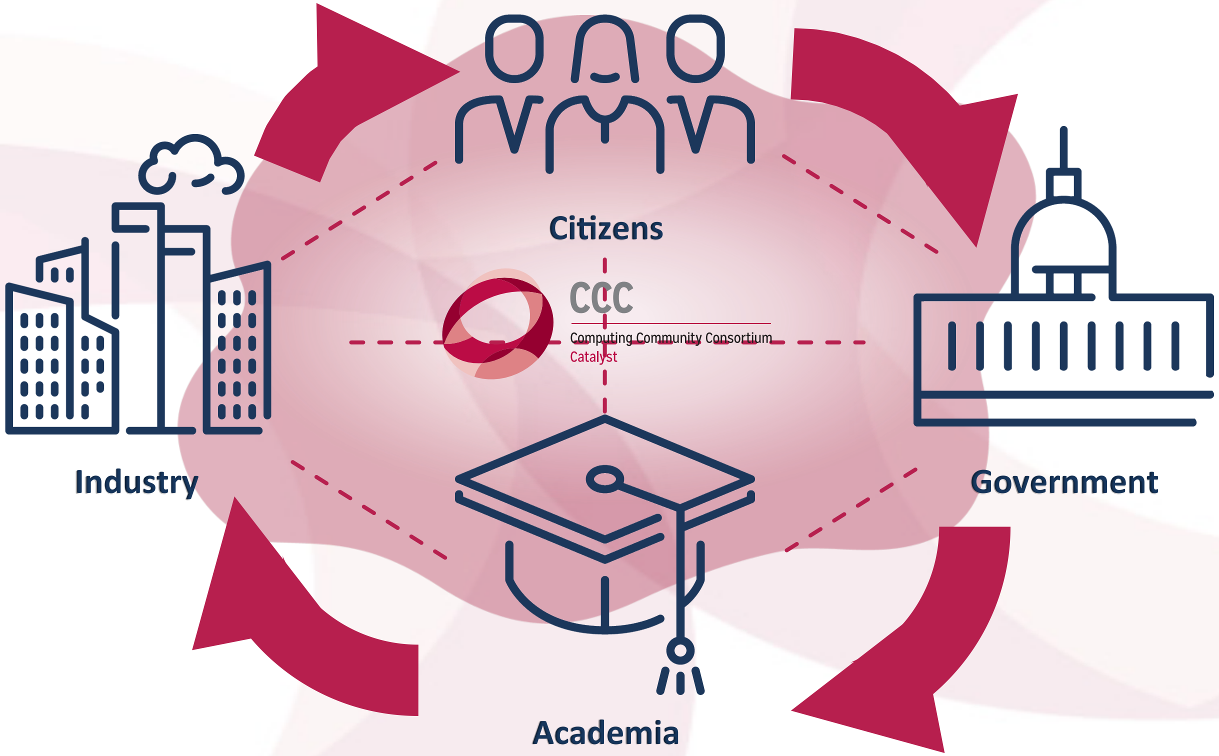
A VISION TO COMPUTE LIKE NATURE: THERMODYNAMICALLY

CCC Briefing @ NSF, May 2020

Todd Hylton, UCSD
Tom Conte, Georgia Tech & CCC
Mark D. Hill, Wisconsin & CCC Chair

1. *Short Preamble (Mark)*
2. ***Main Presentation (Todd)***
3. *Discussion (everyone)*
4. *Other Directions in Prep (Tom)*

COMPUTING COMMUNITY CONSORTIUM (CCC): CATALYZING I.T.'S VIRTUOUS CYCLE

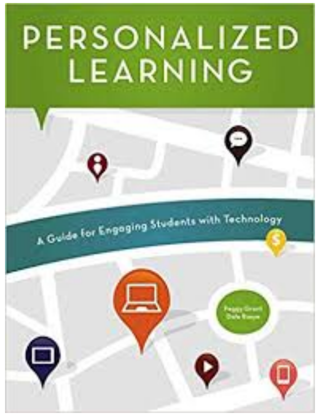


Pre-competitive white papers & workshops catalyzing I.T. research for the nation's benefit

CCC
Computing Community Consortium
Catalyst

Set Up

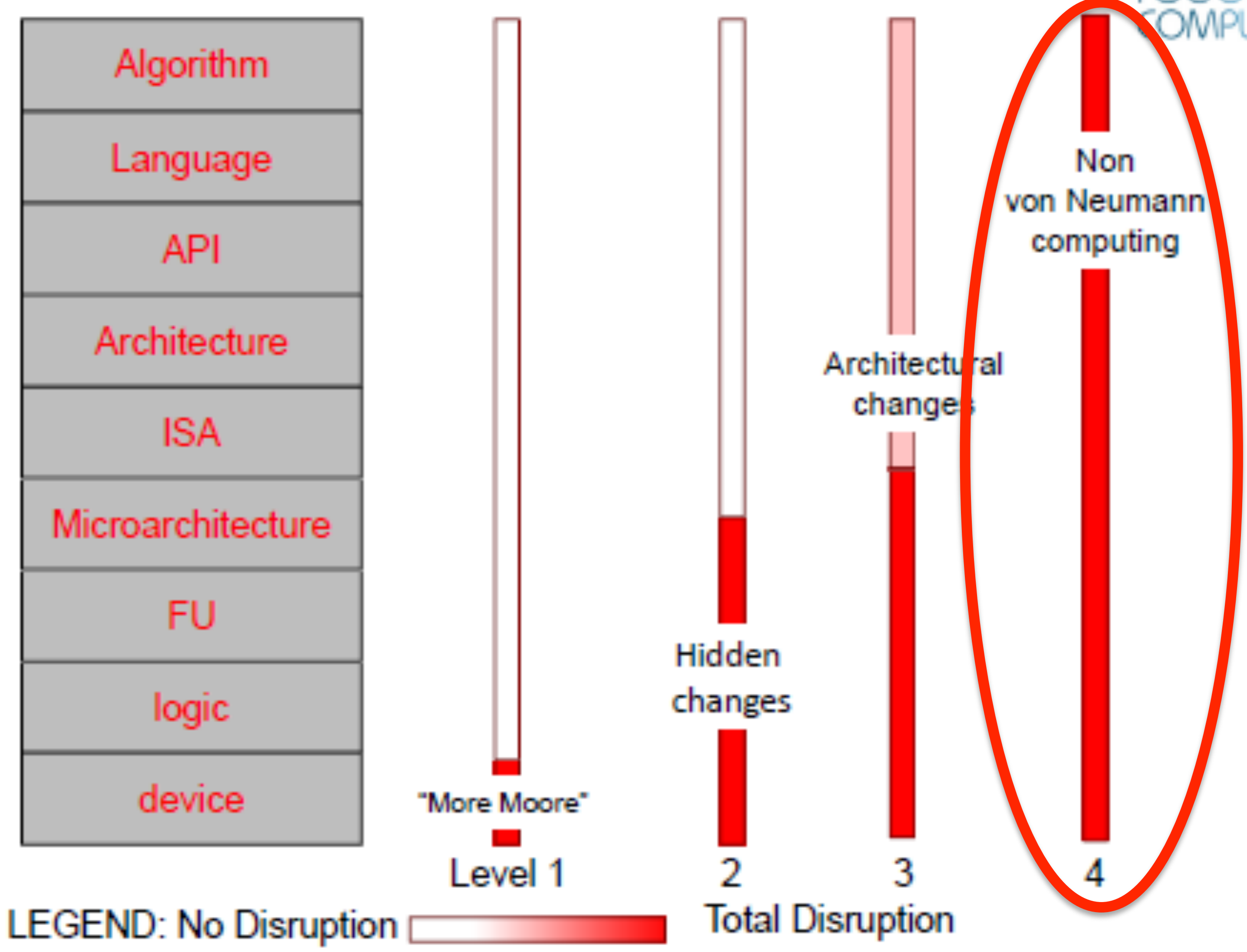
- 21st Century computing promises much:



- Need dramatic energy-performance advances
- Technology no longer provides these advances

➔ Must disrupt computing abstraction "stack"

Potential Approaches vs. Disruption in Computing Stack



E.g., Thermodynamic Computing

CCC THERMODYNAMIC VISIONING PROCESS

- **Spring/Summer 2018:** CCC approves Conte & Hylton proposal; organizing committee works
- **Fall 2018:** Solicited white papers to select participants: ***physicists, computational biologists, computer architects, & hardware researchers***
- **January 2019:** Three-day workshop: two tutorials (theory & physical systems), three break out groups, cross-cutting breakout/discussions, & draft report inputs
- **November 2019:** Workshop report released after vetting: participants, CCC, & external experts
- **February 2020:** AAAS Annual Meeting Presentation: Next Generation Computing Hardware
- **May 2020:** NSF Presentation: Thermodynamic Computing and future hardware systems

CCC PROCESS

- **February 2018: CCC received visioning workshop proposal from Tom Conte and Todd Hylton**
  - Tom and Todd assembled five other organizing committee members from a variety of institutions.

- **Fall 2018: Organizing committee solicited white papers on the topic**
  - Workshop participants were selected based on their white paper.
  - Participants included physicists, computational biologists, computer architects and hardware researchers.

