Hypercomputation and the Grand Challenge in Non-Classical Computation

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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"

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

1. In Vivo -- In Silico : Andrew Bangham

    The Worm, the Weed, and the Bug : breathing life into biological data

2/4. Global Ubiquitous Computing: Science & Design : Morris Sloman

3. Memories for Life : Nigel Shadbolt
5. Architecture of Brain and Mind : Murray Shanahan
6. Dependable Systems Evolution : Jim Woodcock
7. Journeys in Non-Classical Computation : Susan Stepney

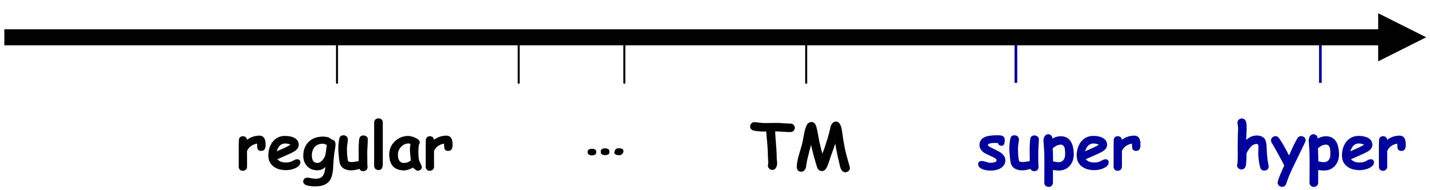
    Robust, adaptable, powerful computation, as **inspired by Nature**

The Grand Challenge

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

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

the classical spectrum of computation



Turing's paper tape

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 …

[David Deutsch, 1997]

computation is *physical*

- computation depends on ***the laws of physics***
- the Turing model of computation assumes Newtonian (classical) physics
- but the world ***is not classical***
  - the Turing model is ***wrong*** in the same kind of way that Newtonian physics is ***wrong***
    - that is : it's pretty much okay in everyday life …

the world is not classical

- models of *hyper*computation based on classical physics are similarly ***wrong***
  - Newtonian gravitational particles (point *masses*) going to 'infinity' in a finite time : ***violates relativity***
- have the same status as models based on other "wrong" physics
  - eg, that **P = NP**, if QM is non-linear
    - (it isn't)

