Demonology

The Curious Role of Intelligence in Physics & Biology

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Physics Department
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Davis Quantum Journal Club
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Abstract

For the lion's share of its history, physics analyzed the inanimate world. Or, that is the view it has of itself. Careful reflection, though, shows that physics regularly invoked an expressly extra-physical agency—intelligence—in its efforts to understand even the most basic physical phenomena. I will survey this curious proclivity, noting that similar appeals to intelligent “demons” go back to Laplace's theory of chance, Poincaré’s discovery of deterministic chaos in the solar system, and Darwin’s explanation of the origin of biological organisms in terms of natural selection. Today, we are on the verge of a new physics of information that will transform problematic “demonology” to a constructive, perhaps even an engineering, paradigm that explains information processing embedded in the natural world. To illustrate I will show how deterministic chaos arises in the operation of Maxwell’s Demon and outline nanoscale experimental implementations ongoing at Caltech's Kavli Nanoscience Institute.

Intelligence & Agency

A Gaggle of Demons

- Laplace’s Demon
- Poincare’s Demon
- Maxwell’s Demon
- Darwin’s Demon

- Agency?
- Intelligence?
- Information?
- Computation?

- Agency?
- Intelligence?
- Information?
- Computation?

Actual topic:
Classical and Quantum Intrinsic Computation

Physics of Information?
Physics of Computation?

Physics of Information?

- Information Age!
- How can information be harnessed?
- What does it mean for a physical system to compute?
- Fundamental physical limits of information processing?

Physics of Computation Meeting (MIT, 1981)

Physics of Computation Conference Endicott House MIT May 6-8, 1981

1 Freeman Dyson
2 Gregory Chaitin
3 James Crutchfield
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5 Panos Ligomenides
6 Jerome Rothstein
7 Carl Hewitt
8 Norman Hardy
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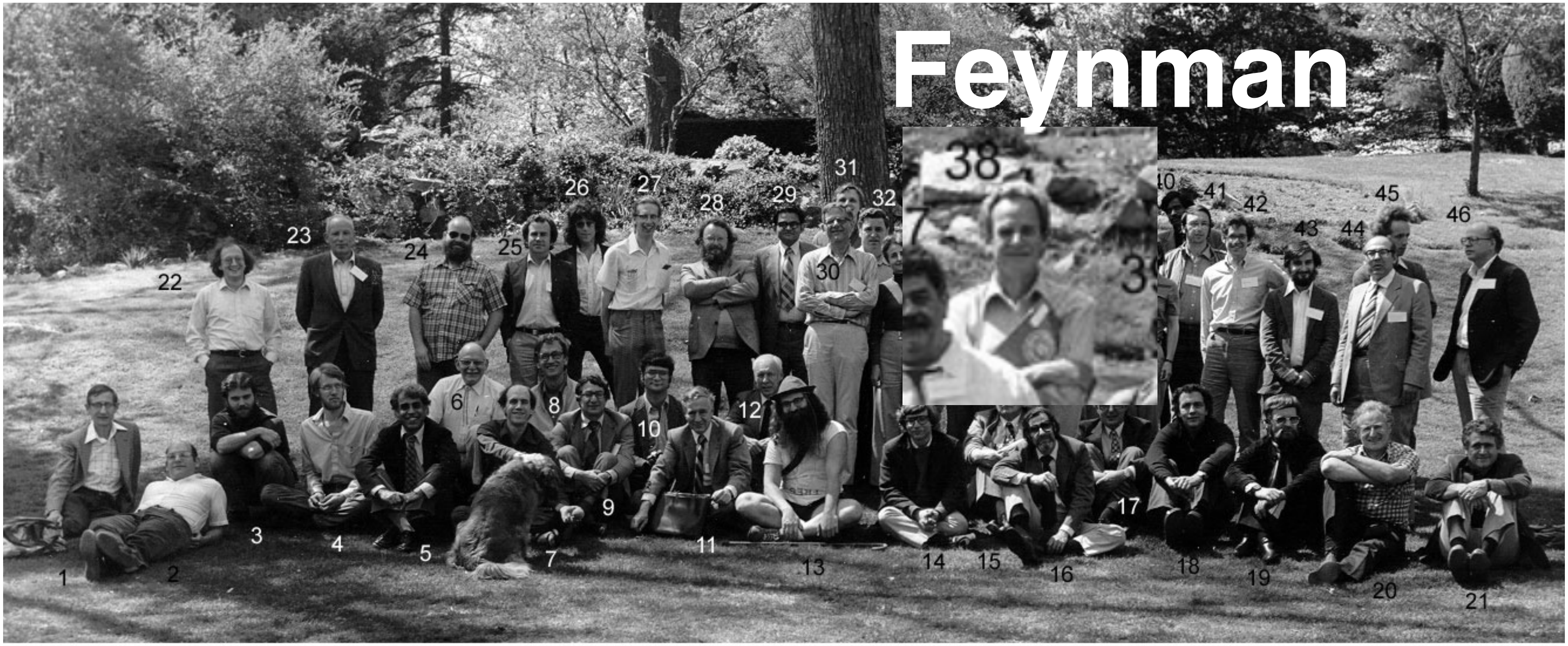

