Thermodynamic Computing: It's All About Energy

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Observations

Today

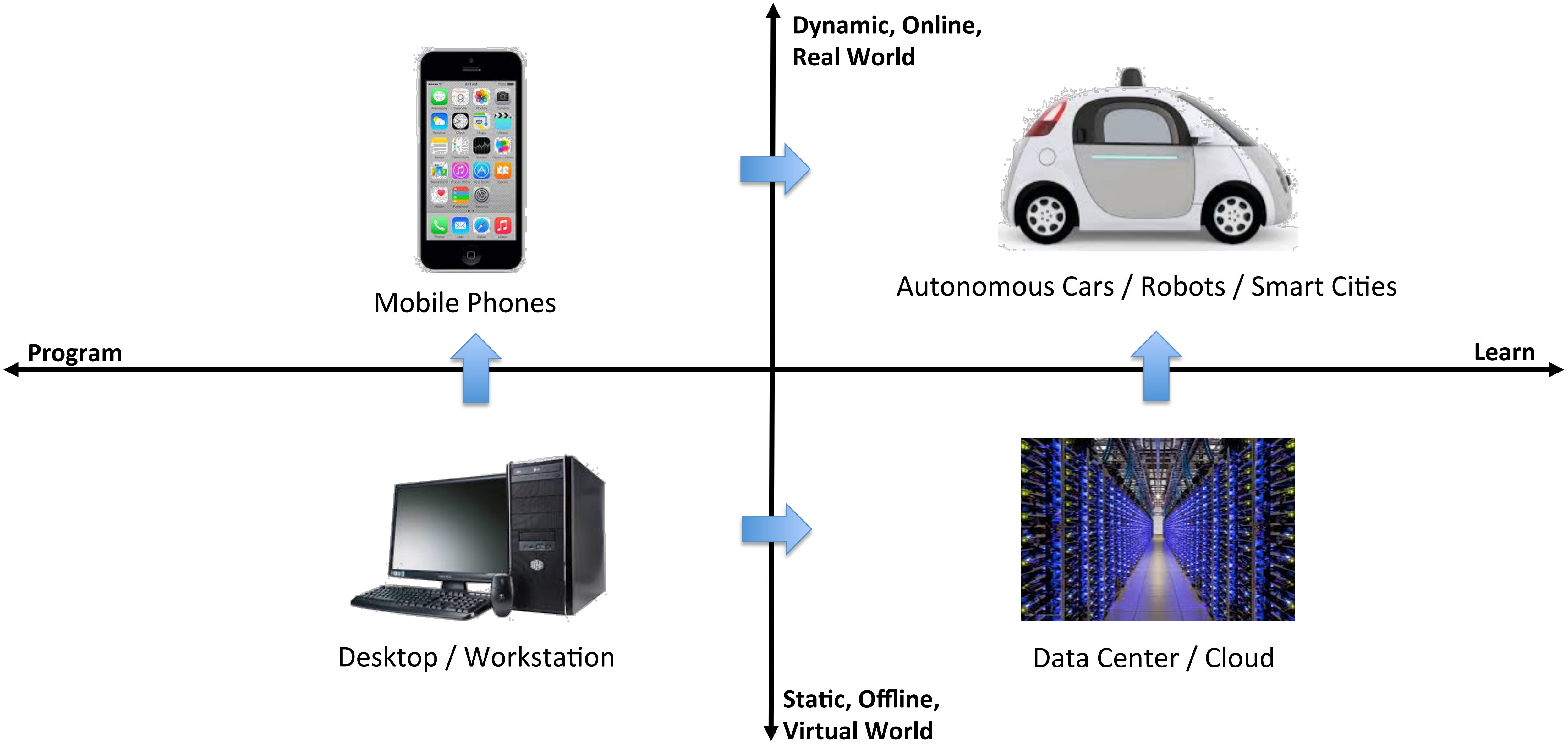
- Computing absorbs 5% of US electrical power production
- Next generation semiconductor fabs are projected to cost $20B
- Moore's law is on its last legs
- Electron devices are comparable in size to biological molecules - thermodynamic fluctuations are a challenge
  - Paradoxically, while avoiding fluctuations 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

Why Thermodynamics?

- Thermodynamics is the *problem* in computing today
- Thermodynamics *organizes everything*
- Thermodynamics *is temporal*
- Electronic systems are extraordinarily well-suited for thermodynamic self-organization

