Evolution *in materio*

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What is Evolution *in materio?*

- The manipulation of a physical system by computer controlled evolution (CCE) of its physical properties

Programming with model-free matter

- The dominant view of computation is based on Boolean logic. Yet *we* are not based on that
- How can we utilize the magnificent potential for computation in the physical world without understanding the rules of the game?

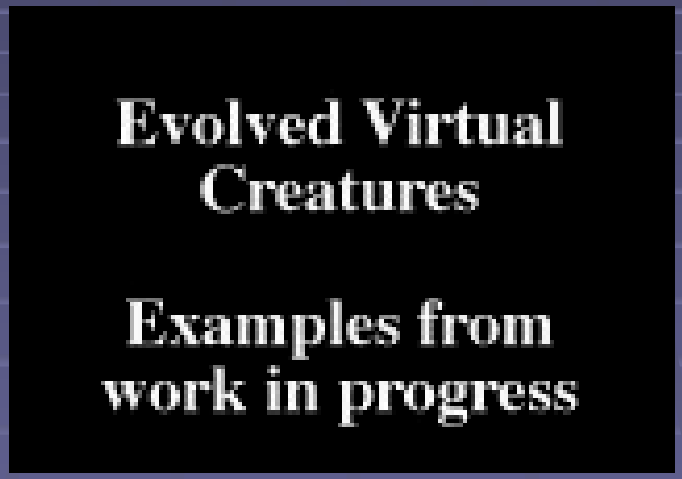
Why we should be interested in evolution *in materio*?

- Natural evolution is *par excellence* an algorithm that exploits the physical properties of materials
- Artificial Evolution may be more effective when the configurable medium has a rich and complex physics
- It holds the promise that we can discover new computational devices

From Evolution *in simulo to* Evolution *in materio*

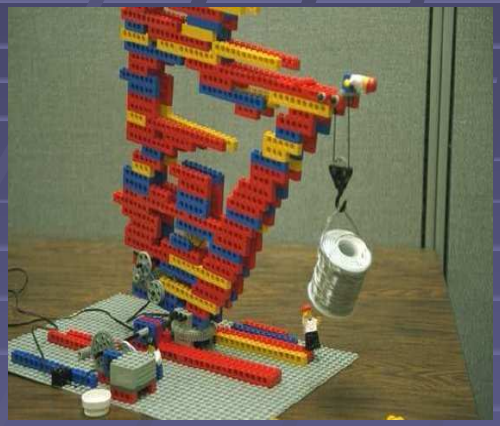
- Evolving using simulated physics
- Evolving in simulation and then building
- Evolving without simulation (in *materio*)

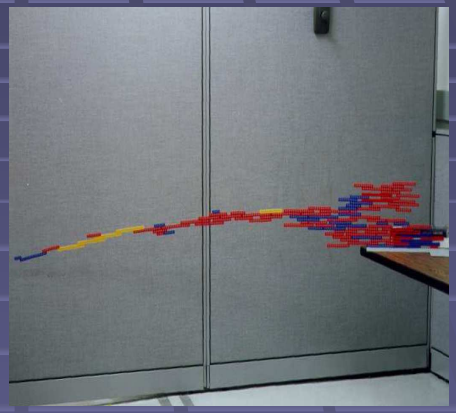
Evolution in simulo: a classic

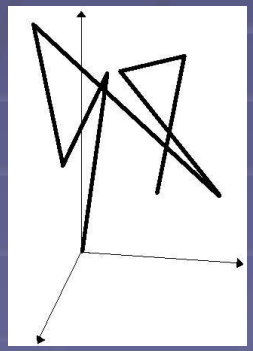


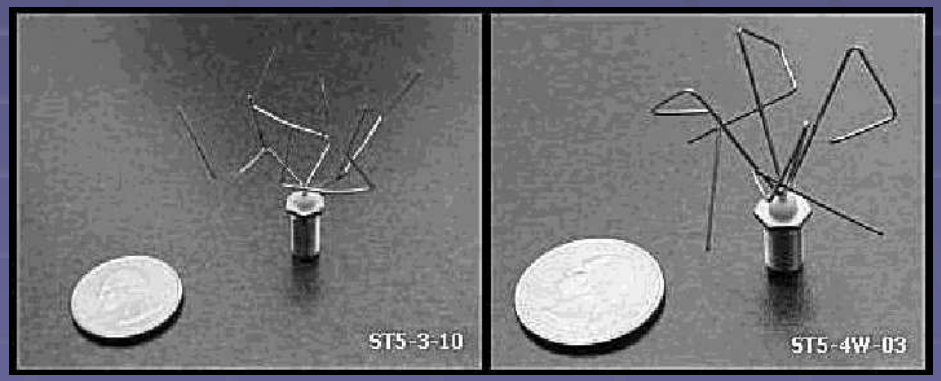
Karl Sims, 1994

From simulation to physical implementation: static structures









(top) Funes and Pollack, Artificial Life 1998.

(bottom left) Linden and Altshuler, Microwave Journal 1996

(bottom right) Lohn et al. 2004

From simulation to physical implementation: moving structures

Pollack et al, Artificial Life, 2001

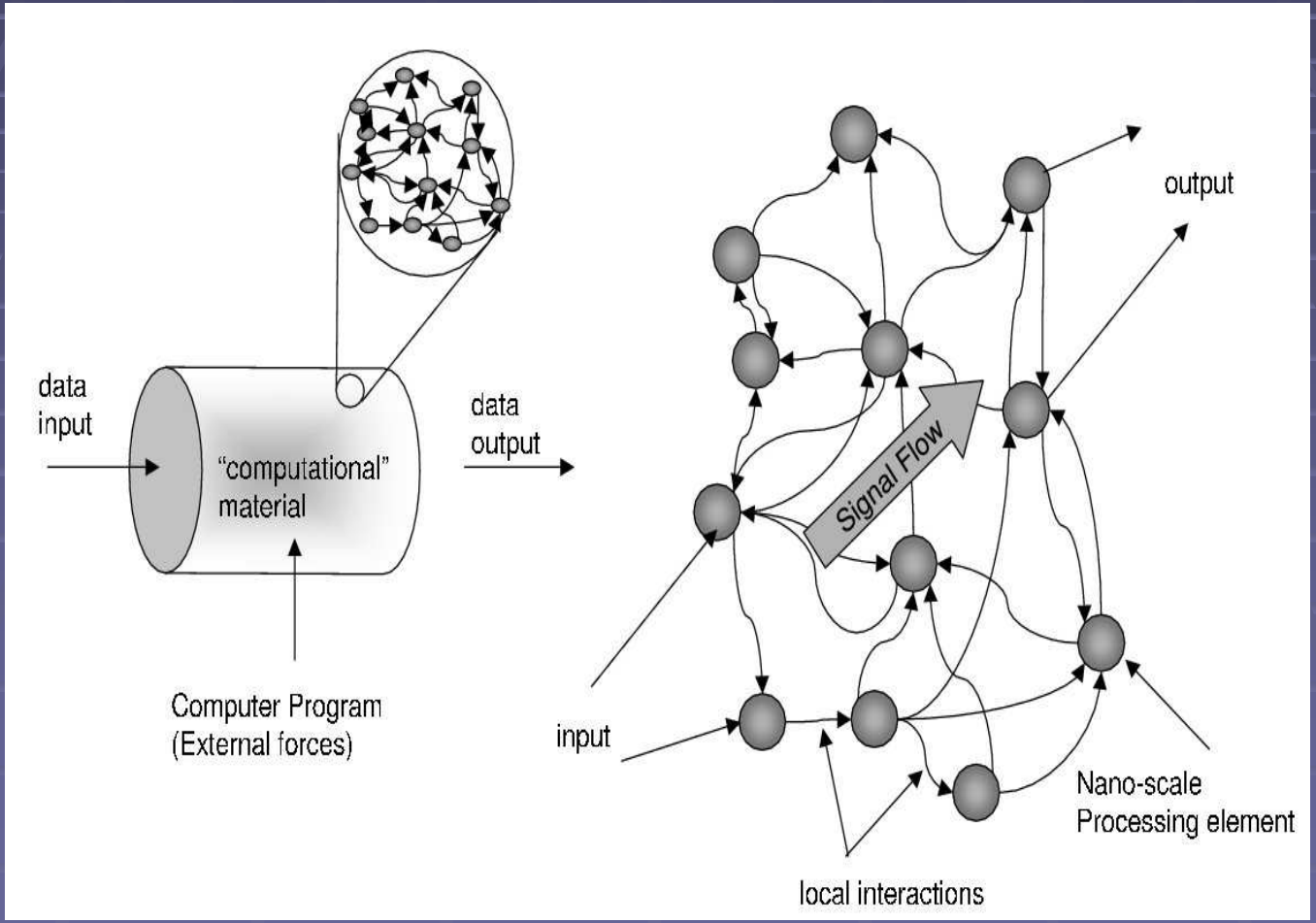
Properties required by evolvable physical media?

- Their physical properties must be affected by changes to external controllable physical variables
- To be evolvable the media must be
  - Strong criterion: must be able to be reset
  - Weak criterion: strong genetic inheritance of physical characteristics

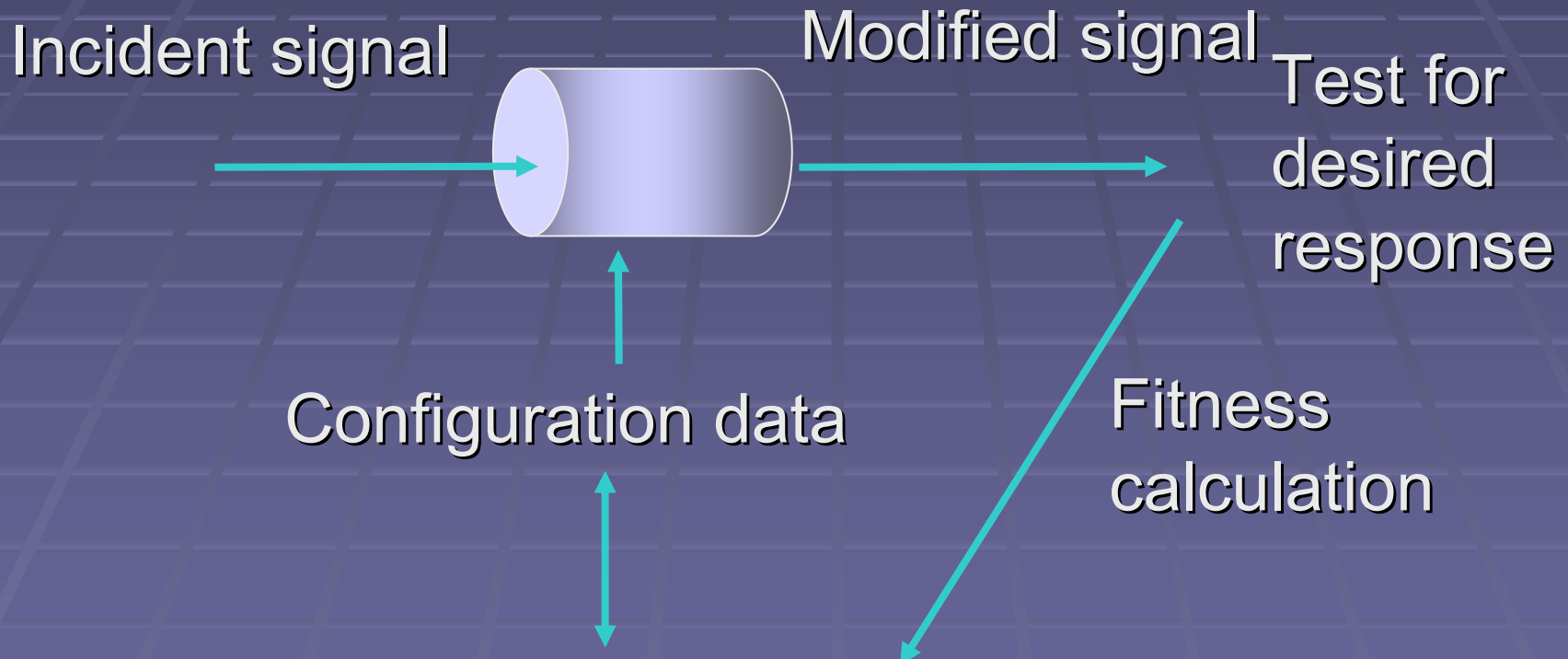
Some dangers of conventional programming…

- “In conventional design the vast majority of interactions that could possibly contribute to the problem are deliberately excluded” (Michael Conrad 1988)
- “Get a computer to do what needs to be done, without telling it how to do it” (Arthur Samuel 1983)
- “Nothing makes sense in computing except in the light of evolution” (Toffoli 2005)

Making matter compute



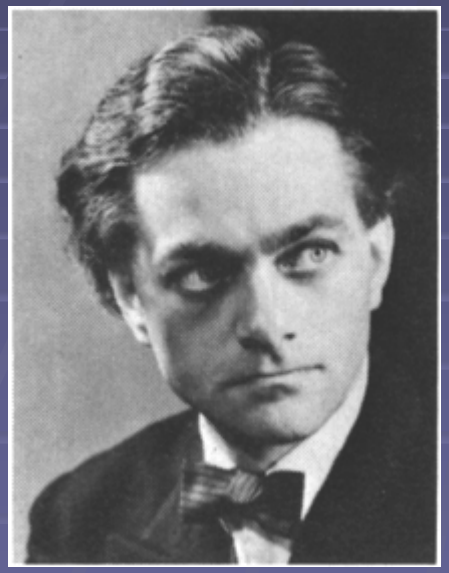
How do you *evolve* matter to compute?