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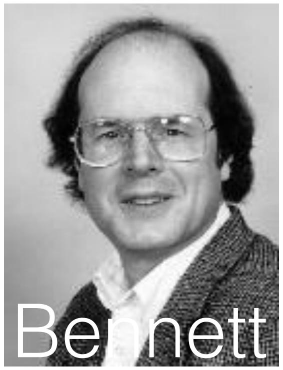
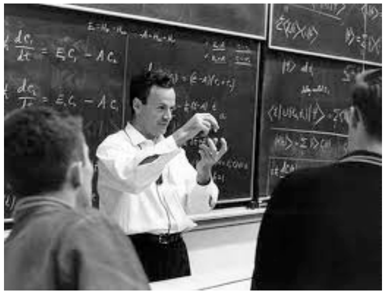
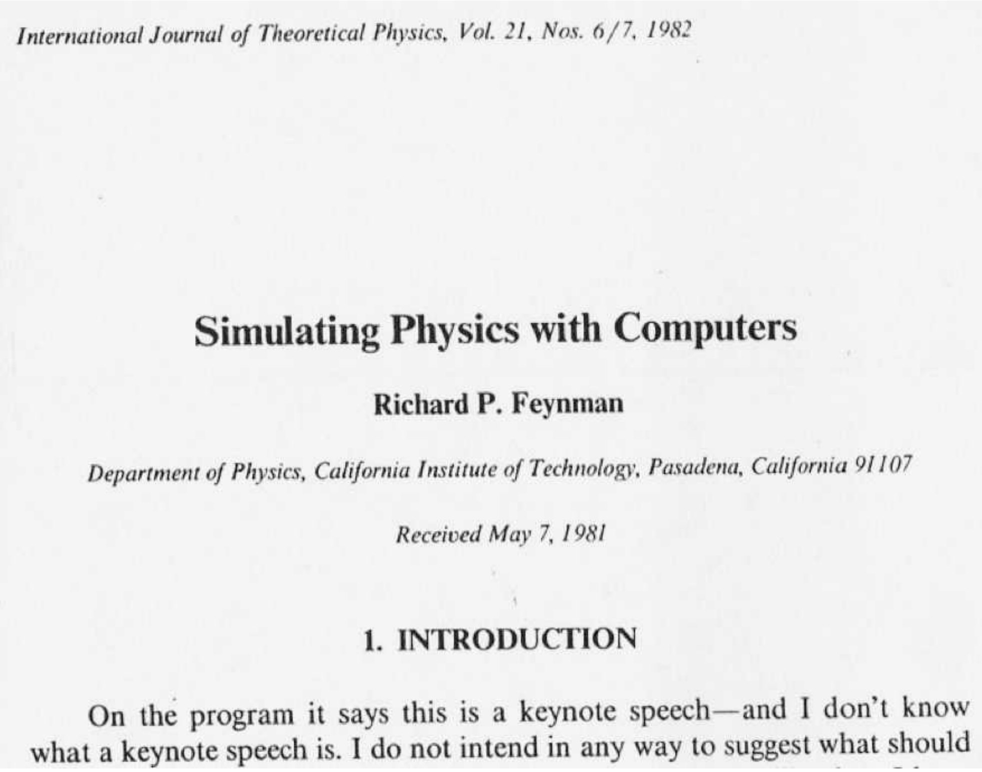


Photo: Charlie Bennett

Physics of Computation Meeting (MIT, 1981)