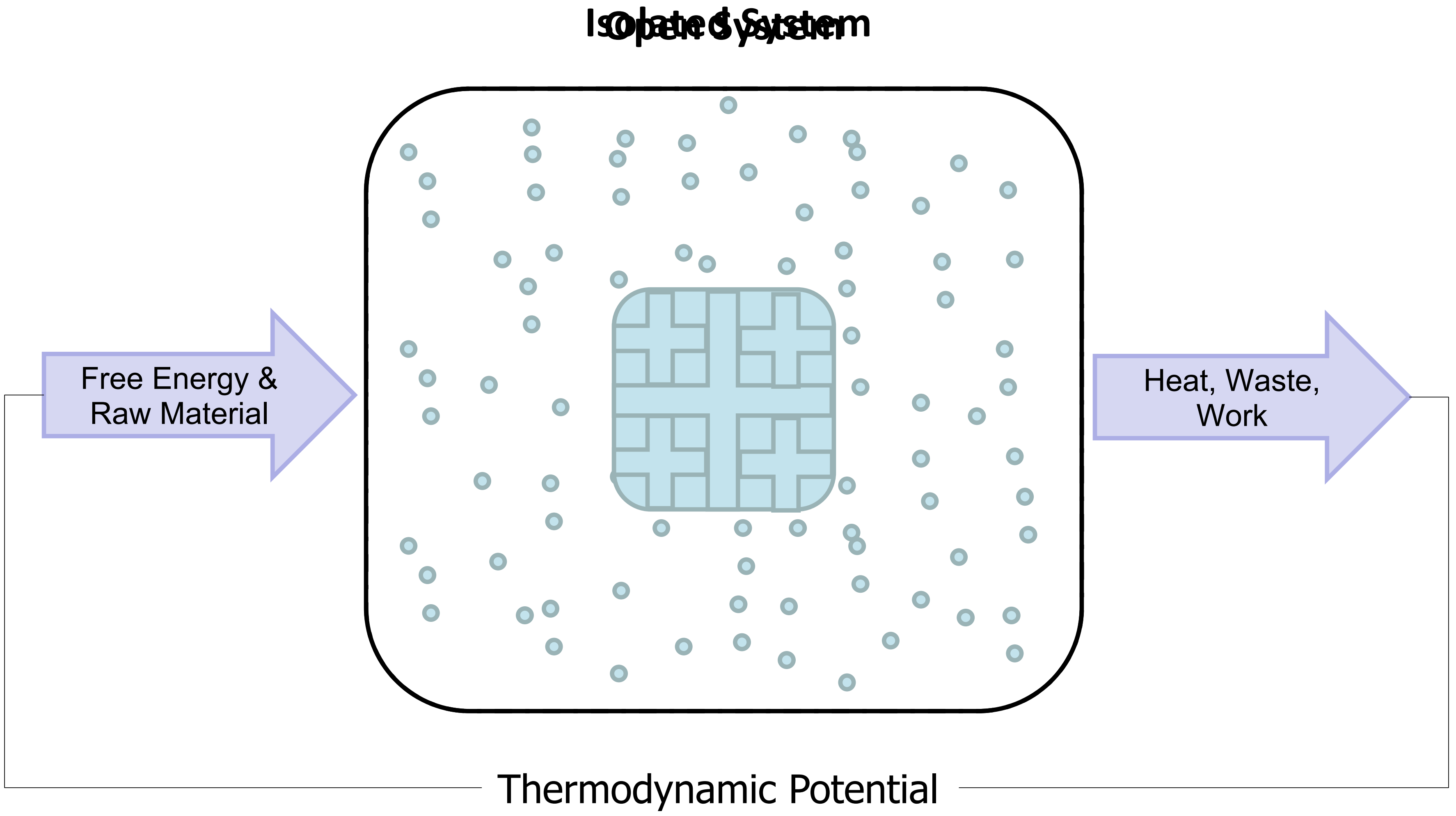
Thermodynamics should be the principal concept in future computing systems

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

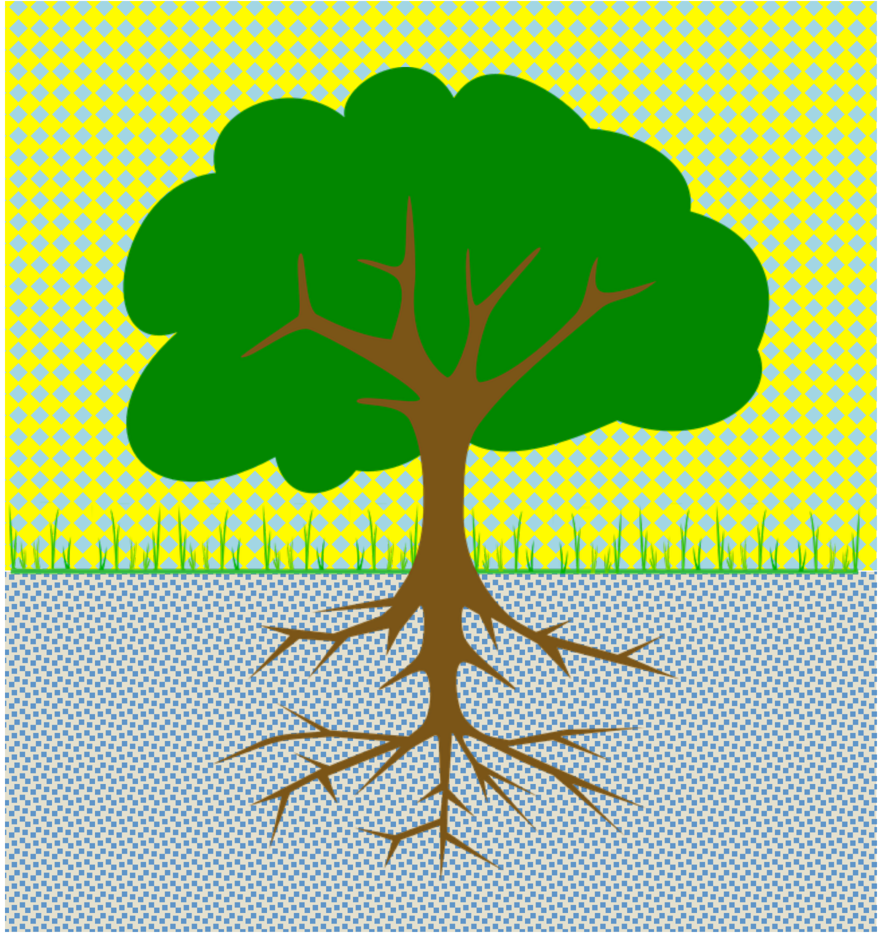


Organizations evolve by relieving thermodynamic potentials and creating thermodynamic entropy in the greater environment.

