Information Theory Meets Quantum Physics

The magic of wave dynamics

Apoorva Patel

Centre for High Energy Physics and

Supercomputer Education and Research Centre

Indian Institute of Science, Bangalore

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Computation

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The availability of different physical interactions makes it possible to design different types of computers.

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Wave algorithms can be useful in situations where spatial resources are cheap and quantum algorithms are fragile.

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Elementary hardware components work as predicted.
Large scale integration (say 10 or more components) is a technological challenge. Noone knows when that will arrive, or what a quantum computer will be used for.

Another Look at Computation

Computation is Processing and Communication of Semantic Information expressed using a Language.

One finds examples of many types of information processing systems in the physical world.

How can a general information theory be systematically developed to cover all types of computational schemes?

How can one design the optimal computer for a given task?

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Optimisation

Minimise physical resources (space, time, energy, . . .).
Software: What is the task? What is the algorithm?
Hardware: How are the operations implemented?
Efficiency of information processing depends on both software and hardware.

Technical Terms

Data: They describe a particular realisation of the physical system, amongst its many possible states.

Information: It is the abstract mathematical property obtained by detaching all the physical characteristics from data.

Knowledge: It is obtained by adding a sense of purpose to the abstract information.

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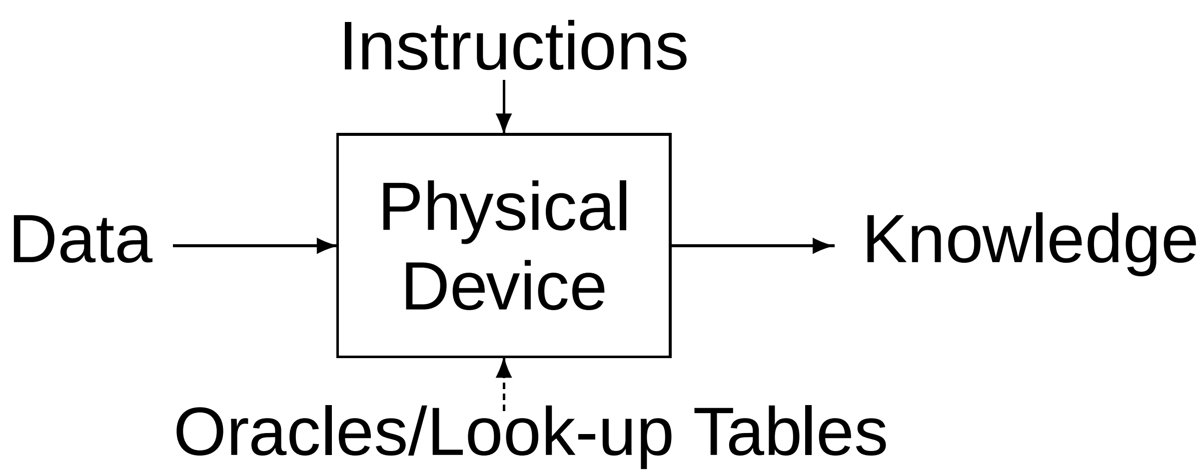
Information = Data - Physical Realisation
Knowledge = Information + Interpretation



Importance of Physics

1. Abstract information can be manipulated with precise mathematical rules, without going into nitty-gritty of its origin or meaning.
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Abstract information theory does not tell us what physical realisation would be appropriate for a particular message, nor does it tell us the best way of implementing a computational task.

These choices have to be made by analysing the type (and not the amount) of information, and inspecting the available physical resources.

Hierarchical Processing of Information

Computers		Living organisms
Data	Input	Environmental signals
Pre-processor	High level	Sense organs
Compiler	$\Uparrow$	Nervous system
Assembler	Translation	Brain
	$\Downarrow$	
Machine code	Low level	Electrochemical signals
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High level processing is abstract, with a wide variety of instructions and subjective adaptations.
Low level processing is directly related to physical properties, with a limited number of instructions and tasks.

At the lowest level of information processing, the physical objects that carry the message have to convey the information as well as its interpretation.

Optimisation Criteria

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2. Practical applications need only bounded error calculations, i.e. non-zero tolerance level for continuous variables (or finite success rate for probabilistic results).

3. Polynomial increase in the number of discrete variables (or trials) can provide exponential increase in precision, e.g. the place value system for numbers.

. . . contd.

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These criteria often confilct, and trade-offs are necessary.
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Nevertheless, the language with the smallest set of building blocks (for a given task) has a unique status in the optimisation procedure.

Minimal Language

- Largest tolerance against errors.

(Discrete variables are spread as far apart as possible in the available range of physical hardware properties.)

- Smallest instruction set.

(Number of possible transformations is limited.)

- High density of packing and quick operations.

(These more than make up for the increased depth of computation.)

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Boolean algebra provides the minimal classical language for encoding information as 1-dimensional sequences.

General Computational Framework

Generalise the concept of a language, from a "sequence of letters" to a "collection of building blocks".

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Collections: The building blocks can be arranged in the space-time in many different ways.
Building blocks: Physical properties (generically encoded using groups) express the meaning of the building blocks.
Processing: Allowed changes in the properties of building blocks exhaust the possible manipulations of information.

