Thermodynamics of Computation
@System Level

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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

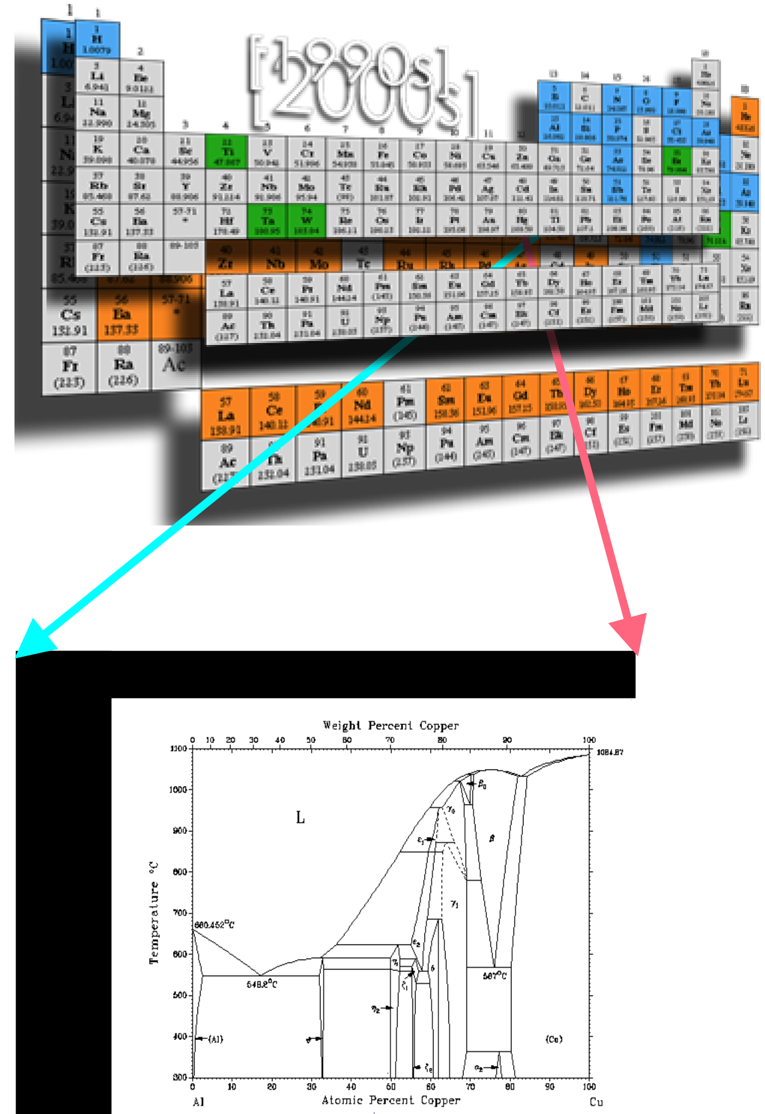
An Informal Survey

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

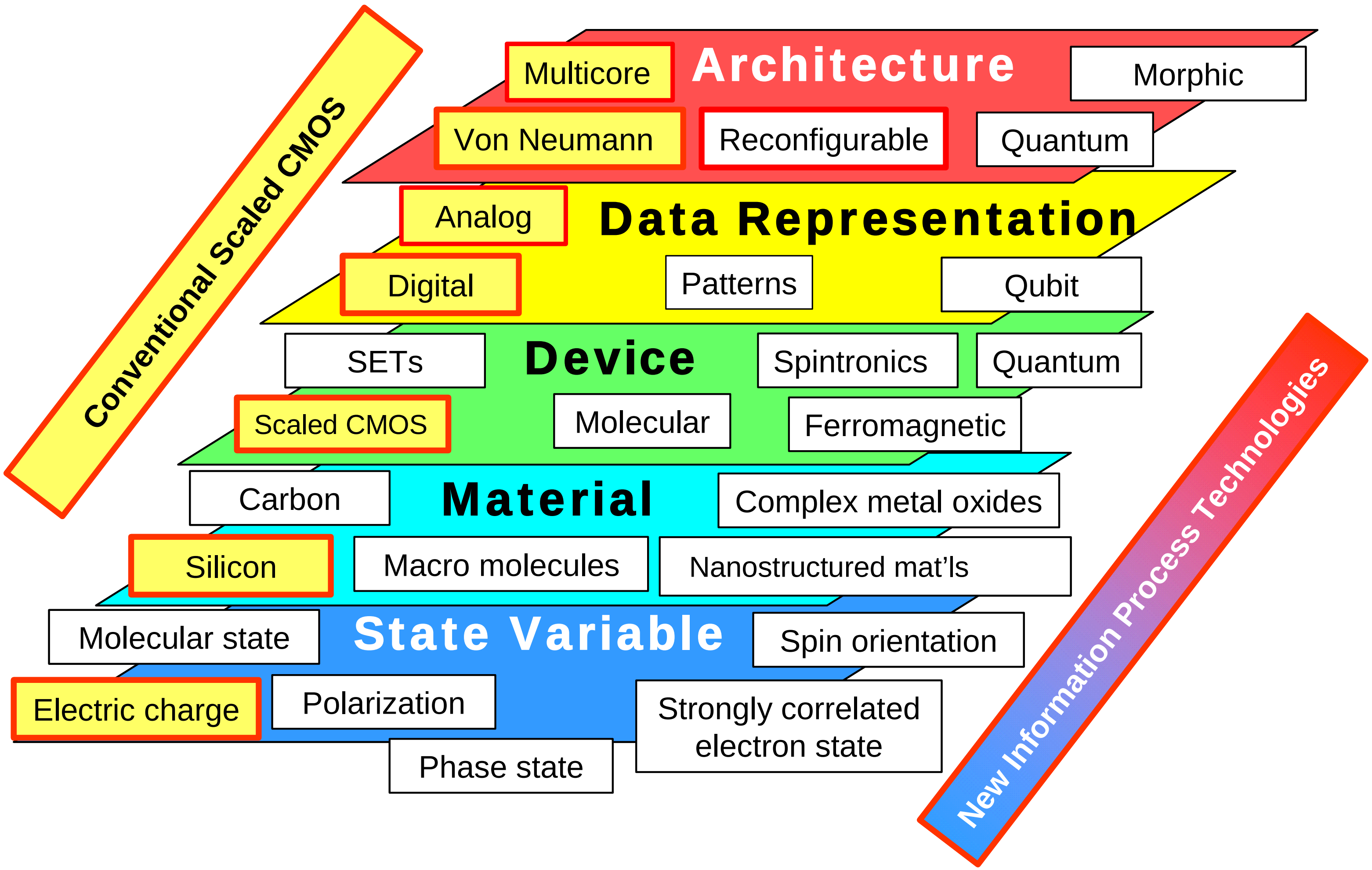
From Chip Design.com

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