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



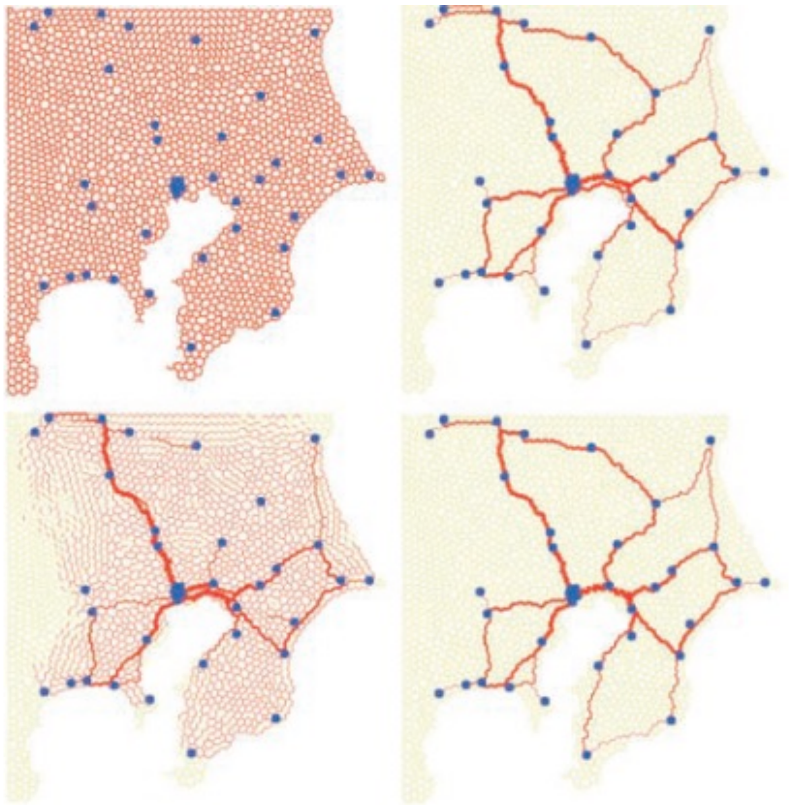
sunlight, space, CO_2

thermodynamic potential

water, minerals

Power Station Arcing

Slime Mold Growth – Tokyo Map



Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D. P., Fricker, M. D., ... & Nakagaki, T. (2010). Rules for biologically inspired adaptive network design. *Science*, *327*(5964), 439-442.

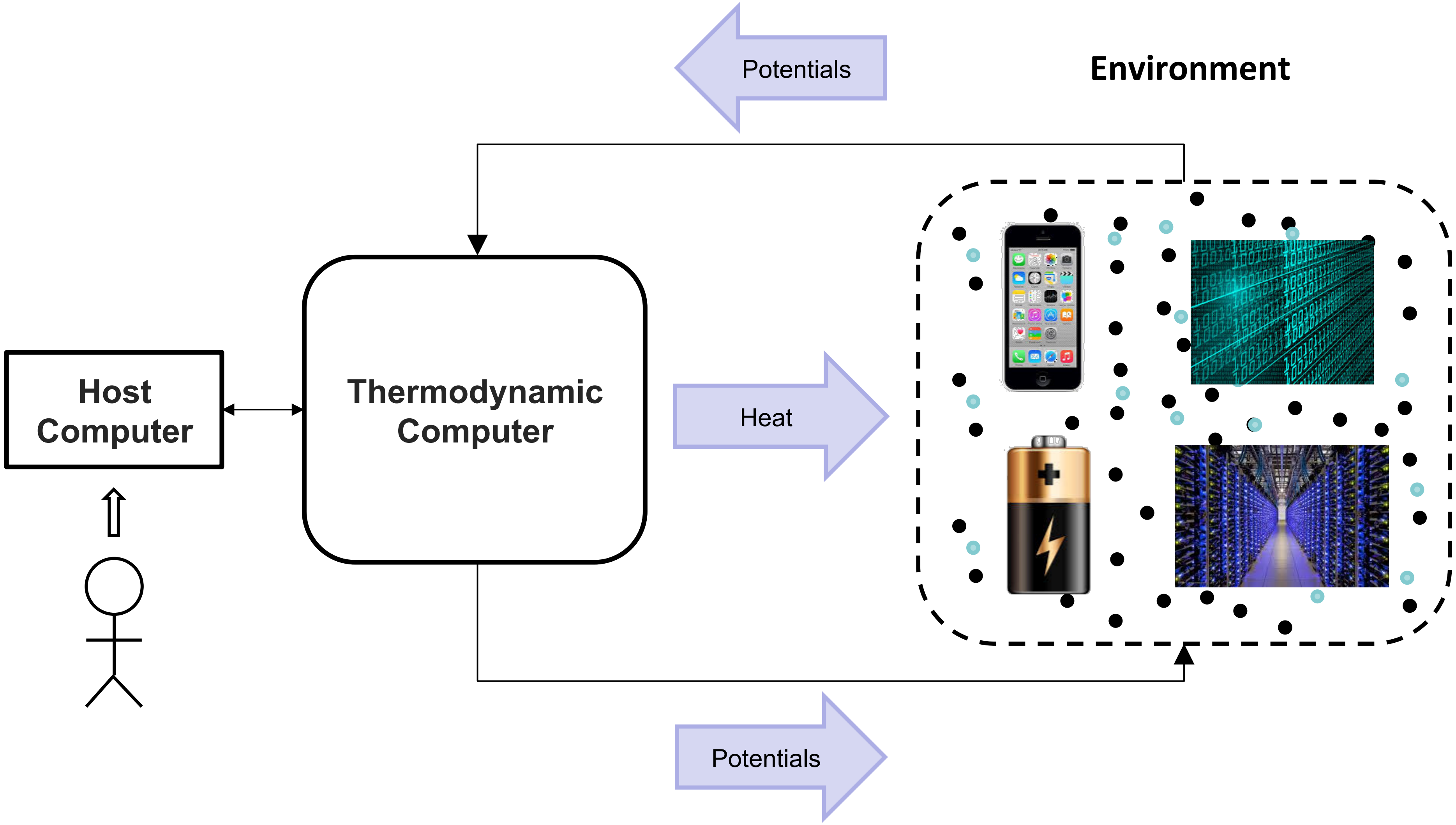
Thermodynamically Evolved Structures

Thermodynamic Evolution is *everywhere*.

