Introduction to Quantum Computing

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https://www.venegas-andraca.org/

February 2025

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The Quantum Hardware+Software Ecosystem

The Quantum Hardware+Software Ecosystem

Quantum computing	Quantum communication	Quantum sensing
Quantum computing solves advanced computational problems by leveraging quantum phenomena to process information and make calculations. Enterprise use of quantum computers is expected to ramp up over the next several years, likely growing dramatically within a decade with the appearance of fault-tolerant quantum machines.	Quantum communication creates secure, theoretically tamper-proof communication networks that can detect interception or eavesdropping. Several quantum communication networks either have been deployed or are in progress, but it likely will be several years before they can overcome the unpredictability of quantum particles.	Quantum sensing devices provide higher responsiveness, accuracy, and performance than conventional sensors, due to the nature and sensitivity of subatomic particles. Quantum sensors are available today for limited production use cases and their availability and capability likely will increase substantially within five to 10 years.

Source: Deloitte analysis.

A Business Leader‘s Guide to Quantum Technology. Deloitte Insights.

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What is quantum computation?

Quantum computation, one of the most recent joint ventures between physics and computer science, may be defined as follows:

> Quantum Computation is a multidisciplinary field focused on the development of computers and algorithms, *i.e. hardware* and *software*, based on the quantum mechanical properties of Nature.

Quantum Physics (1/1)

Quantum physics is a scientific field focused on describing and predicting the behavior or matter and energy at very small scales (about 10^{-10}m and smaller).

Example: atoms and light particles (photons).

Theoretical Computer Science

Theoretical Computer Science, traditionally thought of as a branch of mathematics, is divided into three fields linked by the question

What are the fundamental capabilities and limits of computers?

QC, a multidisciplinary and pervasive field

- Quantum computation is transitioning from an emerging branch of science into a mature research field. A growing number of quantum scientists & engineers are devoting their efforts to identifying and developing cross-fertilising initiatives in fields such as:
  - Artificial intelligence
  - Machine learning
  - Chemistry
  - Finance
  - Image processing

Many new players and interests

- Quantum computation is *also* an emerging market of advanced technology:
  - **Investors**. *Breakoff Capital*, *Quantum Valley Investments*.
  - **Global Companies**. *Microsoft*, *Google*, *IBM*, *Amazon*, *D-Wave*, *Quantinuum*.
  - **Small to Large Companies**. *SandboxAQ*, *1Qbit*, *Rigetti*, *Quantum-South*, *Xanadu*, *Zapata*, *Strangeworks*.
  - **Government**. *EU*, *UK*, *USA*, *Canada*, *Japan*, *China*, *Australia*.

Technological Maturity of Quantum Computers

Different elements of the Quantum Ecosystem show different levels of technological maturity. Examples:

- Quantum Random Number Generators: they are available in the market right now. Example: QRNG chip produced by idquantique for **Galaxy A Quantum**, an edition of the Samsung Galaxy A71 smartphone.
- Quantum Computers: technological maturity similar to that of mainframes built in the mid 60s / early 70s of the XX Century.
- Quantum sensors: some quite advanced, either as prototypes or as ready-to-buy products. Example: quantum gravimeters.

Bits and Qubits - a quick introduction

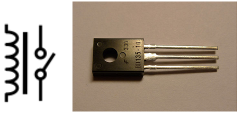
Bits and Qubits - a quick introduction (1/4)

Let us now introduce the basic units of information in classical and quantum computation: bits and qubits.

Bits and Qubits - a quick introduction (2/4)

In classical computation, information is stored and manipulated in the form of **bits**.

As for the mathematical structure of a classical bit, it suffices to define two logical values, traditionally labelled as $\{0, 1\}$ (i.e. a classical bit lives in a scalar space) and to relate those values to two different and mutually exclusive outcomes of a classical measurement.



A relay and a transistor
(Source: Wikimedia Commons)

Bits and Qubits - a quick introduction (3/4)

In quantum computation, information is stored, manipulated and measured in the form of **qubits (= quantum bit)**.

A qubit is a vector that represents the state of two-state quantum-mechanical physical entity.

Bits and Qubits - a quick introduction (4/4)

A qubit may be mathematically represented as a unit vector in the two-dimensional complex vector space $|\psi\rangle \in \mathbb{C}^2$.

Hence, a qubit $|\psi\rangle$ may be written in general form as

$$|\psi\rangle = \alpha|p\rangle + \beta|q\rangle$$

where $\alpha, \beta \in \mathbb{C}$, $||\alpha||^2 + ||\beta||^2 = 1$ and $\{|p\rangle, |q\rangle\}$ is an arbitrary basis spanning $\mathbb{C}^2$.

