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, …

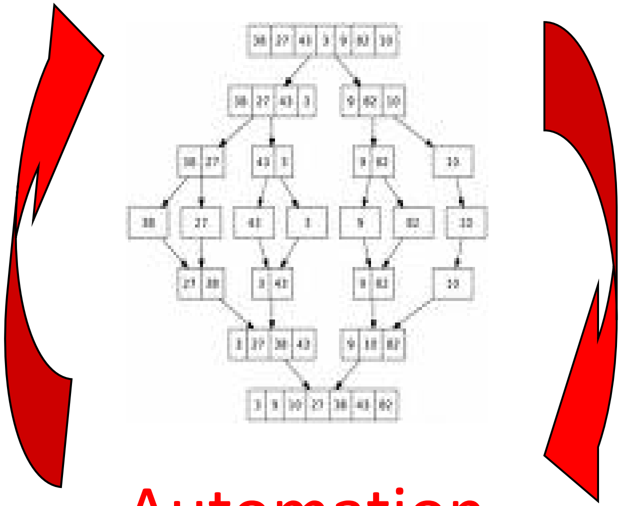
J.M. Wing, "Computational Thinking," *CACM* Viewpoint, March 2006, pp. 33-35.
Paper off http://www.cs.cmu.edu/~wing/

What is Computational Thinking?

Computational thinking is the *thought processes* involved in formulating a problem and expressing its solution(s) in such a way that a computer—human or machine—can effectively carry out.

The Critical Thought Process: Abstraction

Abstractions



Automation

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 Concepts

- 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, Python
- 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-

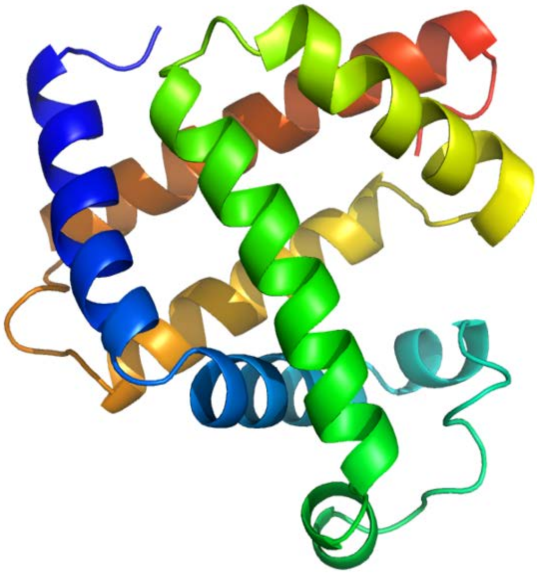
NOT

- Computer literacy, i.e., how to use Word or Excel
- Computer programming, i.e., beyond Java Programming 101

Examples of Computational Thinking in Other Disciplines

One Discipline, Many Computational Methods

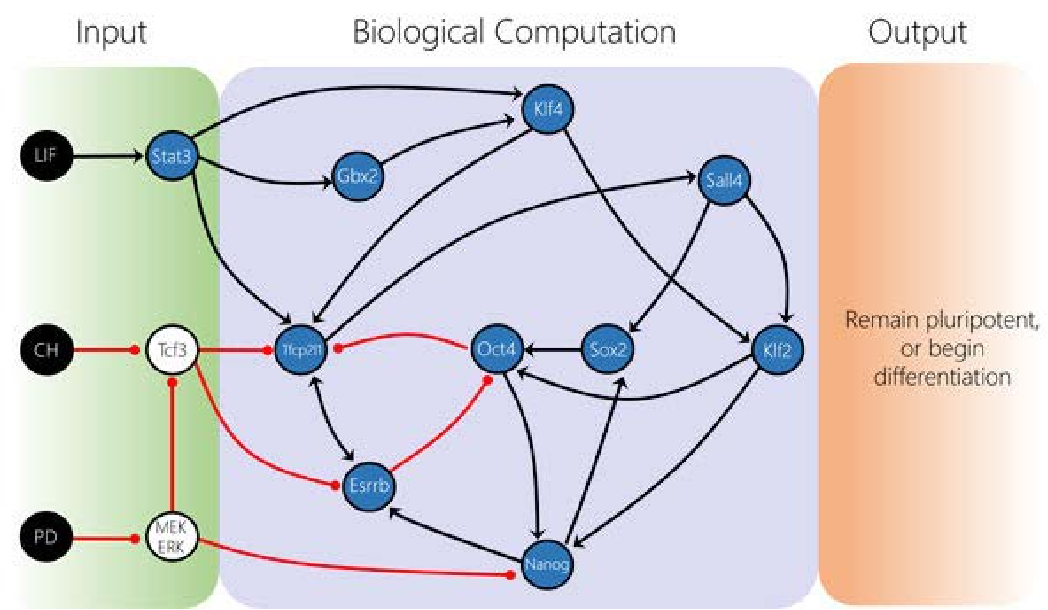
Computational Thinking in Biology



- Shotgun algorithm expedites sequencing of human genome
- Abstract interpretation in systems biology
- Model checking applied to arrhythmia, diabetes, pancreatic cancer
- 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

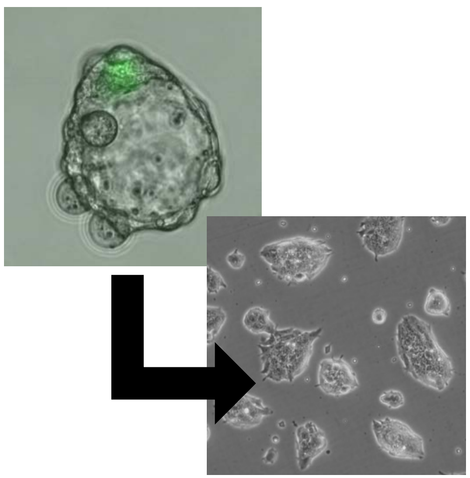
Insight: Models and languages for expressing computational processes are good for expressing the dynamics of biological processes.

Stem Cell Prediction



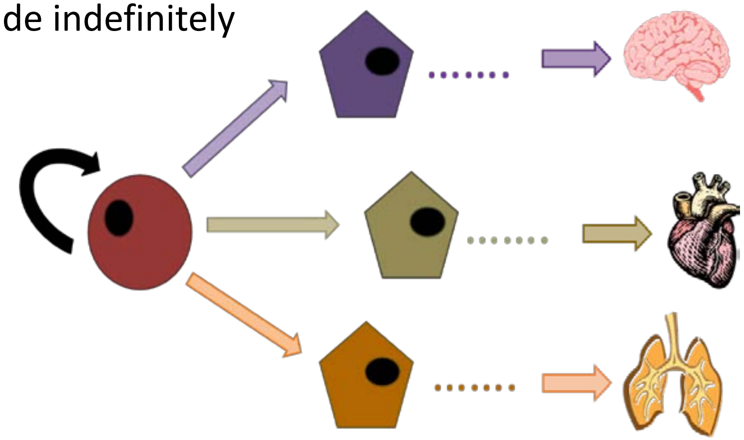
[Dunn et al., “Defining an essential transcription factor program for naïve pluripotency,” *Science,* June 2014, pp. 1156-1160]

