and physical laws in terms of information and computation.**
- **Computing is not a human invention; it already exists in the universe and is responsible for its very origin.**

- Zenil, H. (Ed.) "A computable universe: Understanding and Exploring Nature as Computation", World Scientific, 2013.
- Denning, P. J. "Computing is a natural science", Communications of the ACM, vol. 50, no. 7, pp. 13–18, 2007.

Nature as computation

- **Some pioneering views of computationalism**

John A. Wheeler (1911-2008)



Information constitutes the most fundamental level of physical reality.

Nature as computation

- **Some pioneering views of computationalism**

Richard Feynman (1918-1988)

Nature as computation

- **Some pioneering views of computationalism**

Stephen Wolfram

(1959 -)

Nature as computation

- Supposing we define computation as what a physical object can achieve, then all physical objects compute.
- Under this hypothesis, information can only exist in our world if it is carried by a process.
- So, every bit (or qubit) has to have a corresponding physical carrier.
- One thing is certain: Nature is capable of Turing computation as attested by the existence of digital computers.

Nature as computation

- The proposition that Nature computes does not mean that the Universe is a Turing machine.
- However, given that scientific models can describe much of the world, and that such models are computable, strongly suggests that though Nature may do more than compute, to a large extent its activity does amount to Turing computation.

Nature as computation

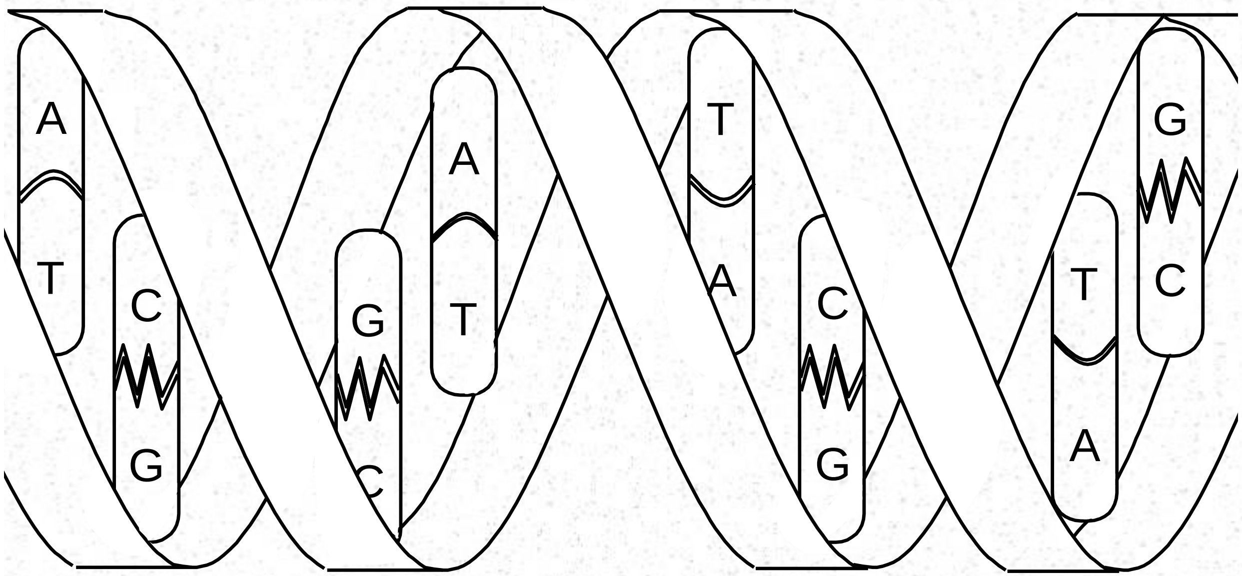
- **The essence of computationalism**

Hector Zenil

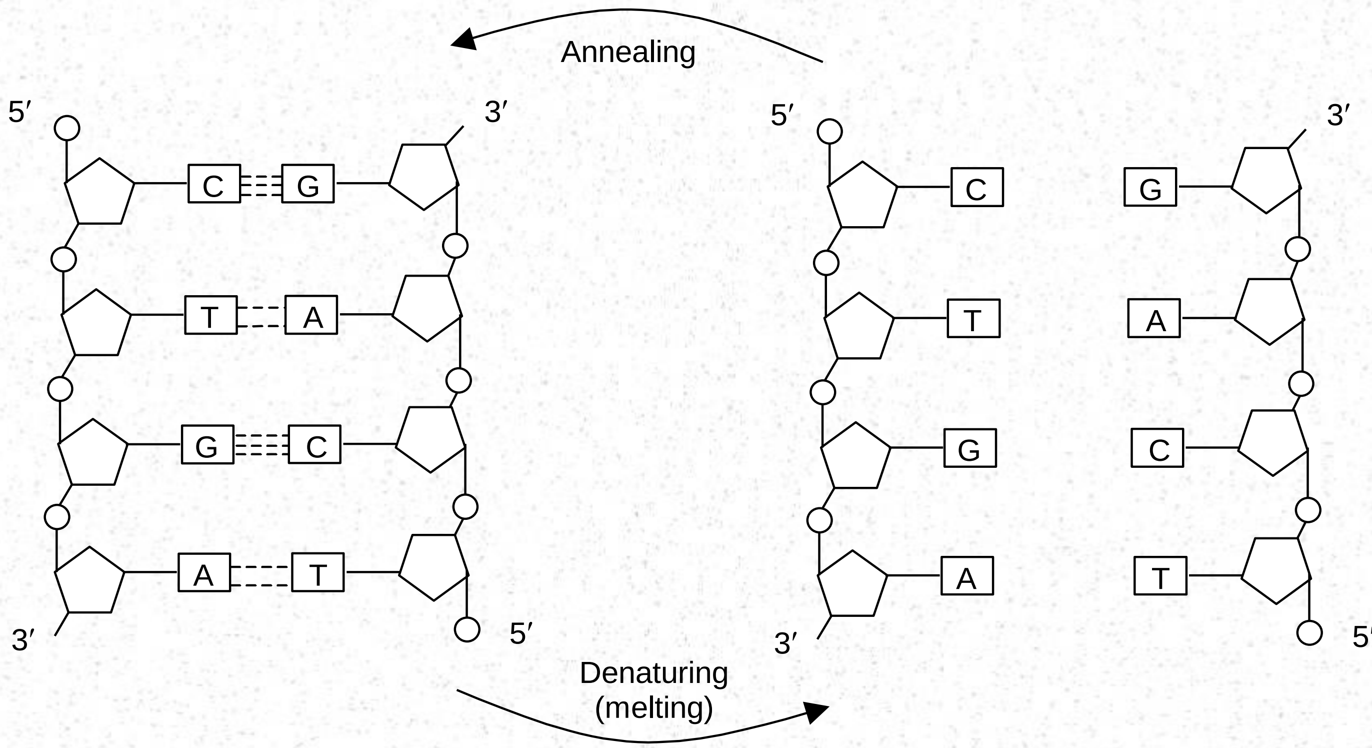
If Nature does more than just compute, we know that it nevertheless can compute, and that it does so very well.

