Computational Thinking

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My Grand Vision

- **Computational thinking** will be a fundamental skill used by everyone in the world by the middle of the 21st Century.
  - Just like reading, writing, and arithmetic.
  - Incestuous: Computing and computers will enable the spread of computational thinking.
  - **In research:** scientists, engineers, ..., historians, artists
  - **In education:** K-12 students and teachers, undergrads, ...

Computing is the **Automation of Abstractions**

**Abstractions**

**Automation**

**Computational Thinking** focuses on the **process of abstraction**
- choosing the right abstractions
- operating in terms of multiple layers of abstraction simultaneously
- defining the relationships between layers

guided by the following concerns...

as in **Mathematics**
Measures of a “Good” Abstraction in C.T.

• Efficiency
  – How fast?
  – How much space?
  – How much power?

• Correctness
  – Does it do the right thing?
    • Does the program compute the right answer?
  – Does it do anything?
    • Does the program eventually produce an answer? [Halting Problem]

• -ilities
  – Simplicity and elegance
  – Usability
  – Modifiability
  – Maintainability
  – Cost
  – ...

as in Engineering

NEW
Computational Thinking, Philosophically

- Complements and combines mathematical and engineering thinking
  - C.T. draws on math as its foundations
  - But we are constrained by the physics of the underlying machine
  - C.T. draws on engineering since our systems interact with the real world
    - But we can build virtual worlds unconstrained by physical reality

- Ideas, not artifacts
  - It’s not just the software and hardware that touch our daily lives, it will be the computational concepts we use to approach living.

- It’s for everyone, everywhere
Sample Classes of Computational Abstractions

- **Algorithms**
  - E.g., mergesort, binary search, string matching, clustering
- **Data Structures**
  - E.g., sequences, tables, trees, graphs, networks
- **State Machines**
  - E.g., finite automata, Turing machines
- **Languages**
  - E.g., regular expressions, ..., VDM, Z, ..., ML, Haskell, ..., Java, Perl
- **Logics and semantics**
  - E.g., Hoare triples, temporal logic, modal logics, lambda calculus
- **Heuristics**
  - E.g., A* (best-first graph search), caching
- **Control Structures**
  - Parallel/sequential composition, iteration, recursion
- **Communication**
  - E.g., synchronous/asynchronous, broadcast/P2P, RPC, shared memory/message-passing
- **Architectures**
  - E.g., layered, hierarchical, pipeline, blackboard, feedback loop, client-server, parallel, distributed
- **...**

**NOT**

- Computer literacy, i.e., how to use Word and Excel or even Google
- Computer programming, i.e., beyond Java Programming 101
Examples of Computational Thinking in Other Disciplines
One Discipline, Many Computational Methods
Computational Thinking in Biology

• Shotgun **algorithm** expedites sequencing of human genome

• DNA sequences are strings in a **language**
• **Boolean networks** approximate dynamics of biological networks
• Cells as a self-regulatory system are like **electronic circuits**
• **Process calculi** model interactions among molecules
• **Statecharts** used in developmental genetics
• Protein kinetics can be modeled as **computational processes**
• **Robot** Adam discovers role of 12 genes in yeast
• **PageRank algorithm** inspires ecological food web
Model Checking Primer

Finite State Machine model $M$

Temporal Logic property $\Phi$

$\Phi = AG \ p$

$AF \ p$, $EG \ p$, $EF \ p$

M’s computational tree

Model Checker

yes

counterexample

$\Phi$ is falsified here.
Model Checking Problem

Let $M$ be a **finite state machine**.
Let $\Phi$ be a **specification** in temporal logic.

Find all states $s$ of $M$ such that:

$$M, s \models \Phi$$

Efficient algorithms: [CE81, CES86, Ku94, QS81, VW94]
Efficient data structures: binary decision diagrams [Br86]
Model Checking in Biology

Goal: Predict Rate of Folding of Proteins

1. Finite State Machine $M$ represents 3-residue protein

2. Temporal Logic Formula $\Phi$
   - a. Will the protein end up in a particular configuration?
   - b. Will the second residue fold before the first one?
   - c. Will the protein fold within $t$ ms?
   - d. What is the probability that (c)?
   - e. Does the state $s$ have $k$ folded residues and have energy $c$?

Model checking can explore state spaces as large as $2^{76} \approx 10^{23}$, 14 orders of magnitude greater than comparable techniques [LJ07].

