

**Evolvable Physical Media**  
**(or Evolution *in materio*)**

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# Evolution *in materio*

- The manipulation of a physical system by computer controlled evolution (CCE) of its physical properties
- Does this mean optimisation? NO!
  - It means the *discovery* of physical properties that can be utilized to help solve the imposed task
- I think that we might be able to use CCE to invent a new technology!

# 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

# The price of programmability

- In conventional design the vast majority of interactions that could possibly contribute to the problem are deliberately excluded (Michael Conrad 1988)

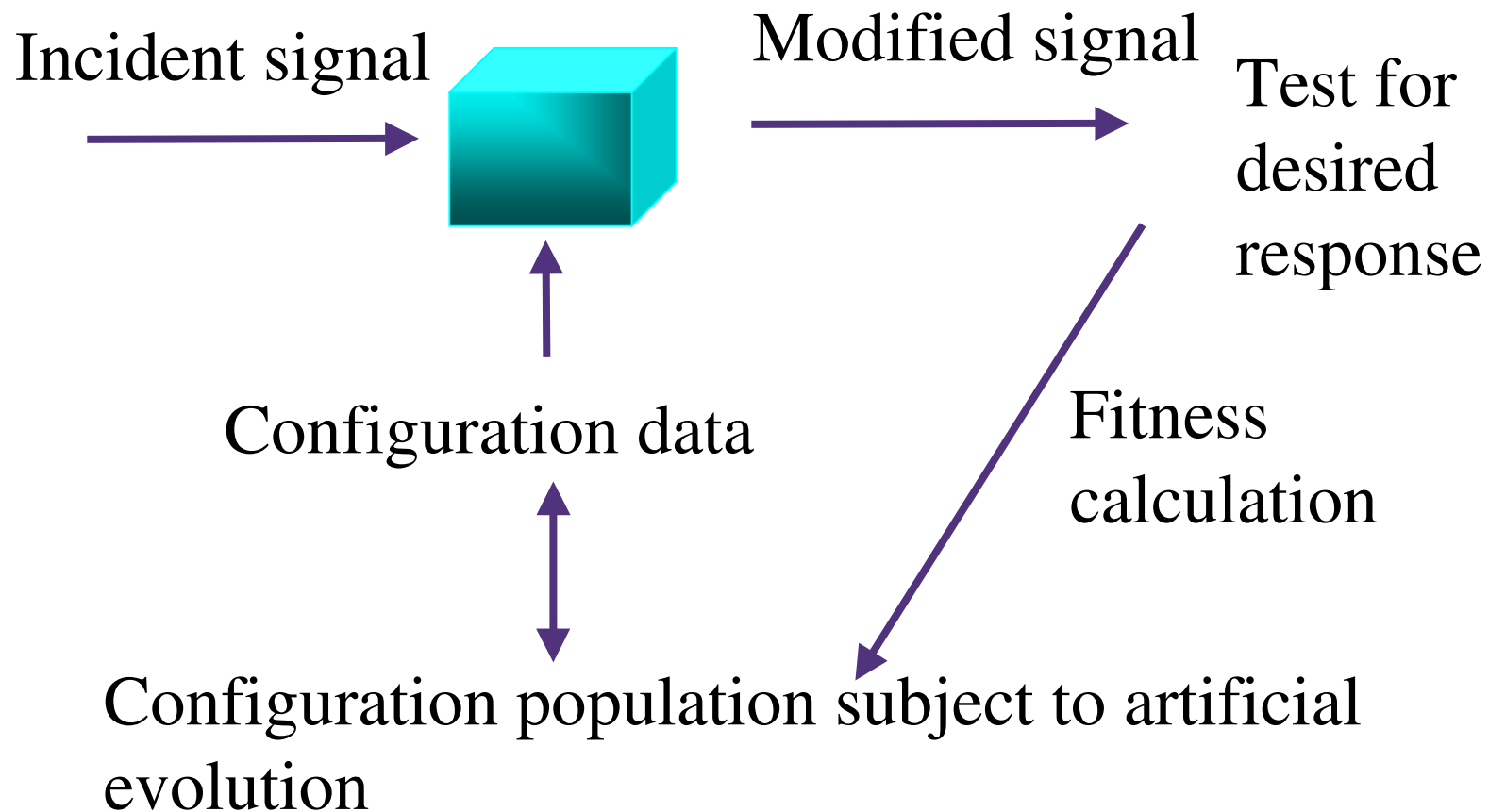
# What are evolvable physical media?

- Systems whose physical properties can be affected by changes to controllable physical variables
- To be evolvable the media must be
  - able to be reset
  - strong genetic inheritance of physical characteristics

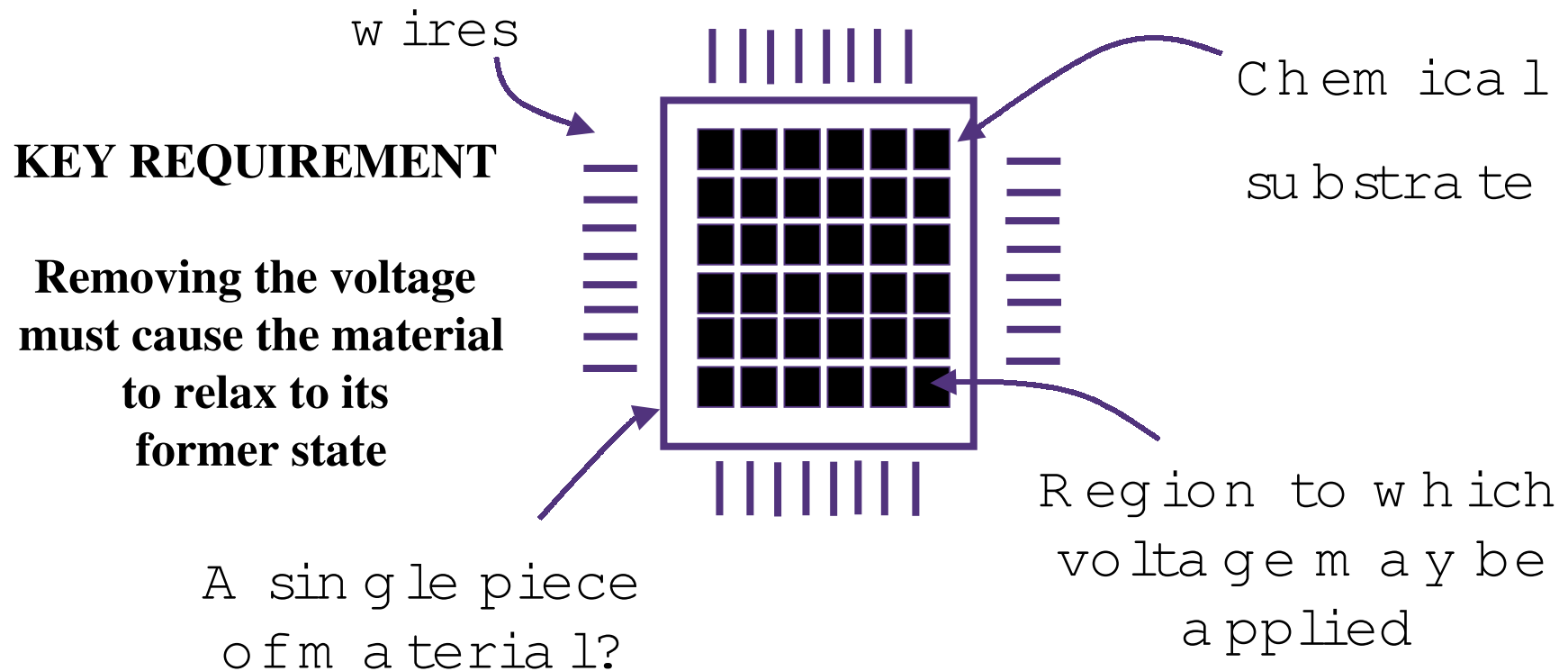
# A tricky question

- What kinds of physical systems are most easily exploited by an artificial intrinsic evolutionary process?

# How do you evolve matter to compute? (view 1)



# The Field Programmable Matter Array (View 2)





# Has anybody demonstrated evolvable physical media?

- Gordon Pask - Ferrous sulphate
- Adrian Thompson - silicon
- Adrian Stoica, Didier Keymeulen, Riccardo Zebulum - silicon
- Huelsbergen, Rietman and Slous - silicon
- Derek Linden - reed switch array
- Paul Layzell and Jon Bird - silicon
- Simon Harding and Julian Miller -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.

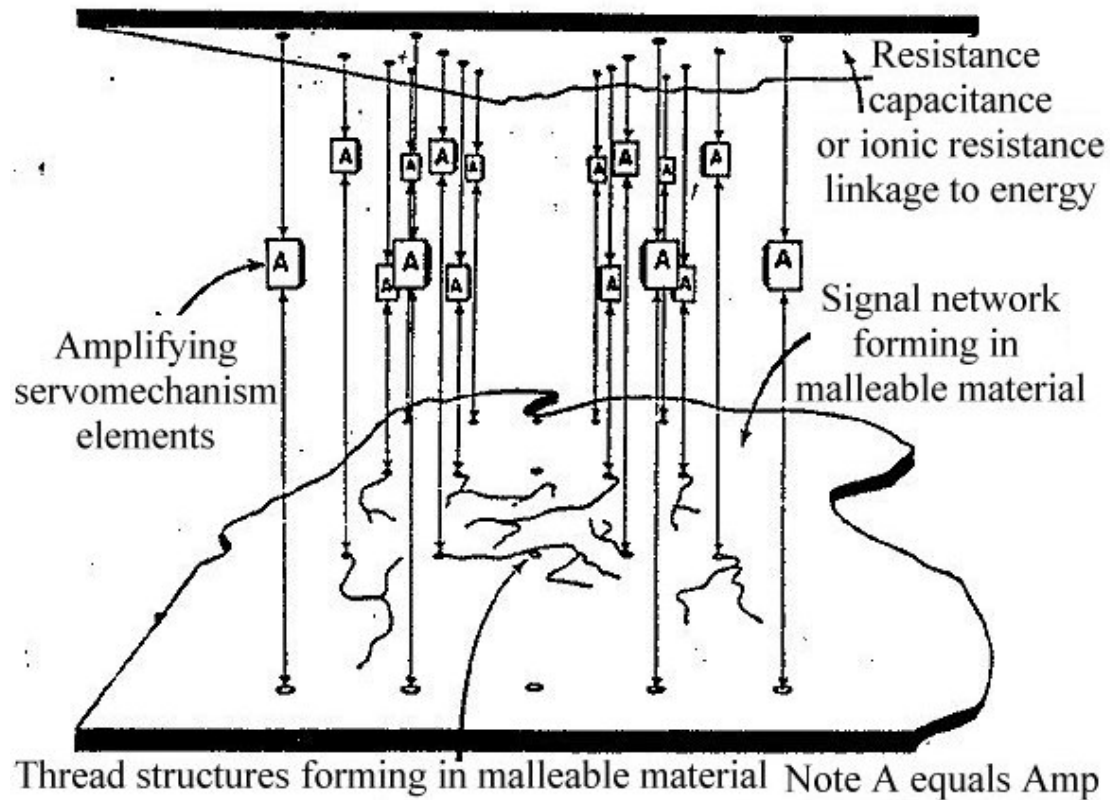
# Some background

- “We believe that if the ‘complexity barrier’ is to be broken, a major revolution in production and programming techniques is required...We may as well start that with the notion that with  $10^{10}$  parts per cubic foot there will be no circuit diagram possible...We would manufacture ‘logic by the pound’, using techniques more like a bakery than of an electronics factory” [see Cariani 1993].
- People were looking for self-wiring, self-organising machines way back then!

