

Computer Science 2008: student research conference
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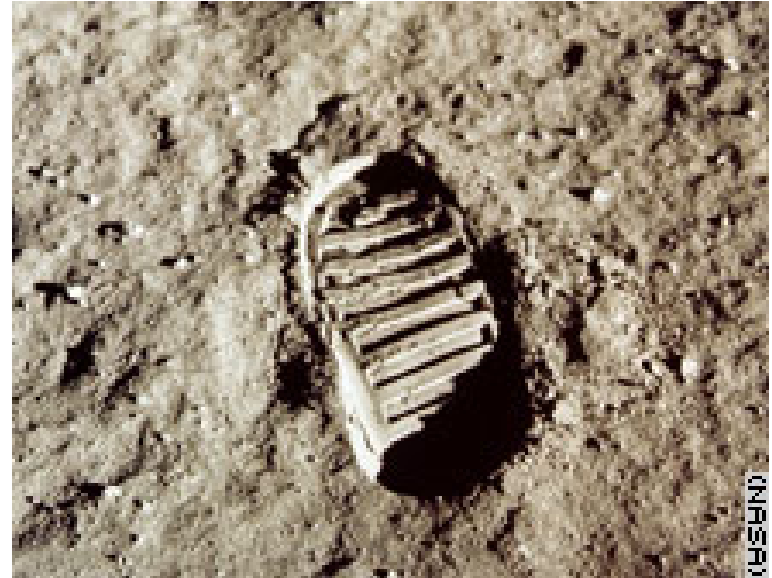
*GC7 : Journeys in
Non-Classical Computation*

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why “Journeys”?

- choosing the right metaphor
- “goal”
 - eg : proving whether $P = NP$
 - know where you are going
 - halting at the end-point
- “journey”
 - eg : Grand Tour of Europe (18th century) / Gap Year (21st century)
 - importance of entire process, not just the destination
 - exploration, open-ended, non-halting, ...



<http://www.cnn.com/2004/TECH/space/07/16/moon.landing/>

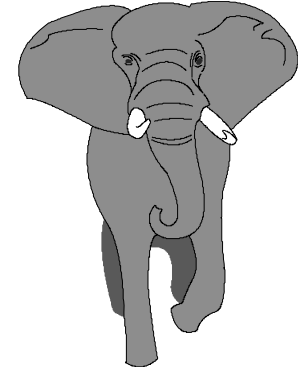
(NASA)

To travel hopefully is a better thing than to arrive.

- Robert Louis Stevenson, “El Dorado”, 1878

why “*non-classical*” computation?

*like defining the bulk of zoology
by calling it the study of
'non-elephant animals'*



– Stan Ulam (attrib)
on the name “non-linear science”

non-linear science /
non-classical computation

Here be Dragons

linear science /
classical computation

classical computation assumptions

- Turing paradigm
 - finite discrete classical state machine, Halting, Universal
 - closed system, predefined state space
- Von Neumann paradigm
 - sequential fetch–execute–store
- algorithmic paradigm
 - initial input ... deterministic function ... final output
 - black–box isolated from the world
- refinement paradigm
 - a known specification is refined to provably correct code
- pure logic paradigm
 - substrate (hardware/physics) is irrelevant

some first steps ...

- hypercomputation
 - exposing underlying implicit assumptions of classical computation
 - using non-Newtonian physics
- unconventional substrates
 - structure and dynamics of complex matter
 - computing what comes naturally
- leading to glimpses of a novel model of computation
- ...

A journey of a thousand miles begins with a single step.