Arbortron Demos – Stanford Complexity Group

Vision for Thermodynamic Computing

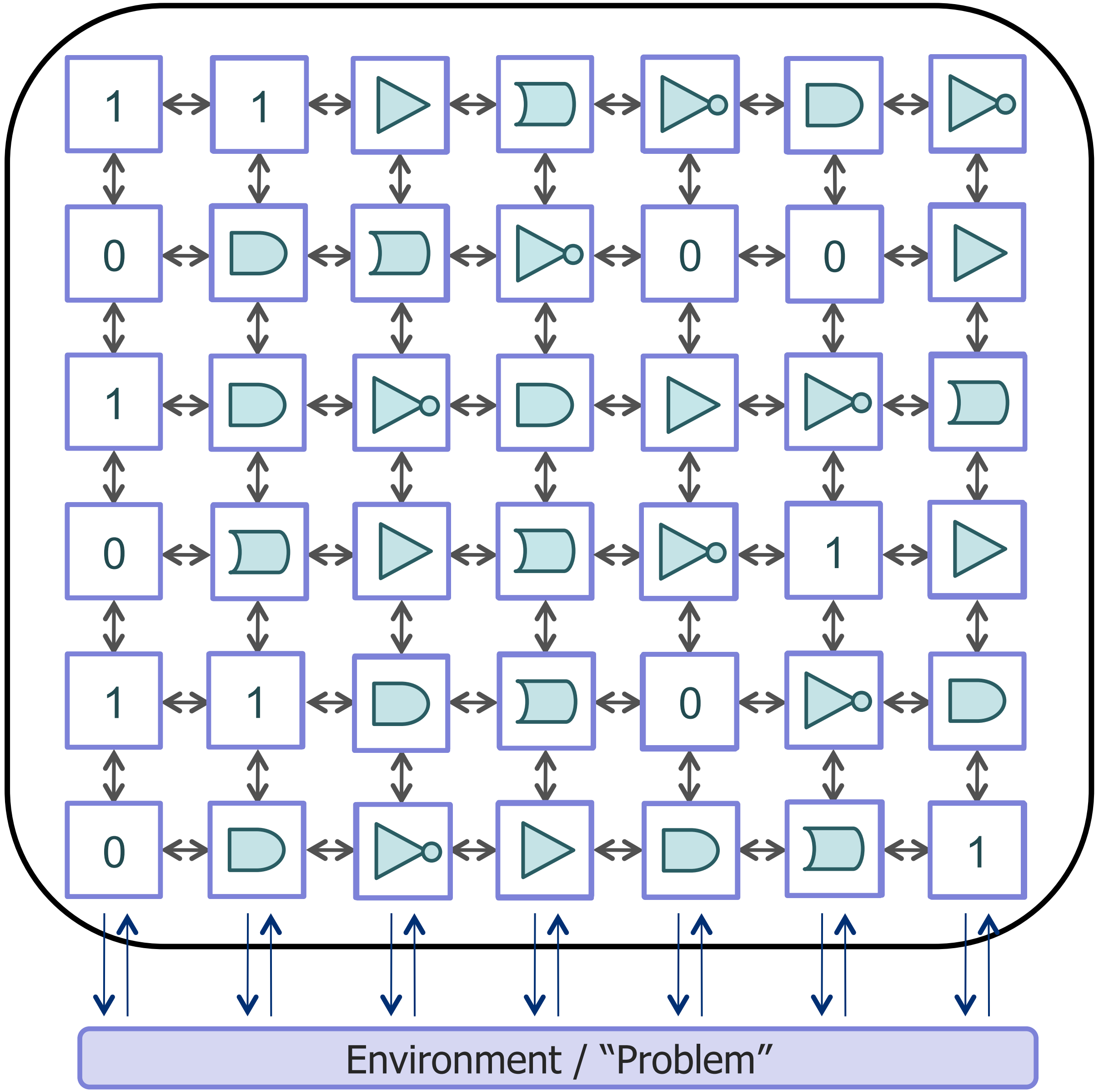
Thermodynamic Computing – System Concept