Nature as computation

DNA computing

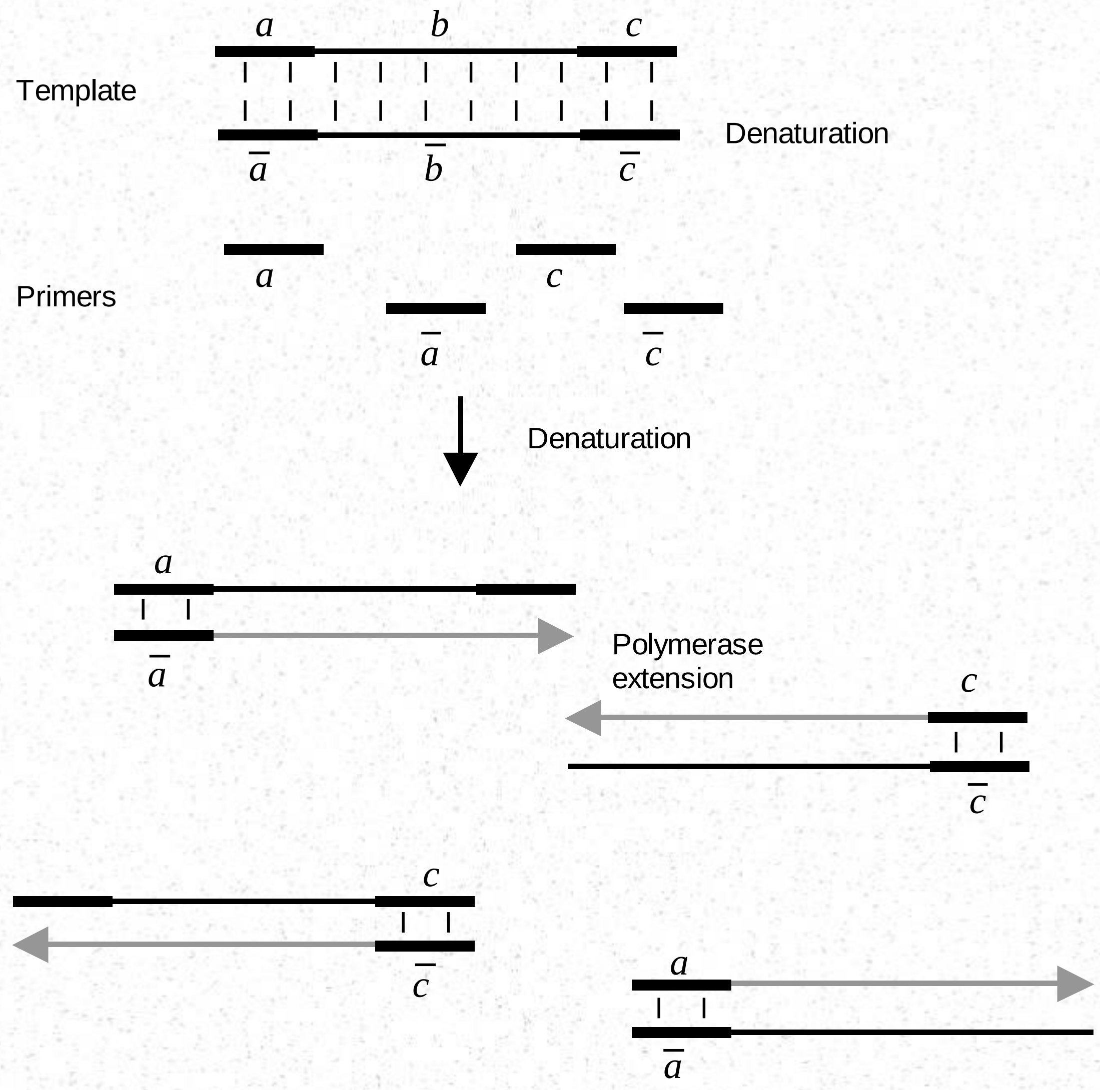


DNA Computing



DNA Computing

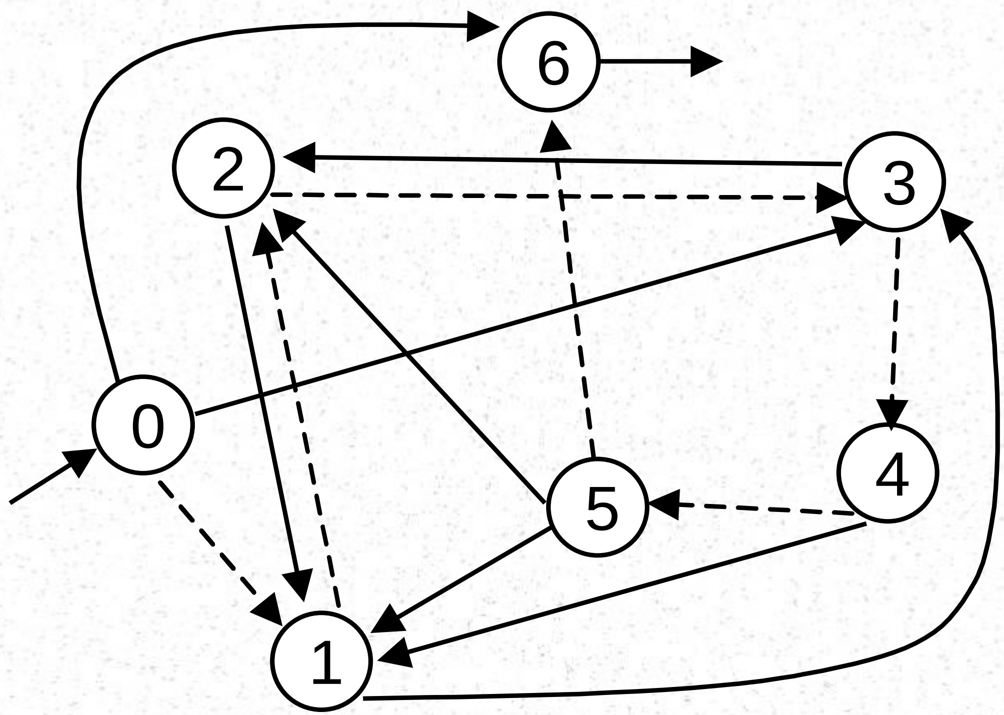
PCR (Polymerase Chain Reaction)



DNA Computing

- **Adleman experiment (Hamiltonian path problem)**

ADLEMAN, L. M. (1994), "Molecular Computation of Solutions to Combinatorial Problems", *Science*, **226**, November, pp. 1021-1024.