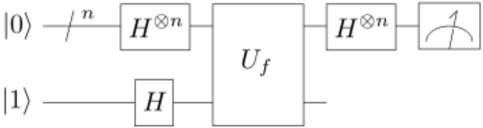
Now that we know what a qubit is, let us talk about...

Quantum Algorithms: Fast and Furious!

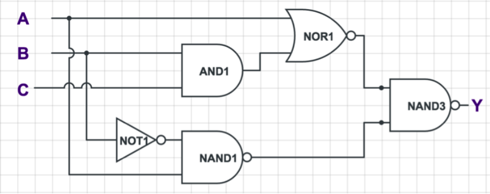
Quantum Gates (1/3)

The rationale behind the development of quantum circuits is very similar to the one followed in the construction of digital circuits:

Quantum Gates (2/3)



Deutsch-Jozsa quantum algorithm.



A digital circuit employing NAND, NOR, NOT and AND gates.

Quantum Gates (3/3)

- The mathematical description of digital circuitry is determined and constrained by the definitions and results of mathematical logic.
- As for quantum circuits, the mathematical description of a quantum gate is determined by the physics of quantum evolution (that is, the behaviour of quantum systems in time).

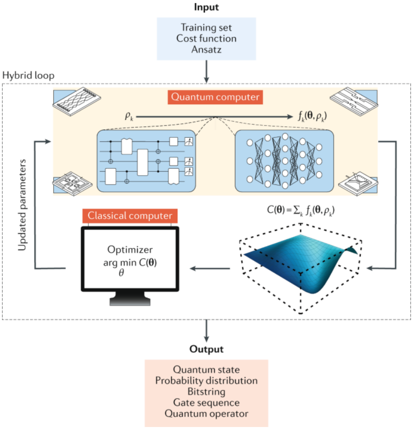
Schrödinger equation

We may also use differential equations to write quantum algorithms:

$$i\hbar \frac{\partial |\psi(t)\rangle}{\partial t} = \hat{\mathbf{H}} |\psi(t)\rangle$$

This is the Schrödinger equation and it is a key equation in the models of quantum annealing and adiabatic quantum computation.

Variational Quantum Algorithms

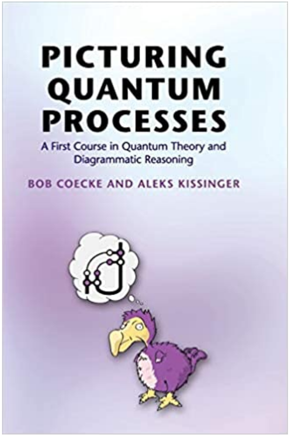


Taken from Cerezo et al. Nat Rev Phys 3, 625–644 (2021)

Programming Platforms for Quantum Algorithms

- State of the art on quantum programming languages:
  - Quantum gate-based graphical interface — IBM.
  - Python, C, C++ plus APIs — D-Wave
  - PennyLane (Quantum Machine Learning Libraries by Xanadu)
  - Amazon Braket - AWS.
  - Full quantum programming languages: yet to come.
- Digital simulation software
  - IBM Q
  - Microsoft
  - D-Wave

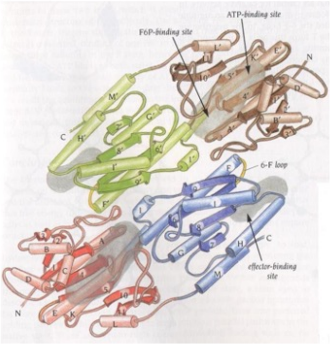
New approaches towards abstraction and problem-solving



Applications of Quantum Computing in Healthcare

Oldie but Goodie: Protein Folding (1/3)

Globular proteins



Schematic diagram of a globular protein.
Introduction to Protein Structure.
C. Branden and J. Tooze.
Taylor and Francis (1999).

The native state of a typical globular protein has, amongst others, the following properties:

1. It is tightly packed as a small-molecule crystal but, in general, a globular protein does <u>not</u> have the spatial regularity of a crystal (**bad** news for complexity in simulation algorithms).

2. Complex globular proteins have domains, i.e. subsets of amino acids that are often independently stable and folded (**helpful** for mathematical and computational analysis).