- **January 2019: Thermodynamic Computing workshop takes place over three days**
  - Workshop opened with two “tutorials,” one on Theory and one on Physical Systems, and a panel on Model Systems.
  - Participants were divided into three breakout groups based on these areas (Theory, Model Systems, and Physical Systems) to identify priority research directions (PRDs) within that area.
  - Participants were later divided into cross-cutting breakout groups to identify cross-cutting PRDs.

CCC PROCESS

- **November 2019: Thermodynamic Computing workshop report is released**
  - Early drafts of report section written during the last day of the workshop.
  - Final drafts put together by the organizing committee and reviewed by participants and some members of the CCC Council before release.

- **February 2020: Todd, Tom, and Mark present on Next Generation Computing Hardware at the AAAS Annual Meeting**

- **May 2020: Presentation with NSF on Thermodynamic Computing and future hardware systems**

A Vision to Compute Like Nature: Thermodynamically

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Presentation to the National Science Foundation

May 13, 2020

Observations

Today

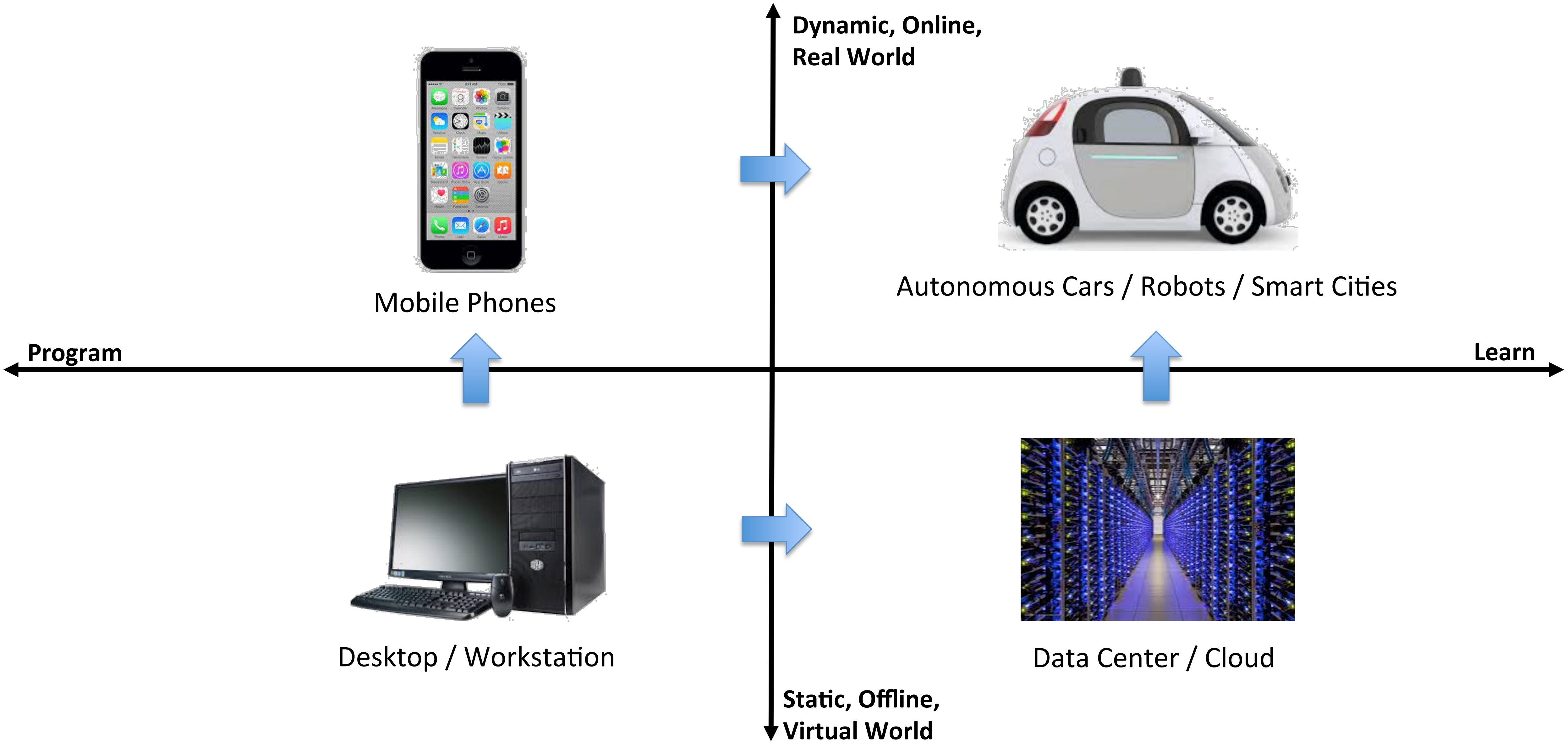
- Computing absorbs 5% of US electrical energy production
- Next generation semiconductor fabs are projected to cost $20B
- Moore's law is on its last legs
- Electron devices are comparable in size to biological molecules - thermodynamic fluctuations are a challenge
  - Paradoxically, while avoiding fluctuations in hardware, we are creating them in software to sample probability distributions and train models

But

- We are ~1000X above the Landauer limit of thermodynamic efficiency
- Our computing systems possess far more computational potential than we can ever program
- We are many orders of magnitude less capable and less energy efficient than brains

We are in the late stages of a mature technology, but we are still a long way from fundamental limits

Technology Landscape



Conceptual Landscape

A Few More Thoughts

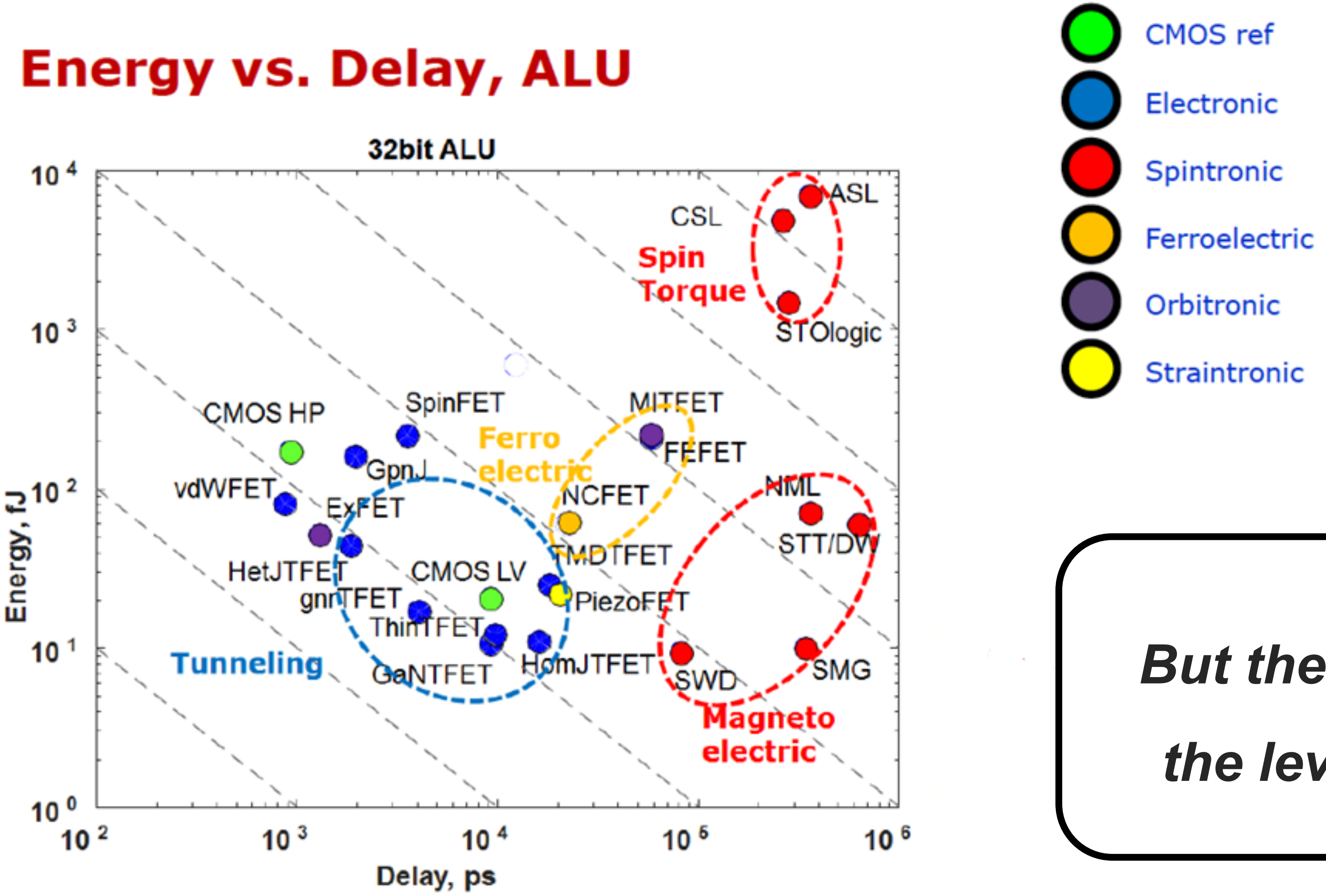
- A primary problem in computing today is that computers cannot organize themselves.
  - Trillions of degrees of freedom doing the same stuff over and over…

- Computing machines are ill-suited to evolving, complex, real-world problems.
  - They can transform energy, but they cannot "evolve" because they are literally frozen

- Machine learning systems universally employ thermodynamic concepts.
  - But they are ad-hoc solutions that lack an overarching physical paradigm

The whole universe organizes itself, but our computers do not

All Computing Devices are Physical Systems



But the physics ends at the level of the device

Courtesy Dimitri Nikonov and Ian Young

Life and Modern Electronic Systems

Requirement	Life	Electronics
Environment	Chemical Potential	Electric Potential
Potential source	Sun / Earth / …	Power Supplies / Inputs
Room Temperature	Yes	Yes
Interaction energies	~0.1-10 V	~0.1-10 V
Interaction scale	Molecular	Nanometer
Result	thermodynamically evolving biological systems	thermodynamically evolving electronic systems?

