UNIVERSITY of CALIFORNIA
SANTA CRUZ

PHYSICAL BOUNDS IN INFORMATION PROCESSING

A thesis submitted in partial satisfaction of the requirements for the degree of

BACHELOR OF SCIENCE

in

PHYSICS

by

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June 2011

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Abstract

Physical Bounds

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The absolute physical limitations of information processing are derived from quantum mechanical and thermodynamic concepts. The quantization of information is explained. The processing speed of a computational model is shown to be limited by the dynamical evolution between orthogonal states. The information capacity of a computational model is shown to be bounded. The fallacies of contemporary computational models due to energy dissipation are revealed, and the utilization of adiabatic processes as a solution is explained.

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1 Introduction

The theory of computation is usually discussed out of physical context. Although computation as it is known today might refer to calculations performed electronically or mentally, a universal notion would define the term as any processing of information. This would infer that many processes such as protein folding, phase transitions, spin interaction, or circuitry are all computational models. Referencing the semantic significance of this, all forms of information processing are intrinsically physical systems dictated by the laws of physics.

Ingenuity has dictated the abilities of human-built computers thus far. Innovations such as the transistor, integrated circuits, and conceptual breakthroughs such as Von Neumanns computer architecture has allowed computational power to increase exponentially. As manufacturing techniques have refined, computational power is increased through volumetric efficiency as the physical space in which the fundamental unit of information–the bit–can occupy becomes smaller and smaller. Indeed, a single bit of information being processed by a modern computer is comprised of a number of electrons, usually on the order of 10^7, in contrast to 10^{17} as required by early transistor logic gates in the 1960s.

While by no means is computer technology decelerating in improvement, it becomes attractive to determine what types of computational limits can be derived from physical law: what bounds exist for which more powerful computers can be built? How might this be done? By construction of a theoretical framework built from various concepts in physics, the ultimate limitations of computational models can be described explicitly using fundamental constants.

Discussing the physics of computation requires a link between physics, information science, and computational models. This first requires computational models to have commonly universal measurements: processing speed and memory space. Conveniently, Boolean logic employed by modern computers is analogous to two-state systems in nature. Therefore, the ultimate limitations of computers can be deduced by a straightforward analysis of physics. The link between physics and fundamental limits of information processing is not new. Information was first linked to physics by attempts of Szilard (1929) to refute a thought experiment of Maxwell. Shannon (1948) developed mathematical theory that suggested entropy as a measure of information. Landauer (1961) subsequently postulated that the energetic cost of a single bit is not associated with information itself, but rather tied to the erasure of that information. Besides computer science, other disciplines have gained new perspectives from these theories; the processing power of the brain for instance could be hypothesized through thermodynamic observations.

The ultimate bounds of computation derived will seem amusingly far from realization, but many aspects of the theory are still of relevance. In particular, it will be seen that the entropy associated with processing information has fascinating thermodynamic implications in contemporary computers, yet a simple physical process yields a very elegant solution.

2 Quantifying Information

2.1 Maxwell's Demon and the birth of Information Theory

A thought experiment by Maxwell subsequently led to the quantification of information. Expressing doubt in the universality of the second law of thermodynamics states, he had devised a paradox now known as Maxwell's demon (fig 2.1) in which he challenged whether the second law of thermodynamics is only true in the statistical limit.