Oldie but Goodie: Protein Folding (2/3)

The Protein Folding Problem

Given the amino acid sequence of a protein, predict its compact three-dimensional native state

The Protein Folding problem is a key challenge in modern science, for both its intrinsic importance in the foundations of biological science and its applications in medicine, agriculture, and many other areas.

Oldie but Goodie: Protein Folding (3/3)

Anfinsen's Thermodynamic Hypothesis

The native fold of a globular protein is usually assumed to correspond to the global minimum of the protein's free energy. This is known as the Thermodynamic Hypothesis which, as stated in C. Anfinsen's Nobel lecture, reads :

"The three-dimensional structure of a native protein, in its normal physiological milieu, is the one in which the Gibbs free energy[2] of the whole system is lowest; that is, that the native conformation is determined by the totality of interatomic interactions and hence by the amino acid sequence, *in a given environment*."

The protein folding problem can be thus analyzed as a global optimization problem.

NP-hard and NP-complete.

[2] G=U + pV - TS, where U =internal energy (kinetic energy due to molecule motion and energy of chemical bonds), p =pressure, V=volume of the molecule, T= temperature and S=entropy.

Molecular Design

A large significant research effort has been made on the development of quantum algorithms to study molecules. The theoretical foundation of this research field is:

- The physics of molecular design and interaction (e.g., molecular docking) must include quantum mechanics. Example: DNA.
- Frequently, problems on the study of molecules can be written as optimization problems. Quantum computers are excellent candidates to solve optimization problems faster than classical computers.

Molecular Design

Article | Open access | Published: 14 August 2023

Molecular design with automated quantum computing-based deep learning and optimization

Akshay Ajagekar & Fengqi You

npj Computational Materials **9**, Article number: 143 (2023) | Cite this article

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Quantum Communications: The Quantum Teleportation Protocol & The Quantum Internet

The No-Cloning Theorem

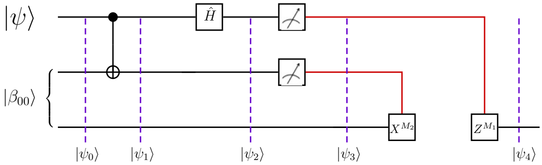
Let me start with an astonishing fact:

The No-Cloning Theorem. It is not possible to create an identical copy of an unknown quantum state.

- Both classical and quantum transmission of information degrade over distance (signal attenuation).
- Attenuation of classical (e.g. digital) signals can be overcome by using signal repeaters/amplifiers.
- As for quantum signals, the fact that we cannot copy quantum information **seems** to be an insurmountable obstacle to build quantum repeaters. Is it so? What can we do?

The Quantum Teleportation Protocol

Goal: to teletransport a qubit $|\psi\rangle$, that is, **the information** contained in a bi-valued quantum mechanical system (for instance, the polarization of a photon).

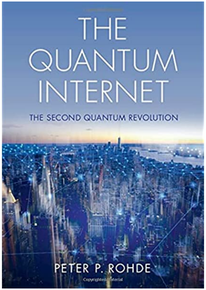


Components:

- A quantum communication channel $|\beta_{00}\rangle = \frac{|00\rangle+|11\rangle}{\sqrt{2}}$
- A classical communication channel (e.g., a telephone line).
- A qubit $|\psi\rangle$.
- Alice and Bob.

The Quantum Internet

Partly due to the No-Cloning Theorem (no exact repeaters of unknown quantum states), the Quantum Teleportation Protocol plays a central role in the theoretical and experimental development of quantum communication networks and, eventually, to the deployment of **Quantum Internet**.



Three Websites of Potential Interest

Quantum Network Explorer

Quantum Communications Hub UK

QuTech (Delft University of Technology)

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Cybersecurity - Threats

Shor's Algorithm

A quantum algorithm developed by Peter Shor, its purpose is to efficiently compute the prime factors of an N-digit integer ($N = 2^n$).

- A classical computer brute-force algorithm would require $O(2^{n/2})$ steps to perform the search.
- Quantum solution: Shor's algorithm, $O(n^3)$ steps.
- Key concept: Shor's algorithm provides exponential acceleration wrt **known** classical algorithms for prime factorization of integers.
- Key threat: Public key Cryptography.

Harvest now, decrypt later

Harvest Now, Decrypt Later (HNDL) consists of having access (and possibly storing) encrypted data that cannot be decrypted now but it will be decrypted at a later time using a quantum computer. In other words, it is scooping encrypted data for future use.

Examples of sensitive data likely to be under HNDL attacks: weapon design, diplomatic communications, and industrial secrets.

