SOCIETÀ ITALIANA DI FISICA
Italian Physical Society

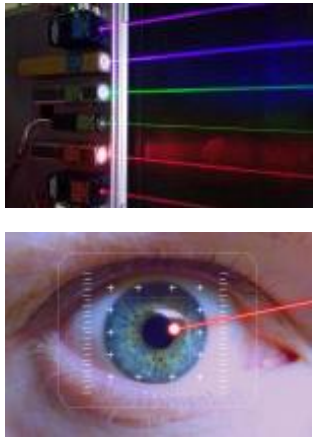
107° Congresso Nazionale

The Second Quantum Revolution at school: teaching Quantum Physics in the context of Quantum Technologies

Maria Bondani

M.L. Chiofalo, E. Ercolessi, O. Levrini, C. Macchiavello, M. Malgieri, M. Michelini, O. Mishina, P. Onorato, F. Pallotta, L. Santi, S. Satanassi, A. Stefanel, C. Sutrini, I. Testa, G. Zuccarini

FIRST QUANTUM REVOLUTION



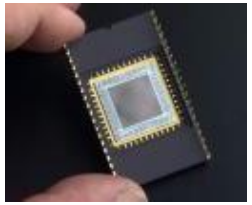
Laser

Fotosintesi

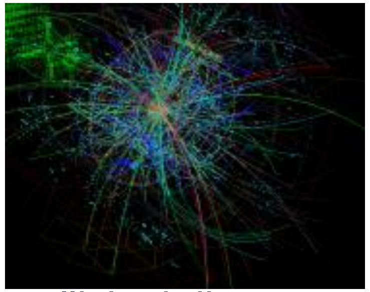
Pannelli solari

Dispositivi a LED

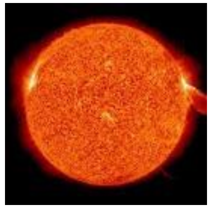
Circuiti integrati



CCD



Collisioni di particelle al CERN



Fusione nucleare

Impianti nucleari

SECOND QUANTUM REVOLUTION

"We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences... we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo"

Erwin Schrödinger [Brit. J. Phil. Sci. 3, 233 (1952)].

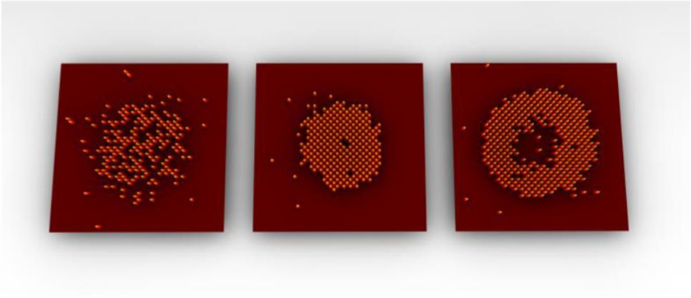
This is no longer true: the second quantum revolution is based on the control of the properties of quantum systems at the level of the single particle

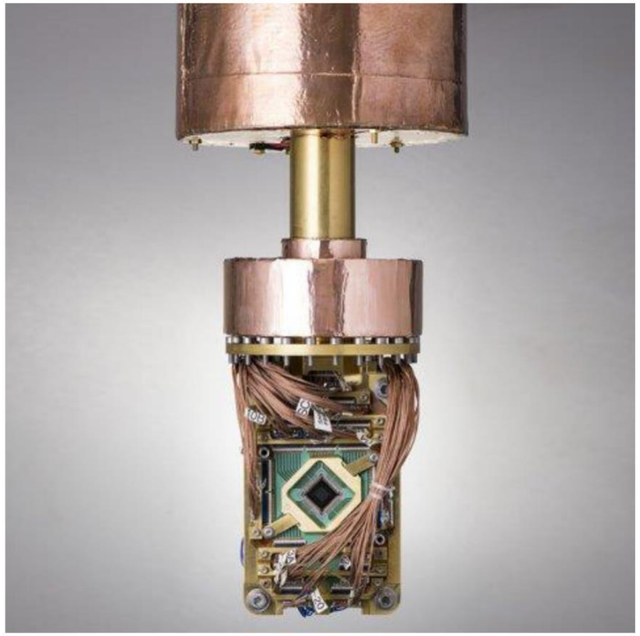
Generation and manipulation of superposition states

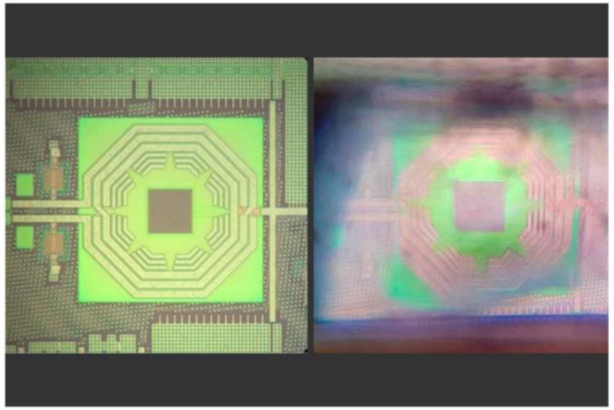
Generation and manipulation of entangled states

SECOND QUANTUM REVOLUTION

- Since more than 20 years:
  - applications and technologies based on principles of Quantum Mechanics
  - technology capable to prepare, control and manipulate single quantum states