DNA Computing

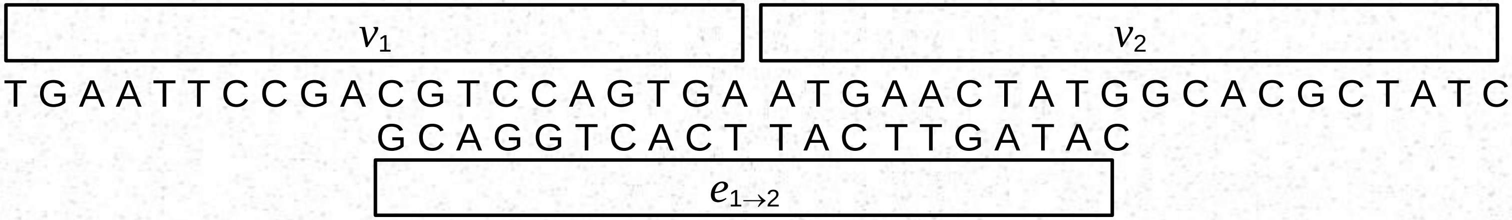
- **Adleman experiment**

$$
\begin{aligned}
v_1 &= 5' - \text{T G A A T T C C G A} \,|\, \text{C G T C C A G T G A} - 3' \\
v_2 &= 5' - \text{A T G A A C T A T G} \,|\, \text{G C A C G C T A T C} - 3' \\
v_3 &= 5' - \text{C A T A G T C C G A} \,|\, \text{T T A G C A G T A G} - 3'
\end{aligned}
$$

$$\downarrow$$

$$
\begin{aligned}
e_{1\to 2} &= 3' - \text{G C A G G T C A C T} \,|\, \text{T A C T T G A T A C} - 5' \\
e_{2\to 1} &= 3' - \text{C G T G C G A T A G} \,|\, \text{A C T T A A G G C T} - 5' \\
e_{1\to 3} &= 3' - \text{G C A G G T C A C T} \,|\, \text{G T A T C A G G C T} - 5'
\end{aligned}
$$

(a)



(b)

Quantum computing

Quantum computing

- Study of the tasks that can be solved by information processing in quantum systems.
- A quantum system is a system that evolves according to the rules of quantum mechanics.
- “Quantum theory is considered to be of fundamental importance, when it comes to the investigation of the basic underlying operations of the physical universe and their relation to computation.” (Penrose, 2013)

Quantum computing

- "The discreteness that quantum mechanics introduces into physical theory is more friendly to the notion of computation than was classical mechanics."
- "The ideas of discreteness and combinatorics might soon be seen to become the dominant driving force underlying the operation of our universe, rather than the continuity and differentiability that classical physics had depended upon for so many centuries."

(Penrose, 2013)

Quantum computing

- In quantum computing, the lack of predictiveness does not result from limitations on the accuracy of the computational simulations that can be carried out (as is the case with digital computers), but even a completely precise simulation would not enable us to predict with confidence what the actual outcome would be.

Quantum computing

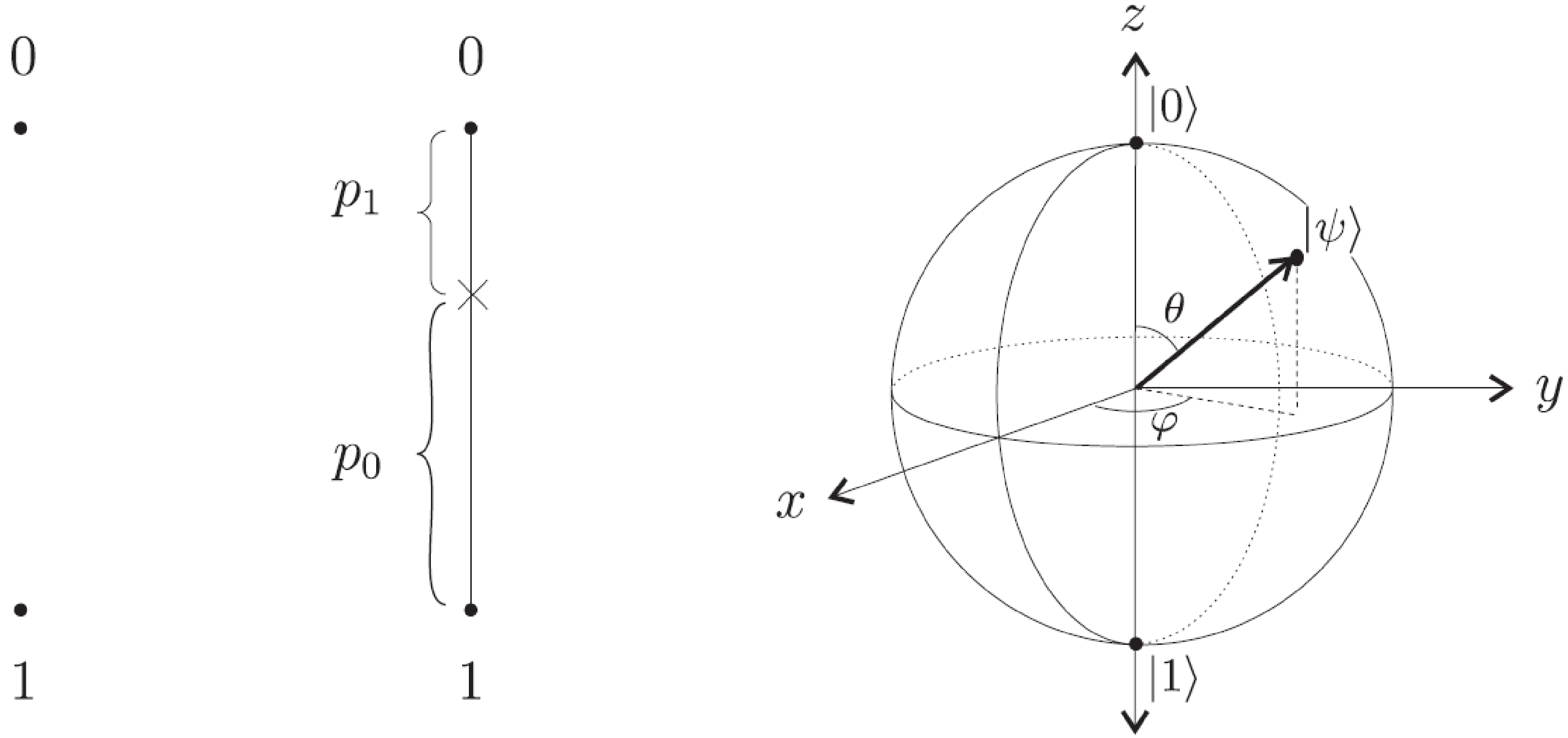
Quantum bits (qubits)