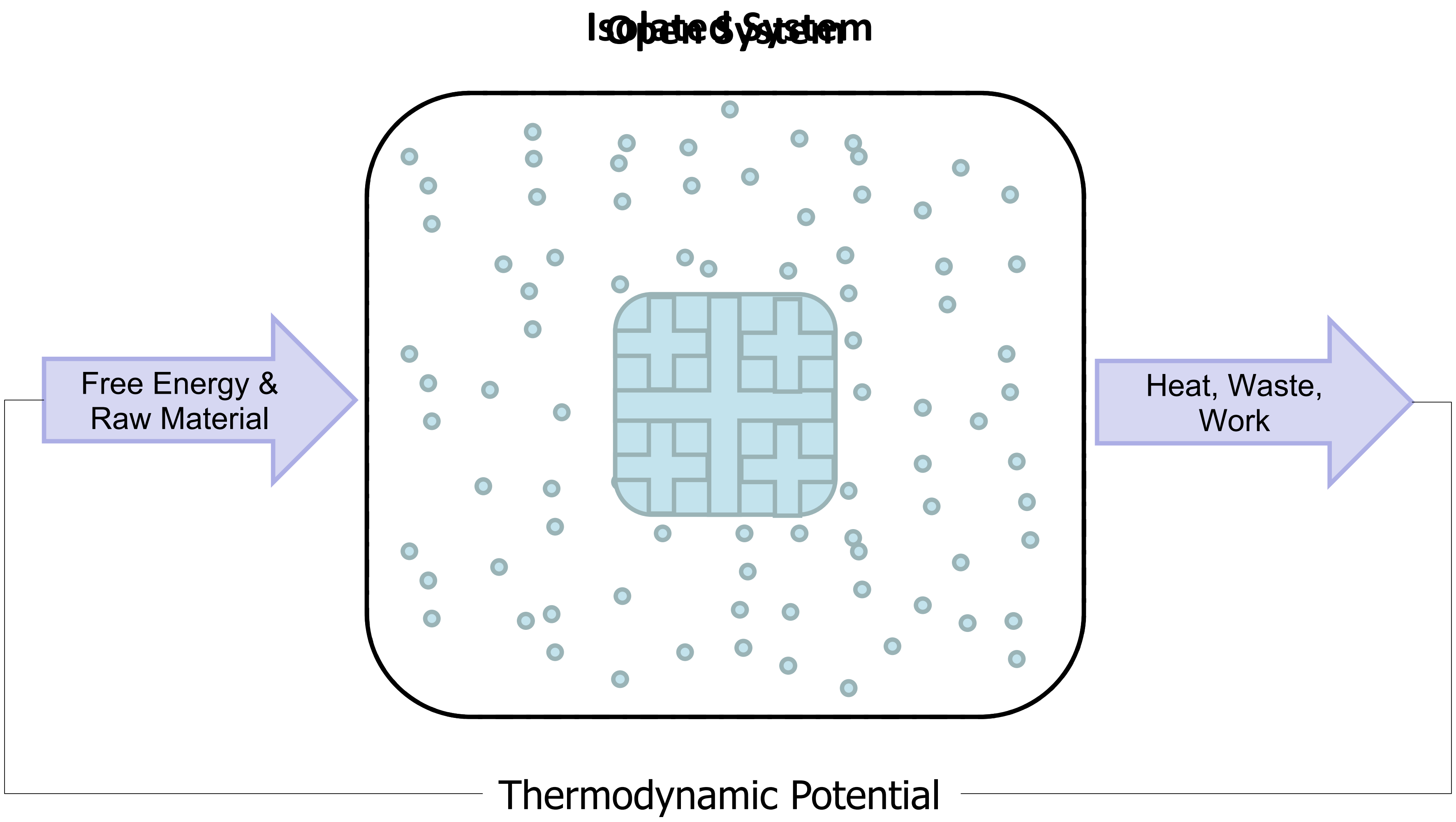
The energy scale of excitations in biological and electronic systems are similar because they both derive from the electronic structure of the materials of which they are composed. *Electronic systems do not evolve today because we design them so that they do not evolve*.

Thermodynamics: Another Look

Laws of Thermodynamics

- **First Law** - Energy is conserved in isolated systems
- **Second Law** – Entropy increases in isolated systems

Thermodynamics of Isolated vs Open Systems

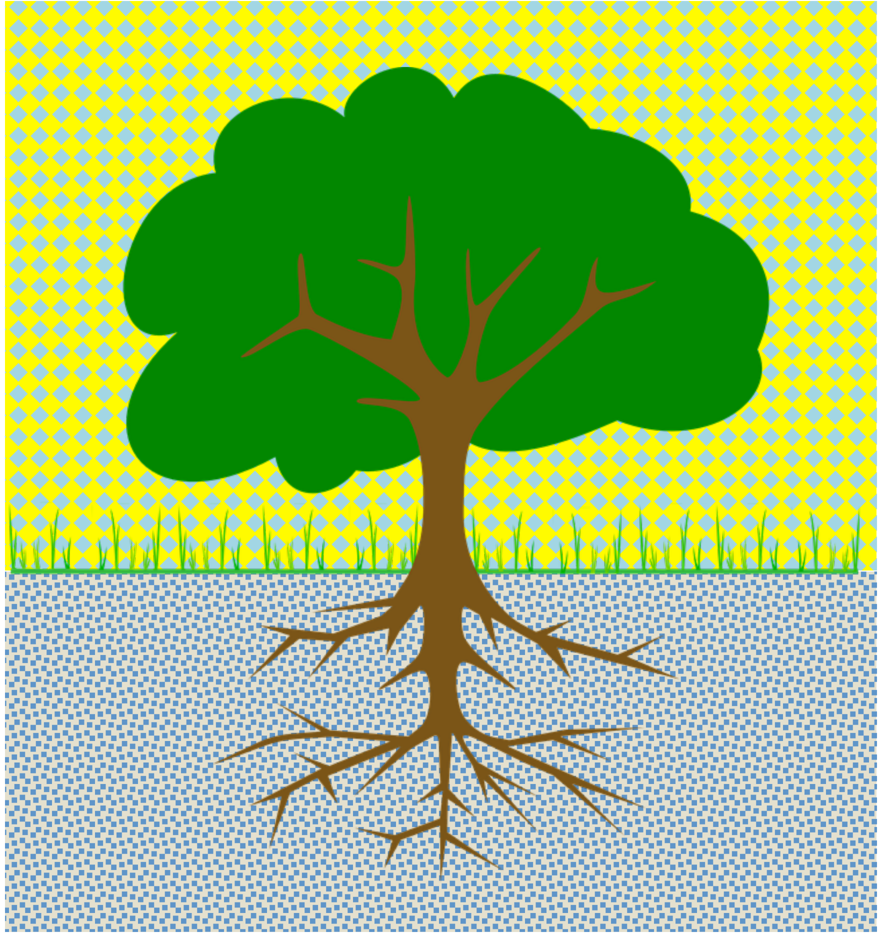


Organizations evolve by relieving thermodynamic potentials and creating thermodynamic entropy in the greater environment.

Tree Thermodynamics

A tree evolves an organization in response to the thermodynamic potential in its environment.