Has anybody demonstrated evolvable physical media?

- Gordon Pask? 1958 - Ferrous sulphate
- Jonathan Mills? 1996 – conducting plastic foam
- Adrian Thompson, 1996 - silicon
- Adrian Stoica, Didier Keymeulen, Riccardo Zebulum, 2000 - silicon
- Huelsbergen, Rietman, Slous, 1998 - silicon
- Derek Linden, 2001 - reed switch array
- Jon Bird and Paul Layzell, 2002 - silicon
- Simon Harding and Julian Miller, 2004 - liquid crystal

Gordon Pask

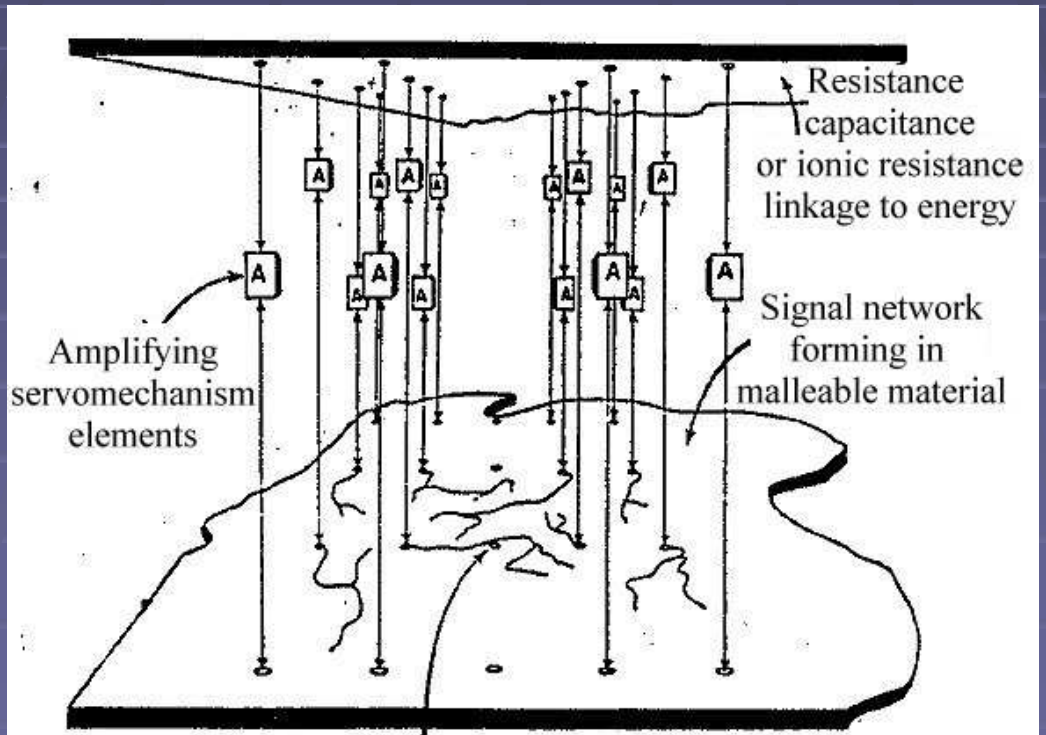


"Physical analogues to the Growth of a Concept" Mechanization of Thought Processes, Symposium 10, National Physical Laboratory, H.M.S.O (London) pp 765-794, 1958.

What Pask was trying to do

- Build a machine without any explicit definition of its parts (self-building)
- Able to build its own “relevance criteria” and find the observables required to solve the task
- He needed a ‘physically rich’ machine which could be adaptively steered

Schematic of Electrode array and Ferrous sulphate medium



Thread structures forming in malleable material Note A equals Amp

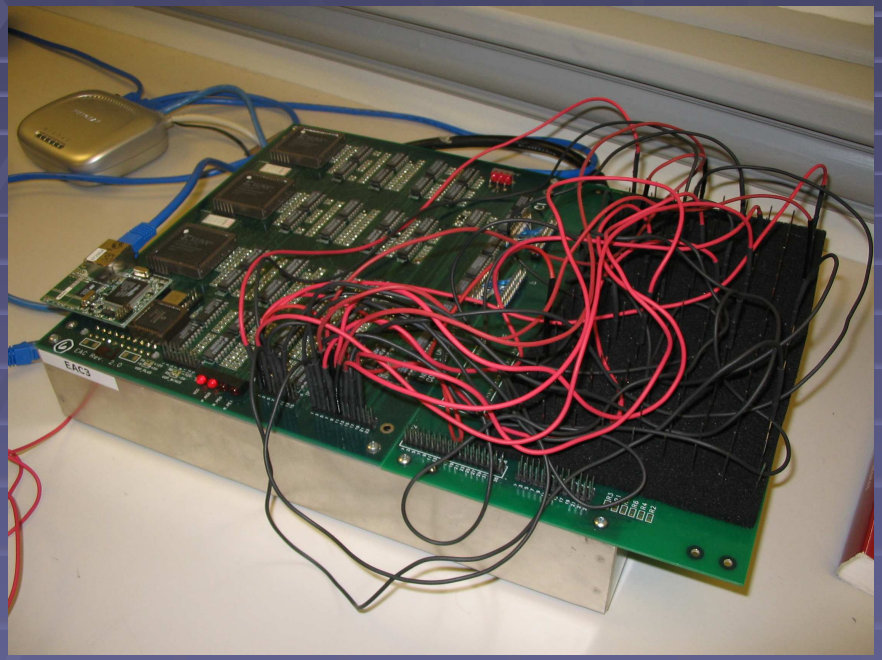
What Pask did

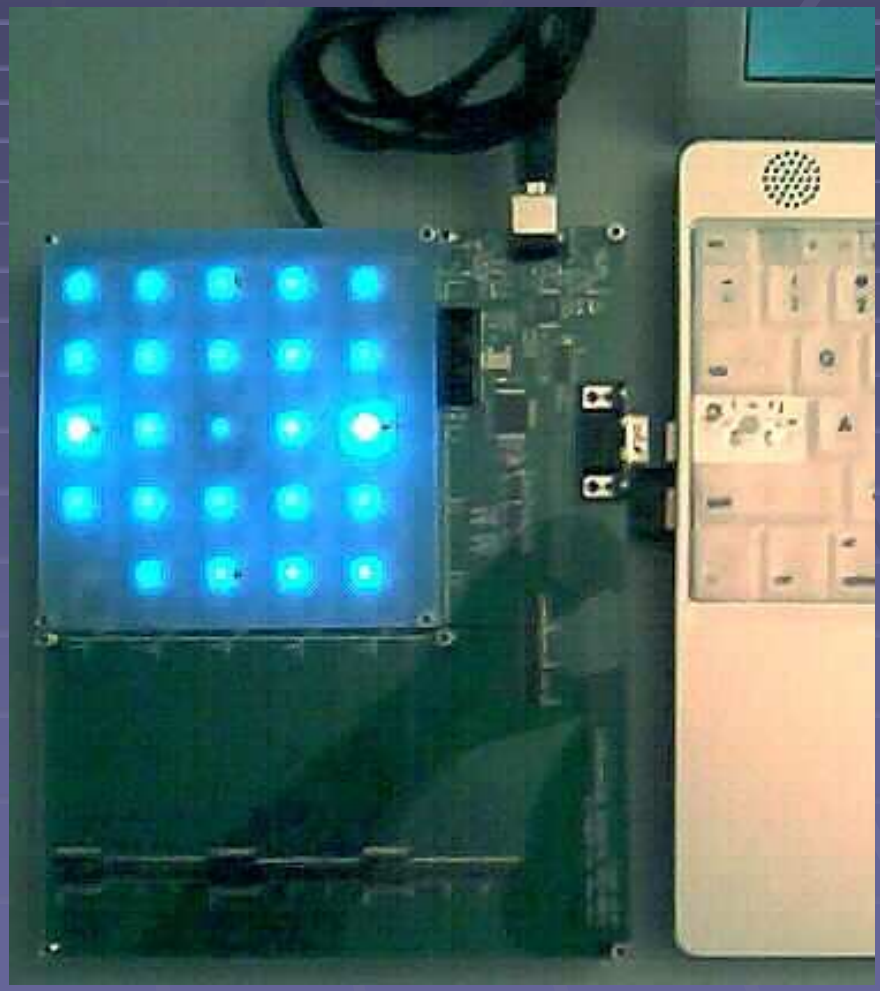
"…the rewarding procedure acts by supplying more current for constructing threads whenever the mode of problem solution, implied by the existence of a certain thread structure, satisfies an external criterion, such as maximising the output of the process. In this learning by reward procedure some threads flourish, others will prove abortive. *It is a lengthy and inefficient kind of learning not unlike natural selection*" - (Pask 1958)

“We have made an ear…”

- “We have made an ear and a magnetic receptor. The ear can discriminate two frequencies, one of the order of fifty cycles per second and the other on the order of one hundred cycles per second. The ‘training procedure’ takes approximately half a day and once having got the ability to recognize sound at all, the ability to recognize and discriminate two sounds comes more rapidly…” - (see Cariani 1993)

