NASCENCE

SEVENTH FRAMEWORK PROGRAMME

NTNU – Trondheim
Norwegian University of Science and Technology

An Investigation of Underlying Physical Properties Exploited by Evolution in Nanotubes Materials

Stefano Nichele, Odd Rune Lykkebø and Gunnar Tufte

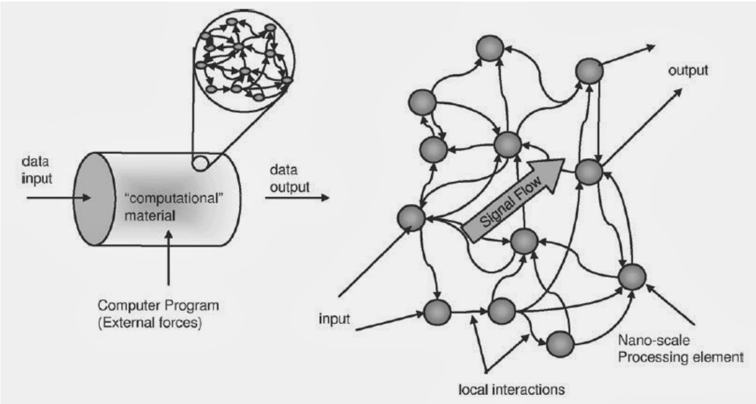
IEEE ICES 2015 – Cape Town
Symposium Series on Computational Intelligence

Outline

- Background Evo-in-Materio
- NASCENCE (NAnoSCale Engineering for Novel Computation using Evolution)
- Evolving physical properties
- Examples
- Conclusion and Future work

Evolution-in-Materio

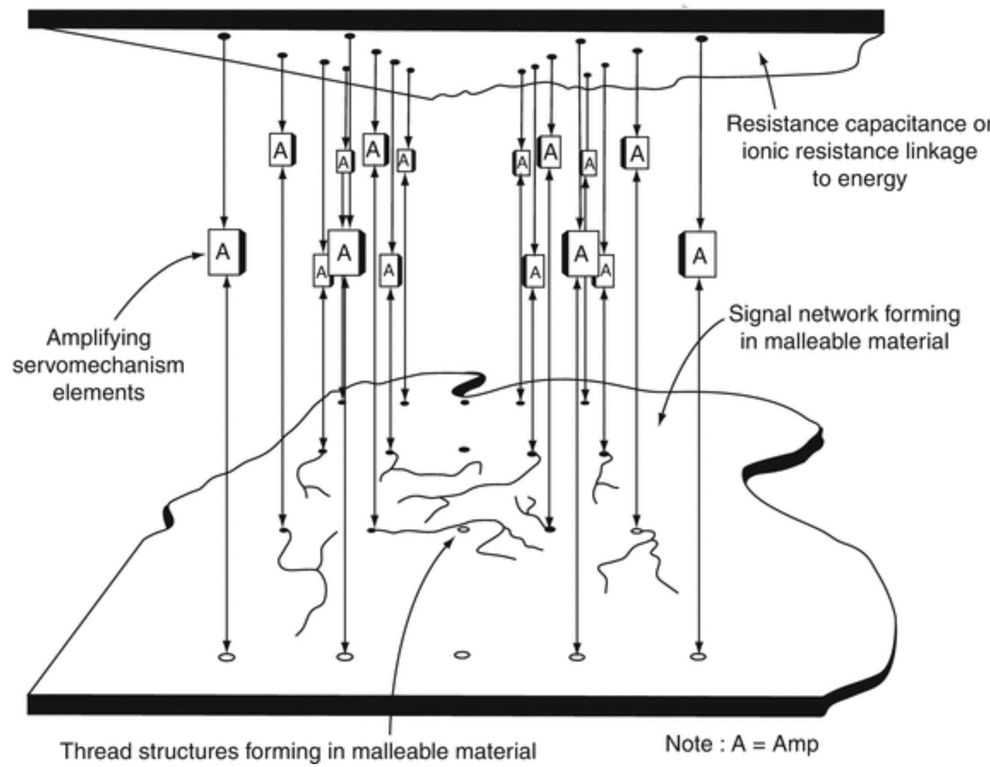
- ”...the manipulation of a physical system using computer controlled evolution (CCE)”
- ”...a kind of unconstrained evolution in which, by the application of physical signals, various intrinsic properties of a material can be configured so that a useful computation function is achieved”



Miller J., Harding S., and Tufte G., Evolution-in-materio: evolving computation in materials. In: Evolutionary Intelligence, vol. 7, no. 1, 2014, pp. 49-67.

Gordon Pask (1958)

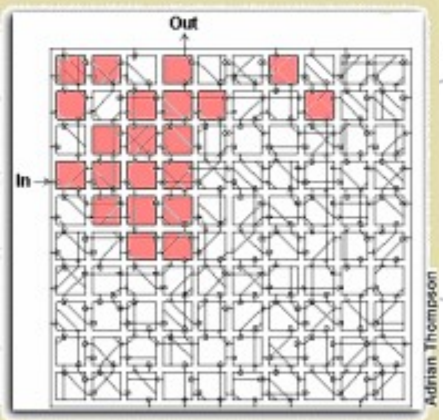
- Grow neural structures in Ferrous Sulphate
- Self-assembly of thread like structures
- Changing current would alter structure
- Frequency discriminator



Pask, G., Physical analogues to the growth of a concept. In: Mechanisation of Thought Processes, no. 10in National Physical Laboratory Symposium, pp. 877-922 (1958)

Adrian Thompson (1996)

