Classical Digital Switch, Quantum information processing, and a Single Synapse

Part 1: *Energy Estimates*

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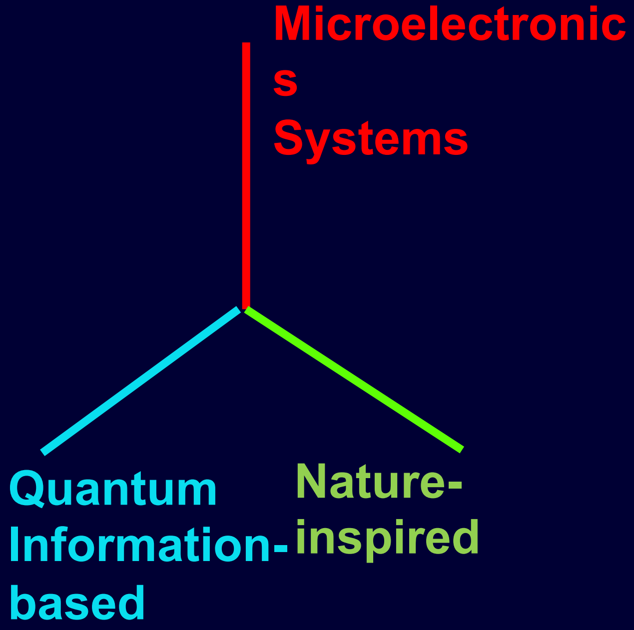
Information Processing:
Similarities and Differences

Three Different Dimensions for Computing

(Sep 14, 2022, EES2 Presentation)

- <u>Microelectronics Systems</u>: The current trajectories, using scaling and specialized architectures are on the Microelectronics Basis
- <u>Nature-inspired</u> represents all the information processing in nature from neuron synapses to photosynthesis
- <u>Quantum Information-based</u> is based on using quantum representations as units of computation and finding algorithms that can simulate quantum and classical processes



Questions to be Addressed

- Top-down estimates have shown > 24 orders of magnitude in energy as a bit is translated to an *instruction* for *simulation of an Application*

- What are can be learned from biological and quantum systems?
- How can we use this to help design energy efficient computing?

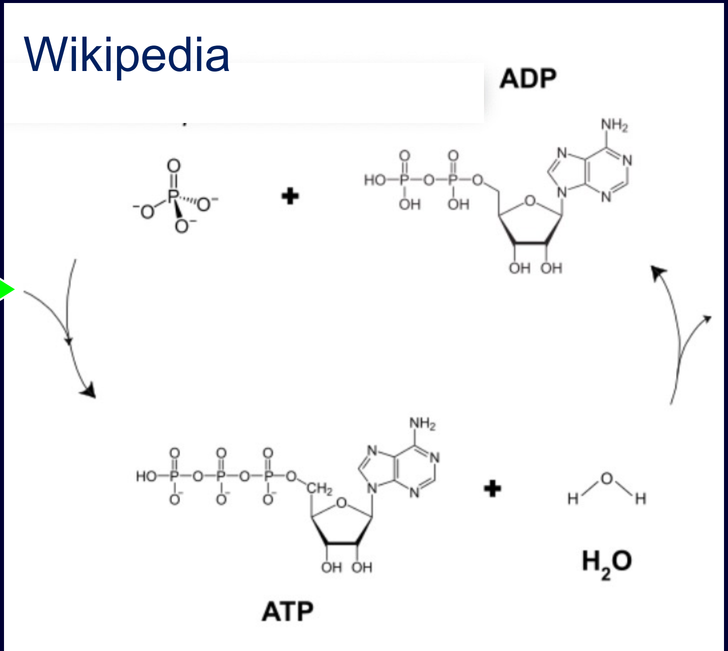
- Two parts:
  - Part 1: Estimate Energy for elemental information processing on the other different dimensions
  - Part 2: Quantify and Identify Pathways for using the lessons from Nature and Quantum Information Processing

Outline

- Recap Biochemistry and Thermodynamical aspects
- Biological System: Single Synapse Processing
- Quantum Information Processing: Quantum Chemistry
  - Simulation in a Classical Digital Computer
  - Emulation in a Quantum System
- Summary and Future Work

