# What is Quantum Computing ?

a.pena@eib.org

Alonso Peña

LinkedIn

# Alonso Peña, PhD, CQF, CMath, FIMA

Quantitative Analyst at European Investment Bank

Luxembourg, Luxembourg, Luxembourg · Contact info

500+ connections

Open to | Add profile section | Add custom button | More

## Analytics

Private to you

**306 profile views**
Discover who's viewed your profile.

**2,466 post impressions**
Check out who's engaging with your posts.

---

**Quantitative Analyst**
European Investment Bank (EIB)
Aug 2019 - Present · 4 yrs 4 mos
Luxembourg

Officer Credit Risk Management

**SDA Professor (Banking and Insurance Department)**
SDA Bocconi School of Management
May 2011 - Jul 2019 · 8 yrs 3 mos
Milan Area, Italy

**Quantitative Analyst (Structured Products)**
Thomson Reuters
2007 - 2011 · 4 yrs

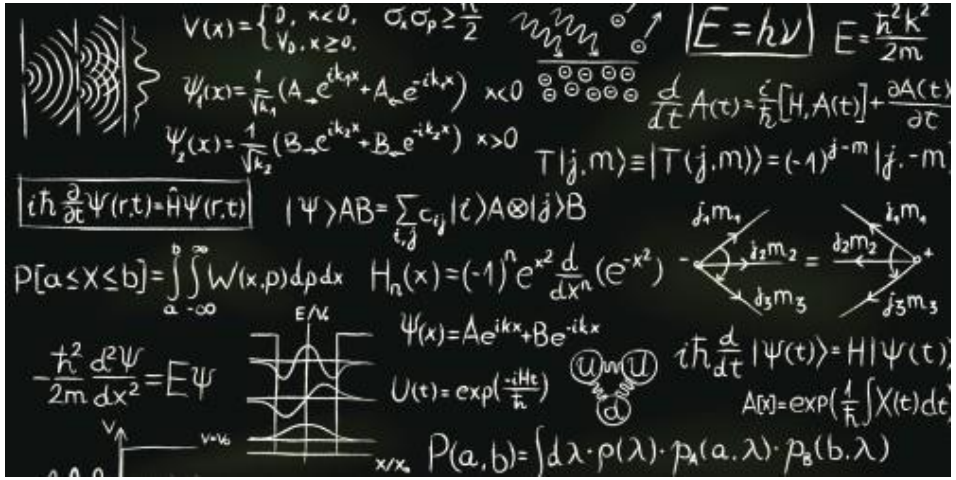
**Quantitative Analyst (Model Validation)**
Unicredit
2003 - 2007 · 4 yrs

**Wellcome Trust Training Fellow (Mathematical Biology), Senior Research Associate, Research Associate**
University of Cambridge
1997 - 2003 · 6 yrs
University of Cambridge


***Disclaimer:*** *I confirm that I act in a private capacity and not as a representative of the EIB and that the opinions expressed are personal and may not necessarily reflect the EIB position.*

# Quantum Computing: Introduction

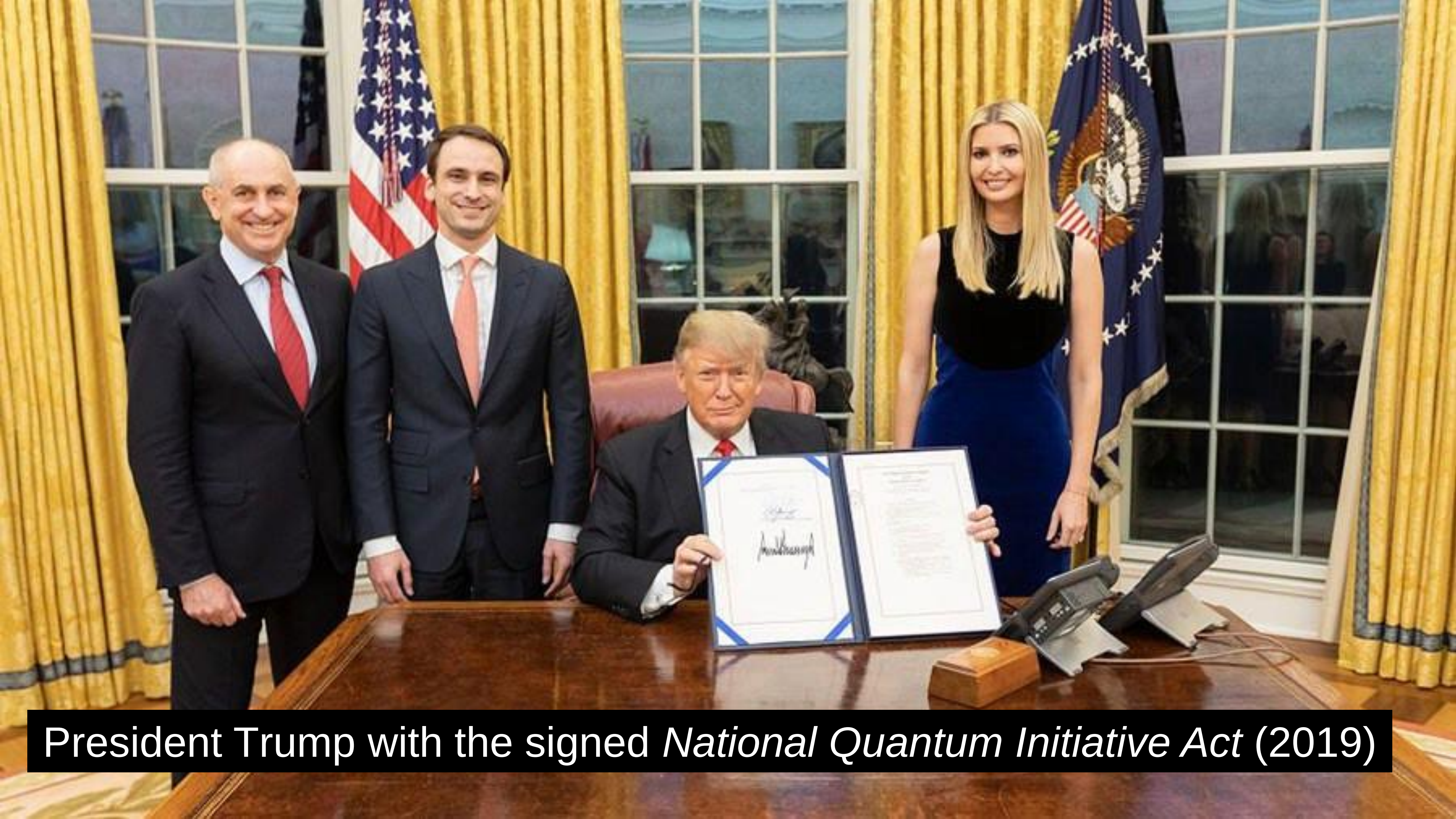
Quantum Physics




Computing


What if ?


**IBM System One:** the first commercial quantum computer, 2019



President Trump with the signed *National Quantum Initiative Act* (2019)

An official website of the United States government Info

⟨quantum|gov⟩

ABOUT STRATEGY SCIENCE COMPETITIVENESS PEOPLE NEWS NQCO

Search...

# NATIONAL QUANTUM INITIATIVE

THE FEDERAL SOURCE AND GATEWAY TO QUANTUM R&D ACROSS THE U.S. GOVERNMENT

Welcome to *quantum.gov*, the home of the National Quantum Initiative and its ongoing activities to explore and promote Quantum Information Science (QIS). The National Quantum Initiative Act provides for the continued leadership of the United States in QIS and its technology applications. It calls for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States. The United States strategy for QIS R&D and related activities is described in the National Strategic Overview for QIS and supplementary documents.

LEARN MORE

## RECENT REPORTS

- Annual Report on the NQI Program Budget, January 6, 2023
- National Security Memorandum 10 on Quantum Computing, May 4, 2022
- Bringing Quantum Sensors to Fruition, March 24, 2022
- QIST Workforce Development National Strategic Plan, February 1, 2022
- The Role of International Talent in Quantum Information Science, October 5, 2021
- A Coordinated Approach to Quantum Networking Research, January 19, 2021
- Quantum Frontiers Report, October 7, 2020
- National Strategic Overview for Quantum Informatio

**www.quantum.gov**

# AGENCIES

U.S. AIR FORCE

U.S.ARMY

DARPA

NASA

NSF

NIST

USDA

www.quantum.gov

# From Academia to Industry

1981

**May 6, 1981. Boston, MA, USA**

Professor Richard Feynman from Caltech, is about to give a **keynote speech** in a conference at MIT

The Nobel laureate will present an idea for a revolutionary new type computer, a **quantum computer**

Feynman's idea was to move away from the **binary representation** of information.

He argued that the basic building block of information ought to be the individual **subatomic particles**.

In fact, to use the unit of information used by nature.

2019

**January 8, 2019. Yorktown Heights, New York, USA**

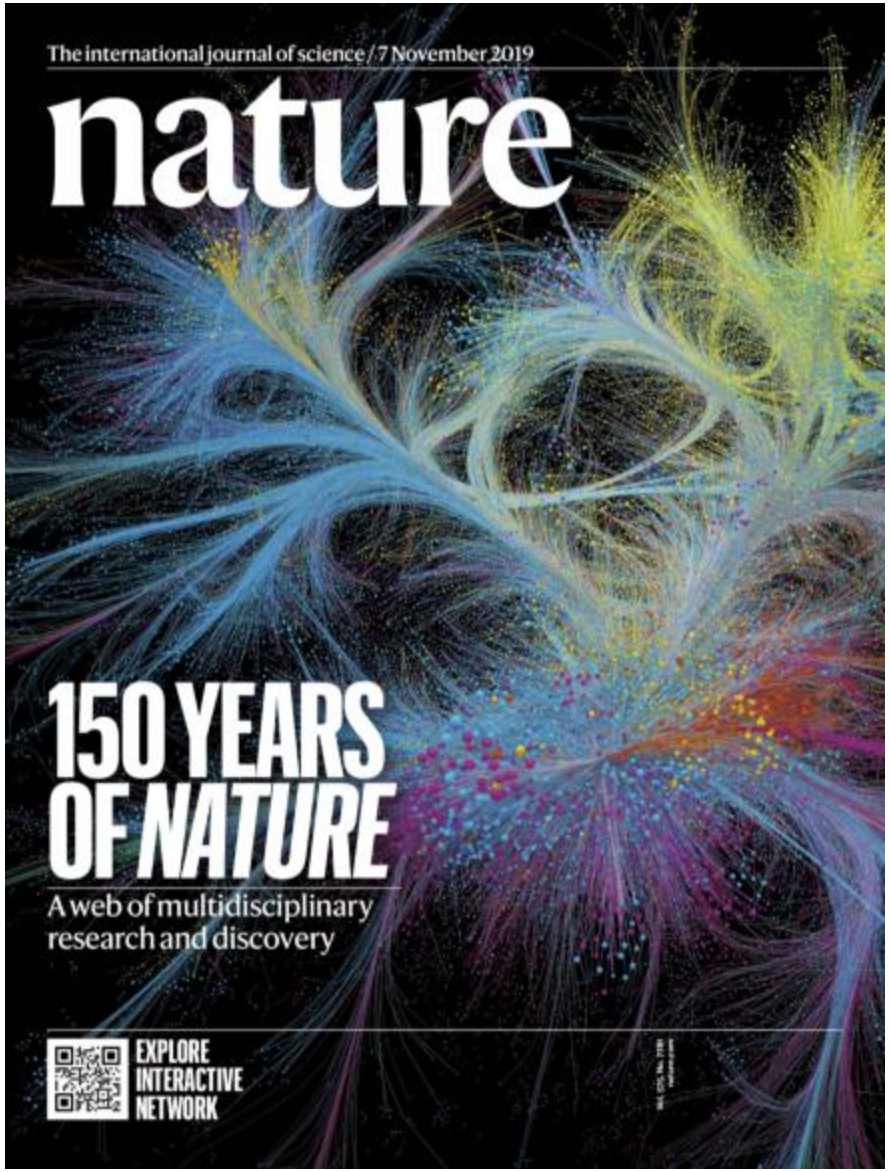
The company International Business Machines (IBM) presents the first **commercial quantum computer** in the world.