Jon Mill's Extended Analogue Computer

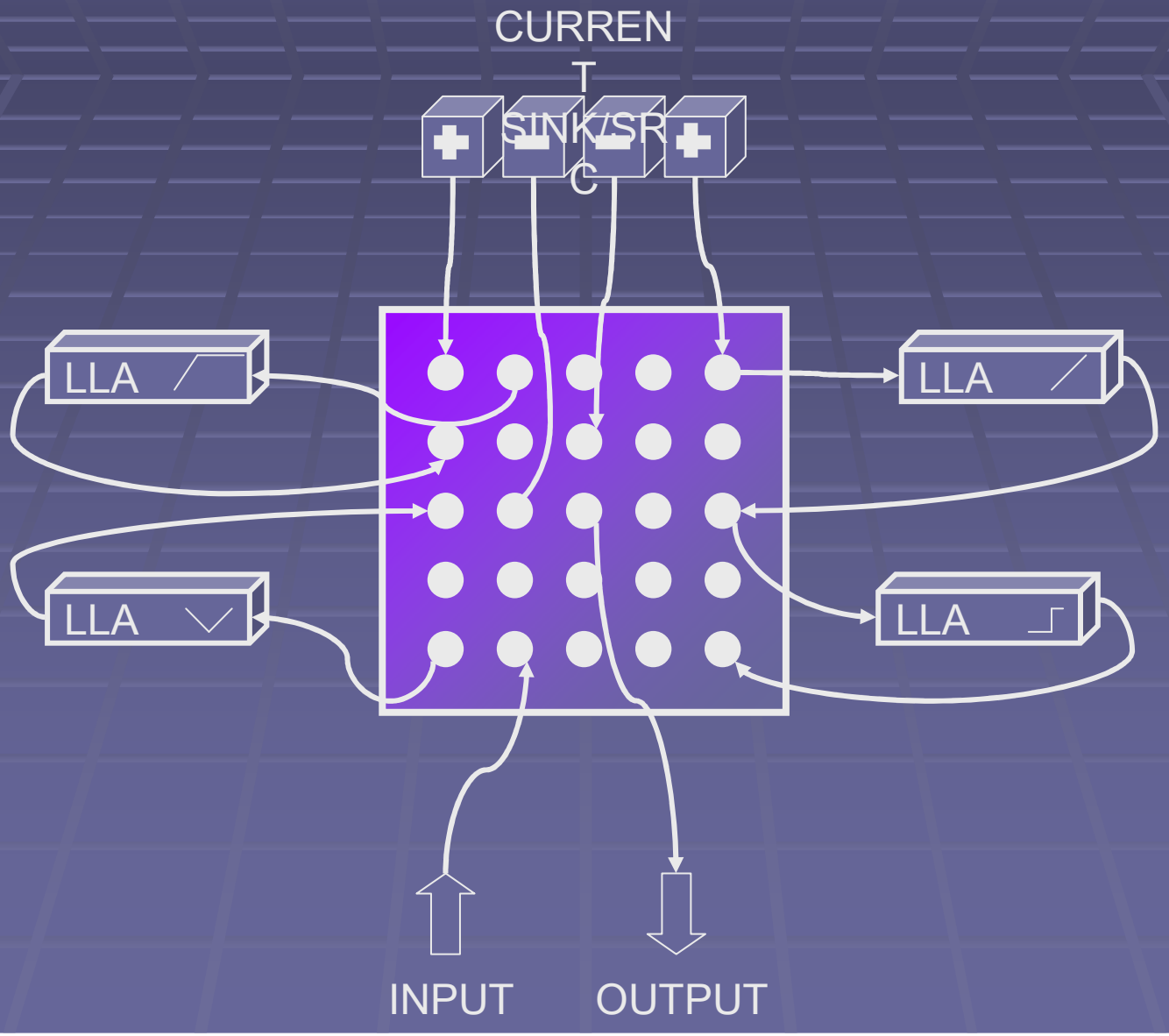




Computing substrate is conducting packaging foam

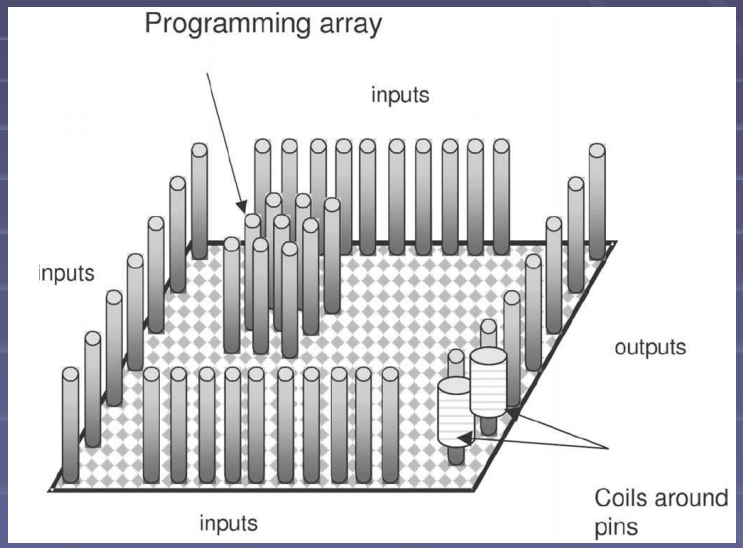
Mills 1996

Extended Analogue Computer



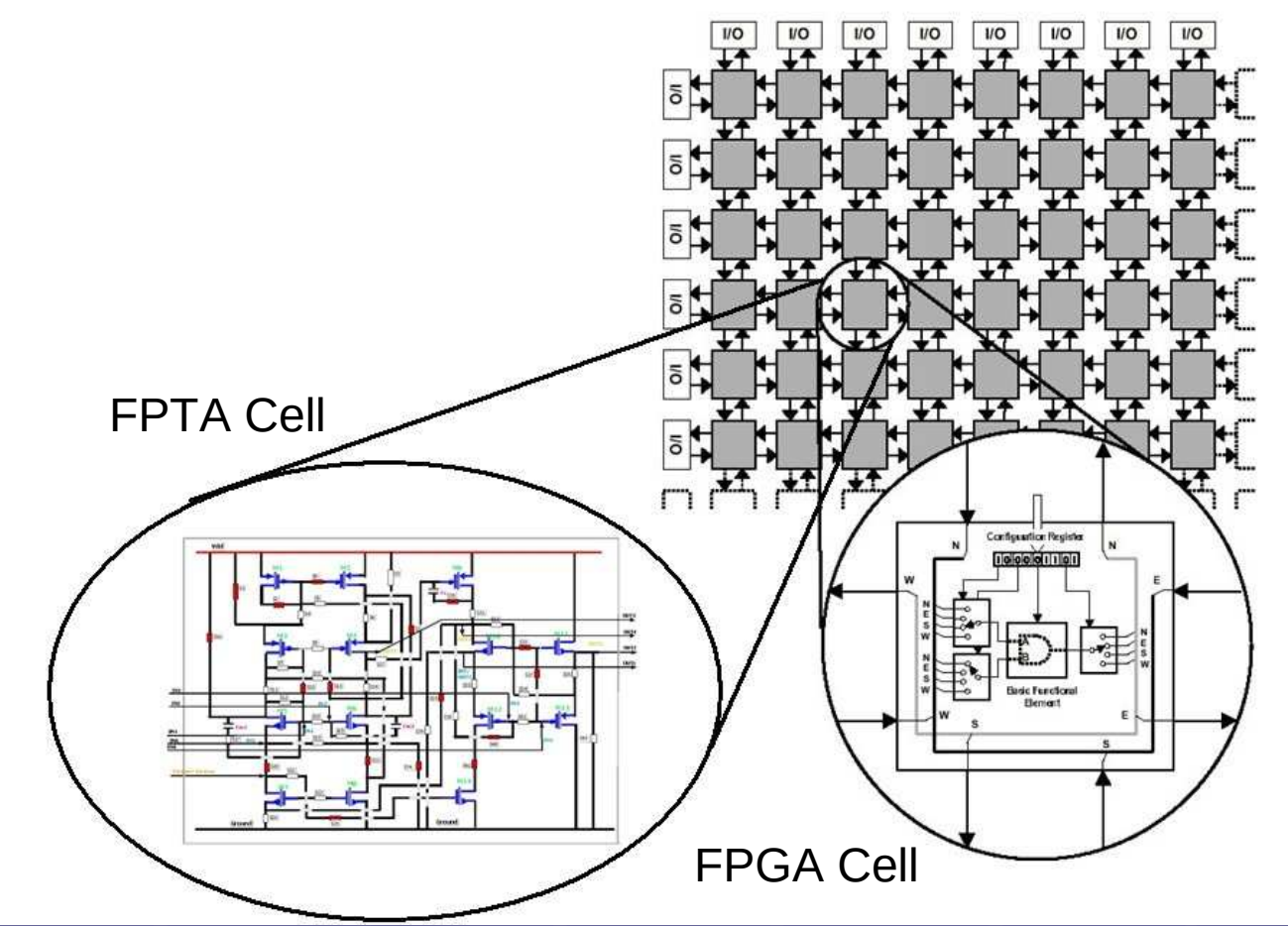
Quantum Dot Computation

- Dots have two spin states
- Array acts as a two dimensional cellular automaton
- Magnetic probes set the initial spin states of the dots
- The dots interact and the states of the output dots are read
- In principle an evolutionary algorithm could decide the initial CA configuration

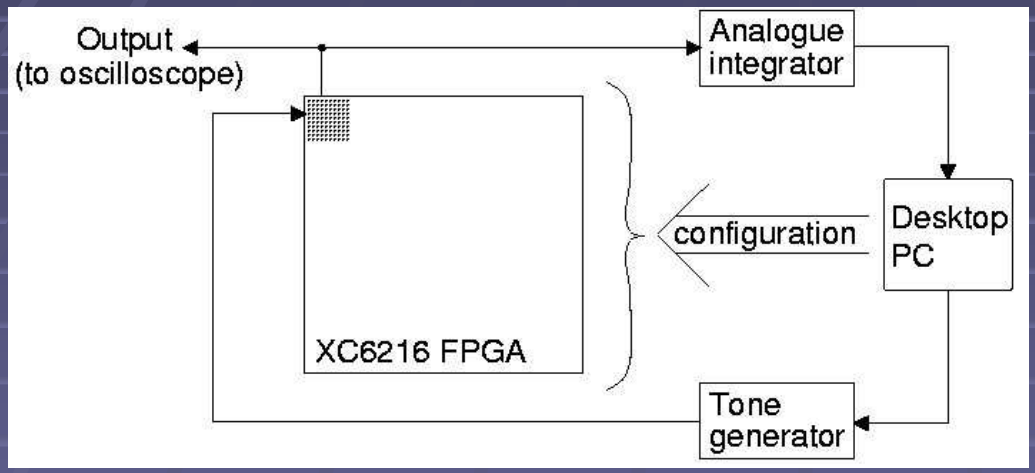


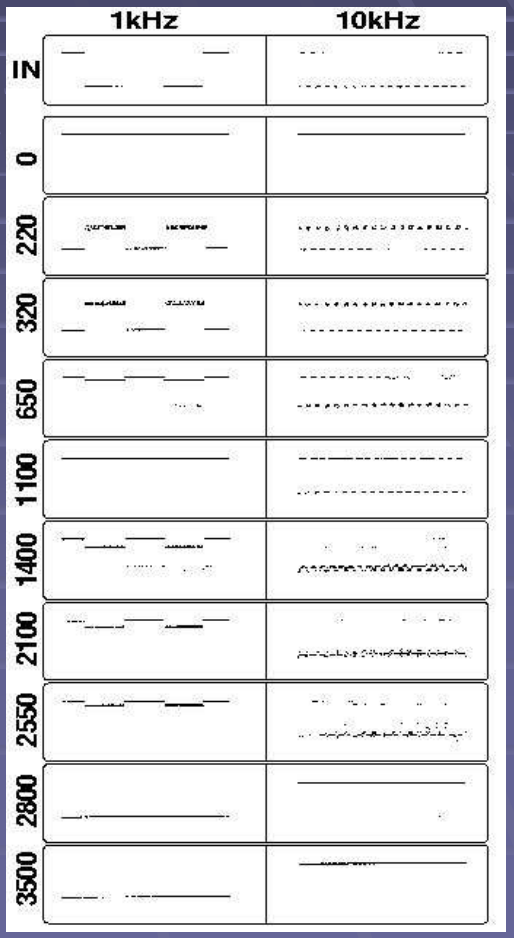
For more detail see: Harding, Miller, Rietman *Journal of Unconventional Computing,* 2008