- Feynman introduces quantum computing





International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

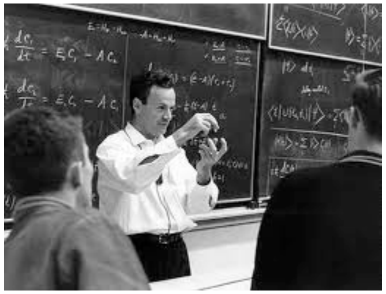
Received May 7, 1981

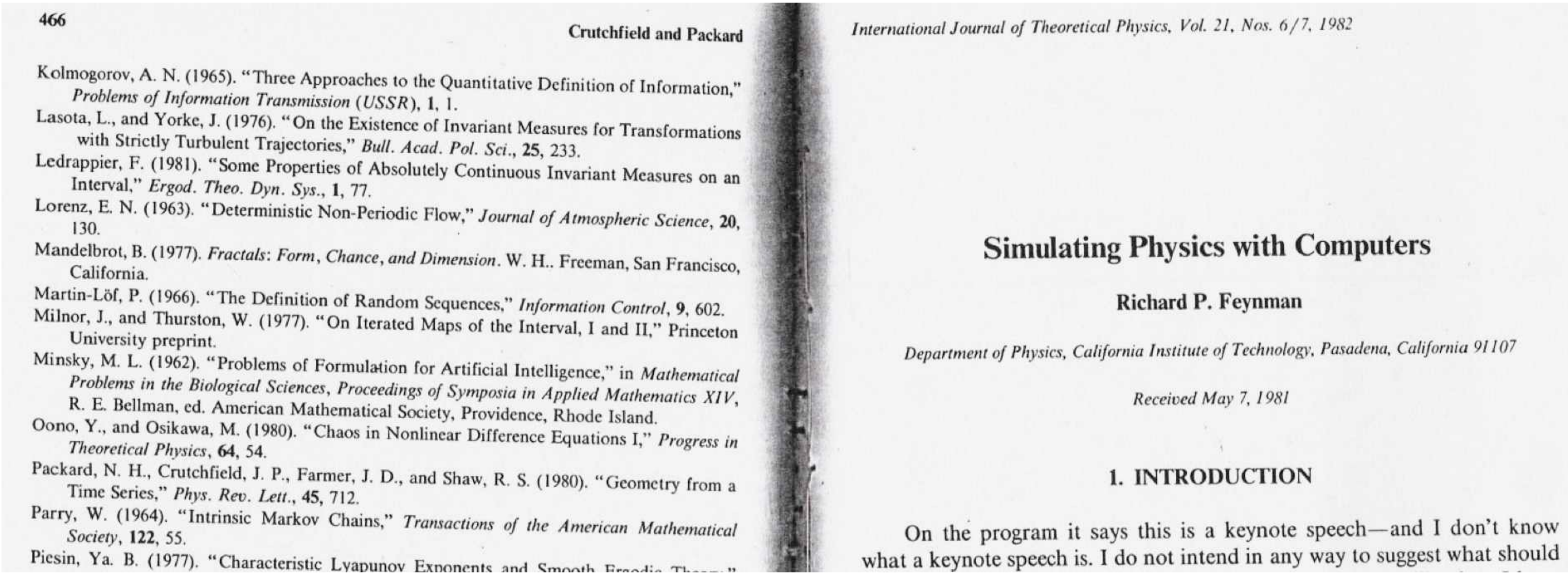
1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should

Physics of Computation Meeting (MIT, 1981)