While the tree's organization reduces entropy locally, it increases the entropy of its environment by expelling heat (low energy photons) and O_2



sunlight, space, CO_2

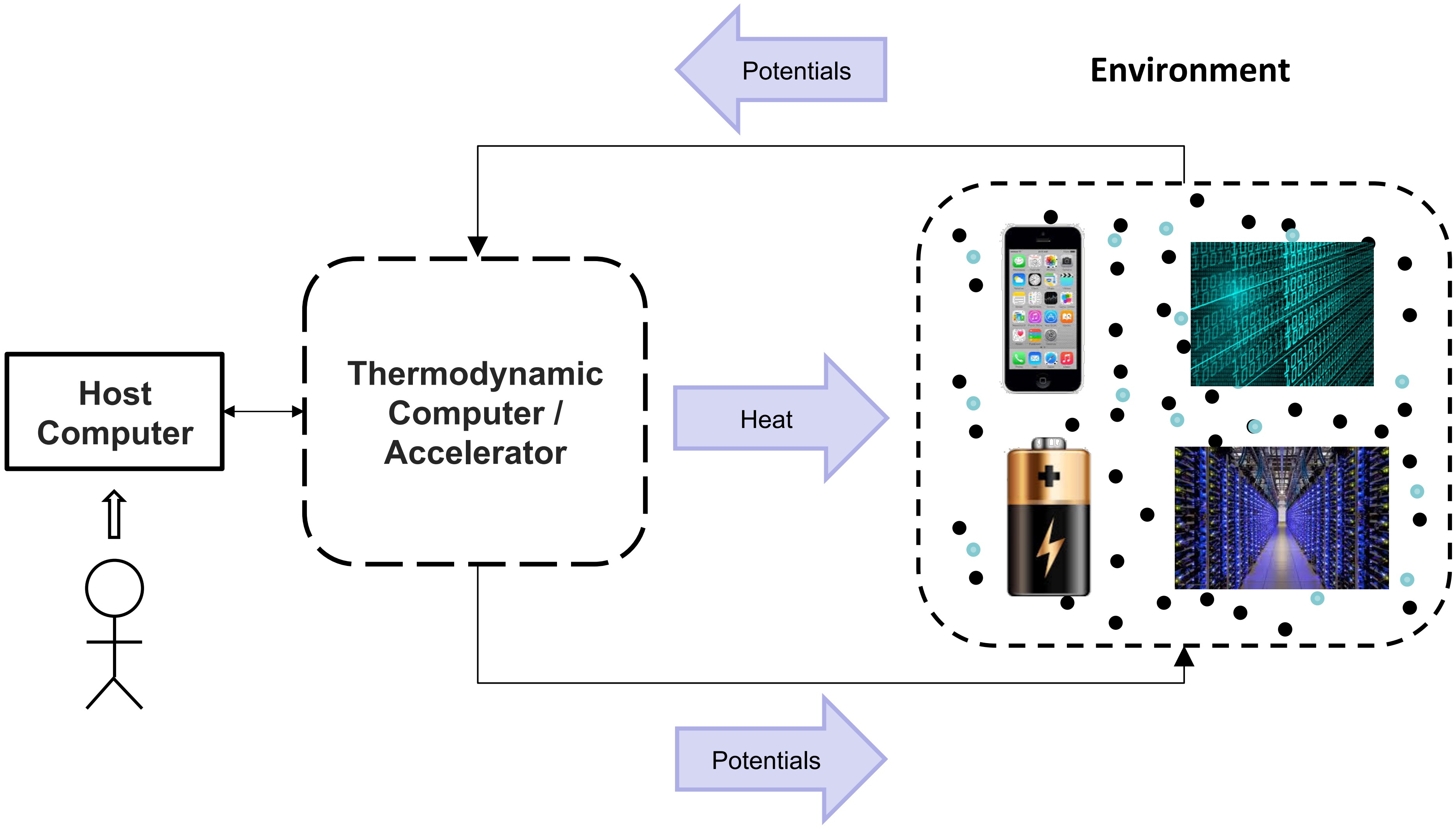
↕ thermodynamic potential

water, minerals

Arbortron Demos – Stanford Complexity Group

Vision for Thermodynamic Computing

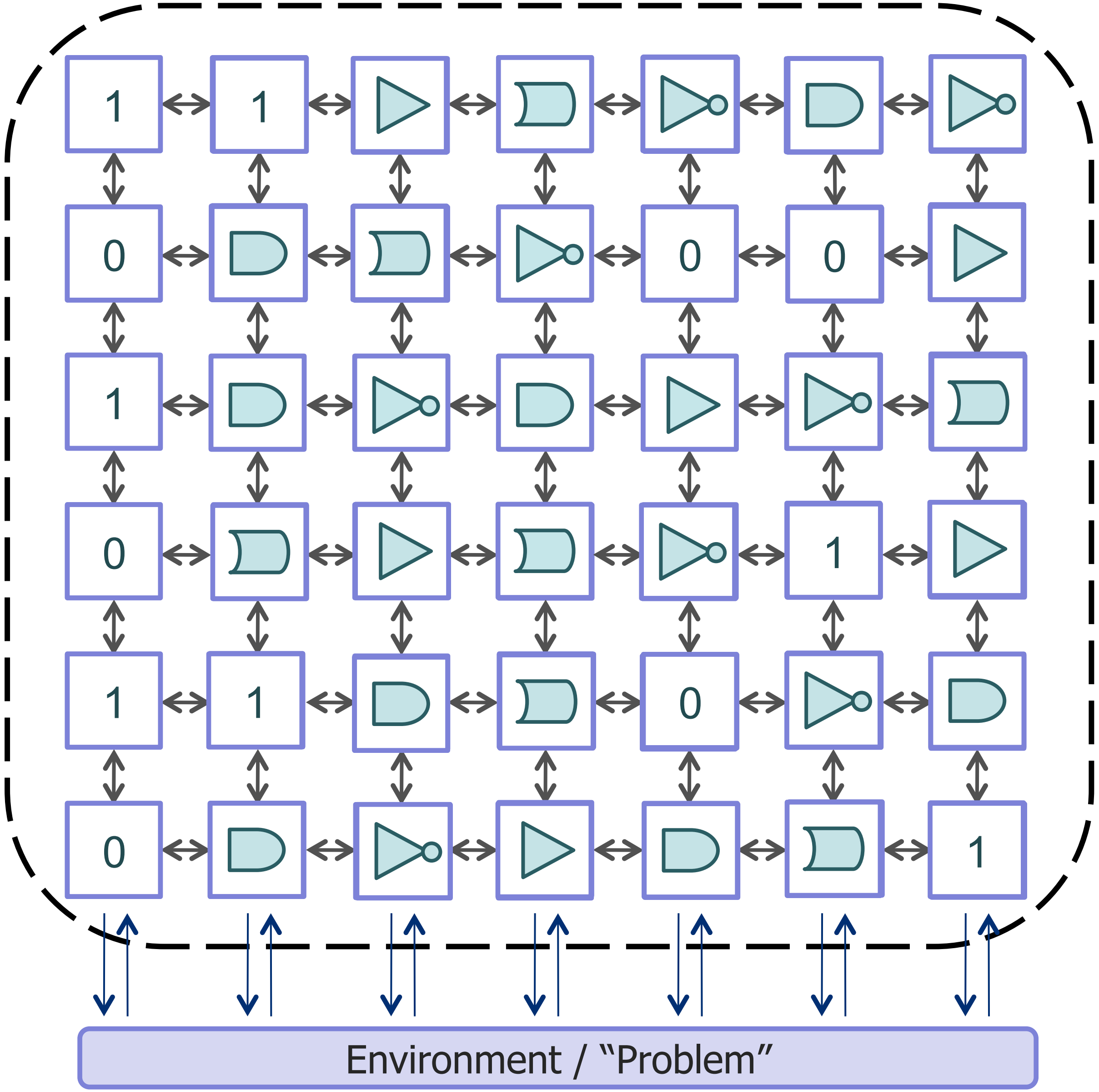
Thermodynamic Computing – System Concept



Thermodynamic Computers are open thermodynamic systems embedded in an environment of electrical and information potential.

Thermodynamic Computing – System Concept

- Networks of thermodynamically evolving nodes form a Thermodynamic Computer
- The "problem" is defined by the energy / information potential in the environment.
- Programmers can fix some of the ECs to define constraints / algorithms that are known to be of value.
- Dissipation within the network creates fluctuations over many length and time scales and thereby "search" for solutions over a very large state space.
- Structure precipitates out of the fluctuating state and entropy production increases in the environment as energy flows through the network and dissipation decreases