Embryonic Stem (ES) Cells

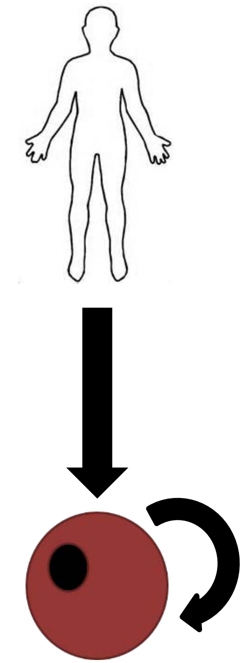


Transient in tissue:
A culture-dependent phenomenon

Self-renewing:
Divide indefinitely



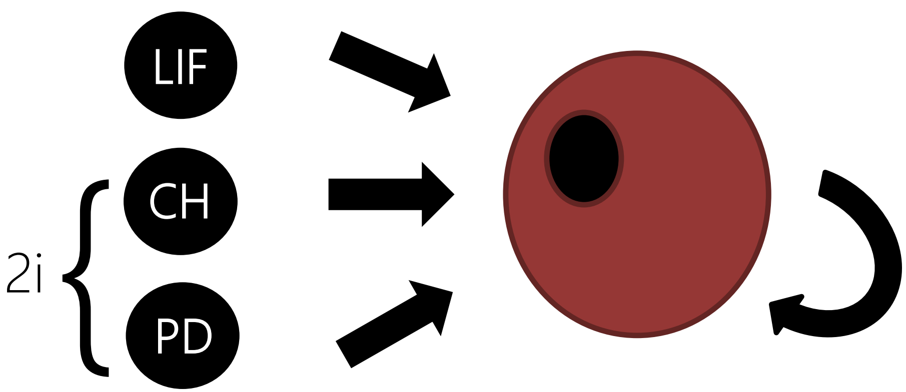
Pluripotent: Generate all adult cell types, and can be re-injected back into the developing embryo



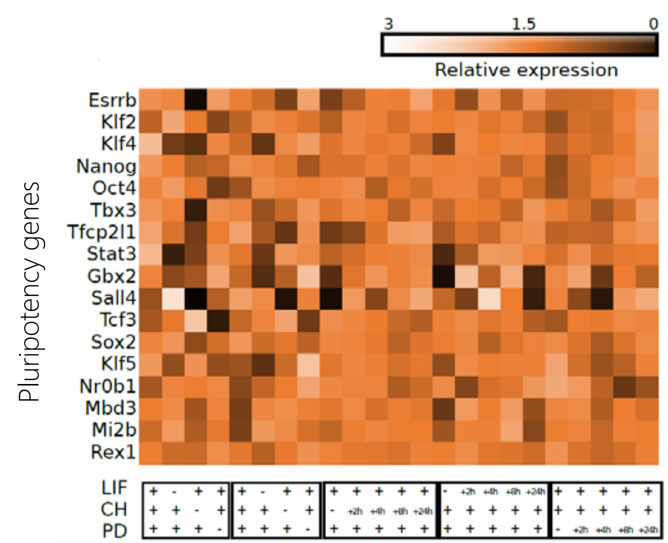
We can **reprogram** adult cells to this state

Extrinsic Signals Control ES Cell Behavior

Whether an ES cell will remain self-renewing, or differentiate towards an adult cell lineage depends on the signals that it receives.

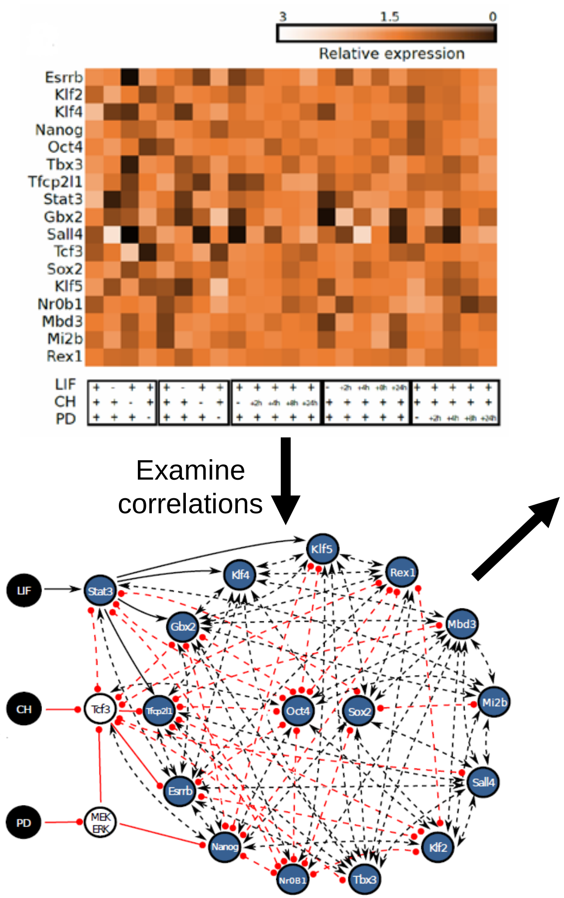


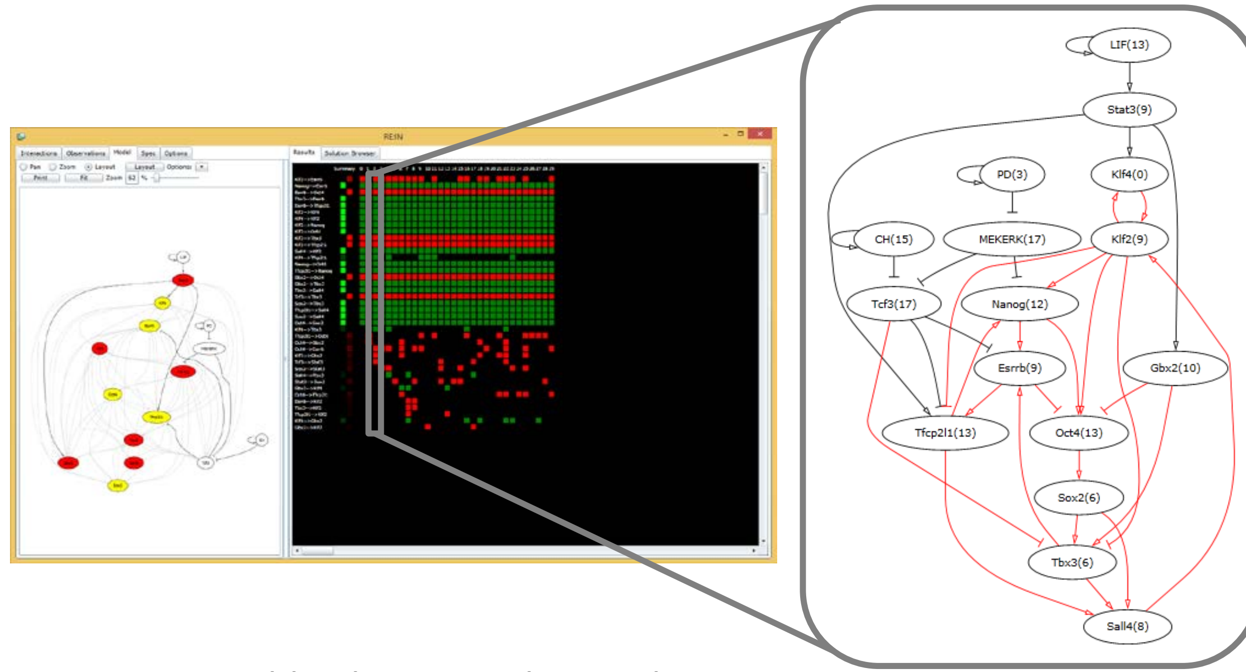
The signals required to sustain ES cells in culture have been progressively refined. Any two of LIF, CH and PD are sufficient.



We can measure the expression of key genes under different combinations of signals to gain insight into the dynamic behavior of the system.