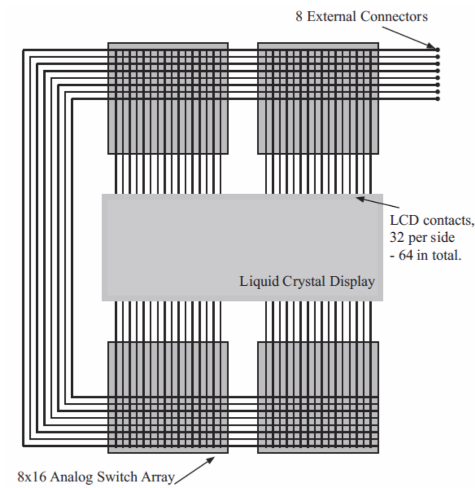
- Artificial evolution to configure a field programmable gate array (FPGA)
- Frequency discriminator: 1kHz and 10kHz
- Computation relied on physical properties of the FPGA chip itself, outside the discrete logical domain
- Much larger space of configurations than top-down engineering
- Exploit natural physical properties of the underlying substrate

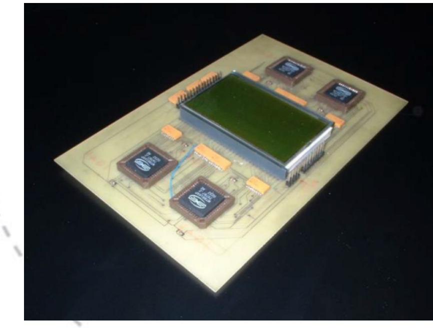


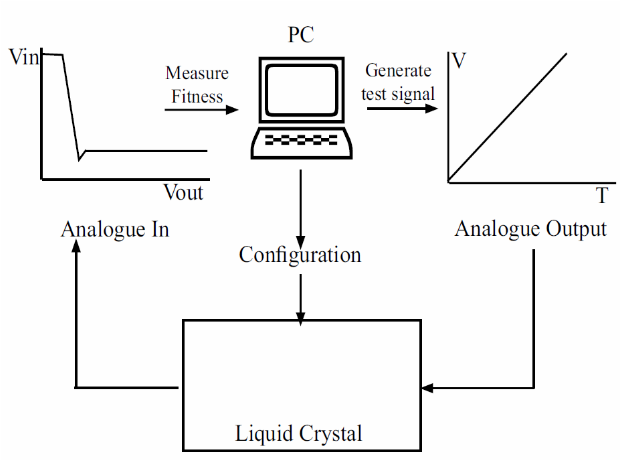
A 10x10 FPGA Array

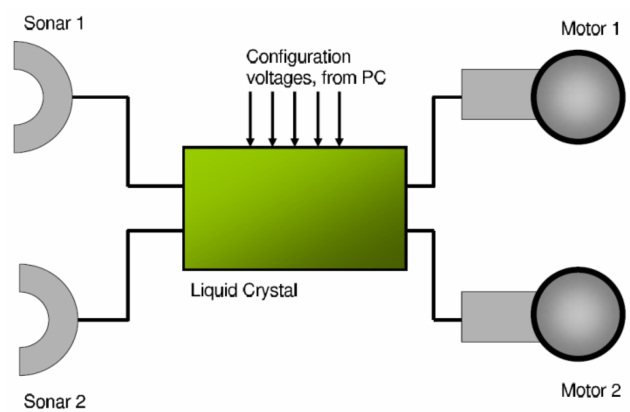
Thompson A., An evolved circuit, intrinsic in silicon, entwined with physics. In: Proc. 1st Int. Conf. on Evolvable Systems (ICES96), pp. 390-405, Berlin, 1997, Springer-Verlag.

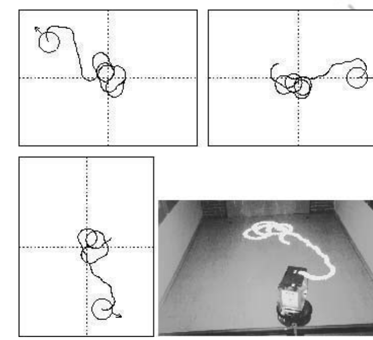
Liquid crystal







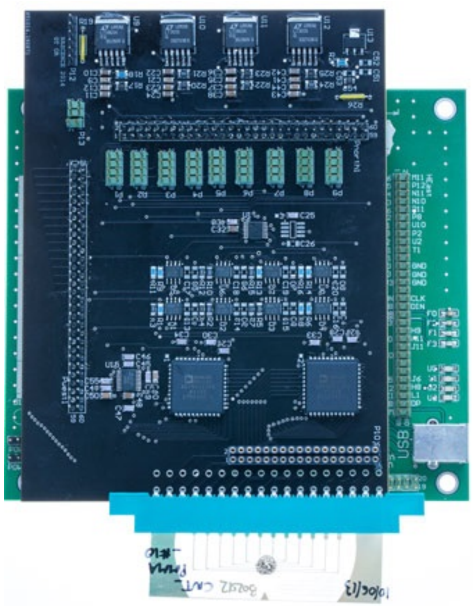


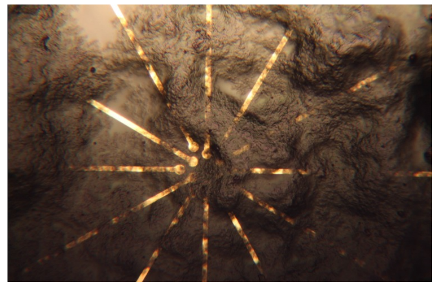


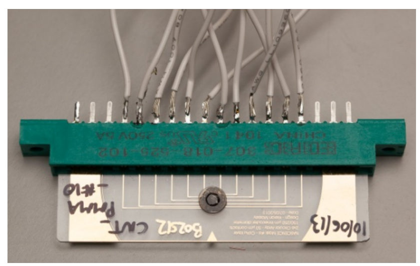
Harding S. and Miller J., Evolution in materio: A real-time robot controller in liquid crystal. In:Proceedings of the 2005 NASA/DoD Conference on Evolvable Hardware, pages 229--238, Washington, DC, USA, 29 June-1 July 2005. IEEE Press.