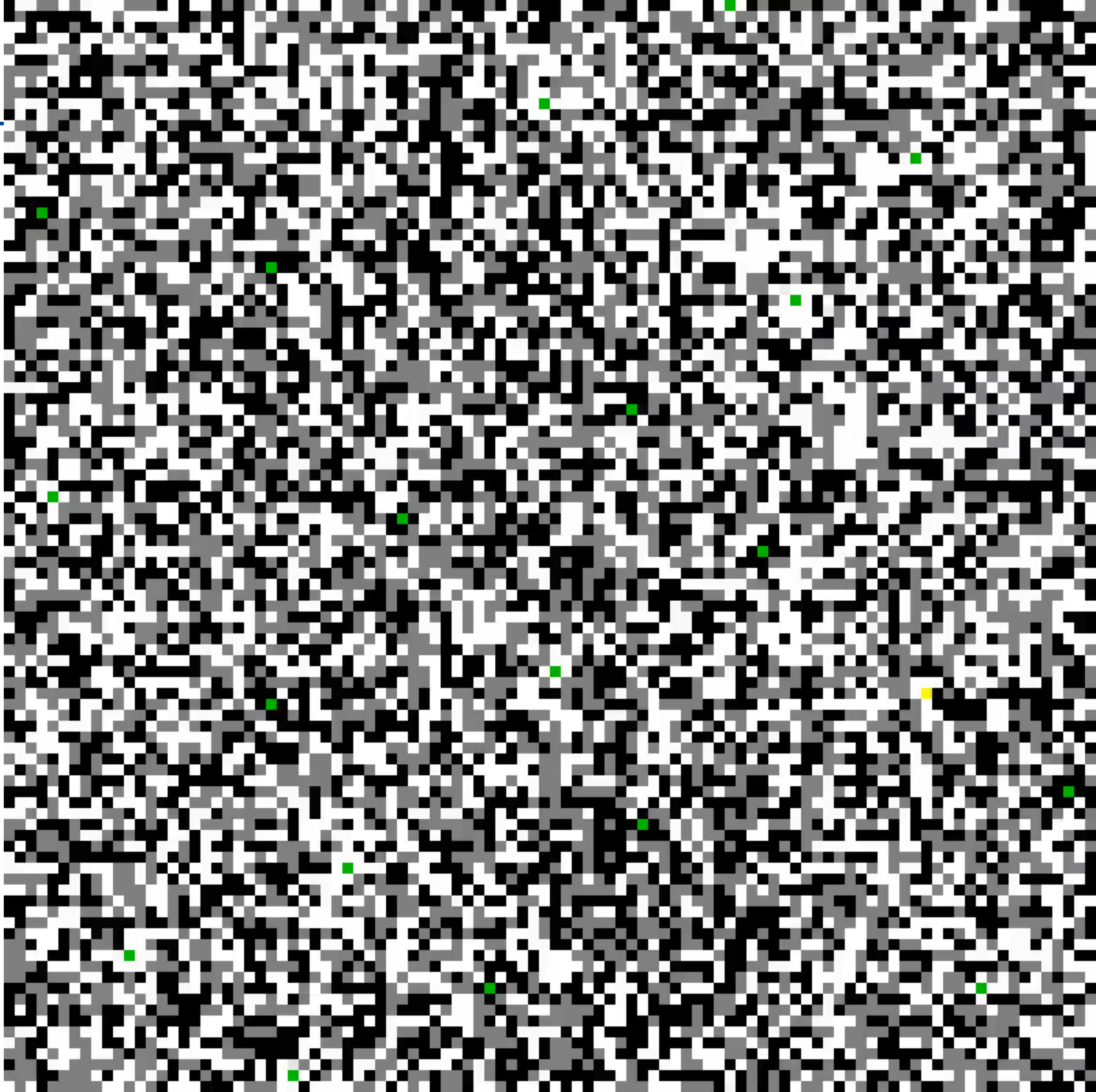
Thermodynamic Neural Network

Environment

- 10 pairs bias nodes of opposite polarity / opposite partition changing state with different periods
- $T_{node} / T_{edge} = 100$

Constraints

- 2D Network
- 10,000 nodes
- 16 nearest neighbor connections
- Periodic boundary conditions



Hylton, T. Thermodynamic Neural Network. *Entropy* **2020**, *22*, 256.

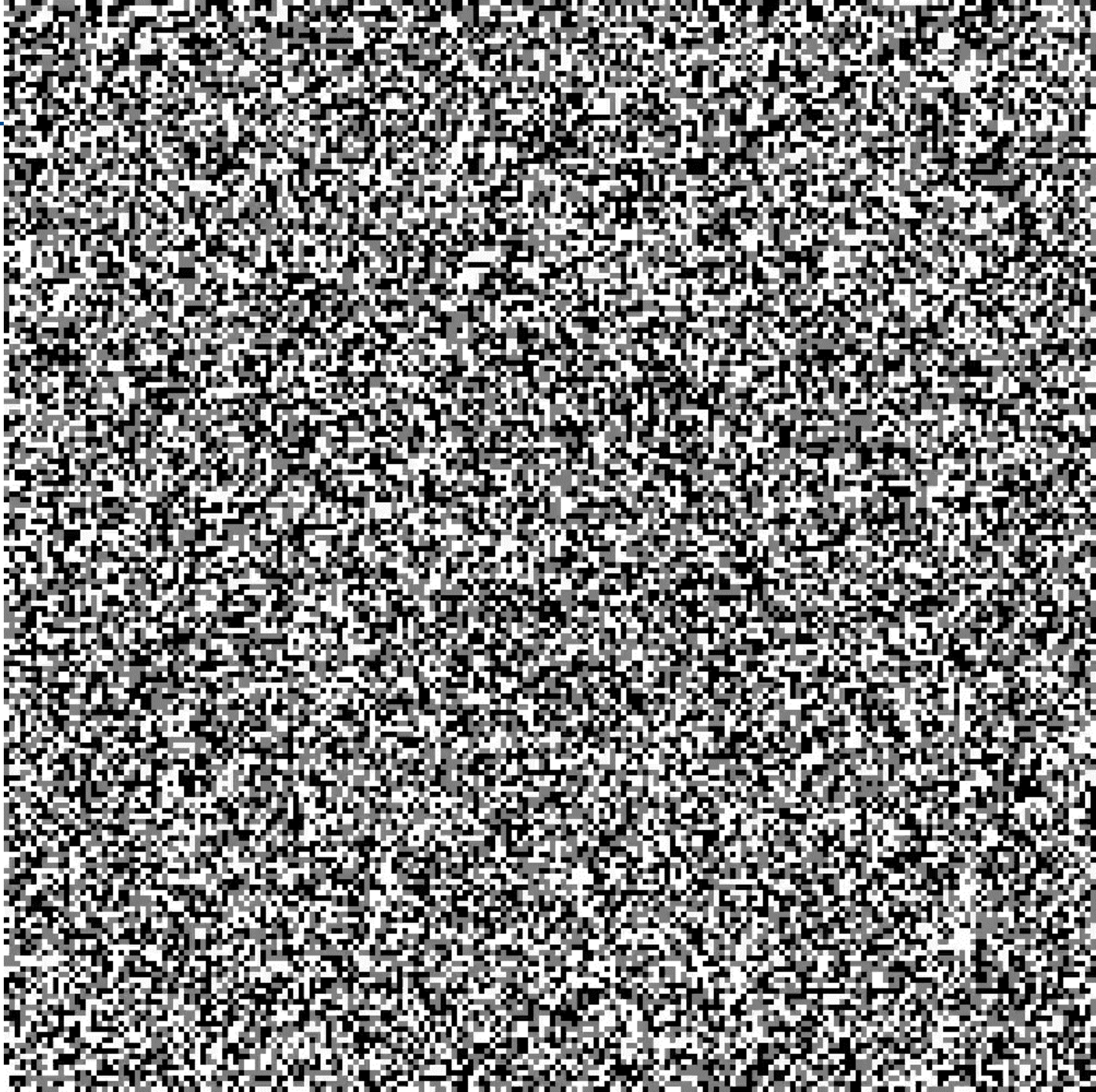
Thermodynamic Neural Network

Environment

- No external biasing
- T_{node} / T_{edge} = **100**

Constraints

- 2D Network
- 40,000 nodes
- 16 nearest neighbor connections
- Periodic boundary conditions

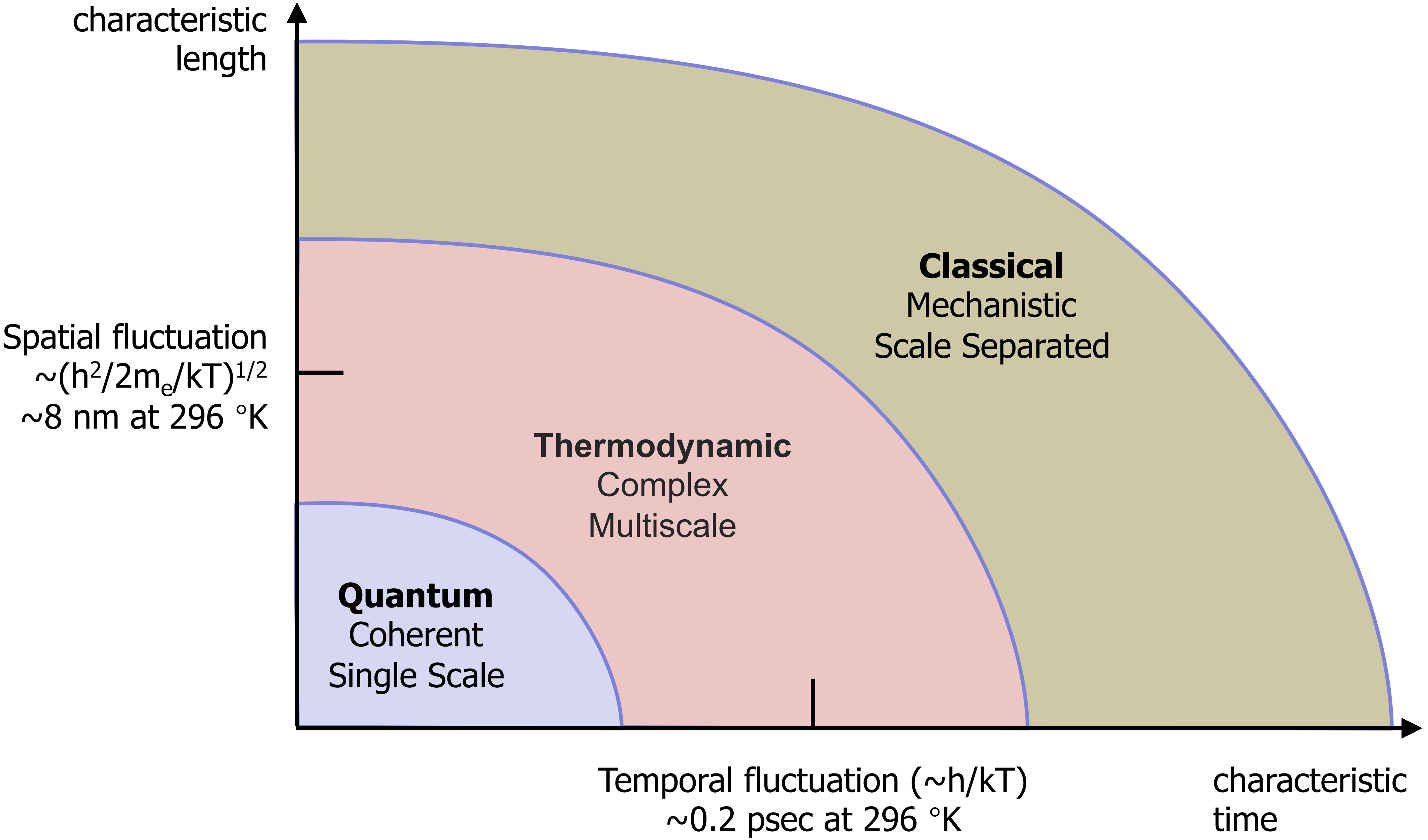


Hylton, T. Thermodynamic Neural Network. *Entropy* **2020**, *22*, 256.

