COSC 494/594
Unconventional Computation

Introduction

Course Information

- Instructor: Bruce MacLennan [he/his/him]
- Course website:
  web.eecs.utk.edu/~mclennan/Classes/494-UC or 594-UC
  Lecture Notes are posted on it (read: LNUC-I.pdf)
- Email: maclennan@utk.edu
- Prereqs: linear algebra (basic CS, physics)
- Grading:
  - Homework (every week or two)
  - Project or two
  - Term paper (on some kind of unconventional computation)
  - Presentation (for 594)
  - Occasional easy pop quizzes

Special Note —

THERE WILL BE NO GUNS IN THIS CLASSROOM

Course Outline

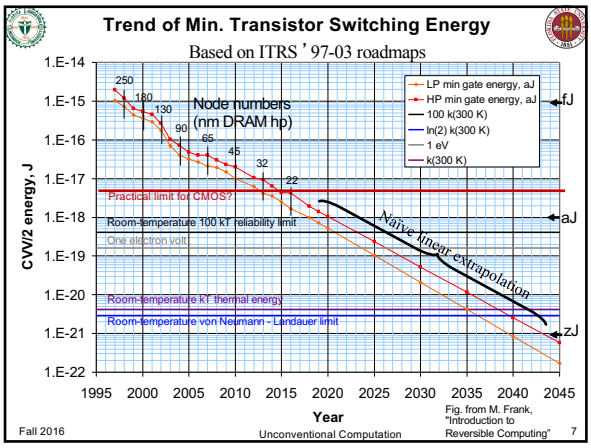
I. Introduction
II. Physics of computation
III. Quantum computation
IV. Molecular computation
V. Analog computation?
VI. Grad presentations on other unconventional computing paradigms

Unconventional Computation

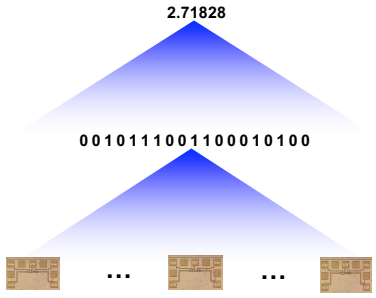
- Unconventional (or non-standard) computation refers to the use of non-traditional technologies and computing paradigms
  - Why would you want to do this?
- Hypercomputation or super-Turing computation refers to computation "beyond the Turing limit"
  - Is this possible?

Post-Moore's Law Computation

- The end of Moore's Law is in sight!
- Physical limits to:
  - density of binary logic devices
  - speed of operation
- Requires a new approach to computation
- Significant challenges
- Will broaden & deepen concept of computation in natural & artificial systems

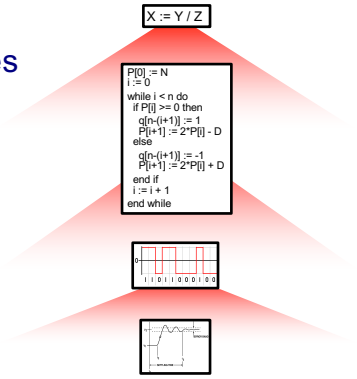


Differences in Spatial Scale



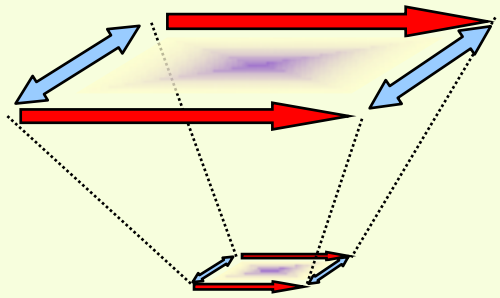
(Images from Wikipedia)

Differences in Time Scale



(Images from Wikipedia)

Convergence of Scales



Implications of Convergence

- Computation on scale of physical processes
- Fewer levels between computation & realization
- Less time for implementation of operations
- Computation will be more like underlying physical processes
- Post-Moore's Law computing ⇒ greater assimilation of computation to physics

Computation is Physical

"Computation is physical; it is necessarily embodied in a device whose behaviour is guided by the laws of physics and cannot be completely captured by a closed mathematical model. This fact of embodiment is becoming ever more apparent as we push the bounds of those physical laws."