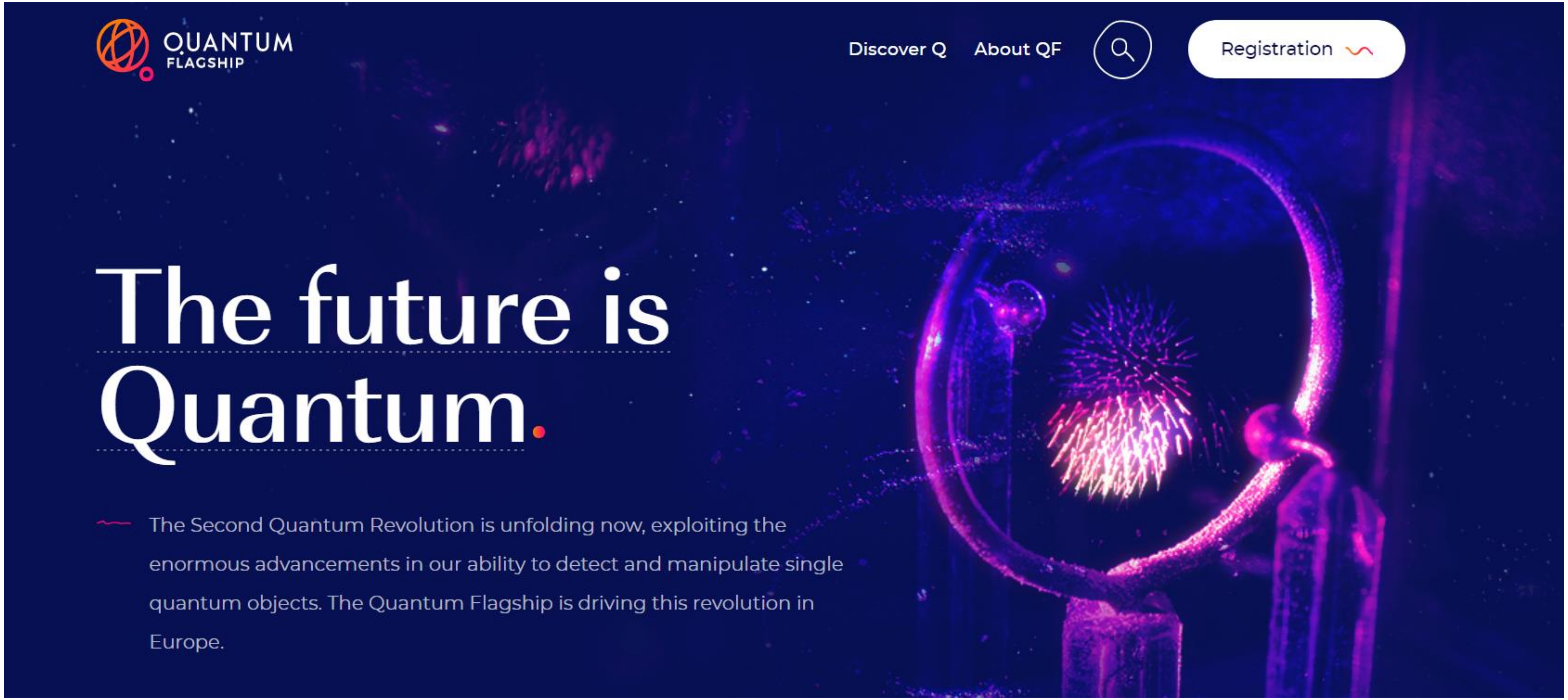
SECOND QUANTUM REVOLUTION

- Since more than 20 years:
  - applications and technologies based on principles of Quantum Mechanics
  - technology capable to prepare, control and manipulate single quantum states
- 2016: Quantum Manifesto
- 2018: European Union Quantum Flagship

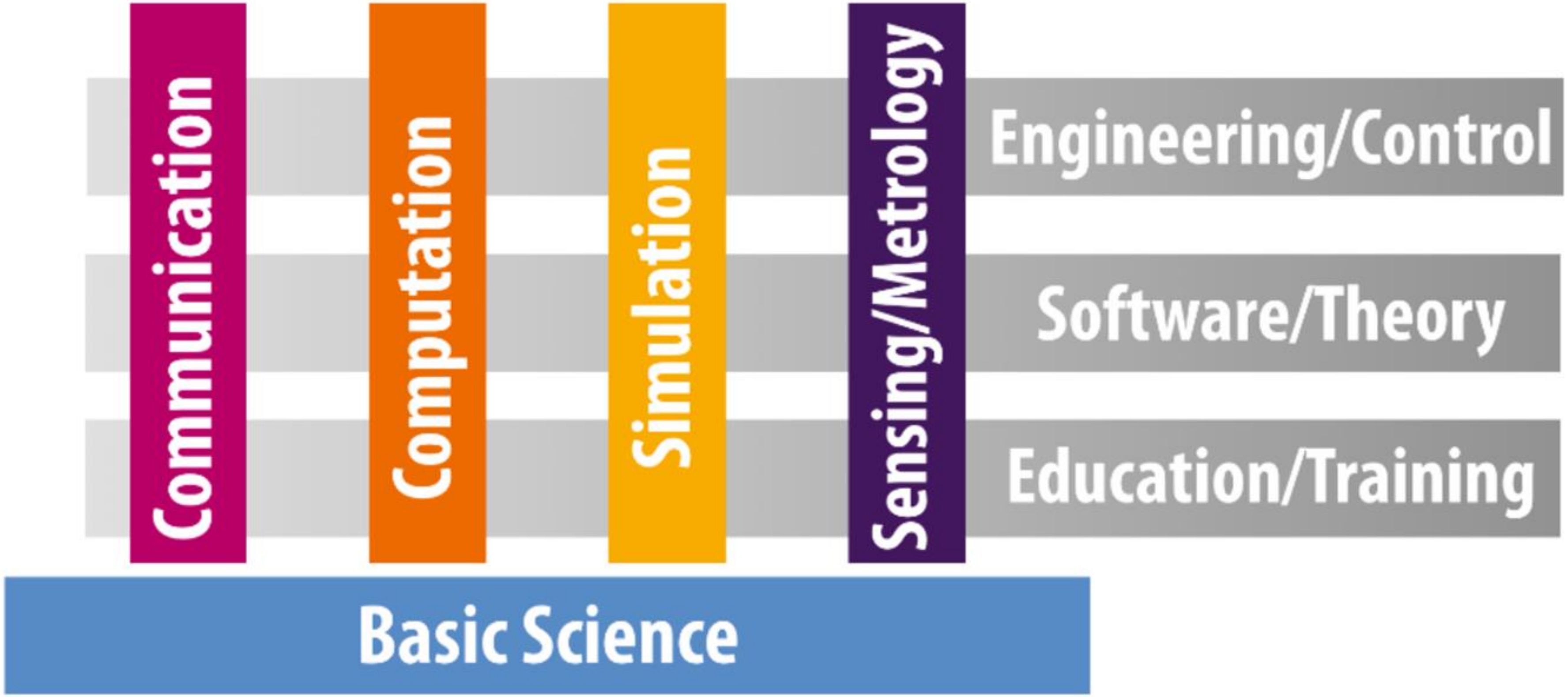
  10-year duration more than 1GEuro

https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf

QUANTUM FLAGSHIP



FLAGSHIP PILLARS



QTEdu - Coordination and Support Action for Quantum Technology Education

Within the European plan

QTEdu aims at the creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment, which is required, not just for a quantum-ready workforce to emerge, but for a well-informed society with knowledge and attitudes towards the acceptance of quantum technologies.