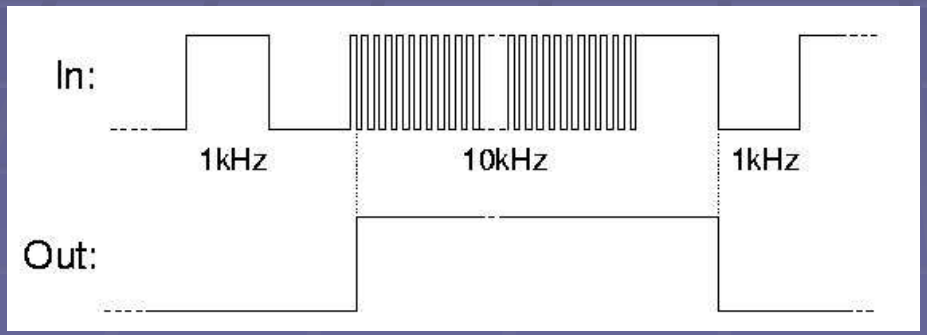
Generic *in silico* evolvable platform



Adrian Thompson's experiment

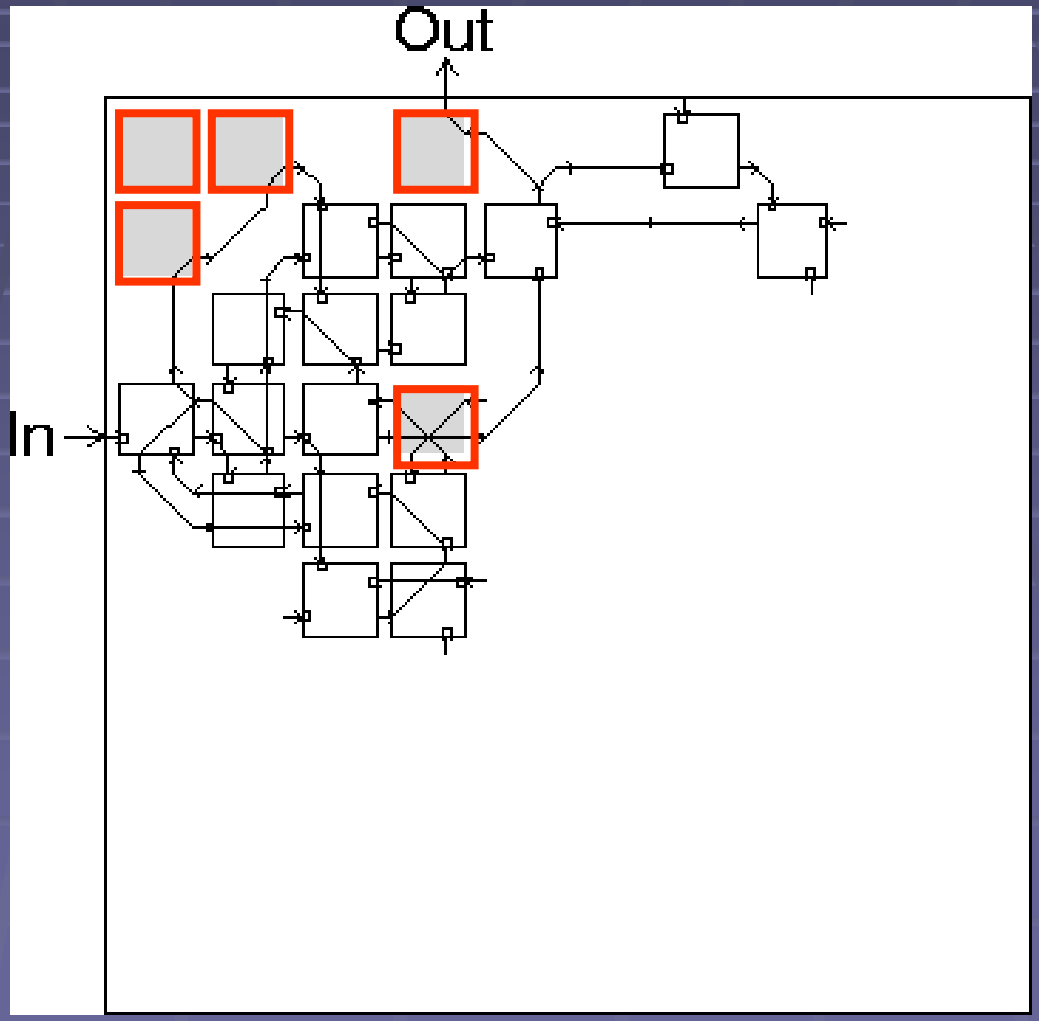






Thompson 1996

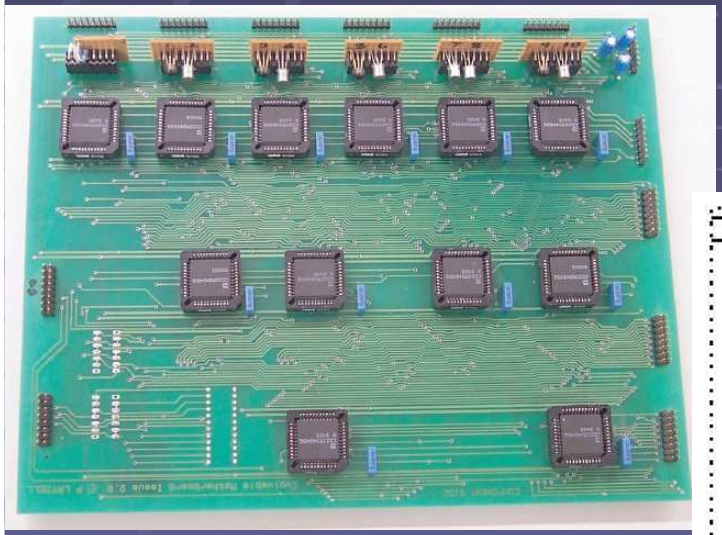
The functional circuit

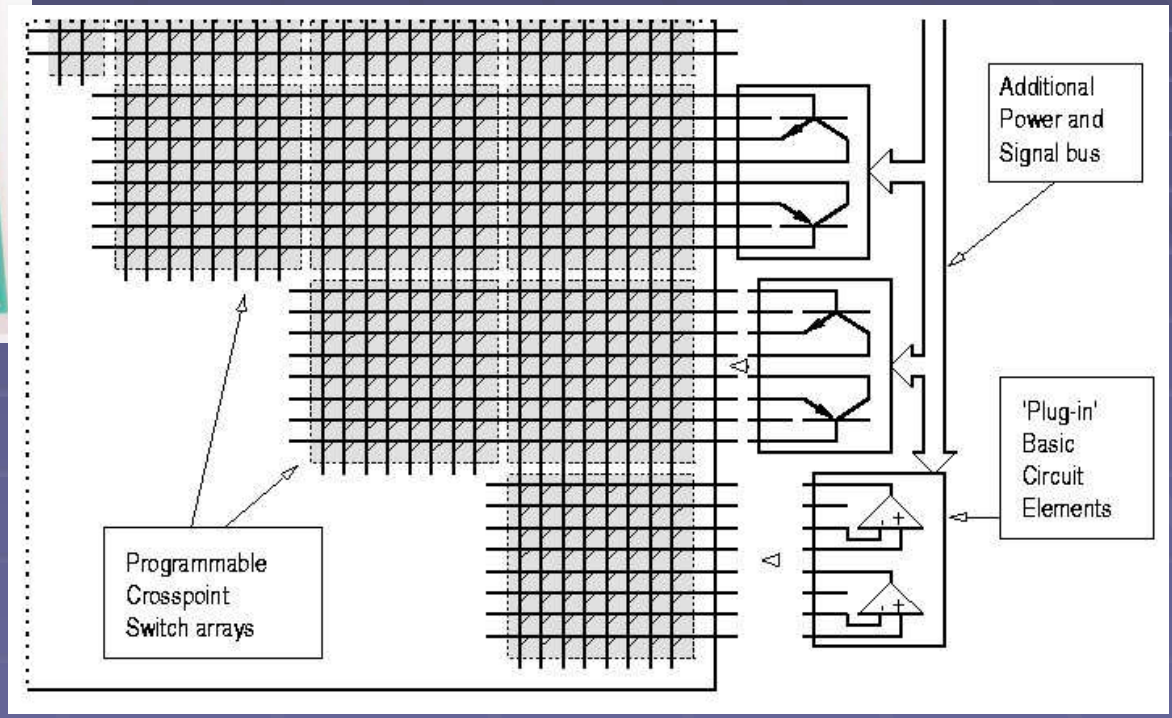


Thompson and Layzell's Conclusion

- Core of timing mechanism is a subtle property of the VLSI medium
- They ruled out:
  - glitches, beat frequencies
  - metastability
  - thermal time-constants (self-heating)
- *Evolution has exploited properties of the system that are at present unknown*

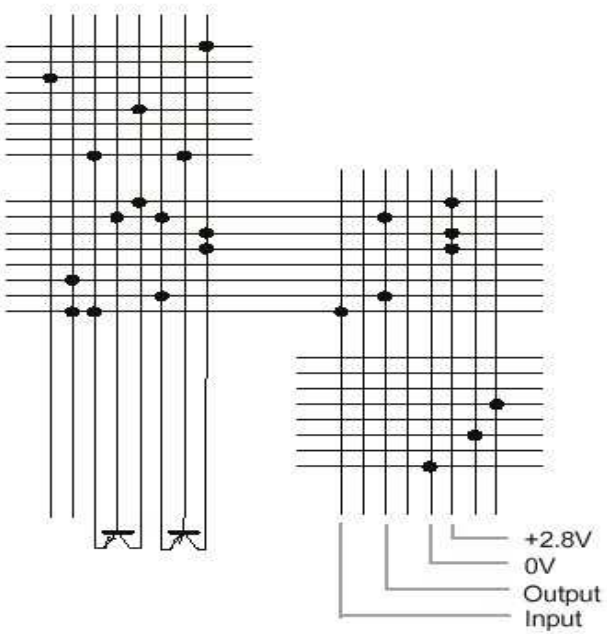
Paul Layzell: Evolvable Motherboard

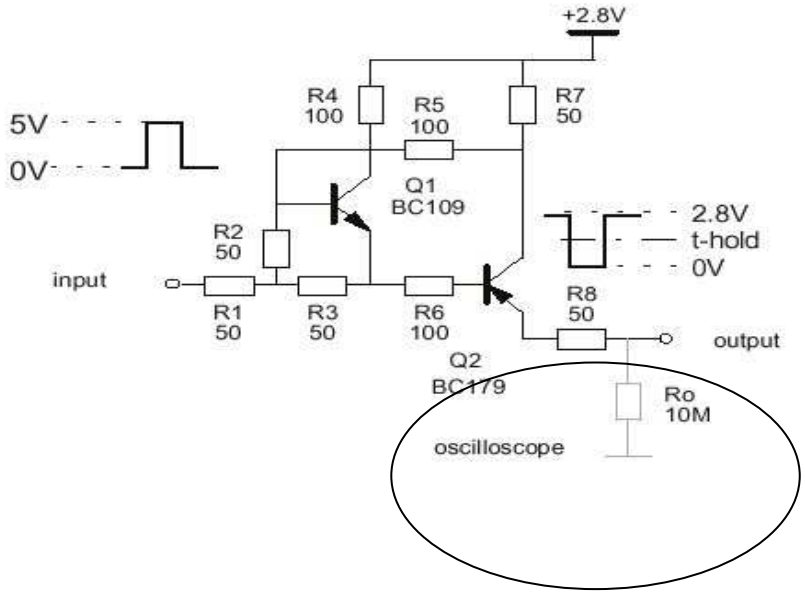




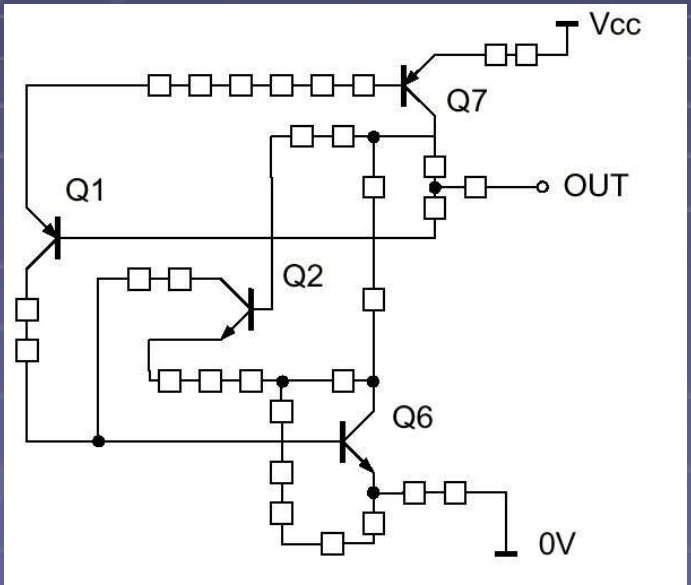
Layzell 1998

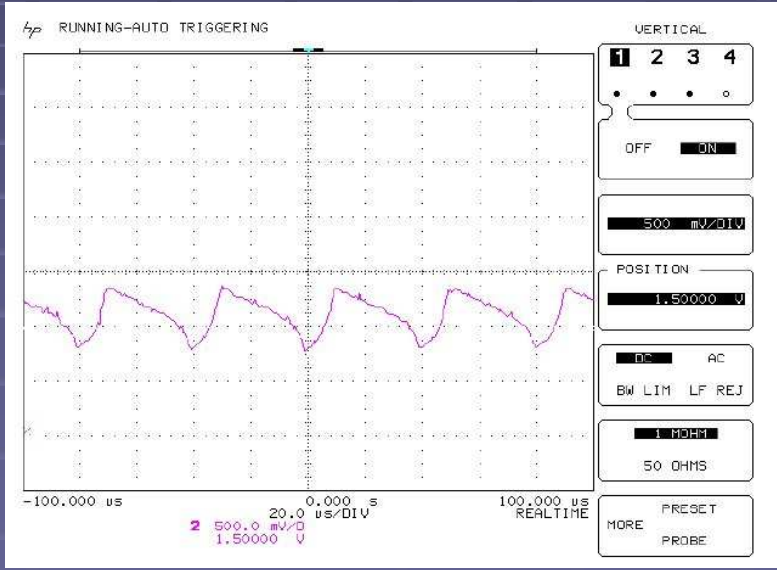
An evolved inverter that used the measurement apparatus as a circuit component!





