REVIEWING THE RELATIONSHIP BETWEEN INFORMATION AND ENERGY, AND THE PHYSICAL LIMITS OF COMPUTATION

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RISE ICE

- Luleå

- 15 projects, from the ground to the cloud
- 20 employees
- 3 MEUR turnover
- Established 2016
RISE ICE facilities
Open source monitoring system
Multiples studies on consumption


What is information? A quick look back at Shannon

Machine 1 produces random information
\[ P(A) = P(B) = P(C) = P(D) = 0.250 \]

Machine 2 produces information according
\[ P(A) = 0.500 \]
\[ P(B) = 0.125 \]
\[ P(C) = 0.125 \]
\[ P(D) = 0.250 \]
Shannon asked how to predict the next symbol

- **Machine 1.** Ask binary questions. Is it (A or B) or (C or D)? If A or B is YES. Then ask a second binary question. Is it A or B? If B is YES, then the uncertainty of Machine 1 is 2 questions per symbol.

- **Machine 2.** Ask binary questions. Is it A? If YES then only 1 question. If NO then ask question: Is it D? If YES then we asked 2 questions. If NO then ask question: Is it B or C?
How many questions on average?

- Machine 2: Ask 1 question 50% of the time to guess A, 2 questions 25% of the time to guess D, 3 questions 25% of the time to guess B or C. So the average number of questions to ask is:

  \[
  \#\text{questions} = 1 \times P(A) + 2 \times P(D) + 3 \times P(B) + 3 \times P(C),
  \]
  which is 1.75 questions per symbol on average.
  
- So if we need to guess 100 symbols from both machines we would need to ask 200 questions for Machine 1, but 175 questions for Machine 2. Machine 2 is producing less information! Less uncertainty or surprise in its output.
Shannon’s information entropy

- Claude Shannon called this measure of uncertainty, information entropy, using the symbol H.
- The units of H are based on the uncertainty of a fair coin flip. Shannon used “bit” based on a fair coin flip.
- \( H(p_1, p_2 \ldots p_n) = \sum_i p_i \times \#\text{questions}_i \)
- \( \#\text{questions}_i = \log_2(\#\text{outcomes}) = \log_2\left(\frac{1}{p_i}\right) \)
- \( H(p_1, p_2 \ldots p_n) = -\sum_i p_i \log_2(p_i) \)
Boltzmann (thermodynamic) Entropy

- In terms of a dilute gas the “thermodynamic” entropy, $S$, is written as
  \[ S = k_B \ln W \]
  where $W$ is the number of real microstates of the gas

- In statistical mechanics, a microstate is a specific microscopic configuration of a thermodynamic system that the system may occupy with a certain probability in the course of its thermal fluctuations.
Boltzmann’s constant

- A universal constant that relates a gas molecules kinetic energy to its temperature, so it is measure in J/K – Joules per Kelvin
- The value is $1.380649 \times 10^{-23}$ J/K and is equal to the Universal Gas Constant, $R$, divided by Avogadro’s constant, $N_A$. $R$ is the energy required to raise 1 mole of a substance by 1 Kelvin and $N_A$ is the number of molecules in 1 mole of a substance.
- Energy required to raise 1 molecule by 1 Kelvin.
- So $S = -k_B \sum_i p_i ln(p_i)$ which reduces to $S = k_B lnW$ if all probabilities, $p_i$, are equal.
Maxwell’s Demon

- Thought experiment proposed by James Clerk Maxwell in 1867.
- The Demon sorts hot and cold (respectively fast and slow moving) particles
- End up with oven (A) and fridge (B) and no energy **consumed**!
- Contradicts second law of thermodynamics (creating order from disorder – reducing Entropy).
- Does it imply a relationship between **information** and **energy**?
Szilard’s answer

- An attempt to explain the paradox of Maxwell’s demon was put forward by Szilard in 1929.
- Szilard argued that there must be an entropic cost associated with the Demon’s acquisition of information.
- Boltzmann’s statistical mechanics definition of entropy involves probability of microstates.
- Therefore an increase in information corresponds to a decrease in entropy. (Brillouin later used negentropy)
- There is still much debate, see the 2015 article – “A few exciting words”: Information and Entropy revisited.