Core Physical Concepts

- *Conservation* – all physical systems are built of conserved physical quantities. Conserved quantities cannot "vanish" but they can be transported through an open system.
- *Potentiation* – non-uniform accumulations of conserved quantities create potentials that disperse them
- *Fluctuation* – Complex systems at finite temperatures spontaneously sample configuration spaces adjacent to their current state of organization
- *Dissipation* – Fluctuation is tied to dissipation via positive feedback. Increased/decreased dissipation-fluctuation results in increased/decreased fluctuation-dissipation.
- *Adaptation* – The positive feedback linking fluctuation and dissipation can stabilize new and destabilize old organizations
- *Equilibration* – All physical systems evolve to find an equilibrium with their environment subject to internal and external constraints
- *Causation* - Spatio-temporal structure in the thermodynamic potentials is reflected in the organizations that evolve from them. These potentials can then be said to "cause" the resulting organizational dynamics.

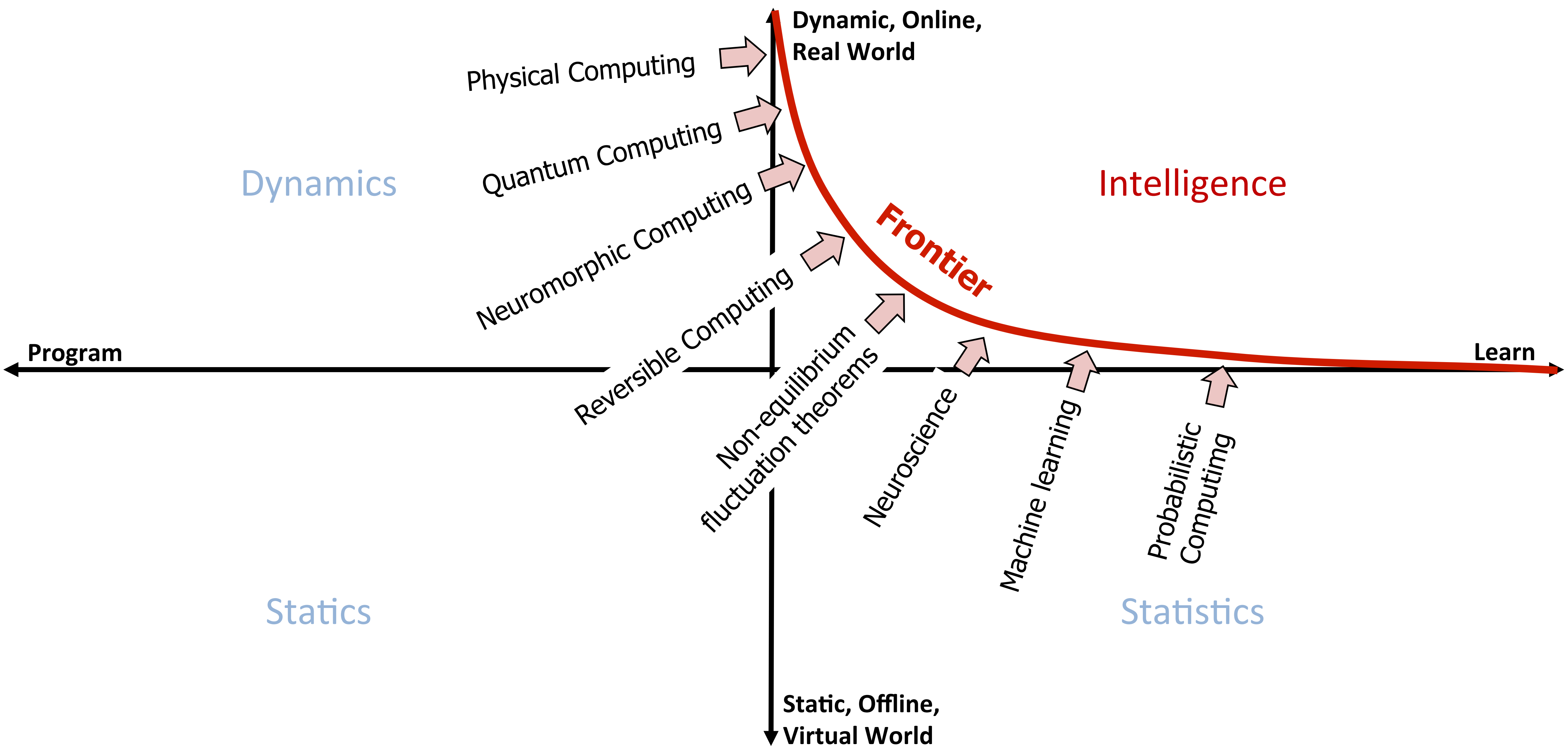
Computational Domains



History of Thermodynamics and Computing

Year	Name	Summary
1824	Carnot	description of a reversible heat engine model driven by a temperature difference in 2 thermal reservoirs - “Carnot Cycle”
1837	Babbage	specification of the first general-purpose computing system, a mechanical system known as the "Analytical Engine”
1865	Clausius	definition of entropy and the first and second laws of thermodynamics
1867	Maxwell	articulation of a thought experiment in which the second law of thermodynamics appeared to be violated - “Maxwell's demon”
1871	Boltzmann	statistical interpretation of entropy and the second law of thermodynamics
1902	Gibbs	authoritative description of theories of thermodynamics, statistical mechanics and associated free energies and ensembles
1905	Einstein	theory of stochastic fluctuations displacing particles in a fluid - “Brownian Motion”
1922	Szilard	connection of information theory and thermodynamic fluctuations; resolution of the paradox presented by Maxwell's demon - “Szilard Engine”
1925	Lenz, Ising	description of model magnetic system widely employed in statistical physics - "Ising Model"
1926	Johnson, Nyquist	description of thermal fluctuation noise in electronic systems - “Johnson Noise”
1931	Onsager	description of reciprocal relations among thermodynamic forces and fluxes in near equilibrium systems - “Onsager Relations”
1932	Von Neumann	developments of ergodic theory, quantum statistics, quantum entropy
1936	Turing	description of a minimalistic model of general computation - "Turing Machine”
1938	Shannon	description of digital circuit design for Boolean operations
1944	Shannon	articulation of communications theory; foundations of information theory; connection of informational and physical concepts of entropy
1945	Von Neumann	description of computing system architecture separating data and programs - the "Von Neumann Architecture"
1945	Eckart, Mauchly	construction of the first electronic computer used initially for the study of thermonuclear weapons - "ENIAC"
1946	Ulam, Metropolis, Von Neumann	first developments of Monte Carlo techniques and thermodynamically inspired algorithms like simulated annealing
1951	Turing	explanation of the development of shapes and patterns in nature - "Chemical Morphogenesis"
1951	Callen, Welton	articulation of fluctuation-dissipation theorem for systems near equilibrium
1955	Prigogine	description of dissipation driven self-organization in open thermodynamic systems - “Dissipative Structures”
1957	Jaynes	articulation of the maximum entropy / statistical inference interpretation of thermodynamics - “MaxEnt”
1961	Landauer	explanation of the thermodynamic limits on erasure of information (or any irreversible operations) - “Landauer Limit”
1982	Hopfield	description of a model neural network based on the Ising Model - "Hopfield Network"
1987	Hinton, Sejnowski	development of a thermodynamically inspired machine learning model based on the Ising Model - "Boltzmann Machine"
1997	Jarzynski	development of an equality relation for free energy changes in non-equilibrium systems - “Jarzynski Equality”
1999	Crooks	development of an equality that relates the relative probability of a space-time trajectory to its time-reversal of the trajectory, and entropy production
2012	Krizhevsky, Sutskever, Hinton	demonstration of deep machine learning technique in modern computer vision task - “AlexNet”

Frontier Landscape



Scientific Challenges

- Develop an **integrated non-equilibrium theory** of fluctuation, dissipation, adaptation, and equilibration that address, for example, long standing problems of stability, noise, quantum effects, reversibility, etc.