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix} = \alpha_0 \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \alpha_1 \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\psi\rangle = \alpha_0 |0\rangle + \alpha_1 |1\rangle, \quad |\alpha_0|^2 + |\alpha_1|^2 = 1$$

Quantum computing

Bloch sphere



Classical bit **Probabilistic bit** **Quantum bit**

Quantum computing

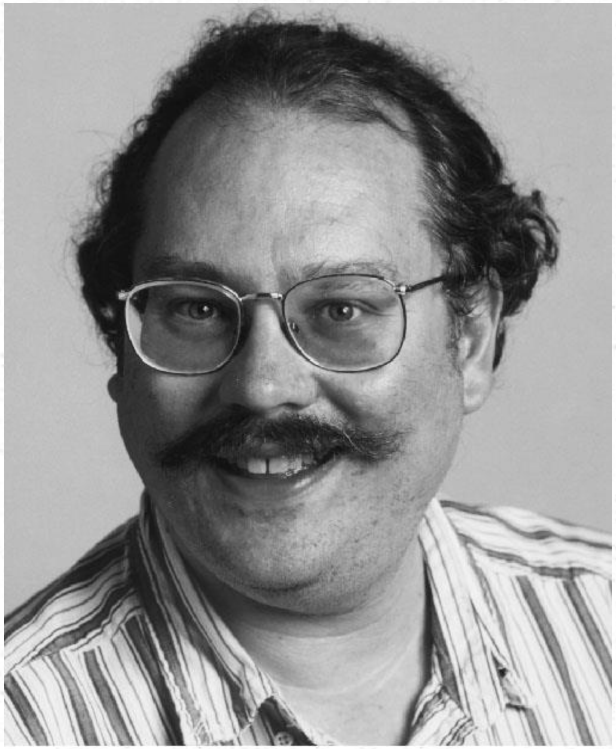
Methodology

- Explores the concepts of quantum superposition and quantum entanglement:
    - ✓ Prepare the input in classical states;
    - ✓ Build a superposition of classical states;
    - ✓ Apply unitary quantum operations in sequence;
    - ✓ Measure the result.

Quantum computing

Most famous quantum algorithms

- Shor's algorithm for factoring a prime number in polynomial time (1994)



Quantum computing

Most famous quantum algorithms

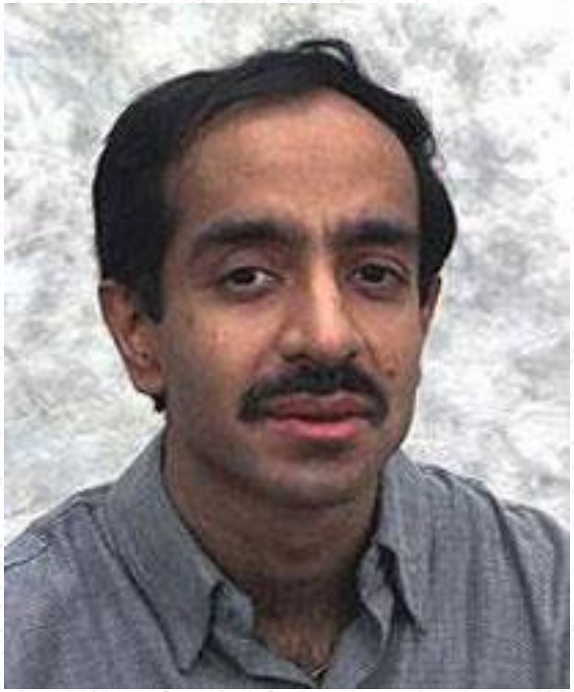
- Shor's algorithm for factoring a prime number in polynomial time (1994)