# 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
- The device would choose its own training set and the type of training variables
- He needed a physically rich machine which could be adaptively steered

# Schematic of Electrode array and Ferrous sulphate medium



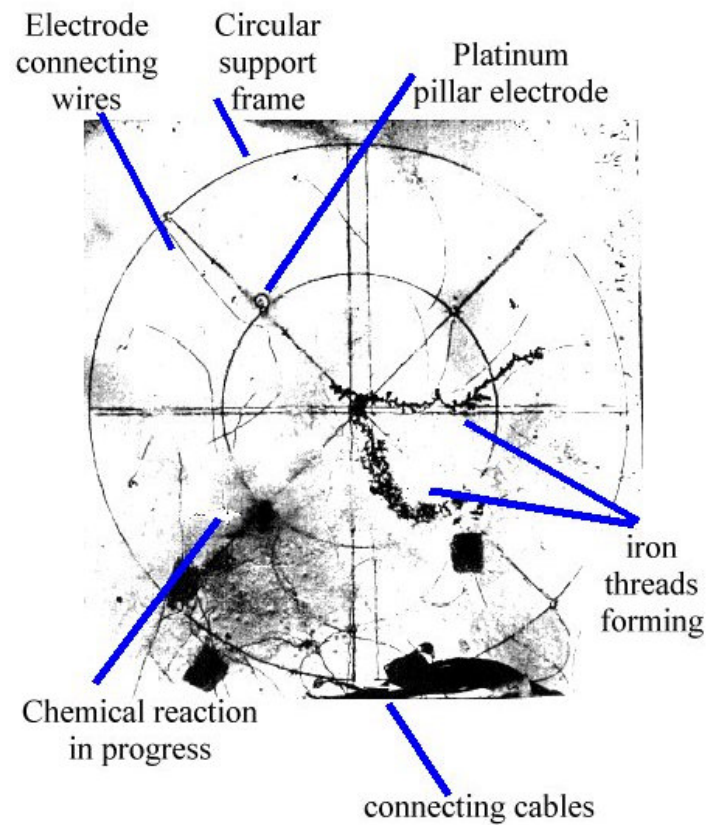
# What Pask did

“..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 58)

# “We have made an ear...”

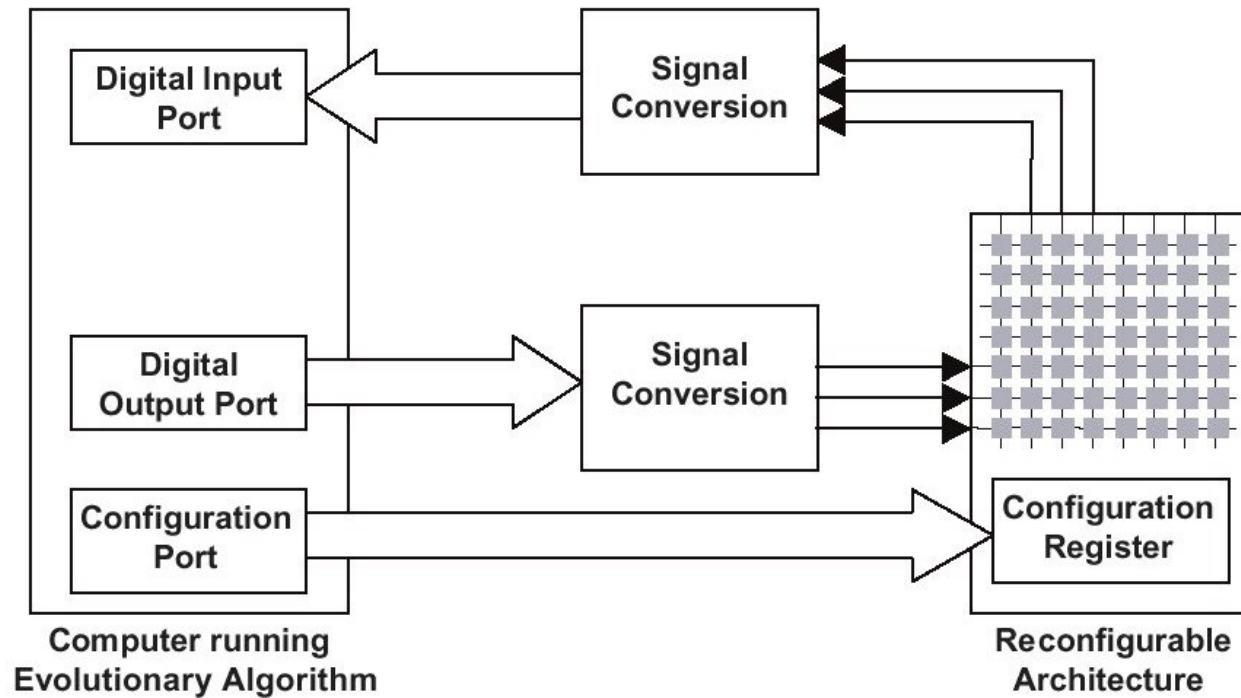
- “We have made an ear and a magnetic receptor. The ear can discriminate two frequencies, one of the order of fifty cycles per second and the other on the order of one hundred cycles per second. The ‘training procedure’ takes approximately half a day and once having got the ability to recognize sound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

# View of actual apparatus

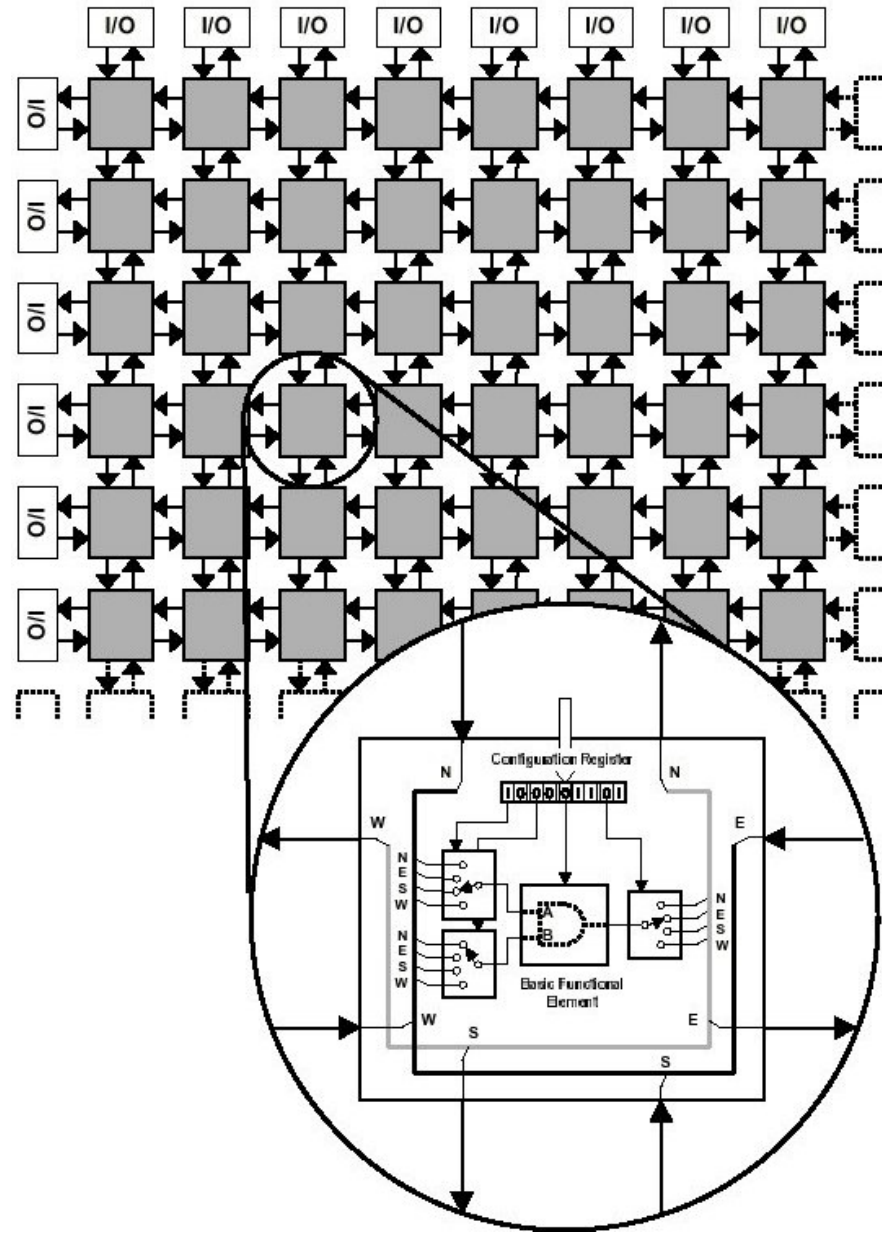




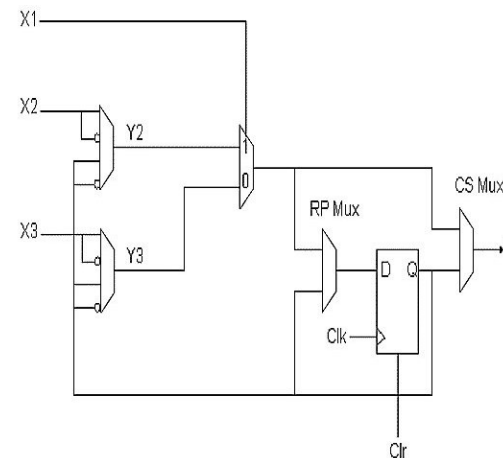
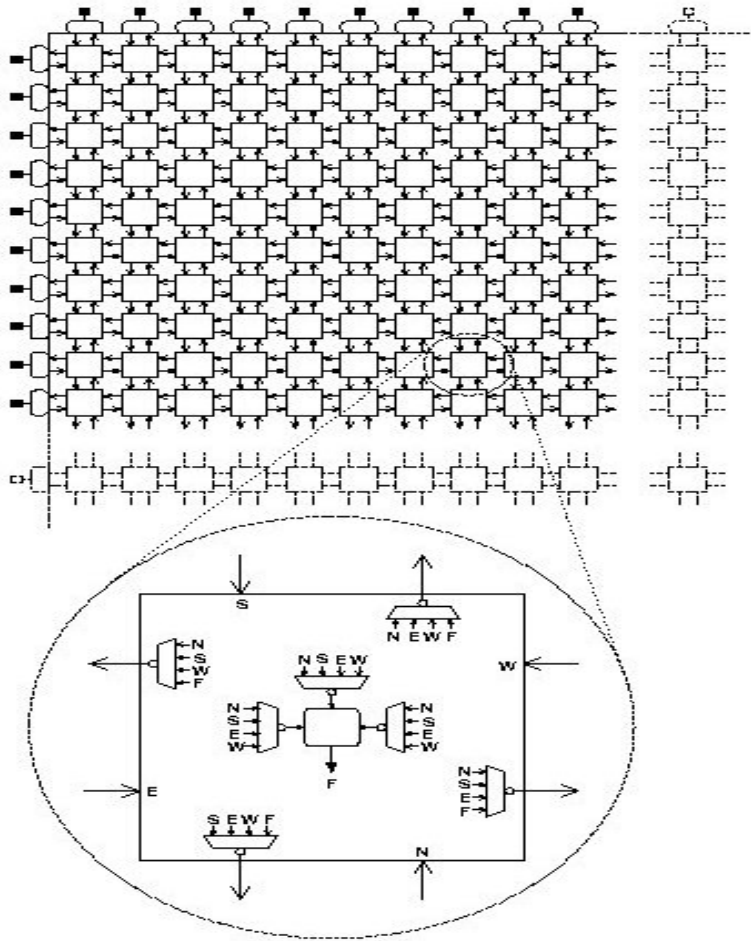
# Modern generic evolvable platform