theoretical, not practical, interest

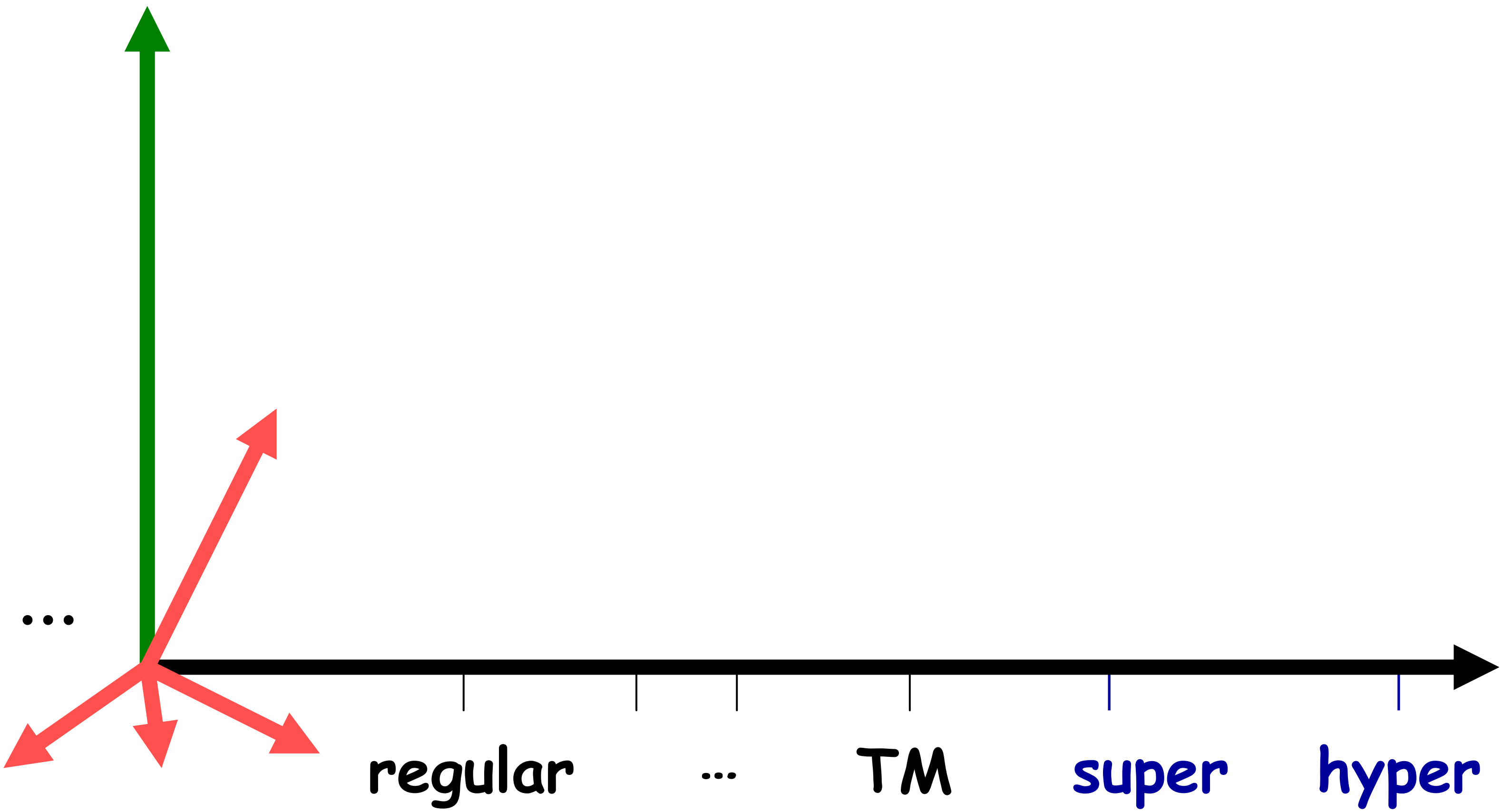
- such models tell us nothing about computation in this, non-classical, world
- still of *theoretical* interest
  - they can give valuable insights into the relationship between physics and computation
    - eg, certain more powerful computational models violate causality
  - constraints on physics from computation?
    - eg, a finite maximum speed required by computational limits?
    - eg, limits on time machines?
- but they are irrelevant to *implementing* a hypercomputer
  - "Ah cannae change the laws o' physics, Cap'n"

it's physics all the way down

- many novel computational ideas start with some physics, abstract out a simple *mathematical model*, then *ignore the physics* ever after
  - unbounded precision measurements in analogue computers
    - your measuring instrument can't be bigger than the universe!
  - exponentially small rotations in Shor's QFT
    - might not be a problem: analyses still being done
  - the energy in the signalling photons from Malament-Hogarth spacetime solutions of the Halting problem
    - if you are cooked by the signalling photons, the computation halted

- just what *are* the laws of physics, anyway?
  - GUTs, string theory, loop quantum gravity, …

not more, not less, but *different*



questioning physical laws

some 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
  - pre-defined output channel
  - 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, unbounded memory, zero power, …

Universality

- invent a new non-standard computational model
  - computing with interacting chemical waves
- first question: can it emulate a Turing machine?
  - elaborate constructions of logic gates from chemical waves
    - elaborate *simulations* of constructions of logic gates…
- if answer = no:
  - go and invent something else;
  - repeat until funding exhausted
- if answer = yes:
  - have an enormous, and glacially slow, (simulation of an) implementation of a TM!

Universality – who cares!

- computability tells us what we can and can't do
    - under certain possibly restrictive assumptions
  - but very little about what we *want* to do
- we *want* computational paradigms that are "easy to program", and "robust"
  - natural ways to express the problems of interest
  - where the consequences of errors are small and contained
  - sufficient for the problems of interest
    - not necessarily all problems!
- the Turing paradigm is *un*natural, and brittle
  - easy to forget just *how* unnatural, until we try to teach programming!