- Feynman introduces quantum computing





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Crutchfield and Packard

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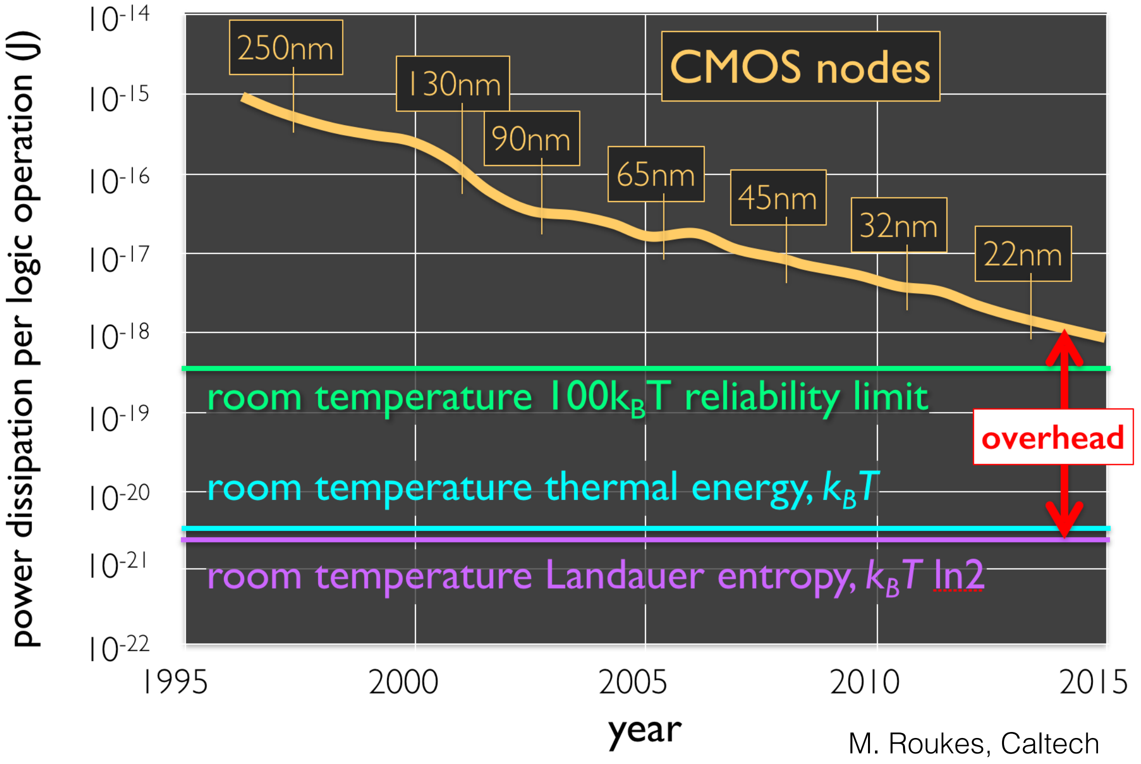
Intrinsic computation there, too!

Physics of Computation

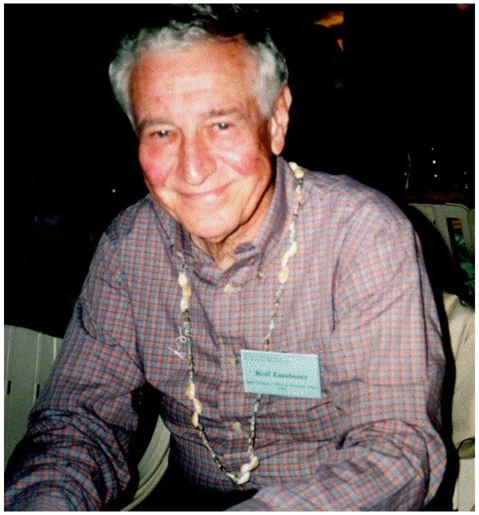
- Moore's law stalled for some time now
- Ever more pressing scientific & engineering issue



M. Roukes, Caltech

Thermodynamics of Computation

- Physical limits on information processing



Rolf Landauer
(1927-1999)

(1993)

- Landauer's Principle (1961):

  Logically irreversible computing forces energy dissipation.

  Erase one bit (Landauer-Bennett):

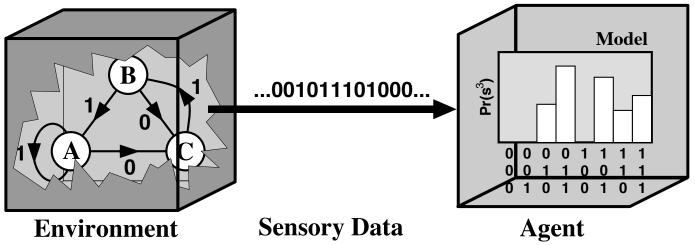
$$\langle Q_{\mathrm{erase}} \rangle \geq k_{\mathrm{B}} T \ln 2$$

Intrinsic Computation

How do physical systems compute?

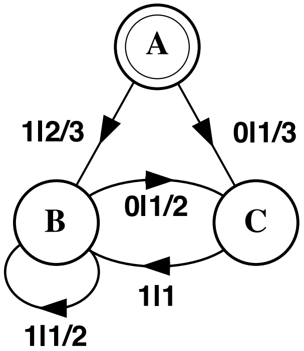
COMPUTATIONAL MECHANICS:

FIND THE HIDDEN MECHANISM



CAUSAL EQUIVALENCE:

$$\overleftarrow{x} \sim \overleftarrow{x}' \Leftrightarrow \Pr(\overrightarrow{X}|\overleftarrow{x}) = \Pr(\overrightarrow{X}|\overleftarrow{x}')$$