Generic *in silico*  
evolvable  
platform

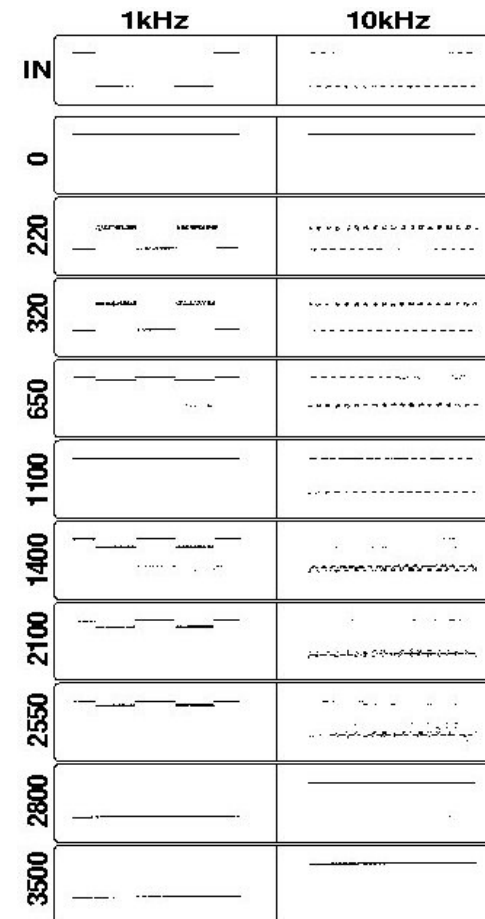
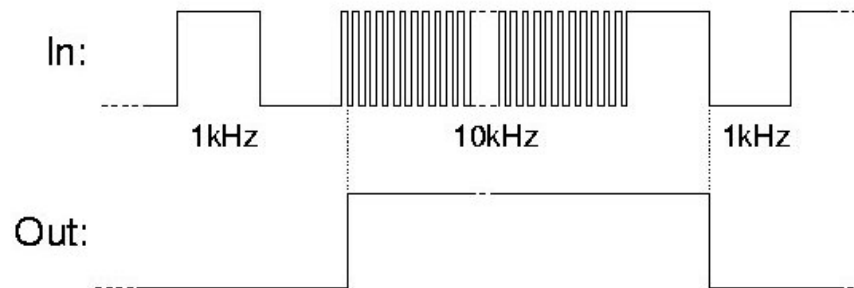
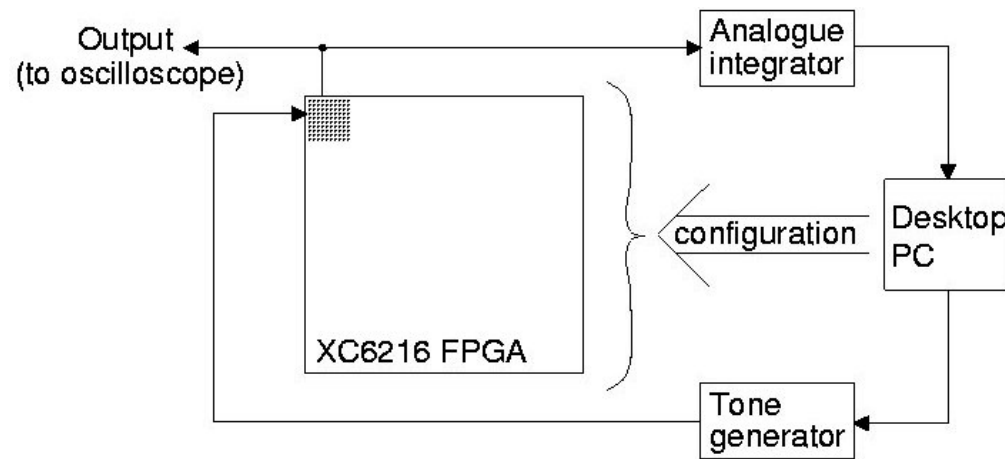