Lao Tzu, Tao Te Ching, Chapter 64, ~600 B.C.

hypercomputation

- **super-Turing computation** : do the same, but faster
 - exponentially faster than the best classical algorithms
- **hypercomputation** : do *more*
 - solve the Halting Problem
 - computing (Turing-)uncomputable numbers
 - ...
- what does it tell us about *computation*?

understanding paper

Turing hoped that his abstracted–paper–tape model was so simple, so transparent and well defined, that it would not depend on any assumptions about physics that could conceivably be falsified, and therefore that it could become the basis of an abstract theory of computation that was independent of the underlying physics. “He thought,” as Feynman once put it, “that he understood paper.” But he was mistaken. Real, quantum–mechanical paper is wildly different from the abstract stuff that the Turing machine uses. The Turing machine is entirely classical

[Deutsch, 1997]

understanding (quantum) physics

- in other words, the entirety of classical computation is based on a *demonstrably false premise*
 - classical physics : only one symbol can appear in each tape location
 - quantum physics : a *superposition* of symbols can appear in each tape location
- **quantum** computation can be **super-Turing** computation
 - there are quantum algorithms that *are* exponentially faster than their classical counterparts
 - but no evidence that it can do *more* (yet)
 - new ways of understanding “information” and “computation”

understanding (relativity) physics

- another false premise:
 - classical physics: the observer (user) and the TM experience the same time
 - General Relativity (GR): the TM can experience *infinite* time whilst the observer experiences only *finite* time
- **GR computation** can give **hypercomputation**
 - can use suitable juggling of space–time structures to solve the Halting Problem
 - makes some implausible *engineering* assumptions
 - but probably no *more* implausible than “unbounded tapes” !

understanding (21st century) physics

- hypercomputation moves the physical basis of computation from the **17th century** (Newtonian) into the *early 20th century* (quantum, GR)
 - this “new” physics is **a century old**
 - although we’ve only recently begun to “believe” some of its weirder consequences ...
 - arguably older than the whole subject of computing!
- what about *late 20th century*, or **21st century**, science?
 - string theory / loop quantum gravity / ...
 - condensed matter – emergent phenomena
 - non-equilibrium thermodynamics – open systems
 - bio-inspired computation
 - ...

virtual machines all the way down

- classical approach:
 - engineer the physical substrate to *implement the (unphysical!) model of computation*
 - and also:
 - (classical) bio-inspired computing additionally has to *implement (simulate) the (bio) substrate*

bio-inspired VM (simulation)

Boolean VM (computing hardware)

silicon substrate (physical material)

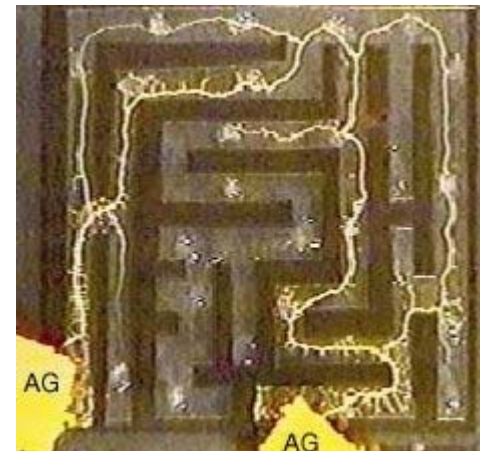
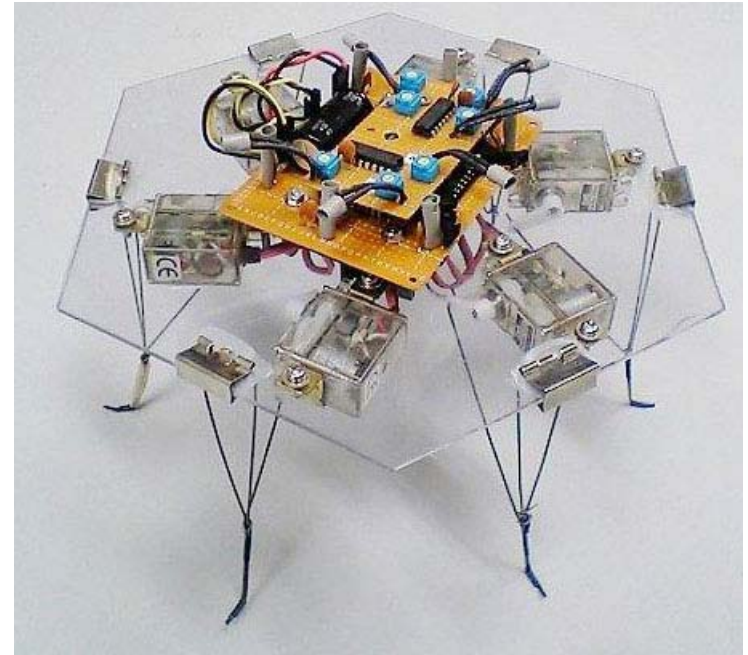
- no wonder these novel paradigms can be inefficient!