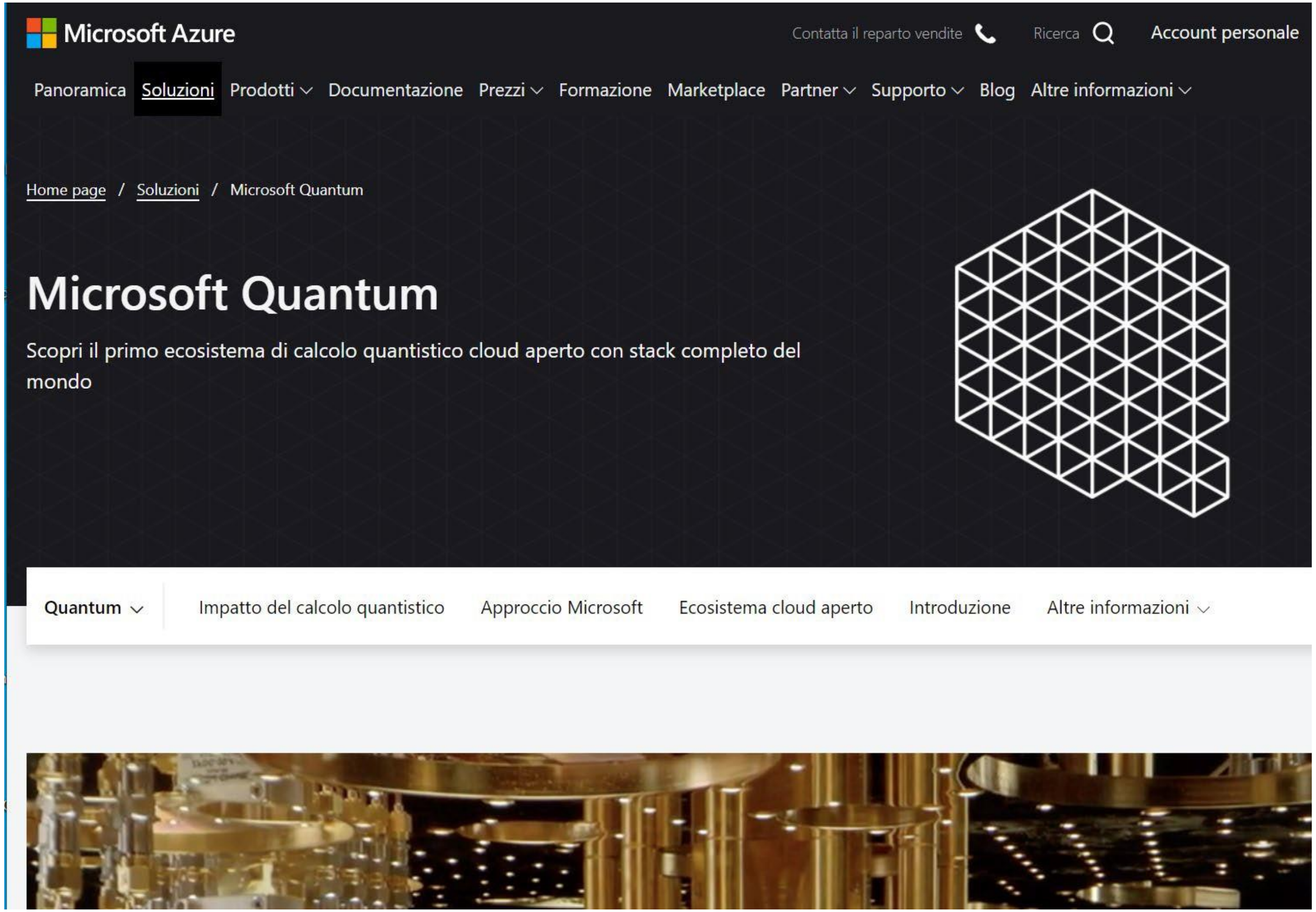
**www.quantum-computing.ibm.com**

Google Research

Scientists at Google Research in California managed to have their quantum system perform a mathematical calculation in **200 seconds that today's most powerful supercomputers would need more than 10,000 years to complete**.

*Quantum supremacy using a programmable superconducting processor*
Frank Arute et al.
***Nature*** volume 574, pages505–510 (2019)



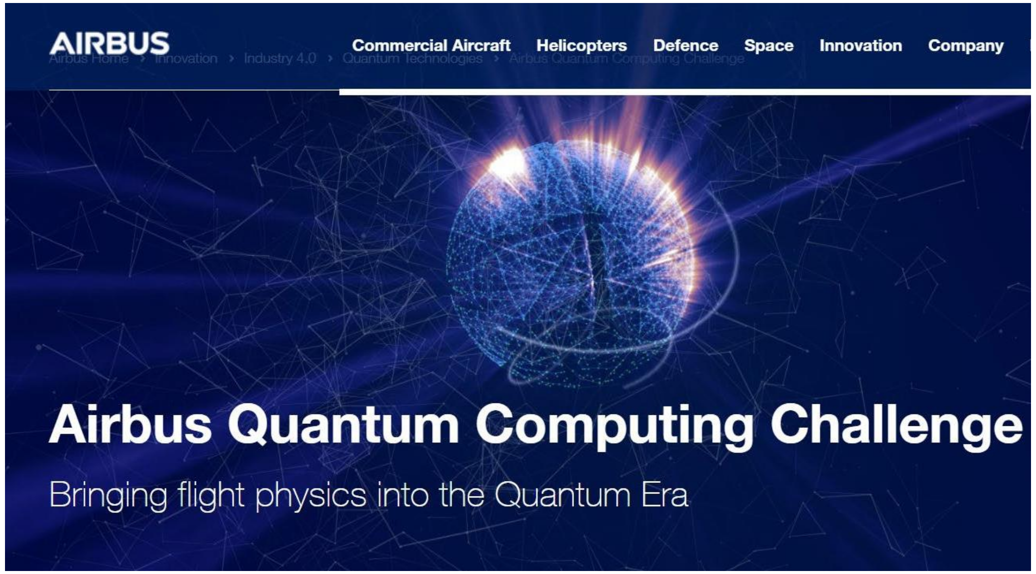



Microsoft Corporation created the **Microsoft Quantum Network** and Q# programming language for quantum computers.

**https://www.microsoft.com/en-us/quantum**

# Quantum Computing: Industrial Applications

pharmaceutical



aerospace engineering


automotive (electric)


cybersecurity

# How quantum computers could help design airplanes

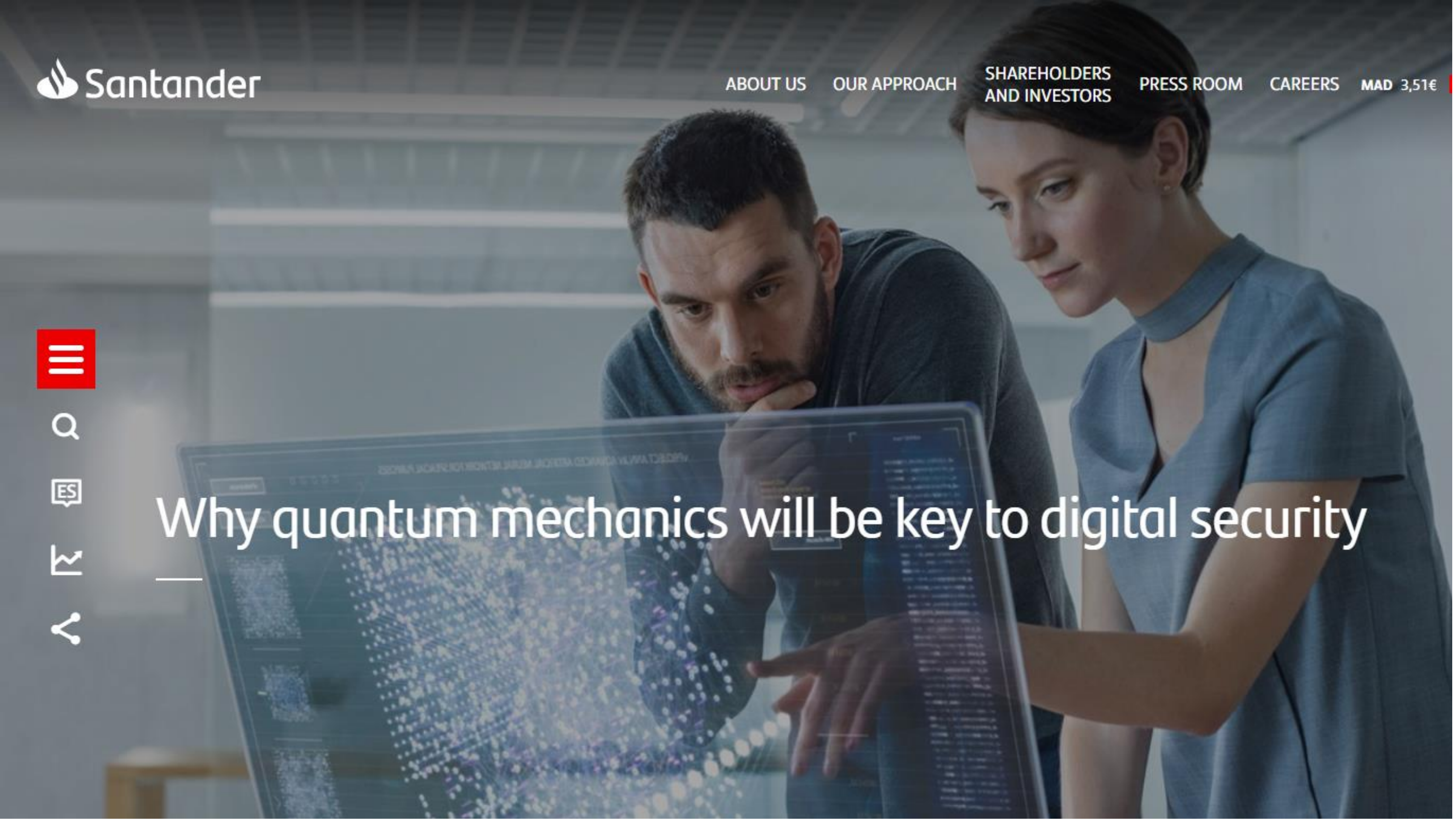
The Boeing Company is looking toward a future where their engineers use quantum computers to help design airplanes.

IBM and Boeing chart a streamlined quantum approach to one of the biggest challenges in aerospace engineering

Watch the video

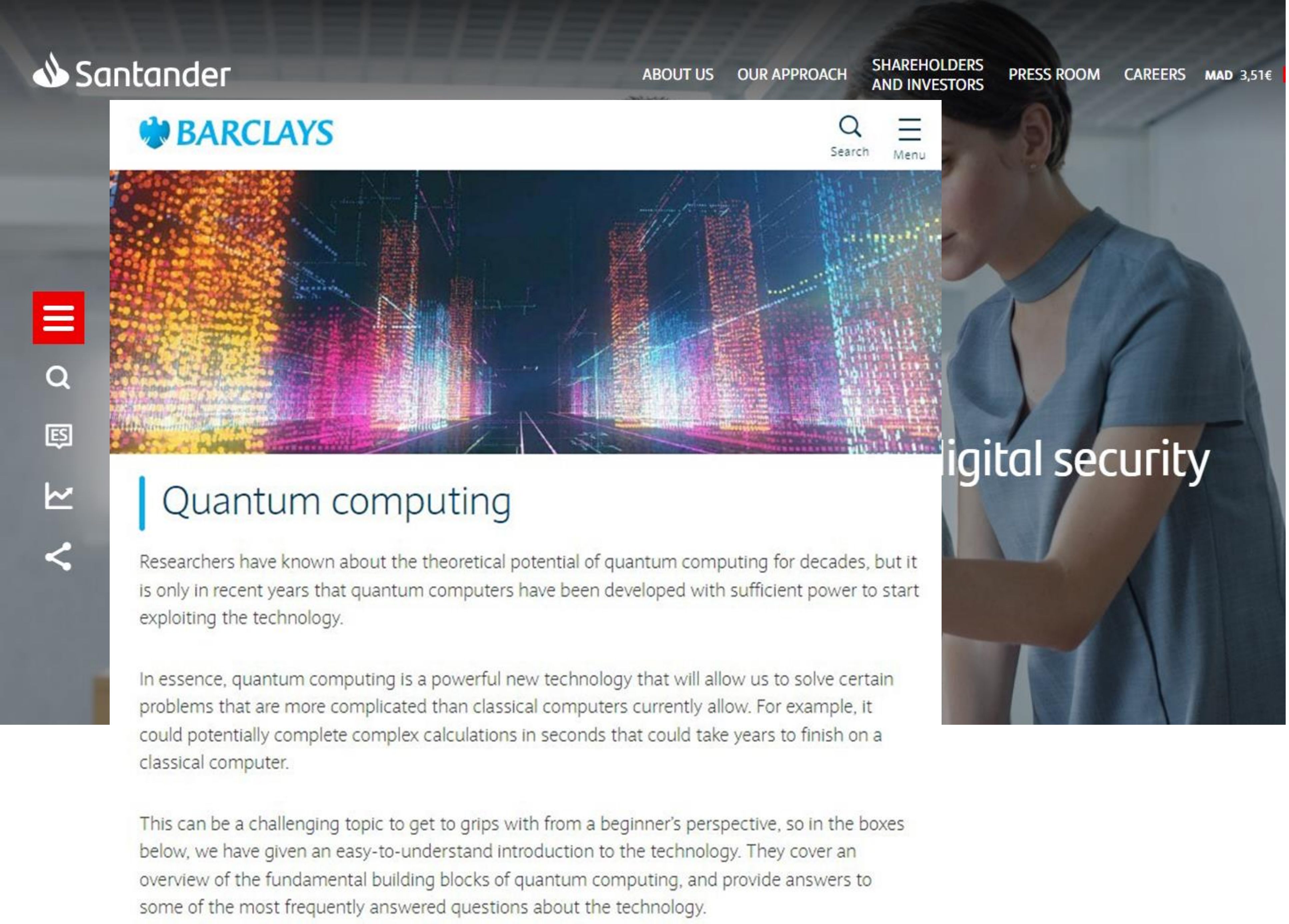
*VIDEO: Boeing seeks new ways to engineer strong, lightweight materials*

**https://youtu.be/BVG97KD9qVg**


Santander
ABOUT US
OUR APPROACH
SHAREHOLDERS AND INVESTORS
PRESS ROOM
CAREERS
MAD 3,51€
ES
Why quantum mechanics will be key to digital security