Information is a physical entity

- Information is physical: writing on stone, printing text in a book – difficult to reverse so thermodynamic entropy always increases.

- In 1961, Rolf Landauer, while working at IBM proposed that the acquisition of one bit of information through erasure of 0 or 1 required dissipation of at least $k_B \sum_i p_i \ln(p_i) T$ J of energy at a temperature $T$ - probabilities of 0 or 1 are $p_1$ and $p_2$ and are equal at 0.5.

- In principle this assumed no thermodynamic objection to a logically reversible operation.

- In 2012 a team of French researchers published in Nature experimental verification to support the Landauer principle.


Antoine Bérut; Artak Arakelyan; Artyom Petrosyan; Sergio Ciliberto; Raoul Dillenschneider; Eric Lutz (8 March 2012), "Experimental verification of Landauer’s principle linking information and thermodynamics", *Nature* 483 (7388): 187–190
Information and Energy

- Of course, there are critics such as Norton who identifies thermal fluctuations as a missing component of Landauer’s argument.
- Rolf Landauer demonstrated that the minimum dissipation of energy in the erasure of 1 bit of information is $2.9zJ$ ($z = Zepto = 10^{-21}$) at 300K (27°C).
- Bennett’s digital tape machine as discussed in Feynman’s Lectures on Computation shows that at room temperature a tape carrying a full fuel load, $2.9zJ$ per bit, carries zero information.
- Could this value of $2.9zJ$ per bit be a physical limit of computation?


Data centre power consumption

Consider the contributing factors to Data Centre Power Consumption:

\[
\text{Power} = (N_{\text{compute}} \times \text{Power/compute}) \times \text{PUE}
\]

- **Competition between:**
  - Demand UP and
  - Consolidate DOWN

- Efficiency of ICT equipment is a function of Moore’s Law

- 10 years of PUE have helped to reduce overhead of a data centre end use energy consumption
### Power consumption of IT hardware

#### Power/compute

\[ \text{Power/compute} = N_{tr} \times \text{Freq} \times E_{tr} \times \text{CompUE} \]

| Number of transistors per datacom has increased for 50 years by Moore’s law and indicates performance. |
| Clock speeds have not really increased since 2005 as it has a significant effect, but is now variable. |
| Energy consumption per transistor is key to total power consumption. |
| Compute Usage Effectiveness Overhead from power supply, xDD, RAM, etc. |

*Note also that* \[ \text{Power/compute} = \alpha \times C \times V^2 \times \text{Freq} + \text{leakage} \]
Energy consumption of a transistor

\[ E_{tr} = E_{\text{FACTOR}} \times (k_B \times T) \]

Energy/Entropy Factor related to the approach of state changes in Field Effect Transistors (FETs): Depends on Voltage and materials.

Physical constant used in statistical mechanics, called the Boltzmann constant with a value of \( 1.38 \times 10^{-23} \text{ J/K} \)

Temperature at which the transistor is operating.
Summary of relationship of $E_{\text{FACTOR}}$ with Data Center Power

**Power** = \((N_{\text{compute}} \times \text{Power/compute}) \times \text{PUE}\)

**Power/compute** = \(N_{tr} \times \text{Freq} \times E_{tr} \times \text{CompUE}\)

\[ E_{tr} = E_{\text{FACTOR}} \times (k_B \times T) \]
Effect of multicore and scaling of gate lengths

Figure 4: Amdahl’s law projections for the dynamic topology. Upperbound of all four topologies (x-axis: technology node).