Group representations fix the structure of the language, and group transformations provide the rules for processing information.

. . . contd.

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The dimension of a group is the number of its generators. In the dual description, the minimal building block set is the d-dim fundamental representation and the 1-dim identity representation.

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In the smallest discrete realisation, the entire group is replaced by a single simplex. A collection of simplices can then represent any quantity to the desired precision (e.g. the place value system for numbers).

Types of Collections

$0 - dim$: Multiple signals at the same point in space and time, i.e. superposition. Different states of internal degrees of freedom encode different signals. Only one signal can be extracted at a time.

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$2 - dim$: Combination of multiple ordered sequences. Information can reside in correlations amongst sequences without being present in any individual sequence.
Examples: Eyes and ears, Space-time codes,
Parallax and gradient detection.

Types of Collections (contd.)

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Particle features: Countability, Order, Number density, Shape, Structure.
Wave features: Superposition, Differential analysis (parallax), Interference (multiple paths).

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$2-dim$: The simplex is a triangle. Triangulation (or its dual hexagonal form) is useful for discrete description of arbitrary surfaces. Graphene structure may become useful in atomic scale lithography.

Types of Building Blocks (contd.)

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$SU(2)$: Description of quantum bits is based on this group with three generators. Arbitrary states of a qubit (including mixed states) can be fully described using a density matrix, which is a linear combination of the four operators $\{1, \sigma_x, \sigma_y, \sigma_z\}$. (Four real numbers $\equiv$ Two complex numbers)

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Larger groups have been used in error correcting codes and cryptography, but not for processing information.

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$d > 1$: In higher dimensions, addition generalises to translation, and multiplication to scale transformation.
But rotations appear as well (non-commutative for $d > 2$).
Algebra generated by lattice transformations is much more powerful than common arithmetic.

More and more group operations become possible with increasing dimensionality.

Database Search

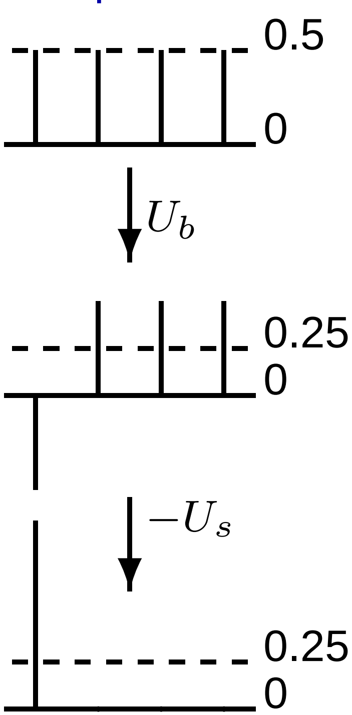
Classical:
Binary tree search is the optimal classical algorithm.
A sorted database of N items can be searched using $\log_2 N$ binary questions.
An unsorted database of N items can be searched using $N/2$ binary questions with memory, and using N binary questions without memory.

Quantum/Wave:
Wave mechanics works with amplitudes and not with probabilities. Superposition of amplitudes can yield constructive as well as destructive interference.
Optimal search solutions differ from the classical ones.

Grover's algorithm: An unsorted database of N items can be optimally searched using $(\pi/4)\sqrt{N}$ binary questions.

Grover's Database Search

The steps of the algorithm for the simplest case of 4 items in the database. Let the first item be desired by the oracle.



	Amplitudes	Algorithmic Steps	Physical Implementation
(1)		Uniform distribution	Equilibrium configuration
	U_b	Quantum oracle	Binary question
(2)		Amplitude of desired state flipped in sign	Sudden perturbation
	$-U_s$	Reflection about average	Overrelaxation
(3)		Desired state reached	Opposite end of oscillation
(4)	Projection	Algorithm is stopped	Measurement

(Dashed line denotes the average amplitude.)

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Video of amplitude amplification in coupled oscillators

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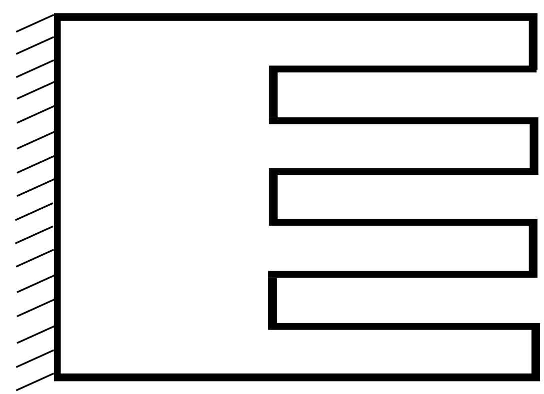
Nanomechanical devices: A coupled oscillator system can provide efficient focusing of energy at a specific location, when one cannot directly control the component concerned.

For example, a comb-shaped cantilever beam can be used as a selective switch or a sensor.