A Reasoning Engine for Interaction Networks

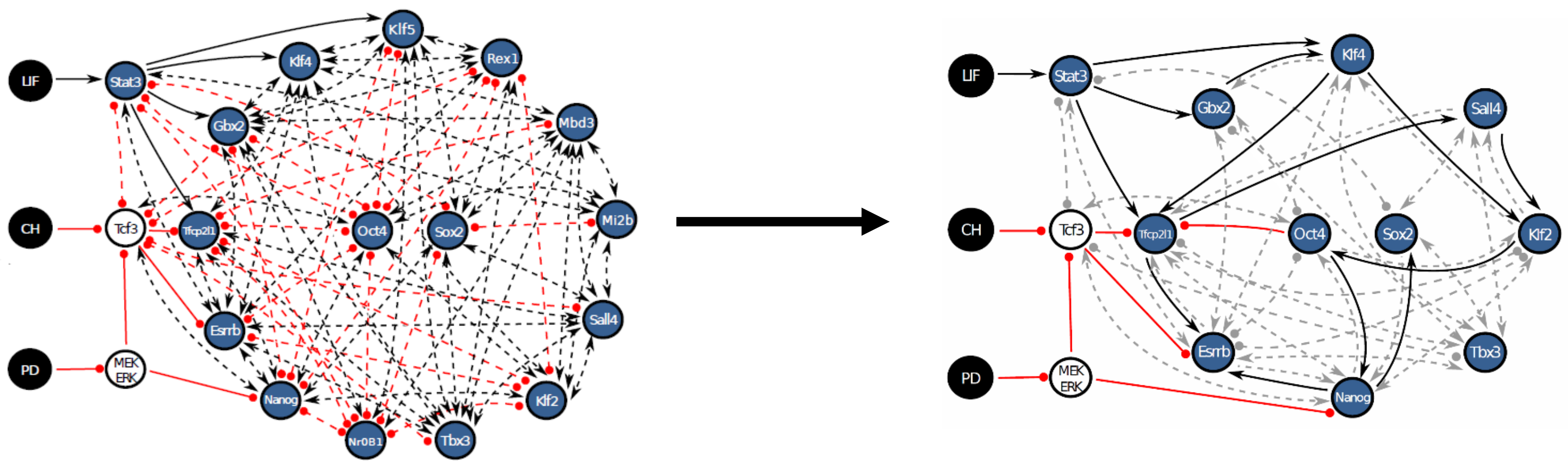




RE:IN is a tool built on Z3 that utilizes Satisfiability Modulo Theories to synthesize only those (out of 10^43) Boolean networks that provably satisfy experimental constraints.

```
IF (signalA AND signalB
 AND NOT signalC  OR …)
THEN remain a stem cell
ELSE (IF NOT signalA …)
     differentiate
```

Biological Computation in Stem Cells



- The set of possible models was constrained by experimentally-observed behaviours
- This set was used to make a large number (53) of non-intuitive predictions of the response of the network to genetic perturbations. These predictions were experimentally validated with over 70% accuracy rate.
- The highlighted interactions show the minimal set required to explain stem cell behaviour: **the essential program governing naïve pluripotency**

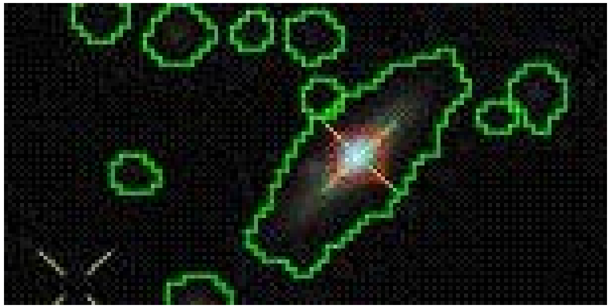
One Computational Method, Many Disciplines

Machine Learning has transformed the field of Statistics.

