GC-7 : Journeys in Non-Classical Computation

The story so far …

Susan Stepney,
Samson Abramsky, Andy Adamatzky,
Colin Johnson, Jon Timmis

September 2008

Department of Computer Science
THE UNIVERSITY of York

The UK Grand Challenges in Computing

- UK Computing Research Committee (UKCRC) initiative
  - to discuss opportunities for advancement of computing science
  - (Nov 2002) original call resulted in 109 submissions, merged and refined into seven "Grand Challenges" -- (Mar 2006) two more added

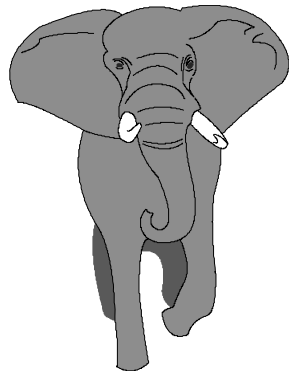
    http://www.ukcrc.org.uk/grand_challenges/index.cfm/

1. In Vivo -- In Silico : Andrew Bangham (UEA)
2/4. Ubiquitous Computing : Design & Science : Morris Sloman (Imperial)
3. Memories for Life : Nigel Shadbolt (Southampton)
5. Architecture of Brain and Mind : Murray Shanahan (Imperial)
6. Dependable Systems Evolution : Jim Woodcock (York)
7. Journeys in Non-Classical Computation : Susan Stepney (York)

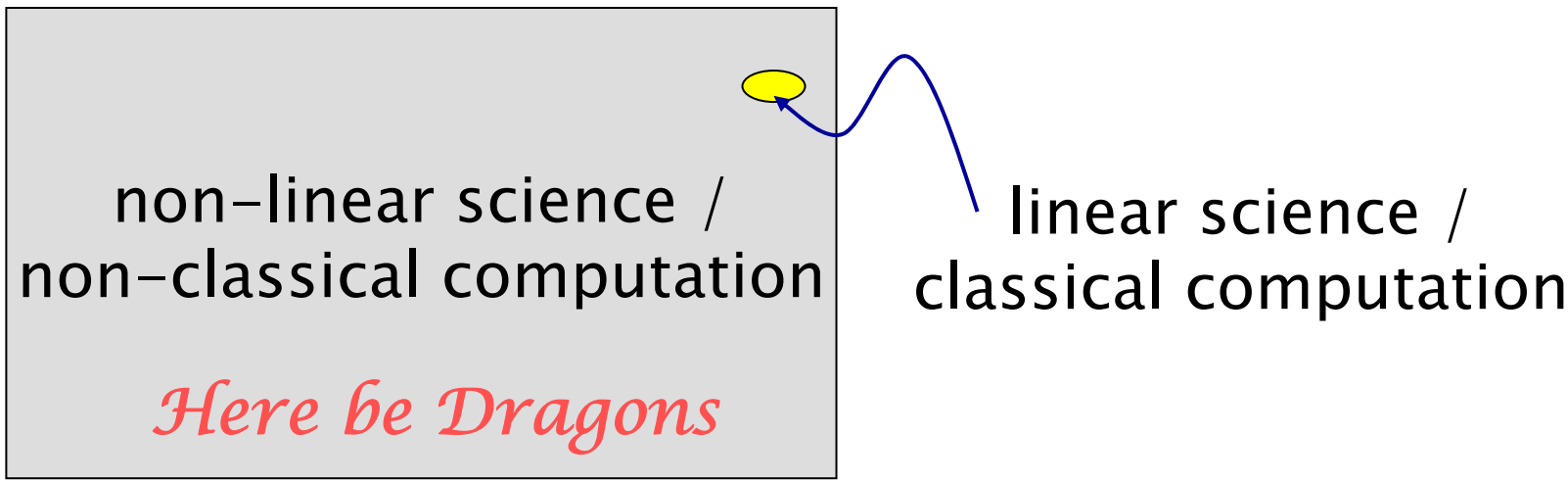
8. Learning for Life : Josie Taylor (OU)
9. Bringing the Past to Life for the Citizen : David Arnold (Brighton)

"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"



why "Journeys"?

- choosing the right metaphor

- "goal" -- eg : proving whether **P = NP**
  - know where you are going
  - know that you have got there
  - halt at the end-point

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

- "journey" -- eg : Grand Tour of Europe
  - importance of entire process, not just the destination
  - exploration, open-ended, non-halting, …

"To travel hopefully is a better thing than to arrive."

– Robert Louis Stevenson, "El Dorado", 1878

some emerging journeys …

- hypercomputation
  - exposing implicit assumptions of classical computation
- interactive computing
  - computing in concert with the real world
- bio-inspired computing ; massive parallelism
  - lessons from the natural world
- embodiment and unconventional substrates
  - computational structure and dynamics of complex matter
- growth and self-assembly
  - open systems, self-defining systems

GC7 as an “umbrella” activity

GC7 is intended to provide a high level, unifying view

- pulling the journeys of exploration together
- noting how the “partial maps” of explored territory join together, and where they overlap
- shedding light on what these teach us about *computation*

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 …)
  - which is arguably older than the whole subject of computing!