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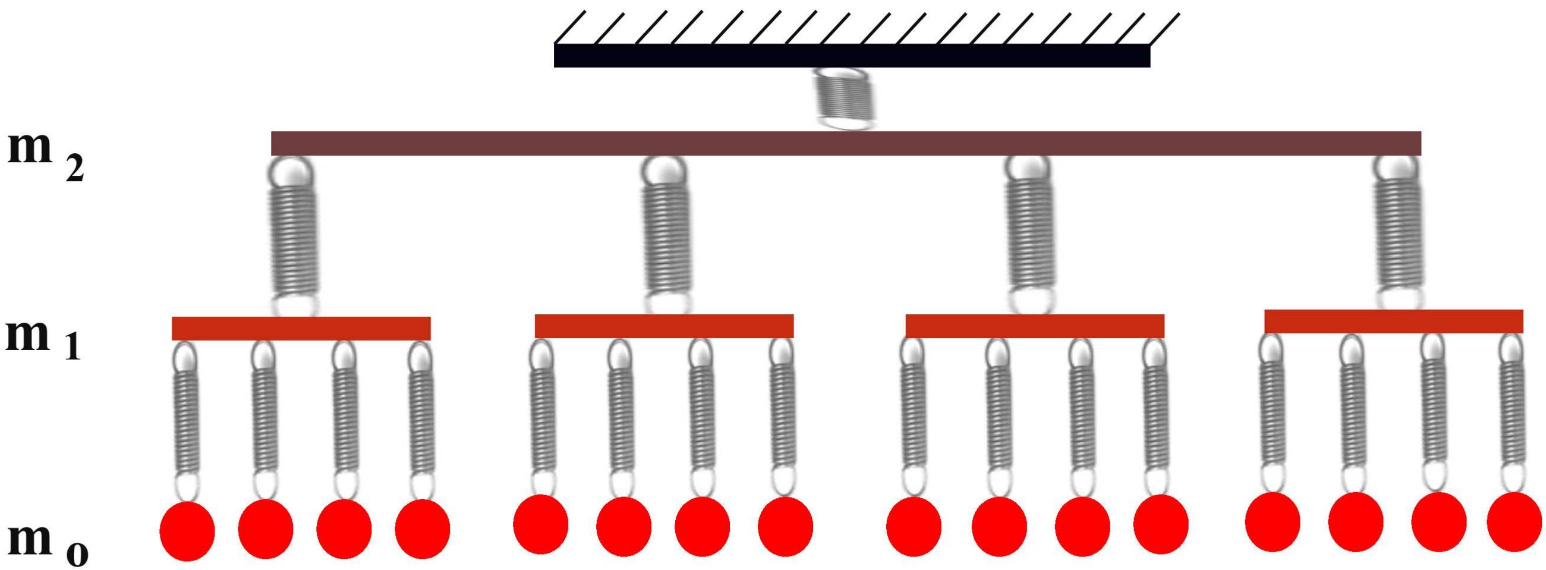
Shock absorbers and vibrational isolation: Instead of damping a single perturbed oscillator, it is much more efficient to disperse the energy into several oscillators while damping them together.

A hierarchical system of oscillators—four small ones coupled to a big one at every level with appropriate mass, spring and damping parameters—can provide a practical realisation of this idea.



(The initial impulse is taken to be a local disturbance, which subsequently spreads out.)

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   Lov Grover's quantum search algorithm.
   (Requires wave dynamics.)
3. Classically two nucleotide bases (one complementary pair) are sufficient to encode the genetic information. That would be a simpler system, and so it would have preceded (during evolution) the four nucleotide base system found in nature.
   Was the advantage provided by the wave algorithm the real incentive for nature to complicate the system?

Outlook

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Biological systems have evolved from the bottom level up, and by trial and error discovered many computational systems over billions of years.

Life is based on a nanotechnology that works—has worked for billions of years. There is a lot to learn from that!

Summary

There is a lot to explore, in both hardware and software!

Hardware: Find methods to deduce optimal physical realisation of building blocks for a given computational task.

Software: Develop group theoretical techniques to construct directly implementable high level instructions.

Wisdom: Learn from biological examples.
Digitally punctuated analog computation, stabilised by feedback, greatly improves energy efficiency.

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2. The depth of computation can be reduced by direct execution of high level instructions. This can be achieved using special purpose components and configurable systems.
   Biology has excelled in creating such systems.

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3. Can fractal arrangement of building blocks be used in some new type of information processing? (Self-similar patterns occur in concatenated error correcting codes.)

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5. Direct physical implementation of complicated group operations can also reduce depth of computation. Can we construct physical building blocks with large group properties?

. . . contd.

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6. $(Z_2)^d$ does not provide the minimal set of building blocks for $d > 1$; it contains 2^d points compared to $(d+1)$ points of a simplex. Simplicial geometry can be more efficient for multi-dimensional information processing.

Some Directions (contd.)

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7. Counting the number of available states (i.e. entropy or information) can be carried out for arbitrary configurations of building blocks. But quantification of correlations amongst the building blocks becomes increasingly complicated with increasing dimensionality. Quantum information theory generalises Boltzmann entropy to von Neumann entropy. What would be a more general framework beyond that?