example: real numbers

- Turing paradigm in digital computers
  - analogue substrate (silicon)
  - VM1 : constrained to implement boolean logic (binary, digital)
  - VM2 : used to implement floating point numbers
    - tricky definitions to get it "right"
- at least two levels of VM from the underlying reals
  - no *wonder* it's difficult and inefficient!
- "but you can't implement real numbers"
  - that's a theoretician's response …
  - look at the actual requirements
    - want real numbers in order to interact with real world
      - noise, bounded precision, …

example: parallelism

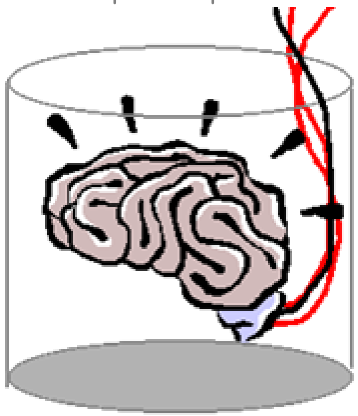
- the real world is *massively* parallel
  - millions, billions … gazillions … of parallel processes
- we want a natural way of modelling these
  - but, classical concurrent programming paradigms are *unnatural*
    - a few *tens* or *hundreds* of threads
    - with complicated synchronisation and deadlock control problems, etc
  - we take an intrinsically parallel world, sequentialise it
    - von Neumann paradigm
  - then implement the wrong sort of concurrency back on
    - no *wonder* it's difficult and inefficient!
- "parallelism gives you no more computational power"
  - that's a theoretician's response …
  - takes no account of interactions with a *real-time environment*

computing in the real world

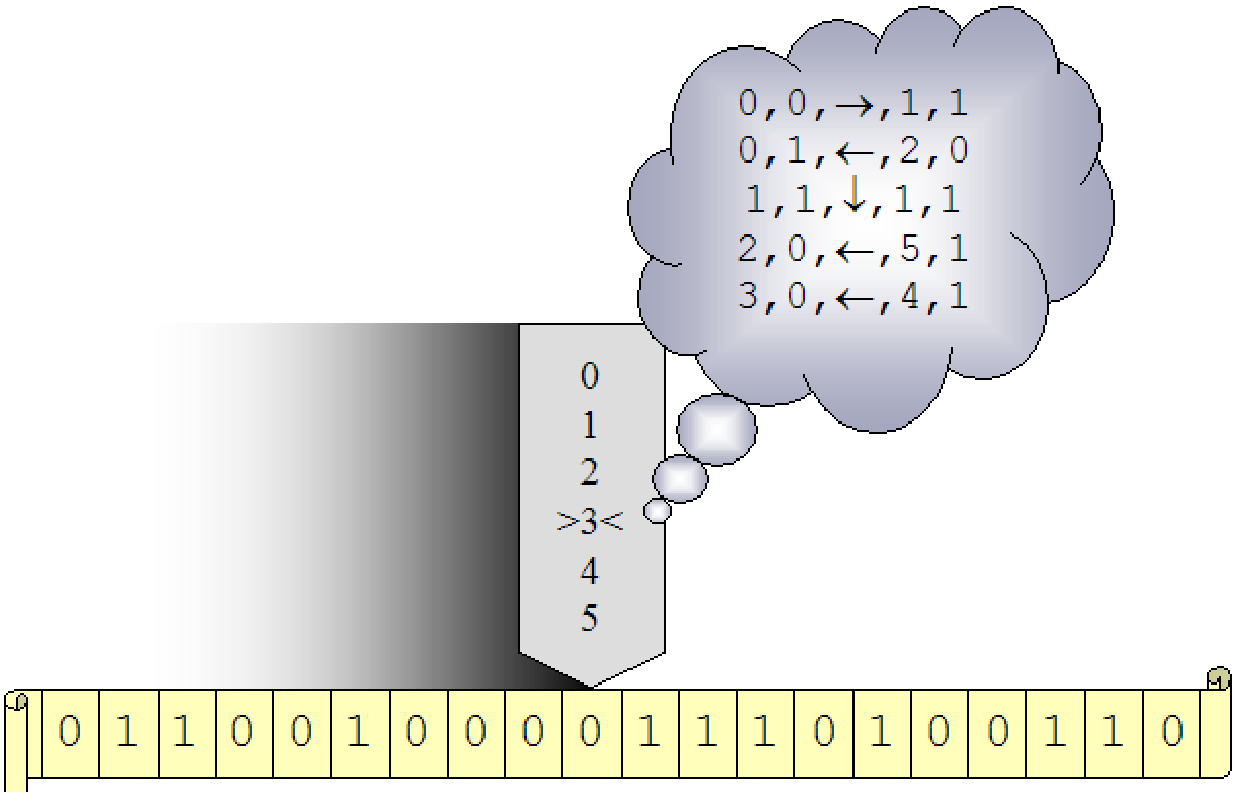
- Turing paradigm : all about ***function calculation***
  - great for payroll systems, and all our other 20th century needs
  - not so good for interacting with the real world, for making "stuff" "smart"
- does the real world compute?
- who cares! we can view many physical, chemical and biological processes *as if* they were computations
  - take the "**computational stance**"
    - Principle of Least Action "computes" shortest path for light
    - water "computes" its own level
    - evolution "computes" fitter organisms
    - DNA and morphogenesis "computes" phenotypes
    - the immune system "computes" antigen recognition
    - …

disembodied computation

http://users.ox.ac.uk/~ball0888/oxfordopen/scepticism.htm



“brain in a vat”