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



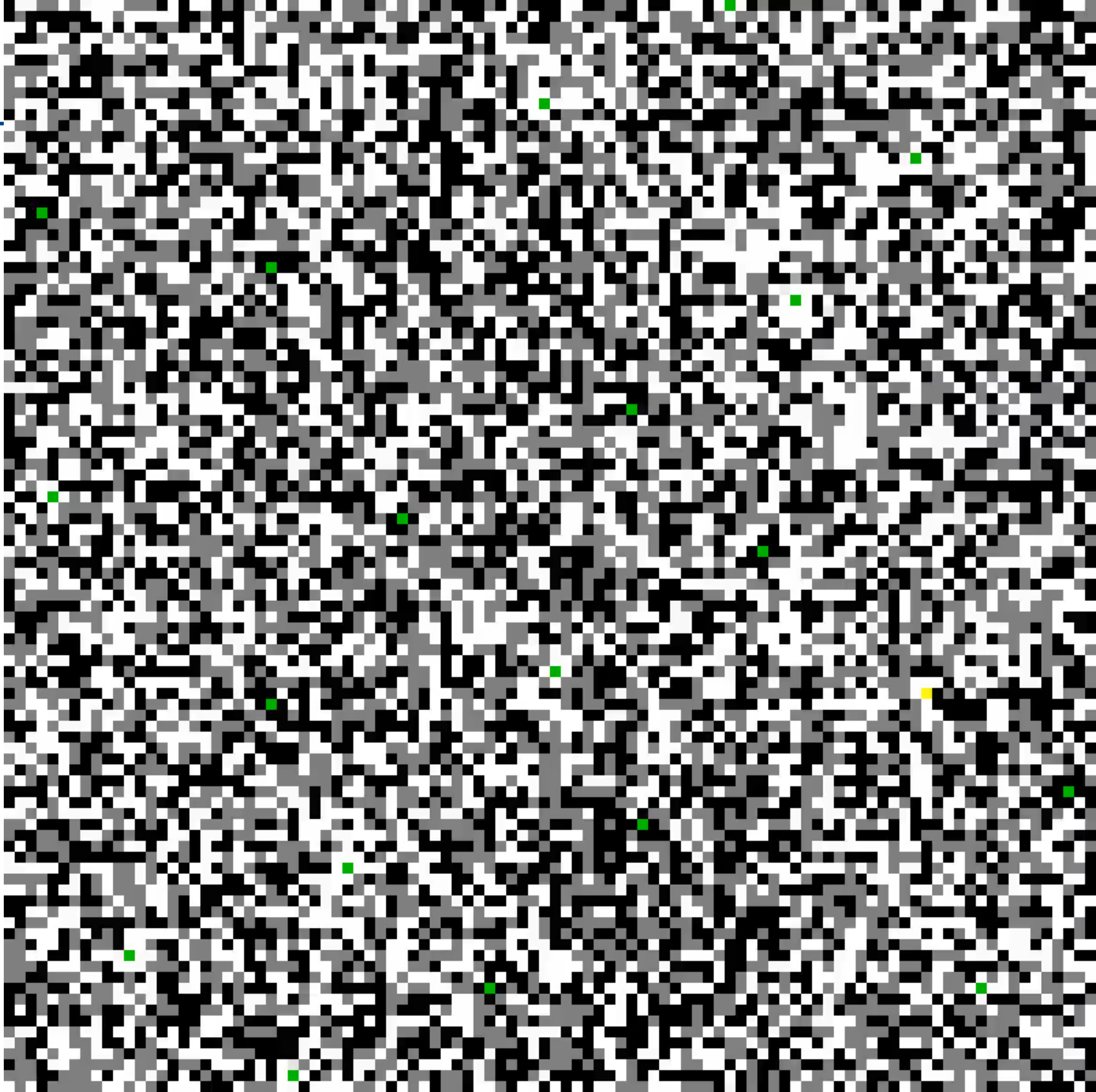
Thermodynamic Neural Network

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
- Bi-partitioned
- Periodic boundary conditions