QTEdu - Conference

European project "QTEdu CSA“

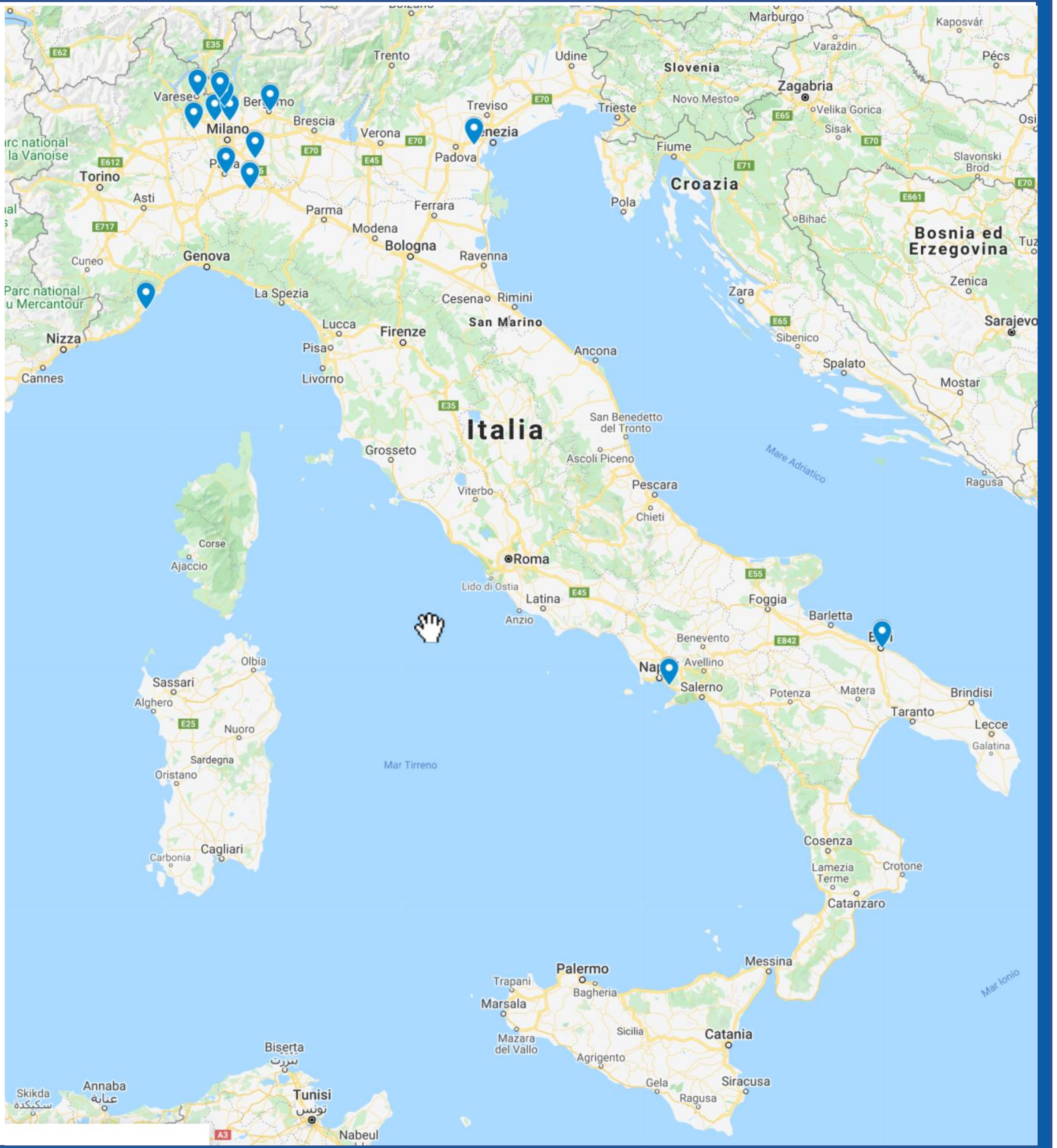
- Event: conference 5/11/2020
- About 2000 connected attendees
- More than 3500 views on youtube

Follow - up

- Collaboration among research groups from several Italian universities [UNInsubria, UNIPV, UNIUD, UNIBO, UNINA, UNIPI, UNITN] and CNR
- Both research groups in quantum physics and in physics education
- Exchanging expertise in different approaches to teaching quantum mechanics
- Recent activities on teaching quantum physics starting from quantum technologies

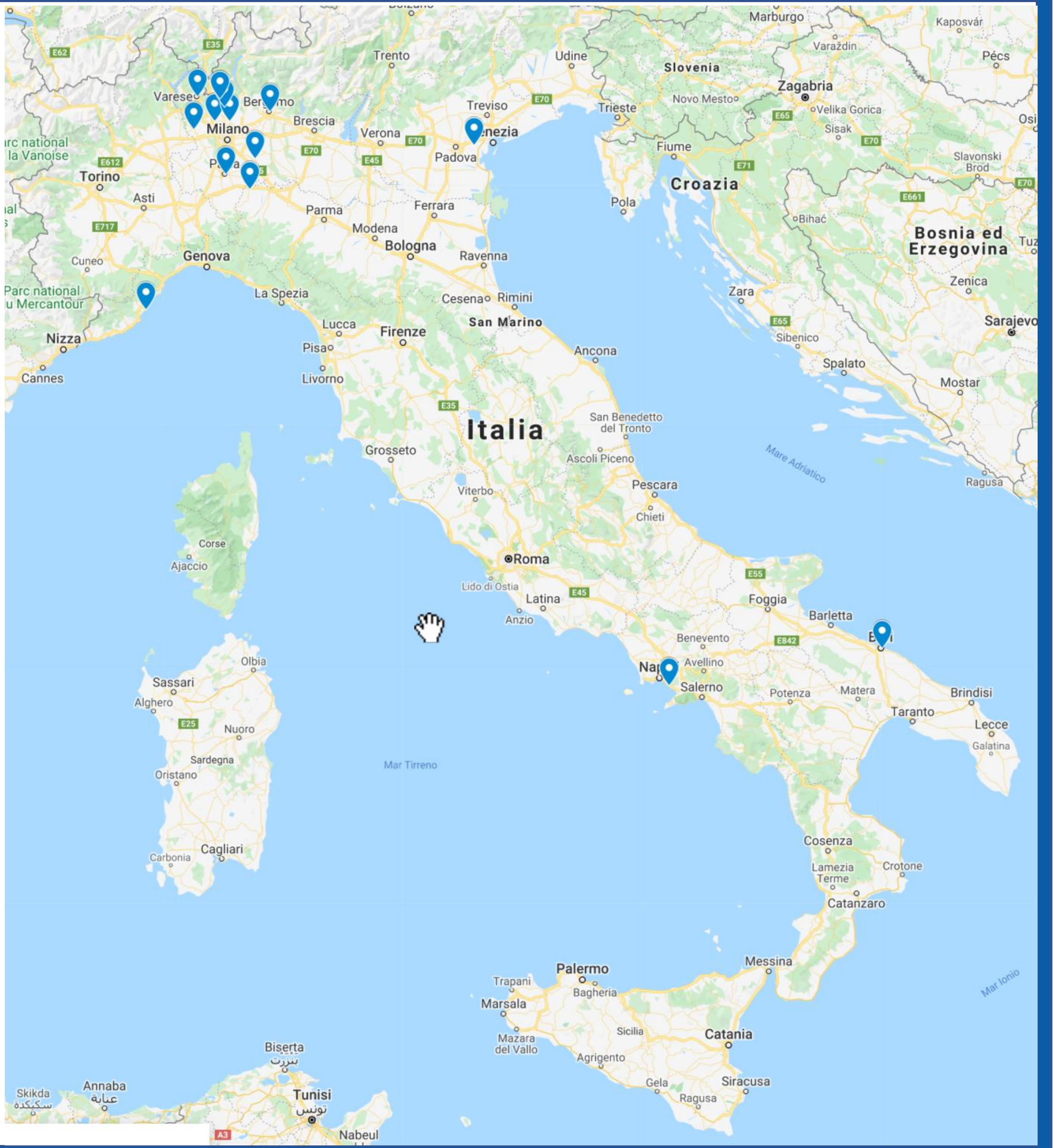
PCTO – Quantum Technologies

- Four-month discussion to prepare the PCTO activity for IV- and V–year high-school students
- PCTO organized by CNR-IFN
- The course is the result of the joint efforts of the community of researchers active in Italy in the field of quantum technologies and physics education, who have a long experience in designing teaching learning sequences about quantum physics with different approaches.