Biochemical System: ATP Hydrolysis

Chemical Energy



Mechanical Work

Heat Energy

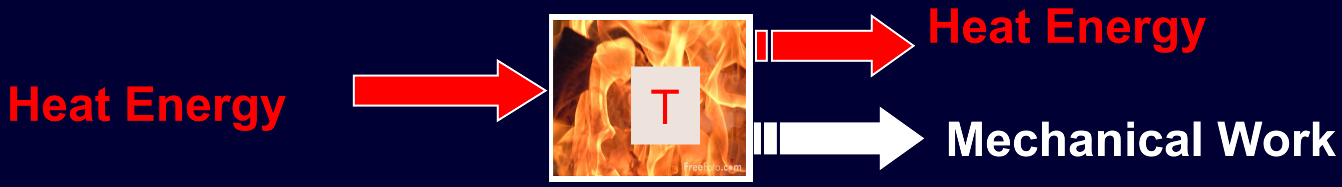
Chemical Energy

Change in Free Energy = ~31.55 ± 1.27 kJ·mol− 1

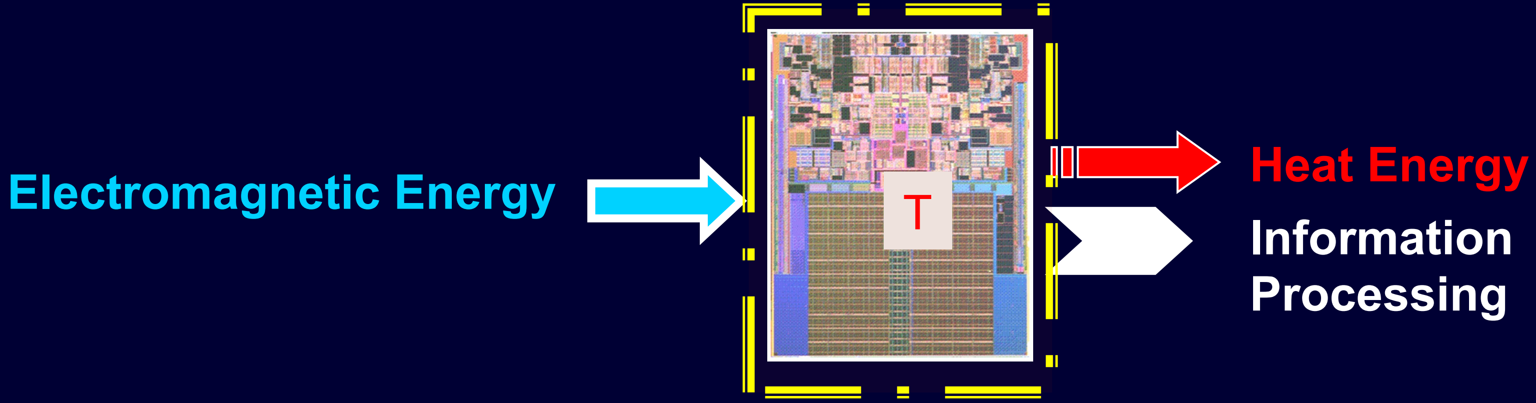
F. Meurer, et al, 2017

Computer as a Thermodynamic System

(a). Heat Engine

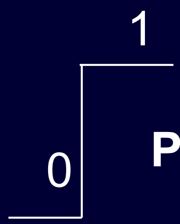


(b). Information Processing Engine



Computing: Digital vs Quantum

Classical Digital Representation



P = 0 or 1

- Discrete, Measurable States, Control
  - A scalable physical system with well characterized bits
  - The ability to initialize and transport bits to one of the two specific fiducial state s
  - Clock synchronization across the system

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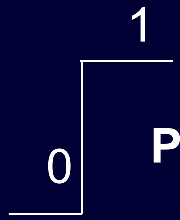
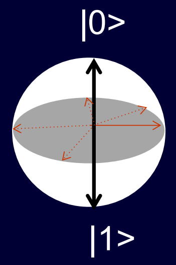
Computing: Digital vs Quantum

Classical Digital Representation



P = 0 or 1

Quantum Real Space Representation

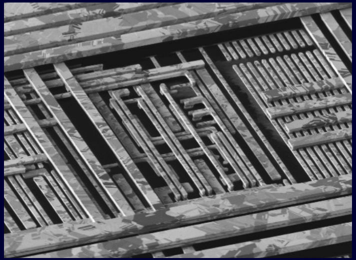


$$|\psi = \alpha \, |0 + \beta \, |1$$

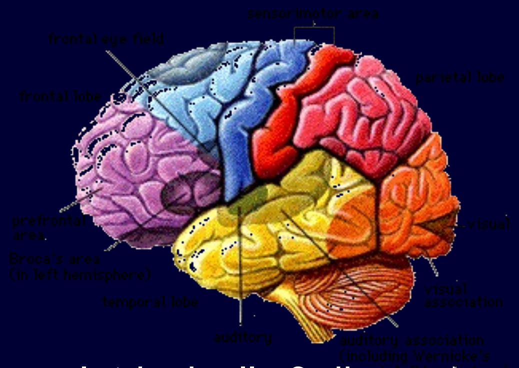
- Discrete, Measurable States, Control
  - A scalable physical system with well characterized bits
  - The ability to initialize and transport bits to one of the two specific fiducial state s
  - Clock synchronization across the system

- Superposition, Entanglement, Control
  - A scalable physical system with well characterized qubits
  - The ability to initialize and transport qubits to specific fiducial state
  - Long relevant decoherence times “much” longer than gate & system operation time

Computing: Digital vs Brain



- Mostly 2 dimensional
- Regular Geometry
- Software upgrades
- **Assembly:** Top-down lithography
- **Number of Switching elements:** ~10 Billion



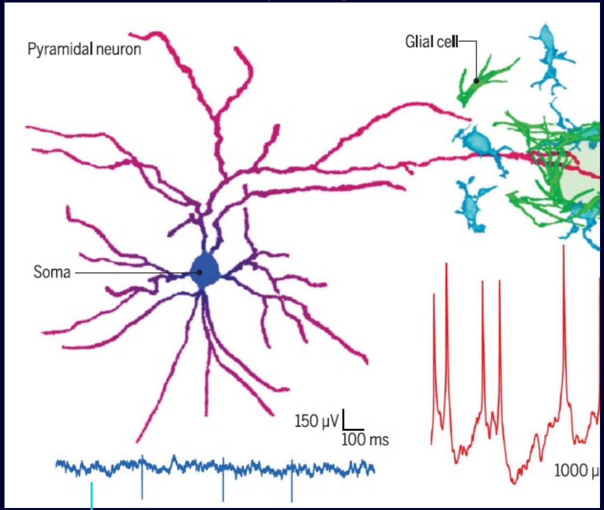
- Intrinsically 3 dimensional
- Irregular Geometry
- **Plastic**: Both "hardware" and "software"
- **Assembly**: Bottoms-up
- **Number of switching elements**: > ~80 Billion neurons or 400 Trillion synapses