System Reliability Perspectives

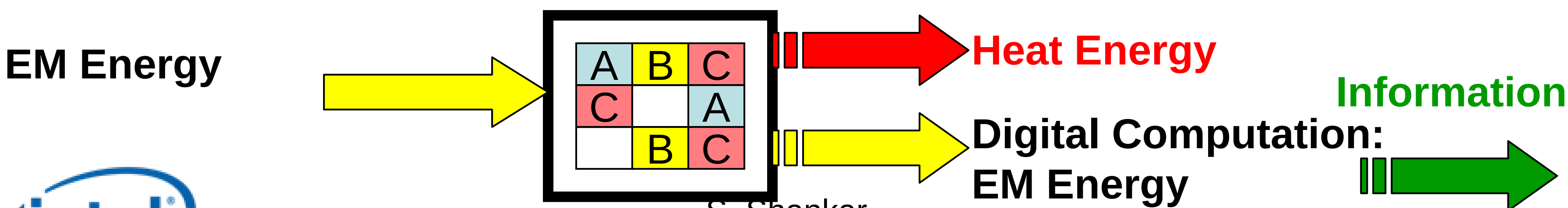
- Current approach: System reliability through device reliability
  - All N devices in the logic system operate correctly $E_b \uparrow$
- Requiring all ideal devices may not end with 'ideal' system
  - Locally optimized components may not result in globally optimized system
  - **Global system optimization**: $E_b \downarrow$??