# The Xilinx 6216 Field Programmable Gate Array (FPGA)

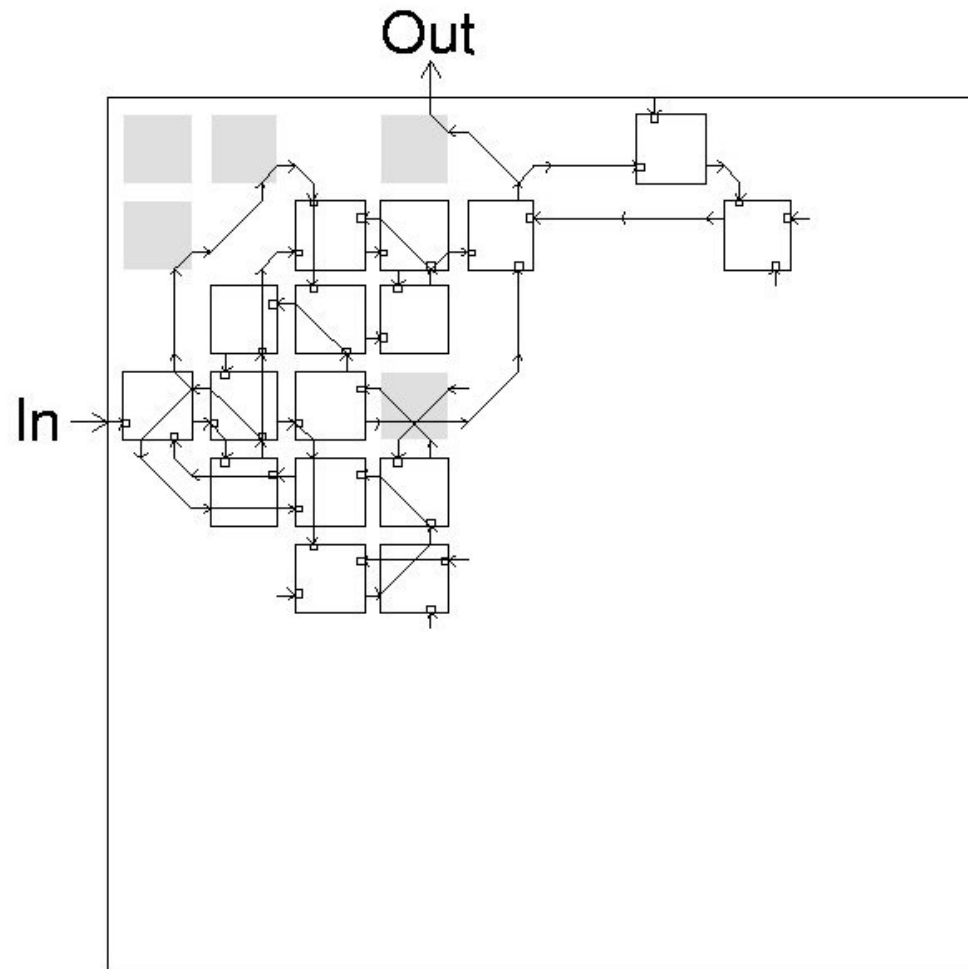


Function unit

# Adrian Thompson's experiment

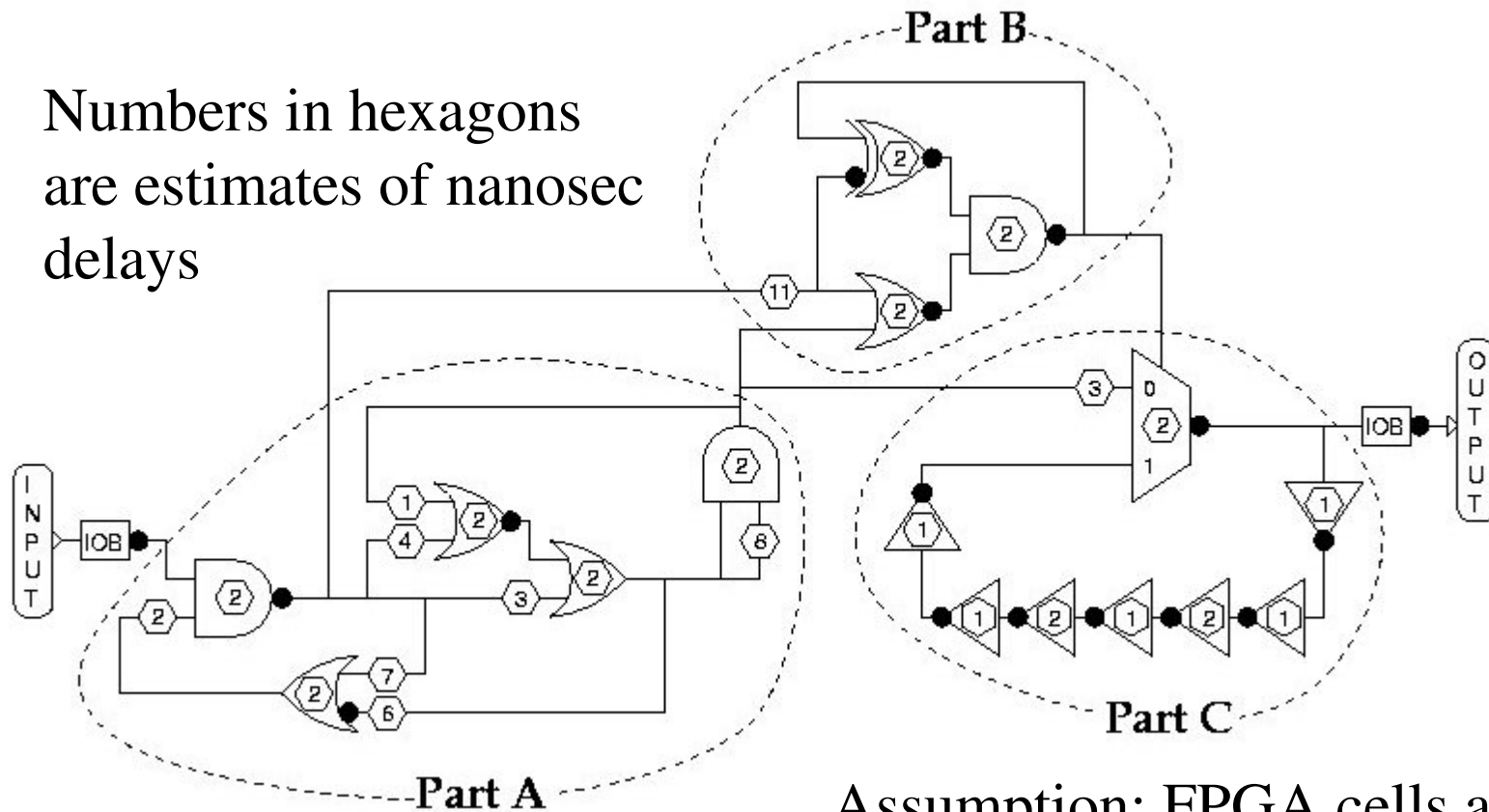


# What were the active parts of the circuit?



# Logic circuit representation of evolved circuit

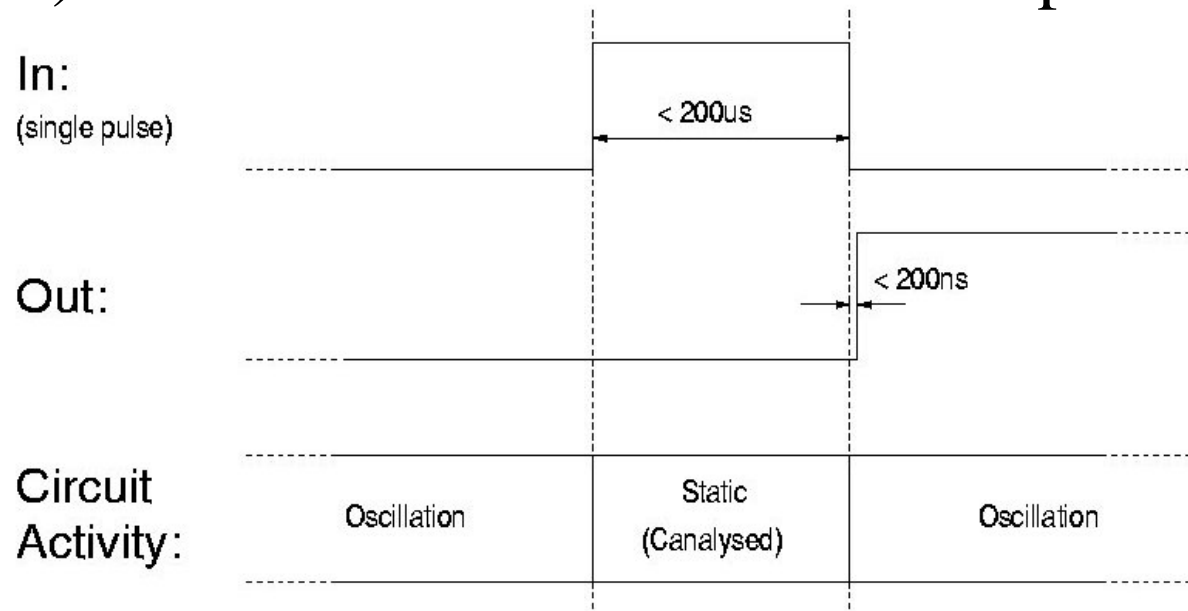
Numbers in hexagons are estimates of nanosec delays



Assumption: FPGA cells acting as Boolean logic gates

# Analysis of circuit

- When input is 1, parts A and B settle to a constant logic state (in 20ns) until next input goes to 0 (part B settles to 1). This selects the Mux in part C own output as input (so oscillates but settles to a logic value). So circuit inactive until end of pulse.



# Further analysis


- Thompson and Layzell checked that there were no circulating glitches (short duration pulses) during static phase
- PSPICE simulation (with extensive variation of gate delays and parasitic capacitance) did not produce real circuit behaviour
- Build CMOS Mux version of circuit didn't reproduce actual circuit behaviour.
- Time delays on connection from A to B&C crucial to evolved circuit behaviour

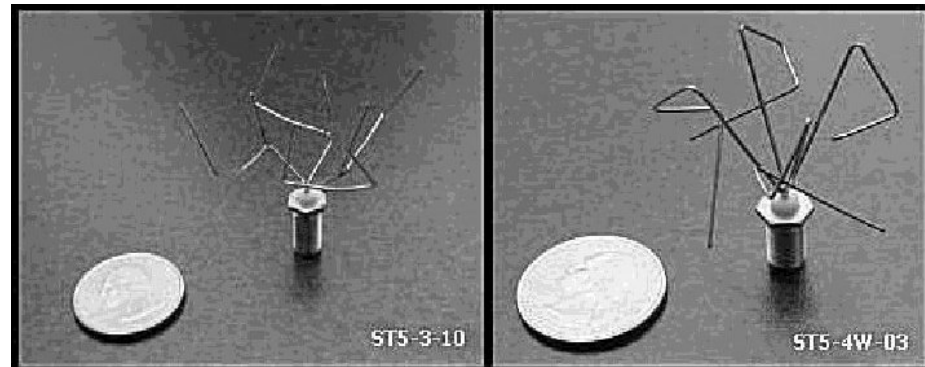
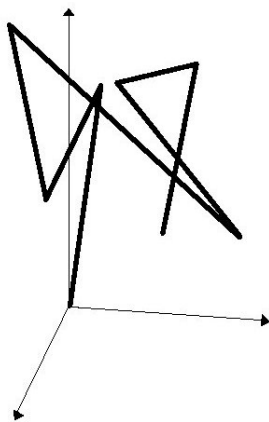


# Conclusion

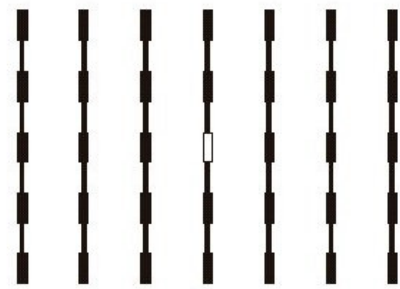
- Core of timing mechanism is a subtle property of the VLSI medium
- They ruled out:
  - glitches, beat frequencies
  - metastability
  - thermal time-constants (self-heating)
- *Evolution has exploited properties of the system that are at present unknown*

# Evolution of antennas

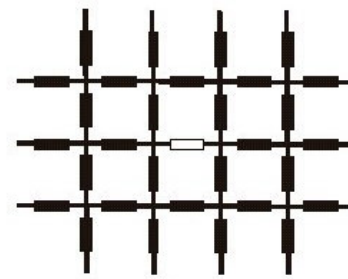
- Physical evolution of antennas using reed switches 
- evolution of wire segment antennas in simulation.



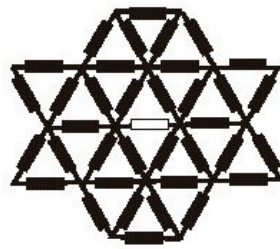
# Topologies of Reed Switches



a.



b.

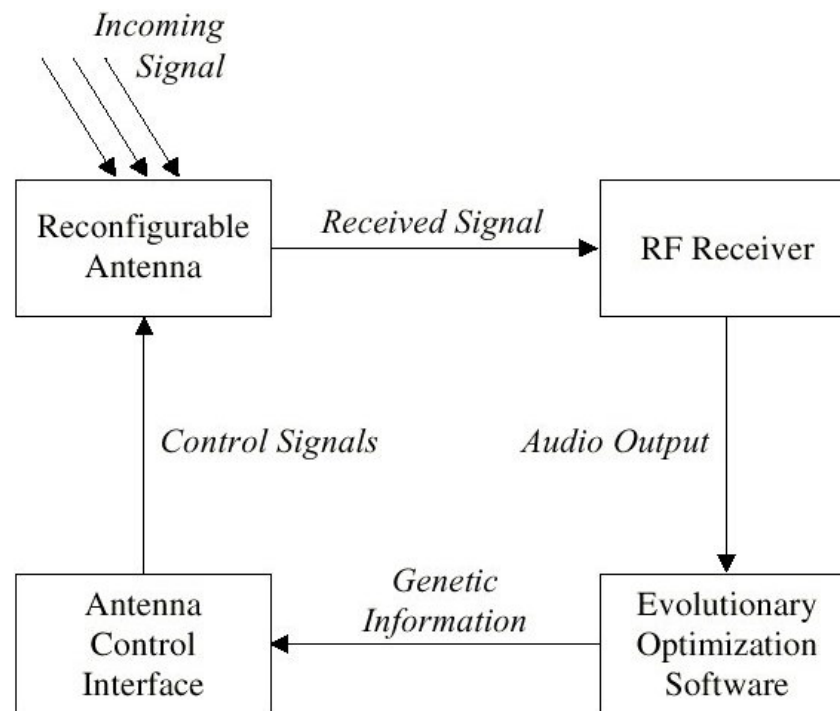


c.

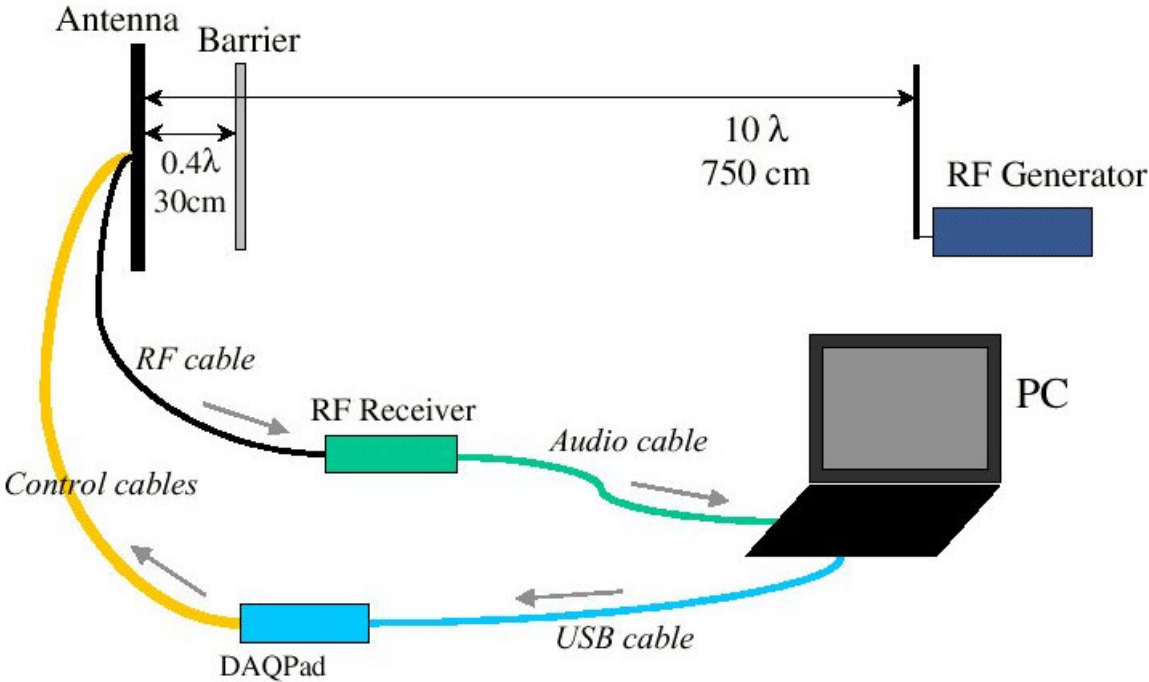


d.