Energy Profile for FKBP-12, Computed via Method

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One Computational Method, Many Disciplines

Machine Learning has transformed the field of Statistics.
Machine Learning in the Sciences

- Brown dwarfs and fossil galaxies discovery via machine learning, data mining, data federation
- Very large multi-dimensional datasets analysis using KD-trees

Astronomy

Medicine
- Anti-inflammatory drugs
- Chronic hepatitis
- Mammograms
- Renal and respiratory failure

Meteorology
- Tornado formation

Neurosciences
- fMRI data analysis to understand language via machine learning
Machine Learning Everywhere

Credit Cards

Supermarkets

Wall Street

Entertainment: Shopping, Music, Travel

Sports
Question (Kearns): Can a Set of Weak Learners Create a Single Strong One?

Answer: Yes, by *Boosting* Algorithms (e.g., [FS99])
Computational Thinking
0.42

+ 0.65

+ 0.92
Computational Thinking in the Sciences and Beyond
CT in Other Sciences

Chemistry
- Atomistic calculations are used to explore chemical phenomena
- Optimization and searching algorithms identify best chemicals for improving reaction conditions to improve yields

Physics
- Adiabatic quantum computing: How quickly is convergence?
- Genetic algorithms discover laws of physics.

Geosciences
- Abstractions for Sky, Sea, Ice, Land, Life, People, etc.
  - Hierarchical, composable, modular, traceability, allowing multiple projections along any dimension, data element, or query
- Well-defined interfaces
CT in Math and Engineering

Mathematics

- Discovering E8 Lie Group:
  18 mathematicians, 4 years and 77 hours of supercomputer time (200 billion numbers).
  Profound implications for physics (string theory)
- Four-color theorem proof

Engineering (electrical, civil, mechanical, aero & astro,...)

- Calculating higher order terms implies more precision,
  which implies reducing weight, waste, costs in fabrication
- Boeing 777 tested via computer simulation alone,
  not in a wind tunnel

Credit: Wikipedia

Credit: Boeing
CT for Society

Economics
- Automated mechanism design underlies electronic commerce, e.g., ad placement, on-line auctions, kidney exchange
- Internet marketplace requires revisiting Nash equilibria model
- Use intractability for voting schemes to circumvent impossibility results

Law
- Inventions discovered through automated search are patentable
- Stanford CL approaches include AI, temporal logic, state machines, process algebras, Petri nets
- POIROT Project on fraud investigation is creating a detailed ontology of European law
- Sherlock Project on crime scene investigation

Humanities
- Digging into Data Challenge: What could you do with a million books?
- Nat’l Endowment for the Humanities (US), JISC (UK), SSHRC (Canada)
- Music, English, Art, Design, Photography, ...

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Educational Implications
Pre-K to Grey

- K-6, 7-9, 10-12
  - Undergraduate courses
    - Freshmen year
      - “Ways to Think Like a Computer Scientist” aka Principles of Computing
    - Upper-level courses
  - Graduate-level courses
    - Computational arts and sciences
      - E.g., entertainment technology, computational linguistics, ..., computational finance, ..., computational biology, computational astrophysics
  - Post-graduate
    - Executive and continuing education, senior citizens
    - Teachers, not just students
Education Implications for K-12

Question and Challenge for the Computing Community:

What is an effective way of learning (teaching) computational thinking by (to) K-12?

- What concepts can students (educators) best learn (teach) when?
  What is our analogy to numbers in K, algebra in 7, and calculus in 12?

- We uniquely also should ask how best to integrate The Computer with teaching the concepts.

Computer scientists are now working with educators and cognitive learning scientists to address these questions.
Computational Thinking in Daily Life
Getting Morning Coffee at the Cafeteria

- coffee
- soda
- straws, stirrers, milk
- cups
- sugar, creamers
- lids
- napkins
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Getting Morning Coffee at the Cafeteria

Especially Inefficient With Two or More Persons...
Better: Think Computationally—Pipelining!

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Computational Thinking at NSF
CDI: Cyber-Enabled Discovery and Innovation

Computational Thinking for Science and Engineering

• Paradigm shift
  – Not just computing’s metal tools (transistors and wires) but also our mental tools (abstractions and methods)

• It’s about partnerships and transformative research.
  – To innovate in/innovatively use computational thinking; and
  – To advance more than one science/engineering discipline.