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

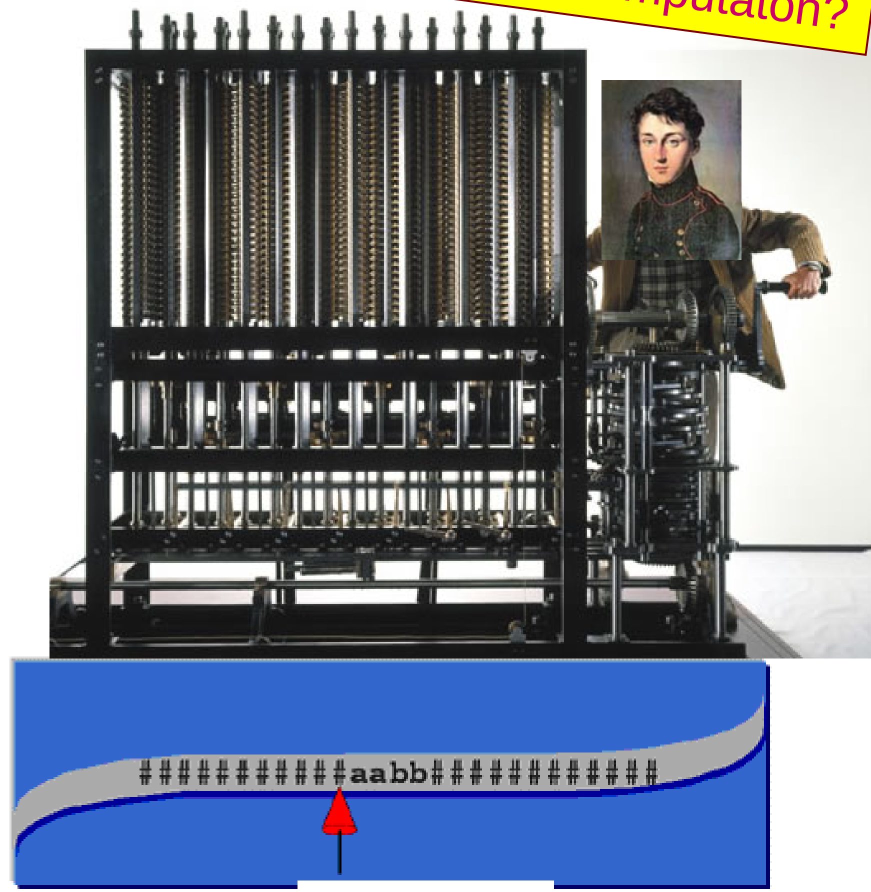


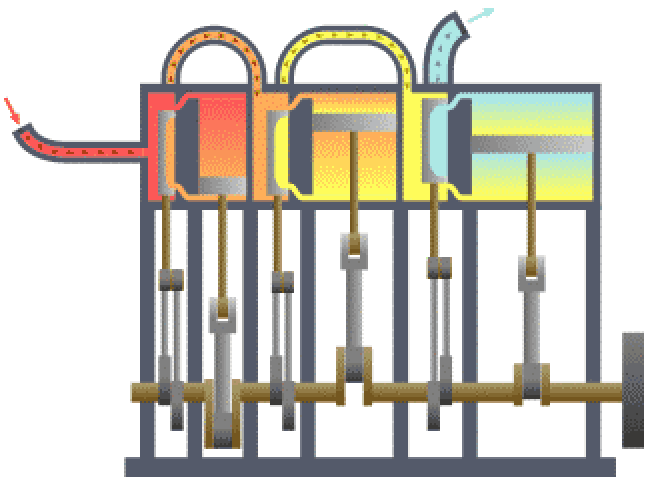
Typical Thermodynamic System

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

The fundamental limits – Carnot's formula

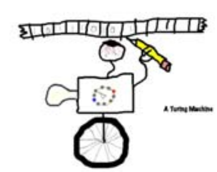
Efficiency of computaton?