# Banking

# Banking



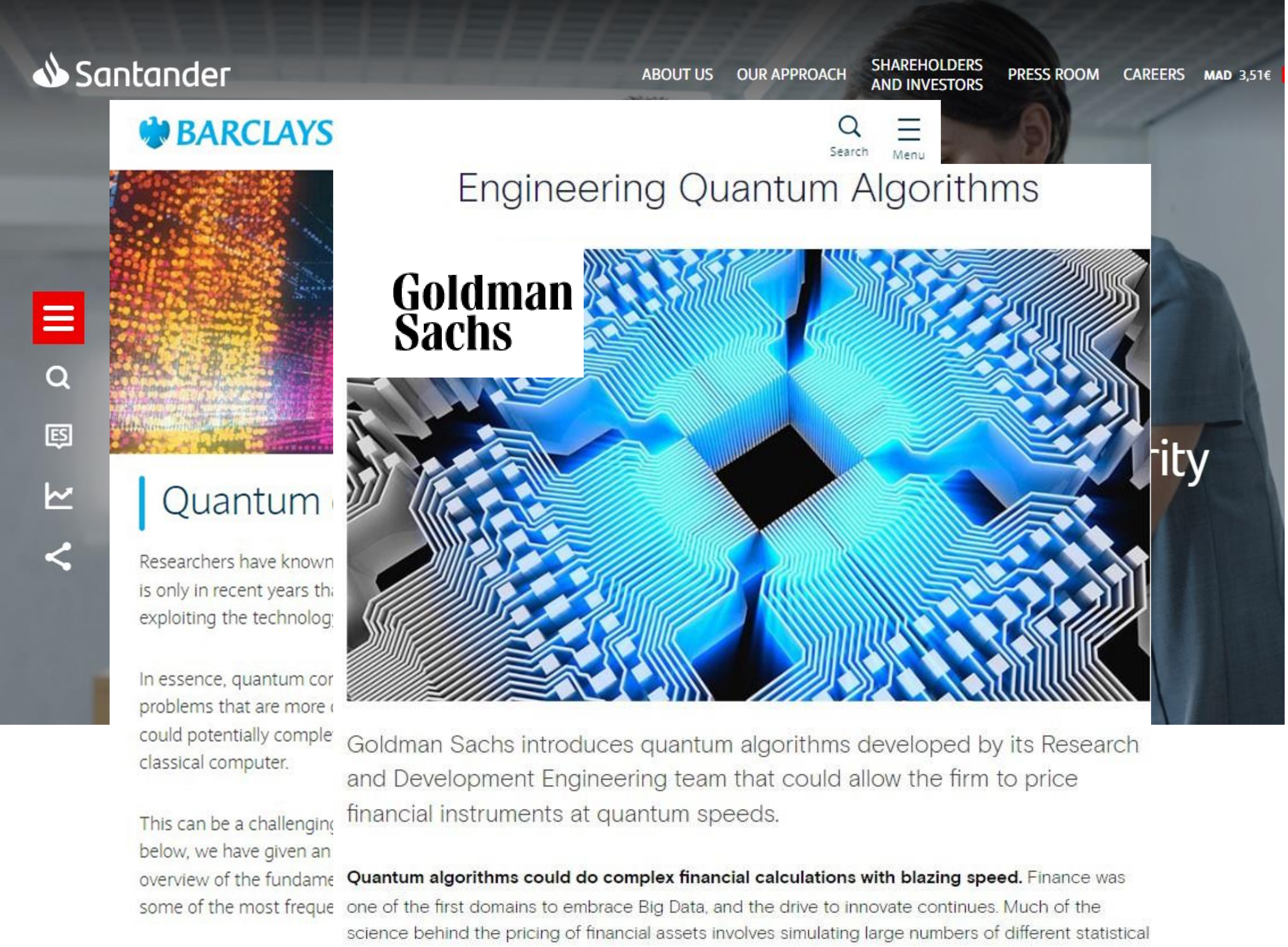

## Quantum computing

Researchers have known about the theoretical potential of quantum computing for decades, but it is only in recent years that quantum computers have been developed with sufficient power to start exploiting the technology.

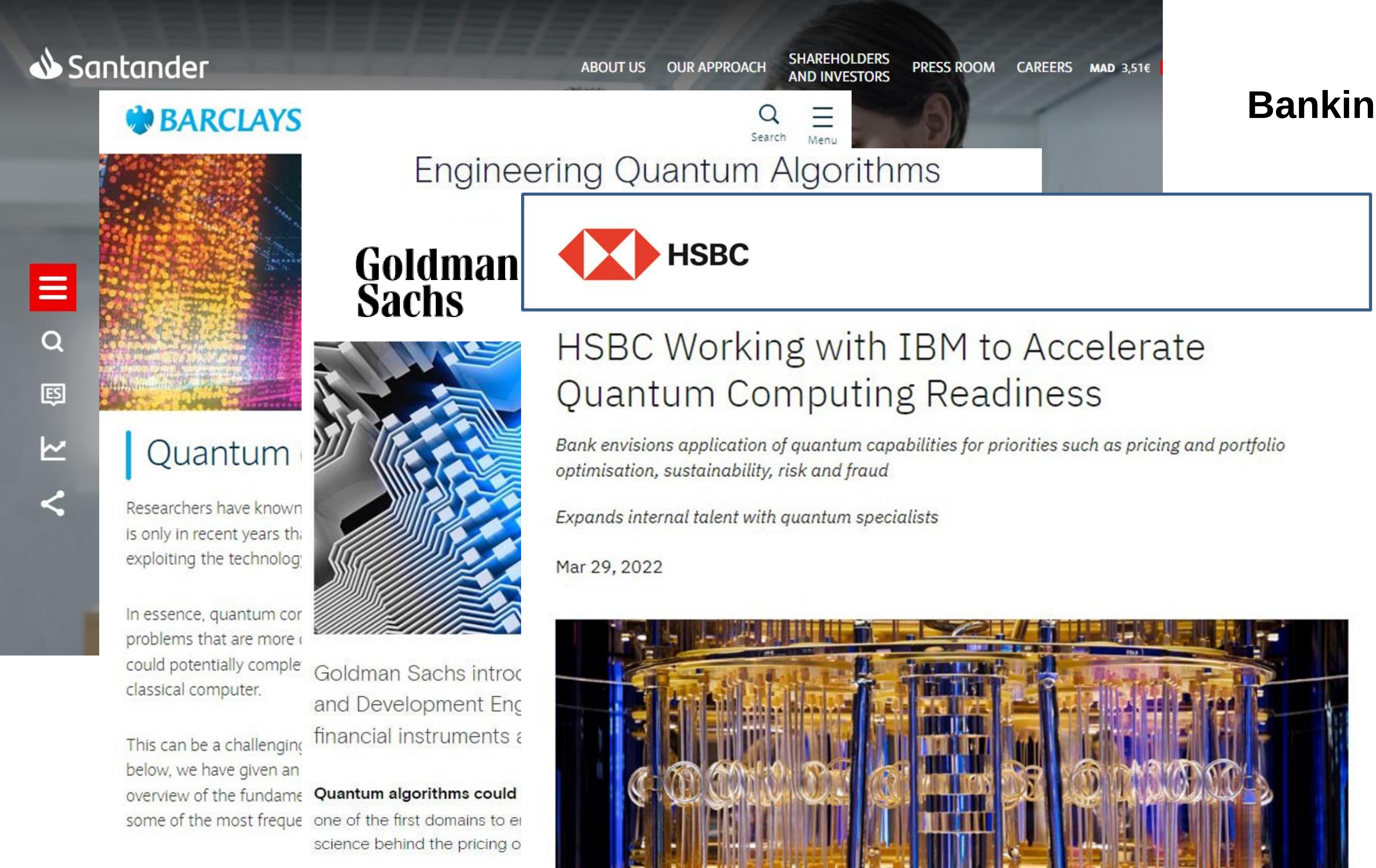
In essence, quantum computing is a powerful new technology that will allow us to solve certain problems that are more complicated than classical computers currently allow. For example, it could potentially complete complex calculations in seconds that could take years to finish on a classical computer.

This can be a challenging topic to get to grips with from a beginner's perspective, so in the boxes below, we have given an easy-to-understand introduction to the technology. They cover an overview of the fundamental building blocks of quantum computing, and provide answers to some of the most frequently answered questions about the technology.

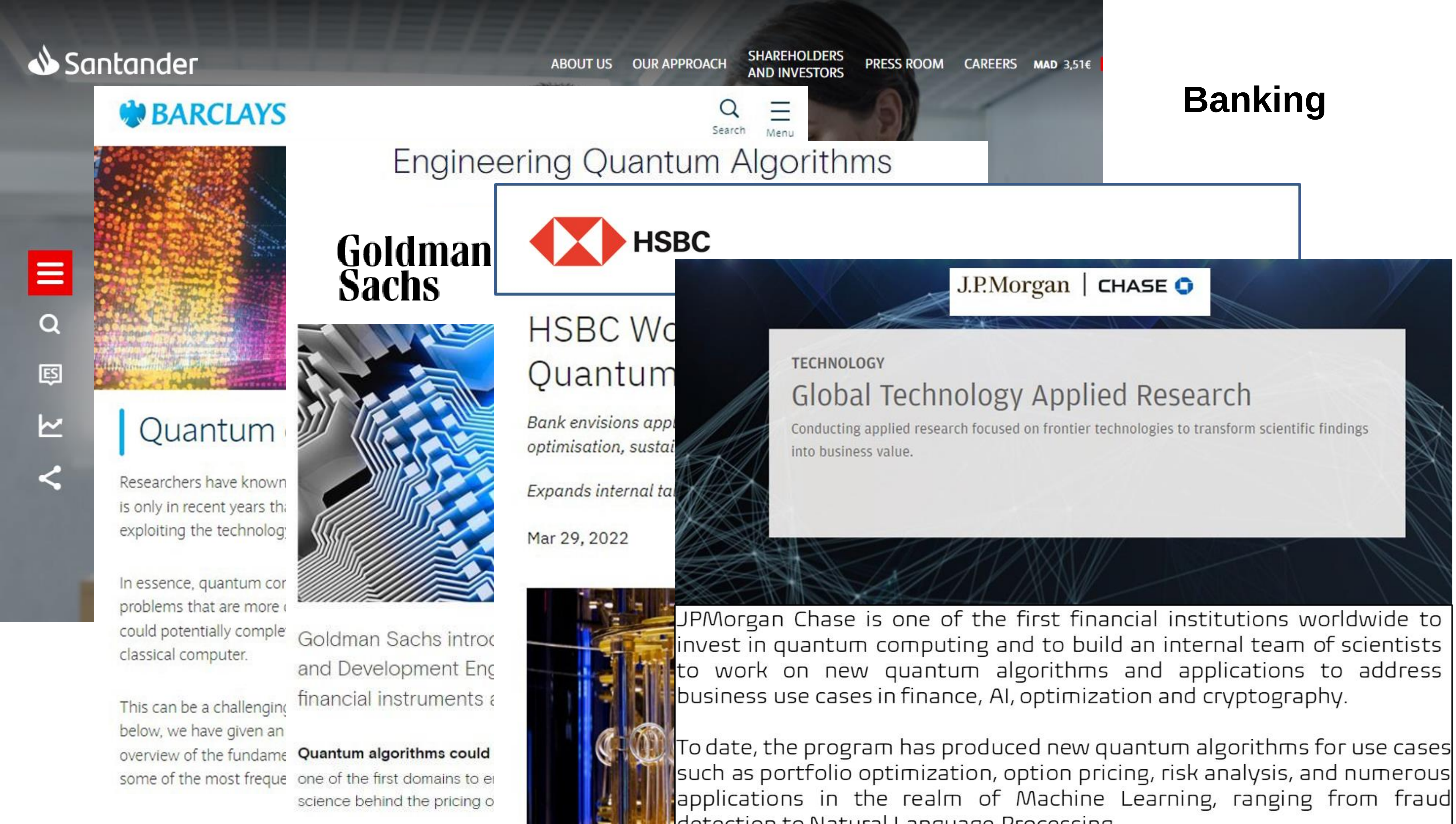
# Banking


Santander
ABOUT US
OUR APPROACH
SHAREHOLDERS AND INVESTORS
PRESS ROOM
CAREERS
MAD 3,51€
BARCLAYS
Search
Menu
Quantum
Researchers have known
is only in recent years th
exploiting the technolog
In essence, quantum co
problems that are more
could potentially comple
classical computer.
This can be a challengin
below, we have given an
overview of the fundame
some of the most freque
Engineering Quantum Algorithms
Goldman Sachs
Goldman Sachs introduces quantum algorithms developed by its Research and Development Engineering team that could allow the firm to price financial instruments at quantum speeds.
Quantum algorithms could do complex financial calculations with blazing speed. Finance was one of the first domains to embrace Big Data, and the drive to innovate continues. Much of the science behind the pricing of financial assets involves simulating large numbers of different statistical
rity

# Banking


Santander
ABOUT US
OUR APPROACH
SHAREHOLDERS AND INVESTORS
PRESS ROOM
CAREERS
MAD 3,51€
BARCLAYS
Search
Menu
Quantum
Researchers have known
is only in recent years th
exploiting the technolog
In essence, quantum cor
problems that are more
could potentially comple
classical computer.
This can be a challengin
below, we have given an
overview of the fundame
some of the most freque
Engineering Quantum Algorithms
Goldman Sachs
Goldman Sachs intro
and Development Eng
financial instruments
Quantum algorithms could
one of the first domains to e
science behind the pricing o
HSBC
HSBC Working with IBM to Accelerate Quantum Computing Readiness
Bank envisions application of quantum capabilities for priorities such as pricing and portfolio optimisation, sustainability, risk and fraud
Expands internal talent with quantum specialists
Mar 29, 2022

# Banking



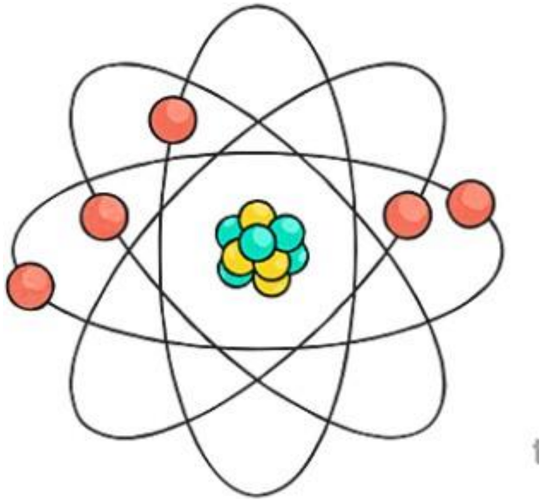

JPMorgan Chase is one of the first financial institutions worldwide to invest in quantum computing and to build an internal team of scientists to work on new quantum algorithms and applications to address business use cases in finance, AI, optimization and cryptography.