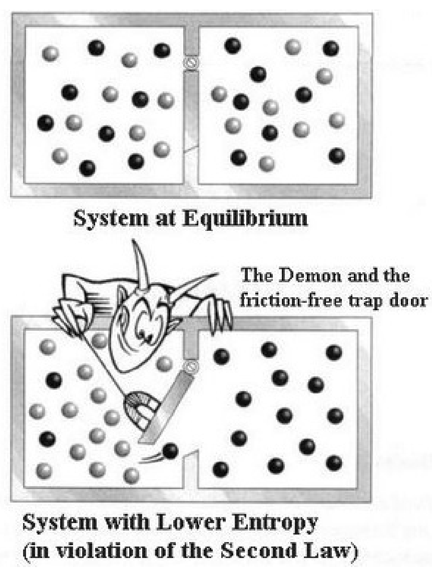

Figure 2.1: Cartoon Representation of Maxwell's Demon

Attempts to refute Maxwell's demon suggested a link between physics and a notion of information. Although many counter arguments to Maxwell's thought experiment were made, it was Szilard (1929) who provided the first quantitative solution. Szilard concluded that an increase of entropy within the demon's brain correlates to a net increase of entropy, which would uphold the second law. Szilard's proof is as follows: Consider an open cylinder with a piston placed in each end. A demon will close a partition in the cylinders, containing the particle in half of the original volume. The demon then determines which side the particle is in, and pushes the opposite piston in. The partition is removed, and the particle will perform work on the opposing piston as it isothermally expands (fig 2.3).

In total, the particle performs

$$\Delta W = \int_{V/2}^{V} p(v)\,\mathrm{d}v = k_B T \int_{V/2}^{V} \frac{1}{v}\,\mathrm{d}v = k_b T ln 2. \tag{2.1}$$

of work in one cycle, where $p = \frac{k_B}{T}$, the law of Gay-Lussac. As argued by Szilard, this 'engine' would produce useful work if in contact with an infinite heat bath. Thus he reasons that gaining knowledge corresponds to an entropy increase that must occur in the demon's brain, upholding the second law of thermodynamics.

In a simpler model, consider a similar system omitting the partition, where a piston is placed randomly within the cylinder [see (fig 2.3)], and a weight attached to a weight/pulley system at either end. Should the position of the particle be known after the cylinder is placed, useful work will be performed as long as the weight is placed on the same side as the particle. Should the

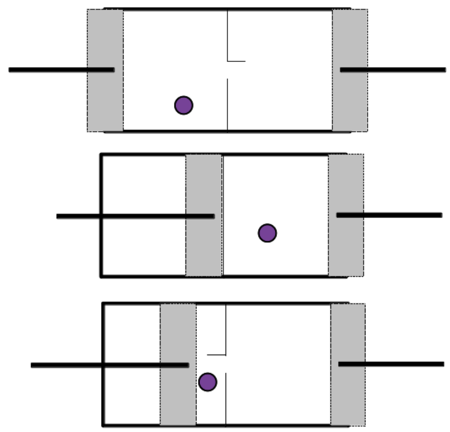

Figure 2.2: Szilard's model. Cylinder is in contact with a large heat reservoir. Top: The particle moves freely within the volume. Middle: The whereabouts of the particle is determined. Partition is closed and opposite piston is pushed in. Bottom: The partition is opened, and work is performed.

weight be attached randomly to either end without knowledge of position, the average amount of work performed over many cycles will be zero. Should the position of the particle be known before placing the weight, the average amount of work performed per cycle will be $k_b T ln 2$.

2.2 The Landauer Limit

Brillouin (1951) disagreed with Szilard, reasoning that the system is a closed black body and that the demon needs to emit light of it's own in order to make any observation of the particles, causing an increase of entropy within the cylinder. Landauer (1961) had applied Szilard's model to computing. Known as Landauer's limit, he eliminated conscious components from Szilard's model showing that it is the inevitable deletion of memory that causes an increase of entropy.

An abstraction is as follows: consider a chain of cylinders, each containing a single particle and representing a bit. A particle placed in the left side of the box represents a '0', while a particle on the right side represents a '1'. (fig 2.4)