Source: Wikipedia

Ack: V.Zhirnov



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)
    - $P, V, U, N_1 \ldots N_n$
- 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 functuional 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

Internal energy

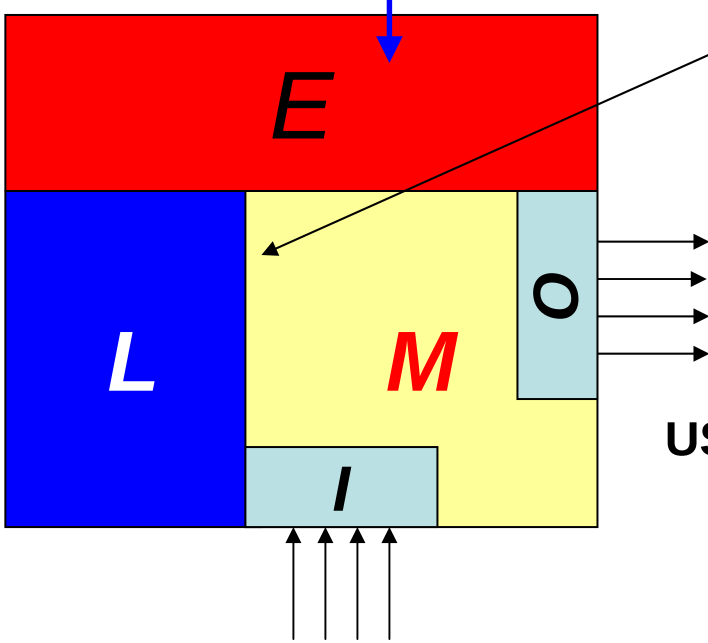
$$dU = \delta Q - \delta W$$

Available work

Heat

Free energy (Isothermal)

$$dA = dU - TdS$$

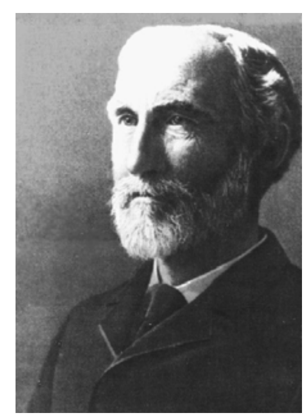


$$W \leq \Delta A$$

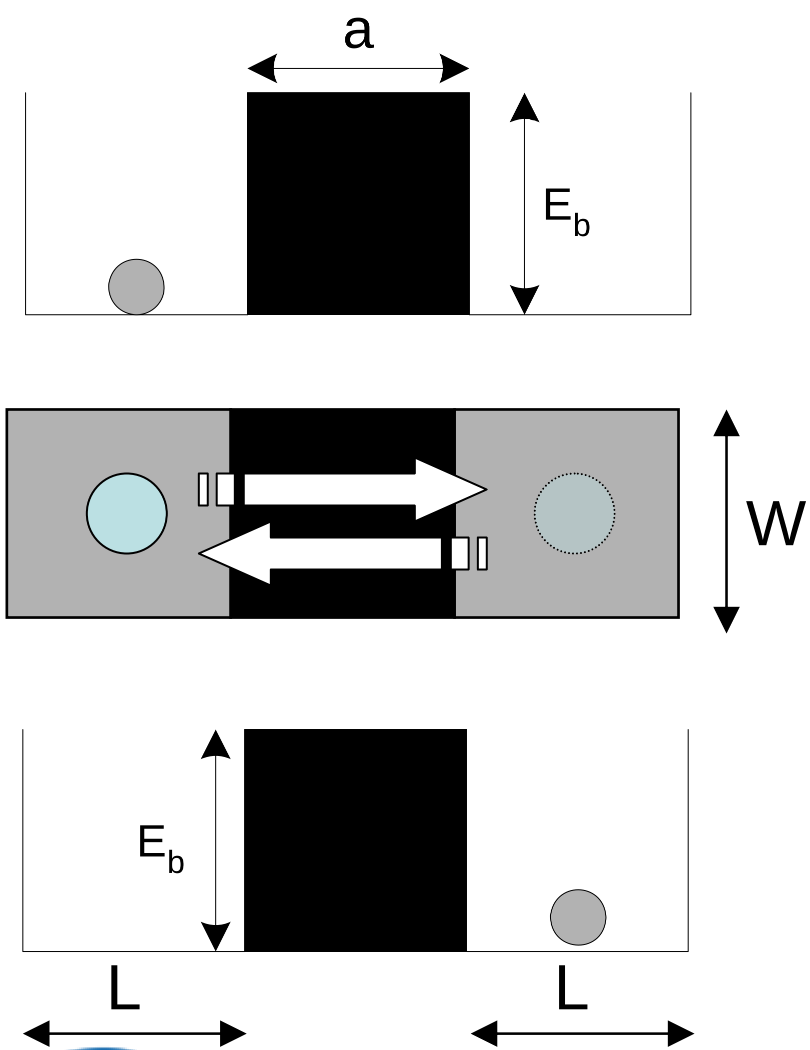
Useful work done **by the system is**
Exergy