To date, the program has produced new quantum algorithms for use cases such as portfolio optimization, option pricing, risk analysis, and numerous applications in the realm of Machine Learning, ranging from fraud detection to Natural Language Processing

# Quantum Computing: The Key Concept

**size**

$10^{-15}$ m

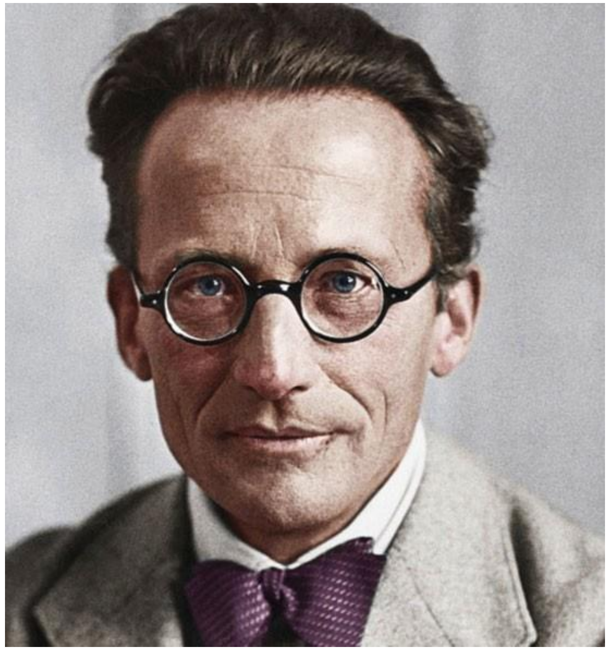


**MICROSCOPIC WORLD**

$10^{+6}$ m

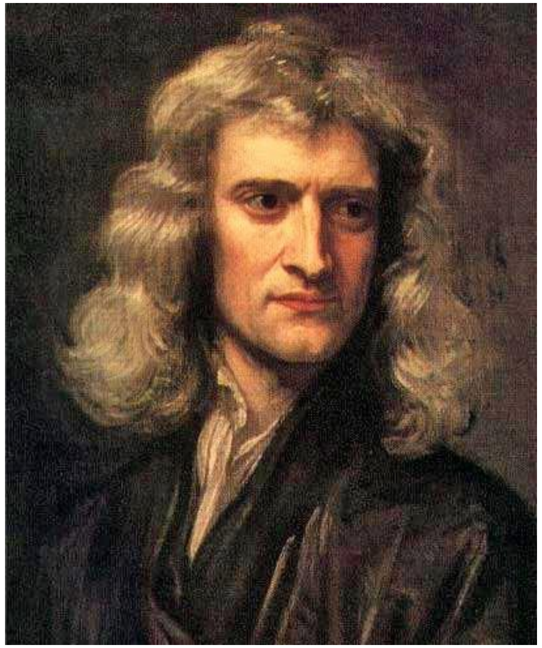
**MACROSCOPIC WORLD**

Schroedinger



**MICROSCOPIC WORLD**

Newton



**MACROSCOPIC WORLD**

Schroedinger

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

**MICROSCOPIC WORLD**

Newton

$$F = G\frac{m_1 m_2}{r^2}$$

**MACROSCOPIC WORLD**

The laws of physics are different depending on your scale (size)

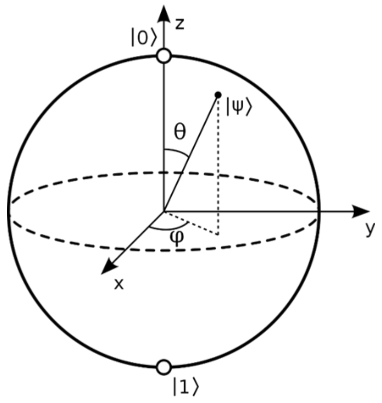
The laws of physics are different depending on your scale (size)

**Quantum computers are machines that allow us to operate in the microscopic world – the quantum world**

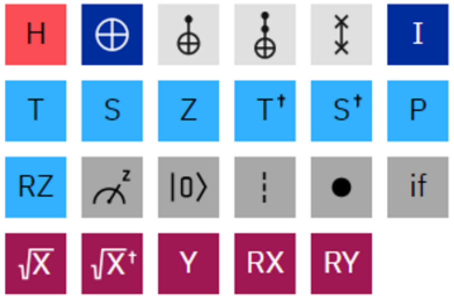
# Quantum Computing: The Three Ingredients

# The Three Ingredients

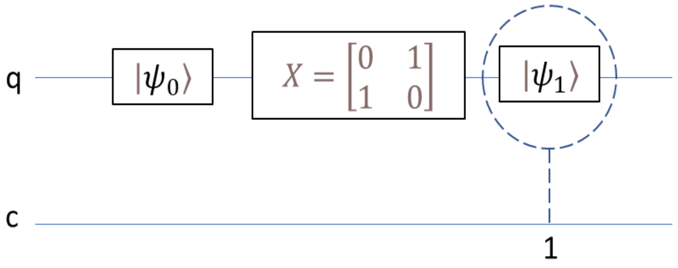
## 1: Qubits




## 2: Quantum Gates




## 3: Quantum Circuits



# Ingredient 1: Qubits

# Definition

**qubit = quantum bit**

# Definition

**bits = black/white**

**qubits = color**

# Definition

bits = black/white


qubits = color

**Definition**

*A qubit $|\psi\rangle$ can be regarded as a vector in a two dimensional complex vector space, where $|0\rangle$ and $|1\rangle$ form its orthonormal basis, called the computational basis."*

$$|\psi\rangle = a\,|0\rangle + b\,|1\rangle$$

qubit

complex, amplitude

vector, direction $|0\rangle$

complex, amplitude

vector, direction $|1\rangle$

## Definition

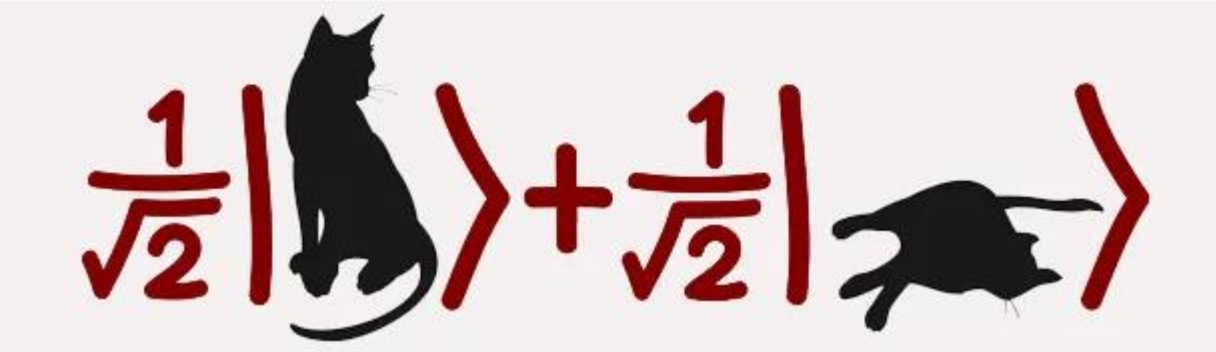
*A qubit $|\psi\rangle$ can be regarded as a vector in a two dimensional complex vector space, where $|0\rangle$ and $|1\rangle$ form its orthonormal basis, called the computational basis."*

$$|\psi\rangle =$$

qubit

## Definition

*A qubit $|\psi\rangle$ can be regarded as a vector in a two dimensional complex vector space, where $|0\rangle$ and $|1\rangle$ form its orthonormal basis, called the computational basis."*

$|\psi\rangle =$ 

qubit

mixed state

cat alive

cat dead

# Definition

**Definition** **visual representation of a qubit**

## Definition visual representation of a qubit

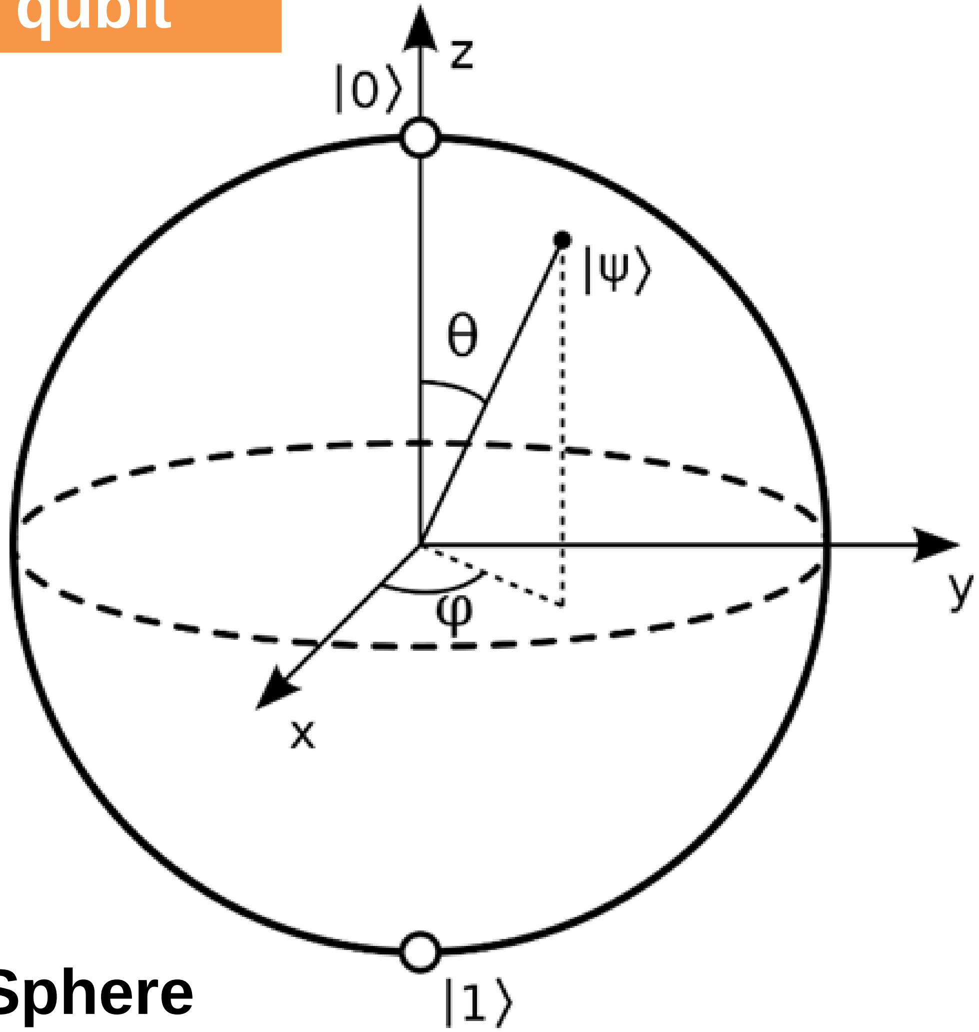
Felix Bloch demonstrated that **any qubit can represented as a point on the surface of a sphere** with two degrees of freedom (Euler's angles)

$$|\psi\rangle = cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\, sin\left(\frac{\theta}{2}\right)|1\rangle$$

**Definition** **visual representation of a qubit**

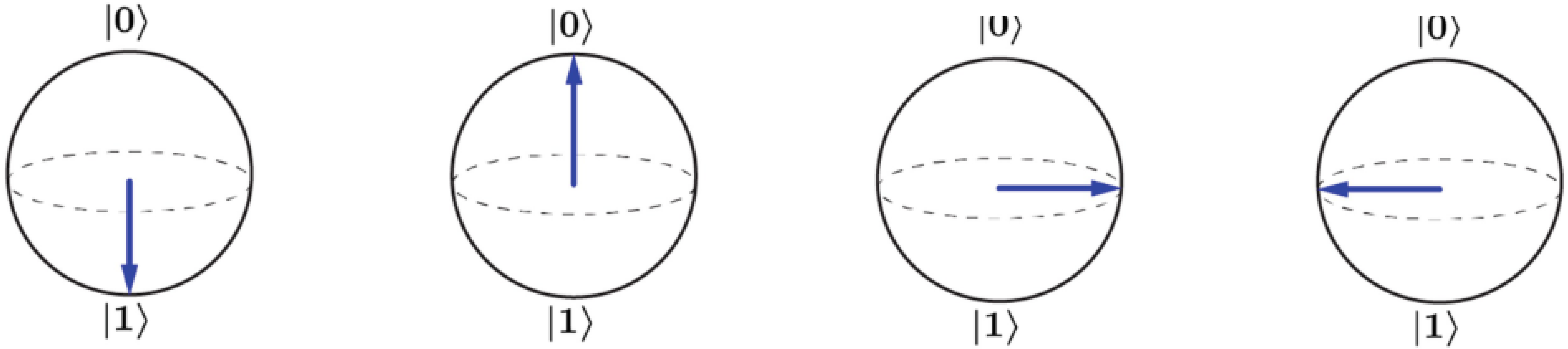
Felix Bloch demonstrated that **any qubit can represented as a point on the surface of a sphere** with two degrees of freedom (Euler's angles)

$$|\psi\rangle = cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\varphi}\, sin\left(\frac{\theta}{2}\right)|1\rangle$$




**Bloch Sphere**

**Definition** **visual representation of a qubit**




$|\Psi\rangle = |1\rangle$ $\quad$ $|\Psi\rangle = |0\rangle$ $\quad$ $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ $\quad$ $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$

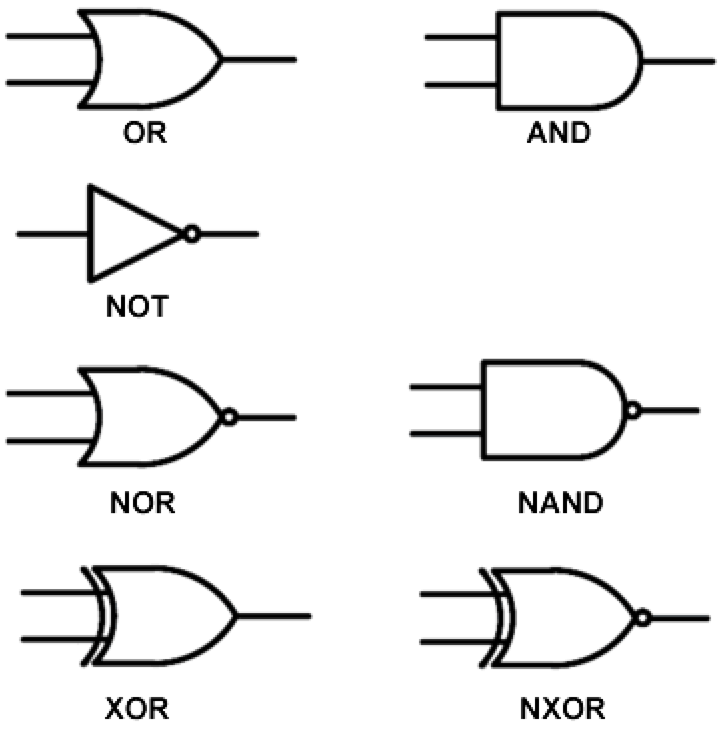
**Examples**

# Ingredient 2: Quantum Gates

## Quantum Gates **Classical Gates**

Classical gates allow the transformation of certain inputs into certain outputs according to some logical rules.