— Susan Stepney (2004)

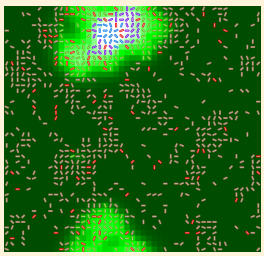
Cartesian Duality in CS

- Programs as idealized mathematical objects
- Software treated independently of hardware
- Focus on *formal* rather than *material*
- Post-Moore's Law computing:
  - less idealized
  - more dependent on physical realization
- More difficult
- But also presents opportunities…

Strengths of "Embodied Computation"

- Information often implicit in:
  - its physical realization
  - its physical environment
- Many computations performed "for free" by physical substrate
- Representation & information processing emerge as regularities in dynamics of physical system

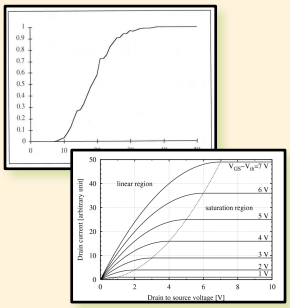
Example: Diffusion



- Occurs naturally in many fluids
- Can be used for many computational tasks
  - broadcasting information
  - massively parallel search for optimization, constraint satisfaction etc.
- Expensive with conventional computation
- Free in many physical systems

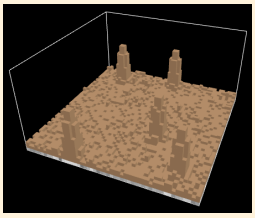
Example: Saturation

- Sigmoids in ANNs & universal approx.
- Many physical systems have sigmoidal behavior
  - Growth process saturates
  - Resources become saturated or depleted
- Embodied computation uses free sigmoidal behavior



(Images from Bar-Yam & Wikipedia)

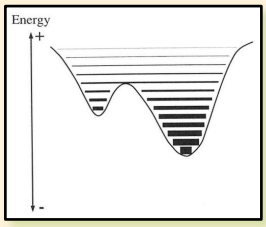
Example: Negative Feedback



- Positive feedback for growth & extension
- Negative feedback for:
  - stabilization
  - delimitation
  - separation
  - creation of structure
- Free from
  - evaporation
  - dispersion
  - degradation

Example: Randomness

- Many algorithms use randomness
  - escape from local optima
  - symmetry breaking
  - deadlock avoidance
  - exploration
- For free from:
  - noise
  - uncertainty
  - Imprecision
- "Free variability"



(Image from Anderson)

"Respect the Medium"

- Conventional computer technology "tortures the medium" to implement computation
- Embodied computation "respects the medium"
- Goal of embodied computation:

  Exploit the physics, don't circumvent it

But is it Computing?

Some Non-Turing Characteristics of Embodied Computation

- Operates in real time and real space
  - with real matter and real energy
  - and hence non-ideal aspects of physical realization
- Often does not terminate
- Often has no distinct inputs or outputs
- Often purpose is not to get an answer from an input
- Often purpose is not to control fixed agent
- Different notions of equivalence and universality

Is EC a Species of Computing?

- The Turing Machine provides a precise definition of computation
- Embodied computation may seem imprecise
- & difficult to discriminate from other physical processes
- Expanding concept of computation beyond TM requires an expanded definition

Non-Turing Computation

Frames of Relevance

- CT computation is a *model* of computation
- All models have an associated *frame of relevance*
  - determined by model's simplifying assumptions
  - by aspects & degrees to which model is similar to modelled system
- Determine questions model is suited to answer
- Using outside FoR may reflect model & simplifying assumptions more than modelled system

Models & Simplifying Assumptions

- Turing computation is a *model* of computation
- A model is like its subject in relevant ways
- Unlike it in irrelevant ways
- A model is suited to pose & answer certain classes of questions
- Thus every model exists in a *frame of relevance* (FoR)
- FoR defines domain of reliable use of model

Example: FoR of Maps

The FoR of Turing Computation

- *Historical roots*: issues of formal calculability & provability in axiomatic mathematics; hence:
  - finite number of steps & finite but unlimited resources
  - computation viewed as function evaluation
  - discreteness assumptions

Idealizing Assumptions

- Finite but unbounded resources
- Discreteness & definiteness
- Sequential time
- Computational task = evaluation of well-defined function
- Computational power defined in terms of sets of functions

Alternate Frames of Relevance for Expanded Notions of Computation

- Natural Computation
  - applying natural processes in computation
  - alternative realizations of formal processes
- Nanocomputation
  - direct realizations of non-Turing computations
  - unique characteristics
- Quantum & Quantum-like Computation
- Molecular Computation

Natural Computation

- *Natural computation* = computation occurring in nature or inspired by it
- Occurs in nervous systems, DNA, microorganisms, animal groups
- Good models for robust, efficient & effective artificial systems (autonomous robots etc.)
- Different issues are relevant

Relevant Issues Outside TC FoR

- Real-time control
- Continuous computation
- Robustness
- Generality, flexibility & adaptability
- Non-functional computation

Relevant Issues Outside TC FoR

- Error, noise & uncertainty are unavoidable
  - must be part of model of computation
  - may be used productively
- Microscopic reversibility may occur
  - e.g., reversible chemical reactions
  - want statistical or macroscopic progress
- Computation proceeds asynchronously in continuous-time parallelism