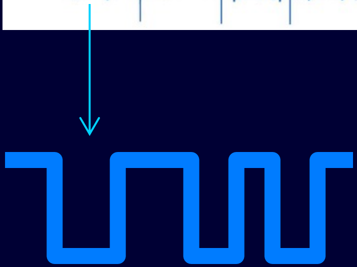
Circuits are efficiently embedded, in a higher dimensional topological dimension (4.54 vs 3.81) (Bassett, 2010)

Single Synapse Processing:
Where a ”bit” is more than a bit

Brain and Computing Element:
Information Processing

J. J. Moore et al. (2017)

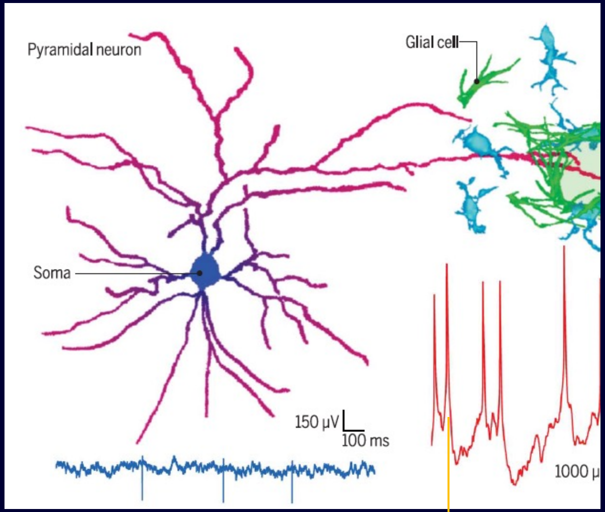




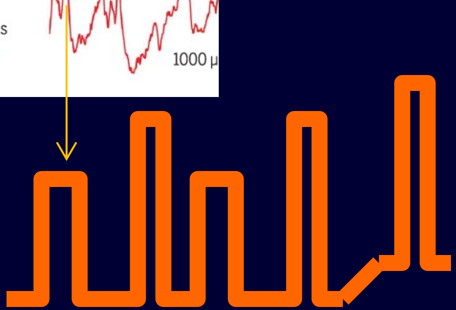
- Large sub-threshold voltage fluctuations

Brain and Computing Element:
Information Processing

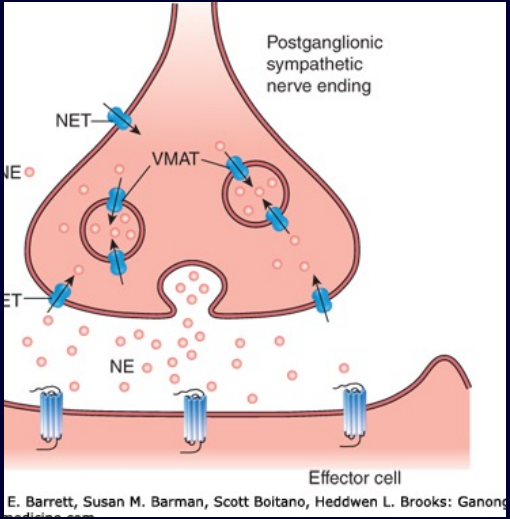
J. J. Moore et al. (2017)



- Large sub-threshold voltage fluctuations
- In dendrites, indicate a hybrid analog-digital code



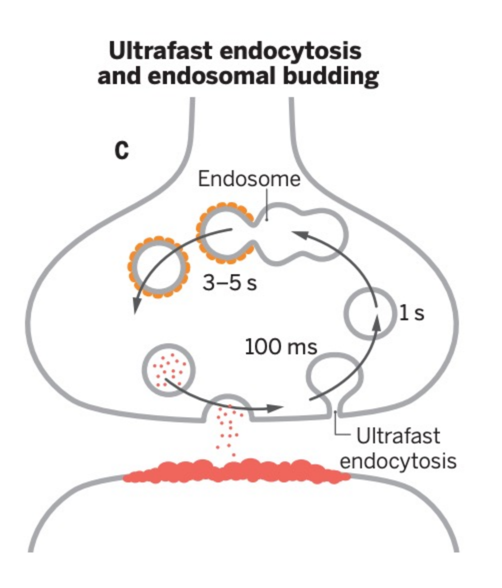
Brain and Computing Element:
Information Processing



Ganong's Rev. of Medical Physiology, 25e

- Large sub-threshold voltage fluctuations
- In dendrites, indicate a hybrid analog-digital code in the dendrite
- Multi-state Processing
  - ~90 genes for neuro modulators
    - Number of neuromodulations are higher
  - Chemical diffusional transport