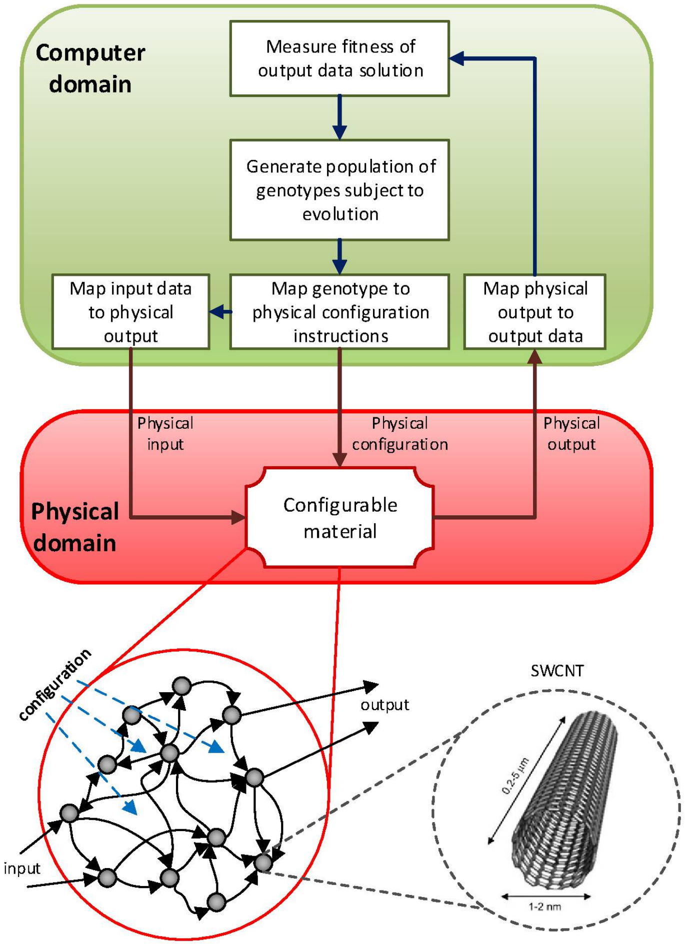
NASCENCE

http://nascence.eu/









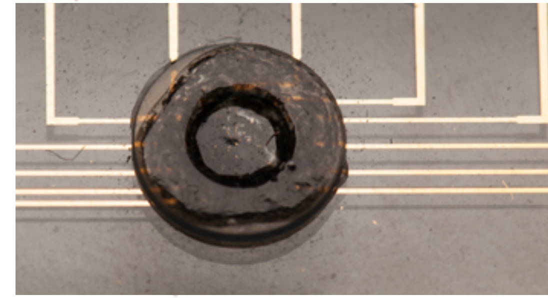
“The aim of this project is to model, understand and exploit the behaviour of evolving nanosystems (e.g. networks of nanoparticles, carbon nanotubes or films of graphene) with the long term goal to build information processing devices exploiting these architectures without reproducing individual components”.

NTNU – Trondheim
Norwegian University of Science and Technology

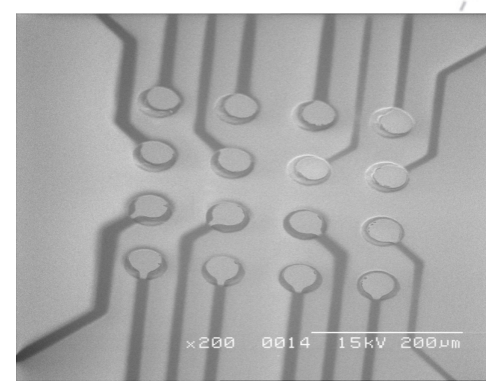
Material parameters

- **Intrinsic**: internal properties of the molecules that compose the material (type of particles, composition). Impact on physical properties (conductivity, charge)
- **External/Environmental**: external stimuli that influence material properties (current, temperature, light). Controllable (evolved) vs non-controllable. Can change the state of the material temporarily or permanently.
- **Construction**: defined when system is build, cannot change afterwards (concentration of molecules, metallic vs semi-conducting nanotubes, electrodes material, size and pitch)

Investigated materials



- 20 µL material:
  - Single-wall carbon nanotubes (SWCNT) – 0.53% or 5% of weight
    - 30% metallic
    - 70% semi-conducting
  - Polybutyl methacrylate (PBMA)