# Switching Energy up to today.

<table>
<thead>
<tr>
<th>Processor Architecture</th>
<th>Year</th>
<th>Feature Size</th>
<th>Switching Energy (zJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentium 486</td>
<td>1989</td>
<td>600nm</td>
<td>41137803</td>
</tr>
<tr>
<td>Pentium M</td>
<td>2003</td>
<td>130nm</td>
<td>325143</td>
</tr>
<tr>
<td>Core</td>
<td>2006</td>
<td>65nm</td>
<td>560819</td>
</tr>
<tr>
<td>Nehalem</td>
<td>2008</td>
<td>45nm</td>
<td>156566</td>
</tr>
<tr>
<td>Sandy Bridge</td>
<td>2012</td>
<td>32nm</td>
<td>74555</td>
</tr>
<tr>
<td>Ivy Bridge</td>
<td>2014</td>
<td>22nm</td>
<td>28994</td>
</tr>
<tr>
<td>Broadwell</td>
<td>2015</td>
<td>14nm</td>
<td>24852</td>
</tr>
<tr>
<td>Intel Xeon Plat 8180</td>
<td>2017</td>
<td>14nm</td>
<td>18743</td>
</tr>
<tr>
<td>AMD Epyc</td>
<td>2017</td>
<td>14nm</td>
<td>13856</td>
</tr>
<tr>
<td>Qualcomm Centriq 2400</td>
<td>2018</td>
<td>10nm</td>
<td>10256</td>
</tr>
</tbody>
</table>

New TriGate FinFETs ~ 3D!

Not all transistors are operational.
**E$_{\text{FACTOR}}$** is linked to Moore’s Law

Moore’s Law: Self-fulfilling prophecy to provide double the number of transistors in the same area every two years.

Cost of transistors is going up. Peaked at 20 million per $ in 2015

End of Dennard scaling.

Getting $E_{\text{FACTOR}}$ down.

- millivolt, transistor size and materials may reduce the $E_{\text{FACTOR}}$, or going 3D, like gate-all-around.

- Waldrop quotes “My bet is that we run out of money before we run out of physics” [Rock’s Law]

<table>
<thead>
<tr>
<th>2015</th>
<th>2017</th>
<th>2019</th>
<th>2021</th>
<th>2024</th>
</tr>
</thead>
<tbody>
<tr>
<td>P70M56</td>
<td>P48M36</td>
<td>P42M24</td>
<td>P32M20</td>
<td>P24M12G1</td>
</tr>
<tr>
<td>&quot;16/14&quot;</td>
<td>&quot;11/10&quot;</td>
<td>&quot;8/7&quot;</td>
<td>&quot;6/5&quot;</td>
<td>&quot;4/3&quot;</td>
</tr>
<tr>
<td>finFET</td>
<td>finFET</td>
<td>finFET</td>
<td>finFET</td>
<td>finFET</td>
</tr>
<tr>
<td>FDSOI</td>
<td>FDSOI</td>
<td>LGAA</td>
<td>LGAA</td>
<td>VGAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>VGAA, M3D</td>
</tr>
</tbody>
</table>


Getting $E_{\text{FACTOR}}$ down.

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Processing information costs energy.

1E-17 J is 10,000 zJ and the $E_{\text{FACTOR}}$ is 3,500 today.

By 2030 the curve shows 1,000 zJ with an $E_{\text{FACTOR}}$ of 350.

Landauer puts the physical limit of $E_{\text{FACTOR}}$ at 0.69.

The switching rate is also important

From Professor Douglas Paul at the University of Glasgow
http://userweb.eng.gla.ac.uk/douglas.paul/SiGe/limits.html

Power (W) = Switch Energy (J) x Switching Rate (s⁻¹)

213,000,000k_B T
213,000k_B T
213k_B T
What are the practical limits of $E_{\text{FACTOR}}$?

$$E_{\text{tr}} = E_{\text{FACTOR}} \times k_B \times T$$

- Frank argues that to measure a signal in the correct state with an error of $p_e (<10^{-40})$ requires the signal energy to be greater than $ln(1/p_e)k_BT$, that is around $100k_BT$.

- Bennet gave an interesting example of DNA polymerization that occurs in cell division to use $\sim 40k_BT$ of energy per step.