USEFUL W

work done <u>on</u> the system



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 (Eb)***
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

Energy Efficient System - Nature

Mitochondria changes in human muscle after prolonged exercise, endurance training and selenium supplementation (1995)

A. J. Zamora • F. Tessier • P. Marconnet I. Margaritis • J.-F. Marini, Eur J Appl Physiol (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)……..

Extreme endurance training: evidence of capillary and mitochondria compartmentalization in human skeletal muscle (1991)

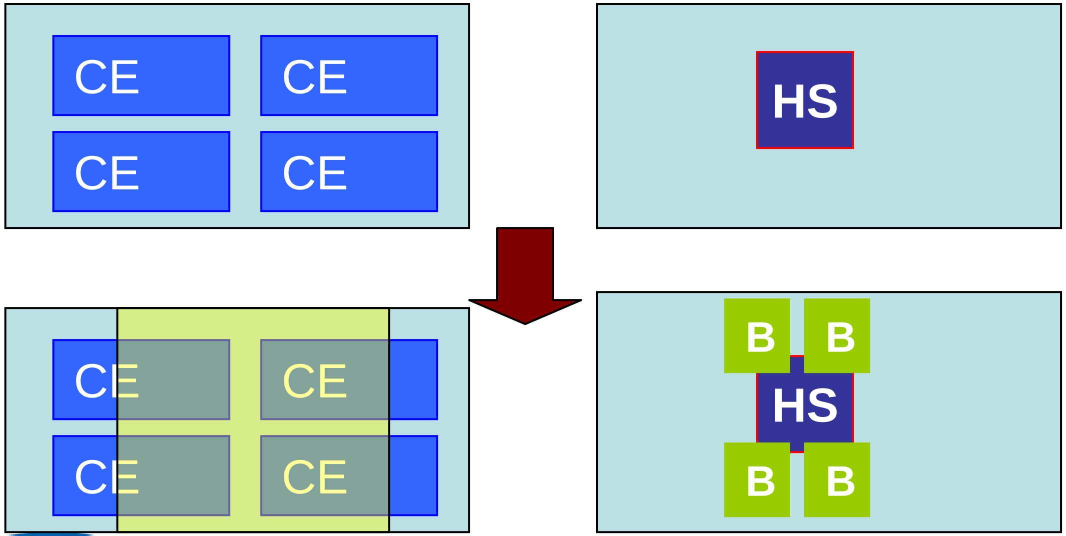
Albert G. Crenshaw I , Jan Frid~n 1, z, Lars-Eric Thornell 1, and Alan R. Hargens 3

Departments of 1 Anatomy and 2 Hand Surgery, University of Ume&, S-90187 Ume&, Sweden 3 Division of Orthopaedics and Rehabilitation (V-151), Veterans Administration Medical Center and University of California, San Diego, California 92161, NASA-Ames Research Center, Moffett Field, California 94035, USA

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.