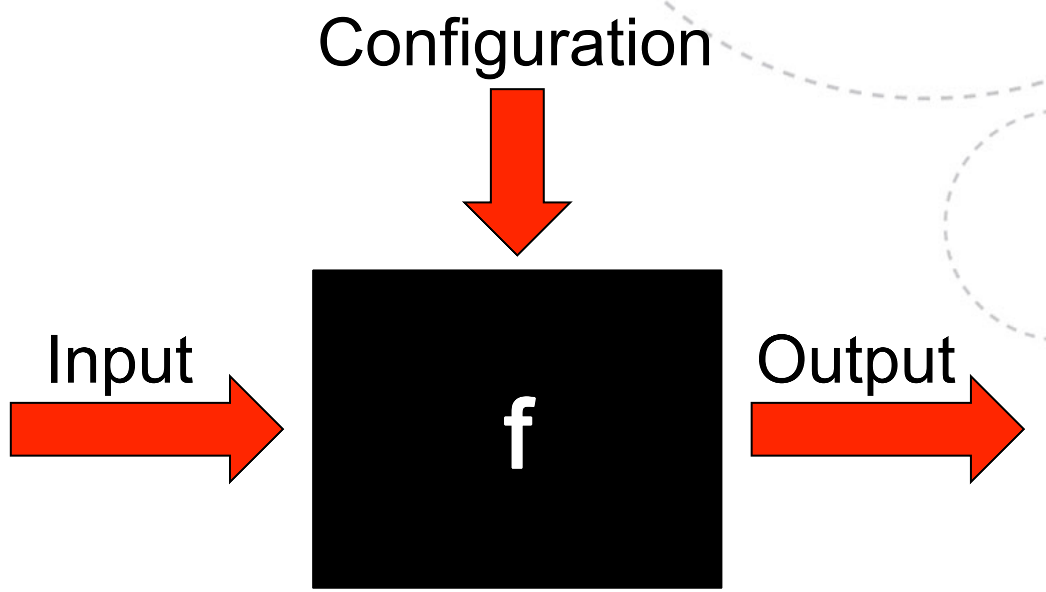
- 4x4 grid of gold microelectrode array
- ”Baked” for 30 min at 90°C ->thick film
- Variable distribution of nanotubes across electrodes

- Materials supplied by Durham University

Black box approach

Solved problems in-materio:

- Traveling Salesman
- Logic gates
- Bin packing
- Machine learning classification
- Frequency classification
- Function optimization
- Graph coloring



- How is the computation performed?
- What are the exploited physical properties?
- What is the best way to exploit them?
- Which signals/configurations?
- How many electrodes?
- ...

- Important for solving bigger instances of the investigated problems
- Number and type of parameters impact on search space / evolvability / computational power

- Focus on square waves -> rich dynamics

Open the black box

- Questions are unanswered
- Input/output abstracted from underlying physics
- Fitness function is problem dependent
- Detached from real physics of the material substrate

- Problem: evolve minimum/maximum difference of output amplitudes on two different pins
- Fitness is directly derived from raw physical output

Nano-materials as complex systems

- Randomly dispersed carbon nanotubes in polymer solution
- Complex system with huge number of tiny elements interacting at local level -> emergent dynamics
- Connected with notion of Edge of Chaos (maximum complexity / computational power)
- Computation may occur in the vicinity of phase transition between
  - Order: little dynamics / information processing and high memory / structure preservation
  - Chaos: no memory and plenty of dynamics.
- Computation at molecular level (evo-in-materio) -> may produce very rich dynamics as the very essence of the material physics is exploited -> needs a balance between order and chaos to compute

Evolution

$$Fitness = \sum_{i=0}^{len(out\_buf)} |Out1_i - Out2_i|$$

Input Pin1	Freq.	Duty cycle	Input Pin2	Freq.	Duty cycle	... # Inputs	Output Pin1	Output Pin2	Free Pin1	... # Free Pins
	1			2		...		...		16

- 400-25000Hz, 0-100%
- Output: 5ms at 250000Hz
- 1 + λ ES, with λ = 4

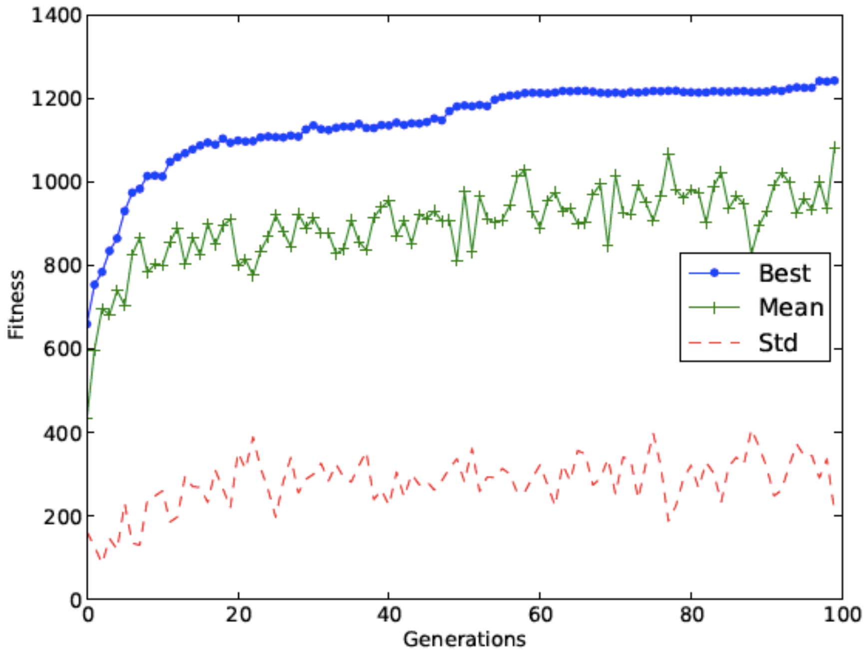


Fig. 13: 0,53% nanotubes, evolve maximum difference on 2 output pins, 5 input pins.