Machine Learning in the Sciences

Astronomy

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



Credit: SDSS

Medicine

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

Meteorology

- Tornado formation

Neurosciences

Credit: LiveScience

- fMRI data analysis to understand language via machine learning

Machine Learning Everywhere

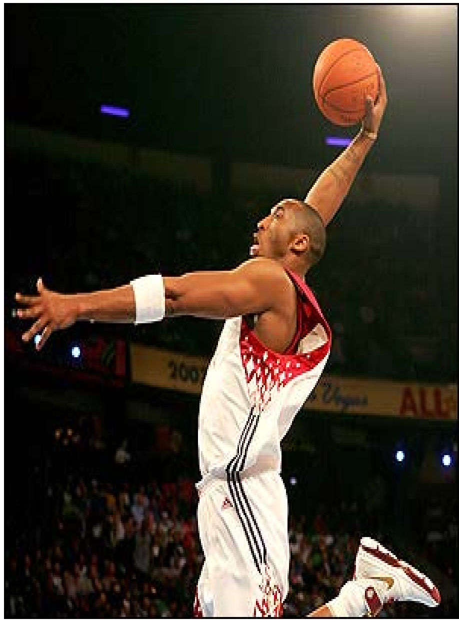
Credit Cards

Supermarkets

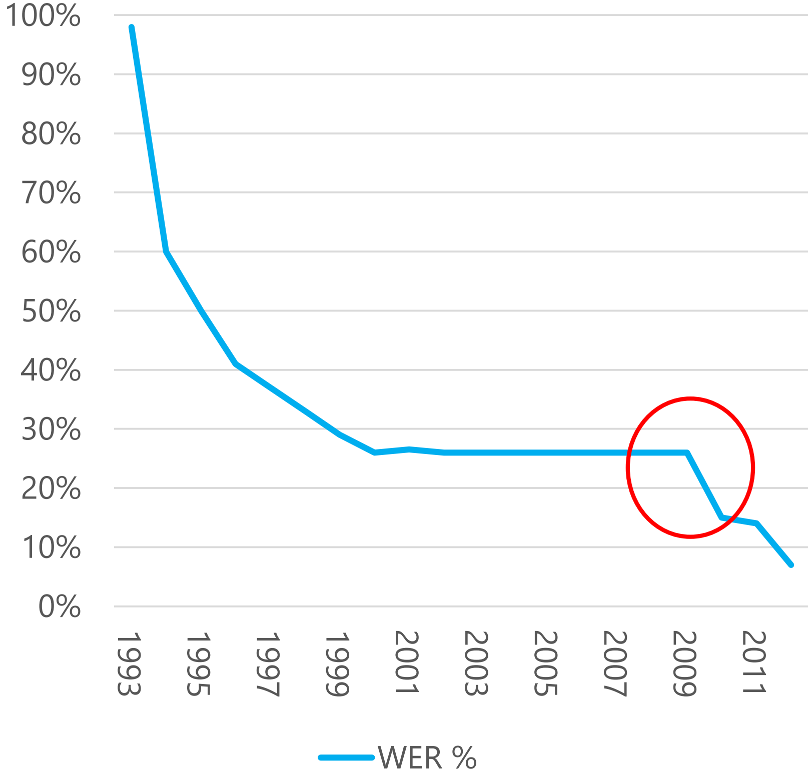
Wall Street

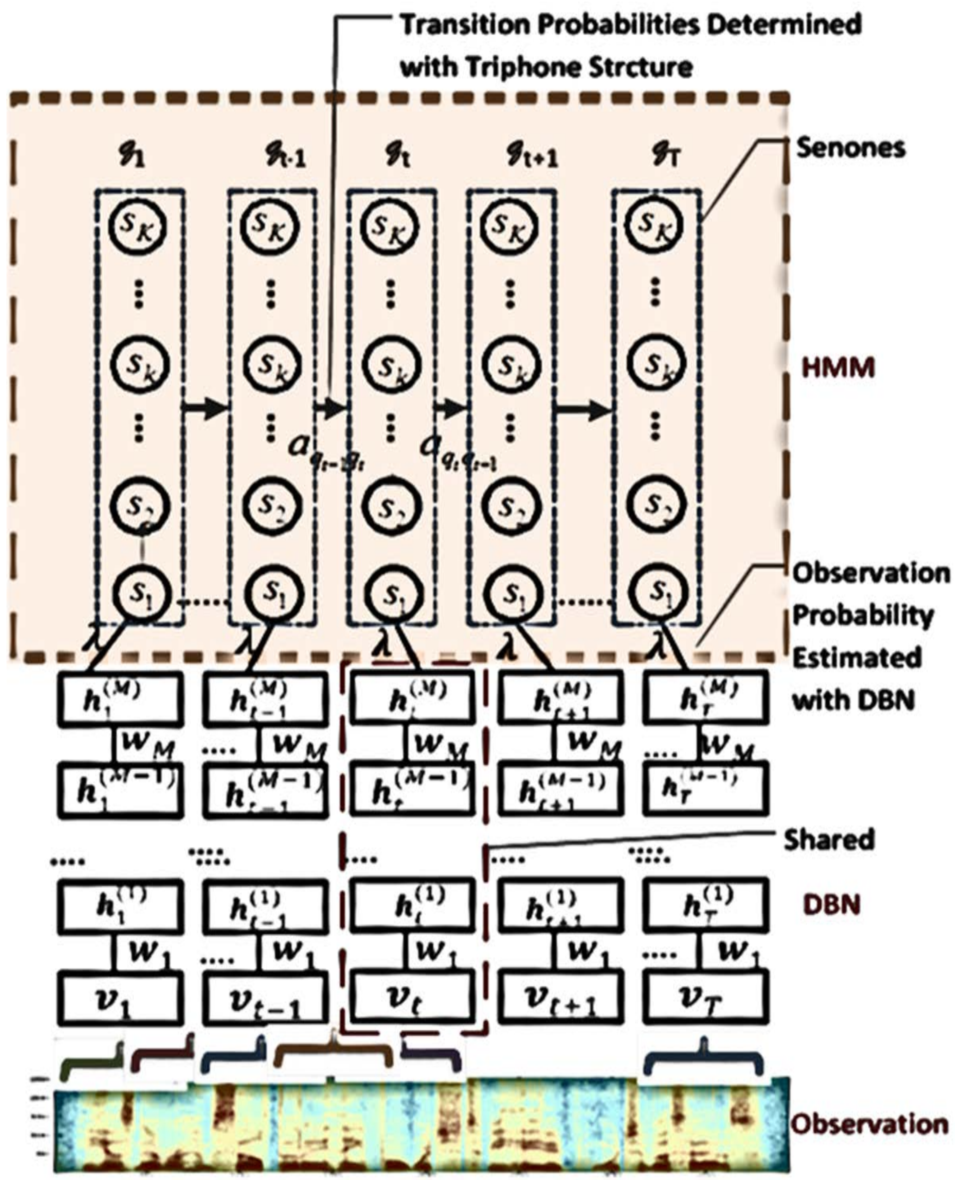
Entertainment:
Shopping, Music, Travel

Sports



Deep Neural Networks





Speech-to-Speech

Tianjin, China, October 2012

English speech of speaker

$\rightarrow$ English text

$\rightarrow$ Chinese text

$\rightarrow$ Chinese speech of same speaker

Skype Translator: Breaking the Language Barriers

December 2014

Stafford Elementary
Tacoma, Washington, USA

Colegio Peterson
Mexico City, Mexico

Historic Achievement: Microsoft researchers reach human parity in conversational speech recognition

Achieving Human Parity in Conversational Speech Recognition

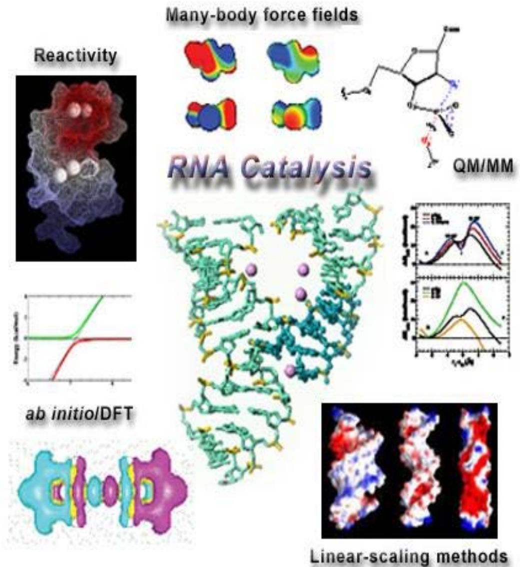
W. Xiong, J. Droppo, X. Huang, F. Seide, M. Seltzer, A. Stolcke, D. Yu, G. Zweig

(Submitted on 17 Oct 2016)

Computational Thinking in the Sciences and Beyond

Computational Thinking in Other Sciences

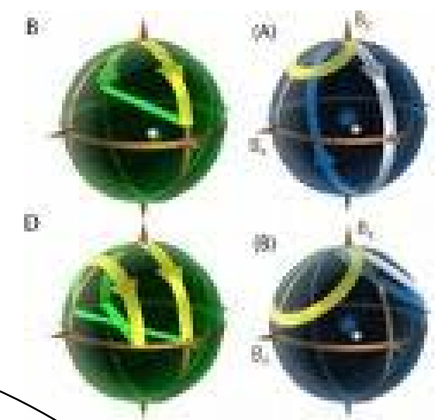
Chemistry



[York, Minnesota]

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

Physics

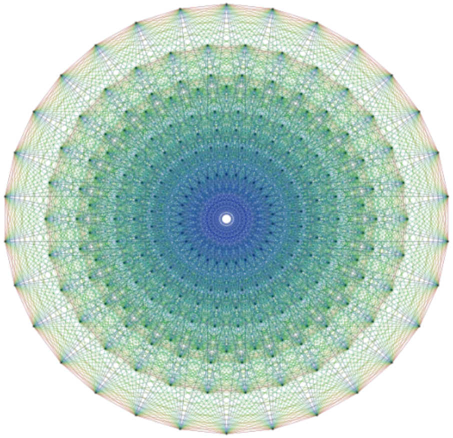


- Adiabatic quantum computing: How quickly is convergence?
- Genetic algorithms discover laws of physics.

Geosciences

- DeepDive: analysis of measurement info buried in geoscience literature
- Cornell’s NSF Expedition on Computational Sustainability
- FetchClimate from MSR: predictive analysis of multiple large datasets

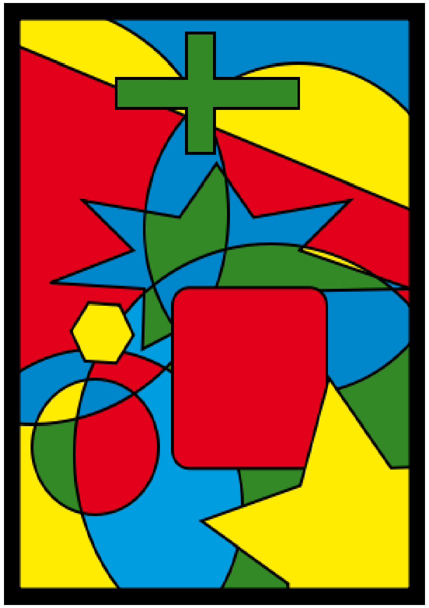
Computational Thinking in Math and Engineering



Credit: Wikipedia

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



Credit: Wikipedia

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

Credit: Boeing

- Calculating higher order terms implies more precision, which implies reducing weight, waste, costs in fabricati
- Boeing 777 tested via computer simulation alone, not in a wind tunnel
- Hybrid automata for modeling and analyzing cyber-physical systems

Computational Thinking for Society

Microsoft Digital Advertising Solutions

Economics

Google AdSense

ebay

Overstock.com Your Online Outlet

- 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

- 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

Law

Healthcare

- Algorithmic medicine
- Software design principles and debugging applied to prescriptions of painkillers
- ONC SHARP Program, NSF Smart Health and Wellness Program, NITRD Senior Steering Group on Health IT