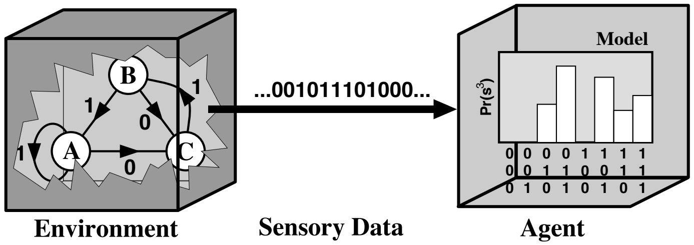
ε-MACHINE: UNIQUE, MINIMAL, & OPTIMAL PREDICTOR

STORED VERSUS GENERATED INFORMATION

$$C_\mu = -\sum_{\sigma \in \boldsymbol{\mathcal{S}}} \Pr(\sigma) \log_2 \Pr(\sigma) \quad \textbf{VERSUS} \quad h_\mu = -\sum_{\sigma \in \boldsymbol{\mathcal{S}}} \Pr(\sigma) \sum_{\sigma' \in \boldsymbol{\mathcal{S}}} \Pr(\sigma'|\sigma) \log_2 \Pr(\sigma'|\sigma)$$

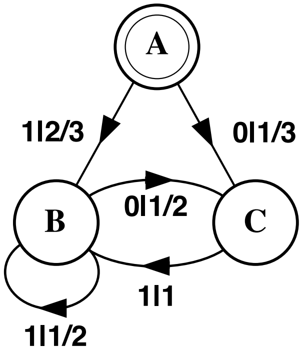
Computational Mechanics:

Find the Hidden mechanism



Causal Equivalence:

$$\overleftarrow{x} \sim \overleftarrow{x}' \Leftrightarrow \Pr(\overrightarrow{X}|\overleftarrow{x}) = \Pr(\overrightarrow{X}|\overleftarrow{x}')$$

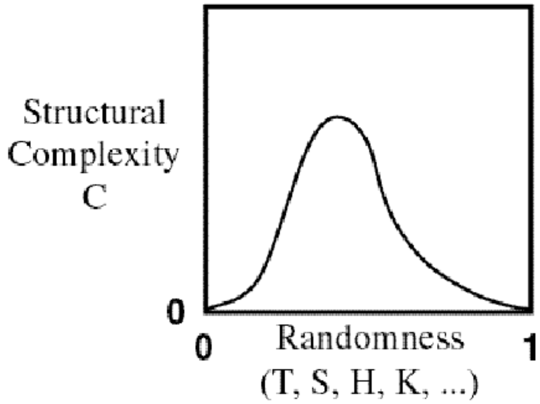


ε-Machine: Unique, minimal, & optimal predictor

Stored versus Generated Information

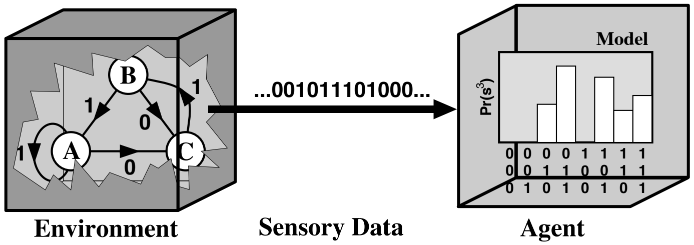
$$C_\mu = -\sum_{\sigma \in \boldsymbol{\mathcal{S}}} \Pr(\sigma) \log_2 \Pr(\sigma) \quad \textbf{versus} \quad h_\mu = -\sum_{\sigma \in \boldsymbol{\mathcal{S}}} \Pr(\sigma) \sum_{\sigma' \in \boldsymbol{\mathcal{S}}} \Pr(\sigma'|\sigma) \log_2 \Pr(\sigma'|\sigma)$$

Structure versus Randomness



COMPUTATIONAL MECHANICS:

FIND THE HIDDEN MECHANISM



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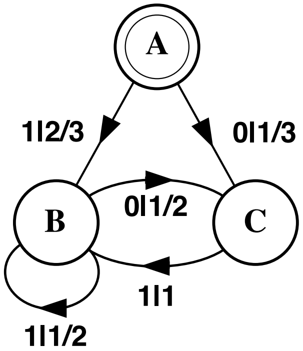

ε-MACHINE: UNIQUE, MINIMAL, & OPTIMAL PREDICTOR

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INTRINSIC COMPUTATION:

1. HOW MUCH HISTORICAL INFORMATION DOES A PROCESS STORE?
2. IN WHAT ARCHITECTURE IS IT STORED?
3. HOW IS IT USED TO PRODUCE FUTURE BEHAVIOR?

J.P. CRUTCHFIELD & K. YOUNG, “INFERRING STATISTICAL COMPLEXITY”, PHYSICAL REVIEW LETTERS 63 (1989) 105-108.