In summary, the problem is...

Problem:

Running Shor's algorithm on a sufficiently large and robust quantum computer will eventually become a threat to public key cryptography.

[Note: according to several roadmaps, those quantum computers will be available in 10 - 15 years time].

Solution:

Change potentially vulnerable cryptography protocols to

Post-Quantum Cryptography Protocols ☺ (NIST)

Cybersecurity - Novel Solutions

I. Quantum Key Distribution

Key distribution

One of the most sensible issues with private key cryptosystems is safe key distribution, i.e., the process of establishing a private key between two users **who cannot use a perfectly secure communication channel**.

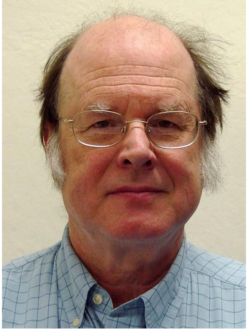
The issue is the fact that, if the channel used to distribute a private key **is governed by the laws of classical physics**, then in principle any (classical) key can be *passively* eavesdropped, i.e. without users becoming aware of this vulnerability.

Quantum Cryptography

Quantum cryptography is a scientific and engineering discipline that exploits the laws of quantum mechanics to perform cryptographic tasks, e.g., secure message transmission.

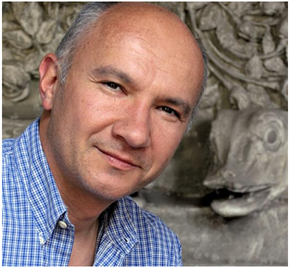
Quantum cryptography is a robust field of science and engineering that has evolved in an emergent high-tech market with companies capable of delivering off-the-shelf products.

QKD VIP



Charles H. Bennett

Gilles Brassard



Artur Ekert

BB84 - Quantum Key Distribution

In 1984, Charles Bennett and Gilles Brassard proposed a quantum key distribution protocol known as **BB84**.

The key idea of BB84 is to produce a key by encoding bits in qubits that are taken from a set composed by the union of the computational and diagonal bases, i.e., a set of four **non-orthogonal** quantum states.

II. Quantum Random Number Generators

Quantum Random Number Generators

0010011101010101001010101000111...

How random is random?

III. Quantum Technology to Protect Blockchain Cryptography Weakness

Quantum Technology to Protect Blockchain Cryptography Weakness

scientific reports

Article | Open Access | Published: 06 April 2023

Quantum-resistance in blockchain networks

Marcos Allende, Diego López León, Sergio Cerón, Adrián Pareja, Erick Pacheco, Antonio Leal, Marcelo Da Silva, Alejandro Pardo, Duncan Jones, David J. Worrall, Ben Merriman, Jonathan Gilmore, Nick Kitchener & Salvador E. Venegas-Andraca

Scientific Reports **13**, Article number: 5664 (2023) | Cite this article

https://publications.iadb.org/en/quantum-resistance-blockchain-networks

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Quantum Sensors

What is a quantum sensor?

A quantum sensor is a physical device that:

- whose behaviour is described by quantum mechanics, and
- we use to collect data from the physical world.

Example: **quantum gravimeters.**

Info and Players

Quantum sensing is a large and mature field of research that is quickly approaching commercial applications. To learn more about this field:

- **Quantum Sensing.** C.L. Degen, F. Reinhard, and P. Cappellaro. Review of Modern Physics 89, 035002 (2017).
- **Quantum sensors for biomedical applications.** N. Aslam et al. Nature Reviews Physics volume 5, pp. 157–169 (2023)
- Follow leading research groups and companies in quantum sensing, e.g. P. Cappellaro's group at MIT, Sanbox AQ, Mexican Division of Quantum Information [DICU] (more on DICU shortly).

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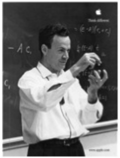
Many new players and interests

- Quantum computation is *also* an emerging market of advanced technology:
  - **Investors**. *Breakoff Capital*, *Quantum Valley Investments*.
  - **Global Companies**. *Microsoft*, *Google*, *IBM*, *Amazon*, *D-Wave*, *Quantinuum*.
  - **Small to Large Companies**. *SandboxAQ*, *1Qbit*, *Rigetti*, *Quantum-South*, *Xanadu*, *Zapata*, *Strangeworks*.
  - **Government**. *EU*, *UK*, *USA*, *Canada*, *Japan*, *China*, *Australia*.