“black box”

http://digitalphysics.org/Publications/Petrov/Pet02a2/Pet02a2.htm

natural embodied computation

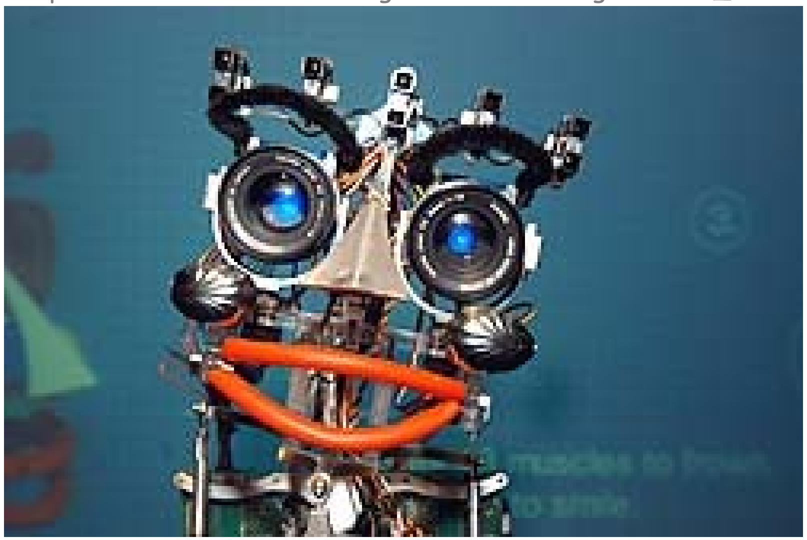
http://home2.vr-web.de/~mycenia/rm-down-under/April/168a_termite_mound.jpg

continually sensing the ever-changing world, acting based on the current state of the world, and further changing the world