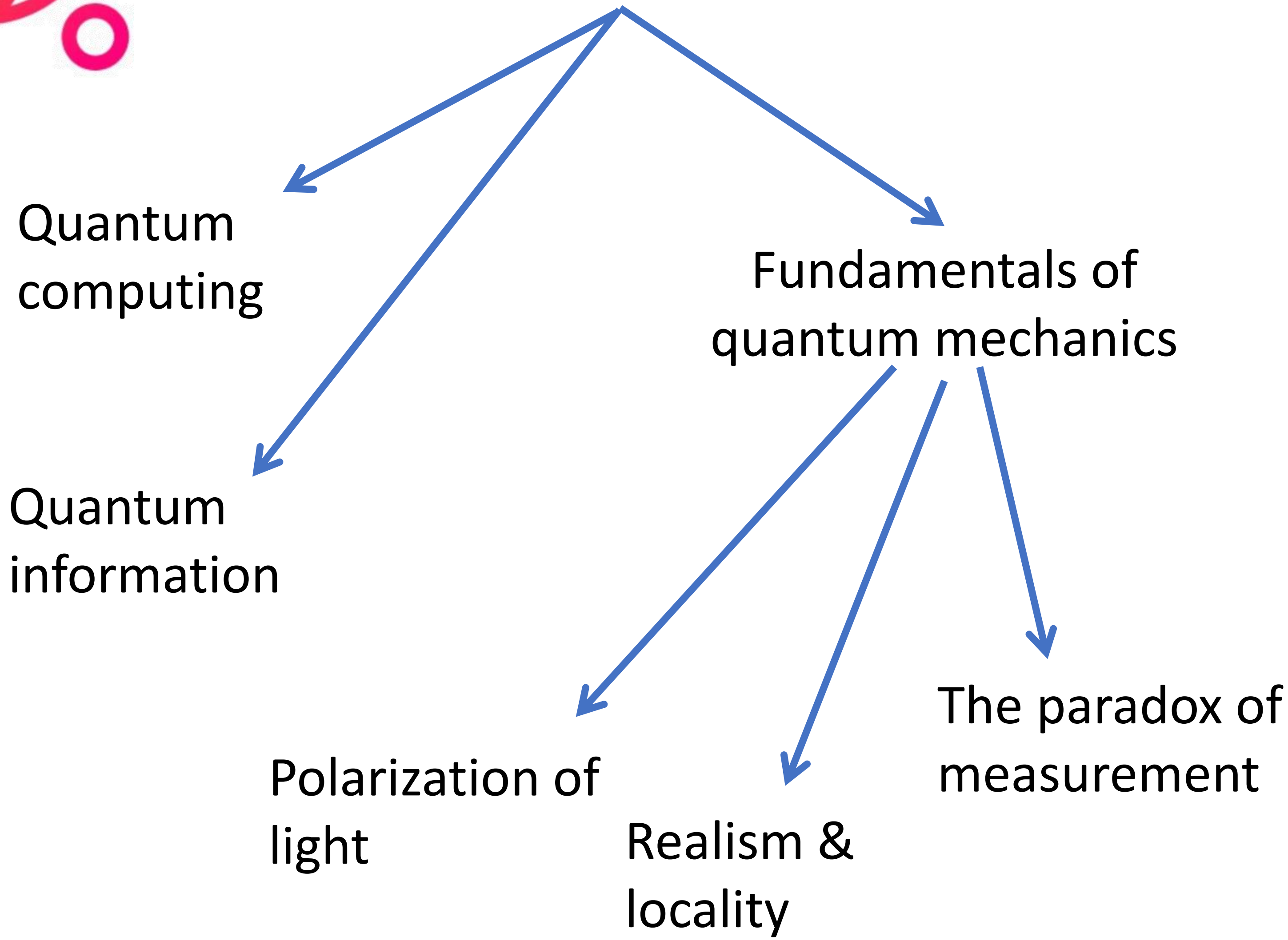


PCTO – Quantum Technologies

- The sample comprised 279 Italian high-school students from 16 different schools.
- The course was restricted to students attending the fourth (N = 101, average age: 18.0±0.4s.d.) and fifth (N = 178; average age: 19.0 ±0.5 s.d) year of the high school.
- The great majority (82%) of the students attended Liceo Scientifico (math-oriented high school), about 12% attended an applied science course (natural sciences-oriented high school), while about 6% attended a technical school.
- 73.8% participants declared themselves male, 24.4% female, while 1.8% of them declared of not being represented by their gender at birth.



PLENARY INTRODUCTORY LECTURES



Two-step course:

- Plenary introductory lectures based on two-state approach to introduce three key concepts: superposition, entanglement, quantum measurement.
- Specialized activities for smaller groups based on different approaches to consolidate the concepts from a fundamental viewpoint.

ORGANIZATION AND METHODOLOGY

- Four introductory lectures – about one hour each
- Three in-depth lectures – about one hour and a half each
- One final lecture – about one hour and a half

- Alternating presentations with simulations and excercises

- Clickers to keep attention and verify understanding

Domanda [Zoom clicker 1]

$CNOT(\vert Q_1Q_2\rangle) = ?$	QUAL E' IL RISULTATO DELL'APPLICAZIONE DEL GATE $CNOT$ AL QUBIT $\vert Q_1Q_2\rangle = \frac{\sqrt{3}}{2}\vert 00\rangle + \frac{1}{2}\vert 11\rangle$?
A.	$CNOT(\vert Q_1Q_2\rangle) = \frac{1}{2}\vert 00\rangle + \frac{\sqrt{3}}{2}\vert 11\rangle$
B.	$CNOT(\vert Q_1Q_2\rangle) = \frac{\sqrt{3}}{2}\vert 01\rangle + \frac{1}{2}\vert 10\rangle$
C.	$CNOT(\vert Q_1Q_2\rangle) = \frac{\sqrt{3}}{2}\vert 00\rangle + \frac{1}{2}\vert 10\rangle$
D.	$CNOT(\vert Q_1Q_2\rangle) = \frac{\sqrt{3}}{2}\vert 00\rangle + \frac{1}{2}\vert 01\rangle$

CLICKER 1

Consideriamo un qubit nello stato $|q_0\rangle = \frac{1}{2}|0\rangle + \frac{\sqrt{3}}{2}|1\rangle$

quanto vale la probabilità che lo stato sia misurato in $|1\rangle$?

A. $\frac{3}{4}$ B. $\frac{1}{4}$ C. $\frac{1}{2}$ D. $\frac{\sqrt{3}}{2}$

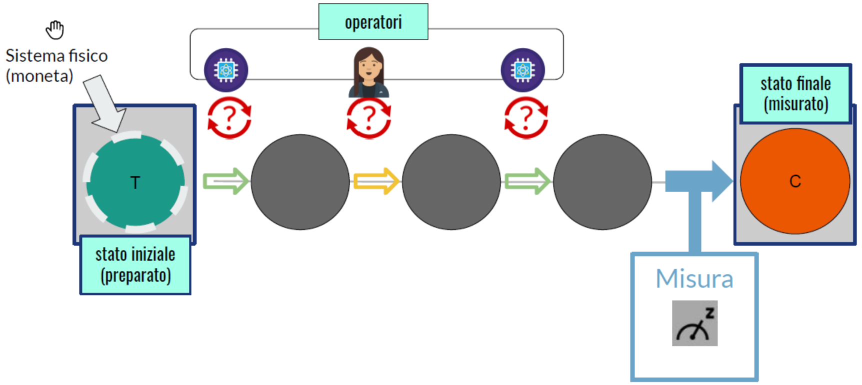
PLENARY INTRODUCTORY LECTURES – LECTURE 1