J.P. CRUTCHFIELD, “BETWEEN ORDER AND CHAOS”,
NATURE PHYSICS 8 (JANUARY 2012) 7-24.

Intrinsic Computation: Consequences

A system is unpredictable
if it has positive entropy rate: $h_\mu > 0$

A system is complex
if it has positive structural complexity: $C_\mu > 0$

A system is emergent
if its structural complexity increases over time:

$$C_\mu(t') > C_\mu(t), \text{ if } t' > t$$

A system is hidden
if its crypticity is positive: $\chi = C_\mu - \mathbf{E} > 0$

Summary (classical)

- Randomness = Unpredictability (incompressibility)
- How Nature is structured is how Nature computes
- Intelligence ~ Memory and organization
- Information engines (demons):
  - Information Processing Second Law
  - Modularity dissipation: Architecture costs!
- Deterministic chaos drives heat engine functioning

- See:
  - http://csc.ucdavis.edu/~cmg/
  - http://informationengines.org/

nature physics

INSIGHT | REVIEW ARTICLES

| DOI: 10.1038/NPHYS2190

Between order and chaos

James P. Crutchfield

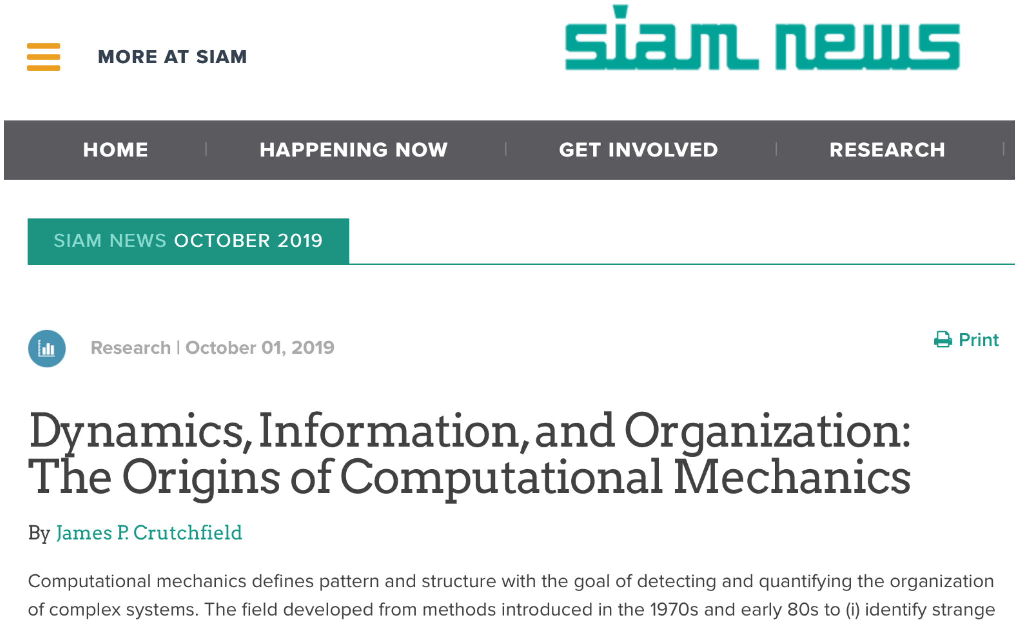
What is a pattern? How do we come to recognize patterns never seen before? Quantifying the notion of pattern and formalizing the process of pattern discovery go right to the heart of physical science. Over the past few decades physics' view of nature's lack of structure—its unpredictability—underwent a major renovation with the discovery of deterministic chaos, overthrowing two centuries of Laplace's strict determinism in classical physics. Behind the veil of apparent randomness, though, many processes are highly ordered, following simple rules. Tools adapted from the theories of information and computation have brought physical science to the brink of automatically discovering hidden patterns and quantifying their structural complexity.

One designs clocks to be as regular as physically possible. So much so that they are the very instruments of determinism. The coin flip plays a similar role; it expresses our ideal of the utterly unpredictable. Randomness is as necessary to physics as determinism—think of the essential role that 'molecular chaos' plays in establishing the existence of thermodynamic states. The clock and the coin flip, as such, are mathematical ideals to which reality is often unkind. The extreme difficulties of engineering the perfect clock[1] and implementing a source of randomness as pure as the fair coin testify to the fact that determinism and randomness are two inherent aspects of all physical processes.