understanding embodiment

- instead, **directly** exploit the computational power of the substrate
 - analogue computation
 - reduced power consumption
 - one kind of *embodied* computation
- ultimate: embodied biological computation
 - *computation in evolved materials*
- a (very!) long term goal!

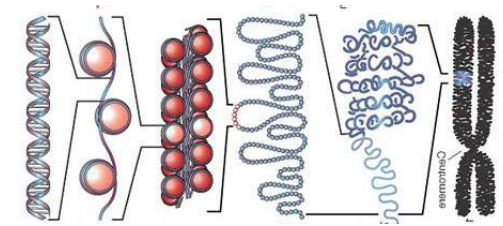
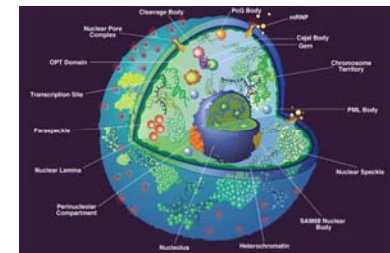
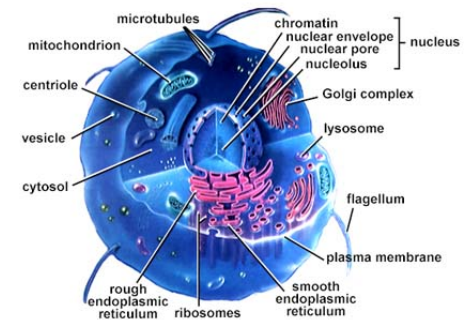
biological substrates: “wet” computation

- DNA
 - base pair matching
 - graph problems
- bacteriorhodopsin protein
 - 3D optical memory
- leech neurons
 - hybrid NNs
- bacteria and slime moulds
 - robot controllers
 - graph problems
 - ...



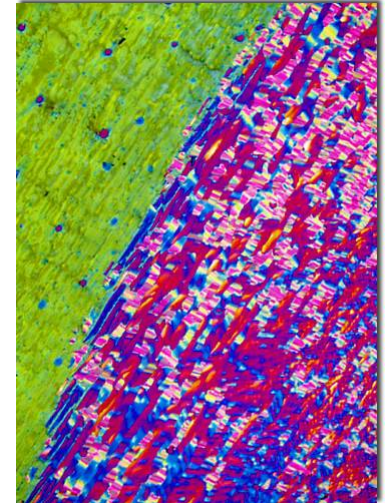
wanted: theory of substrate computation

- *how does wet computation help us get new **theories** of computation, new **insights** into computation?*
- problem: bio-materials have **4 bn years of evolution** behind them
 - extremely complex, extremely complicated
 - not seeing the “primitive” substrate
 - masking any **general principles** of substrate computation
- so first, look to simpler substrates
 - physics and chemistry -- **unevolved**