- If we cannot get $E_{\text{FACTOR}}$ down, then we reduce temperature, $T$!


Superconducting Computing!

- IBM ran a project from 1973-1983 on this – terminated due to the success of Si.

- At 4K and an $\text{E}_{\text{FACTOR}}$ of 1,500, a cryotron (Buck’s superconducting switch) would use 83 $\text{zJ}$ and switching frequency of less than 125 THz limited by Planck Constant.


So what about the cryogenics cost?

- A CPU with 5 billion cryotron gates and operating at 3GHz would consume 1.25W of power compared to 160W plus the cryogenics overhead (commercially available use 20kW).

- Candidate for 3D.

**BUT**

Computing is logically irreversible, it is not possible to travel backwards through the logic gates and get back to the initial state.

Bennett, Fredkin, Toffoli, Feynman, Frank and others preset theories behind reversible computing. It is a subject area in its own right.

Feynman talked about computing through reversible logic gates and then de-computing (i.e. reversing the computation), thus not having to dissipate heat on the basis that this would also be physically reversible.

Reversible logic

**Reversible computing**

- Snider and workers presented a paper in 2012, which demonstrated experimentally that there is no Landauer limit in computation – they observed a dissipation of $0.04kT < 0.69kT$. This was achieved using *adiabatically clocked reversible circuits*.

## Neuromorphic computing

<table>
<thead>
<tr>
<th>Platform:</th>
<th>Human brain</th>
<th>Neurogrid</th>
<th>BrainScaleS</th>
<th>TrueNorth</th>
<th>SpiNNaker</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology:</strong></td>
<td>Biology</td>
<td>Analogue, sub-threshold</td>
<td>Analogue, over-threshold</td>
<td>Digital, fixed</td>
<td>Digital, programmable</td>
</tr>
<tr>
<td>Microchip:</td>
<td>Neurocore</td>
<td>HiCANN</td>
<td></td>
<td></td>
<td>18 ARM cores</td>
</tr>
<tr>
<td>Feature size:</td>
<td>10 µm$^2$</td>
<td>180 nm</td>
<td>180 nm</td>
<td>28 nm</td>
<td>130 nm</td>
</tr>
<tr>
<td># transistors:</td>
<td>23 M</td>
<td>15 M</td>
<td>5.4 B</td>
<td>100 M</td>
<td></td>
</tr>
<tr>
<td>die size:</td>
<td>1.7 cm$^2$</td>
<td>0.5 cm$^2$</td>
<td>4.3 cm$^2$</td>
<td>1 cm$^2$</td>
<td></td>
</tr>
<tr>
<td># neurons:</td>
<td>65 k</td>
<td>512</td>
<td>1 M</td>
<td>16 k</td>
<td></td>
</tr>
<tr>
<td># synapses:</td>
<td>~100 M</td>
<td>100 k</td>
<td>256 M</td>
<td>16 M</td>
<td></td>
</tr>
<tr>
<td>power:</td>
<td>150 mW</td>
<td>1.3 W</td>
<td>72 mW</td>
<td>1 W</td>
<td></td>
</tr>
<tr>
<td>Board/unit:</td>
<td>PCB</td>
<td>20 cm wafer</td>
<td>PCB</td>
<td>PCB</td>
<td></td>
</tr>
<tr>
<td># chips:</td>
<td>16</td>
<td>352</td>
<td>16</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td># neurons:</td>
<td>1 M</td>
<td>200 k</td>
<td>16 M</td>
<td>768 k</td>
<td></td>
</tr>
<tr>
<td># synapses:</td>
<td>4 B</td>
<td>40 M</td>
<td>4B</td>
<td>768 M</td>
<td></td>
</tr>
<tr>
<td>power:</td>
<td>3 W</td>
<td>500 W</td>
<td>1 W</td>
<td>80 W</td>
<td></td>
</tr>
<tr>
<td>Reference system:</td>
<td>1.4 kg</td>
<td>20 wafers in 7 × 19” racks</td>
<td>600 PCBs in 6 × 19” racks</td>
<td></td>
<td></td>
</tr>
<tr>
<td># neurons:</td>
<td>100 B</td>
<td>4 M</td>
<td>460 M</td>
<td></td>
<td></td>
</tr>
<tr>
<td># synapses:</td>
<td>$10^{15}$</td>
<td>1 B</td>
<td>460 B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>power:</td>
<td>20 W</td>
<td>10 kW</td>
<td>50 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed versus biology:</td>
<td>1×</td>
<td>1×</td>
<td>10 000×</td>
<td>1×</td>
<td></td>
</tr>
</tbody>
</table>