In 1927, van der Pol, a Dutch engineer, listened to the tones produced by a neon glow lamp coupled to an oscillating electrical

Perception is made all the more problematic when the phenomena of interest arise in systems that spontaneously organize.

Spontaneous organization, as a common phenomenon, reminds us of a more basic, nagging puzzle. If, as Poincaré found, chaos is endemic to dynamics, why is the world not a mass of randomness? The world is, in fact, quite structured, and we now know several of the mechanisms that shape microscopic fluctuations as they are amplified to macroscopic patterns. Critical phenomena in statistical mechanics[7] and pattern formation in dynamics[8,9] are two arenas that explain in predictive detail how spontaneous organization works. Moreover, everyday experience shows us that nature inherently organizes; it generates pattern. Pattern is as much the fabric of life as life's unpredictability.



SIAM NEWS OCTOBER 2019

Research | October 01, 2019

Dynamics, Information, and Organization: The Origins of Computational Mechanics

By James P. Crutchfield

Computational mechanics defines pattern and structure with the goal of detecting and quantifying the organization of complex systems. The field developed from methods introduced in the 1970s and early 80s to (i) identify strange

https://sinews.siam.org/Details-Page/dynamics-information-and-organization-the-origins-of-computational-mechanics

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SIAM NEWS NOVEMBER 2019

Research | November 01, 2019

Computational Mechanics: Three Decades of Applications and Extensions

By James P. Crutchfield

In part I of this article, published in the October issue of SIAM News, the author provided a thorough introduction to computational mechanics that documented the field's multifaceted origin.

https://sinews.siam.org/Details-Page/computational-mechanics-three-decades-of-applications-and-extensions

Quantum Computational Mechanics

- **Quantum Computational Complexity**:
  - *Quantum Automata and Quantum Grammars,* C. Moore & JPC, **Theoretical Computer Science** 237 (2000) 275-306.

- **Quantum Compression of Classical Processes**:
  - *Occam's Quantum Strop: Synchronizing and Compressing Classical Cryptic Processes via a Quantum Channel*, J. R. Mahoney, C. Aghamohammadi, & JPC, **Scientific Reports** 6 (2016) 20495.
  - *Minimized State-Complexity of Quantum-Encoded Cryptic Processes*, P. M. Riechers, J. R. Mahoney, C. Aghamohammadi, & JPC, **Physical Review A** 93:5 (2016) 052317.
  - *Strong and Weak Optimizations in Classical and Quantum Models of Stochastic Processes,* S. Loomis & JPC, **Journal of Statistical Physics** 176:6 (2019) 1317-1342.
  - *Optimizing Quantum Models of Classical Channels*: The reverse Holevo problem, S. Loomis, C. Aghamohammadi, J. R. Mahoney, & JPC; **arxiv.org:1709.08101**.
  - *Thermal Efficiency of Quantum Memory Compression*, S. Loomis & JPC; **arxiv.org:1911.00998**.

- **Quantum Advantage**:
  - *The Ambiguity of Simplicity*, C. Aghamohammadi, J. R. Mahoney, & JPC, **Physics Letters A** 381:14 (2017) 1223-1227.
  - *Extreme Quantum Advantage when Simulating Strongly Coupled Classical Systems,* C. Aghamohammadi, J. R. Mahoney, & JPC, **Scientific Reports** 7 (2017) 6735.
  - *Extreme Quantum Memory Advantage for Rare-Event Sampling*, C. Aghamohammadi, S. P. Loomis, J. R. Mahoney, & JPC, **Physical Review X** 8 (2018) 011025.

- **Quantum Measurement**:
  - *Measurement-Induced Randomness and Structure in Controlled Qubit Processes*, A. Venegas-Li, A. Jurgens, & JPC; **arxiv.org:1908.09053**.

- **Classical and Quantum Causal Irreversibility**:
  - *Causal Asymmetry in a Quantum World*, J. Thompson, A. J. P. Garner, J. R. Mahoney, JPC, V. Vedral, & M. Gu; **Physical Review X** 8 (2018) 031013.