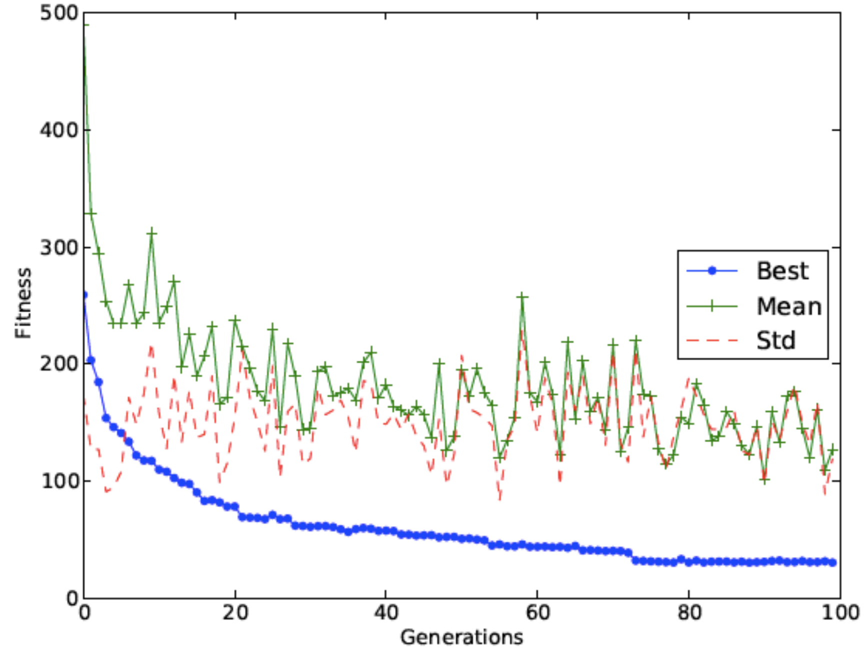


Fig. 16: 0,53% nanotubes, evolve minimum difference on 2 output pins, 5 input pins.

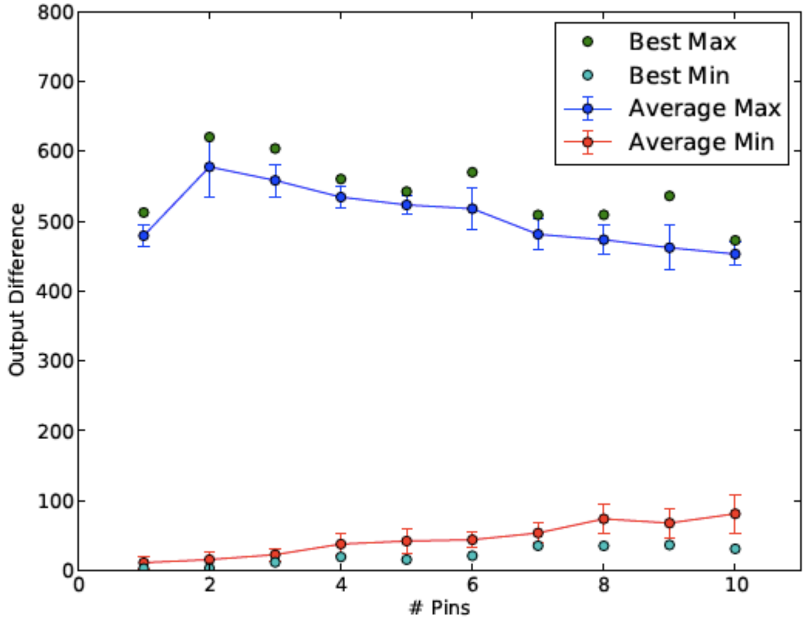


Fig. 20: 5,00% nanotubes, comparison summary, evolvability range.

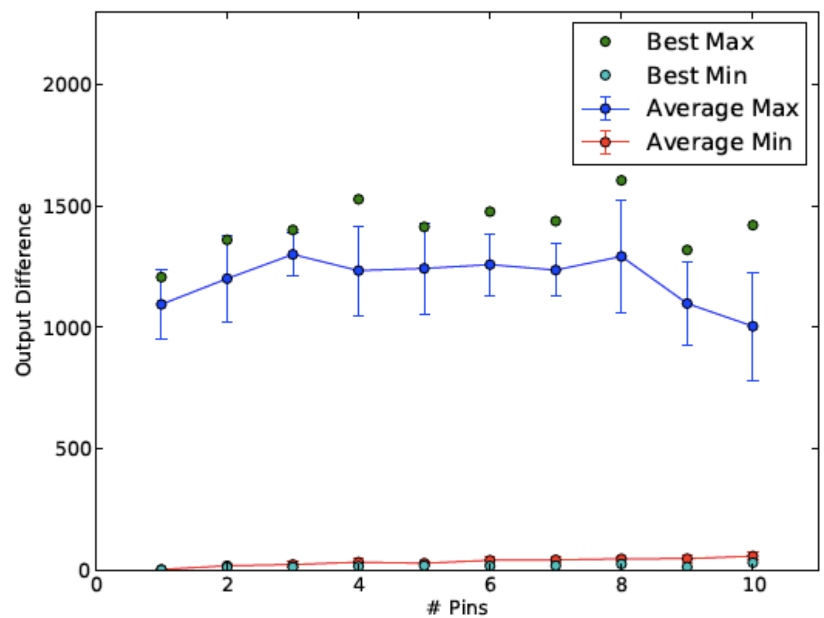


Fig. 21: 0,53% nanotubes, comparison summary, evolvability range.