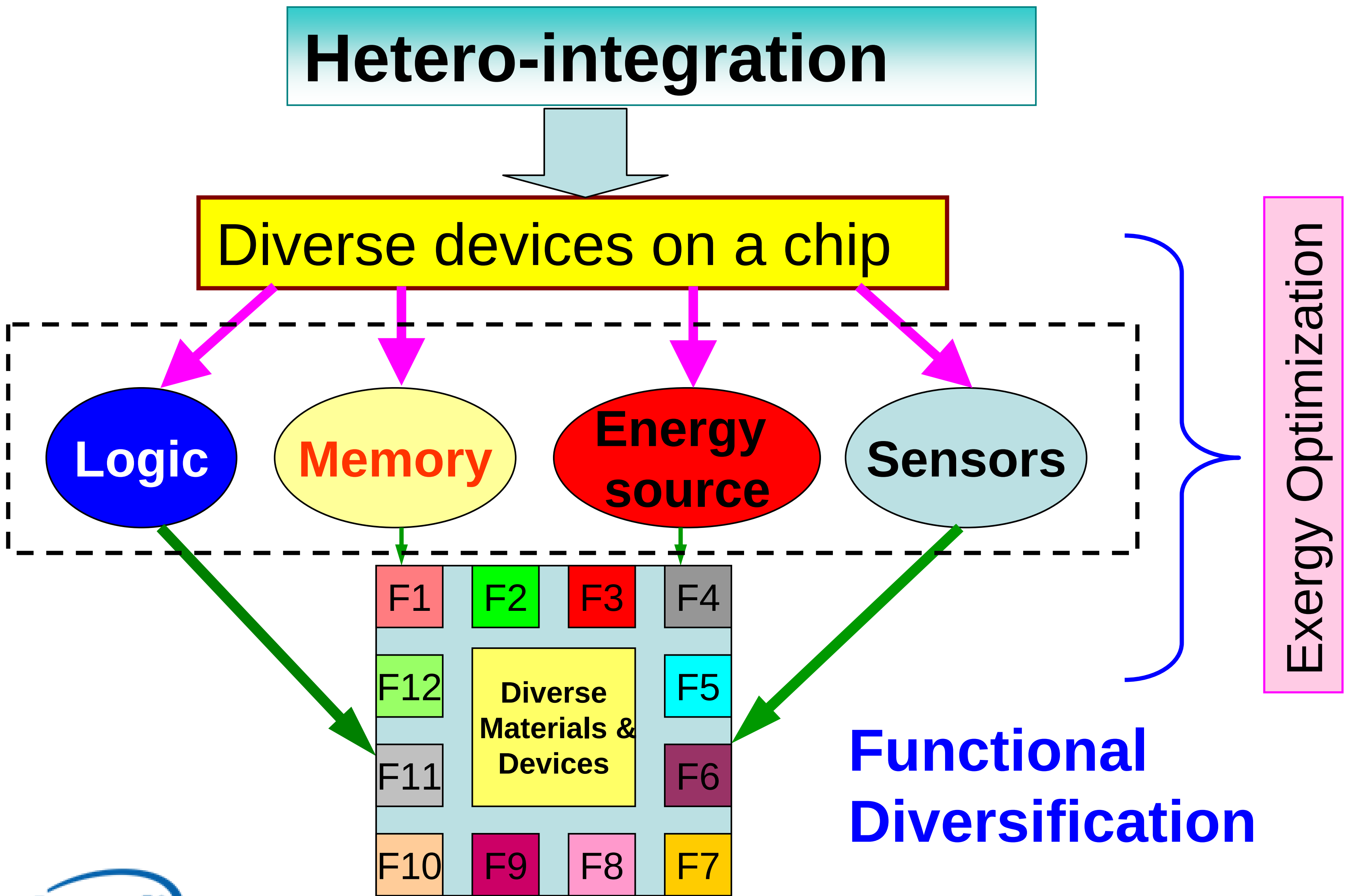
Energy Efficient System - Example

- Fundamental premise
  - Electromagnetic energy delivered; Heat energy removed; all within same micro domain
- Micro-power sources demonstrated
  - Cymbet Corp demonstrated rechargeble 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



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*