Reseting this memory into a reusable state (all 0's) requires each cell to be compressed so that the state space is collapsed and the particle is known to be in the left side. This is done by compressing each cell from the right, collapsing the volume v into $\frac{v}{2}$ and thus causing an entropy increase of $N k_b ln 2$ where N is the number of bits compressed and k_b is the Boltzmann constant. The role of information here is emphasized: in this model the state of each cell is unknown. Should the state the cells be known, an adiabatic process can reset the memory and thus entropy is conserved. For instance, instead of collapsing the state space, each '1' cell can be rotated by π very slowly. Thus, the deletion of a single bit of information is associated with a release of energy of at least

$$k_b T ln 2 \tag{2.2}$$

where T is the temperature of the system. 'Landauer's limit', as it is now known, had been the first ultimate physical limit of information processing. For instance, enumerating every possibility of a 128-bit encryption key means that 2^{128} bit flips must occur. The enumeration alone of each possible number, adhering to Landauer's limit of $k_b T ln 2$ (where T=300K), would require $10^{18} J$ of energy. In comparison, the atomic bomb ("Fat Man") that detonated over Nagasaki in WWII yielded a high estimate of $10^{14} J$ of energy. Considering actual computing processes and the fact that current computers dissipate about 10^5 times Landauer's limit per bit flip, this estimate is grossly

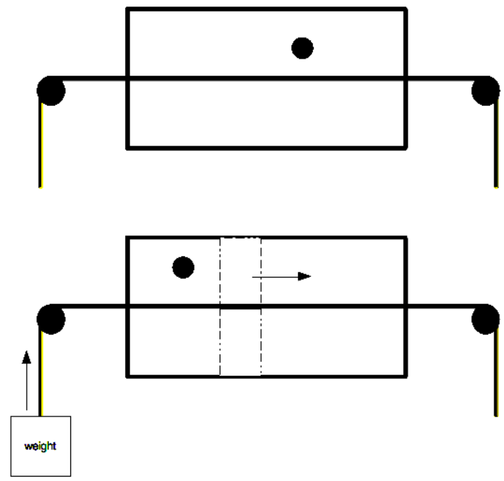

Figure 2.3: A Different Version of Szilard's Engine

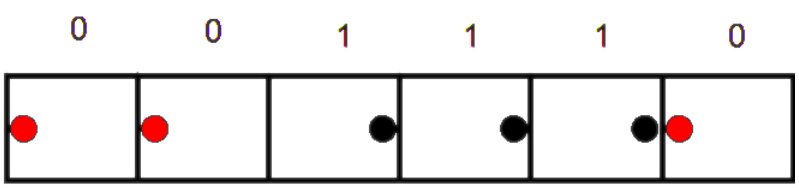

Figure 2.4: Abstraction of physical memory. A tape of atoms where a particle on the left side of the cylinder represents a '0' while a particle on the right represents a '1'. The tape is uniformly in contact with a heat bath.

underestimated. Landauer (1961) had suggested that computing be reversible, in which the computer would only use time invertible processes requiring theoretically zero free energy to operate. To be discussed later, physical reversibility in a computer is difficult to achieve, but adiabatic operation of irreversible circuitry in contemporary computers has the same desired effect.

3 The Physics of Information Processing

3.1 The Margolus-Levitin Theorem

A simple two state system allows for the minimum degrees of freedom in information processing; the quantum mechanical evolution between states is finite in time and thus is a bound of computational speed (Margolous et al 1998). These states must be distinguishable from each other and thus mutually orthogonal. The time-energy uncertainty principle

$$\Delta E \Delta t \geq h \tag{3.1}$$

is a suggestion of the elapsed time during evolution of a quantum system into an orthogonal state, which would equally apply to a one-particle bit such as $|0\rangle \rightarrow |1\rangle$. Margolus et al (1998)present a more robust version, considering not the standard deviation of energy but rather the average bounded energy. Consider a quantum state

$$|\psi_0\rangle = \sum_n c_n |E_n\rangle \tag{3.2}$$

which evolves by

$$|\psi_t\rangle = \sum_n c_n e^{-i\frac{E_n t}{\hbar}} |E_n\rangle . \tag{3.3}$$

This is orthogonal to an initial state when

$$S(t) = \langle\psi_0|\psi_t\rangle = \sum_n |c_n|^2 e^{-i\frac{E_n t}{\hbar}} = 0. \tag{3.4}$$

Using the inequality $cosx \geq 1 - \frac{2}{\pi}(x + sinx)$, $Re(S) = 1 - \frac{2E}{\pi\hbar}t + \frac{2}{\pi}Im(S)$, both Re(S) and Im(S) must equal zero for S(t)=0, then

$$0 \geq 1 - \frac{4Et}{h} \tag{3.5}$$

and thus

$$t = \frac{h}{4E} \tag{3.6}$$

is the time required for the system to transition between orthogonal states.