Evolved oscillator circuit and output response (Layzell)





In 20 runs 10 were successful to within 1% with a minimum amplitude of 100mV

Analysis of evolved oscillators

- Difficult to clarify how the circuits work
- If transistors are replaced by nominally identical ones, the output frequency can change by up to 30%
- Simulation of circuits with parasitic capacitance failed to oscillate
- Some oscillators only worked while a nearby soldering iron was switched on!
- Programmable switches' characteristics are almost certainly important for circuit operation

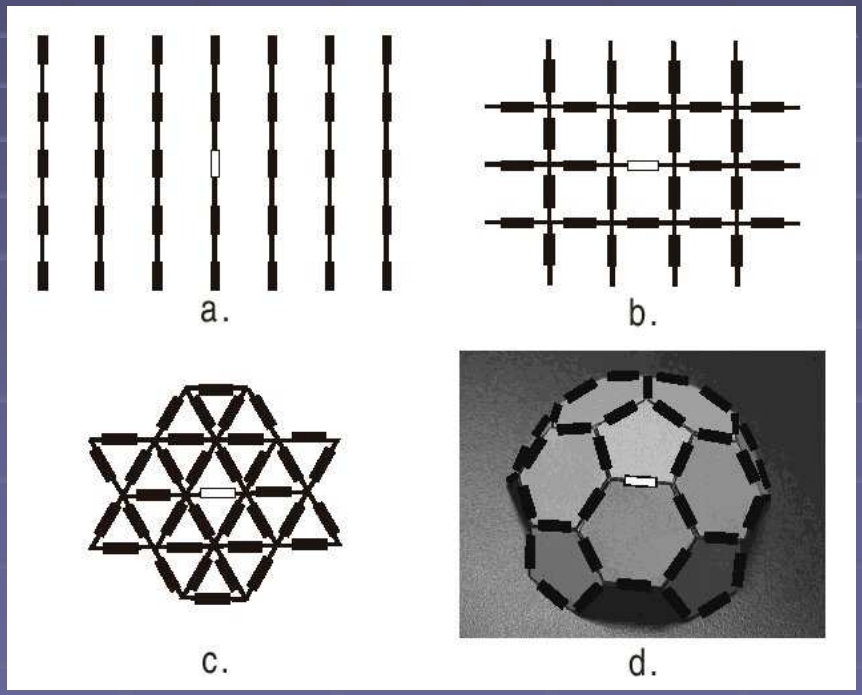
An evolved radio

- Some circuits that achieved high fitness were found to be amplifying radio signals (generated by nearby PCs) that were stable enough over the sampling period to give good fitness scores
- The circuit board tracks were being used as an aerial!

Bird and Layzell 2002

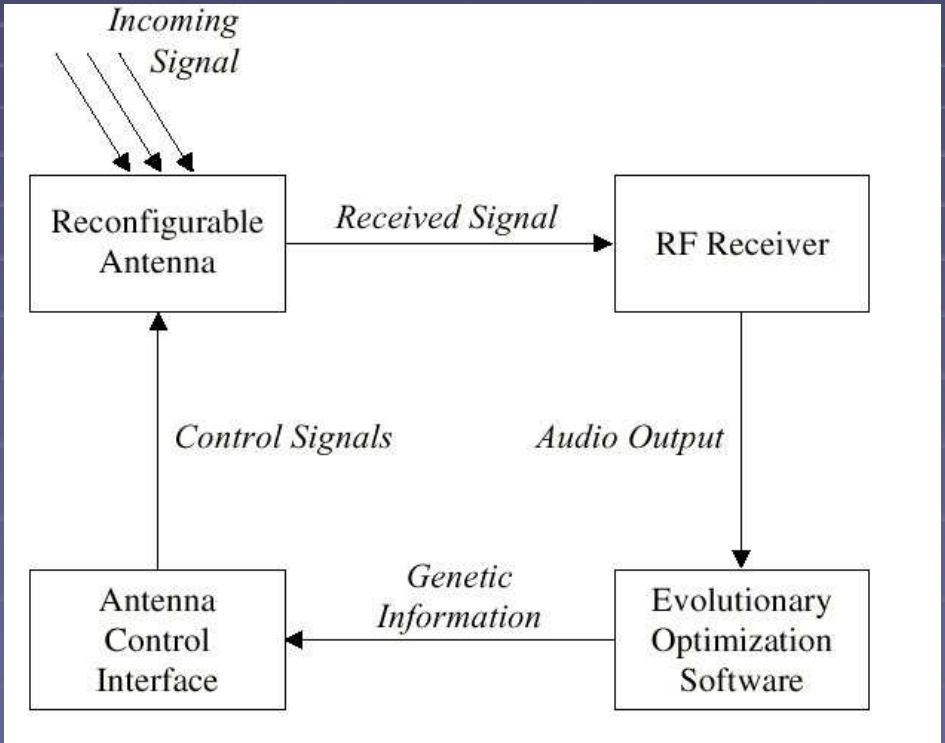
Evolution of antennas

- Physical evolution of antennas using reed switches



Linden 2001

Evolve and test apparatus



Evolution *in silico* or *in materio?*

- Unconstrained evolution in silicon is possible
- Intrinsic evolution often utilizes incidental environmental effects to achieve a solution
- Although these can be a nuisance we should not give up. *It is too early to worry about analysis.*
- Other material systems may have advantages. At the very least evolution may tell us that computational circuits can be constructed in unusual systems. This may inspire conventional design in such systems (i.e. evolution as a discovery tool)

What material systems could we use?

- Liquid crystal
- Conducting and electroactive polymers
- Electrochromic glass
- Voltage controlled colloids
- Irradiated Silicon
- Langmuir-Blodgett films
- nanoparticle suspensions
- microbial consortia
- Excitable media (reaction diffusion systems)
- Biological neurons

Effects of applied fields on nanoparticle suspensions

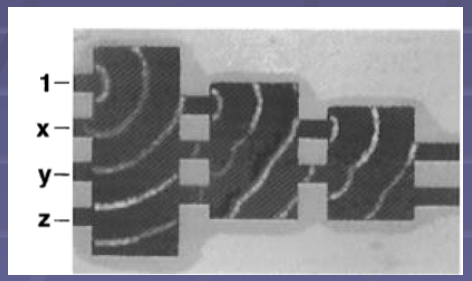
- Gold nanoparticles in water form wires and other structures under the influence of an alternating electric field

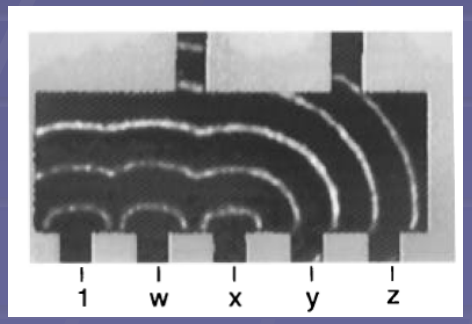
Hermanson et al., Science, 2001

- Scientists at Rensselaer Polytechnic Institute found that the contact angle of a droplet of nanofluid solution changes when exposed to an electric field. February 19, 2008

Source: http://www.physorg.com/news122660454.html

Computation through reaction-diffusion processes





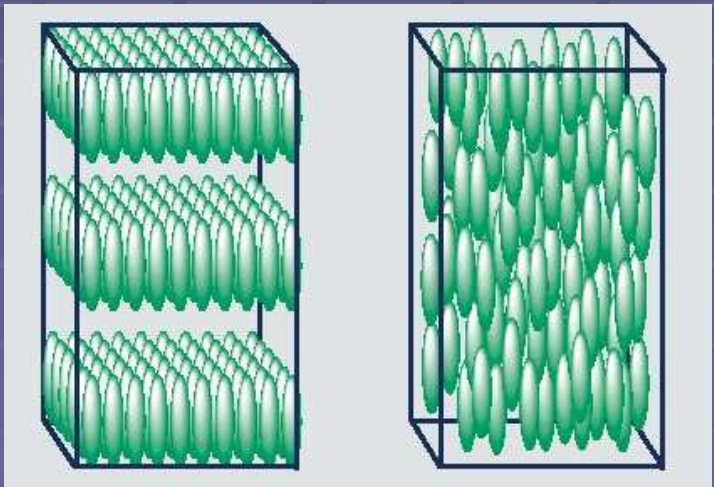
Massively parallel computing device

- micro-volumes of the chemical medium act as elementary processors; data and the results of the computation are encoded as concentration profiles of the reagents,
- Computation is performed via the spreading and interaction of waves caused by the local disturbances.
- Drawbacks: slow, difficult to control, uncertain programmability

Adamatzky et al 2005

Liquid crystal programmable matter?

- Mesoscopic organisation:
  - Size between atomic and macroscopic. Such systems exhibit emergent organised behaviour