Brain and Computing Element:
Information Processing



Watanabe,
2015

- Large sub-threshold voltage fluctuations
- In dendrites, indicate a hybrid analog-digital code in the dendrite
- Multi-state Processing
  - ~90 genes for neuro modulators
  - Chemical diffusional transport
- Recycling molecules

Single Synapse Processing: *Quantifying Energy*

Energy of a synapse (1)

Biological Entity	Gross Power (W)	Net Power, assuming 70% utilitarian (W)	0.5 millisecond	Frequency of State Switching (Hz)	Energy/Switching (Joules/switching)	Energy/Switching (eV/switching)	Number of Transistors or Switches	Energy/State Switching/Neuron (Joules/switching)
Human Brain (Synpases)	20	14	6.00E-04	1.67E+03	8.40E-03	5.25E+16	8.00E+14	1.05E-17

- Synapse Switching is using 8.75-10.5 atto joules (*top-down*)

Energy of a synapse (2)

- Synapse Switching is using ~0.77 atto joules (*bottom-up*)

Weight of the brain (gram)	1400
Synpases/gm	7.14E+10
Molecules of glucose metabolized/synapse/sec	8.84E+02
Molecules of glucose metabolized/synapse/millisec	8.84E-01
ATP produced by glycolysis oxidation/synapse/millisec	28
Total ATP/synapse/millisec	29.8
Synaptic transmission from presynaptic action potential arrival to postsynaptic evoked current 0.6 ms	0.6
Total ATP/synapse (ATP)	17.88
Total J/synapse (Joules/synapse)	7.72E-19
Ratio of Synapse to Thermodynamic Limit	96.25

Quantum Information Processing

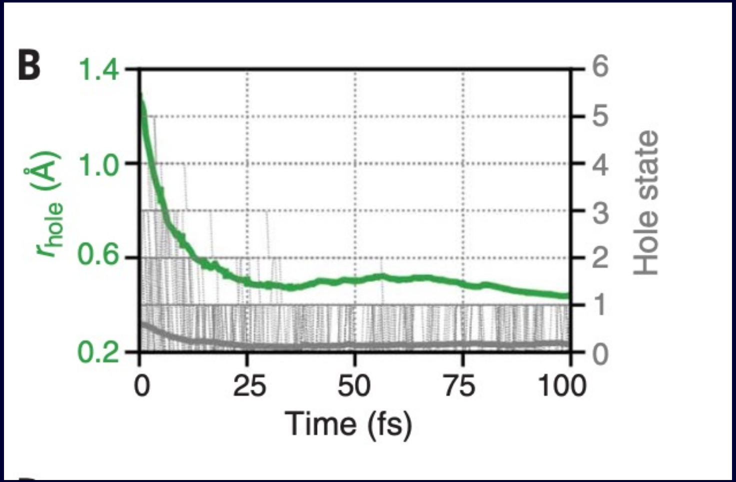
Simulating Chemistry on a Classical Digital Computer

Energy Estimate for a Chemical Reaction

$$H_2O^+ + H_2O \rightarrow OH + H_3O^+$$

Radiolysis of Water

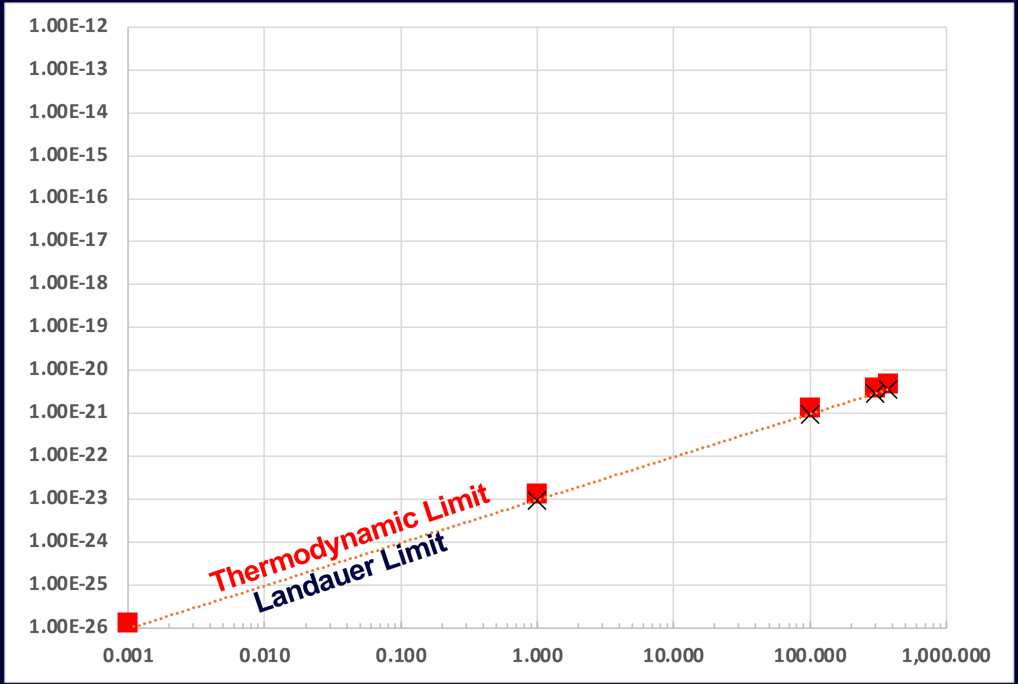
Loh et al, 2020



- Fastest chemical reaction (experimental):
  - 46 ± 10 fs, tentatively assigned to the decay of the H2O+ radical cation via proton transfer
- Energy for Proton Transfer 1.33×10^{-20} Joules