The number of mutually orthogonal states that a computational system of average energy E can transition through then defines its maximum processing rate. Margolous et al (1998) generalize this result to a string of orthogonal states. Let

$$|\psi_0\rangle = \sum_n^{N-1} \frac{1}{\sqrt{N}} |n\epsilon_1\rangle , \tag{3.7}$$

as if a 1-d harmonic oscillator where $\epsilon_1 = \frac{h}{\tau}$ and assume that the system passes through N states over time τ, then $\tau_\perp = \frac{\tau}{N}$. After m intervals of time, this state is

$$|\psi_m\rangle = \sum_n^{N-1} \frac{1}{\sqrt{N}} e^{-\frac{2\pi i n m}{N}} |n\epsilon_1\rangle \tag{3.8}$$

then

$$\langle\psi_0| H |\psi_0\rangle = \epsilon_1 \sum_{n}^{N-1} \frac{n}{N} = \epsilon_1(\frac{N-1}{2}) = \frac{1}{N}(\frac{h}{\tau_\perp})(\frac{N-1}{2}) \tag{3.9}$$

and so the minimum transition time needed for a system to flip between N orthogonal states is

$$\tau_\perp = \frac{N-1}{N}\frac{h}{2E}. \tag{3.10}$$

The fundamental interpretation of this result is that processing speed of *any* computational model is ultimately limited to energy.

While the result was derived by considering a system that transitions through a single state at a time, the result is independent of architecture: a macroscopic system of particles will have the same processing speed regardless of whether it was designed to process a single bit, or many, at a time. The equal division of the system of energy E into any amount of subsystems for example will still result in a computational model performing no greater than $2E/\pi\hbar$ operations per second.

3.2 Memory Limits

Shannon (1948) defined a new quantity known as 'information entropy' which can be applied to quantify a bound on the memory capacity of a computational model. Shannon's idea was analogous to statistical mechanics describing information as a 'state', quantifying the amount of information gained from a single letter of the alphabet, for example. The information gained from this letter flowing through a channel would be directly related to the amount of uncertainty in the system. Brillouin (1956) applies this theory to show that the reduction of entropy in any system corresponds to a gain of information:

$$I \equiv S_0 - S_1 = klog\frac{W_0}{W_1}, \tag{3.11}$$

where W represents the number of micro states. Considering an ensemble of two state spins comprising the entirety of a computational model, the amount of information contained in bits (it's memory space) is

$$I = \frac{S(E,V)}{k_B ln2} \tag{3.12}$$

where S is the Boltzmann entropy. Thus a system with finite memory I can process

$$\frac{k_B ln2E}{\pi\hbar S(E,V)} \tag{3.13}$$

operations per bit·second.

Lloyd (2000) suggested that this limit should be refined using the canonical ensemble in consideration of programming. As discussed in the previous section, a system's processing speed is fundamentally a limit of transitions between orthogonal states. Depending ultimately on average energy E regardless of architecture, it seems logical to utilize the microcanonical ensemble. However, a system will not necessarily require all of it's memory depending on the computation at hand, even causing suboptimal speed. Calculation of S should therefore be done using the canonical ensemble. With this treatment, the ultimate processing speed becomes governed by temperature.