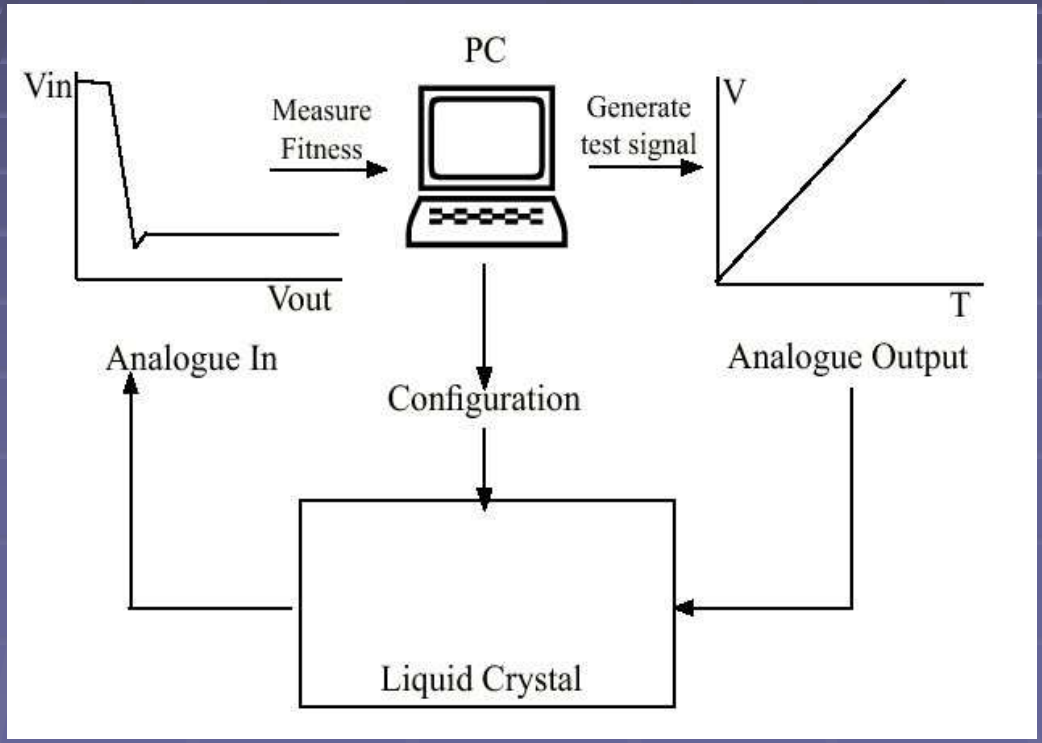
smectic nematic

Organic elongated polar molecules that are affected by electric fields

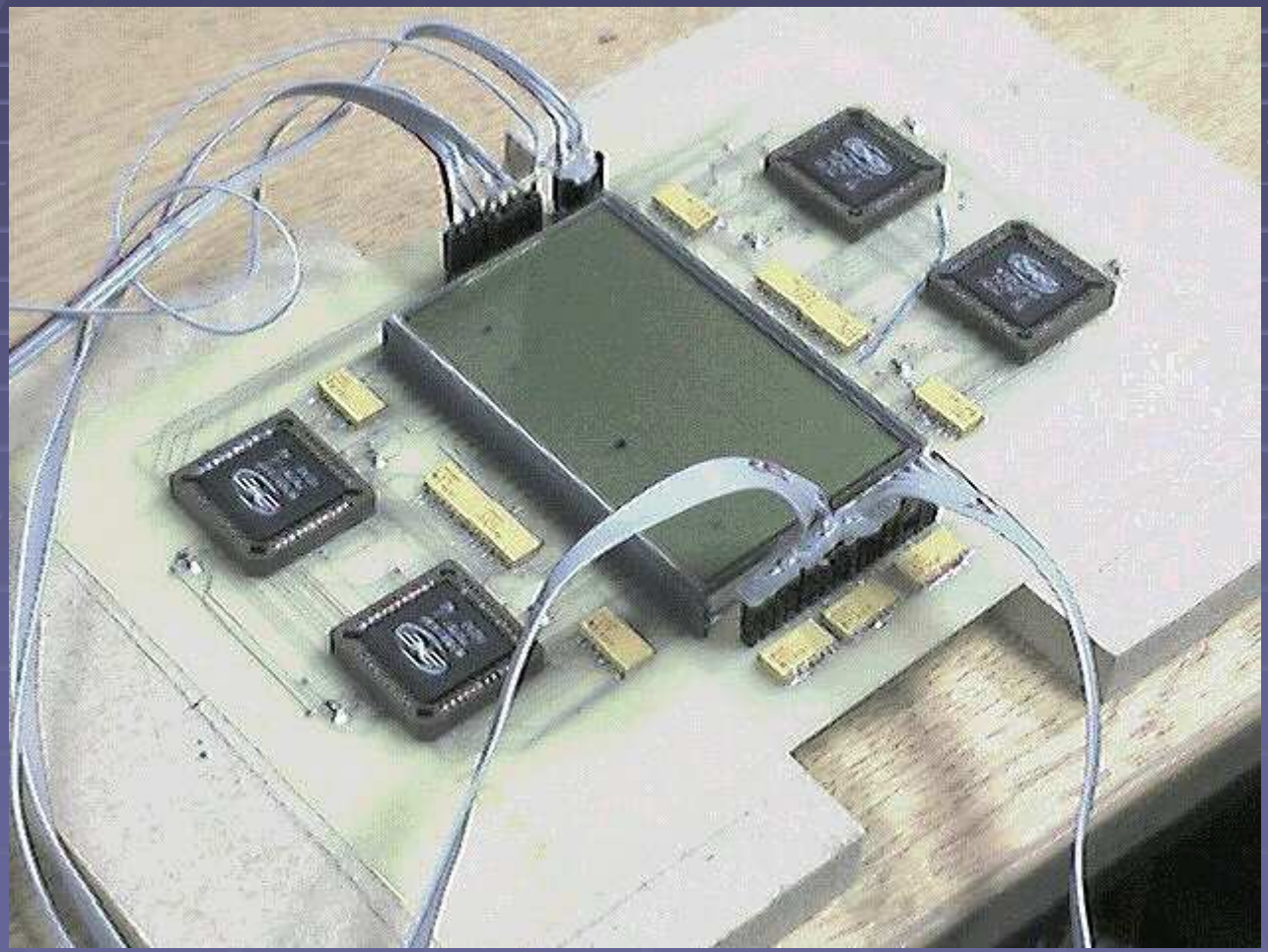
Many other types: dye-doped, polymer dispersed, conducting, discotic

Evolution in Liquid Crystal

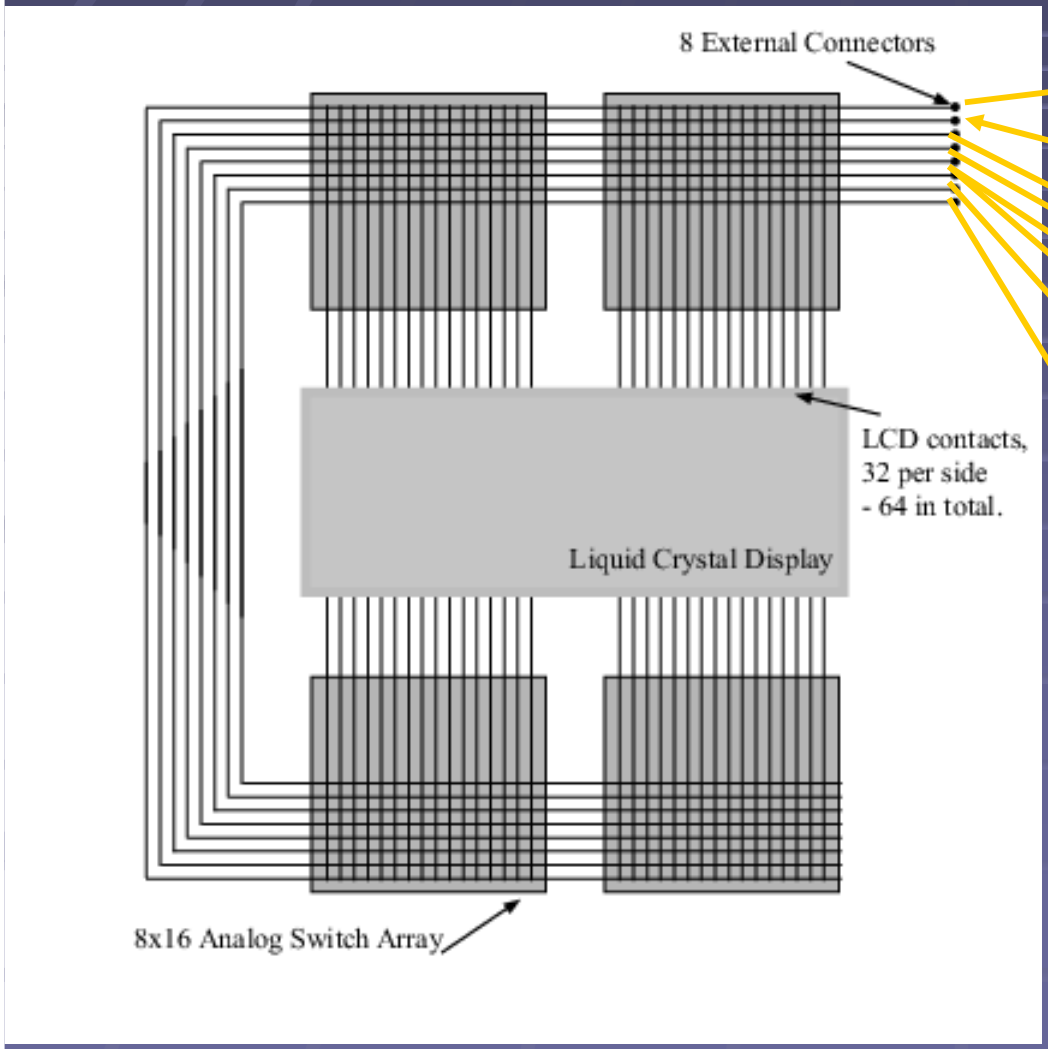
- It is possible to evolve computational functions in liquid crystal (Harding and Miller 2004 onwards)



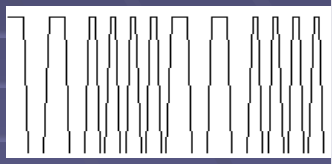
In materio evolution in progress



LC Evolvable Motherboard



LC OUTPUT



INPUT SIGNAL

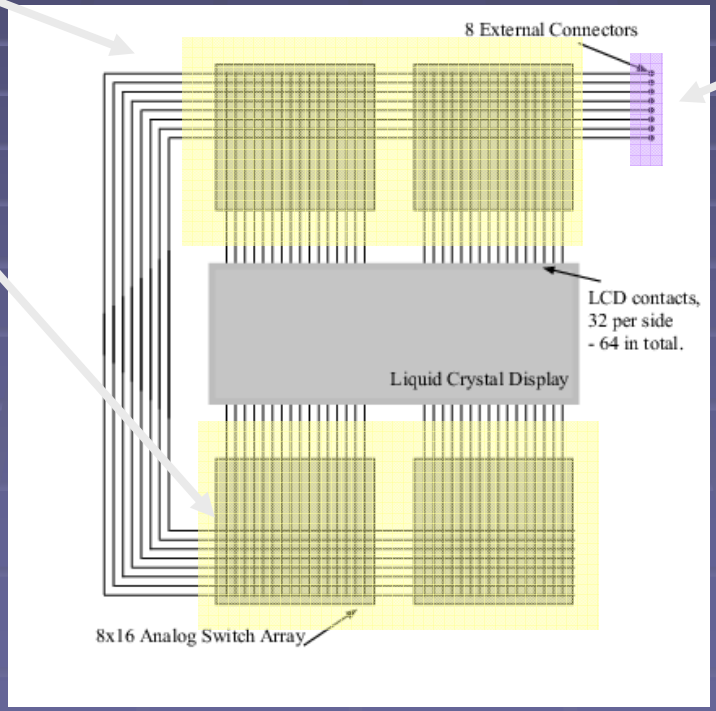
GND

CONFIGURATION
VOLTAGES

Genotype representation

0 1 2 6 3 7 2 4 8 3 0 1 7 3 5 1 3 5 ....