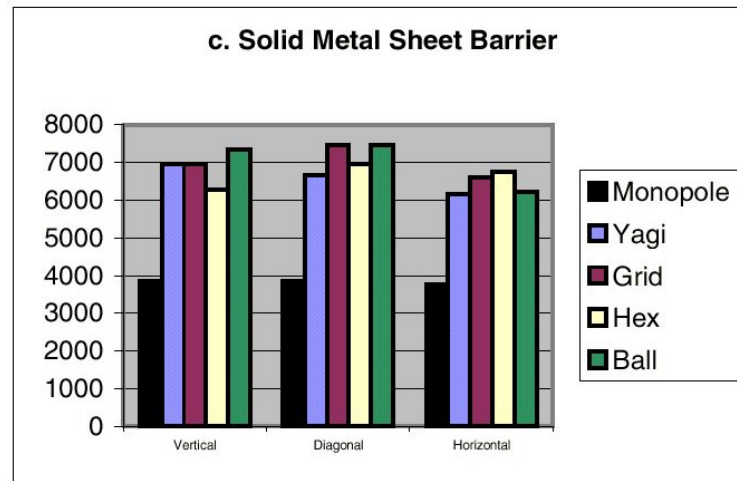
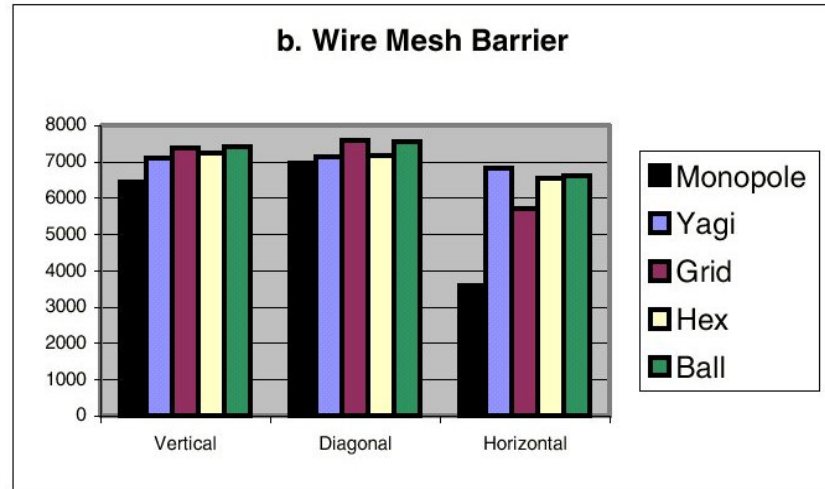
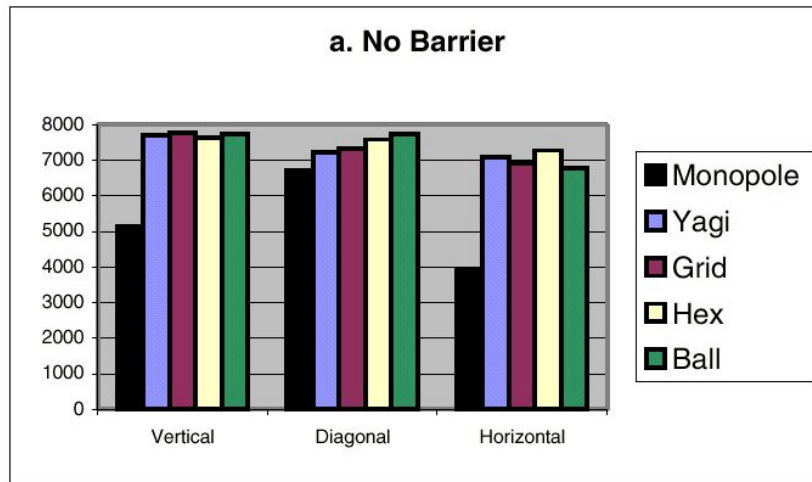
# Evolve and test apparatus



# Test set-up

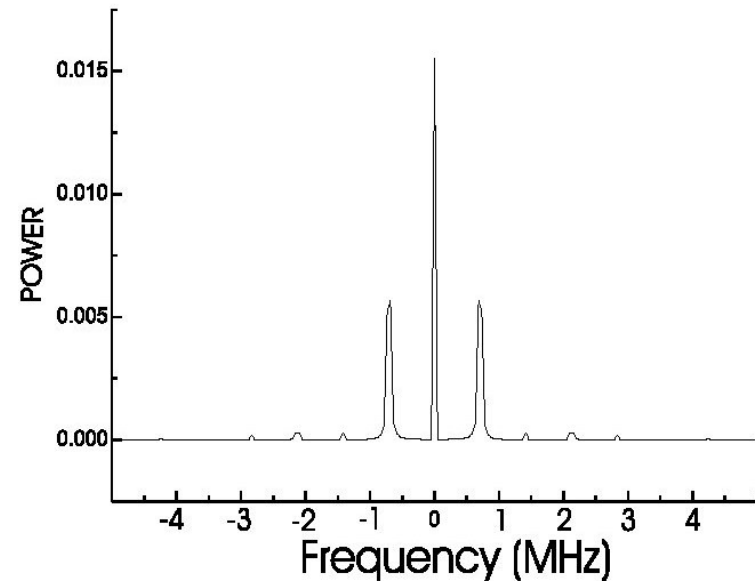
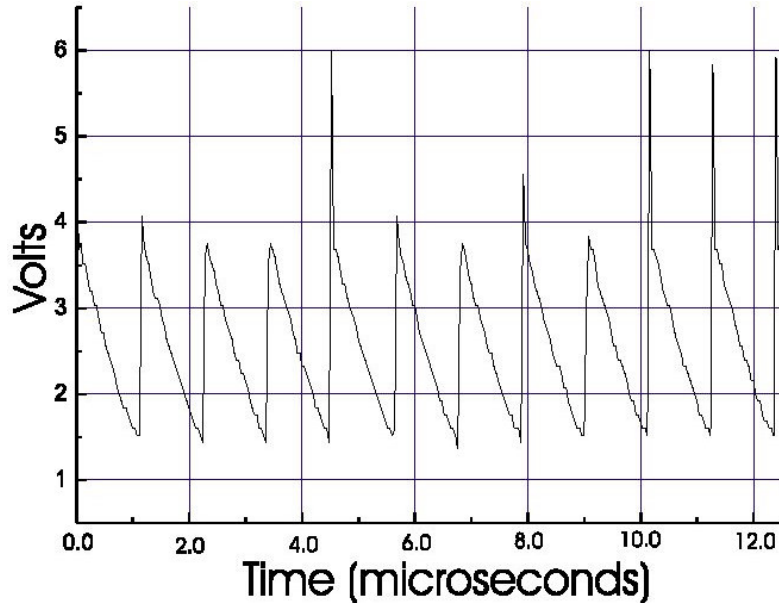