http://www.dandelion.org/ant/ant_images.htm

embodied : in an environment

http://www.24hourmuseum.org.uk/content/images/2004_0170.JPG



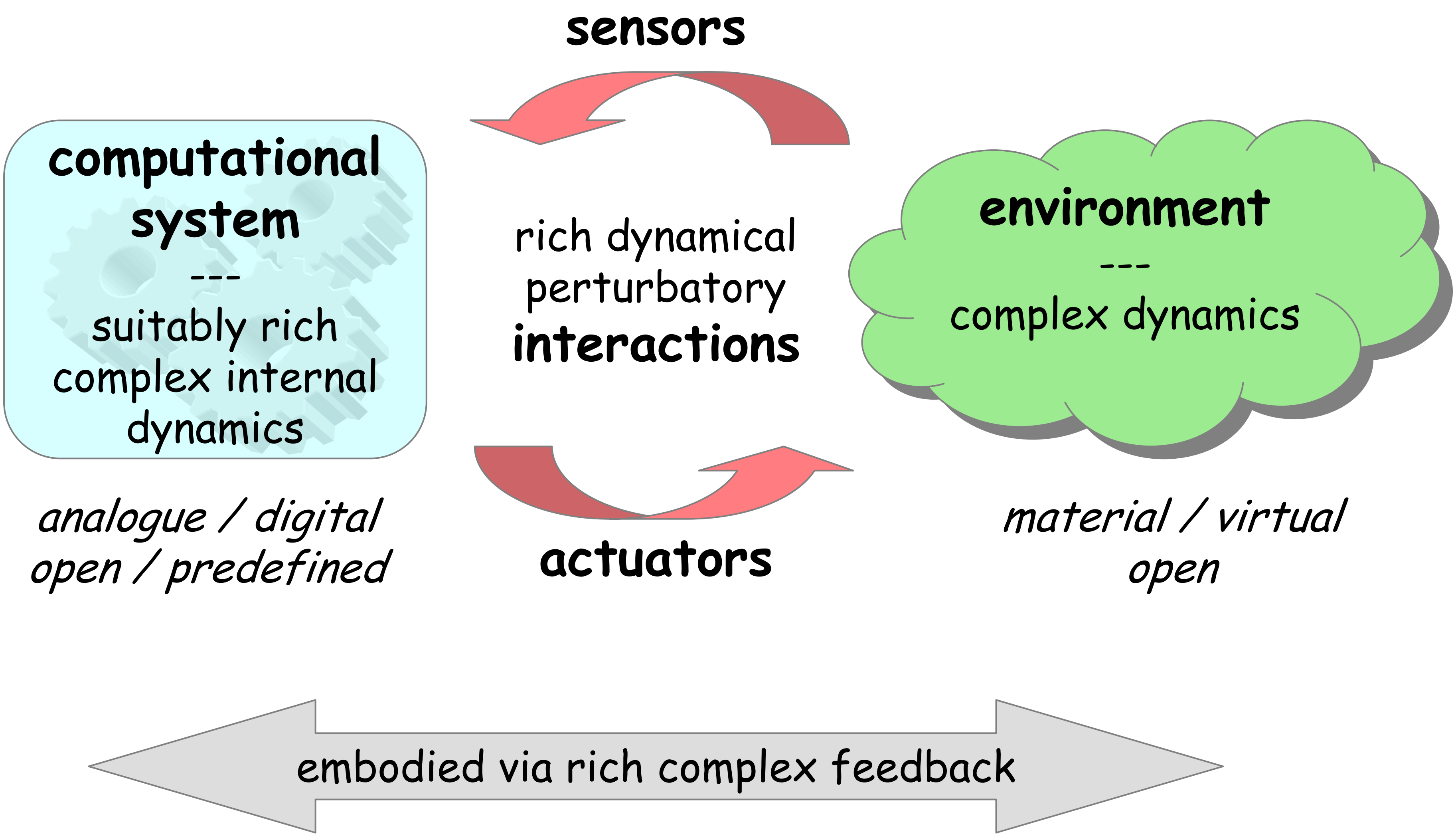
continual rich sensory environmental input

http://www.piaggio.ccii.unipi.it/robotics/images/hand.jpg

sophisticated outputs; environmental manipulation (**stigmergy**)

"the environment [is] a rich and active resource—a partner in the production of adaptive behavior" [Clark, 1997]

embodiment model



the power of embodiment

- rich interaction allows the system to transfer some of its computational burden (memory / state / processing) *to the environment*

- may allow *new classes* of problems to be solved
  - exploiting vastly more computational power

- both richness *and* constraints of environment contribute to this power
  - richness gives environment vast computational power
  - constraints give some solutions "for free" (or much cheaper)
    - constraining the space to a smaller region
    - constraining the computation to particular trajectories

gateway events

- a change to a system that leads to huge increases in kinds and levels of complexity
  - opens up a whole new ***kind*** of phase space to the system's dynamics
- gateway events during evolution of life on earth:
  - eukaryotes (organisms with a cell nucleus) • oxygen atmosphere • multi-cellular organisms • grass • …
- gateway events during the development of mathematics:
  - each introduction of a new class of numbers (negative, irrational, imaginary, …) • dropping Euclid's parallel postulate • …

openness

- Turing paradigm
  - input-output function
    - path of computation irrelevant (modulo complexity issues)
  - pre-defined state space
    - known before computation starts
    - constant until computation halts
- far-from-equilibrium systems
  - stable patterns and structures from the constant flow of matter / energy / information (**emergent** properties)
  - process *is* the trajectory in the phase (state) space
- evolution of the state, *and* of the phase space itself
  - as the structures develop and grow, new possibilities open up
  - new dimensions of behaviour

environmental hypercomputation

- wanted: a computational paradigm that ***naturally*** includes
  - noise
  - non-determinism
  - massive parallelism
  - processes / trajectories
  - embodied interaction with a dynamic environment
  - gateway events in an evolving phase/state space
  - physics all the way down
    - as opposed to a logico-mathematical mindset
  - and a whole lot more non-Turing, non-Von, non-classical stuff …

“I wouldn’t start from here”

- hypercomputation
  - better
  - more
  - *different*

- we mustn’t get caught in a “Turing straight-jacket”
  - it affects the questions we ask
    - who *cares* about universality, about halting?
  - and therefore the models we build

- question everything
  - *especially* whether “Turing” is the right place to start the questioning!