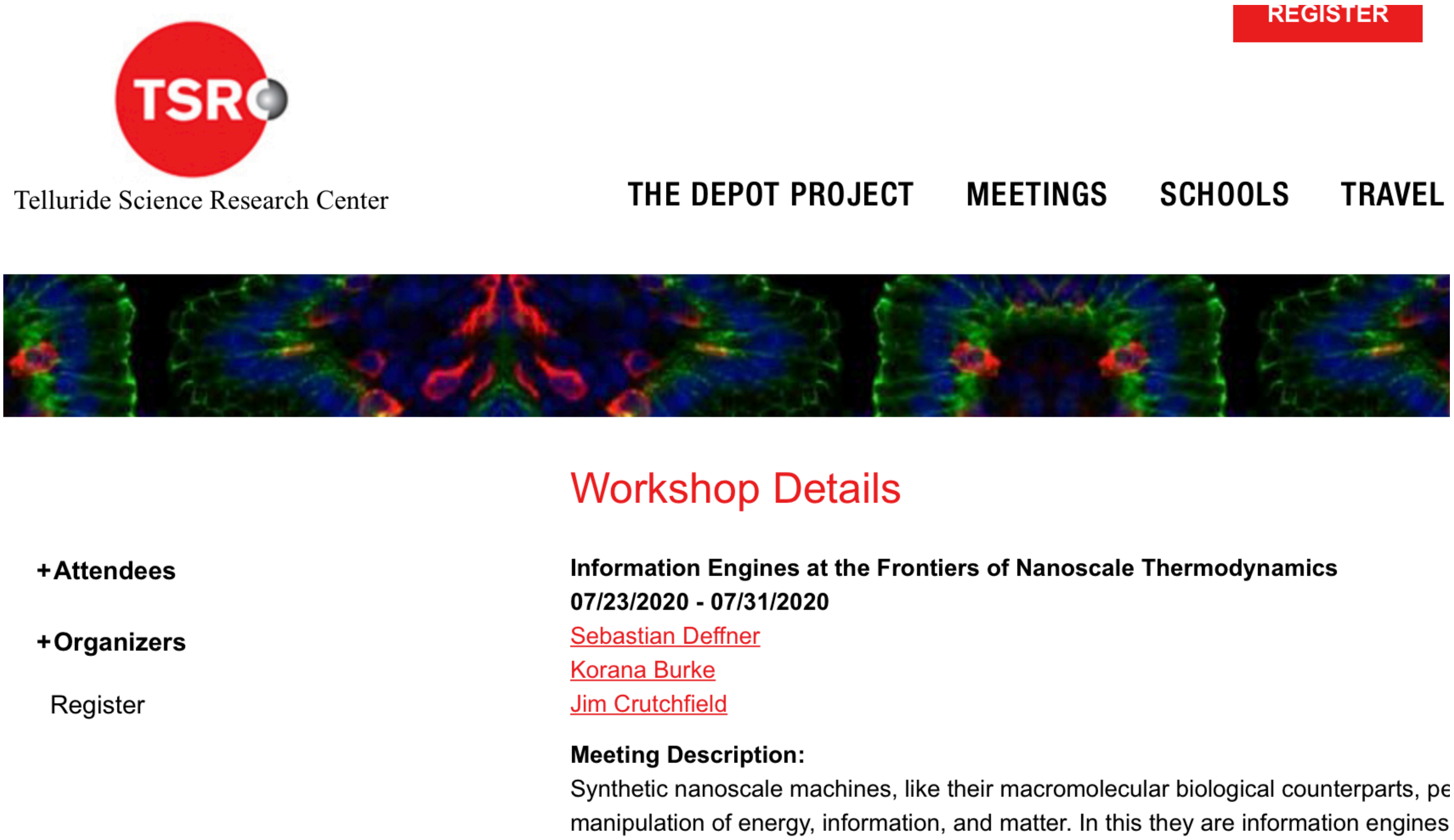
Follow-on Talks?

- Sam Loomis: Quantum compression
- Ariadna Venegas-Li: Quantum measurement
- David Gier: Information for quantum processes
- Fabio Anza: Dynamics of many-body localization

Graduate Courses:
Physics of Information & Computation
Physics 256 A & B
Winter and Spring 2020

http://csc.ucdavis.edu/~chaos/courses/ncaso/

- Dynamical Systems & Measurement (aka Symbolic Dynamics)
- Information and Computation Theories
- Classical Computational Mechanics
- Quantum Computational Mechanics
- Nonequilibrium Thermodynamics
- Systems:
    - Chaotic Dynamical Systems, Spin Systems, Cellular Automata, Hidden Markov Models, Chaotic Crystals, Quantum Dynamics, Information Engines



Workshop Details

Information Engines at the Frontiers of Nanoscale Thermodynamics
07/23/2020 - 07/31/2020
Sebastian Deffner
Korana Burke
Jim Crutchfield

Meeting Description:
Synthetic nanoscale machines, like their macromolecular biological counterparts, pe
manipulation of energy, information, and matter. In this they are information engines

Thanks!