The Physics of Computation

Directions from the Quantum World

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http://www.iisc.ac.in/initiative-on-quantum-technologies/

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Acknowledgments

Lattice gauge theories:

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Genetic Languages:  Semiclassical Gravity:

T. Padmanabhan
Computation

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The meaning arises from mapping physical properties (hardware) to mathematical terminology (software).
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Optimisation of physical resources required to implement a given task is always desirable. There is a lot to learn from what biological systems have discovered over billions of years!
What is a quantum computer?

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Still no one knows what a quantum computer will really be used for.
Early Days

In 1982, Richard Feynman taught a course at Caltech, titled “The Physics of Computation", together with John Hopfield and Carver Mead. The syllabus was vague, and various topics were covered in a chaotic manner, but the course was full of insights. He repeated the course the next year.

“Feynman Lectures on Computation” is a refined version of what was taught in that course.
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On my Graduation day (Caltech, 1984)
It is inevitable

“Because the nature isn’t classical, damn it . . .”

—R.P. Feynman

Laws of classical physics are convenient and useful, and yet only approximations (that are not fully understood) to the underlying laws of quantum physics.

Science: Observe and explain phenomena. Theorise!
Technology: Design and control phenomena. Optimise!

Yesterday’s science becomes tomorrow’s technology.
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Quantum effects (discreteness, dispersion, tunnelling etc.) have been considered “undesirable nuisance” in the classical computer design.

Why not go to the other side, where classical effects (decoherence, thermal fluctuations etc.) become “undesirable nuisance” in the quantum computer design?
Shrinking computer circuits

Moore’s Law – The number of transistors on integrated circuit chips (1971-2016)

Moore’s law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore’s law.

Number of transistors on a chip doubles every two years.

1948: First transistor, size $\sim 1$ cm. Today: VLSI circuits, size 22 nm.

Atomic size, 0.1 nm, is not very far!

First nanotechnology, and then decoherence, will have to be conquered along the way.
It is a breakthrough

Computers are physical devices, not mere mathematical entities to implement algorithms. Quantum mechanics demonstrates that complex numbers are physical. (We nevertheless carry the burden of history in the nomenclature—“real” and “imaginary” components.)
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Superposition allows multiple signals at the same point at the same time. All of them can be simultaneously processed, and any one of them can be selectively observed (e.g. radio or mobile phone transmissions). This offers an SIMD parallel computing paradigm with no extra hardware. Which algorithms can exploit this?
Computational Framework

A language is an aperiodic collection of building blocks. Information is encoded by the properties, the arrangement and the transformations of the building blocks.

Mathematical groups are useful in describing the language alphabet and grammar. Digitisation of continuous spaces (of physical properties) allows error correction.
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The minimal language (based on the smallest discrete group for the given task) is often the optimal language.

- Largest tolerance against errors.
- Smallest instruction set.
- High density of packing and quick operations.
- Simplest language, without need of translation.
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Building blocks can have multiple properties.

- Boolean algebra: Minimal classical language for encoding information as 1-dimensional sequence of letters. Cartesian structure $({\mathbb{Z}_2}^d$ encodes $d$-dimensional information.
- Quantum computation: Simultaneous 0- and 1-dimensional information in qubits.
- Protein structure: Simultaneous 1- and 3-dimensional information using amino acids.
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Although, in the $2^n$-dimensional Hilbert space of $n$ qubits, we can superpose $2^n$ components evolving in parallel, we can measure only $n$ binary observables at the end.

So the exponential gain of superposition is limited by the restriction to extract only a small number of output results.
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Efficient algorithms, in terms of both the input size and the output size, have been constructed for several linear algebra problems. They need local interactions and $k$-local observables.
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• Random walks represent a diffusion process. Classical diffusion operator is the Laplacian: $\frac{\partial P}{\partial t} = \nabla^2 P$. $E(\vec{k}) \propto |\vec{k}|^2$ produces the characteristic Brownian motion signature: $distance \propto \sqrt{time}$. Relativistic quantum evolution with $E(\vec{k}) \propto |\vec{k}|$ produces the signature: $distance \propto time$

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- Multi-fermion wavefunctions are totally antisymmetric determinants (easy to compute).
  Multi-boson wavefunctions are completely symmetric permanents (hard to compute).

  Boson sampling with $n$ identical photons naturally generates $n!$-component symmetric state.
Grover Search (An Example)

The key feature of the algorithm is wave dynamics, and not entanglement. Using a single oracle call, the algorithm identifies 1 out of 4 items in the database. In contrast, a Boolean algorithm identifies only 1 out of 2 items.

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<tr>
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<td>Reflection about average</td>
<td>Overrelaxation</td>
</tr>
<tr>
<td>0.25</td>
<td>Desired state reached</td>
<td>Opposite end of oscillation</td>
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<tr>
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A mechanical model

Grover’s algorithm is an amplitude amplification process. A system of coupled wave modes can execute it, provided
(1) Superposition of modes maintains phase coherence.
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Possible Uses

• Focusing of energy can be used as a selective switch.
• Energy amplification can speed up catalytic processes.
• Fast dispersal of energy can be used in shock absorbers.
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A hierarchical system of oscillators—four small ones coupled to a big one at every level with appropriate mass, spring and damping parameters—can be a practical model.