Number of Bits	Classical algorithm	Shor's algorithm
512	4 days	**34 seconds**
1024	100 thousand years	**4.5 minutes**
2048	100 million years	**36 minutes**
4096	100 billion years	**4.8 hours**

Quantum computing

Most famous quantum algorithms

- Grover's algorithm for searching an unstructured database or an unordered list (1996)



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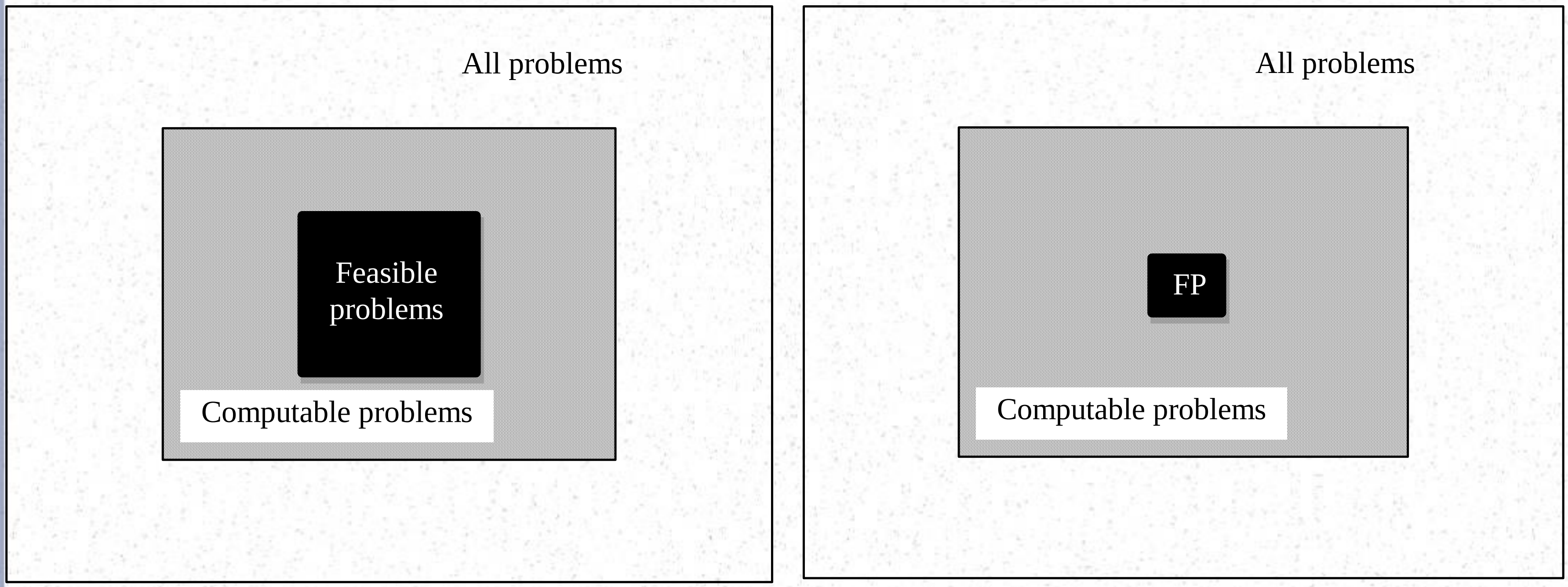
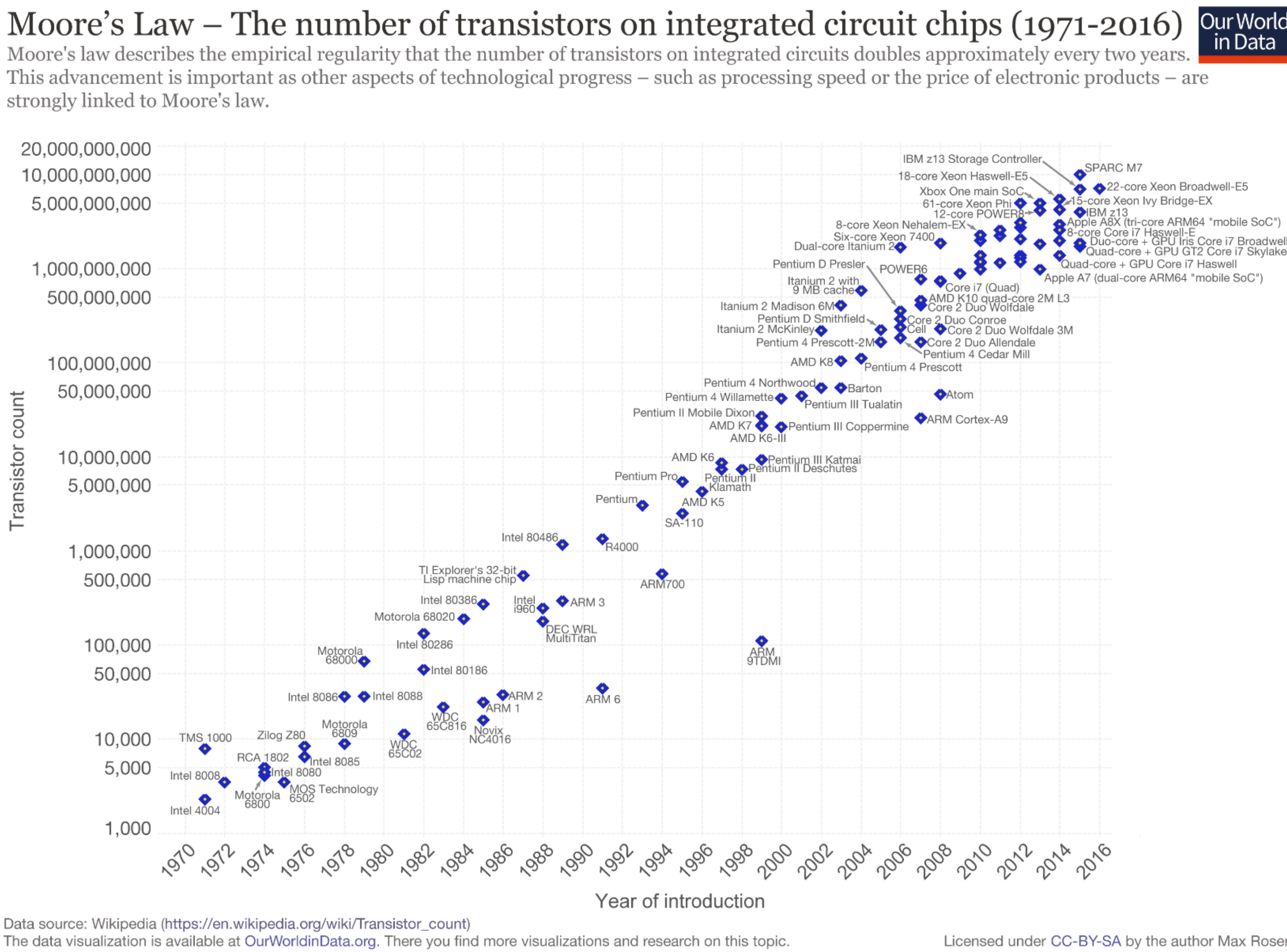
A Challenging Scenario for Computer Science / Engineering