**Inputs: binary (0, 1)**
**Output: binary (0, 1)**



Ingredient 2: Quantum Gates

# Quantum Gates

Quantum Gates

Quantum gates allow the transformation of quantum information into quantum information following certain matrix rules.

**Inputs: qubit**
**Output: qubit**

| Creation Function | Gate Name | Matrix Representation |
|---|---|---|
| H hGate | Hadamard gate | $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$ |
| ID idGate | Identity gate | $\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$ |
| X xGate | Pauli X gate | $\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$ |
| Y yGate | Pauli Y gate | $\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$ |
| Z zGate | Pauli Z gate | $\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$ |

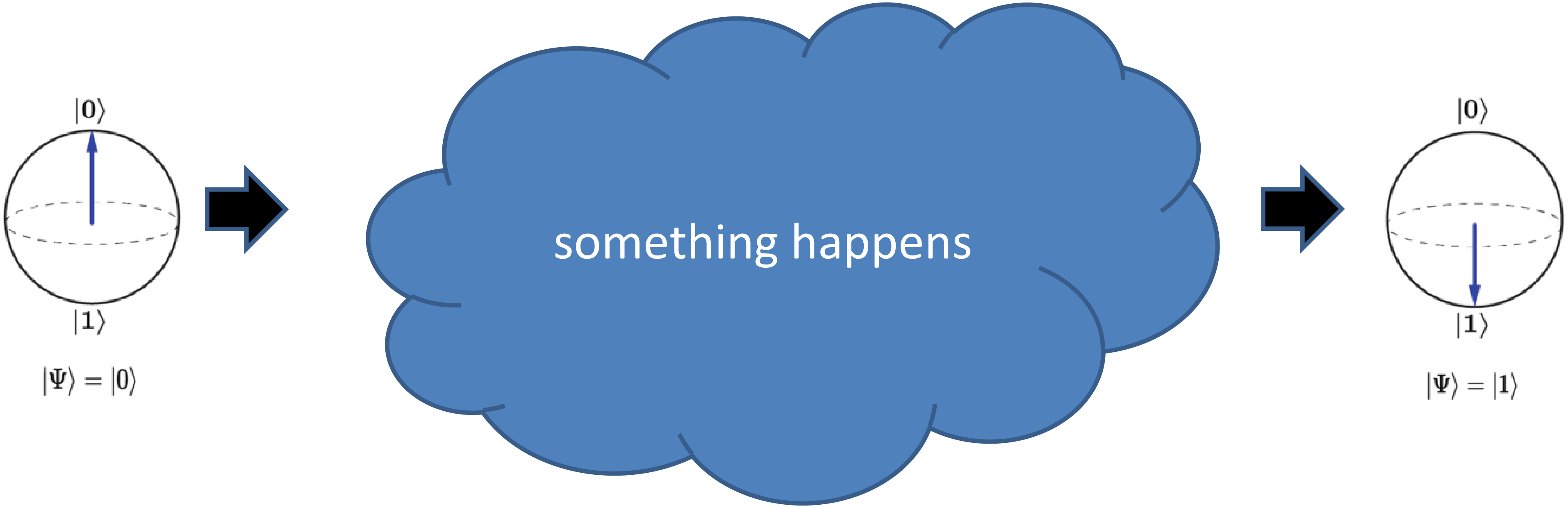
# Ingredient 3: Quantum Circuit

# Quantum Circuit

a series of quantum gates (matrix operations) applied to qubits

# Quantum Circuit

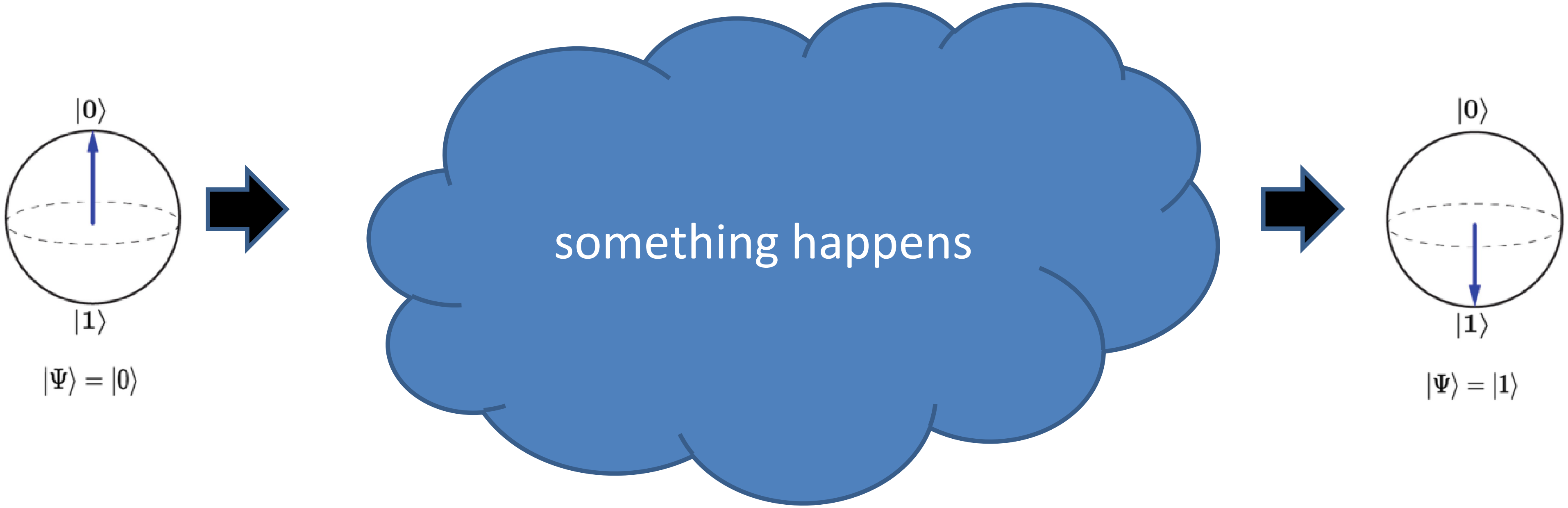
a series of quantum gates (matrix operations) applied to qubits



Ingredient 3: Quantum Circuits

**Quantum Circuit** **Example: circuit to flip qubit (i.e. Hello World)**

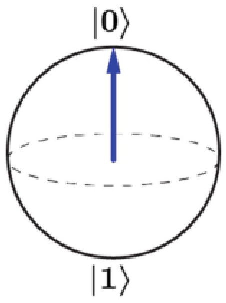
a series of quantum gates (matrix operations) applied to qubits



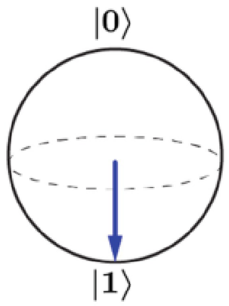
## Quantum Circuit

**Example: circuit to flip qubit (i.e. Hello World)**

a series of quantum gates (matrix operations) applied to qubits




$|\Psi\rangle = |0\rangle$

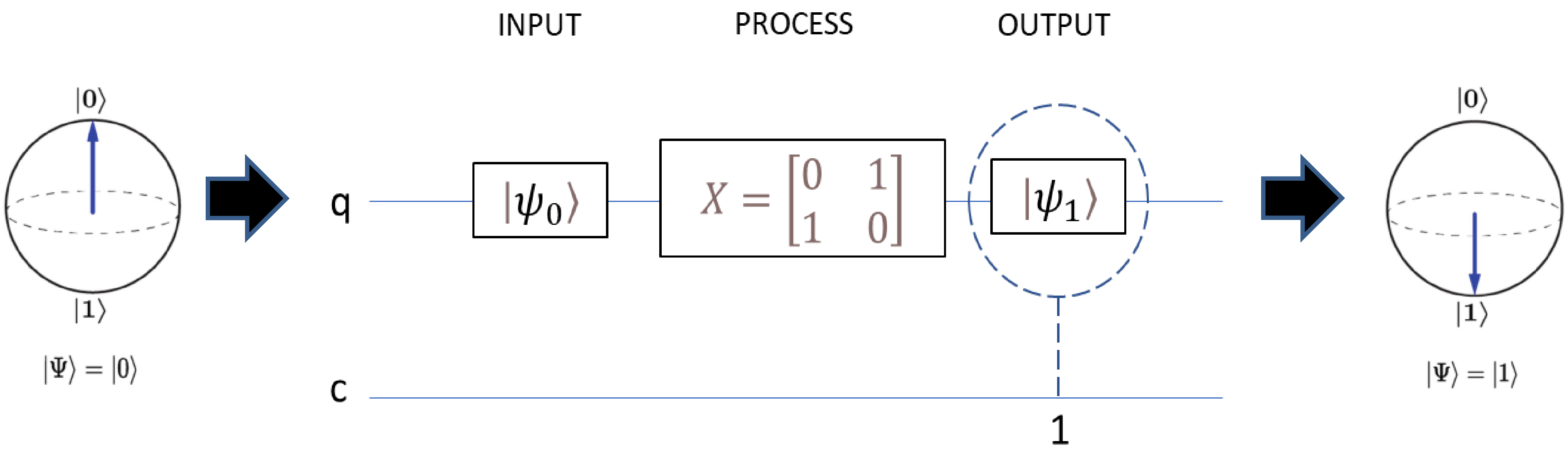



$|\Psi\rangle = |1\rangle$

## Quantum Circuit

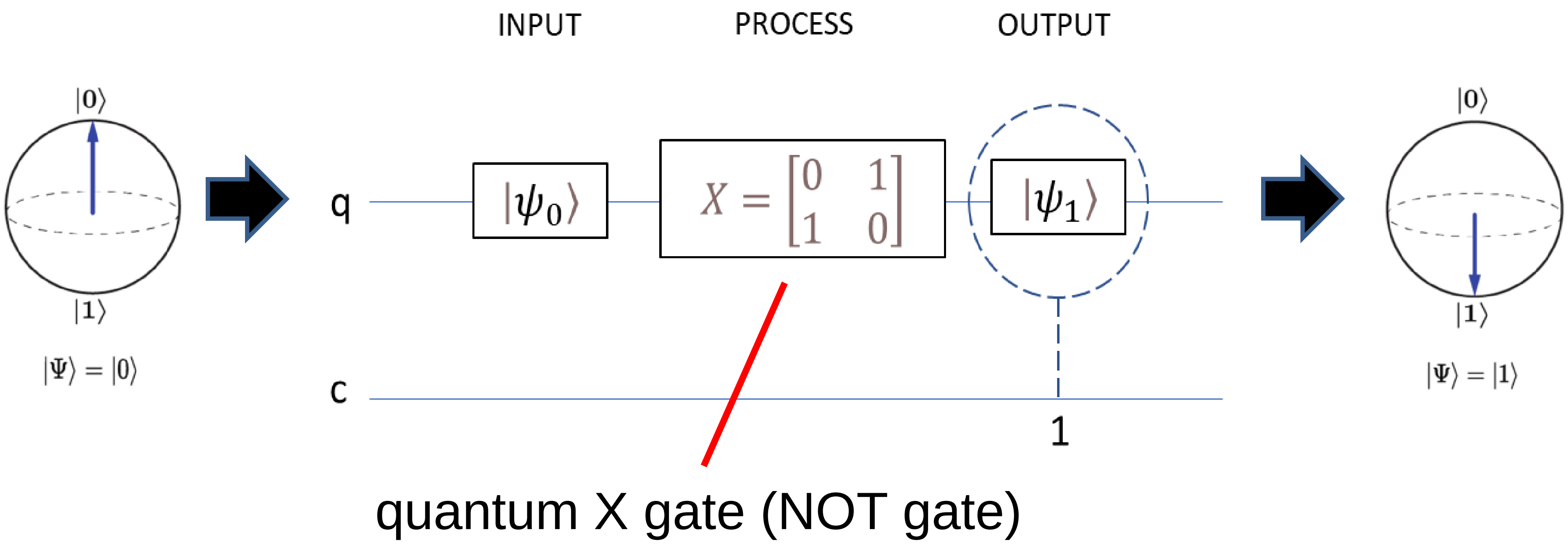
**Example: circuit to flip qubit (i.e. Hello World)**