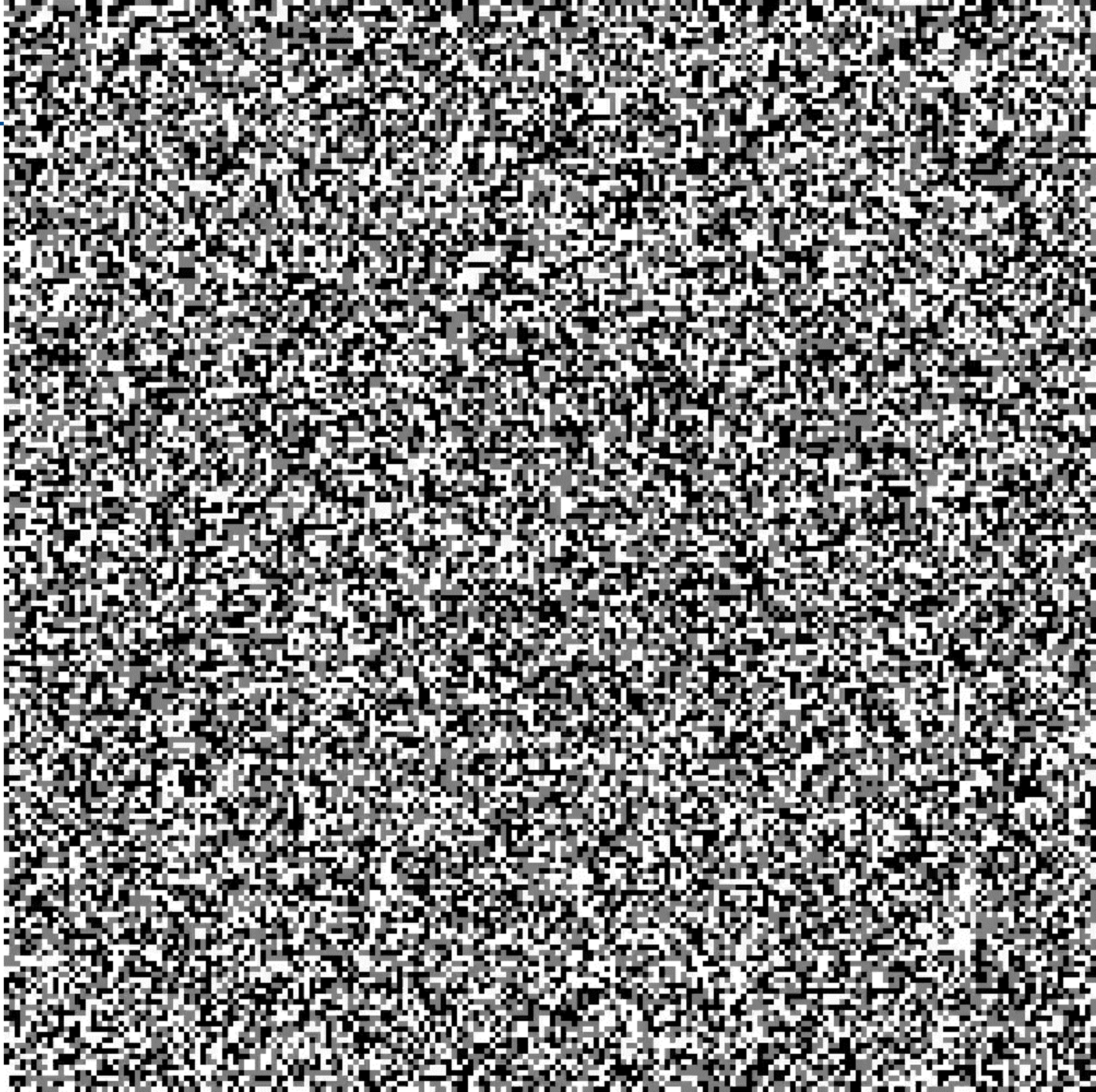
Thermodynamic Neural Network

Environment

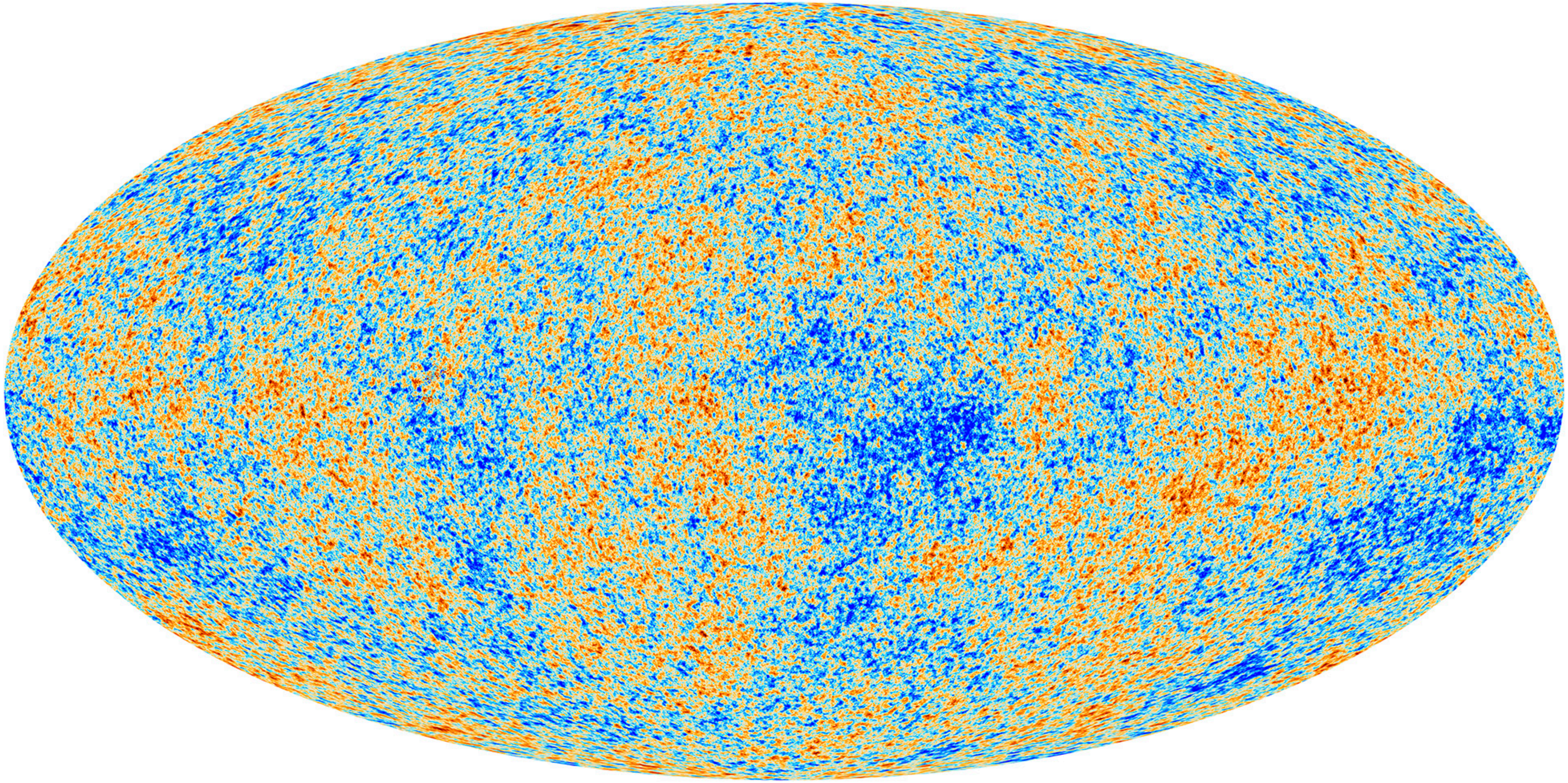
- No external biasing
- T_{node} / T_{edge} = **100**