0.2 -0.4 1.4 3.4 3.9



Ground (fixed)

Input signal (fixed)

Output signal (fixed)

5 input voltages in range -10v to +10v discretized in 16bit levels

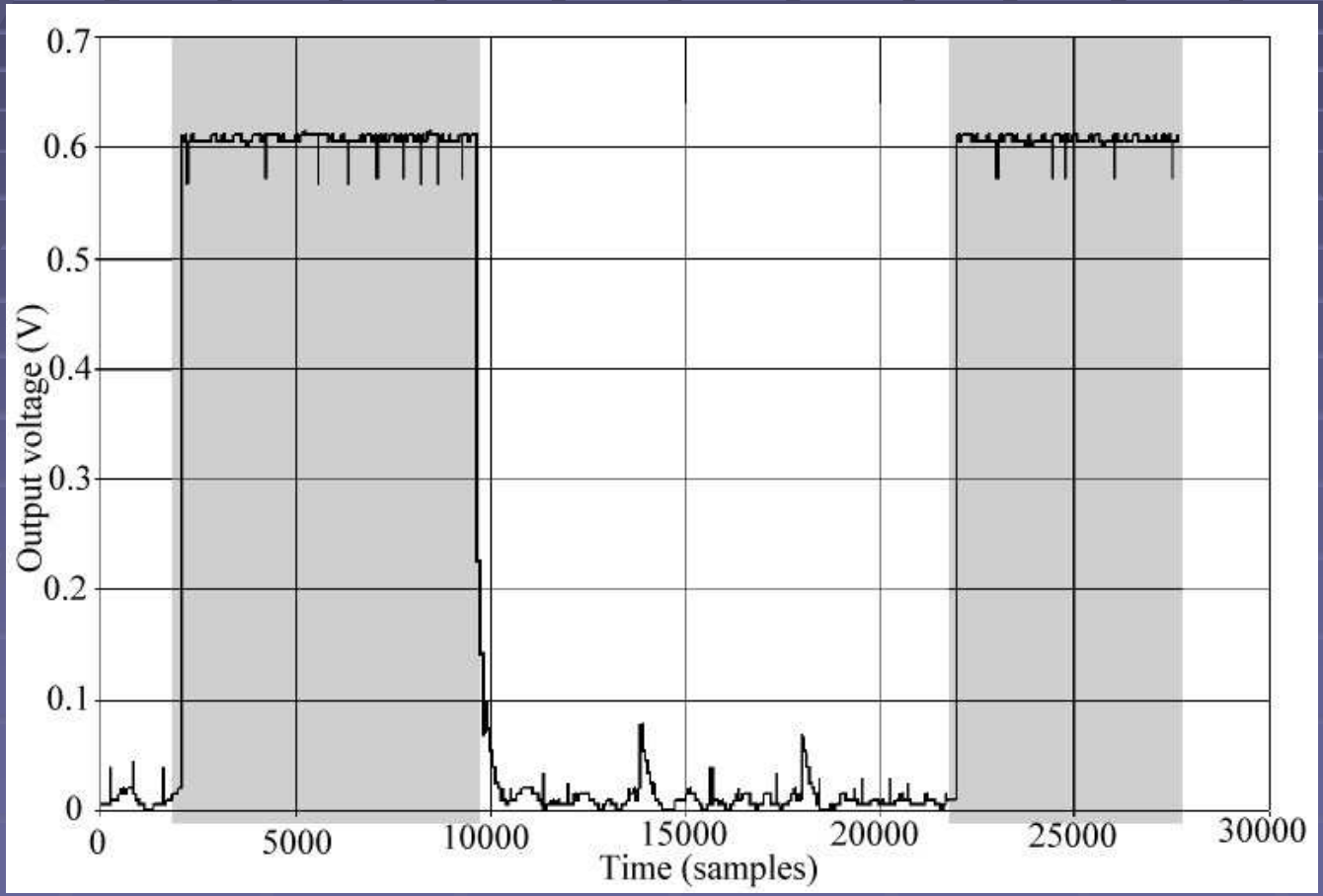
Genetic Algorithm

- Population 40
- Top 5 genotypes promoted. Population filled with tournament selected (size 5) others that were mutated (5 mutations each)
- 100 generations.
- It took approximately 1 minute to evalute each generation

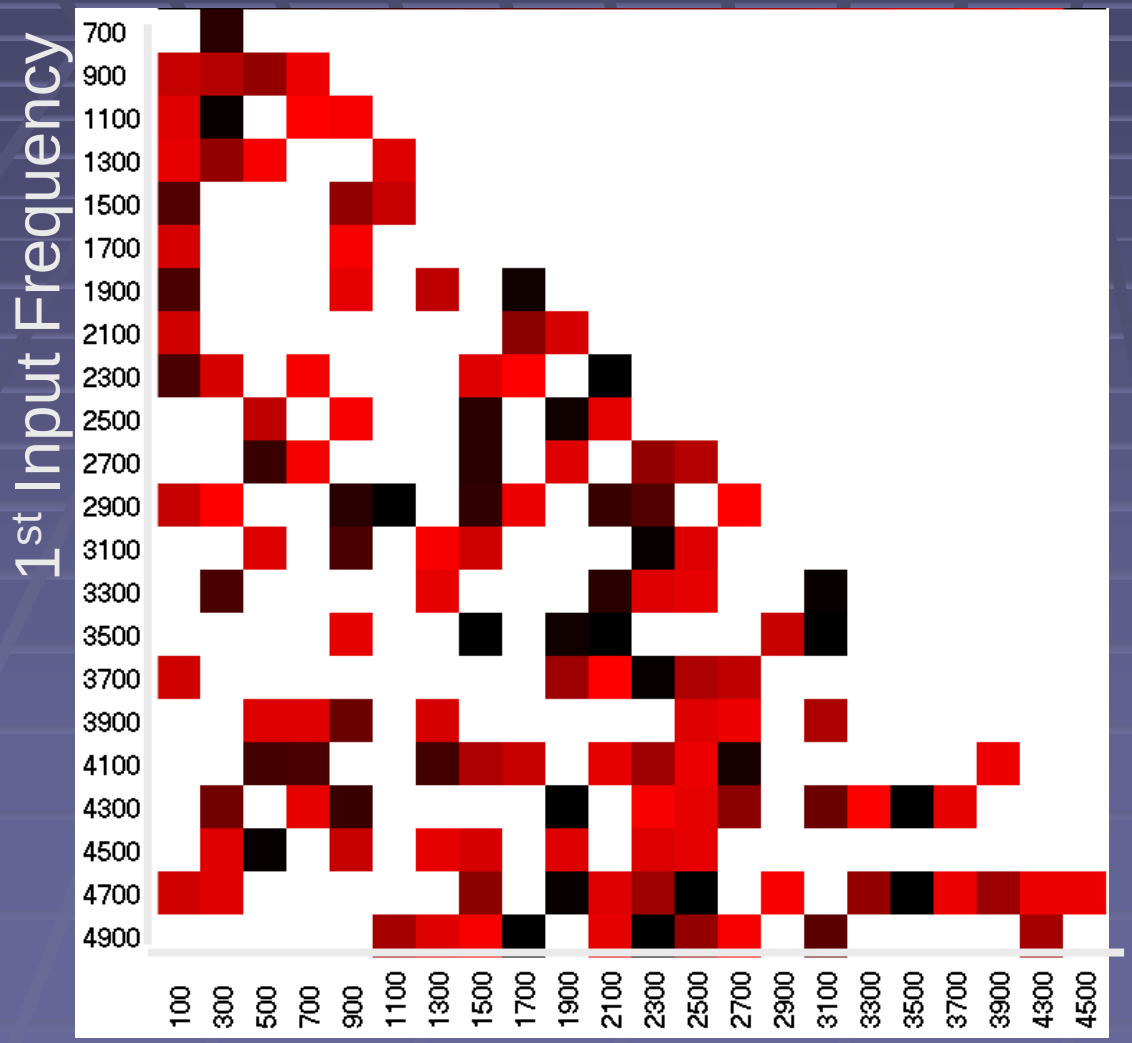
Task: Tone discriminator

- Evolve a “circuit” that can discriminate between two possible applied signals:
  - Signals were square waves, 0-5V, 100Hz, 5kHz
- Test sequence:
  - 250ms 5Khz, 250ms 100Hz, 250ms 5KHz
  - Reward: count percentage output < 0.1V for 100Hz and output >0.1V for 5kHz
- Many pairs of frequencies were tried and proved successful

Best evolved “circuit” response



Evolved tone discriminators for other frequencies



Average generations to find solution

10

100

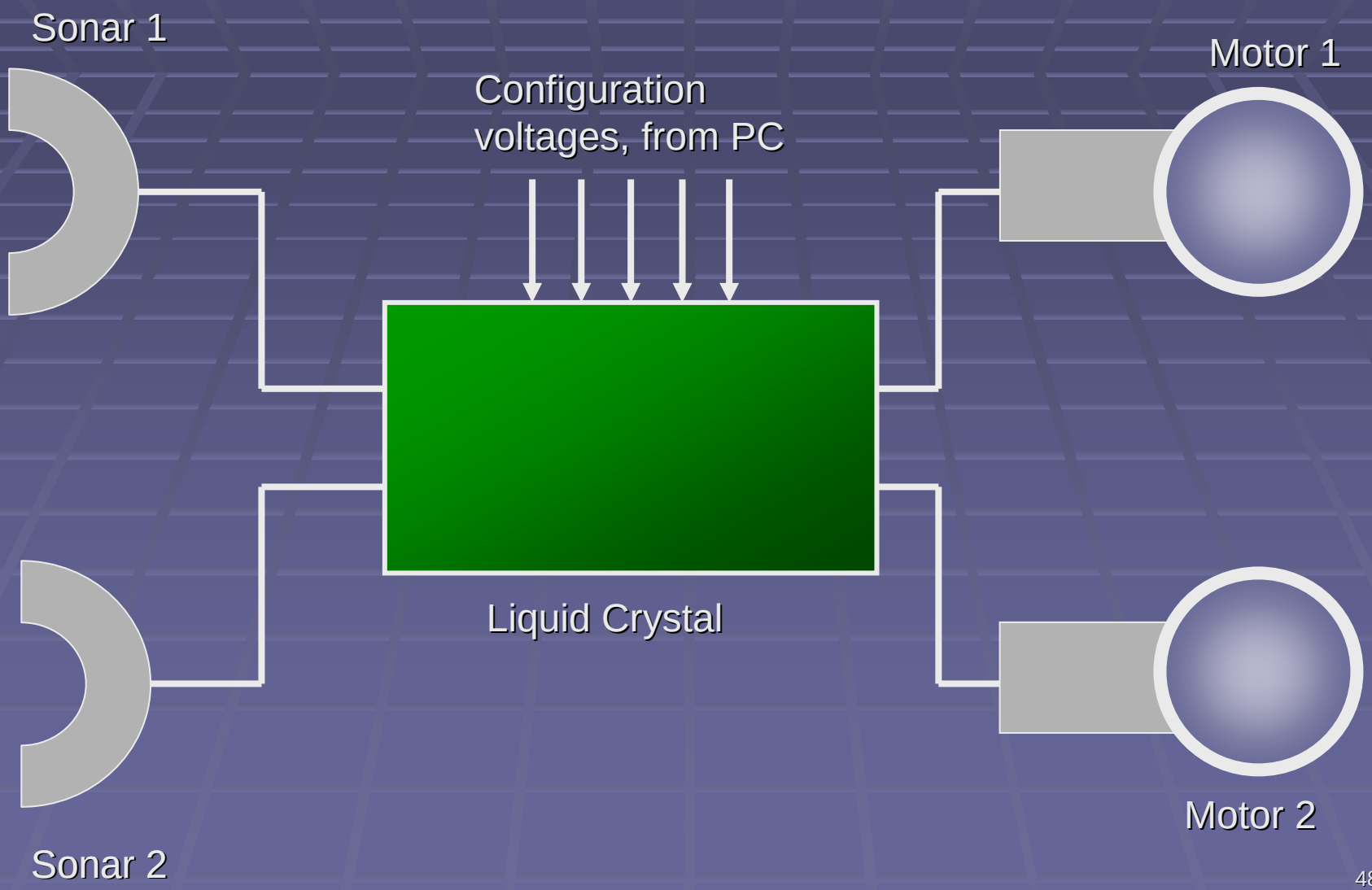
Some Analysis

- Crosspoint switches unlikely to be involved as they are designed for high frequency audio/video signals.
  - feedthrough capacitance is 0.2pF and the switch capacitance is 20pF.
- Is the LCD is acting as a configurable RC network?
- When an evolved configuration is reloaded it fails to work, however if a population contains that individual it evolves to work in 2-3 generations