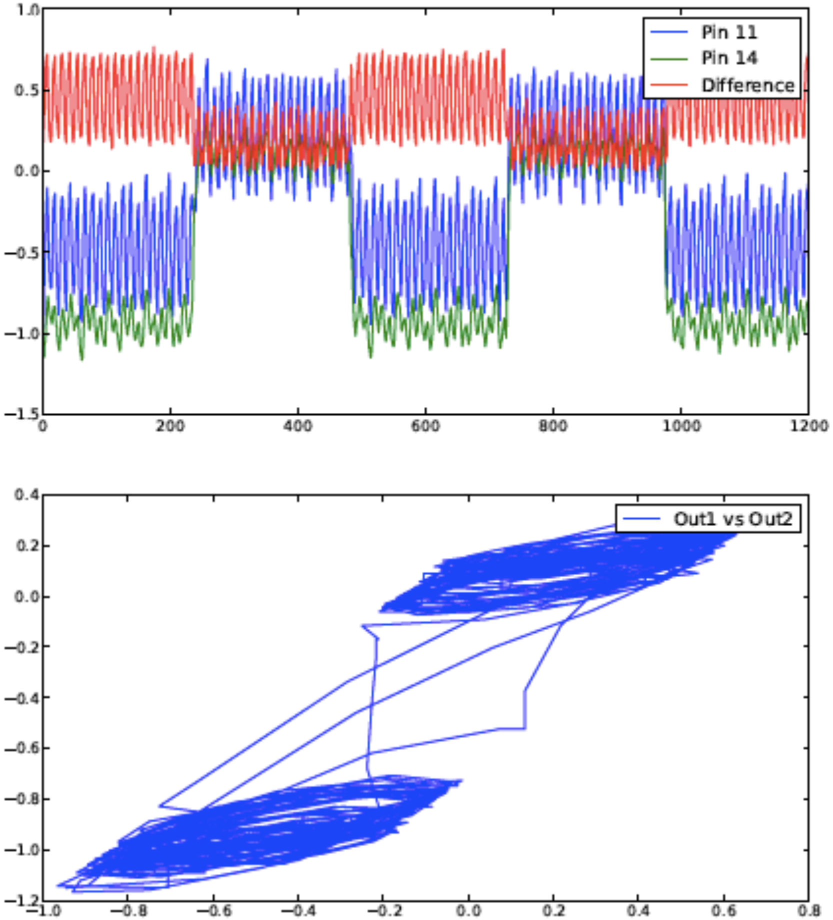


Fig. 22: Material B09S12, 0.53% nanotubes, example with 4 input pins.

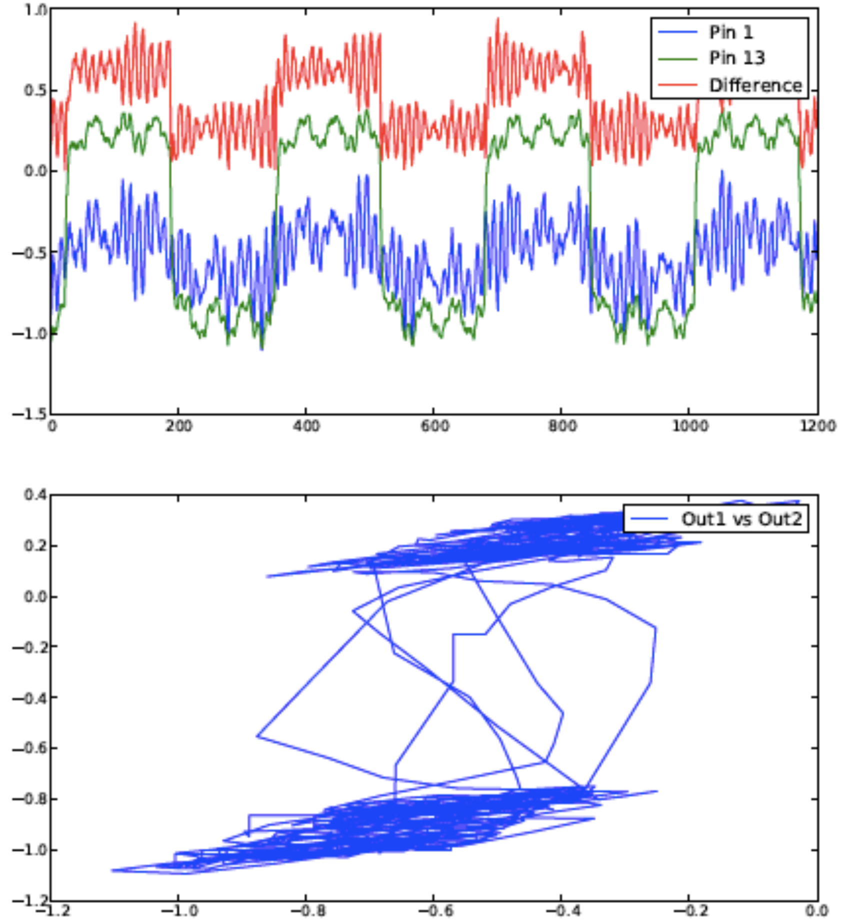


Fig. 23: Material B09S12, 0.53% nanotubes, example with 5 input pins.

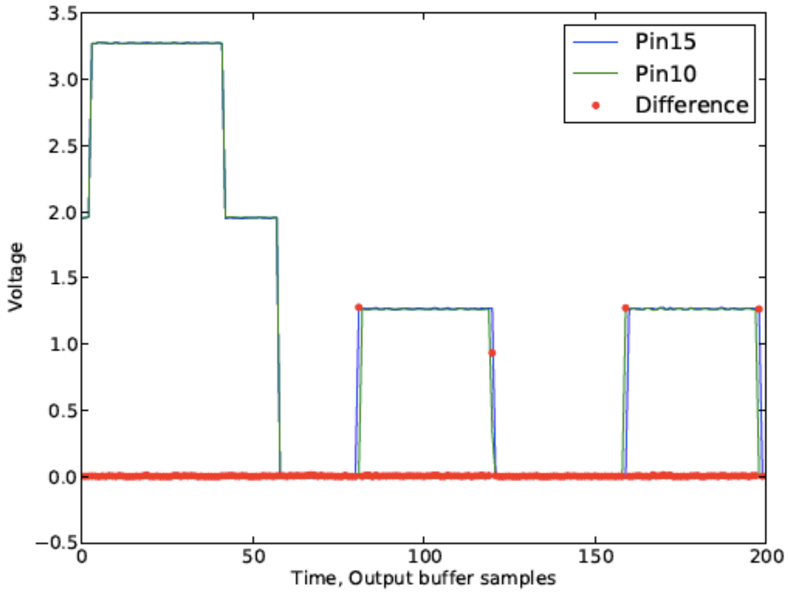


Fig. 26: 5,00% nanotubes, example with 2 inputs, evolve min difference. Input pin 4: 3208 Hz, duty cycle 94%; Input pin 13: 400 Hz, Duty cycle 79%, Output pins: 15, 10.