Energy Estimates

Energy in *Joules*



Temperature in *Kelvin*

- Limits of system in equilibrium with surroundings

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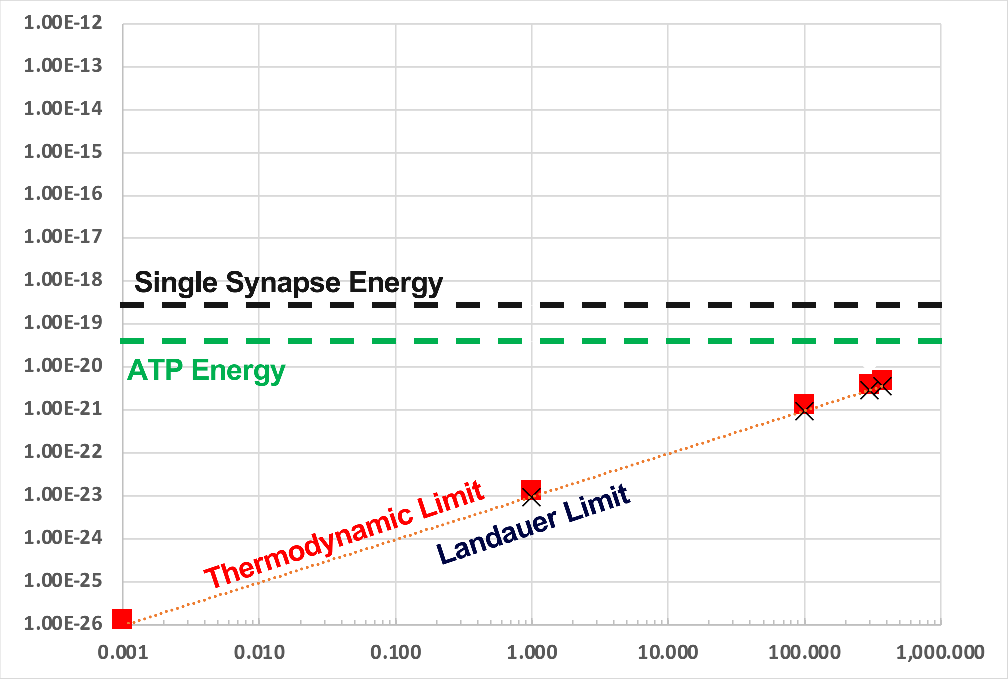
Energy Estimates



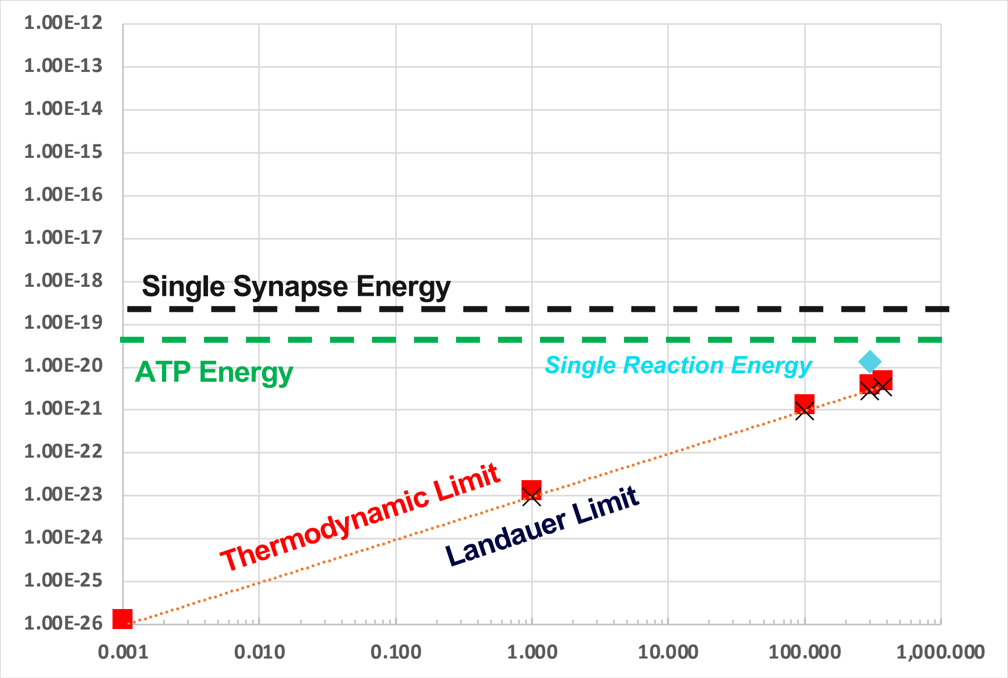
Energy in *Joules*

Temperature in *Kelvin*

- Biological energy in living systems (complex and thermodynamic non-equilibrium)