Timeline (theory)

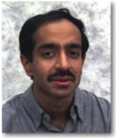
Timeline (Theory)



Feynman
QM computers

Deutsch
Universal QTM

Shor
Integer factorization



Grover
Search an unsorted DB

Nishimori
Quantum Annealing

DiVincenzo
Criteria to construct
a QC

Aharonov
Quantum Walks

Farhi
Quantum Adiabatic
Computation

Companies (1/3)

Companies

D:Wave
The Quantum Computing Company™

Quantum Annealers
SaS and direct selling.

Amazon Braket

Multiplatform Quantum Programming

Microsoft Quantum

Topological quantum computation
Classical simulators of quantum algorithms

IBM Q™

16, 25, 50, 127 qubit universal computer. SaS.
Software platform for development environment.

QUANTINUUM

Honeywell + CQC
Quantum hardware and Software

Google

Universal quantum computer
Quantum simulation of quantum systems

Companies (2/3)

Companies

XANADU
Quantum algorithms
Machine learning

Quantum-South
Quantum optimization algorithms

QURECA
quantum resources & careers

ZAPATA
Quantum algorithms
Programming Platform

rigetti
Quantum algorithms
Quantum hardware

$|\Psi\rangle$
Unconventional Computing
Quantum algorithms

Companies (3/3)