• Investments by all directorates and offices
  – FY08: $48M, 1800 Letters of Intent, 1300 Preliminary Proposals, 200 Full Proposals, 36 Awards
  – FY09: $63M+, 830 Preliminary Proposals, 283 Full Proposals, 53+ Awards
  – FY10: 320 Full Proposals, ... holding panels now ....
  – FY11 President’s Request: > $100M
Range of Disciplines in CDI Awards

- Aerospace engineering
- Astrophysics and cosmology
- Atmospheric sciences
- Biochemistry
- Biomaterials
- Biophysics
- Chemical engineering
- Civil engineering
- Communications science and engineering
- Computer science
- Cosmology
- Ecosystems
- Genomics
- Geosciences

- Linguistics
- Materials engineering
- Mathematics
- Mechanical engineering
- Molecular biology
- Nanocomputing
- Neuroscience
- Proteomics
- Robotics
- Social sciences
- Statistics
- Statistical physics
- Sustainability
- ...

... advances via Computational Thinking
Range of Societal Issues Addressed

- Cancer therapy
- Climate change
- Environment
- Sustainability
- Visually impaired
- Water
C.T. in Education: National Efforts

Computational Thinking

Computing Community

ACM-Ed
CRA-E
NSF
CSTA
College Board
National Academies
workshops

Rebooting

BPC
CPATH
K-12
AP

CSTB “CT for Everyone” Steering Committee
- Marcia Linn, Berkeley
- Al Aho, Columbia
- Brian Blake, Georgetown
- Bob Constable, Cornell
- Yasmin Kafai, U Penn
- Janet Kolodner, Georgia Tech
- Larry Snyder, U Washington
- Uri Wilensky, Northwestern
Computational Thinking, International

UK Research Assessment (2009)

The Computer Science and Informatics panel said
“Computational thinking is influencing all disciplines....”

par Jeannette M. Wing

Cet article fait suite aux divers interviews que nous avons faits et qui nous invitaient à une réflexion sur les fondements de notre discipline et ses aspects philosophiques et épistémologiques. Aujourd’hui l’article de Jeannette Wing nous conduit à réfléchir sur l’utilité et l’ubiquité de la pensée informatique et ses implications, mais aussi sur l’essence même de cette pensée.
Spread the Word

• Help make computational thinking commonplace!

To fellow faculty, students, researchers, administrators, teachers, parents, principals, guidance counselors, school boards, teachers’ unions, congressmen, policy makers, ...
Thank you!
References (Representative Only)

- **Computational Thinking**

- **Model Checking, Temporal Logic, Binary Decisions Diagrams**

- **Computational Thinking and Biology**
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Machine Learning and Applications
- Symbolic Aggregate Approximation, Eamonn Keogh, UC Riverside, [http://www.cs.ucr.edu/~eamonn/SAX.htm](http://www.cs.ucr.edu/~eamonn/SAX.htm) (applications in Medical, Meteorological and many other domains)
- The Auton Lab, Artur Dubrawski, Jeff Schneider, Andrew Moore, Carnegie Mellon, [http://www.autonlab.org/autonweb/2.html](http://www.autonlab.org/autonweb/2.html) (applications in Astronomy, Finance, Forensics, Medical and many other domains)

Computational Thinking and Astronomy
- Sloan Digital Sky Survey @Johns Hopkins University, [http://www.sdss.jhu.edu/](http://www.sdss.jhu.edu/)

Computational Thinking and Chemistry

Computational Thinking and Economics
- Michael Kearns, Computational Game Theory, Economics, and Multi-Agent Systems, University of Pennsylvania, [http://www.cis.upenn.edu/~mkearns/#gamepapers](http://www.cis.upenn.edu/~mkearns/#gamepapers)
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- Computational Thinking and Law
  - Stanford Computational Law, http://complaw.stanford.edu/

- Computational Thinking and Medicine
  - Institute for Computational Medicine, Johns Hopkins University, http://www.icm.jhu.edu/
  - See also Symbolic Aggregate Approximation, Eamonn Keogh, UC Riverside, http://www.cs.ucr.edu/~eamonn/SAX.htm

- Computational Thinking and Meteorology
  - See also Symbolic Aggregate Approximation, Eamonn Keogh, UC Riverside, http://www.cs.ucr.edu/~eamonn/SAX.htm

- Computational Thinking (especially Machine Learning) and Neuroscience

- Computational Thinking and Sports
  - Lance Armstrong’s cycling computer tracks man and machine statistics, website
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