- **Bridge the gaps** separating classical and quantum computing

- Clarify and expand the **relationships among** information theory, computation, and thermodynamics

Potential Impacts

- **To science:** Enable computation **near fundamental limits** of efficiency
- **To technology:** Enable a very large increase in the capabilities of **small, low-cost, computing systems**, such as perceptual capabilities that rival those of animal sensory systems
- **To society: Improve outcomes in most human enterprise**, including medicine, business, agriculture, defense, security, leisure

- See report for many more impacts

Research Directions

- Extend **non-equilibrium fluctuation theorem development** toward the domain of thermodynamic computing;
- Develop **model systems** to support the refinement of thermodynamic computing theory and development;
- Characterize existing semiconductor and **unconventional computing components near thermodynamic limits** where fluctuations are avoidable, then compare results to theoretical predictions; and
- **Integrate recent theoretical and experimental results** on small-scale, fluctuating devices into larger component systems

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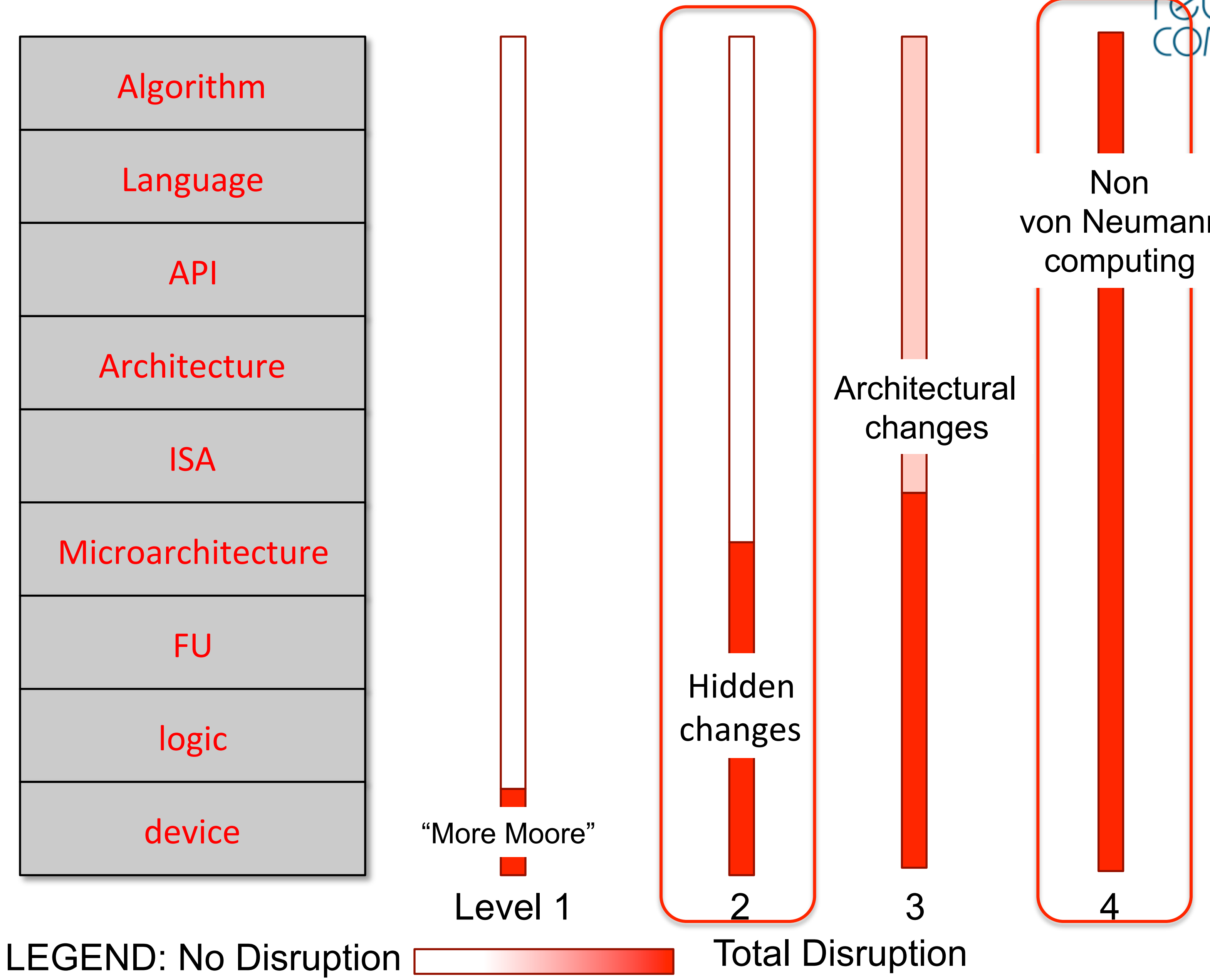
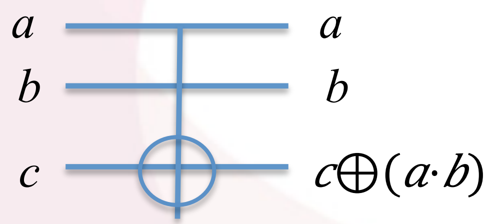
Potential Approaches vs. Disruption in Computing Stack



LEVEL 2: FOLLOW-ON TO THERMODYNAMIC COMPUTING WORKSHOP: *REVERSIBLE CLASSICAL COMPUTING*

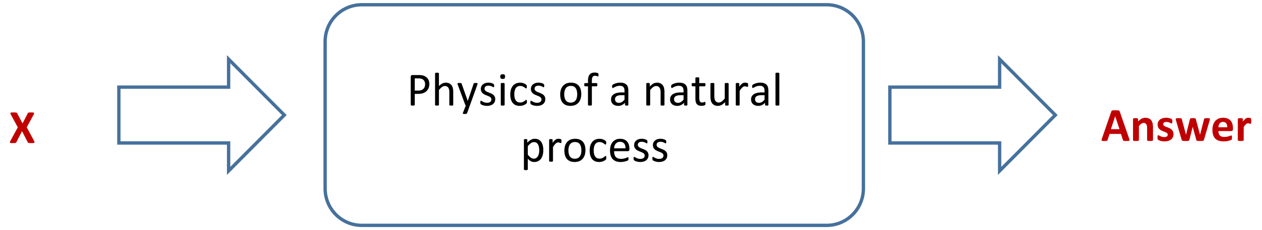
- ***Landauer limit***: erasing a bit costs $kT\ln(2)$ energy
- Beyond this limit: ***avoid erasing bits*** via ***reversible functions***
- E.g., Toffoli gate (logic complete)



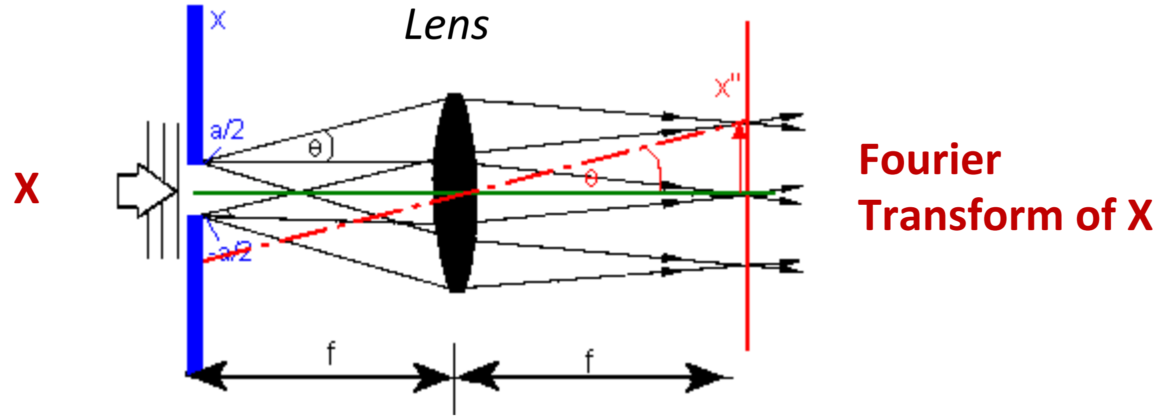
(commonly used in quantum computing)

- Potential to build ***classical pipelined processors*** with reversible logic
  - Niobium cryogenic (4K) or in room temperature CMOS processes
- Also of interest: ***hybrid reversible/irreversible processors***
- ***CCC Workshop on Reversible Computing planned for late 2020***

Level 4: Physical, Analog(ous) computing

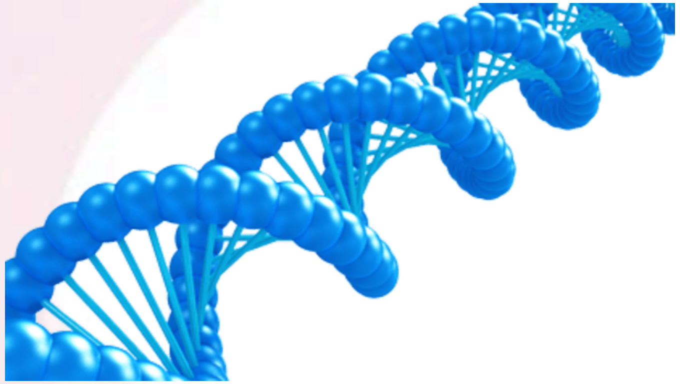


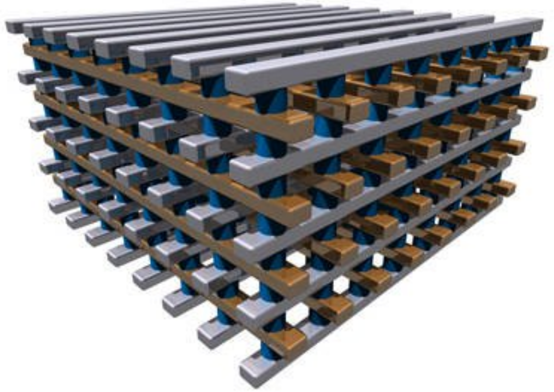
Example #1: Find the Fourier transform of a signal X