Constraints

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



Cosmic Microwave Background Fluctuations

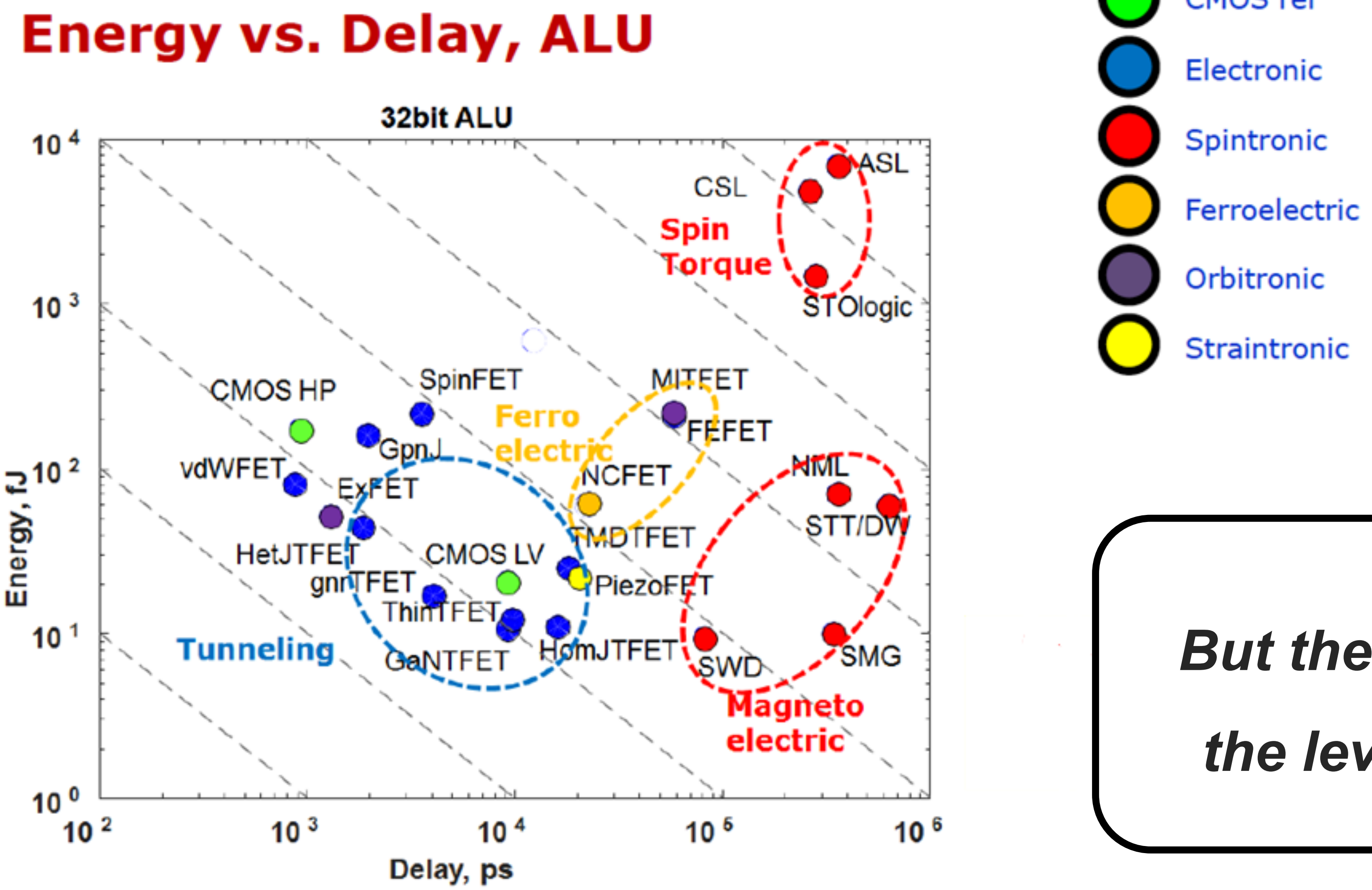


European Space Agency Planck satellite in 2013

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.