# Results

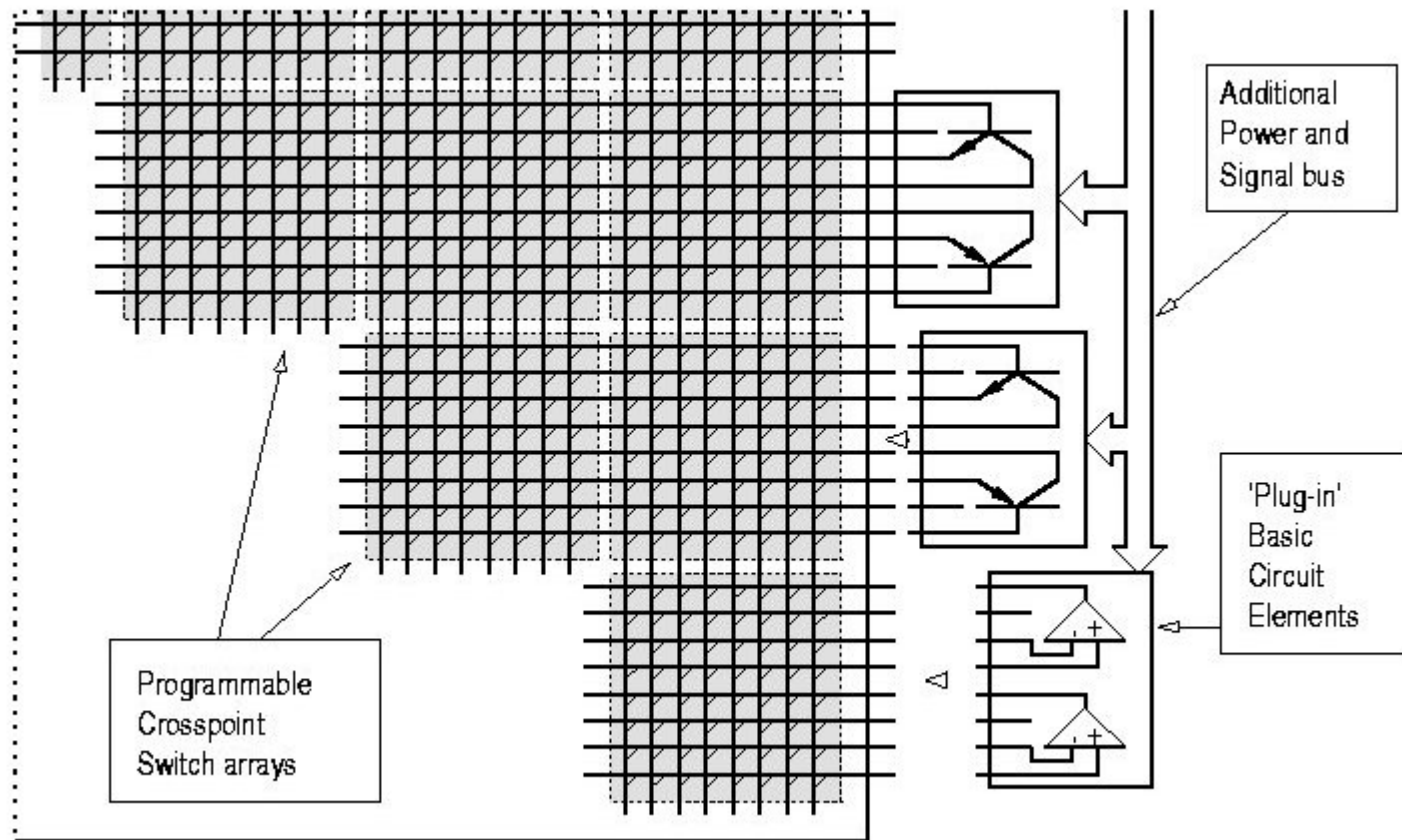


# Evolution of Astable Multivibrators *in Silico*

- Huelsbergen, Rietman and Slous
- Also used the Xilinx 6216

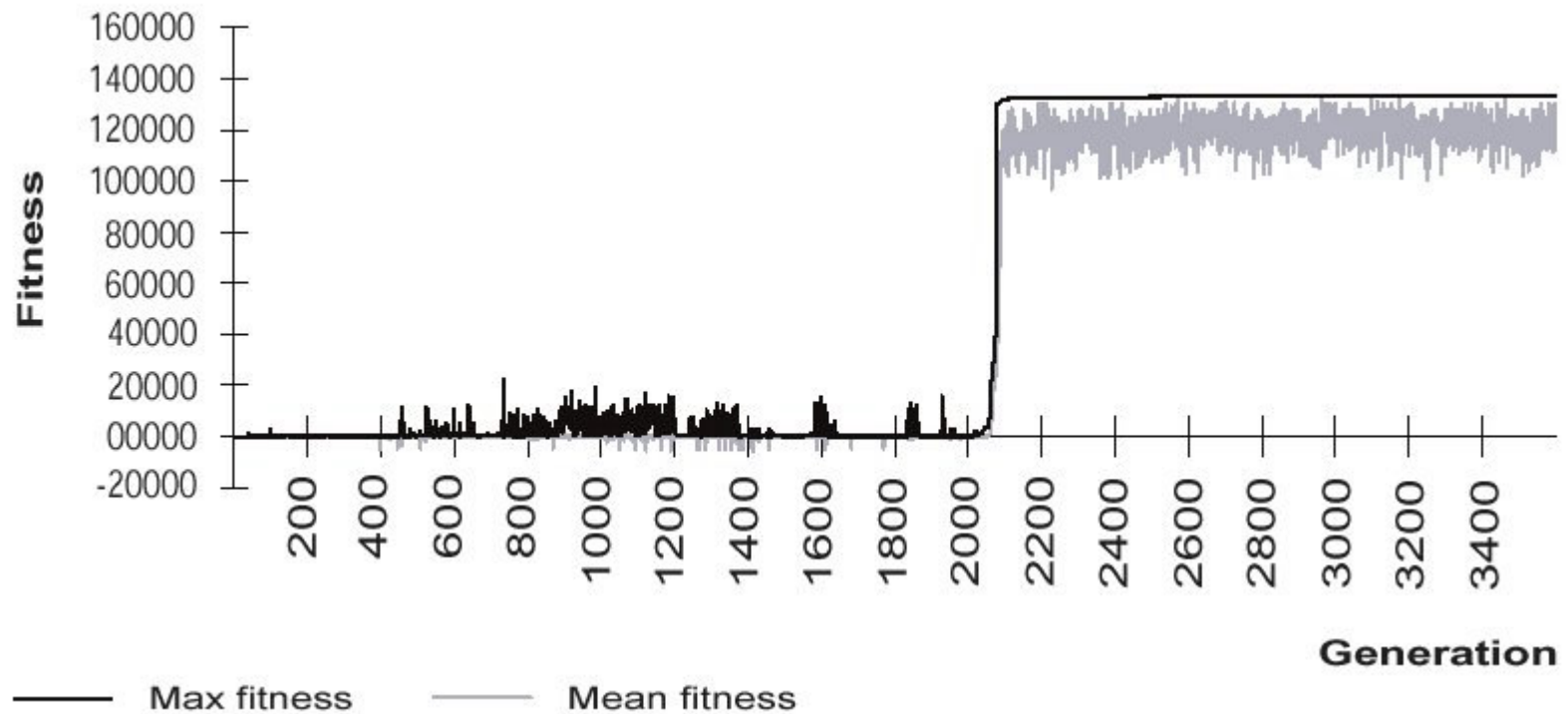


# Paul Layzell: Evolvable Motherboard

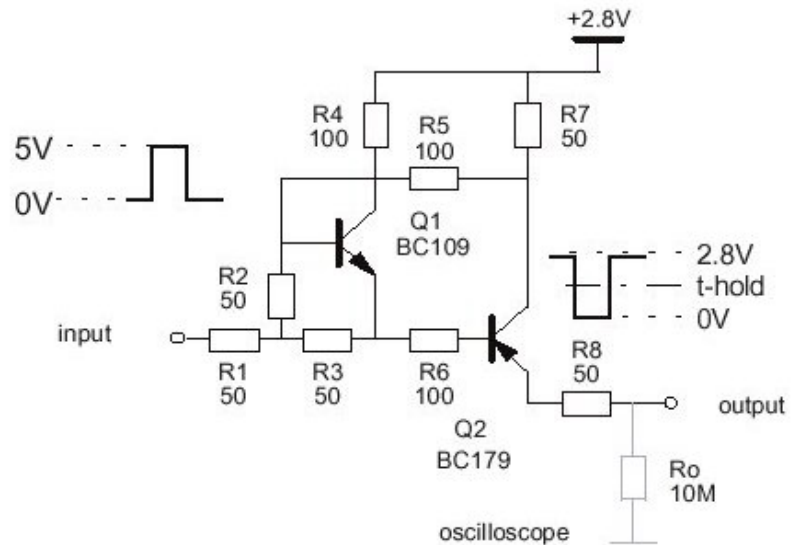
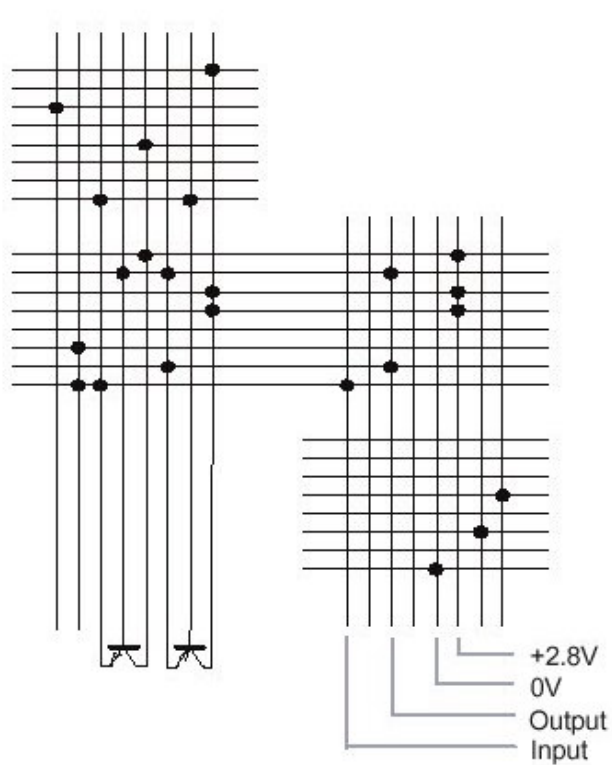




# Evolution of inverter fitness



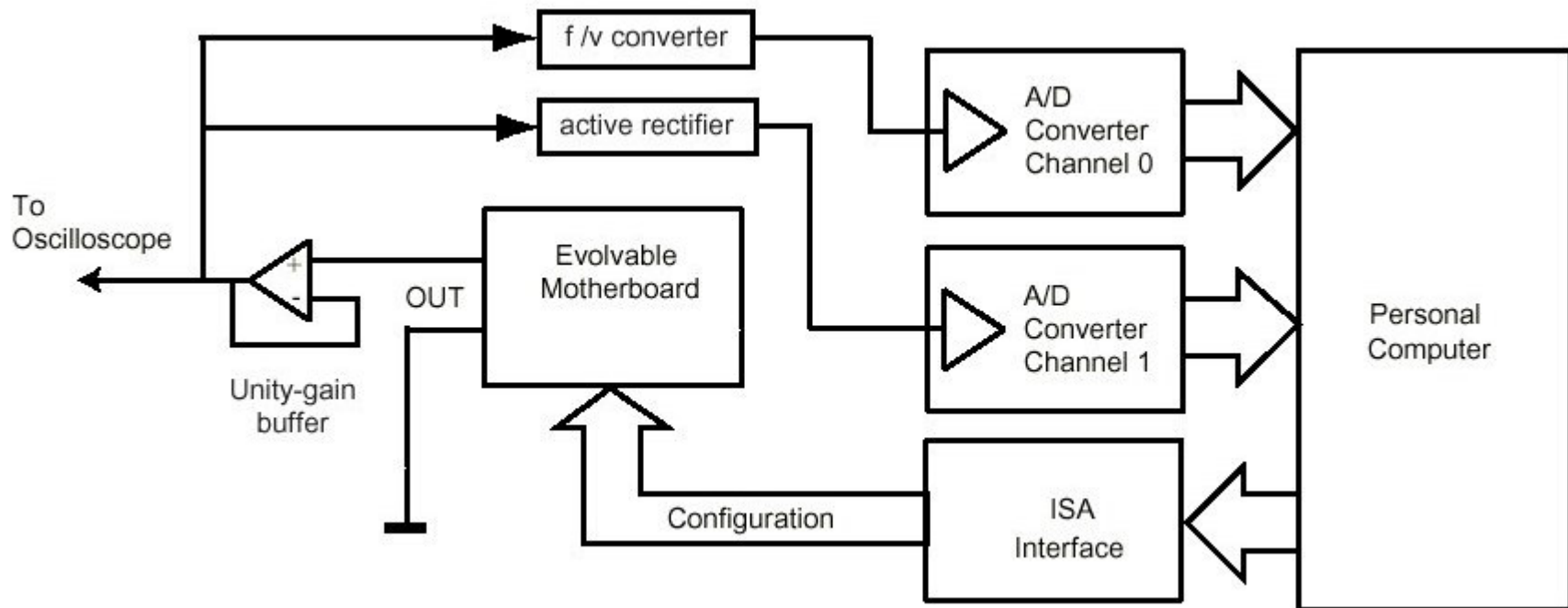
# An evolved inverter that used the measurement apparatus as a circuit component!



# Evolving an Oscillator

- Fitness function chosen to reward high-amplitude signals present at output
- Huelsbergen et al. sampled through an a/d converter and were troubled by aliasing errors.
- Layzell used a frequency to voltage converter to avoid aliasing errors
- target frequency was 25KHz

# Evolving an oscillator

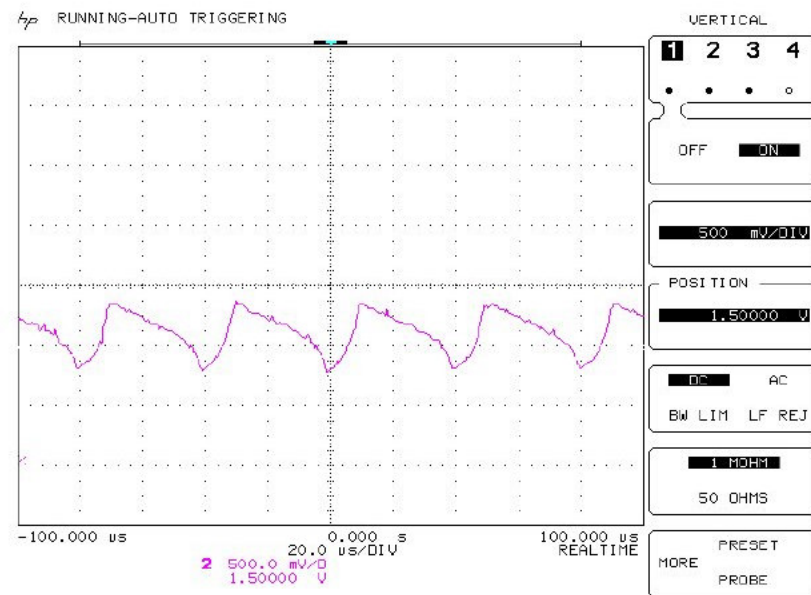
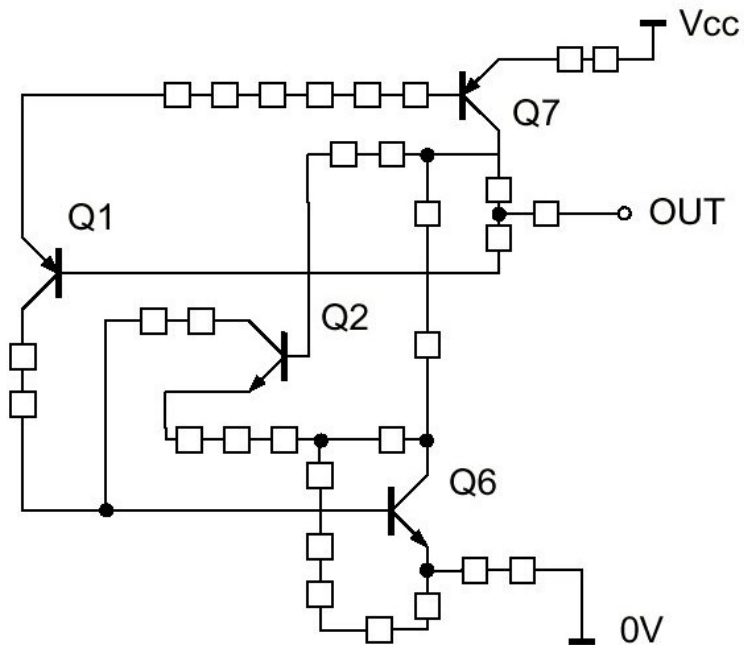


# Evolved Oscillator: fitness function

$$\text{fitness} = \begin{cases} \bar{a} + k \frac{f_{\min}}{f_{\max}} \left( f_{\text{target}} - \left| f_{\text{target}} - \bar{f} \right| \right), & \text{if } \bar{f} > 60 \text{ Hz} \\ \bar{a}, & \text{if } \bar{f} \leq 60 \text{ Hz} \end{cases}$$

- $\bar{a}$  and  $\bar{f}$  represent output amplitude and frequency average over 20 samples,  $f_{\min}$  and  $f_{\max}$  are the maximum and minimum of 20 frequencies sampled.