Real-Time Control

- Real-time (RT) response constraints
- Asymptotic complexity is usually irrelevant
  - Input size typically constant or of limited variability
  - Computational resources are bounded
- Relevant: relation of RT response rate to RT rates of its components

Continuous Computation

- Inputs & outputs often:
  - Are continuous quantities
  - Vary continuously in real time
- Computational processes often continuous
- More or less powerful than TMs?
- Obviously can be approximated by discrete quantities varying at discrete times, *but* …

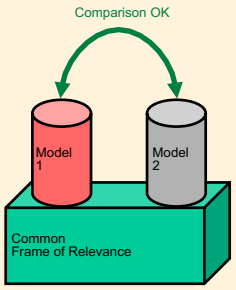
"Metaphysics" of Reals

- "Metaphysical issues":
  - Turing-computable reals vs. standard reals
  - Standard reals vs. non-standard reals
- Results depend on "metaphysical issues" ⇒ outside FoR of model
- Naïve real analysis is sufficient for models of natural computation

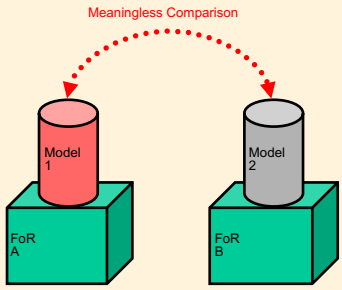
Cross-Frame Comparisons

- Can we compare models with different FoRs?
- Yes: can translate one to other's FoR
- Typically make incompatible simplifying assumptions
- Results may depend on specifics of translation
- E.g., how are continuous quantities represented in TC?

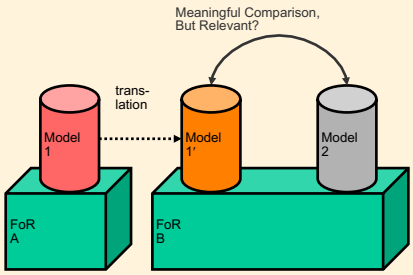
Within-Frame Comparison



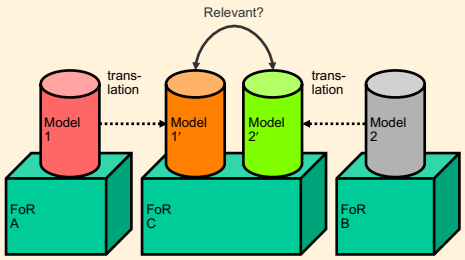
Cross-Frame Comparison



Translated Comparison



Translation to Third Frame



Super-Turing vs. Non-Turing

- Notion of Super-Turing computation is relative to FoR of Turing computation
- Super-Turing computation is important, but so is *Non*-Turing computation

Some Issues in Non-Turing Computation

- What is computation in broad sense?
- What FoRs are appropriate for non-Turing computation?
- Models of non-Turing computation
- How fundamentally to incorporate error, uncertainty, imperfection, reversibility?
- How systematically to exploit new physical processes?

Expanding the Range of Physical Computation

- Digital VLSI becoming a vicious cycle?
- A limit to the number of bits and flops
- Alternative technologies are surpassed before they can be developed
- False assumption that binary logic is the only way to compute
- How to break out of the vicious cycle?

What is Computation?

- What distinguishes computing (physically realized information processing) from other physical processes?
- Computation is a *mechanistic process,* the purpose or function of which is the *abstract manipulation* (processing) of *abstract objects*
- Purpose is *formal* rather than *material*
- Does not exclude embodied computation, which relies more on physical processes

Possible Physical Realizations of Computation

- Any abstract manipulation of abstract objects is a potential computation
  - *de novo* applications of math models
  - applications suggested by natural computation
- But it must be physically realizable
- *Any reasonably controllable, mathematically described, physical process can be used for computation*

Some Requirements

- Speed, but:
  - faster is not always better
  - slower processes may have other advantages
- Feasibility of required transducers
- Accuracy, stability & controllability as required for the application
  - natural computation shows ways of achieving, even with imperfect components

Matching Computational & Physical Processes

- Familiarity of binary logic maintains vicious cycle
- Natural computation shows alternate modes of computation, e.g.:
  - information processing & control in brain
  - emergent self-organization in animal societies
- Openness to usable physical processes
- Library of well-matched computational methods & physical realizations

General-Purpose Computation

- Value of general-purpose computers for all modes of computation
- "Universality" is relative to frame of relevance
- E.g., speed of emulation is essential to real-time applications (natural computation)
- Merely computing the same function may be irrelevant

Conclusions

- Turing model of computation exists in a frame of relevance
  - not appropriate to natural computation, nanocomputation, quantum / quantum-like computation
  - central issues of these include continuity, indeterminacy, parallelism
- Broader definition of computation is needed
- Facilitates new implementation technologies
- Improves understanding of computation in nature