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</tr>
<tr>
<td>Fingerprint</td>
<td>HiCANN</td>
<td>HiCANN</td>
</tr>
<tr>
<td># Fins</td>
<td>180 nm</td>
<td>15 M</td>
</tr>
<tr>
<td># Devices</td>
<td>512</td>
<td>0.5 cm²</td>
</tr>
<tr>
<td># Power</td>
<td>100 k</td>
<td>1.3 W</td>
</tr>
<tr>
<td># Wafers</td>
<td>20 cm wafer</td>
<td>20 cm wafer</td>
</tr>
<tr>
<td># Racks</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td># Wafers in rack</td>
<td>800 k</td>
<td>00 W</td>
</tr>
<tr>
<td># Wafers in 7 x</td>
<td>0 M</td>
<td>00 W</td>
</tr>
<tr>
<td># Wafers in 7 x</td>
<td>000</td>
<td>0 wafers in 7 x</td>
</tr>
</tbody>
</table>

**Table 1:** Comparison of neuromorphic computing systems.

What technology will do the computing of the future?

- CMOS with millivolt, reduce feature size, going 3D and using new materials (error rate, gate-all-around, leakage/quantum effects, heat issue, EUV, new materials still in the lab) \[ E_{tr} = 100k_B T \]

- Superconducting (switch count per unit volume too low) \[ E_{tr} > h/(t_{delay}) \]

- Quantum (problem specific, still the challenge of error correction) \[ E_{tr} > h/(t_{delay}) \]

- Reversible (complex logic) \[ E_{tr} = 0.04k_B T \]

- Dark silicon/multicore (software development needed) \[ N_{tr} < N_{tr} \]

- Approximate computing (specialised application) [low bit operations]

- Neuromorphic (potential energy efficiency issues, application specific and massively parallel)
Store, transmit and compute digital information bottom up approach for 2030

- Battle between digital growth and energy efficiency of compute, storage and transmission of digital information.

- **Xu** based on Hilbert and Lopez:

<table>
<thead>
<tr>
<th>Year</th>
<th>Storage</th>
<th>Communication</th>
<th>General-Purpose Computing</th>
<th>Special-Purpose Computing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>21 PB</td>
<td>59 PB</td>
<td>0.3 PIPS</td>
<td>0.44 PIPS</td>
</tr>
<tr>
<td>2007</td>
<td>277 EB</td>
<td>537 EB</td>
<td>6.39 EIPS</td>
<td>189 EIPS</td>
</tr>
<tr>
<td>2030</td>
<td>140 ZB</td>
<td>272 ZB</td>
<td>18 ZIPS</td>
<td>2 570 ZIPS</td>
</tr>
</tbody>
</table>


We do need better predictions of the future of energy consumption by the microelectronics infrastructure, but this depends on what is next for the core technology.

Clear that the way that we do computation has reached an exciting point. One such individual from the Rebooting Computing project did say “the semiconductor industry has been boring for the last 40 years, it is not getting interesting!”

Whilst a focus on energy consumption of the devices and infrastructure is important, perhaps even more important for the future is the consumption of resource and material, such as rare earth metals.

As well as the core data centres and supercomputing centres, more energy is consumed by the digital networks and with 5G poised to grow, future network energy consumption needs to be checked.

Reduce digital profligacy and increase digital sobriety.