# Evolved circuit and output response



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 but 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 arial!



# 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)

# Should Evolvable Matter be on the ‘edge of chaos’

- Langton observed that interesting computation in cellular automata occurs on the ‘edge of chaos’. This suggests a good place to look in materials.
- Supramolecular systems
- Mesoscale systems (see ‘The Middle Way’ in refs)
- IDEA: Use a genotype to define a physical order in a resettable material where chaos removes the order

# What material systems should we use?

- Liquid crystal
- Conducting and electroactive polymers
- Voltage controlled colloids
- Irradiated Silicon
- Langmuir-Blodgett films
- nanoparticle suspensions
- microbial consortia

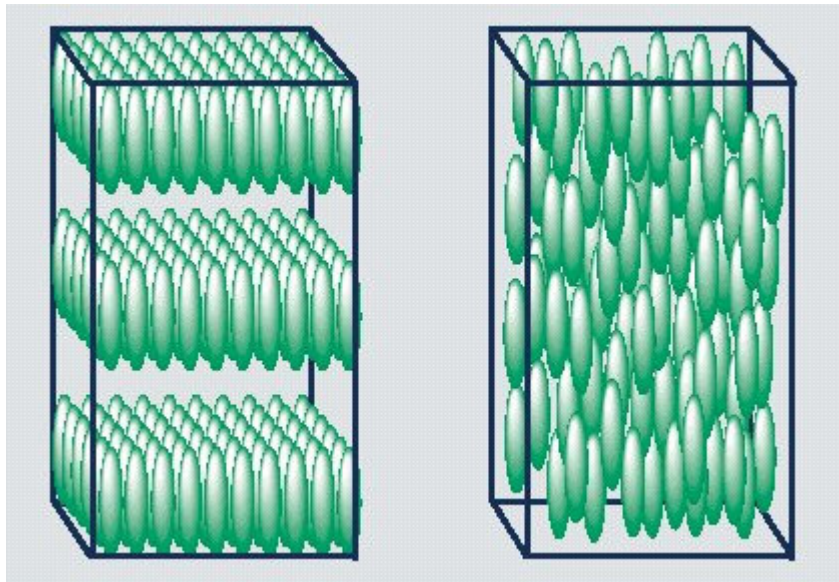
# Growing wires in nanoparticle suspensions

- "Dielectrophoretic Assembly of Electrically Functional Microwires from Nanoparticle Suspensions" Science Vol 294 November 2001



# Liquid crystal programmable matter?

- Mesoscopic organisation



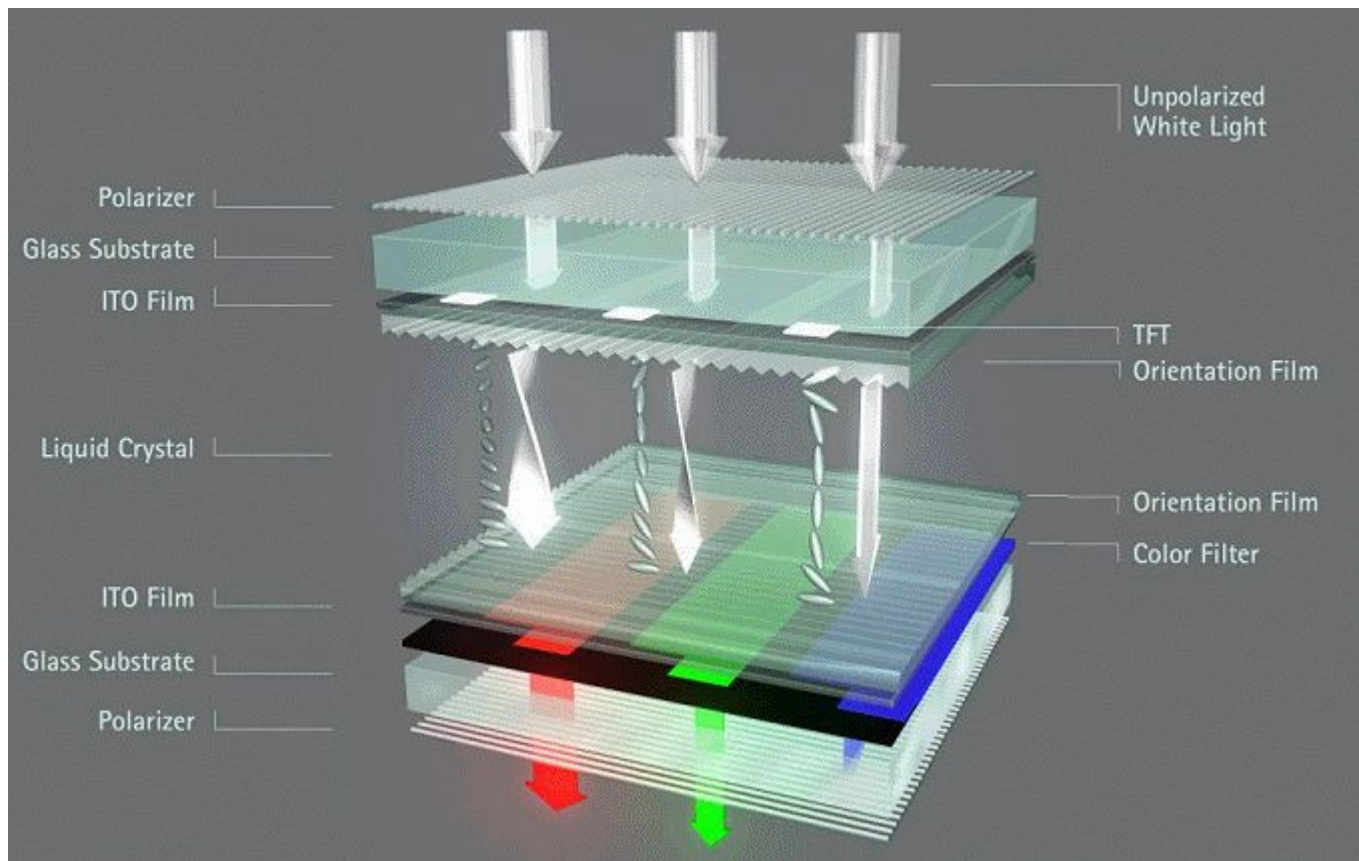
Smectic

nematic

Organic elongated Polar molecules

Many other types

# Twisted nematic LC Display



# Types and uses of liquid crystal

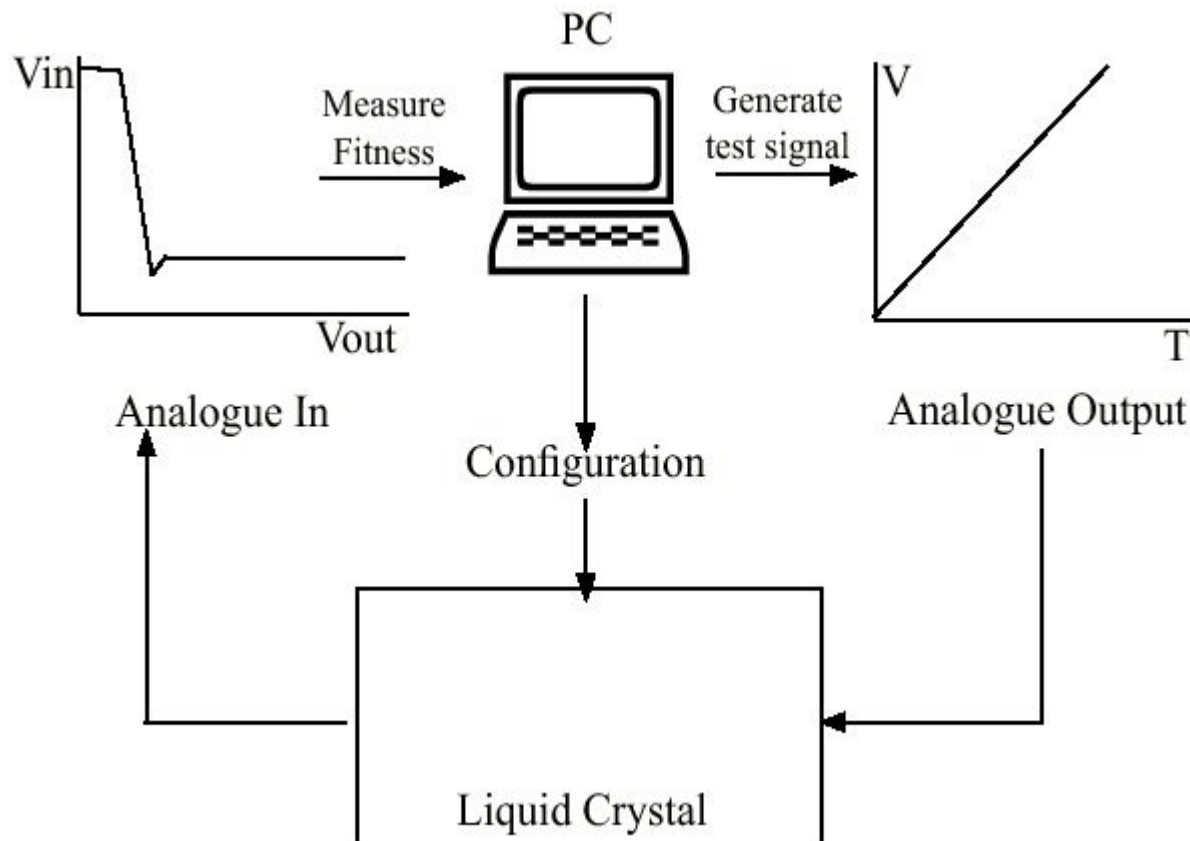
- Dye doped
- polymer dispersed
- discotic
- in plane systems