Elisa Ercolessi, UniBO – Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN

Objective: quantum state, superposition state

Content: qubits, Dirac representation, role of probability in quantum mechanics

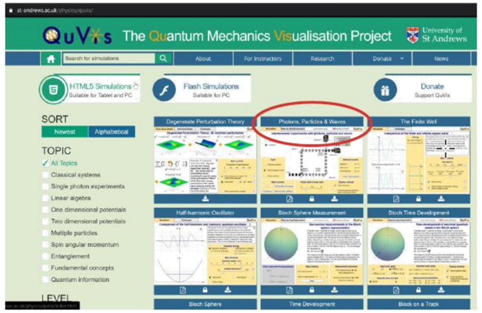
1. **Classical and quantum coin-flipping game**
2. **How to describe a quantum coin: bits and qubits**
    - notazione di Dirac
    - sovrapposizione
    - rappresentazione visuale
3. **Operations on quantum coin: single qubit quantum logic gates**
    - I, NOT, Z, H
4. **Physical examples of qubits**
    - Single photon after a beam splitter (Quvis, MILQ https://www.milq.info/en/)
    - Electronic spin
    - Cavity atom
    - Superconducting circuits



SINGOLO FOTONE

Simulazioni per paragonare il comportamento di diversi stati della luce.

Quvis – The Quantum Mechanics Visualisation project



https://www.st-andrews.ac.uk/physics/quvis

PLENARY INTRODUCTORY LECTURES – LECTURE 2

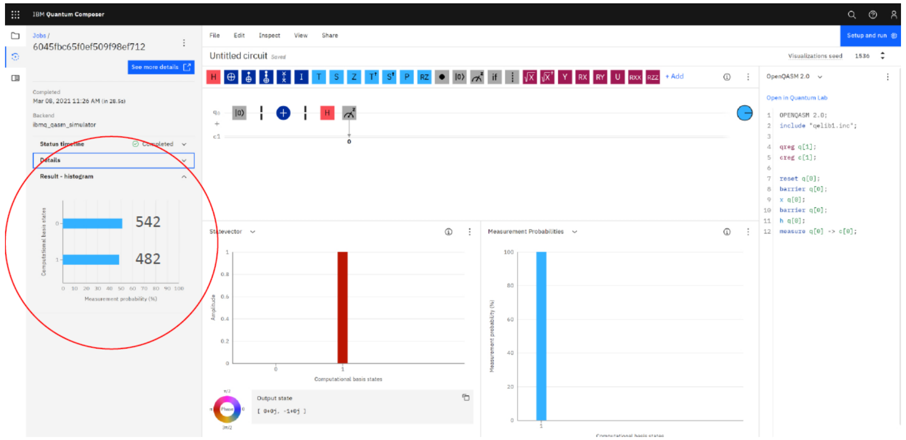
Elisa Ercolessi, UniBO – Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN

Objective: measurement

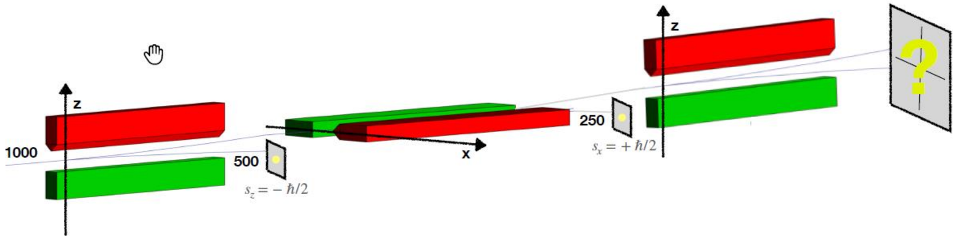
Content: representation of quantum measures, role of probability, non-compatible measurements

1. **Introduction to IBM Quantum experience**
   - Again on the logic of H, NOT, Z, X and exercises on IBMQ
   - definition of coefficients of superposition states (probability amplitude), probability, and measurement
2. **Stern-Gerlach experiment**
   - simulated experiments for sequences of Stern-Gerlach apparatuses performed using QuVis
   - discussion on the logical necessity of describing the spin state of the electron as a superposition state
3. **Esperimenti con il QuVis**
   - difference between mixtures and superposition states
   - sequence of three Stern Gerlach apparatuses

ESEMPIO – misura dello stato



ESPERIMENTO #4



PLENARY INTRODUCTORY LECTURES – LECTURE 3

Elisa Ercolessi, UniBO – Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN

Objective: entanglement

Content: separable and entangled states, correlated measurements

1. Introduction

- two-qubit states (basis elements, normalization)
- difference between entangled state and separable state
- measurement of single qubits in many qubit states
- Bell states: invariance upon basis rotation
- reprise of Stern-Gerlach experiments to discuss the value of reality to be attributed to the variables

2. IBMQ interlude

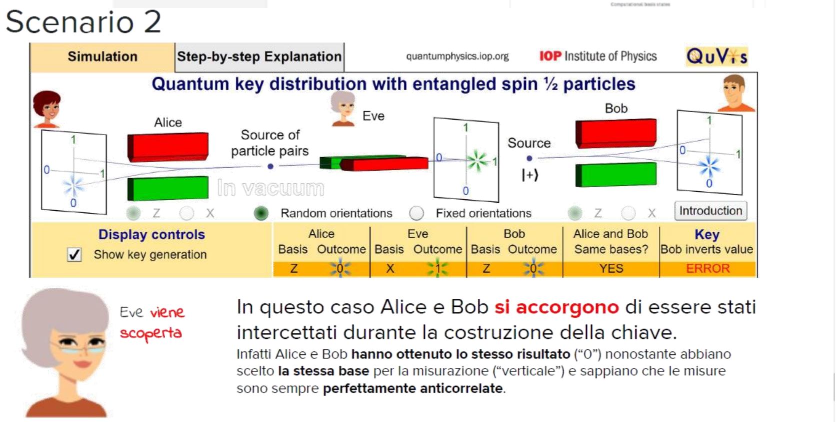
- quantum circuit to generate entangled states

3. Application of entanglement

- QuVis: cryptographic protocol BBM92

4. Historical contextualization

- EPR paradox (Schroedinger's cat): locality and realism
- Bell's inequalities: classical correlations vs entanglement



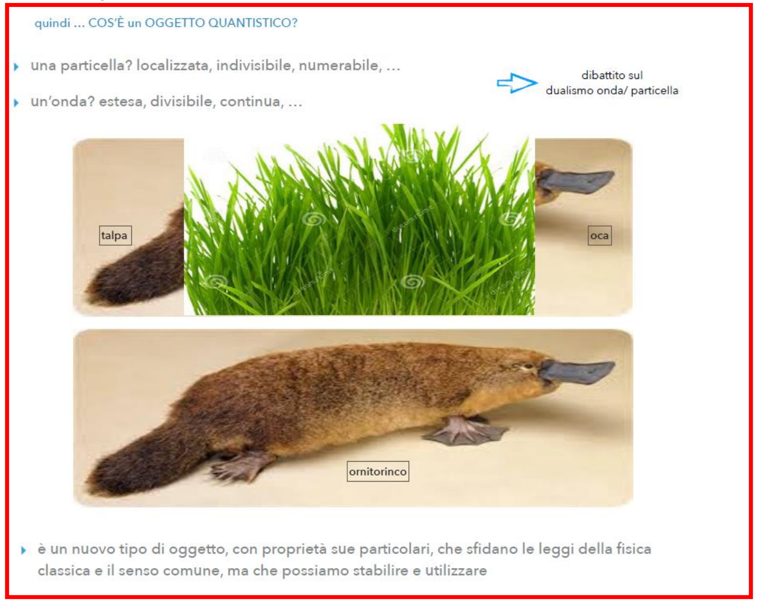
PLENARY INTRODUCTORY LECTURES – LECTURE 4