a series of quantum gates (matrix operations) applied to qubits



**Quantum Circuit** **Example: circuit to flip qubit (i.e. Hello World)**

a series of quantum gates (matrix operations) applied to qubits



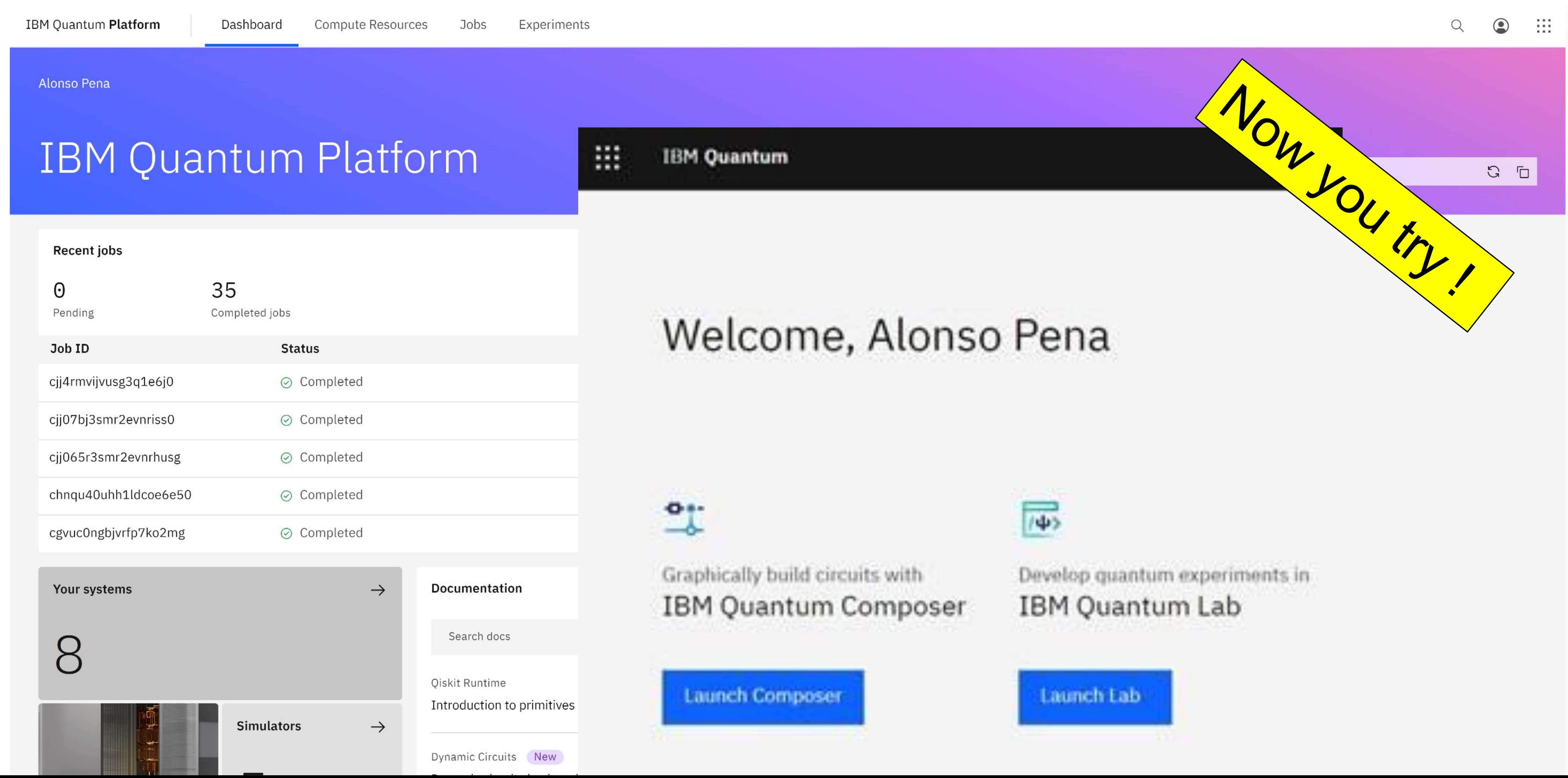
Now you try !

Quantum Computing: In Practice

Now you try !

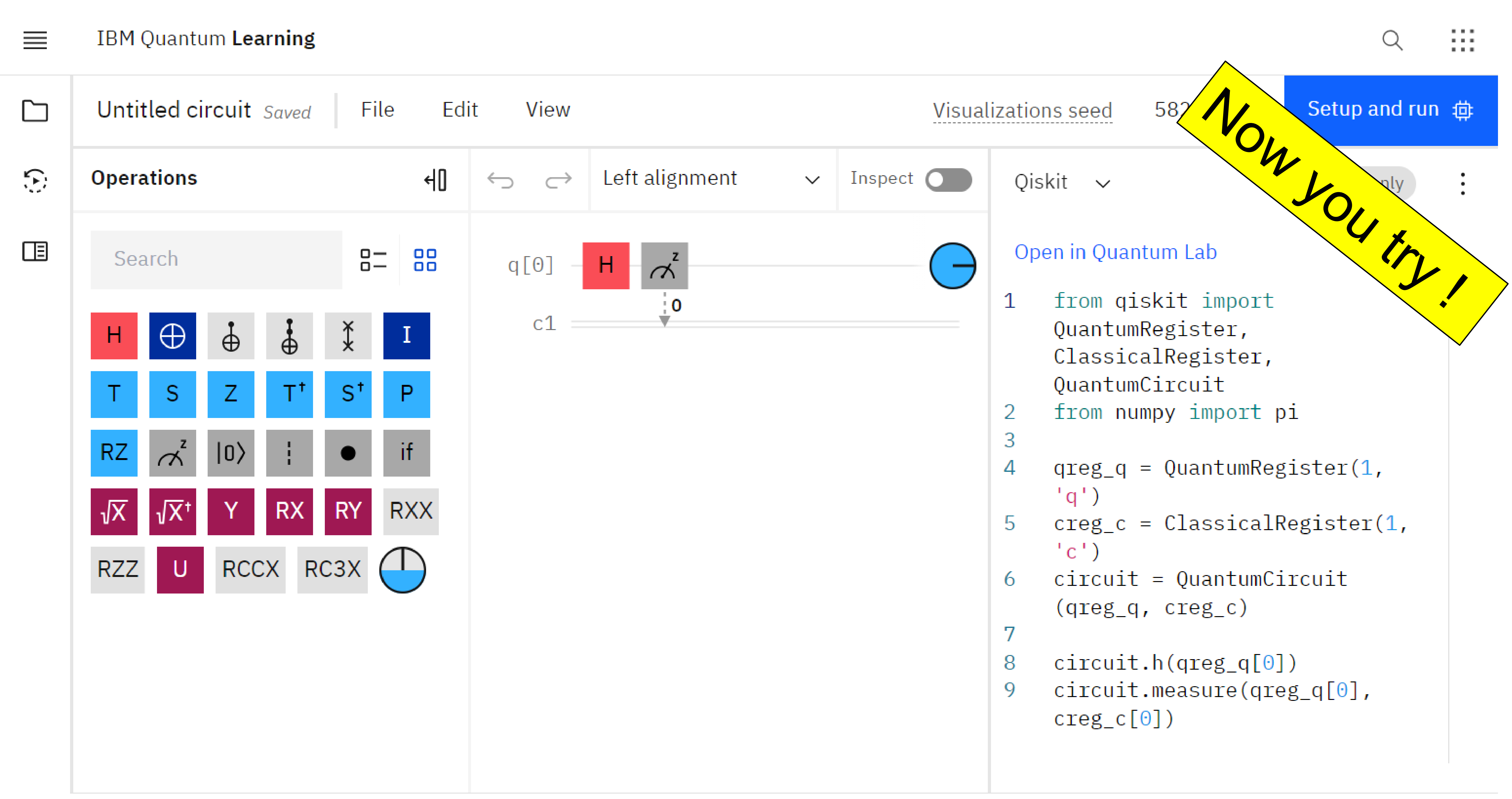
Now you try !

**www.ibm.com/quantum**




Now you try !

Register FREE and use the online platform




Construct your own quantum circuits at IBM Quantum Composer

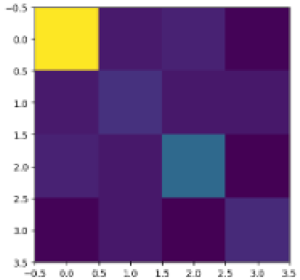
Qiskit

python™

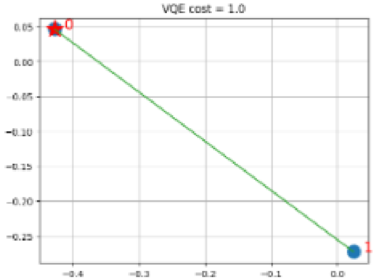
Now you try !

# Finance Tutorials ¶

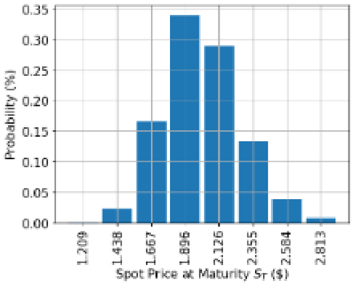
Quantum Amplitude Estimation



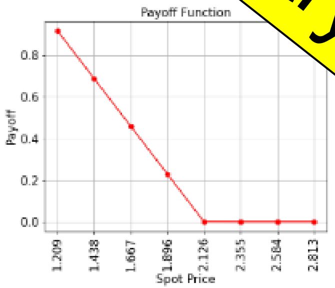
Portfolio Optimization



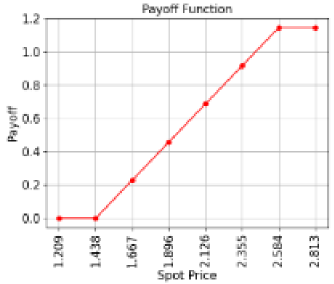

Portfolio Diversification



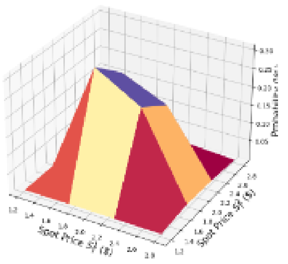

Pricing European Call Options



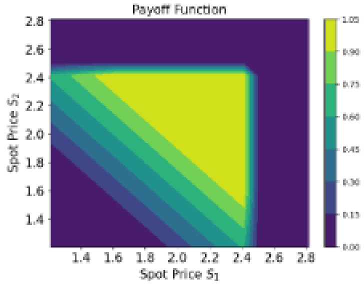

Pricing European Put Options



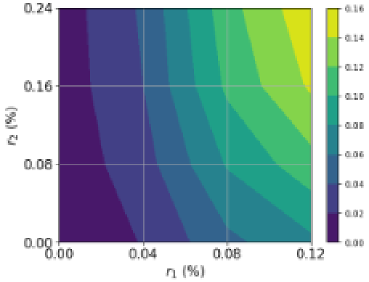

Pricing Bull Spreads



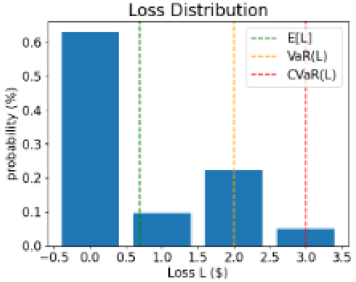
Pricing Basket Options




Pricing Asian Barrier Spreads




Pricing Fixed-Income Assets




Credit Risk Analysis

Write and run your own quantum Python programs at IBM Quantum Lab

Bamboo Paper

IBM Quantum Learning

File Edit View Run Kernel Tabs Settings Help

Markdown

3 (ipykernel)

Now you try !