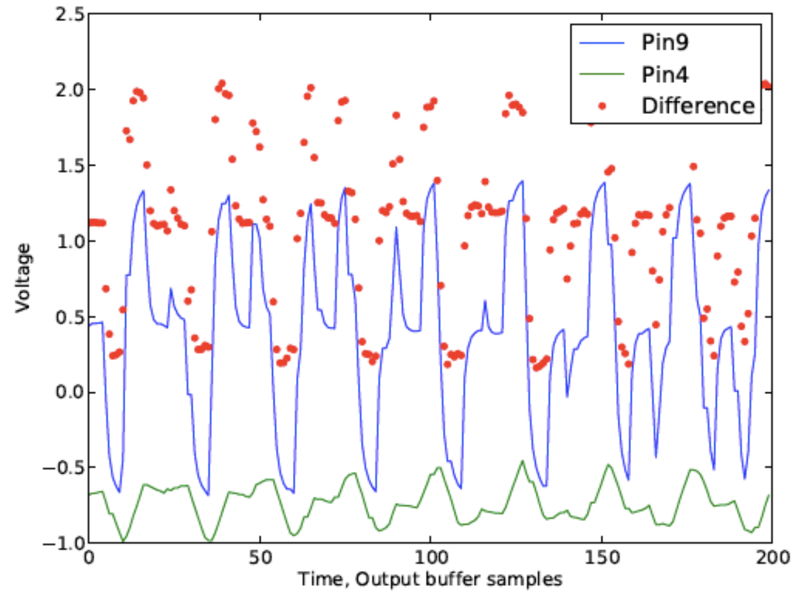


Fig. 28: 0,53% nanotubes, example with 2 inputs, evolve max difference. Input pin 10: 9595 Hz, duty cycle 79%; Input pin 8: 20299 Hz, Duty cycle 91%, Output pins: 9, 4.

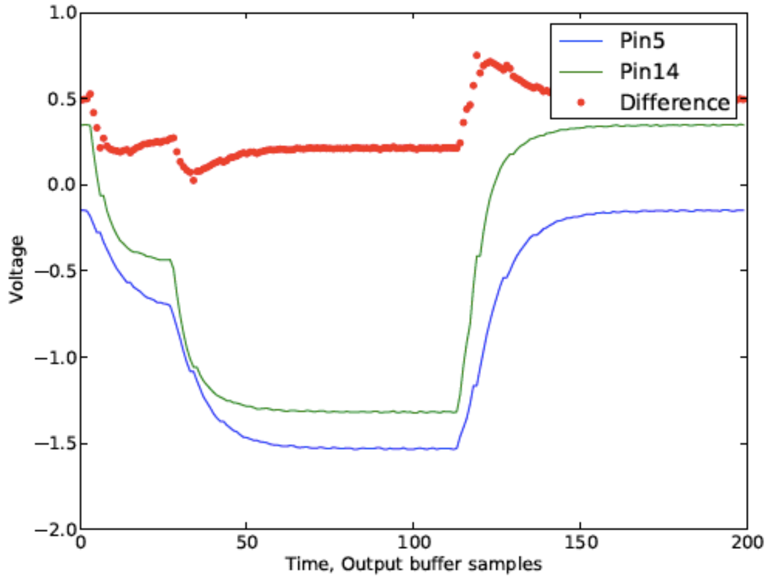


Fig. 30: 0,53% nanotubes, example with 2 inputs, evolve min difference, low frequencies. Input pin 9: 1391 Hz, duty cycle 86%; Input pin 10: 1135 Hz, Duty cycle 17%, Output pins: 5, 14.

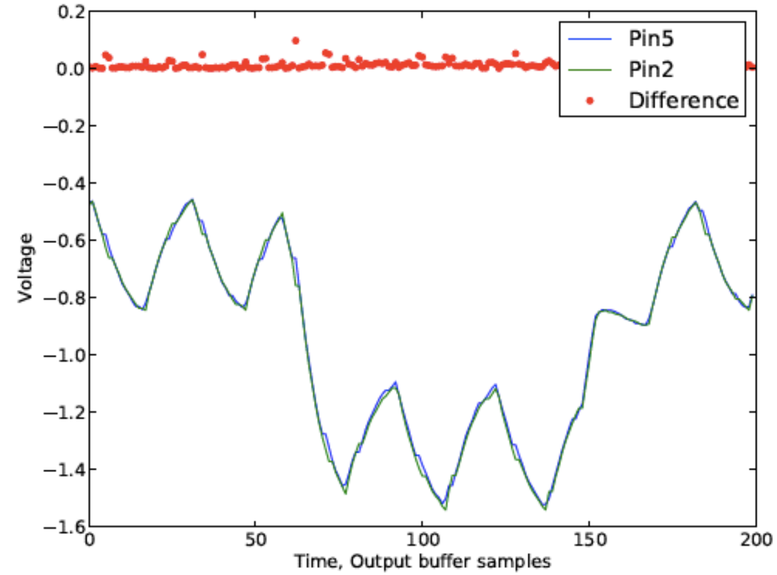


Fig. 31: 0,53% nanotubes, example with 2 inputs, evolve min difference, high frequencies. Input pin 9: 1391 Hz, duty cycle 86%; Input pin 10: 8266 Hz, Duty cycle 17%, Output pins: 5, 2.