# Evolution in Liquid Crystal

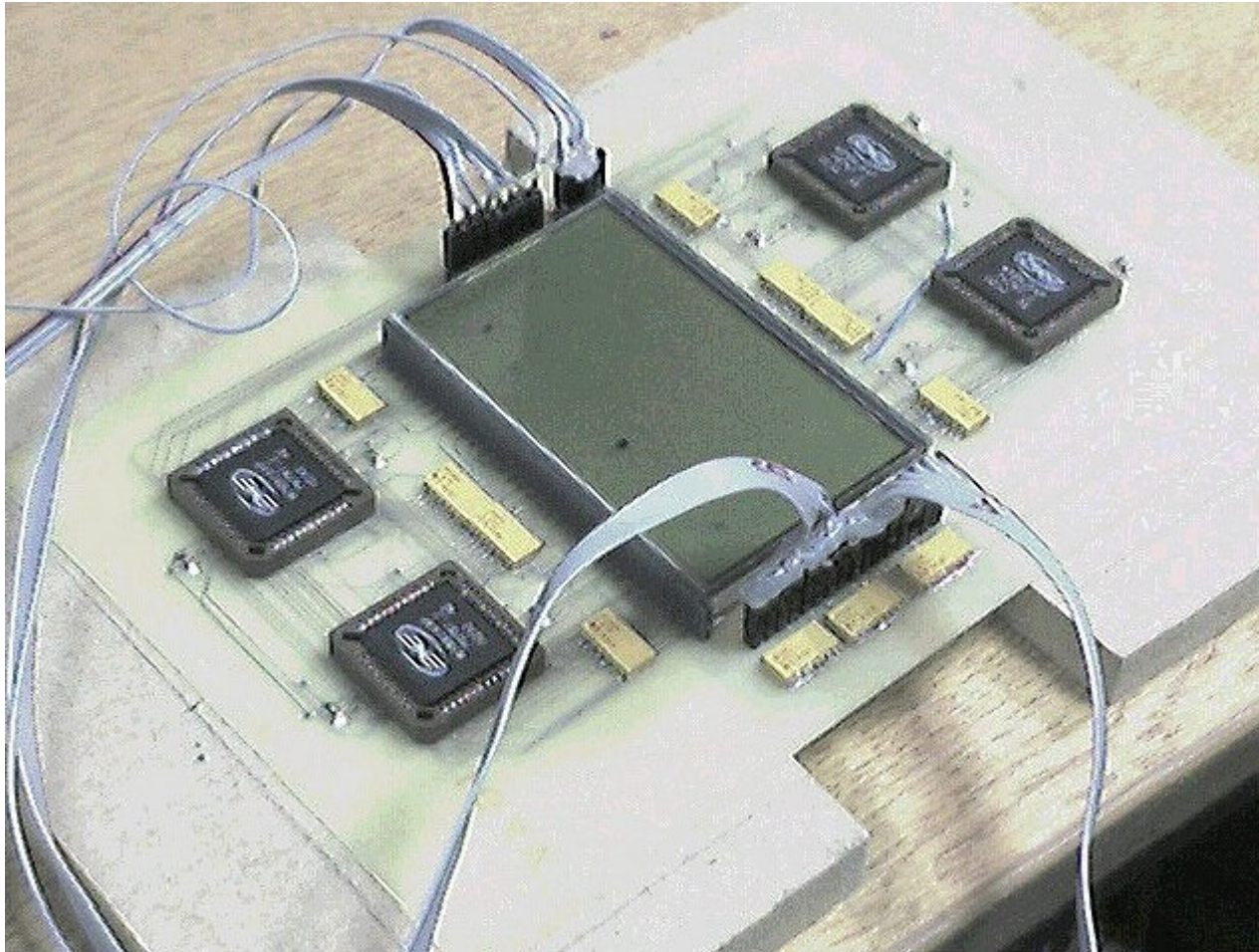
- This year Simon Harding and myself carried out evolution in a novel medium: liquid crystal
- We have evolved a number of functions using a Liquid Crystal Display
- The rest of the tutorial is about that work



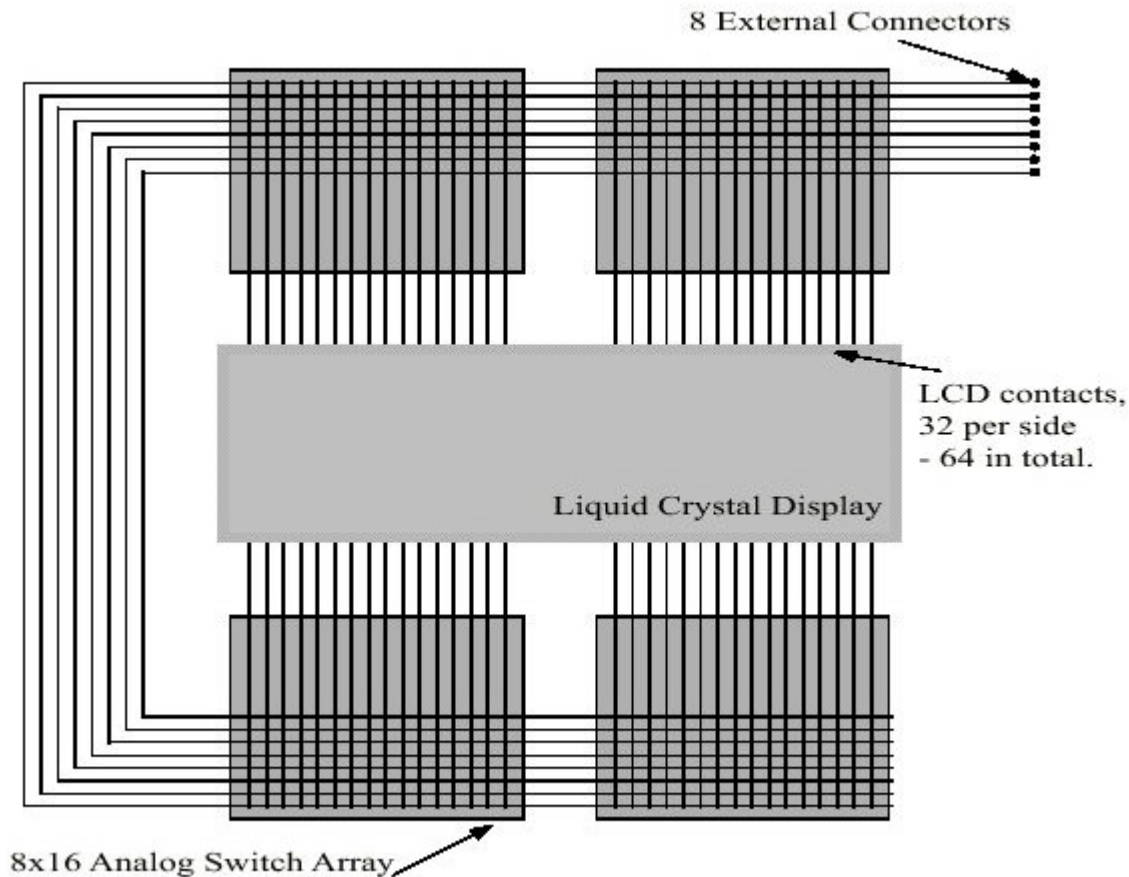
# Experimental setup



In materio evolution in progress



# Inputs and Outputs to LCD



8 connectors:

Ground (fixed)

input signal  
(fixed)

output signal  
(fixed)

5 voltages (-10v  
- 10v)

# Genetic representation

- Genotype in two parts
- First part
  - 64 integers in range 0-8:
    - 64 contacts on the LCD that can be connected to any of eight points (or not connected - left to float)
    - constrained: only one contact can connect to the incident applied signal and one to the output pickup
- Second part
  - 5, 16 bit integers that represents voltages -10v to +10v

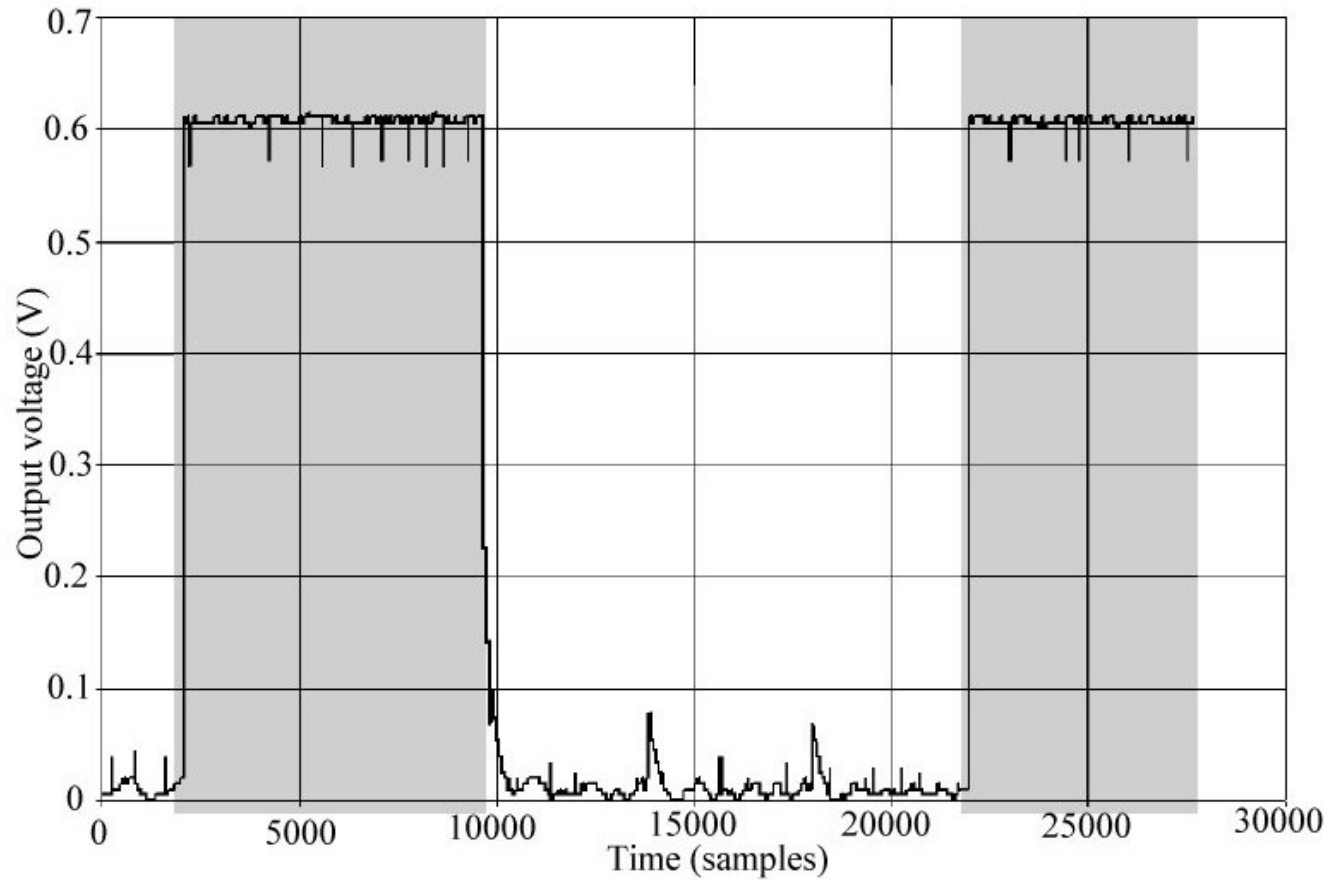
# Genetic Algorithm

- 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 evaluate 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 (i.e. 1250 pulses 5KHz, 25 pulses 100 Hz, 1250 pulses)
- Reward: count percentage output  $< 0.1V$  for 100Hz and output  $> 0.1V$  for 5kHz

# Best evolved ‘circuit’ response



# Analysis (preliminary)

- Crosspoint switches unlikely to be involved as they are designed for high frequency audio/video signals. The feedthrough capacitance is 0.2pF and the switch capacitance is 20pF.
- Our current hypothesis is that the LCD is acting as a configurable RC network but there is much more work to be done to confirm/deny this
- 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



# Further work

- Increase density of connections to Liquid crystal display
- Increase number of applied voltages
- Robot control
- Use different types of LC
- Attempt to evolve solutions to much harder problems
- Understand how the devices work
- Examine potential of other physical systems

# Conclusions

- To be able to evolve things you need richness
- It is time to let 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.
- I would like to see the growth of “evolution in materio” as a research community

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