Thermodynamics of Computation
@System Level

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Virtual Immersion Architectures
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• C.P Snow on the 4 Laws of Thermodynamics
  – Zeroth: "You must play the game."
  – First: "You can't win."
  – Second: "You can't break even."
  – Third: "You can't quit the game."

• 0-2 laws are relevant to computing
• 3rd could be replaced “4th” => Moore’s law of scaling
Outline

• Intent
  – A Generic Abstraction of Computing Systems for Energy-Entropy Trade-offs Analysis
• Materials
• Energy/Power minimization
• Many new directions to leverage scaling
• Architecture, software, and thermodynamics
An Informal Survey

• Where will the device design growth be in ten years?
  – Multicore 12%
  – Programmable 14%
  – Wireless 16%
  – Low-Power 26%
  – IP 9%
  – New Technology 23

From Chip Design.com
Changing Paradigm

Materials

- Modern CMOS scaling is as much about material innovation as dimensional scaling
- Material Combinations enable engineering new properties
  - Nano-materials by Design
Changing Paradigm
Architecture and State Variable

Conventional Scaled CMOS

Multicore
Von Neumann
Reconfigurable
Morphic

Analog

Digital

ARCHITECTURE

Data Representation

Patterns
Qubit

SETs
Spintronics
Quantum

Material

Carbon
Complex metal oxides

Silicon
Macro molecules
Nanostructured mat'l's

Molecular state
Spin orientation

State Variable

Electric charge
Polarization
Phase state

Strongly correlated electron state

New Information Process Technologies

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System Reliability Perspectives

• Current approach: System reliability through device reliability
  – All N devices in the logic system operate correctly $E_b \uparrow$

• Requiring all ideal devices may not end with ‘ideal’ system
  – Locally optimized components may not result in globally optimized system
  – Global system optimization: $E_b \downarrow$ ??
Thermodynamics and a ~century

- Sir Arthur Stanley Eddington, Cambridge (1915), If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

- Prof. Seth Lloyd, MIT (2004): Nothing in life is certain except death, taxes and the second law of thermodynamics. All three are processes in which useful or accessible forms of some quantity, such as energy or money, are transformed into useless, inaccessible forms of the same quantity. That is not to say that these three processes don't have fringe benefits: taxes pay for roads and schools; the second law of thermodynamics drives cars, computers and metabolism; and death, at the very least, opens up tenured faculty positions.
Thermodynamics of Computation @System Level

- Thermodynamics is the study of energy transformation properties common to all systems.
- Goal is to use thermodynamics, which incorporates relations between system’s components and determines the most energy efficient systems.
Typical Thermodynamic System

The discipline of Thermodynamics appeared in response to the practical need to increase the **EFFICIENCY** of heat engines.

The fundamental limits – Carnot’s formula


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Synergetic Use of Several Languages

- **Physics/Mechanics**
  - State variable (SV)
  - Dynamical evolution of SV

- **Physics of Computing:**
  - Charge, spin etc. state

- **Thermodynamics**
  - Macroscopic observable (MO)
    - $P, V, U, N_1...N_n$

- **Thermodynamics of Computing**
  - Need to define MO
Thermodynamics of Computing
Macroscopic observables

- Thermodynamics
  - \( U \) – internal energy
  - \( W \) – output work
  - \( A \) – free energy
  - \( V \) – volume

  \( N_1 \ldots N_n \), number of type \( i \) particles

- Thermodynamics of Computing
  - Energy of internal energy source
  - Output information
  - Binary throughput
  - Volume

  - e.g. the number of different functional primitives, e.g.
  - OR the number of different elemental tiles
Thermodynamically Efficient Architecture

- An energy efficiency or first law efficiency will determine the most efficient process based on losing as little energy as possible relative to energy inputs. What we (trying to) do today

‘available energy’ – Gibbs (1878),

- An exergy efficiency or second-law efficiency will determine the most efficient process based on losing and destroying as little available work as possible from a given energy inputs.

Potential for future nano-architectures design?
Thermodynamics of Computing

\[ dU = \delta Q - \delta W \]

Internal energy

Heat

Available work

Free energy (Isothermal)

\[ dA = dU - TdS \]

Available work

Useful work done by the system is Exergy

USEFUL W

work done on the system

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Binary Switch - Basics

Key Characteristics:
1. Confinement (Energy)
2. Barrier (Energy)
3. Information carrier (Charge)

Geometrical Parameters:
1. Confinement Width (W) & Length (L)
2. Barrier Length (a)
3. Information carrier (Charge)

System Parameters:
1. Barrier Energy (E_b)
2. Temperature (T)
3. Charge (e)
Next Steps

- Geometrical Representation of the system
- Map the representation to thermodynamics
- Include heterogeneous micro-systems
- Include realistic heat terms (dissipation)
- Estimate available energy
Mitochondria changes in human muscle after prolonged exercise, endurance training and selenium supplementation (1995)

……..The number of mitochondria per area (QA) and the relative surface occupied by the total mitochondria profile area (AA) were estimated. The mean area per mitochondrion (~) was obtained by the quotient AA/QA. The effects of the isolated or combined independent variables T, E and Sel were analysed by nonparametric tests. Training induced significant increases in both QA (30%, P < 0.001) and AA (52%, P<0.001)……..

Albert G. Crenshaw I, Jan Frid~n 1, z, Lars-Eric Thornell 1, and Alan R. Hargens 3

Biopsies from the medial gastrocnemius muscle of three experienced endurance runners who had completed an ultramarathon run (160 km) the previous day were assessed for their oxidative characteristics………..An abundance of subsarcolemmal mitochondria located close to the capillaries, efficient capillary proliferation between fibres where sharing can occur and greater relative distribution and size of type I fibres are, collectively, efficient characteristics of extreme endurance training.
Energy Efficient System - Example

• Fundamental premise
  – Electromagnetic energy delivered; Heat energy removed; all within same micro domain

• Micro-power sources demonstrated
  – Cymbet Corp demonstrated rechargeable batteries (12 μ-amp hour at 3.8 V)
  – Lal (Cornell) demonstrated radio isotopes (6mW/cc)

• Array of power sources integrated
  – Local Power delivery
Nano-architectures: Diversity-on-Chip

Hetero-integration

Diverse devices on a chip

Logic
Memory
Energy source
Sensors

Exergy Optimization

Functional Diversification
Summary

• Materials are an integral part of the new devices moving forward
• Energy/Power minimization is a universal macro-constraint for on-chip architectures
  – Performance should not (& does not have to) be sacrificed
• Many new directions to leverage scaling
  – New materials, devices, topologies
  – Functional diversification
    • Power sources, capacitors
    • Application-specific processors
• Architecture and software need consideration to enable scaling => Thermodynamics of Computation at System Level is a more systematic way to leverage scaling