# Pricing European Call Options

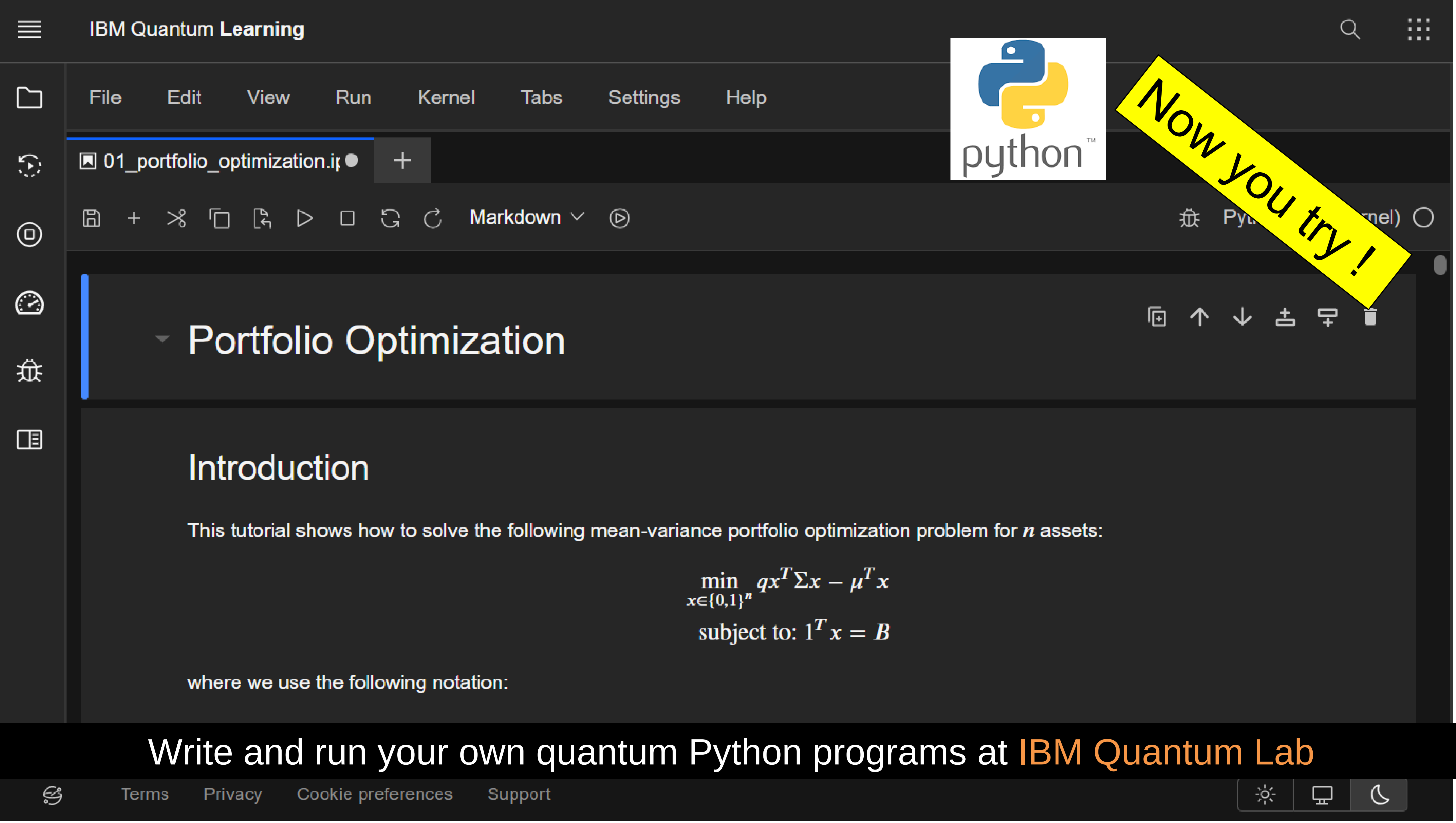
## Introduction

Suppose a European call option with strike price $K$ and an underlying asset whose spot price at maturity $S_T$ follows a given random distribution. The corresponding payoff function is defined as:

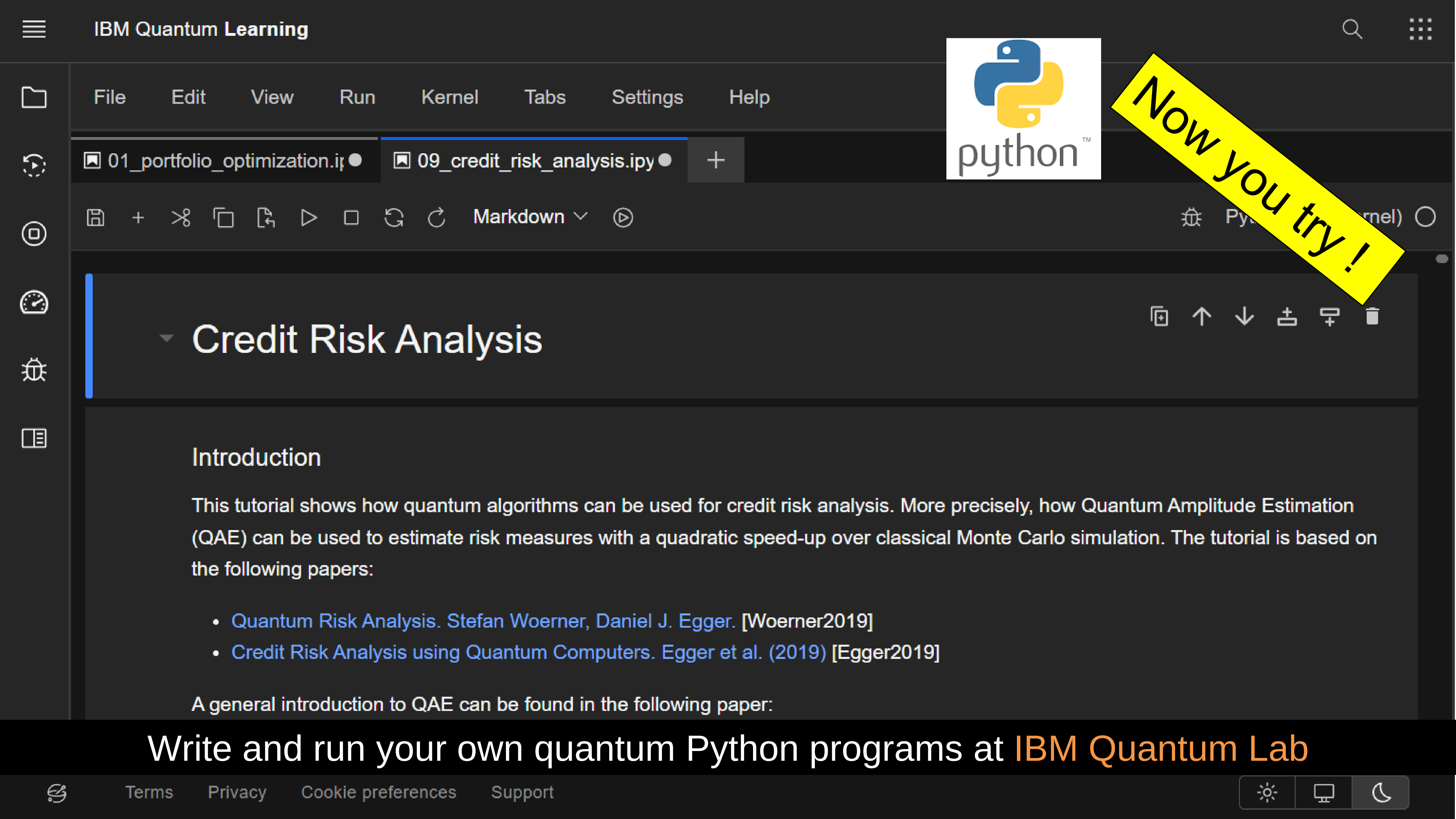
$$\max\{S_T - K, 0\}$$

In the following, a quantum algorithm based on amplitude estimation is used to estimate the expected payoff, i.e., the fair price before discounting, for the option:

Write and run your own quantum Python programs at IBM Quantum Lab

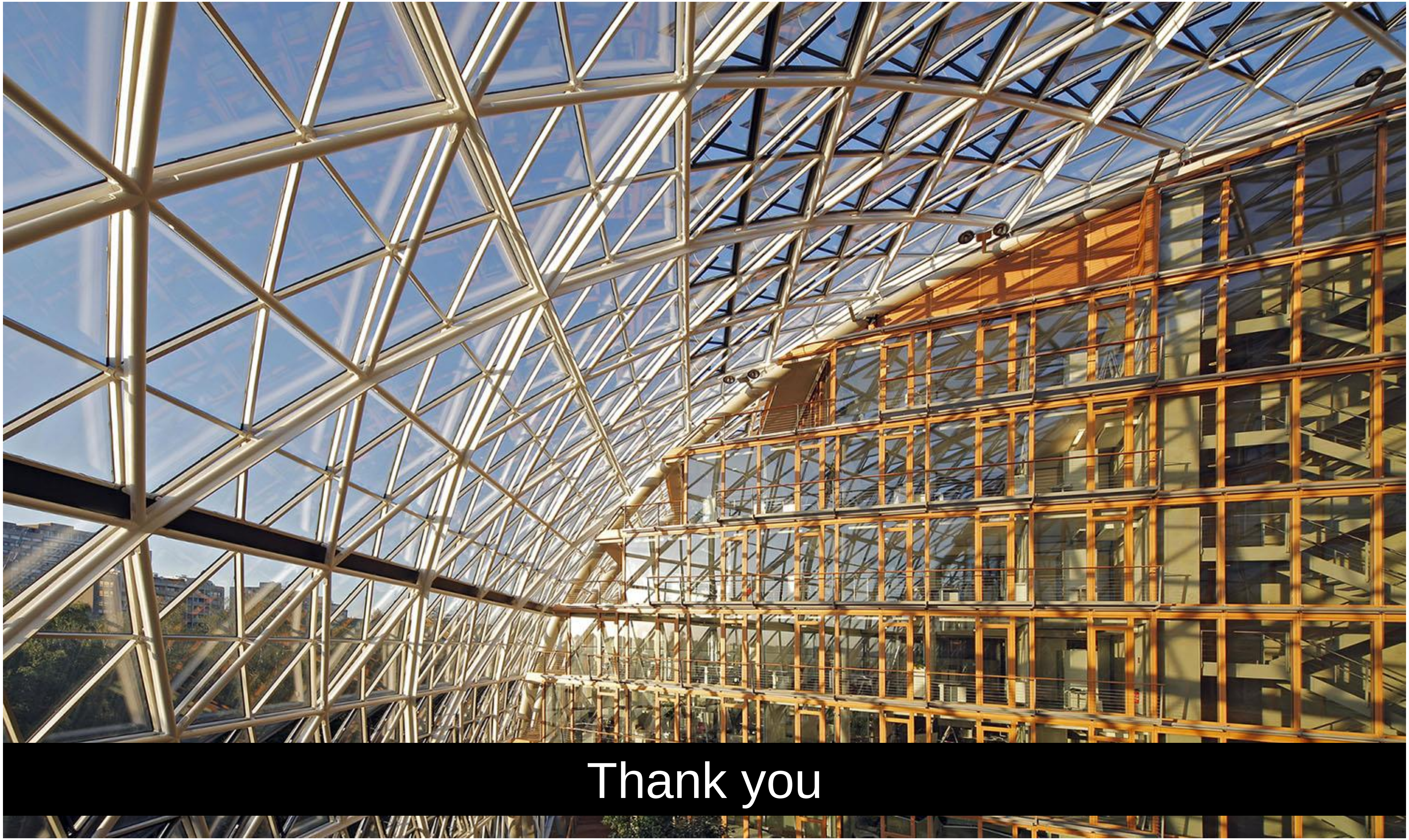



Write and run your own quantum Python programs at IBM Quantum Lab




Now you try !

Write and run your own quantum Python programs at IBM Quantum Lab



Thank you

# Quantum Computing: References


EXPERT INSIGHT
Dancing with Qubits
How quantum computing works and how it can change the world
Robert S. Sutor
Quantum Computation and Quantum Information
MICHAEL A. NIELSEN and ISAAC L. CHUANG
Quantum Science and Technology
Christian Kollmitzer
Stefan Schauer
Stefan Rass
Benjamin Rainer Editors
Quantum Random Number Generation
Theory and Practice
Springer
QUANTUM COMPUTING FOR COMPUTER SCIENTISTS
Noson S. Yanofsky
Mirco A. Mannucci
N. David Mermin
Quantum Computer Science
An Introduction

Quantum Information Processing (2023) 22:51
https://doi.org/10.1007/s11128-022-03777-2

# Quantum computing for financial risk measurement

Sascha Wilkens[1] · Joe Moorhouse[2]

Received: 12 February 2022 / Accepted: 25 November 2022


**Abstract**

Quantum computing allows a significant speed-up over traditional CPU- and GPU-based algorithms when applied to particular mathematical challenges such as optimisation and simulation. Despite promising advances and extensive research in hard- and software developments, currently available quantum systems are still largely limited in their capability. In line with this, practical applications in quantitative finance are still in their infancy. This paper analyses requirements and concrete approaches for the application to risk management in a financial institution. On the examples of Value-at-Risk for market risk and Potential Future Exposure for counterparty credit risk, the main contribution lies in going beyond textbook illustrations and instead

www.nature.com/scientificreports

scientific reports

Check for updates

OPEN

# Copula-based risk aggregation with trapped ion quantum computers

Daiwei Zhu[1,3]✉, Weiwei Shen[2,3], Annarita Giani[2], Saikat Ray-Majumder[2], Bogdan Neculaes[2] & Sonika Johri[1]

Copulas are mathematical tools for modeling joint probability distributions. In the past 60 years they have become an essential analysis tool on classical computers in various fields. The recent finding that copulas can be expressed as maximally entangled quantum states has revealed a promising approach to practical quantum advantages: performing tasks faster, requiring less memory, or, as we show, yielding better predictions. Studying the scalability of this quantum approach as both the precision and the number of modeled variables increase is crucial for its adoption in real-world applications. In this paper, we successfully apply a Quantum Circuit Born Machine (QCBM) based approach to modeling 3- and 4-variable copulas on trapped ion quantum computers. We study the training of QCBMs with different levels of precision and circuit design on a simulator and a state-of-the-art trapped ion quantum computer. We observe decreased training efficacy due to the increased complexity in parameter optimization as the models scale up. To address this challenge, we introduce an annealing-inspired strategy that dramatically improves the training results. In our end-to-end tests, various configurations of the quantum models make a comparable or better prediction in risk aggregation tasks than the standard classical models.