Computational Thinking for Society

Archaeology

- eHeritage Project, Microsoft Research Asia
- Digital Forma Urbis Romae Project, Stanford
- Cathedral Saint Pierre, Columbia

Journalism

- Crowd sourcing as a new way of getting news tips from sources
- Algorithmic approach to validate credibility of sources
- Digital Media and Learning Initiative, MacArthur Foundation

Humanities

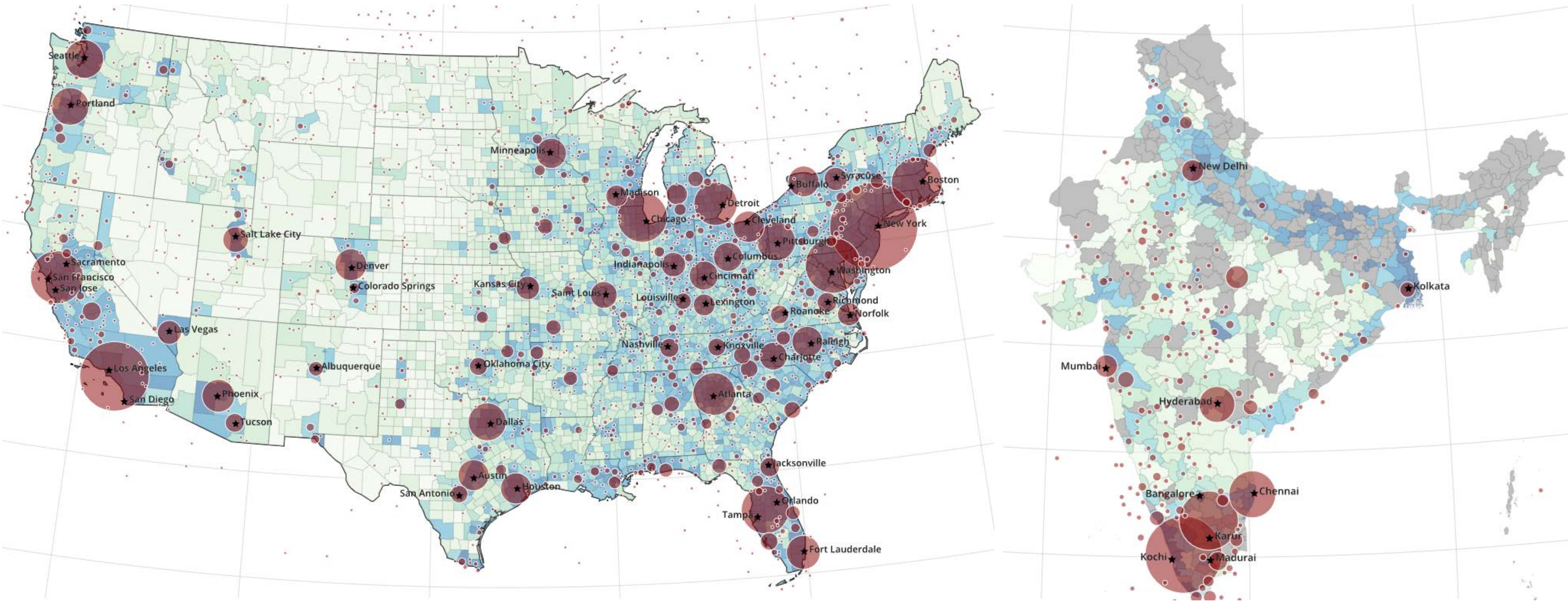
- Digging into Data Challenge: What could you do with a million books?
  Nat'l Endowment for the Humanities (US),
  JISC (UK), SSHRC (Canada)
- Music, English, Art, Design, Photography, …

Computational Social Science: Learning about Crowdworkers

- <u>Computational:</u> digital studies produce the *nodes* (people) and *edges* (relationships) in a network

- <u>Anthropology</u>: qualitative studies produce the *variety of nodes* (individuals, institutions) and *meaning of edges* (motivations, hierarchies, power dynamics)

Mapping the Crowd

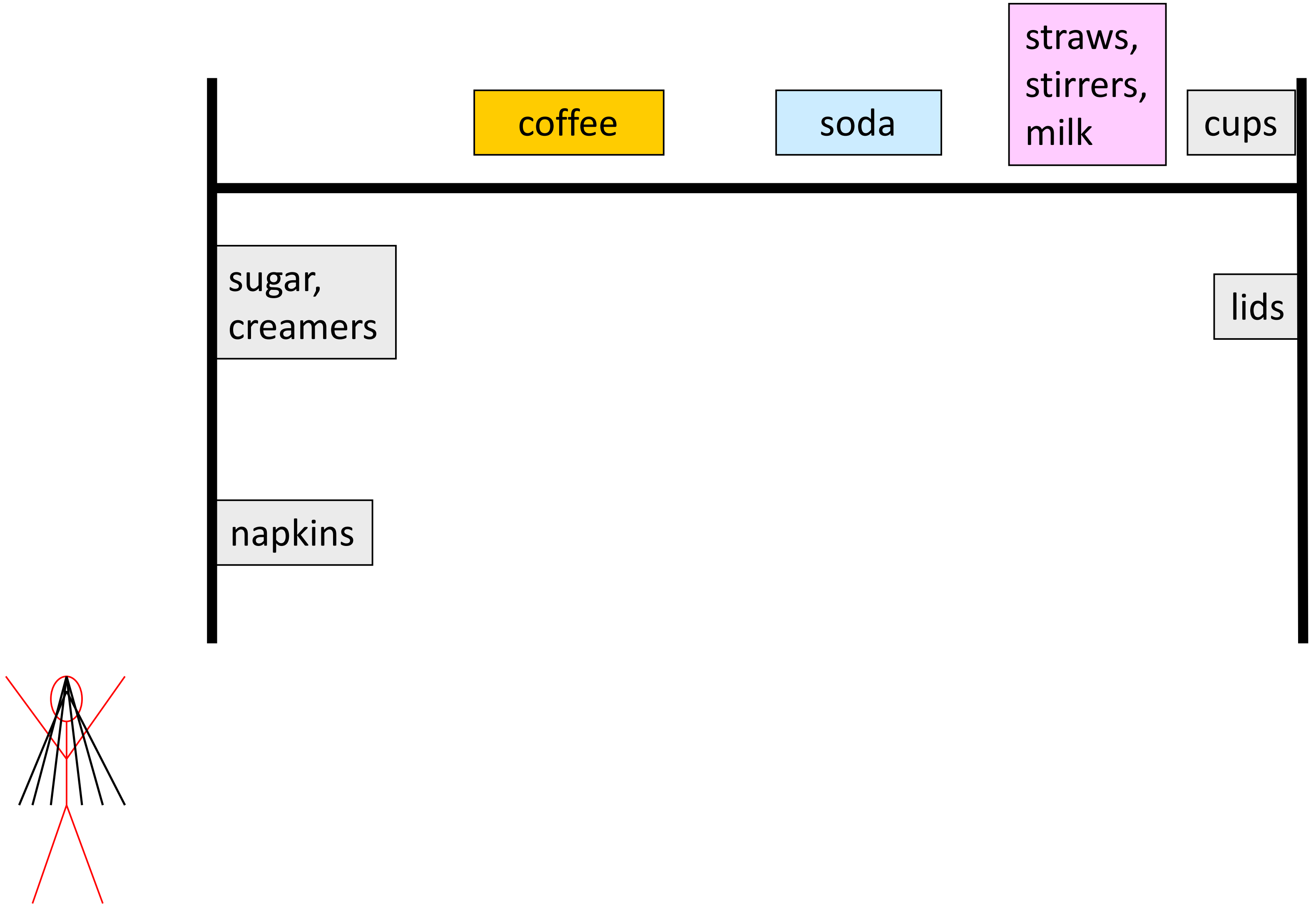


Self-reported locations for ~10,000 participants in a map task on Amazon Mechanical Turk. Coloration of counties/districts is by *population density*.