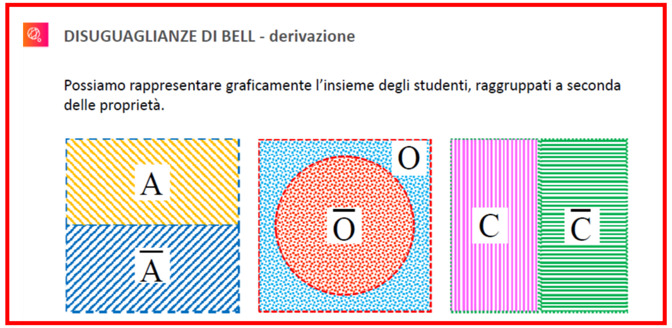
Elisa Ercolessi, UniBO – Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN

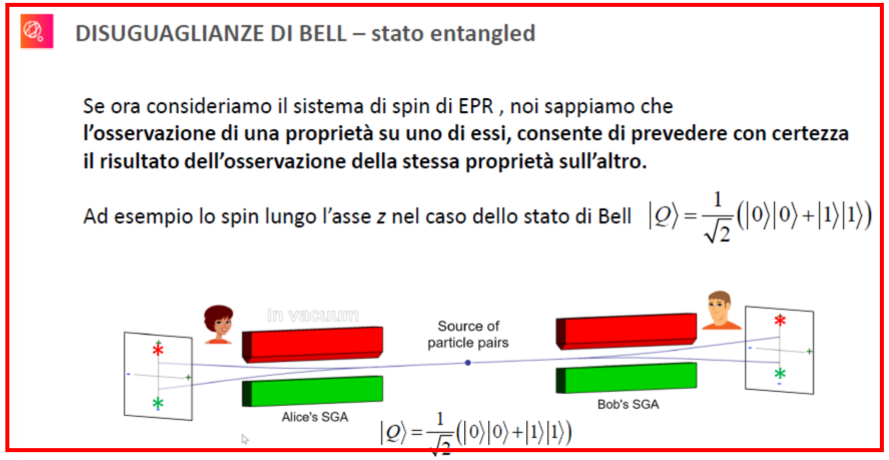
Objective: synthesis of concepts and formalism

Content: axiomatic conceptual framework of quantum mechanics, interpretative problems

1. **Summary of the concepts discussed in the previous lectures**
   - highlight the connections among the concepts
   - introduce concepts intentionally not mentioned in the lectures but that the students will encounter in their course of study
     - Uncertainty principle
     - Wave function
     - Dualism
2. **Interpretative problems in quantum mechanics**
   - EPR paradox
   - Bell's inequalities





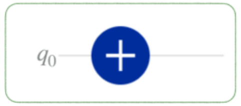


SPECIFIC PATHS - QUANTUM COMPUTING

Sara Satanassi, UniBO - Claudio Sutrini, UniPV - Maria Bondani, CNR-IFN

Porte logiche ad un qubit

Esempio: NOT quantistico X



IN	OUT
$\|0\rangle$	$X\|0\rangle = \|1\rangle$
$\|1\rangle$	$X\|1\rangle = \|0\rangle$
$\|Q\rangle = a\|0\rangle + b\|1\rangle$	$X\|Q\rangle = b\|0\rangle + a\|1\rangle$

Esempio: gate Z

IN	OUT
$\|0\rangle$	$Z\|0\rangle = \|0\rangle$
$\|1\rangle$	$Z\|1\rangle = -\|1\rangle$
$\|Q\rangle = a\|0\rangle + b\|1\rangle$	$Z\|Q\rangle = a\|0\rangle - b\|1\rangle$

Porte logiche ad un qubit

Esempio: gate Hadamard H

IN	OUT
$\|0\rangle$	$H\|0\rangle = \|+\rangle = \frac{1}{\sqrt{2}}\|0\rangle + \frac{1}{\sqrt{2}}\|1\rangle$
$\|1\rangle$	$H\|1\rangle = \|-\rangle = \frac{1}{\sqrt{2}}\|0\rangle - \frac{1}{\sqrt{2}}\|1\rangle$
$\|Q\rangle = a\|0\rangle + b\|1\rangle$	$H\|Q\rangle = \frac{a+b}{\sqrt{2}}\|0\rangle + \frac{a-b}{\sqrt{2}}\|1\rangle$

crea uno stato di ¡ sovrapposizione !

trasforma la base $|0\rangle, |1\rangle$ nella base $|+\rangle, |-\rangle$

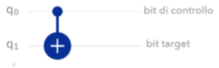
Sistemi composti: porte a due qubit

CNOT
(controlled NOT)

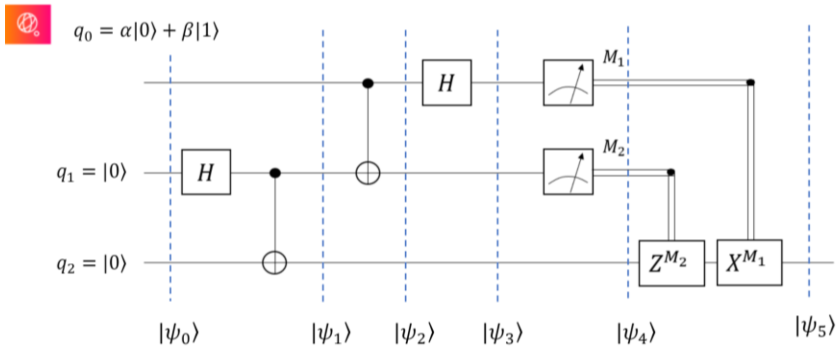
IN	OUT
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$\|01\rangle$
$\|10\rangle$	$\|11\rangle$
$\|11\rangle$	$\|10\rangle$

bit ausiliario, di controllo

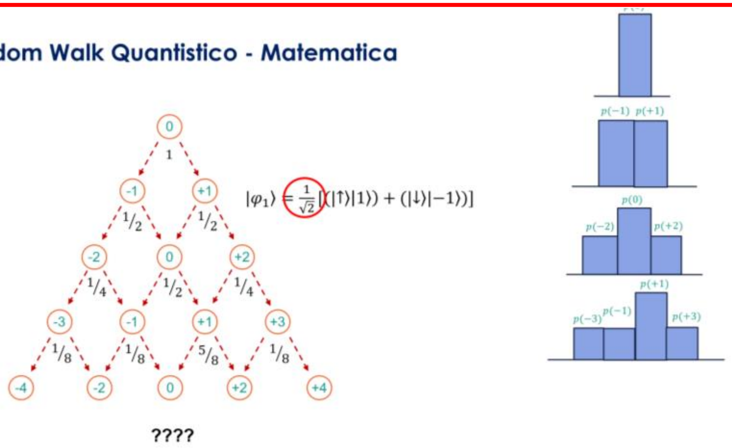
bit target, su cui si fa il NOT, solo se il controllo è 1