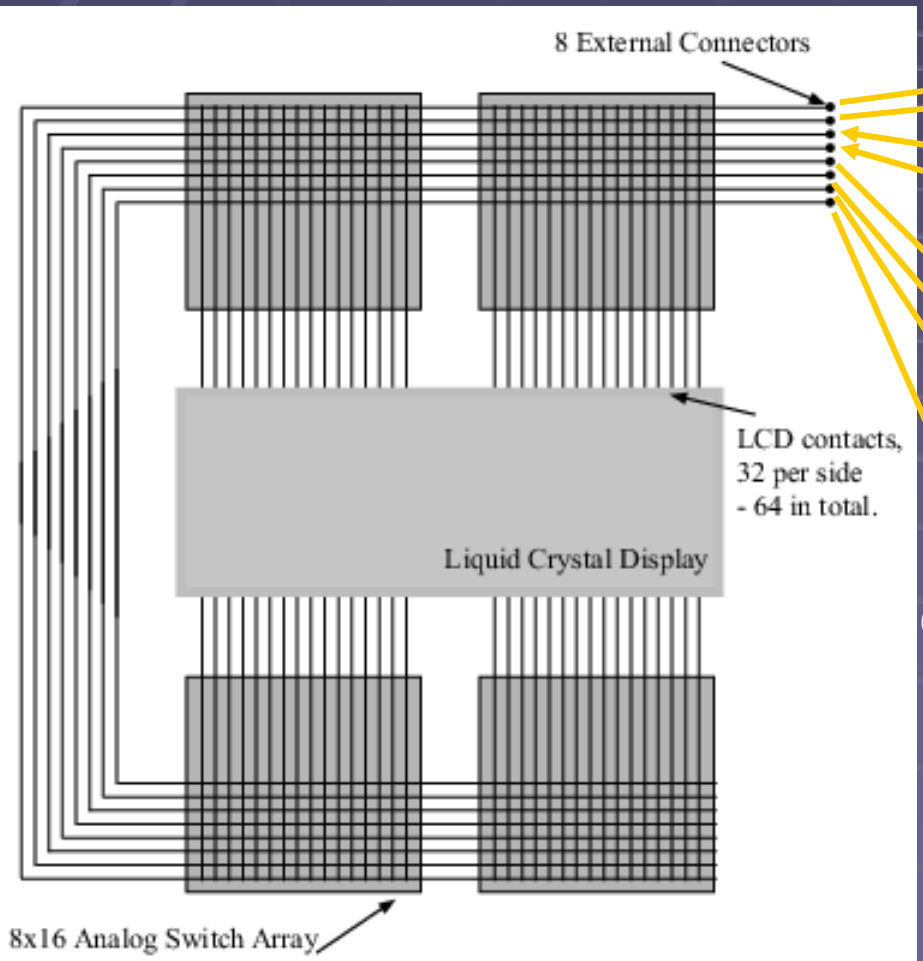
Robot Task

- Evolve a liquid crystal display to control a simulated robot
- Robot must explore the environment and avoid wall collision
- The robot can “hear” frequencies in each of two “ears” whose pitch is inversely proportional to the distance of the ear from point of contact with barrier
- Robot has two motors

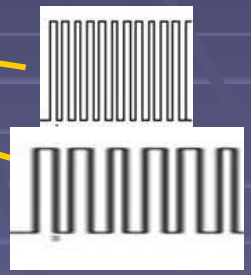
A Robot Controller In LC



Connections to LC for Robot Task



MOTOR
OUTPUTS



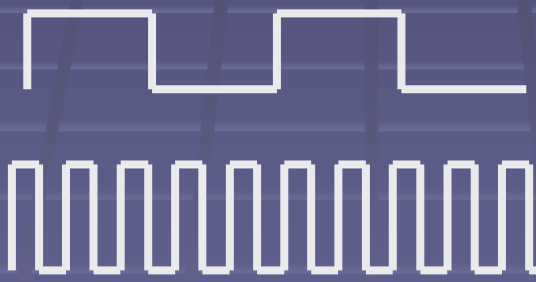
INPUT SIGNALS

GND

CONFIGURATION
VOLTAGES

“Sonar” technical stuff

- Output from sonar is a square wave whose frequency is inversely proportional to “time of flight”
- Output scales from 1hz to 5kHz



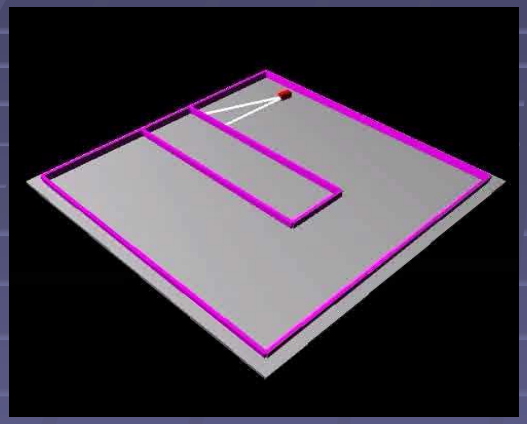
Near objects

Far objects

- Distance is sampled every 100ms, and output oscillator frequencies updated. Adds noise and slow response to external change.

Evolved Solutions

1



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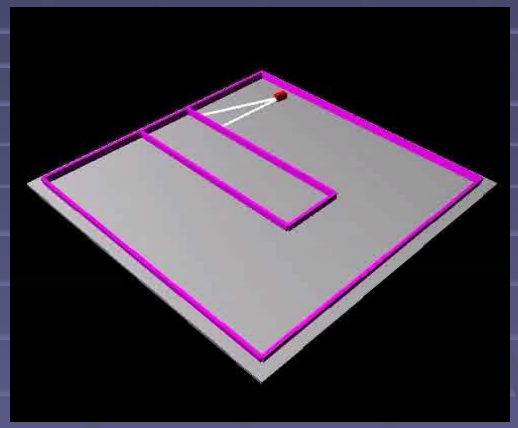

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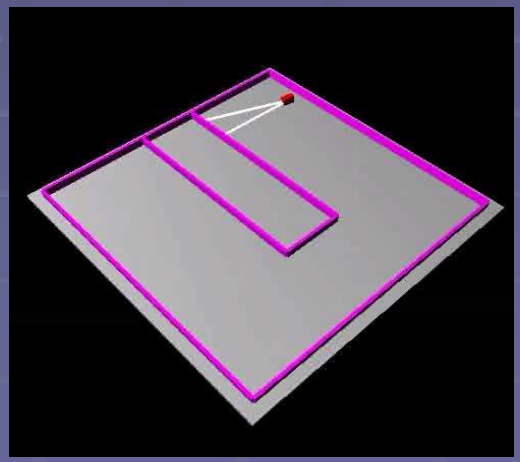

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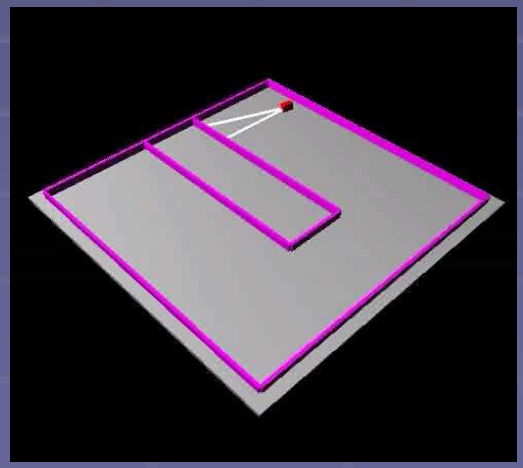
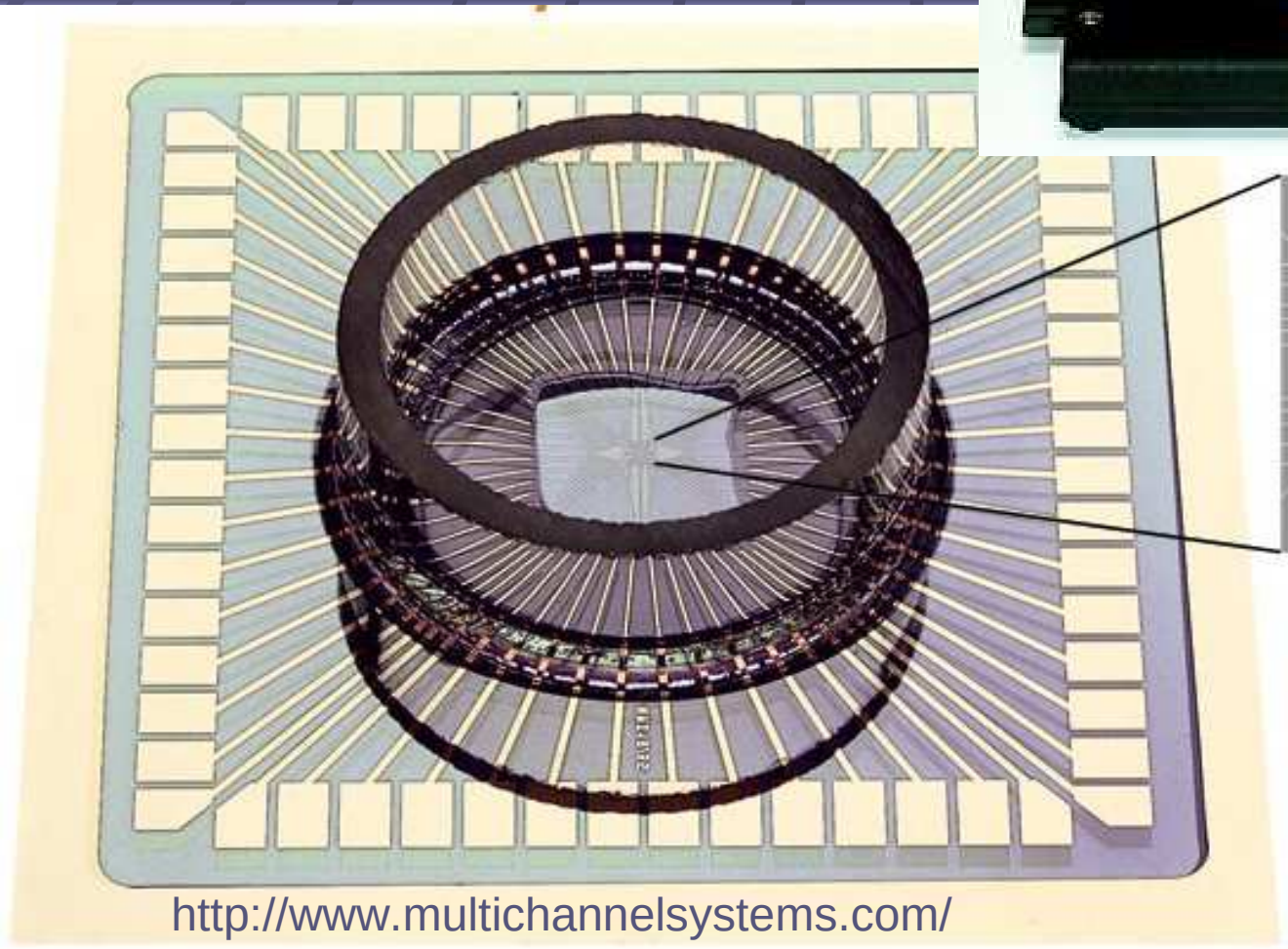
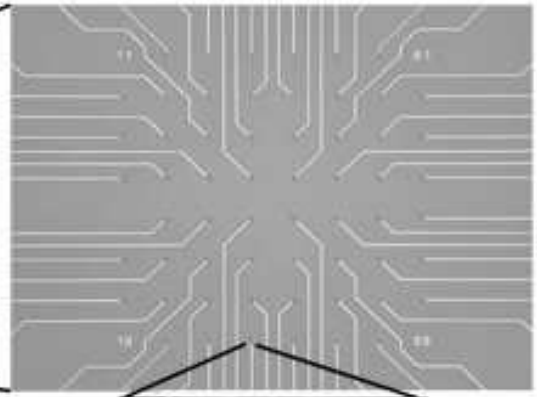
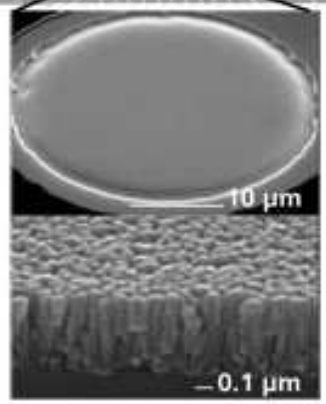


The future: An evolvable microelectrode array device?







http://www.multichannelsystems.com/

Further work

- Build a evolvable microelectrode array device
- Use different types of LC, nanoparticle suspensions
- Attempt to evolve solutions to much harder problems
- Understand how the devices work
- Examine potential of other physical systems

Thoughts

- Evolution in materio is an automated *discovery* process. It can help us find material substrates that can be utilized for computation
- It potentially can allow "programming" at a molecular level (massively parallel)
- It is probably most useful for tasks where it is difficult to construct efficient conventional solutions (i.e. AI problems)

Conclusions

- To be able to evolve things you need phenotypic richness
- It is feasible for us to get computer controlled evolution to create technology for us. Not tell it what technology it must use.
- We know it has already created the technology of living things.
- We need more people to try “evolution in materio”

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