Before Now



The aim of natural computing is to deal with computable problems located at the hatched area.

A Challenging Scenario for Computer Science / Engineering



A Challenging Scenario for Computer Science / Engineering

- Moore's law is the observation that, over the history of computing hardware, the number of transistors on integrated circuits doubles (thus exhibits an exponential rate) approximately every two years.

- The problem is that, with even a linear increase in the size of the computable problems, they will require a factorial increase in the computational power.

$$n! \cong \sqrt{2\pi n}\left(\frac{n}{e}\right)^n$$

A Challenging Scenario for Computer Science / Engineering

- When to use nature-inspired computation?

- In the context of optimization:
  - You do not know what the optimal solution looks like;
  - You do not know how to find it in a principled way;
  - You have very little heuristic information to go on;
  - A brute-force search is out of the question;
  - Given a candidate solution, you can test it easily and assess how good it is.

A Challenging Scenario for Computer Science / Engineering

- When to use nature-inspired computation?

- In the context of learning:
  - When bottom-up approaches are preferable to top-down approaches.
  - Under the lack of information at the design phase, learning methods can be used for on-the-job improvement of existing machine designs.
  - The required knowledge about certain tasks might be too large. So, this knowledge can be gradually acquired by machines that can learn.

A Challenging Scenario for Computer Science / Engineering

- Notice that a problem difficult to solve using a digital computer may exhibit distinct degrees of complexity when treated by means of alternative information processing devices (novel computing paradigms).

- Computing by novel means:
  - DNA computing
  - Quantum computing

Is there space for novel natural computing proposals?