Energy Estimates

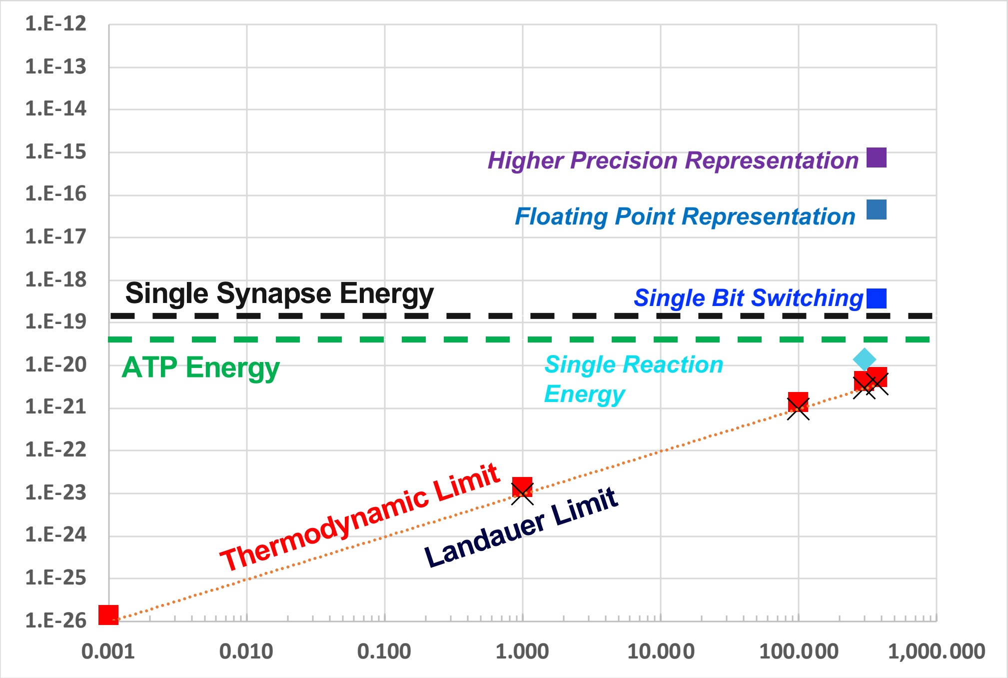
Energy in *Joules*



Temperature in *Kelvin*

- Energy at the quantum level for the fastest measured reaction

Energy Estimates

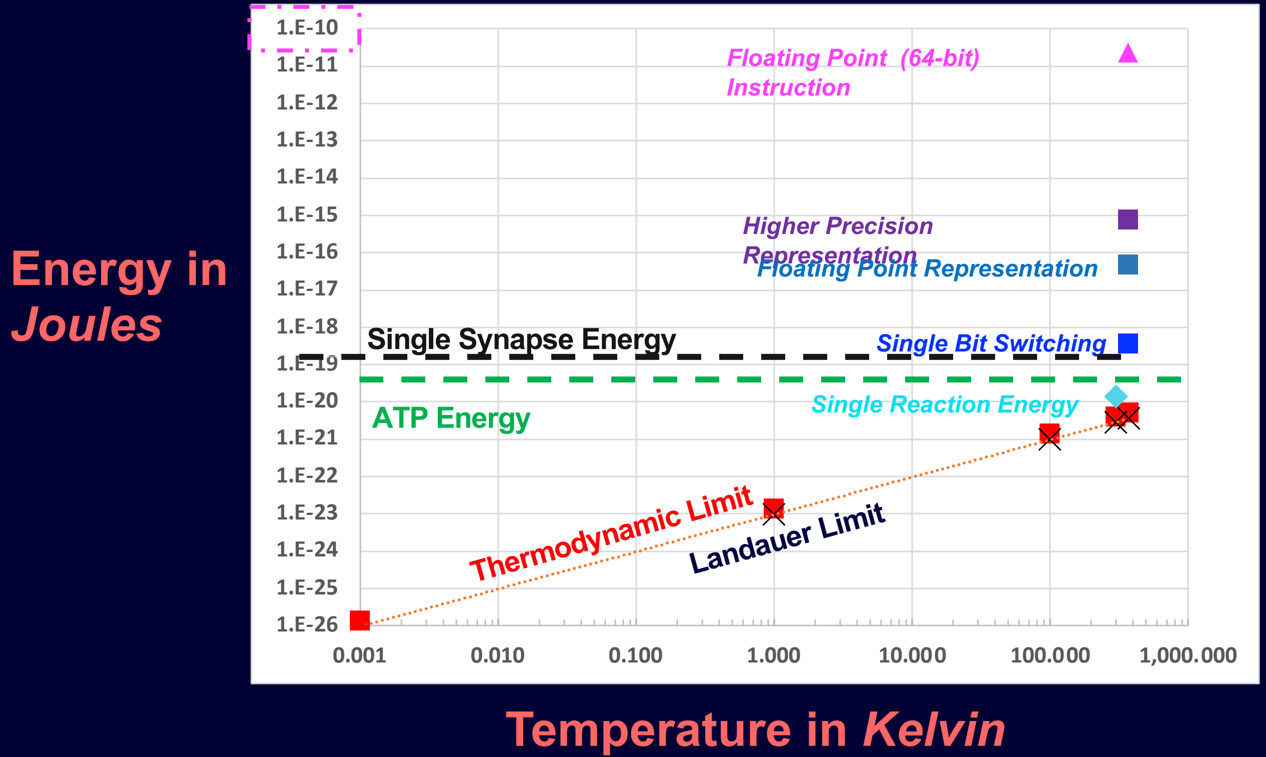


Energy in *Joules*

Temperature in *Kelvin*

- Increasing energy as information processing is reaching into digital domain

Energy Estimates

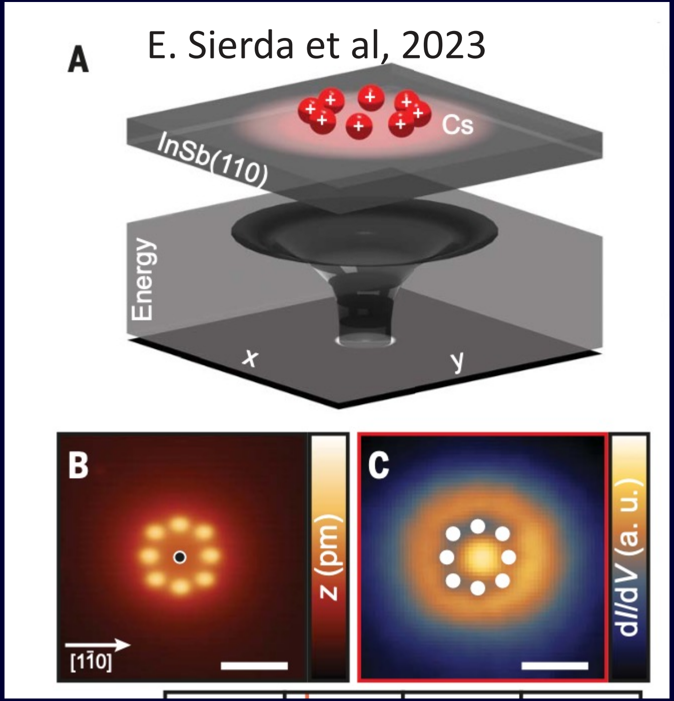


- Increasing energy as information processing is reaching into digital domain at instructional level

Quantum Information Processing

Quantum Chemistry Emulation
on a Quantum Computer

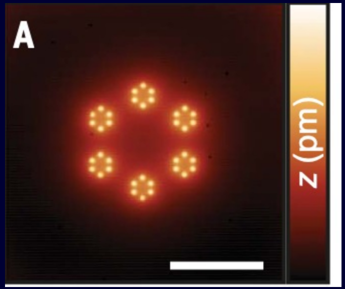
Quantum Chemistry: *Setup*



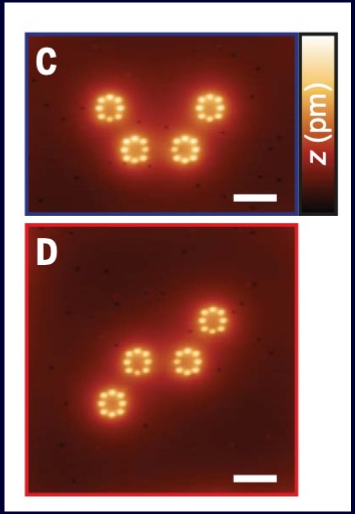
- An artificial atom from Cs atoms on InSb(110) and bonding/antibonding orbitals of coupled artificial atoms
- 42 layers of InSb and Clusters of Cs Atoms
- Clusters of Cesium Atoms put together to mimic synthetic atoms and molecules
- Constant Current Scanning Tunneling Microscopy
    - 200 mV and 20 pA

Quantum Chemistry: *Setup*

E. Sierda et al, 2023



- **Benzene:** Six Cesium Atoms-cluster per benzene CH molecule leading to total 36 Cesium atoms



- **Butadiene:** Eight Cesium Atoms-cluster per C-H molecule leading to total 32 Cesium atoms

Quantum Chemistry: *Emulation*

- System variables
  - 93.5 nm^2 X 27.2 nm
  - 100 electrons per InSb atom
  - ~9400 Atoms

Potental for Stabilizing STM Tip (V)	2.00E-01
Current (Amp)	2.00E-11
Max Time (Second)	100
Min Time (Second)	8.30E-03
Max Energy (Joules)	**4.00E-10**
Minimum Energy (Joules)	**3.32E-14**