All Computing Devices are Thermo-physical Systems



But the physics ends at the level of the device

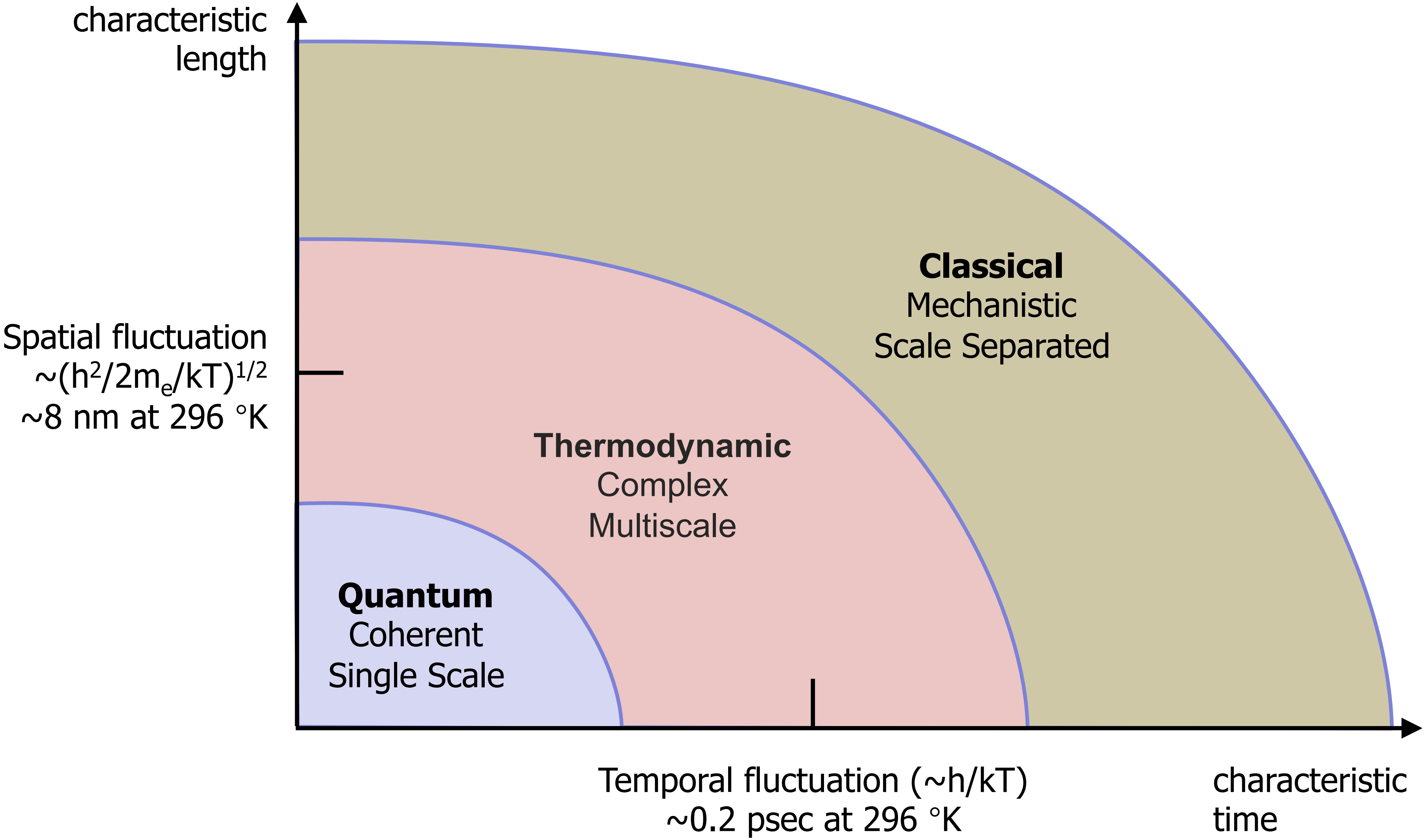
Courtesy Dimitri Nikonov and Ian Young

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*.

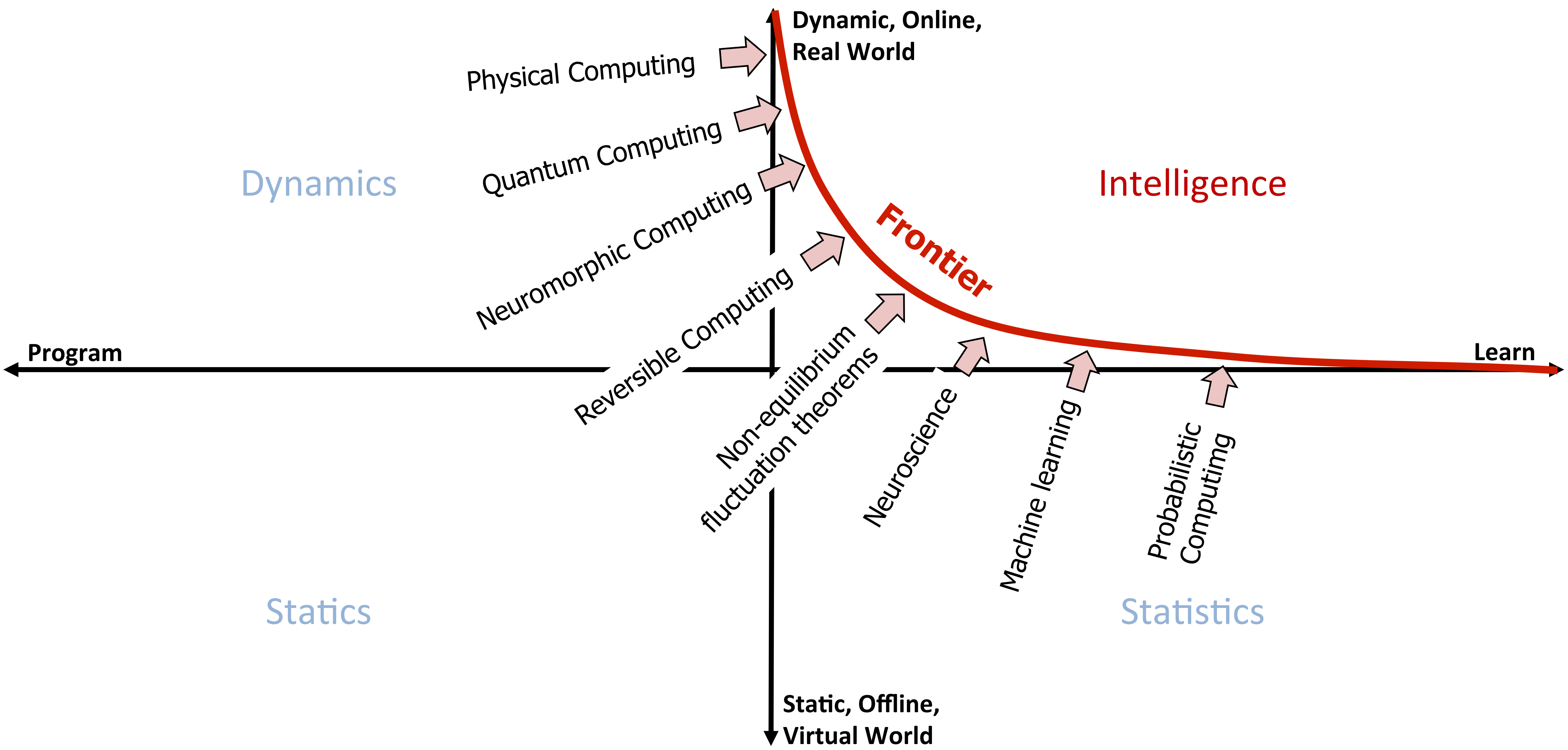
Computational Domains



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



Appendix

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.