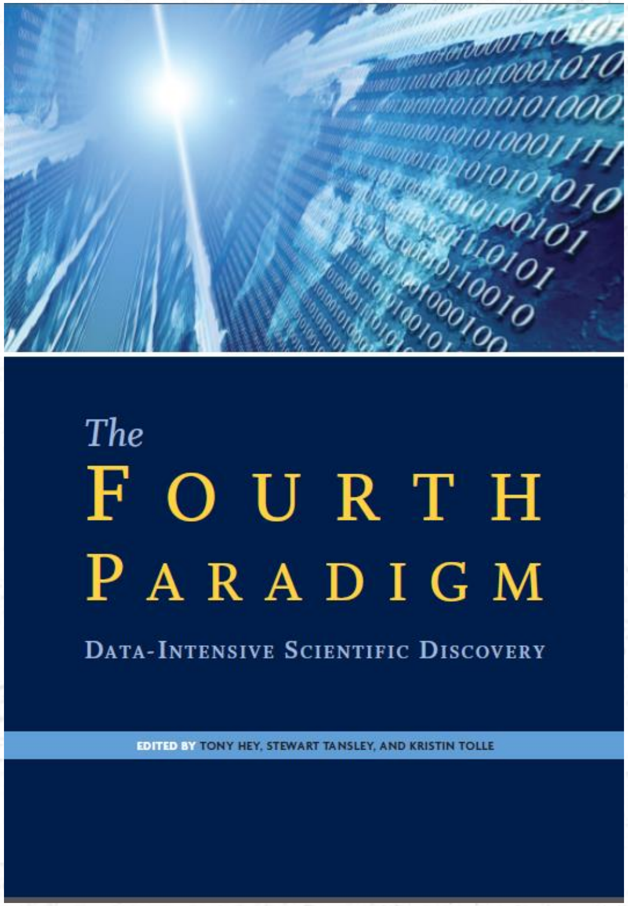
- In recent years, the fields of discrete and continuous optimization have witnessed the appearance of several metaheuristics based on a metaphor of some natural process. The paper

Sörensen, K. "Metaheuristics - the metaphor exposed", International Transactions in Operational Research, vol. 22, pp. 3-18, 2015.

pointed out the risks of following an unscientific direction when exploring those metaphors.

Is there space for novel natural computing proposals?

- Natural computation (and Computational Intelligence as a whole) has a major role to play in establishing and developing the Fourth Paradigm for Science.



Is there space for novel natural computing proposals?

- Nature-inspired algorithms were named one of Scientific American magazine’s 10 “World Changing Ideas 2010”

A new physics theory of life

Jeremy England

The origin and subsequent evolution of life follow from the fundamental laws of Nature and “should be as surprising as rocks rolling downhill”.

A new physics theory of life

- Living things tend to be much better at capturing energy from their environment and dissipating the energy as heat.
- When a group of atoms is driven by an external source of energy and is surrounded by a heat bath, it will often gradually restructure itself in order to dissipate increasingly more energy.

A new physics theory of life

- Consequently, under certain conditions, matter inexorably acquires the key physical attribute associated with life.

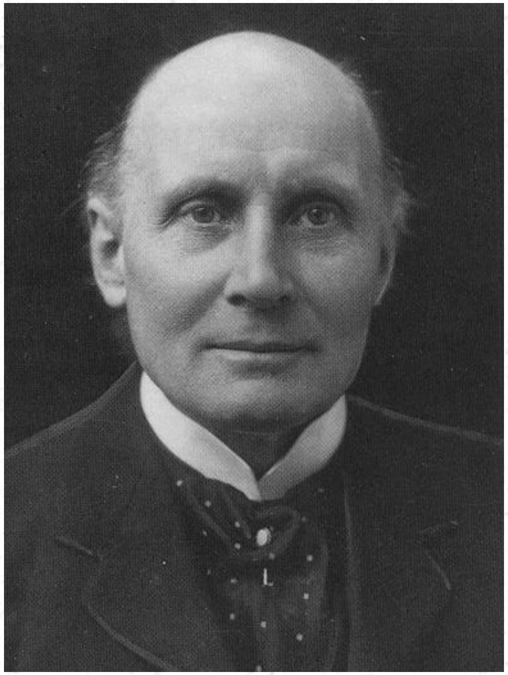
- We then have the underlying physical principle driving the origin and evolution of life (dissipation-driven adaptation of matter), fully consistent with the second law of thermodynamics.

A new physics theory of life

- If this new theory is in the right direction, the same physics responsible for the origin of life could explain the formation of many other patterned structures in Nature, such as snowflakes.

Perunov, N.; Marsland, R.A. & England, J.L. “Statistical physics of adaptation”, Physical Review X , vol. 6, no. 2, 021036, 2016.

Natural computing



"Nature is about the perpetual pursuit of novelty."

Alfred North Whitehead
(1861 — 1947)

Renowned researcher in the area of Philosophy of Science, especially with regard to the foundations of Mathematics. Together with Bertrand Russell wrote Principia Mathematica, a book that was ranked by Modern Library as the twenty-third in a list of the hundred most important books in non-fiction English of the twentieth century.

Natural computing

Dancoff's Law:

"The most effective solution occurs when the greatest number of mistakes are made consistent with survival".

Dancoff, S.M. & Quastler, H. "The Information Content and Error Rate of Living Things", Quastler, H (Ed.). Essays on the Use of Information Theory in Biology, Urbana: University of Illinois Press, 1953.

Acknowledgement

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