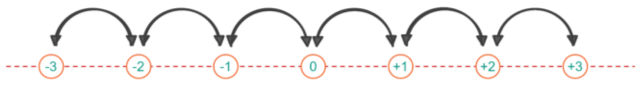
Teleportation



Random Walk Quantistico - Matematica



Il modello



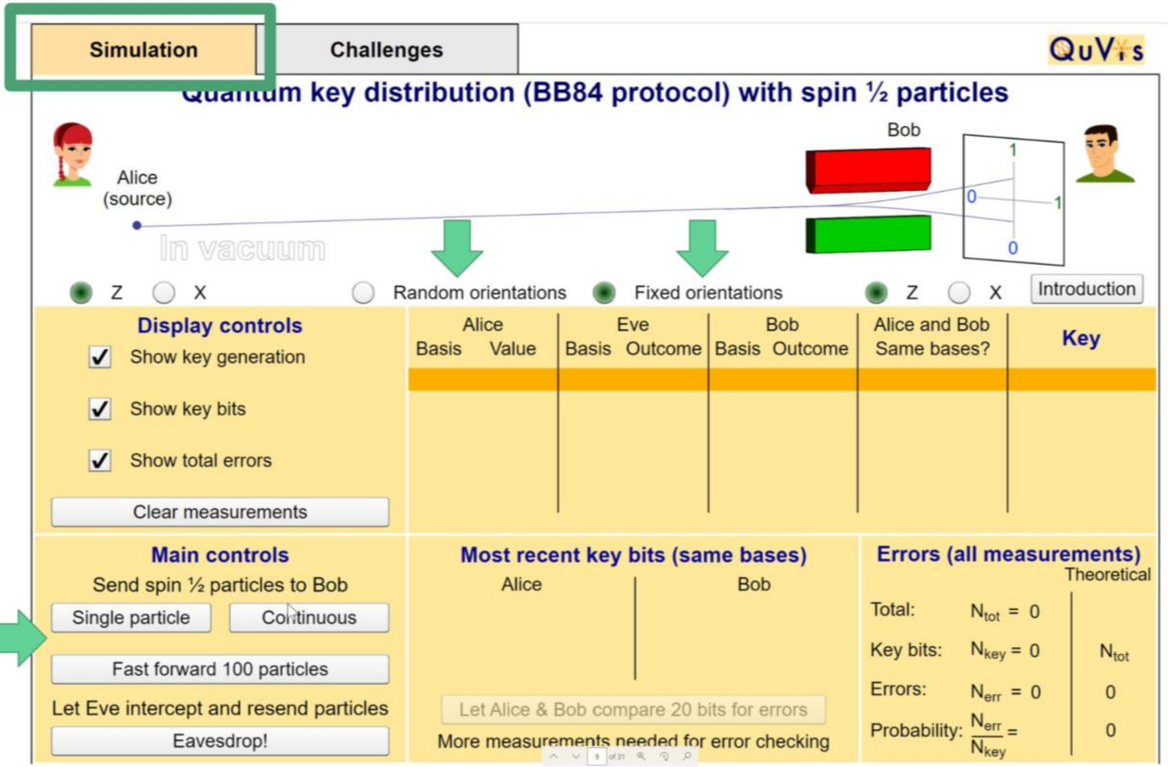
Flip coin H

Prima	Dopo
$\|\uparrow\rangle$	$\frac{\|\uparrow\rangle + \|\downarrow\rangle}{\sqrt{2}}$
$\|\downarrow\rangle$	$\frac{\|\uparrow\rangle - \|\downarrow\rangle}{\sqrt{2}}$

Operatore di shift: $S = |\uparrow\rangle\langle\uparrow| \otimes \sum_i |i+1\rangle\langle i| + |\downarrow\rangle\langle\downarrow| \otimes \sum_i |i-1\rangle\langle i|$

SPECIFIC PATHS - QUANTUM INFORMATION

Claudio Sutrini, UniPV – Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN

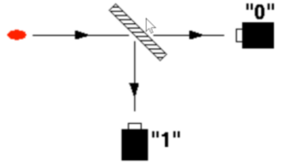


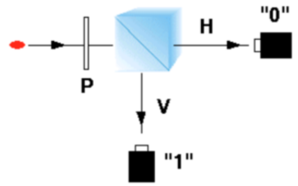
Quantum random number generator

Un generatore quantistico di numeri casuali si basa su un processo fisico la cui casualità è garantita dalle leggi della Meccanica Quantistica.

Esempi di tali processi sono:

- Misura di un singolo fotone a valle di un beam splitter: stato di sovrapposizione di cammini
- Misura di un singolo fotone polarizzato a 45° a valle di un beam splitter





- Decadimenti nucleari
- Emissione di singoli atomi/molecole

SPECIFIC PATHS – FUNDAMENTALS: POLARIZATION

Marisa Michelini – Lorenzo Santi – Alberto Stefanel, UniUD

SPECIFIC PATHS – FUNDAMENTALS: MEASUREMENT PARADOX

Massimiliano Malgieri, Giacomo Zuccarini, UniPV

IL PARADOSSO DELLA MISURA

Il gatto di Schrödinger e altri animali fantastici (e dove trovarli)

Massimiliano Malgieri
Giacomo Zuccarini

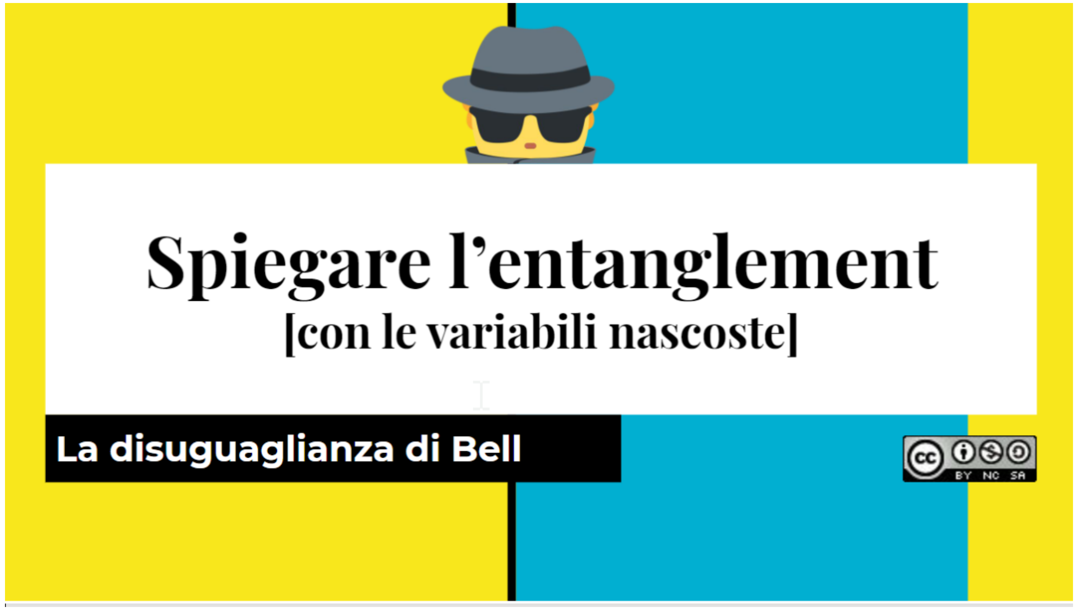
UNIVERSITÀ
DI PAVIA

Panoramica delle lezioni

- l'evoluzione quantistica dei sistemi, alcuni suoi aspetti fondamentali, e il suo protagonista: lo stato
- una situazione fisica a voi nota: lo spin di un atomo
- la legge della dinamica quantistica, la trasformazione dell'evoluzione temporale
- due esempi: uno qualitativo e uno nel contesto dello spin (la sua evoluzione in un campo magnetico uniforme)
- le «porte logiche» come forme di evoluzione temporale
- attività sulle porte logiche => importanti proprietà dell'evoluzione temporale
- un'altra forma di evoluzione dei sistemi quantistici: la misurazione
- il «Paradosso della misura»
- le prime trattazioni: Von Neumann e Copenhagen => il problema persiste, emergono ulteriori paradossi
- il gatto di Schrödinger e altri animali fantastici (e dove trovarli)