3.3 Maximum Memory Space

The maximum memory space is a bound dictated by entropy as shown in the previous section. Clearly, as entropy is increased, more memory is available. Entropy itself has physical bounds. Bekenstein (1981) determined an approximation to the maximum entropy of a system through a study of black hole thermodynamics. Just as Landauer's law had spawned from a refute of Maxwell's paradox, Bekenstein sought to disprove 'Wheeler's Demon'. Wheeler et al (1971) questioned the applicability of thermodynamics to black holes pointing out that a 'classical' black hole (accepted to have zero temperature and thus zero entropy) consuming mass from its exterior conflicted with the notion that the total entropy of the universe *must* increase. Bekenstein sought to form a theory in which black holes would have a non-zero entropy and temperature, describable entirely by observable quantities of mass, charge and angular momentum. Hawking (1971) calculated the area of a black and found it to be analogous to entropy; the theorem was refined and the Bekenstein-Hawking entropy was determined to be

$$S_{BH} = \frac{A}{l_P^2} = \frac{c^3 A}{4G\hbar} \tag{3.14}$$

where l_P is the Planck length and $A = 16\pi(GM/c^2)^2$ is the area derived from the event horizon and mass of the black hole.

With a well defined value of a black hole's entropy, Bekenstein calculated a maximum entropy bound for a definite system. In a thought experiment, Bekenstein imagined lowering a system with defined mass m and entropy S into a black hole of entropy S_b and mass $M >> m$. The black hole entropy thus changes by

$$\Delta S_b = k((M+m)^2 - M^2) \approx 2Mmk \tag{3.15}$$

where k $= \frac{c^3}{4G\hbar}16\pi(G/c^2)^2$. The second law implies that the sum of the entropy from the black hole and the lowered system never decrease. This implies the inequality

$$\Delta S_b - S \geq 0 \tag{3.16}$$

which can be rewritten

$$S \leq \frac{4\pi r_h mc^2}{\hbar} \tag{3.17}$$

by substituting the well defined black hole radius $r_h = \frac{2Gm}{c^2}$ and the rest energy $E = mc^2$ of the lowered system. To eliminate the black hole from the bound requires further thought experiments. Reducing the radius of the black hole so that it is large enough to still consume the system, $4r_h \rightarrow \xi R$ where the coefficients are absorbed in ξ. Different thought experiments yield slightly different results for ξ, but Bekenstein himself calculates $\xi = 2\pi$ and thus a system of energy E that can be contained within a radius R has a maximal entropy limited by the 'Bekenstein bound':

$$S_{max} \leq \frac{2\pi RE}{\hbar c} \tag{3.18}$$

where E is the total energy. The maximum amount of information that a system can contain is as (eq 3.13):

$$I = \frac{2\pi RE}{\hbar c k_B ln2}. \tag{3.19}$$

This result has meaning in *many* fields, such as an estimate for the computational capacity of the universe by Lloyd (2002) or a suggestion by Lloyd (2000) that particle collisions could be used to perform computations. The amount of information in bits required to *perfectly* simulate the human brain or body could be derived simply by substitution of the energy $E = mc^2$ into (eq 3.19).

3.4 Compressing a computer

It was discussed in section 3.1 that a computer will have the same processing speed whether it was designed to process single bits at a time, or multiple ones simultaneously. As the processing speed is bound strictly to the energy E of the system, dividing the system into subsystems would allow parallel architectures to be implemented.

The number of operations per second that can be processed on a single bit was calculated by determining the minimum time required to transition between orthogonal states. Consider two separated particles representing a single processor. As shown in (fig 3.1), concentrating the energy into a minimal amount of processors causes the bit processing time t_{flip} (eq 3.6) to minimize. However, doing this would be redundant without minimizing t_{com}, the time required for signals to travel. Reducing t_{com} is a matter of compressing the bits together. Assuming the bits communicate via electromagnetic waves, compressing becomes detrimental at high densities as the strong and weak interaction forces will eventually take precedence. Lloyd (2000) suggests that as the computer is compressed past these scales, a treatment using theories of quantum gravity is needed. The operation and specification of computational models at this point is unknown as the number of degrees of freedom becomes a convoluted theory. However, as the computational model is compressed further, the Schwarzchild radius for the system is reached and the computer becomes a black hole. The computer then has the well defined maximum entropy calculated in section 3.3, t_{com} is minimized and thus this computational model operates absolutely serial in nature.