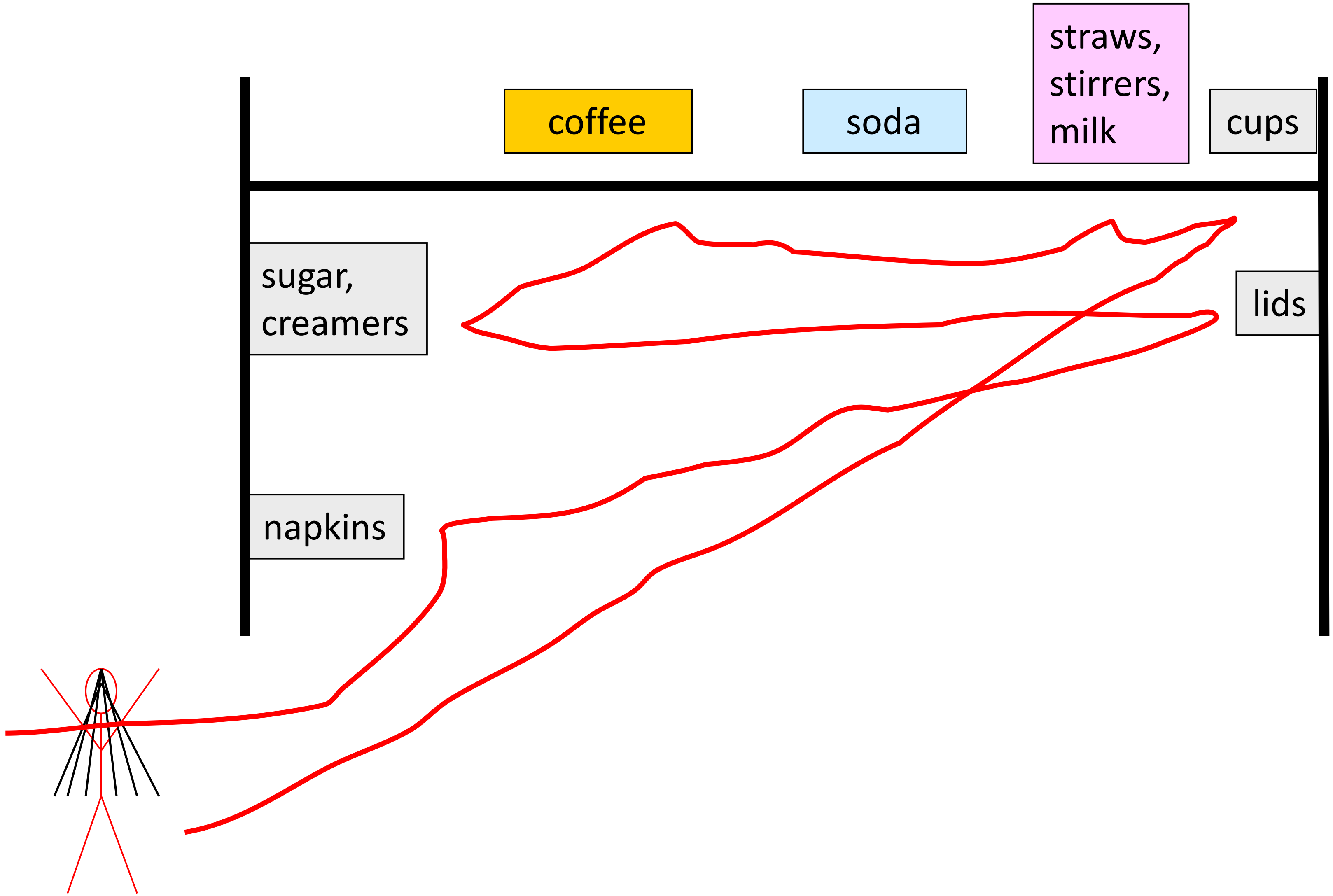
Data supports Theory of Imperfect Competition