# Option Pricing using Quantum Computers

Nikitas Stamatopoulos[1], Daniel J. Egger[2], Yue Sun[1], Christa Zoufal[2,3], Raban Iten[2,3], Ning Shen[1], and Stefan Woerner[2]

[1]Quantitative Research, JPMorgan Chase & Co., New York, NY, 10017

[2]IBM Quantum, IBM Research – Zurich

[3]ETH Zurich



**We present a methodology to price options and portfolios of options on a gate-based quantum computer using amplitude estimation, an algorithm which provides a quadratic speedup compared to classical Monte Carlo methods. The options that we cover include vanilla options, multi-asset options and path-dependent options such as barrier options. We put an emphasis on the implementation of the quantum circuits required to build the input states and operators needed by amplitude estimation to price the different option types. Additionally, we show simulation results to highlight how the circuits that we implement price the different option contracts. Finally, we examine the performance of option pricing circuits on quantum hardware using the IBM Q Tokyo quantum device. We employ a simple, yet ef-**

ist for the simplest types of options [2], the simplifying assumptions on the market dynamics required for the models to provide closed-form solutions often limit their applicability [3]. Hence, more often than not, numerical methods have to be employed for option pricing, with Monte Carlo being one of the most popular due to its flexibility and ability to generically handle stochastic parameters [4, 5]. However, despite their attractive features in option pricing, classical Monte Carlo methods generally require extensive computational resources to provide accurate option price estimates, particularly for complex options. Because of the widespread use of options in the finance industry, accelerating their convergence can have a significant impact in the operations of a financial institution.

By leveraging the laws of quantum mechanics a

npj | Quantum Information www.nature.com/npjqi

ARTICLE OPEN

# Quantum risk analysis

Stefan Woerner[1] and Daniel J. Egger[1]

We present a quantum algorithm that analyzes risk more efficiently than Monte Carlo simulations traditionally used on classical computers. We employ quantum amplitude estimation to price securities and evaluate risk measures such as Value at Risk and Conditional Value at Risk on a gate-based quantum computer. Additionally, we show how to implement this algorithm and how to trade-off the convergence rate of the algorithm and the circuit depth. The shortest possible circuit depth—growing polynomially in the number of qubits representing the uncertainty—leads to a convergence rate of $O(M^{-2/3})$, where $M$ is the number of samples. This is already faster than classical Monte Carlo simulations which converge at a rate of $O(M^{-1/2})$. If we allow the circuit depth to grow faster, but still polynomially, the convergence rate quickly approaches the optimum of $O(M^{-1})$. Thus, for slowly increasing circuit depths our algorithm provides a near quadratic speed-up compared to Monte Carlo methods. We demonstrate our algorithm using two toy models. In the first model we use real hardware, such as the IBM Q Experience, to price a Treasury-bill (T-bill) faced by a possible interest rate increase. In the second model, we simulate our algorithm to illustrate how a quantum computer can determine financial risk for a two-asset portfolio made up of government debt with different maturity dates. Both models confirm the improved convergence rate over Monte Carlo methods. Using simulations, we also evaluate the impact of cross-talk and energy relaxation errors.

*npj Quantum Information* (2019)5:15 ; https://doi.org/10.1038/s41534-019-0130-6

## INTRODUCTION

Risk management plays a central role in the financial system. Value at risk (VaR),[1] a quantile of the loss distribution, is a widely

It has already been shown how AE can be used to price financial derivatives with the Black–Scholes model.[13,14]

In this article, we extend the use of AE to the calculation of

# Quantum Computation for Pricing the Collateralized Debt Obligations

Hao Tang,[1,2,*] Anurag Pal,[1,2] Tian-Yu Wang,[1,2] Lu-Feng Qiao,[1,2] Jun Gao,[1,2] and Xian-Min Jin[1,2,†]

[1] *Center for Integrated Quantum Information Technologies (IQIT), School of Physics and Astronomy and State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China*

[2] *CAS Center for Excellence and Synergetic Innovation Center in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

**Collateralized debt obligation (CDO) has been one of the most commonly used structured financial products and is intensively studied in quantitative finance. By setting the asset pool into different tranches, it effectively works out and redistributes credit risks and returns to meet the risk preferences for different tranche investors. The copula models of various kinds are normally used for pricing CDOs, and the Monte Carlo simulations are required to get their numerical solution. Here we implement two typical CDO models, the single-factor Gaussian copula model and Normal Inverse Gaussian copula model, and by applying the conditional independence approach, we manage to load each model of distribution in quantum circuits. We then apply quantum amplitude estimation as an alternative to Monte Carlo simulation for CDO pricing. We demonstrate the quantum computation results using IBM Qiskit. Our**

only a few stochastic equations for derivative pricing have found analytical solutions[20,21], while most can only be solved numerically by repeating random settings a great many times in an uncertainty distribution (*e.g.* normal or log-normal distribution), which therefore consumes much time. The quantum amplitude estimation (QAE) algorithm was raised[32] in 2002. It is newly suggested as a promising alternative to the Monte Carlo method, as it shows a quadratic speedup comparing to the latter[10]. So far, applications of QAE for option pricing[11] and credit risk analysis[12] have been demonstrated.

Considering the wide use of Monte Carlo simulation and the large variety of pricing models, the involvement of quantum techniques in finance is still at its infancy. Credit derivatives are frequently mentioned financial instruments because of the strong demand for tackling default risks in finance industry. Collateralized debt obligation (CDO) is a multi-name credit derivative backed on a pool of portfolios of defaultable assets (loans, bonds,

# Quantum Algorithms for Portfolio Optimization

Iordanis Kerenidis
jkeren@irif.fr
CNRS, IRIF, Université Paris Diderot,
Paris, France

Anupam Prakash
anupam@irif.fr
CNRS, IRIF, Université Paris Diderot,
Paris, France

Dániel Szilágyi
dszilagyi@irif.fr
CNRS, IRIF, Université Paris Diderot,
Paris, France

## ABSTRACT

We develop the first quantum algorithm for the constrained portfolio optimization problem. The algorithm has running time $\widetilde{O}\left(n\sqrt{r}\frac{\zeta\kappa}{\delta^2}\log\left(1/\epsilon\right)\right)$, where $r$ is the number of positivity and budget constraints, $n$ is the number of assets in the portfolio, $\epsilon$ the desired precision, and $\delta, \kappa, \zeta$ are problem-dependent parameters related to the well-conditioning of the intermediate solutions. If only a moderately accurate solution is required, our quantum algorithm can achieve a polynomial speedup over the best classical algorithms with complexity $\widetilde{O}\left(\sqrt{r}n^{\omega}\log(1/\epsilon)\right)$, where $\omega$ is the matrix multiplication exponent that has a theoretical value of around 2.373, but is closer to 3 in practice.

We also provide some experiments to bound the problem-dependent factors arising in the running time of the quantum algorithm, and these experiments suggest that for most instances the quantum algorithm can potentially achieve an $O(n)$ speedup over its classical counterpart.

## KEYWORDS

It has been suggested that quantum techniques like Feynman integrals could be useful for option pricing [3]. There has also been experimental work where the IBM quantum computers have been used to explore quadratic speedups for option pricing [24, 29] and work on quadratic speedups for option pricing using Monte Carlo methods [26]. While some of these results lack provable guarantees, they indicate the strong interest in both the quantum algorithms and mathematical Finance communities in developing applications of quantum computers to computational finance.

Very recently, Lloyd and Rebentrost [27] proposed a quantum algorithm for the unconstrained portfolio optimization problem. Their algorithm uses quantum linear system solvers to obtain speedups for portfolio optimization problems that can be reduced to unconstrained quadratic programs, which in turn are reducible to a single linear system. The main limitation of their algorithm is that it can not incorporate positivity or budget constraints, thus restricting its applicability to real world problems that can have complex budget constraints. The reason for this limitation is algorithmic, the constrained portfolio optimization problem is known to be equivalent to quadratic programming (QP), a class of optimization problems

# Credit Risk Analysis using Quantum Computers

Daniel J. Egger,[1] Ricardo García Gutiérrez,[2] Jordi Cahué Mestre,[2] and Stefan Woerner[1,*]
[1]*IBM Research – Zurich*
[2]*IBM Spain*
(Dated: July 9, 2019)

We present and analyze a quantum algorithm to estimate credit risk more efficiently than Monte Carlo simulations can do on classical computers. More precisely, we estimate the economic capital requirement, i.e. the difference between the Value at Risk and the expected value of a given loss distribution. The economic capital requirement is an important risk metric because it summarizes the amount of capital required to remain solvent at a given confidence level. We implement this problem for a realistic loss distribution and analyze its scaling to a realistic problem size. In particular, we provide estimates of the total number of required qubits, the expected circuit depth, and how this translates into an expected runtime under reasonable assumptions on future fault-tolerant quantum hardware.

## I. INTRODUCTION

Economic Capital, a key tool of risk management, is computed by financial service firms to determine the amount of risk capital that they require to remain solvant in the face of adverse yet realistic conditions [1]. Financial service firms are exposed to many forms of risk [2] such as credit risk which is the risk of a monetary loss resulting from a counterparty failing to meet a financial obligation [3, 4]. For instance, a payment may not be made in due time or at all. Risk metrics such as Value at Risk and the Economic Capital Requirement (ECR) algorithms on a gate based quantum computer. In Section IV, we show simulation results for small instances of the considered models. Section V analyzes the scaling of the algorithm for problems of realistic size as well as the resulting quantum advantage.

## II. CREDIT RISK ANALYSIS

ECR summarizes in a single figure the amount of capital (or own funds) required to remain solvent at a given confidence level (usually linked to the risk appetite or

•Barkoutsos P, Nannicini G, Robert A, Tavernelli I, Woerner S: Improving variational quantum optimization using CVaR. Quantum 4(256), 1 (2020)
•Benedetti M, Lloyd E, Sack S, Fiorentin, M: Parameterized quantum circuits as machine learning models. Quant. Sci. Technol. 4(4), 043001 (2019)
•Bera RK. The Amazing World of Quantum Computing. Springer Nature, 2020.
•Biamonte J, Wittek P, Pancotti N, Rebentrost P, Wiebe N, Lloyd S: Quantum machine learning. Nature 549(7671), 195–202 (2017)
•Carrera Vazquez A, Woerner S: Efficient state preparation for quantum amplitude estimation. Phys. Rev. Appl. 15, 034027 (2021)
•Chakrabarti S, Krishnakumar R,Mazzola G, Stamatopoulos N, Woerner S, Zeng WJ: A threshold for quantum advantage in derivative pricing. Quantum 5(463), 1 (2021)
•Egger DJ, Gutiérrez RG, Mestre JC, Woerner S: Credit risk analysis using quantum computers. IEEE Trans. Comput. 70(12), 2136–2145 (2020)
•Fontanela F, Jacquier A, Oumgari M: A quantum algorithm for linear PDEs arising in finance. SIAM J. Financ. Math. 12(4), SC98–SC114 (2021)
•Jacak JE, Jacak WA, Donderowicz WA et al. Quantum random number generators with entanglement for public randomness testing. Sci Rep 10, 164 (2020).
•Loredo R. Learn Quantum Computing with Python and IBM Quantum Experience. Packt Publishing, 2020.
•Martin A, Candelas B, Rodríguez-Rozas A, Martín-Guerrero JD, Chen X, Lamata L, Orús R, Solano E, Sanz M: Toward pricing financial derivatives with an IBM quantum computer. Phys. Rev. Res. 3, 013167 (2021)
•Miyamoto K: Bermudan option pricing by quantum amplitude estimation and Chebyshev interpolation. EPJ Quant. Technol. 9, 3 (2022)
•Miyamoto K, Kubo K: Pricing multi-asset derivatives by finite-difference method on a quantum computer. IEEE Trans. Quant. Eng. 3, 1–25 (2022)
•Montanaro A, Pallister S, Quantum algorithms and the finite element method. Phys. Rev. A 93, 032324 (2016)
•Norlén H. Quantum Computing in Practice with Qiskit and IBM Quantum Experience. Packt Publishing, 2020.

•Nielsen MA, Chuang IL. Quantum Computation and Quantum Information: 10th Anniversary Edition. Cambridge University Press, 2010.
•Orús R, Mugel S, Lizaso E: Forecasting financial crashes with quantum computing. Phys. Rev. A 99, 060301 (2019)
•Pistoia M, Ahmad SF, Ajagekar A, Buts A, Chakrabarti S, Herman D, Hu S, Jena A, Minssen P, Niroula P, Rattew A, Sun Y, Yalovetzky R: Quantum Machine Learning for Finance. Working paper, JP Morgan Chase Bank, September (2021). arXiv:2109.04298.
•Ramos-Calderer S, Pérez-Salinas A, García-Martín D, Bravo-Prieto C, Cortada J, Planagumà J, Latorre JI: Quantum unary approach to option pricing. Phys. Rev. A 103, 032414 (2021)
•Rebentrost P, Gupt B, Bromley TR: Quantum computational finance: Monte Carlo pricing of financial derivatives. Phys. Rev. A 98, 022321 (2018)
•Scherer W. Mathematics of Quantum Computing: An Introduction. Springer-Nature, 2019.
•Kondratyev A.: Non-differentiable leaning of quantum circuit born machine with genetic algorithm. Wilmott 2021(114), 50–61 (2021)
•Stamatopoulos N, Mazzola G, Woerner S, Zeng WJ: Towards quantum advantage in financial market risk using quantum gradient algorithms. Quantum 6, 770 (2022)
•Stamatopoulos N, Egger DJ, Sun Y, Zoufal C, Iten R, Shen N, Wörner S: Option pricing using quantum computers. Quantum 4(291), 1 (2020)
•Sutor RS. Dancing with Qubits: How quantum computing works and how it can change the world. Packt Publishing, 2019.
•Tang H, Wu W, and Jin XM: Quantum Computation for Pricing Caps using the LIBOR Market Model. Working paper, Shanghai Jiao Tong University, July (2022). arXiv:2207.01558
•Tang H, Pal A, Wang T, Qiao L, Gao J, Jin X: Quantum computation for pricing the collateralized debt obligations. Quant. Eng. 3(4), e84 (2021)
•Venturelli D, Kondratyev A: Beyond Markowitz with Quantum Annealing. Risk, June (2019)
•Woerner S, Egger DJ: Quantum risk analysis. Quantum Information 5(15), 1 (2019).
•Yanofsky NS, Mannucci MA. Quantum Computing for Computer Scientists. Cambridge University Press, 2008.