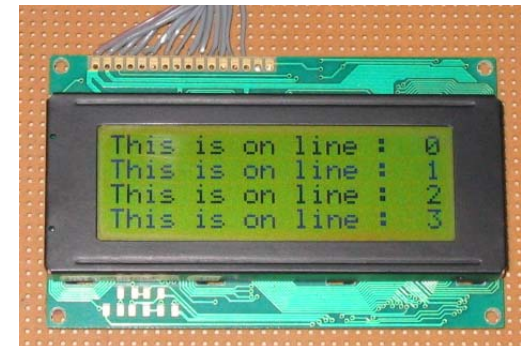
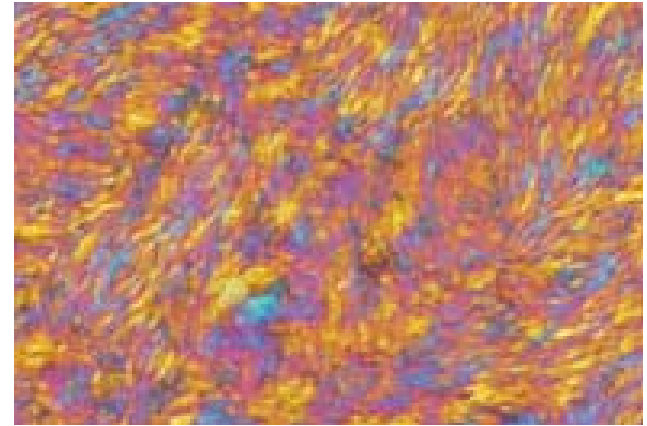
“edge of chaos” substrates?

- motivation: “**edge of chaos**” = maximal complexity, maximal “computational power”?
- critical region, phase transition
 - between “solid” : all structure/memory, no dynamics/processing
and “fluid” : plenty of dynamics, no structure
- so: look at material substrates with *both* complex **structure** (memory) and complex **dynamics** (processing) over a wide range of length/timescales
 - also: start with materials that have existing commercial (laboratory) technology base



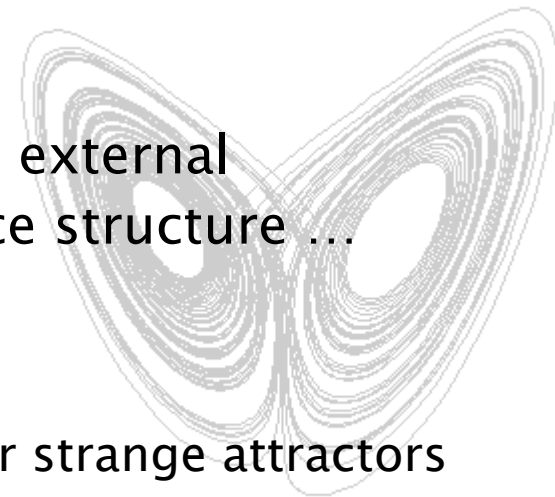
candidate substrate : liquid crystals

- poised between **solid** and **liquid**
- dynamics
 - molecules flow / rotate
- structure
 - orientational order on wide range of length scales
- LCD chip packages
 - tone discriminator
 - robot controller
- soft condensed matter
 - from liquid crystals to bio-materials



model of *in materio* computing

- possible computational model
 - higher level abstractions of the complex detailed **dynamics** :
trajectories through phase/state space to attractors
 - trajectories controlled/determined by the laws of physics
- associated programming model
 - manipulate various system parameters (eg, external modulating fields) to affect this phase space structure ...
 - move the attractors
 - cause bifurcations
 - switch between unstable periodic orbits near strange attractors
 - ... and hence influence the trajectory (the computation)
- *novel computational model* ... but still somewhat static ...



the (a) story still to come ...?

dynamics

- computation = trajectories through phase space to attractors
- programming = manipulating the structure of that phase space

+ co-construction

- “meta-dynamics”
 - “**growth**” of *new* (kinds of) *degrees of freedom* as computation proceeds
- co-construction of the phase space in which the dynamics (computation) occurs
 - *trajectories through, and affecting, a dynamic phase space*

= *novel computational model* ... of biological computation and emergent systems?

The Grand Challenge

to produce a fully mature science
of all forms of computation,
that embraces the classical and
the non-classical paradigms

- many journeys,
one Challenge
- like all science, the
Challenge is an
ongoing journey

<http://www.cs.york.ac.uk/nature/gc7/>