Computational Thinking in Daily Life

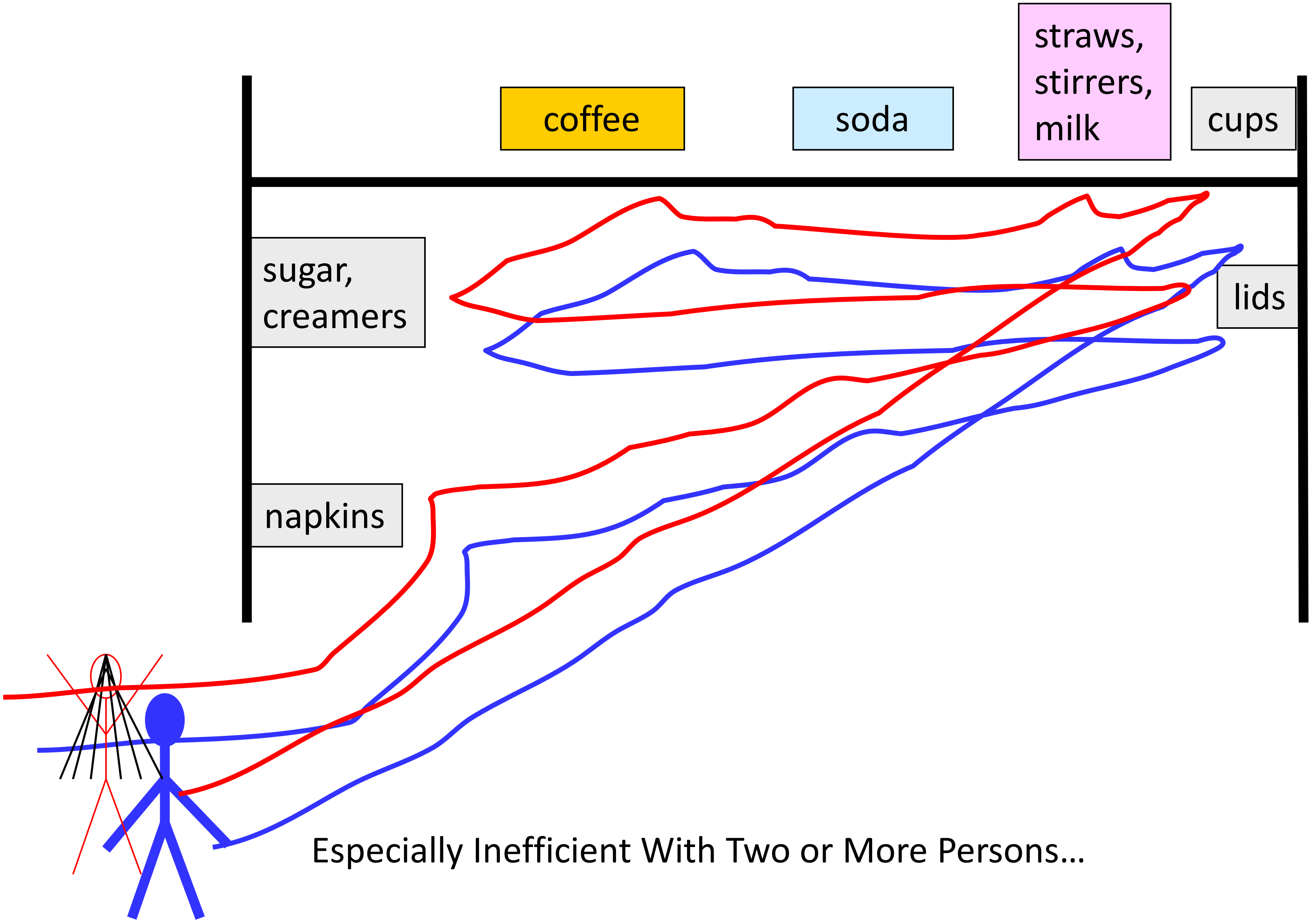
Getting Morning Coffee at the Cafeteria



Getting Morning Coffee at the Cafeteria

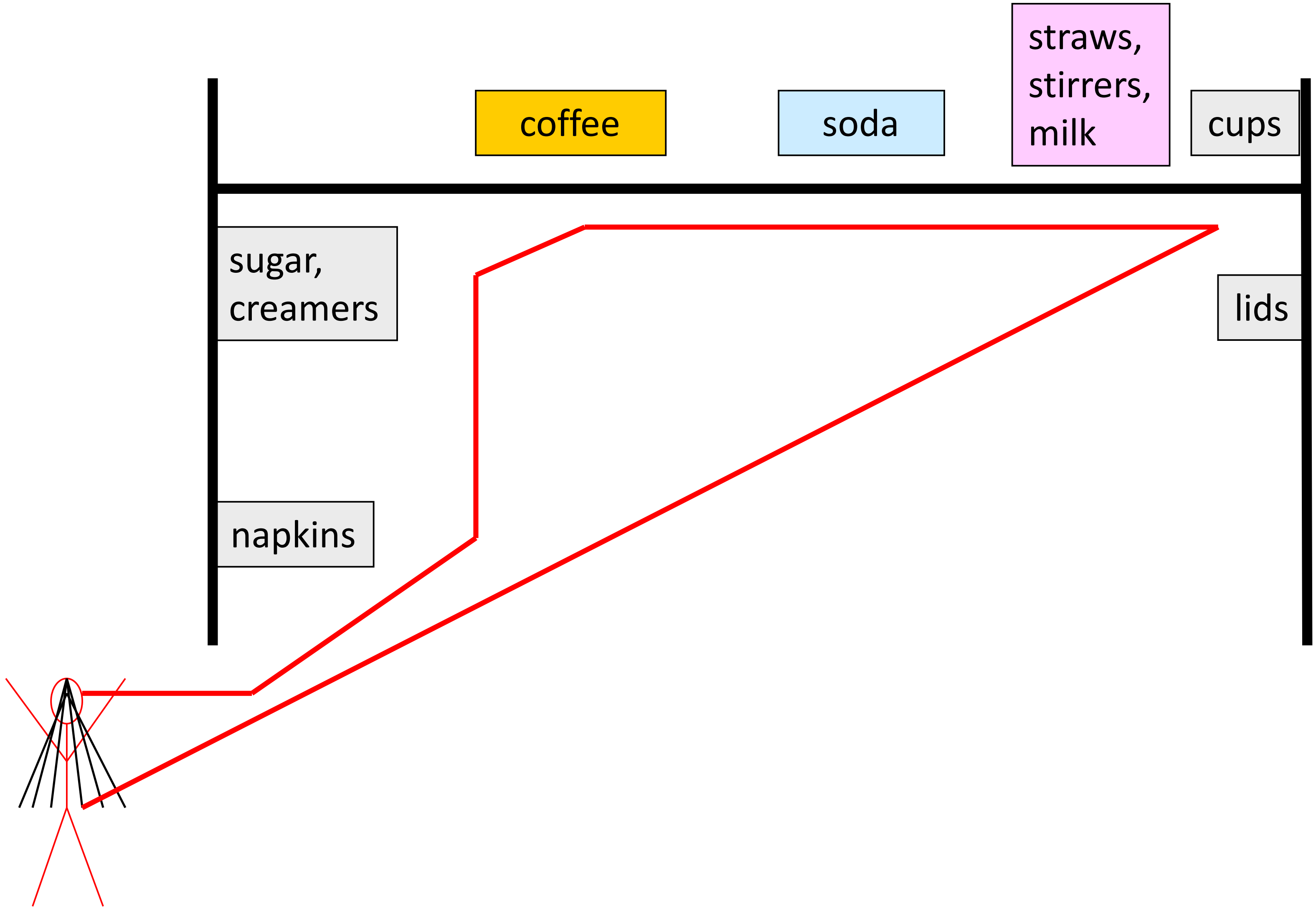


Getting Morning Coffee at the Cafeteria



Especially Inefficient With Two or More Persons…

Better: Think Computationally—Pipelining!



Computational Thinking in Education

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.

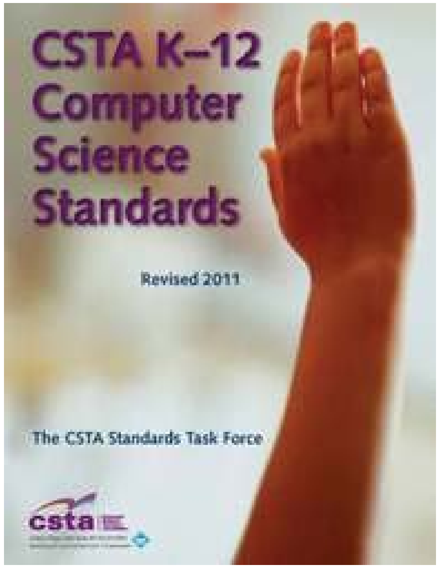
Computer scientists are now working with educators and cognitive learning scientists to address these questions.

United States Efforts

High School

CS Principles: http://csprinciples.org

- With NSF support, revision of CS AP courses



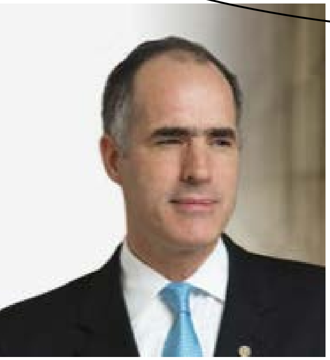
K-12

http://www.csta.acm.org/

- *Computational Thinking Resource Set: A Problem-Solving Tool for Every Classrooom*
- K-12 Computer Science Standards