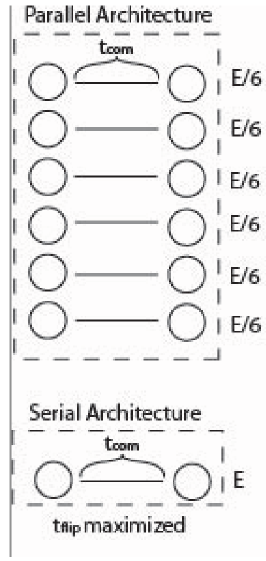

Figure 3.1: Parallel vs Serial Architecture. Partitioning E into subsystems results in a shorter t_{flip}

Whether the a black hole computer would ever be possible is an open question. Before the theory of Hawking radiation, a black hole was assumed to destroy all information contained in it. Whether Hawking radiation contains any discernible information is unknown (Lloyd suggests decoding it via string theory), but would be the only candidate for an output of such a computer.

If a much more parallel architecture is desired, the efficiency can be maximized by adjusting density so that $t_{com} \approx t_{flip}$.

3.5 Error Rate Tolerance

The cooling of a computer is strictly a process of heat transfer through conduction or radiation. The study of this is a useful endeavor to current energy-dissipative processors, and future reversible computers.

Any computer is susceptible to errors; even with the computer isolated from the external environment and interactions, there will always be noise introduced in the input of the computer; instructions must be sent from the external environment which at some point will be interacting with some other uncontrollable system. Such errors would require deletion, or rejection of the bits out of the computer through radiation.

In order to maximize the erasure of errors out of the computer, it should be constructed in a way that the errors are ejected at the blackbody temperature. Thus error rejection is limited to the rate of energy flux. The Stefan-Boltzman law $\frac{P}{A} = \sigma T^4$ divided by the Landauer limit $k_B T ln2$

joules per bit gives the maximal error rejection rate

$$\frac{A\sigma T^4}{k_B T_E ln2} \tag{3.20}$$

bits per second, where A is the surface area of the computer, σ is the Stefan-Boltzmann constant, T_E is the temperature of the environment, and T is the temperature of the computer. A bound of maximum error rejection naturally dictates a restraint on error rate; computational models must be constructed to adhere to this bound, otherwise they would overheat and obliterate themselves.

4 Contemporary Applications

The previous chapters discussed the ultimate physical limits to computation. However, such a study might be vain in today's scope: obtaining the maximal processing speed bound would require the conversion of mass into energy, and realizing the memory limits require complete control of a model's degrees of freedom. Landauer's limit is a much more relevant bound and consideration of it will be of utmost importance within the next few decades.

4.1 Reversible Computing

The use of physically reversible logic gates would greatly increase a processor's energy efficiency and minimize heat dissipation. Modern processors utilize transistor implementations of Boolean logic gates. Because the Boolean functions utilized are irreversible, extraneous heat is generated as each bit is processed through a likewise irreversible circuit. The voltage applied to each of two inputs, A&B as seen in (fig 4.1), results in a single logic 0 or logic 1 output; the dumping of the wires to ground through a resistance causing dissipation of energy.

CMOS gates are discussed here rather than other logic families because of their relevance in contemporary computing; notably they are the computer industry's choice for use in processors.

The logical processes of these gates, with the exception of the NOT gate, is not reversible; given a logic output of 0 or 1, it is not possible to deduce the original logic inputs of the gate that processed it. However G De et al. Mey (2008) demonstrated that CMOS family logic gates can be physically reversible if operated abiabatically.