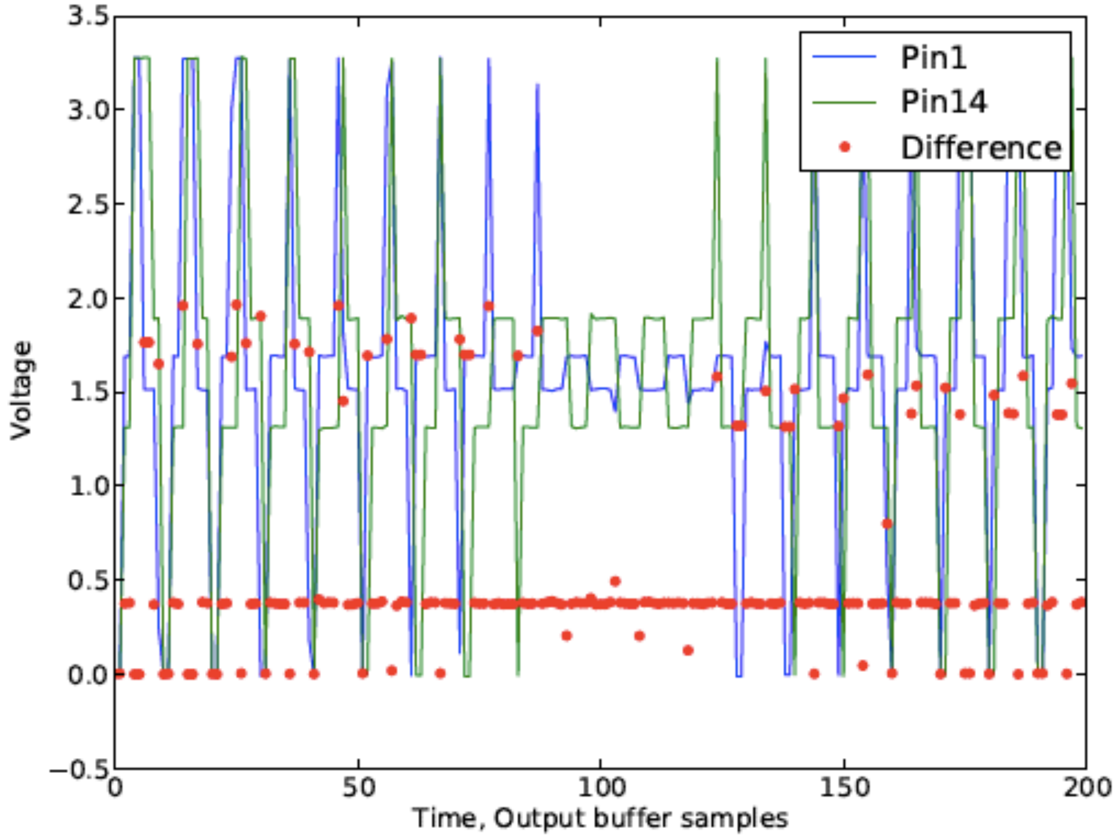
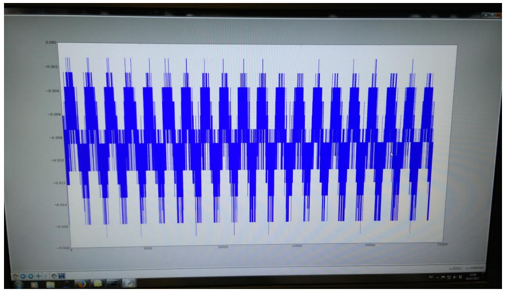


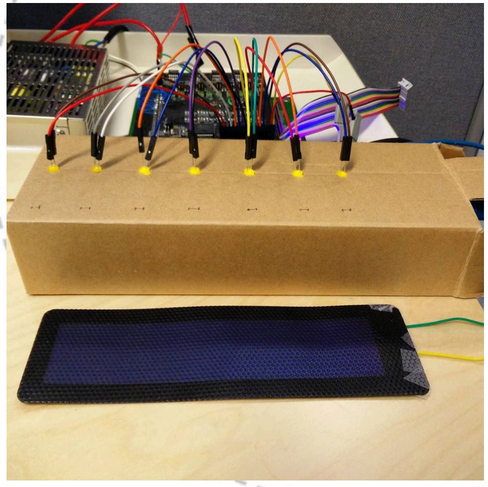
Fig. 24: 5,00% nanotubes, example with 2 inputs, evolve max difference. Input pin 13: 23945 Hz, duty cycle 27%; Input pin 2: 24576 Hz, Duty cycle 96%, Output pins: 1, 4.

Conclusion

- Evo-in-Materio -> black box
- Open the black box
- Range of evolvability
- Unanticipated strategies
- Non linearity
- Rich dynamics -> towards chaos

Future work





- Chua's circuit in materio
- Physical reservoir computing
- Movable materials, e.g. mixed with liquid crystals
- Computation with light in amorphous silicon solar panels

Special Session

Evolutionary Physical SYstems and Matter (EPSyM)

IEEE World Congress on Computational Intelligence 2016 (IEEE WCCI 2016)

Conference dates: July 25th to 29th 2016
Paper submission deadline: January 15th 2016

Vancouver, Canada

Organizers

Stefano Nichele
The Norwegian University of Science and Technology, Trondheim, Norway

Gunnar Tufte
The Norwegian University of Science and Technology, Trondheim, Norway

Stefano Nichele
www.nichele.eu