Companies

MULTIVERSE COMPUTING

Quantum Algorithms for Finance

SANDBOXAQ

Quantum algorithms and AI

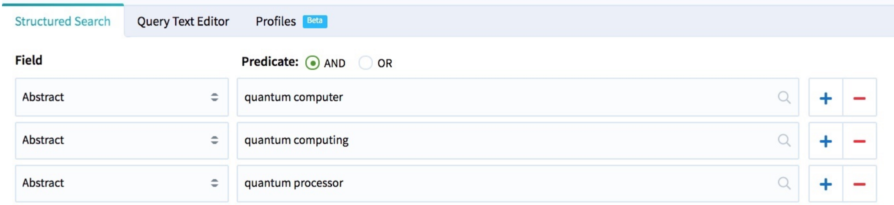
evolution

Quantum Cryptography

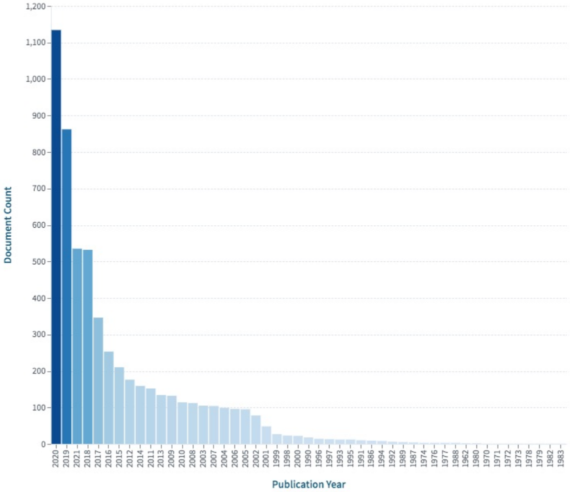
PQSHIELD

Post-Quantum Cryptography

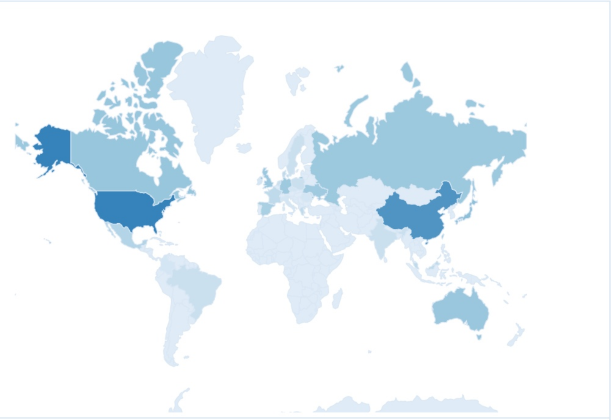
Patents (1/4) - lens.org



Patents (2/4) - lens.org



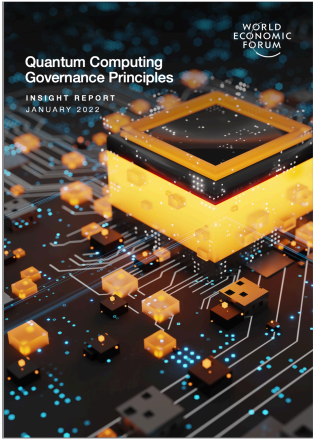
Patents (3/4) - lens.org



Patents (4/4) - lens.org

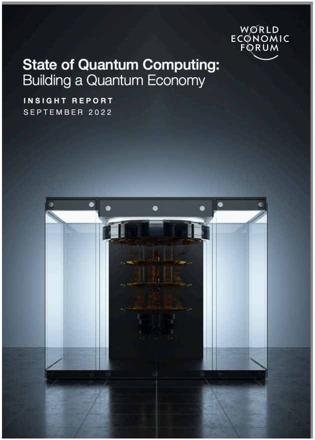
Ibm	354
Dwave Sys Inc	243
Intel Corp	208
Google Llc	159
Microsoft Technology ...	157
Ruban Quantum Tech ...	150
D Wave Systems Inc	124
Rigetti & Co Inc	96
Microsoft Corp	62
D-wave Systems Inc	59

White Papers on Quantum Technology - World Economic Forum (1/9)



Link to the pdf file at the WEF website

White Papers on Quantum Technology - World Economic Forum (2/9)



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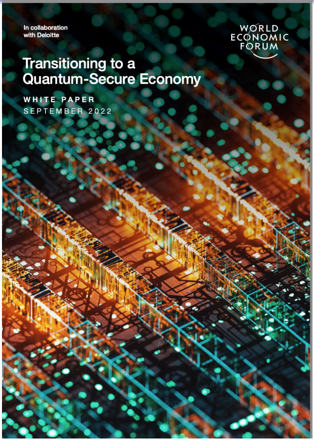
White Papers on Quantum Technology - World Economic Forum (3/9)



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White Papers on Quantum Technology - World Economic Forum (4/9)

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White Papers on Quantum Technology - World Economic Forum (5/9)

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White Papers on Quantum Technology - World Economic Forum (6/9)

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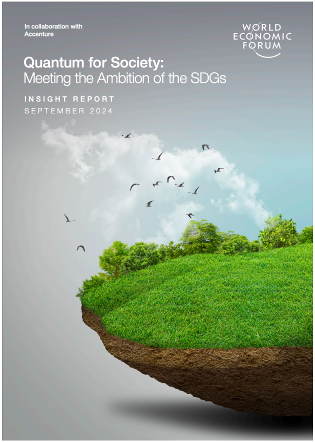
White Papers on Quantum Technology - World Economic Forum (7/9)



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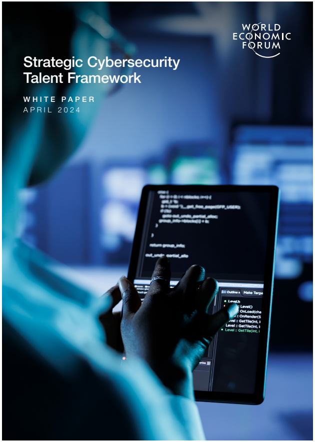
White Papers on Quantum Technology - World Economic Forum (8/9)



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White Papers on Quantum Technology - World Economic Forum (9/9)

Co-author of this paper

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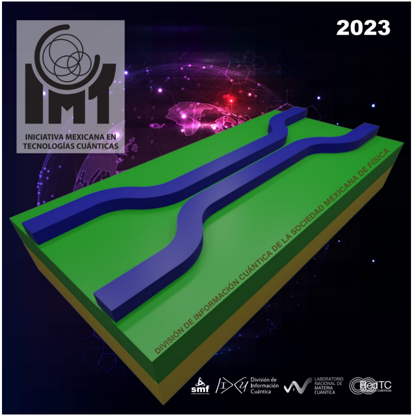
Mexican Quantum Ecosystem

Mexican Quantum Ecosystem (1/2)

- Cinvestav Querétaro - Lab. de Tecnologías Cuánticas.
- CIO - Professor Roberto Ramírez.
- ICN UNAM - Professor Alfred U'Ren.
- UASLP - Professor Eduardo Gómez.
- CNyN UNAM - Professor Fernando Rojas Iñiguez
- Cinvestav - Professor Oscar Rosas-Ortiz
- ITESM - Professor Salvador E. Venegas-Andraca.
- DICU - SMF & Red de Tecnologías Cuánticas.
- CENAM

Mexican Quantum Ecosystem (2/2)



Link to the pdf file at the DICU website

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Who we are (1/15)

The Unconventional Computing Lab

We focus on the following areas:

- Scientific research
- Engineering research
- Tech and knowledge transfer to the industry
- Novel educational methods to teach quantum technologies

Who we are (2/15)

The Unconventional Computing Lab

- We founded the field of quantum computation in Mexico.
- Quantum algorithms.
- Quantum Walks.
- Emerging fields of quantum computation, e.g. Quantum Image Processing and Quantum Machine Learning.
- Classical/digital simulation of quantum algorithms .
- Novel methods for training quantum engineers.