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

1. What is the information processing task carried out by the genetic machinery of every living organism?
   Assembling molecules by picking up components from an unsorted database.

2. What is the optimal way of carrying out this task?
   Lov Grover’s quantum search algorithm. (Requires wave dynamics.)

3. What is the signature of this algorithm?

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(2Q + 1) \sin^{-1} \frac{1}{\sqrt{N}} = \frac{\pi}{2} \implies \begin{cases} 
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Telltale signatures of wave dynamics (vibronic modes) are present in:
- Enzyme catalysis, photosynthesis, olfaction, magnetoreception by birds.
Quantum Technologies

The field of quantum technologies is poised for significant breakthroughs in the coming years. Many organizations have formulated detailed roadmaps.

Europe roadmap: https://arXiv.org/abs/1712.03773
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Developments in quantum technologies will also push classical technologies in new directions.
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- **Precise electromechanical nanosensors can be made with 2D materials (involving both photons and phonons).**

- **Quantum imaging with entangled photons can be highly accurate.**
  
  Quantum precision is $1/N$, compared to classical $1/\sqrt{N}$ scaling of central limit theorem.
References

All papers are easily accessible at http://arXiv.org/


Hardware Design Criteria

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• A scalable physical system with well characterized qubits.
• The ability to initialize the state of the qubits to a simple fiducial state (e.g. the ground state).
• Long decoherence time compared to logic operation time.
• An addressable universal set of quantum gates.
• A qubit-specific measurement capability.
• The ability to interconvert stationary and flying qubits (for communication between CPU and memory).
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Error correction needs discrete variables with error rate below a particular threshold.
## Qubit Count

http://quantumcomputingreport.com/scorecards/qubit-count/ (Jan 2018)

<table>
<thead>
<tr>
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<th>Technology</th>
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<tbody>
<tr>
<td>Intel</td>
<td>Gate</td>
<td>Superconducting</td>
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<td>TBD</td>
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<td>Ion Trap</td>
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<td>Spin</td>
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<td>Gate</td>
<td>Neutral Atoms</td>
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<td>Quantum</td>
<td>Rydberg Atoms</td>
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<td>TBD</td>
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<td>Quantum</td>
<td>Ion Trap</td>
<td>53</td>
<td>TBD</td>
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<tr>
<td>D-Wave</td>
<td>Annealing</td>
<td>Superconducting</td>
<td>2048</td>
<td>5000</td>
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<td>Annealing</td>
<td>Superconducting</td>
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<td>Qtm Neural Network</td>
<td>Photonic</td>
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<td>Digital</td>
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<td>Microsoft – PC</td>
<td>Software</td>
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<td>Microsoft – Azure</td>
<td>Software</td>
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<td>Rigetti – Forest</td>
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<td>ETH Zurich</td>
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</table>
# Qubit Quality

[Check the original report for the latest updates](http://quantumcomputingreport.com/scorecards/qubit-quality/) (Jan 2018)

<table>
<thead>
<tr>
<th>Computer</th>
<th>Qubit Count</th>
<th>Connectivity</th>
<th>T1 (µsec)</th>
<th>T2/T2* (µsec)</th>
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</thead>
<tbody>
<tr>
<td>IBM QX2</td>
<td>5</td>
<td>2 4</td>
<td>2.4 44.9</td>
<td>63.1 53.2 27.7 61.4 44.5</td>
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<tr>
<td>IBM QX4</td>
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<td>2 4</td>
<td>2.4 36.2</td>
<td>54.8 48.1 14.9 55.7 31.1</td>
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<td>2 6</td>
<td>3.9 47.5</td>
<td>173.5 80.1 15.6 94.2 41.3</td>
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<td>2 6</td>
<td>3.9 47.5</td>
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</table>

<table>
<thead>
<tr>
<th>Computer</th>
<th>1-Qubit Gate Fidelity</th>
<th>2-Qubit Gate Fidelity</th>
<th>Read Out Fidelity</th>
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<tbody>
<tr>
<td>IBM QX2</td>
<td>99.71% 99.88% 99.79%</td>
<td>94.22% 97.12% 95.33%</td>
<td>92.20% 98.20% 96.24%</td>
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<tr>
<td>IBM QX4</td>
<td>99.83% 99.96% 99.88%</td>
<td>95.11% 98.39% 97.11%</td>
<td>94.80% 97.10% 95.60%</td>
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<tr>
<td>IBM QX5</td>
<td>99.59% 99.87% 99.77%</td>
<td>91.98% 97.29% 95.70%</td>
<td>88.53% 96.66% 93.32%</td>
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<tr>
<td>IBM QS1_1</td>
<td>96.93% 99.92% 99.48%</td>
<td>82.28% 98.87% 95.68%</td>
<td>69.05% 93.55% 83.95%</td>
</tr>
</tbody>
</table>

- Fault tolerant quantum computers need error rate \(< \sim 10^{-3} - 10^{-4} \) (local qubits)
- \(~10^{-2} \) (topological qubits)

Number of logical qubits reached so far is ZERO.