Level 4: Other potential physical computing processes

- (Thermodynamic, Quantum)
- Optical-based (FFT example)
- Neuroscience inspired
- Device physics: e.g., ReRAM
- Biological genetic processes: RNA/DNA





- **UNDISCOVERED OTHERS: cross-disciplinary surveying**

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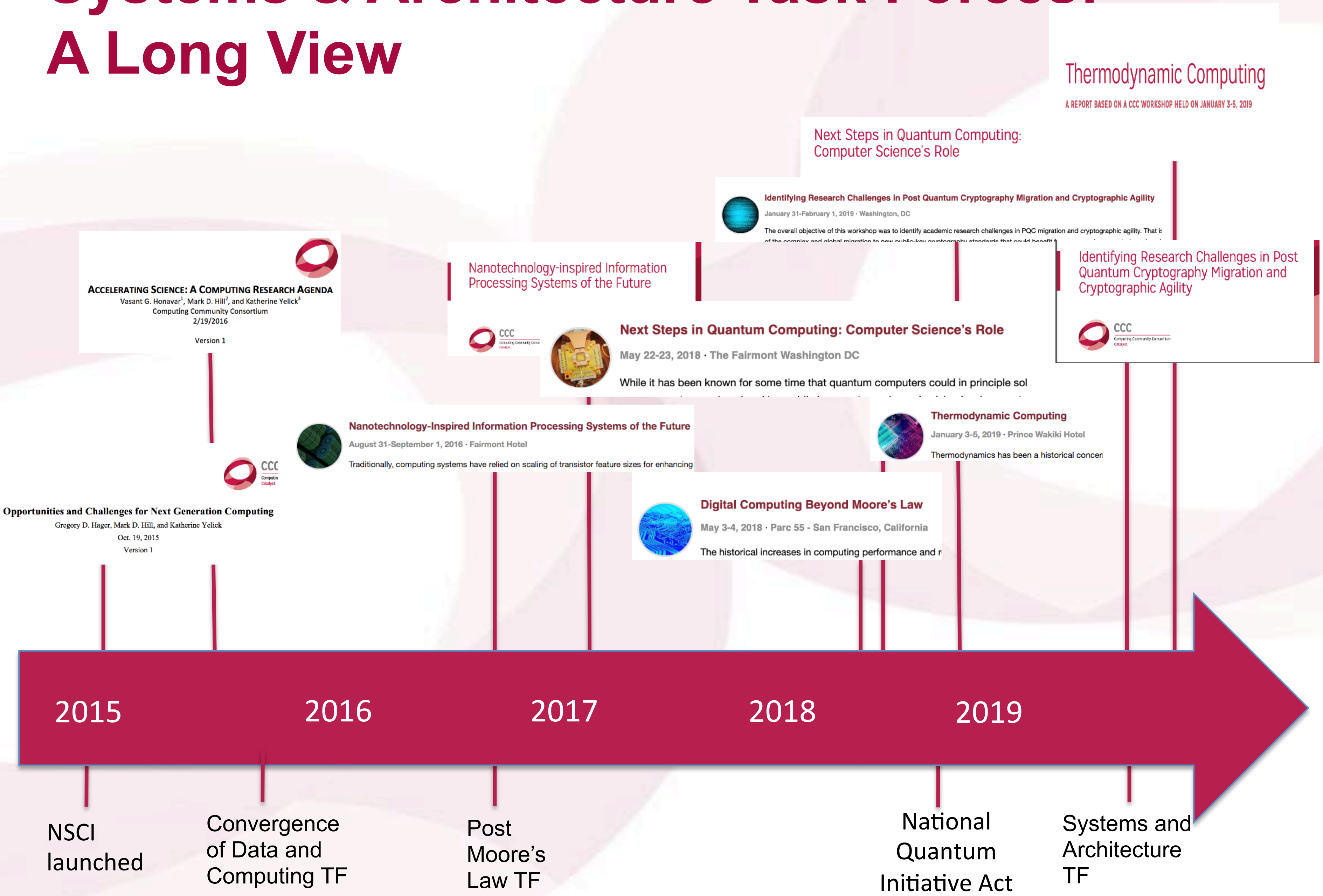
Appendix

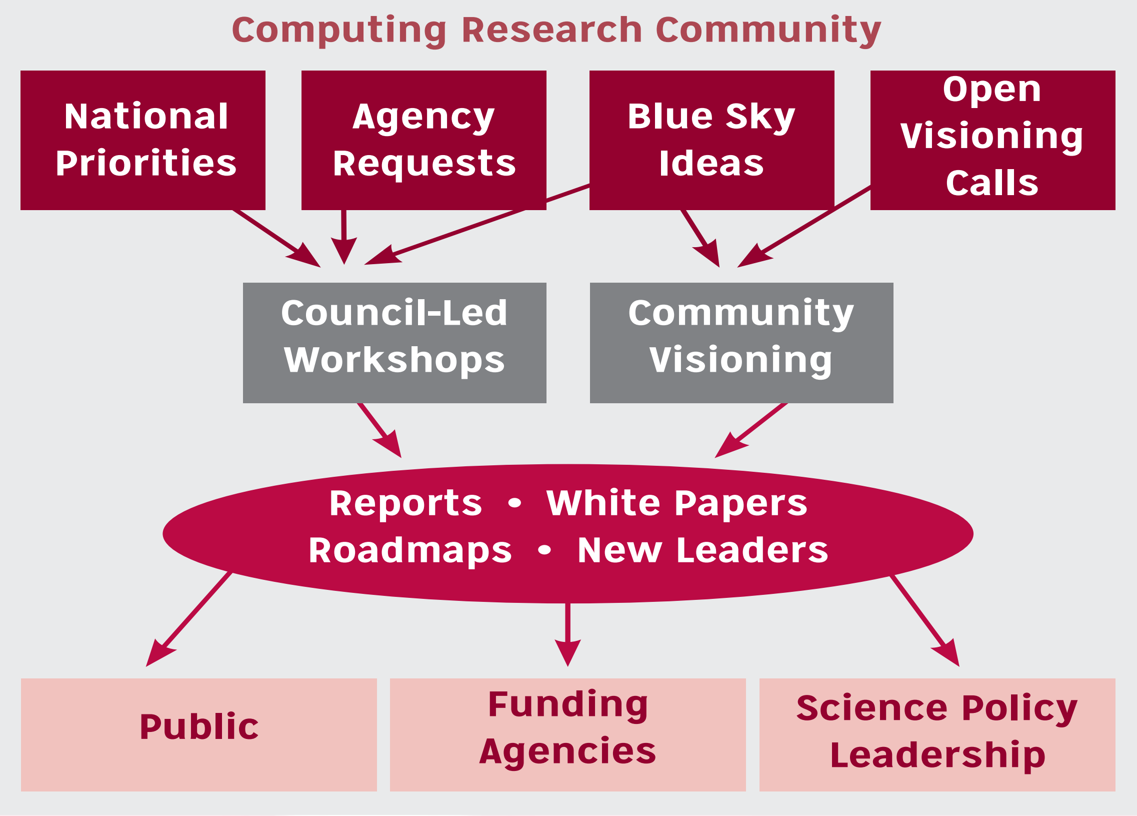
Systems & Architecture Task Forces: A Long View



Community Consortium

COMPUTING COMMUNITY CONSORTIUM

The **mission** of the Computing Research Association's Computing Community Consortium (CCC) is to **catalyze** the computing research community and **enable** the pursuit of innovative, high-impact research.



Bring the computing research community together to envision audacious research challenges.

Communicate these challenges and opportunities to the broader national community.

Facilitate investment in these research challenges **by key stakeholders**.

Inculcate values of **leadership** and service by the computing research community.

Inform and influence early career researchers to engage in these community-led research challenges.

Talking points

- Where we imagine the next generations of computing technology, we also lack the conceptual foundations required for success. As it has been throughout the history of computing, physics, and thermodynamics in particular, is the right place to look for new ideas.
- Non-equilibrium thermodynamics drives the evolution of organization. Thermodynamics is universal, implies order as well as disorder and examples are everywhere.
- Thermodynamic computing is the connection of machines into the real thermodynamics of their environment so that they can organize themselves, the same way that everything else does.
- We can guide this evolution so that it does something that we want, just like we do every day when we build something or grow something or teach something. We “mold” them, or “constrain” them, or “train” them to solve problems that we care about. We don’t “program” them, we create a path and let nature take its course.
- Thermodynamic computing means making elementary physical concepts – ideas like conservation, potentiation, fluctuation, dissipation, equilibration, adaptation and causation – the foundations for the future of computing.