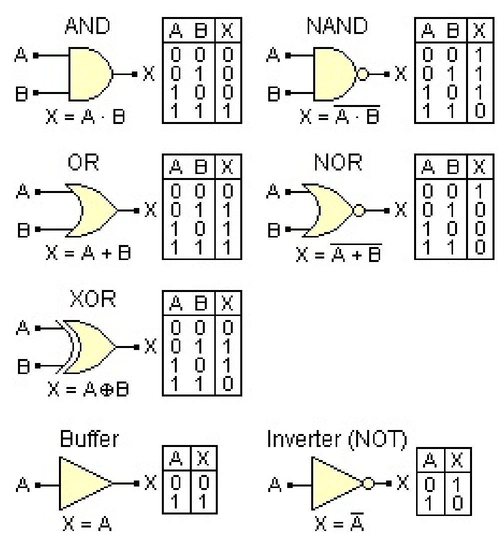

Figure 4.1: Truth Tables for Logic Gates

4.1.1 Adiabatic Logic Gates

G De Mey et al's (2008) study of the CMOS NOT showed that energy stored in parasitic capacitances is what is dissipated as heat in a CMOS logic circuit. In (fig 4.2), applying no voltage at V_{in} represents a logic input '0'. Then, $V_{out} = V_{BB}$ and energy $\frac{1}{2}C_2V_{BB}^2$ is stored in C_2. If voltage is then applied at V_{in} to represent the logic input '1', T_2 will conduct instead of T_1 and the energy stored in the C_2 will be dissipated as heat. C_1 will then charge and store energy $\frac{1}{2}C_1V_{BB}^2$ which is also also equal to the heat dissipated

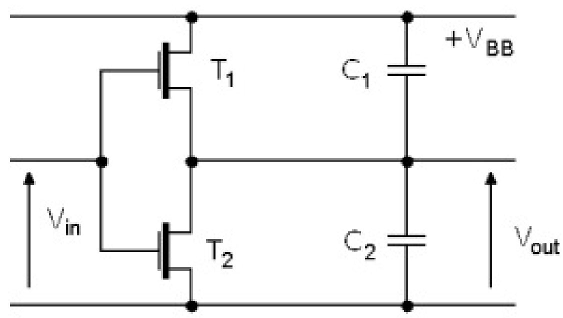

Figure 4.2: CMOS NOT gate

in T_2. Therefore,

$$\frac{1}{2}(C_1 + C_2)V_{BB}^2 \tag{4.1}$$

is the amount of heat generated in a CMOS logic circuit changing from input $0 \to 1$ or $1 \to 0$.

Koller et al (1993) examined the possibilities of using adiabatic processes, namely adiabatic charging, to greatly decrease the energy dissipated in logic circuits. Consider the circuit in (fig 4.3); closing the switch and slowly increasing the voltage so that the charging time $T >> RC$, the capacitor will hold charge $Q = C/V$ but the current will be $I = CV/T$. Joule's law then says that the energy dissipated is

$$Q = I^2RT = (\frac{CV}{T})^2RT. \tag{4.2}$$

Compared to a quick discharging, slowly varying the power supply voltage (at a level above the transistor threshold) will decrease energy dissipation by a factor of $\frac{2CR}{T}$ per logic change. Increasing T, the dissipated energy will approach zero.

G De Mey et al (2008) applies a similar argument to energy dissipation in CMOS logic gates by studying the charging of a capacitance through a diode. The difference in energy dissipation between operating a gate irreversibly vs reversibly is found to differ by

$$\Delta Q = nk_BTln2, \tag{4.3}$$

where n is the number of electrons comprising the input. This result reaffirms an earlier limit: the difference in energy dissipation is simply Landauer's limit times n.

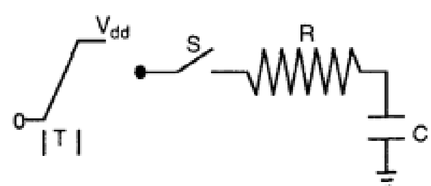

Figure 4.3: Charging a load capacitance through a switch

Adiabatic operation of logic gates greatly reduces heat dissipation in computing processes but at the obvious expense of speed. As adiabatic operation requires $T >> RC$, this tradeoff will always remain true. Resistance and capacitance RC of the circuitry and thus the required time T is reduced with scaling; it may be worthwhile to implement adiabatic operation in certain applications should processing speed already be sufficient.

4.1.2 Reversible Logic

Bennett (1973) realized that logical reversibility could be used to perform computations with no expense of energy dissipation. Contemporary logic gates are logically irreversible (with the exception of the NOT gate); comprising of two inputs yet only one output, their operation requires that 'garbage' bits are discarded through dissipation. Recognizing this flaw, Bennett conceived reversible logic functions by stipulating that each primitive component of a computer have an equal number of inputs to outputs. In this method, garbage bits do not require erasure but would instead be reused to reverse the computation.