Who we are (3/15)

The Unconventional Computing Lab

We have plenty of experience on knowledge transfer to companies in Mexico and USA

Tec transfers quantum computing knowledge to AstraZeneca

The renowned biopharmaceutical company's Global Technology Centre (GTC) has received the first program on this subject in Mexico from Tec de Monterrey.

By CARLOS GONZALEZ | GUADALAJARA CAMPUS - *01/04/2021*

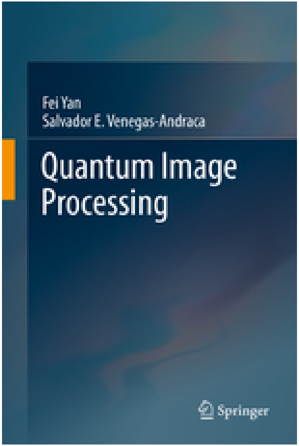
AstraZeneca and the Tec's Guadalajara campus have designed a knowledge transfer program for various cutting-edge technologies, including **quantum computing**, which the pharmaceutical company will apply to **quantum bioinformatics**, a tool for **designing new drugs**.

This training forms part of **AstraZeneca Guadalajara's** strategy for the **global evolution of information technology** (IT), which it has been working on in collaboration with Tec de Monterrey since 2018.

Quantum computing is a branch of technology that began in the 1980s. Its objectives include the **simulation of complex physical systems** and the **solution of highly complex computational problems** in less time than that taken by current digital technology.

Current development and road maps predict that powerful quantum computers will become available in the short term.

Who we are (4/15)



Springer, 2020

Who we are (5/15)

INTERFACE

royalsocietypublishing.org/journal/rsif

Research

Check for updates

Cite this article: Santiago-Alarcon D, Tapia-McClung H, Lerma-Hernández S, Venegas-Andraca SE. 2020 Quantum aspects of evolution: a contribution towards evolutionary explorations of genotype networks via quantum walks. *J. R. Soc. Interface* **17**: 20200567.

Quantum aspects of evolution: a contribution towards evolutionary explorations of genotype networks via quantum walks

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Who we are (6/15)

Who we are (7/15)

Revista de Administración Pública

INNP

Tecnología cuántica y Ciberseguridad

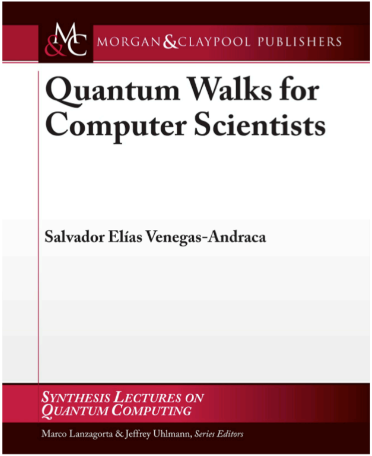
Salvador E. Venegas Andraca

Resumen: En la tecnología cuántica, campo del conocimiento en que se conjugan la física, la matemática, la ciencia computacional y la ingeniería, buscamos entender cómo la física cuántica (la física de lo tremendamente pequeño) se puede utilizar para incrementar dramáticamente nuestra capacidad de recolección, procesamiento, transmisión y almacenamiento de la información.

En este artículo se presenta una introducción sucinta a las nociones fundamentales de la tecnología cuántica así como algunos de los retos y oportunidades más importantes que esta tecnología tiene en el ámbito de la ciberseguridad.

Revista del INAP, 148, pp. 209-230 (2019).
Vol. especial Ciberseguridad Nacional

Quantum Walks (8/15)



Quantum Walks (9/15)