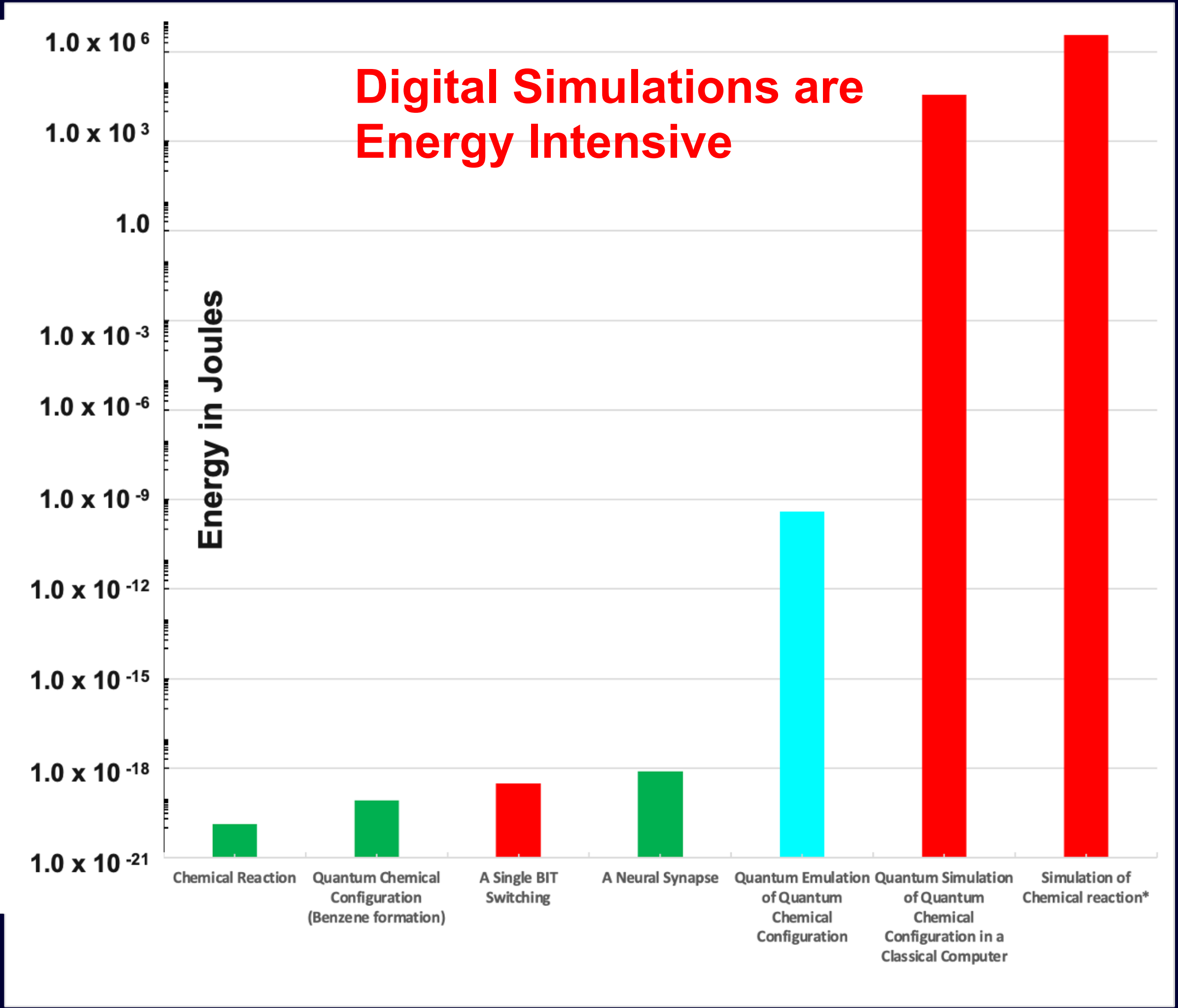
- Energy to emulate Benzene and Butadiene varies from 3.3×10^{-14} to 4×10^{-10} Joules

Quantum Chemistry: *Simulation*

- Energy to simulate Benzene and Butadiene ~3.7 x 10^4 to Joules

Ack: C. Musgrave, W.A. Goddard@Caltech

	Time to Compute (Seconds)	Power (Watts)	Energy (Joules)
Benzene	294	125	3.68E+04
Butadiene	295	125	3.69E+04



Digital Simulations are
Energy Intensive
Energy in Joules
1.0 x 10 6
1.0 x 10 3
1.0
1.0 x 10 -3
1.0 x 10 -6
1.0 x 10 -9
1.0 x 10 -12
1.0 x 10 -15
1.0 x 10 -18
1.0 x 10 -21
Chemical Reaction
Quantum Chemical Configuration (Benzene formation)
A Single BIT Switching
A Neural Synapse
Quantum Emulation of Quantum Chemical Configuration
Quantum Simulation of Quantum Chemical Configuration in a Classical Computer
Simulation of Chemical reaction*

Summary

- Translation from Bit to Instruction to Simulation leads to energy efficiency loss
  - BIT Utilization gives a clue
  - Intrinsic thermodynamics associated with energy transduction in computing
- Chemical Reactions and Biological Entities are energy efficient
  - BIT is more than a bit
- Quantum Emulation of a quantum system is less energy intensive than Digital Simulation of the same system
- Ongoing
  - Part 2: Developing methodology for quantifying complexity in different computing systems
  - Energy Estimates for different Neural Networks & Neuromorphic Architectures

Acknowledgements and References

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- R. Zare (Stanford), C. Musgrave Jr., W. Goddard (Caltech)
- A. Reuther (MIT-LL)

Papers in Progress

1. Shankar, S. 2021 "*Lessons from Nature for Computing: Looking beyond Moore's Law with Special Purpose Computing and Co-design*", 2021 IEEE High Performance Extreme Computing Conference (HPEC) (pp. 1-8).
2. Shankar, S, Reuther, A, 2022, "*Trends in Energy Estimates for Computing in AI/Machine Learning Accelerators, Supercomputers, and Compute-Intensive Applications*", 2022 IEEE High Performance Extreme Computing Conference (HPEC)
3. Shankar, S., *Energy Estimates Across Layers of Computing: From Devices to Large-Scale Applications in AI/Machine Learning in Natural Language Processing, Scientific Computing, and Crypto coin Mining* (in preparation)
4. *A Logical Framework for Information Processing* (in preparation)
5. *Energy-based Scaling for Computing* (in preparation)