A schematic of a fully reversible computer is shown in (fig 4.4). Given a data input, the logic units **M** will yield an answer which is copied. At this point, the garbage bits and the answer are then processed through $\mathbf{M^{-1}}$, yielding the original input. Thus, no energy need be dissipated by the computer.

4.2 The Very Next Steps

Landauer's limit seems to be the most forthcoming physical bound in computer technology. G. De Mey et al (2008) predicts that this theoretical limit will not be reached until 2050. Until then, the gradual improvement of semiconductor manufacturing should sufficiently meet the needs of humanity. Silicon devices still have much room for innovation anyway. Intel's 2011 debut of consumer level 22 nm "3-D Tri-Gate" CMOS processors (touted as having 3-D, or vertically standing transistors) hint that many geometrical improvements can still be made. IBM is currently researching the possibility of stacked silicon chips in which water flows through 50-micron wide cooling structures built into each layer; adiabatic operation of logic gates would additionally aid in circumventing heat related issues.

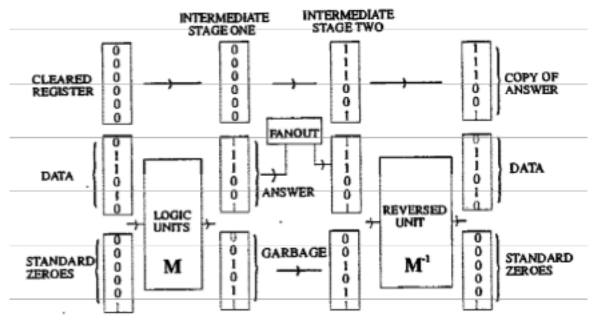

Figure 4.4: Zero Entropy Loss Reversible Computer

When Landauer's limit is finally reached, the only other option of increasing the performance to density ratio of computers is to implement reversible computation. Quantum computation is the most promising candidate of such, utilizing unitary operations to insure that the computations are reversible (not to mention quantum computation is innately more powerful than classical computing). Entirely new methods of computing are of huge research interests, such as the possibility of using DNA (the replication of which is a reversible process) or the mechanisms of protein folding to process information. Any sort of quantum or biological computer (a 'natural' computer) would not only be advantageous because of their reversibility but also because of other inherent features. For example, the ability to generate truly random numbers (as cannot be performed by contemporary computers) allows a natural computer to utilize much more powerful algorithms.

5 Conclusion

The true significance of the analysis of "information processing" or "computational models" is more qualitative than quantitative. Although the term "information processing" invokes a notion of human-made technology, in fact "information processing" has occurred long before the advent of mankind. The effect is reciprocal; man-made computers can be understood as fundamental processes of nature in the same way nature can be envisioned as computers themselves.

It is shown that information is an intrinsically physical and quantifiable entity, the processing of which must therefore adhere to physical law. Many speculations can then be made from this perspective. For instance, it is shown in this paper that a computational model's processing speed is bound to energy, suggesting that computers will one day possess unfathomable capabilities. Some use these theories to speculate on various biological phenomenon, such as the true processing power of the human brain given its heat output. Yet some advocate an even more philosophical perspective, like Hollis R. Johnson (Indiana University) and David H. Bailey (Lawrence Berkeley National Lab) do in their paper *Information Storage and the Omniscience of God* (2003) in which they analogize humans as computers, whose interactions with the universe are actually divine inputs from an omnipresent being. Whether or not their hypothesis is true, their paper goes to show that the study of information processing from a physics perspective is not useless; attempts to explain the mysteries of the universe is always a worthwhile cause–a reflection of the spirit of physics in its own way.

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[4.1] From: http://www.chem.uoa.gr/applets/appletgates/text_gates2.htm

[4.2] (G De et al. Mey 2008)

[4.3] (Koller et al. 1993)

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