Quantum Inf Process (2012) 11:1015–1106
DOI 10.1007/s11128-012-0432-5

Quantum walks: a comprehensive review

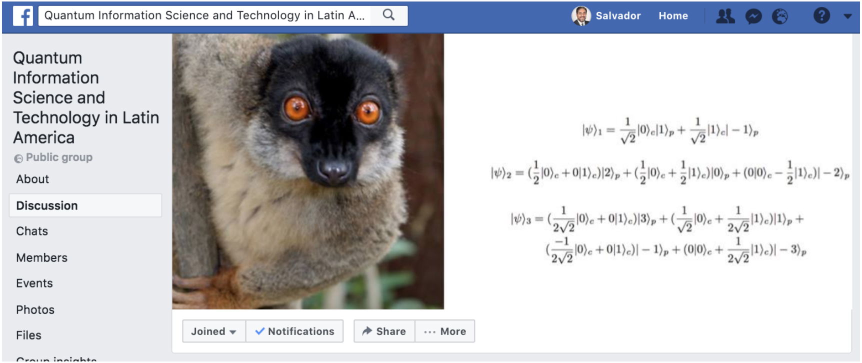
Salvador Elías Venegas-Andraca

Received: 24 January 2012 / Accepted: 11 June 2012 / Published online: 8 July 2012

Abstract Quantum walks, the quantum mechanical counterpart of classical random walks, is an advanced tool for building quantum algorithms that has been recently shown to constitute a universal model of quantum computation. Quantum walks is now a solid field of research of quantum computation full of exciting open problems for physicists, computer scientists and engineers. In this paper we review theoretical advances on the foundations of both discrete- and continuous-time quantum walks, together with the role that randomness plays in quantum walks, the connections between the mathematical models of coined discrete quantum walks and continuous quantum walks, the quantumness of quantum walks, a summary of papers published on discrete quantum walks and entanglement as well as a succinct review of experimental proposals and realizations of discrete-time quantum walks. Furthermore, we have reviewed several algorithms based on both discrete- and continuous-time quantum walks as well as a most important result: the computational universality of both continuous- and discrete-time quantum walks.

Keywords Quantum walks · Quantum algorithms · Quantum computing · Quantum and classical simulation of quantum systems

Who we are (10/15)



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Quantum Information Science and Technology in Latin America

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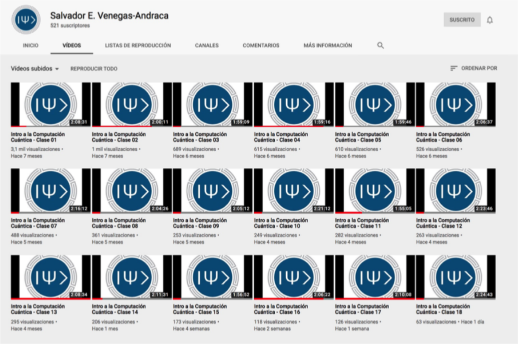
Who we are (11/15)



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Who we are (12/15)

The Unconventional Computing Lab
Salvador E. Venegas-Andraca's Research Group

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Reach us at: contact at unconventionalcomputing.org

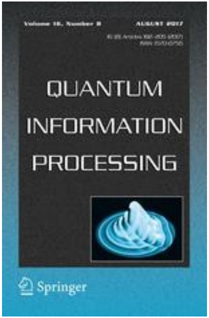
Welcome to The Unconventional Computing Lab!

Established in 2004, *the year we founded the field of Quantum Computing in Mexico*, our lab contributes primarily to the understanding of the physical, mathematical, implementation, and societal aspects of computation. We are interested in all aspects of mathematics, computer science, and computer technology, with a particular interest on quantum computing and emergent computational paradigms.

We produce groundbreaking science towards understanding the ultimate capacities and limits of computation imposed by physics and mathematics. Furthermore, we develop engineering methods to transform our scientific advances into products and services useful to humanity and non-human animals.
We are an international and multicultural laboratory, our members and associates are affiliated to academic institutions from all over the world.

https://unconventionalcomputing.org/

Who we are (13/15)



QIP Website

Please submit your papers to Quantum Information Processing.
S.E. Venegas-Andraca, Associate Editor.

Who we are (14/15)

WORLD
QUANTUM DAY
APRIL 14

https://worldquantumday.org/

Who we are (15/15)

INTERNATIONAL YEAR OF
Quantum Science
and Technology

https://quantum2025.org/

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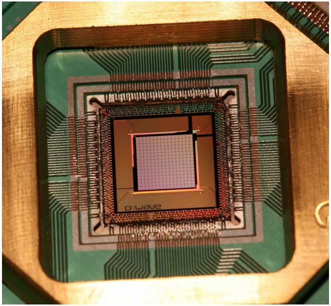
Conclusions (1/3)

Many conclusions but the most important to me are:

Conclusions (2/3)

Timex Sinclair 1000, CPU Zilog Z80A, 2K RAM, hooks to TV, cassette as memory



D-Wave Quantum Processor

Conclusions (3/3)

A better future for Humankind!

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Thanks!

Thank you very much!
Questions?

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