www.code.org

- non-profit to ensure CS is available to all high school students

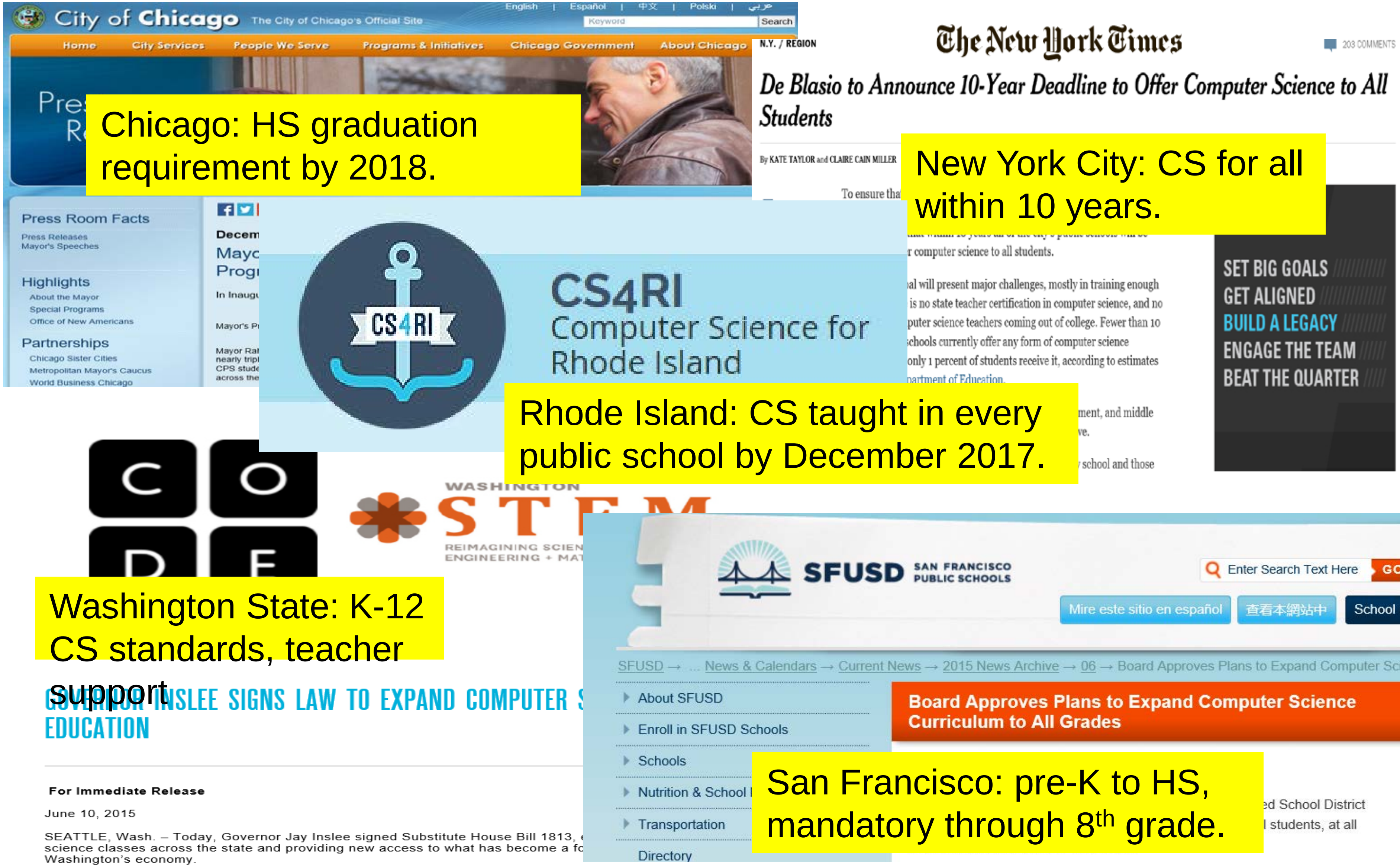


Congress

Computer Science Education Act (H.R.5929) 2010

- proposed by PA Senator Casey and CO Representative Polis.

US Goal: Give Access to Computer Science to Every High School Student



Chicago: HS graduation requirement by 2018.

New York City: CS for all within 10 years.

Rhode Island: CS taught in every public school by December 2017.

Washington State: K-12 CS standards, teacher support

San Francisco: pre-K to HS, mandatory through 8th grade.

President Obama 2016 State of the Union Address

NSF funds $25M for Computer Science for All with a commitment of $100M more over the next four years.

"In the coming years, we should build on that progress, by providing pre-K for all, offering every student the hands-on computer science and math classes that make them job-ready on day one." [Obama, January 12, 2016]

United Kingdom Efforts

British Royal Society (2012): *Shut down or restart? report*

`` “Computational thinking” offers insightful ways to view how information operates in many natural and engineered systems.

…

3. *Every child should have the opportunity to learn Computing at school.* We believe that:

• Every child should be expected to be ‘digitally literate’ by the end of compulsory education, in the same way that every child is expected to be able to read and write. ‘’

Computing At School (K-12)

COMPUTING AT SCHOOL
EDUCATE · ENGAGE · ENCOURAGE
In collaboration with BCS, The Chartered Institute for IT

Establish computer science as a foundational subject discipline, like math or physics, that ever child should learn, from primary school onwards.

An entirely new K-12 subject, Computer Science, started in England, Sept 2014.

Other International Efforts


China

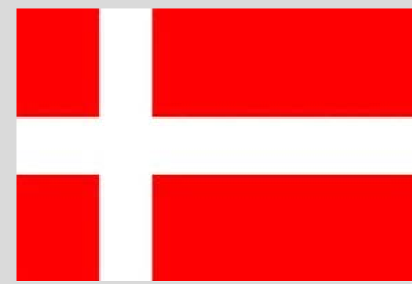

Australia


Germany


Korea


India


Finland


Denmark


Singapore


Israel


Belgium

Sweden?

Computational Thinking, International

计算思维

周以真

计算思维代表着一种普遍的认识和一类普适的技能，每一个人，而不仅仅是计算机科学家，都应热心于它的学习和运用。

计算思维建立在计算过程的能力和限制之上，由人由机器执行。计算方法和模型使我们敢于去处理那些原本无

一步问：一个近似解是否就足够了，是否可以利用一下随机化，以及是否允许误报（false positive）和漏报（false negative）？计算思维

In *Bulletin of Specif*, December 2008

La pensée informatique

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.

Jeannette M. Wing

Computational Thinking – Informatisches Denken[1]

Übersetzung: Hermann Hellwagner (AAU Klagenfurt), Gerti Kappel und Radu Grosu (TU Wien)

Informatisches Denken stellt eine universell einsetzbare Haltung und Fähigkeit dar, die alle lernen und nutzen sollten, nicht nur Informatiker.

COMMUNICATIONS OF THE ACM March 2006/Vol. 49, No. 3

Computational Thinking - Jeannette Wing

Communications of the ACM vol. 49, n° 3, Mars 2006, pp. 33-35

Il Pensiero Computazionale

Il pensiero computazionale si basa sul potere e sui limiti dei processi di elaborazione, siano essi eseguiti da un essere umano o da un macchina. I metodi ed i modelli computazionali ci danno il

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PENSAMENTO COMPUTACIONAL – Um conjunto de atitudes e habilidades que todos, não só cientistas da computação, ficaram ansiosos para aprender e usar.

RESUMO

Apresenta-se aqui a tradução do trabalho intitulado "Computational Thinking", da americana Jeannette Wing, professora de Ciência da Computação e chefe do Depart
de Ciência da Computação na Universidade de Carnegie Mellon, Pittsburgh, PA. O t

컴퓨팅적 사고

컴퓨팅적 사고는 컴퓨터 과학자뿐만이 아니라 누구나 배워서 활용할 수 있는 보편적인 사고이자 기술이다.

컴퓨팅적 사고는 사고의 주체가 컴퓨터건 사람이건 간에 전산처리의 힘과 한계에 기반해 있다. 컴퓨팅적 방법론과 모델을 통해 우리는 혼자서는 만들 수 없는 시스템을 설계하고 어려운 문제를 해결할 수 있을 거라는 자신감을 얻을 수 있다. 우리는 컴퓨팅적 사고를 통해 수수께끼와 같은 기계 지능의 난제에 도전한다. 인

을 이용하는 것이 용이한지, 거짓 양성 (false positives)과 거짓 음성 (false negatives)[2]을 허락해도 될지 고민할 것이다. 우리는 컴퓨팅적 사고를 통해 축소, 내장, 변형이나 시뮬레이션과 같은 기법으로 무척이나 어려워 보이는 문제를 이미 해결 방법을 알고 있는 문제로 재구성할 수도 있다.

Computational Thinking

計算論的思考

基礎

Jeannette M. Wing（Microsoft Research and Carnegie Mellon University）
翻訳：中島秀之（公立はこだて未来大学）

［原文］Jeannette M. Wing：Computational Thinking, Communications of the ACM, Vol.49, No.3, pp.33-35（Mar. 2006）より許可を得て翻訳.

これは Wing の 2006 年のエッセイである．これが出た当時，我々日本の研究者仲間も似たような感覚を持っていたので，このエッセイを歓迎した．すぐに誰かが翻訳するものだと思っていたら，2014 年の現在に至るまでその気配はない．書いてあることが我々研究者には当たり前だった（のでわざわざ翻訳しようと思わなかった）し，

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!

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