- what about **late 20th century** and **21st century** physics?
  - exotica : string theory / loop quantum gravity / …
  - condensed matter – emergent phenomena
  - non-equilibrium thermodynamics – open systems

breaking the rules

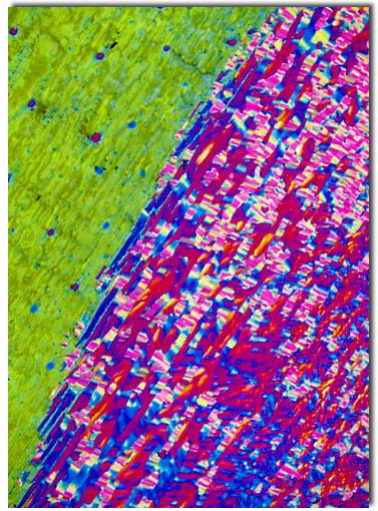
- but hypercomputation is, in some sense, still "playing the Turing game"
  - trying to build a "better" TM
  - questioning *some* of the underlying assumptions
  - there are others!
- what further classical assumptions can we *identify*, and then *break*?
  - and then use the results to understand computation better!
- let's look at the "substrate independent" assumption / requirement ...

substrate independent *v.* embodied

- eg : analogue computation
  - real numbers with reduced power consumption
- one kind of *embodied* computation
  - where the physical properties of the substrate provide (some of) the computational power
- ultimate: embodied biological computation
  - *computation in evolved materials*
  - a (very!) long term goal!
- so, a first step: *in materio* computation
  - computation embodied in *un*evolved materials

“edge of chaos” substrates?

- motivation: “**edge of chaos**” = maximal complexity, maximal “computational power”?

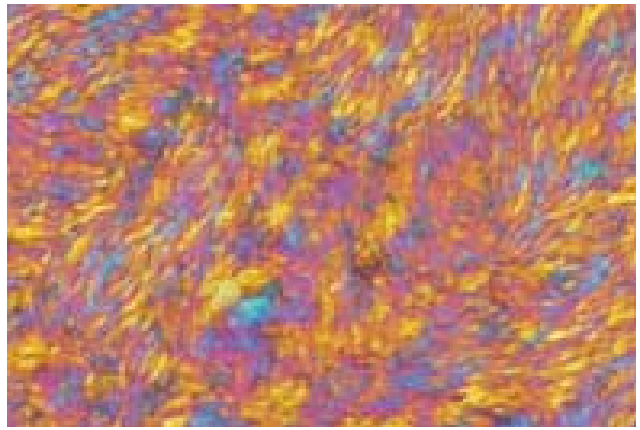


- critical region, phase transition
  - between “solid” : all structure/memory, no dynamics/processing and “fluid” : plenty of dynamics, no structure
- so: look at material substrates with *both* complex ***structure*** (memory) and complex ***dynamics*** (processing) over a wide range of length/timescales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

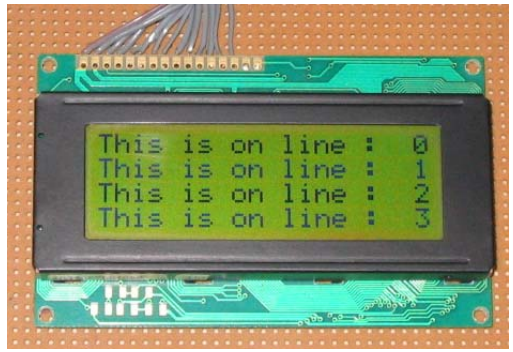
http://www.molecularexpressions.com/dna/magneticfield/magneticfield11.jpg

example : liquid crystals

- poised between **solid** and **liquid**
- dynamics
  - molecules flow / rotate
- structure
  - orientational order on wide range of length scales



- LCD chip packages
  - [Harding & Miller]



- soft condensed matter
  - from liquid crystals to bio-materials

http://www.trnmag.com/Stories/2004/022504/Nanotube_mix_makes_liquid_crystal_Brief_022504.html

http://home.iae.nl/users/pouweha/lcd/images/lcd/lcd-pic16c84.jpg

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 …

co-construction of space

- classical: predetermined state space and computation
  - predetermined data structures, parameters
  - predetermined degrees of freedom
- non-classical: co-construct state space and computation
  - dynamic data structures, growth grammars
  - "growth" of *new degrees of freedom* as computation proceeds
    - also encompasses "death", or collapse of degrees of freedom
    - not merely new "nodes" or more dimensions, but new *kinds* of dimensions, new possibilities
  - necessary for understanding/building *emergent systems*
    - *biological systems co-construct their state spaces*

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/