SPECIFIC PATHS – FUNDAMENTALS: REALISM AND LOCALITY

Filippo Pallotta, UnInsubria - Maria Bondani, CNR-IFN



INTERPRETAZIONI DELLA MECCANICA QUANTISTICA

La Meccanica Quantistica è una teoria fisica.

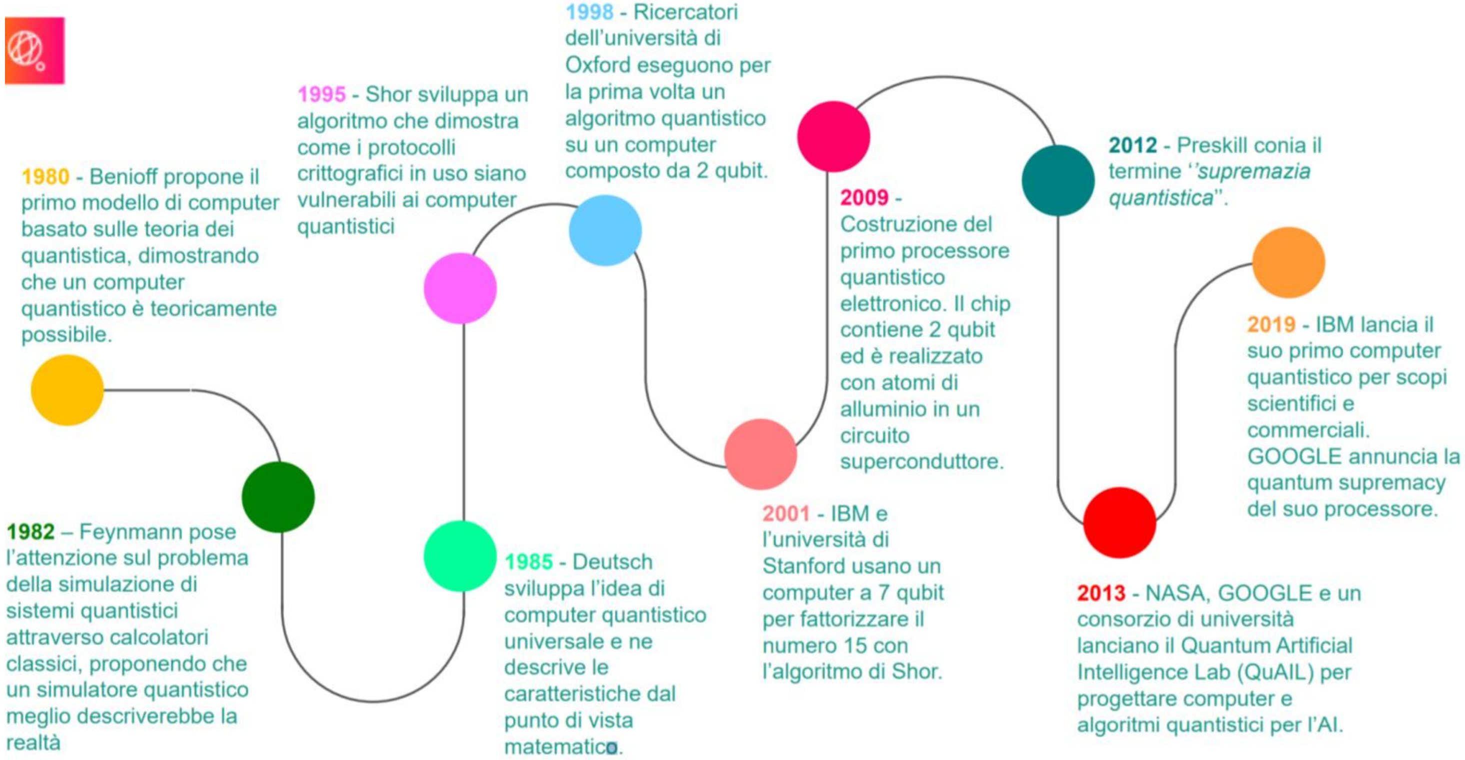
- È il nostro attuale "modello standard" per descrivere il comportamento della materia e dell'energia alle scale più piccole (fotoni, atomi, nuclei, quark, gluoni, leptoni, ...).
- Fino ad ora la Meccanica Quantistica non ha mai fallito.
- Come tutte le teorie, consiste in un formalismo matematico, più una interpretazione del formalismo.
- A differenza di altre teorie fisiche, il formalismo della Meccanica Quantistica è stato accettato ed utilizzato da quasi un secolo, mentre la sua interpretazione rimane controversa.

FINAL LECTURE

Sara Satanassi, UniBO – Maria Bondani, CNR-IFN

Objective: social and cultural relevance of second quantum revolution

Content: examples of articles on quantum technologies, description of present quantum technologies, description of new jobs in quantum technologies



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06/01/2011

Il Sole 24 ORE

Stampa l'articolo | Chiudi

LA MACCHINA DEI QUANTI

LUCA TREMOLADA

21/04/2013

Il Sole 24 ORE

Stampa l'articolo | Chiudi

21 aprile 2013

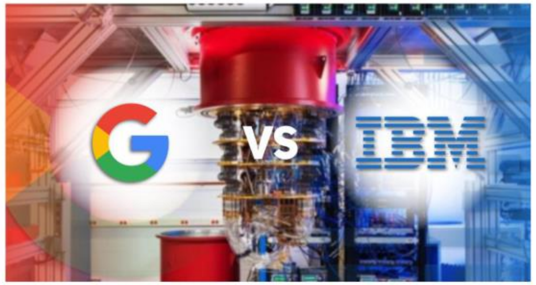
L'intreccio quantico che non teme il «rumore»

di Marco Passarello

CYBERSECURITY

La scommessa da un miliardo di euro dell'Europa sulle tecnologie quantistiche

Il dibattito: a clash of The Titans



https://www.geeksforgeeks.org/who-will-win-the-quantum-supremacy-debate-google-or-ibm/

24 Tecnologia Economia digitale

di In edicola col Sole Fiume di denar

VIZIO | POTENZA DI CALCOLO

Il computer quantistico è realtà. Supremazia di Google ma Ibm non ci sta

24/10/2019

Risolto in 200 secondi un calcolo che un supercomputer tradizionale risolverebbe in 10.000 anni. Google conquista la supremazia nel quantum computing ma Ibm non ci sta e non ci crede.

FINAL LECTURE

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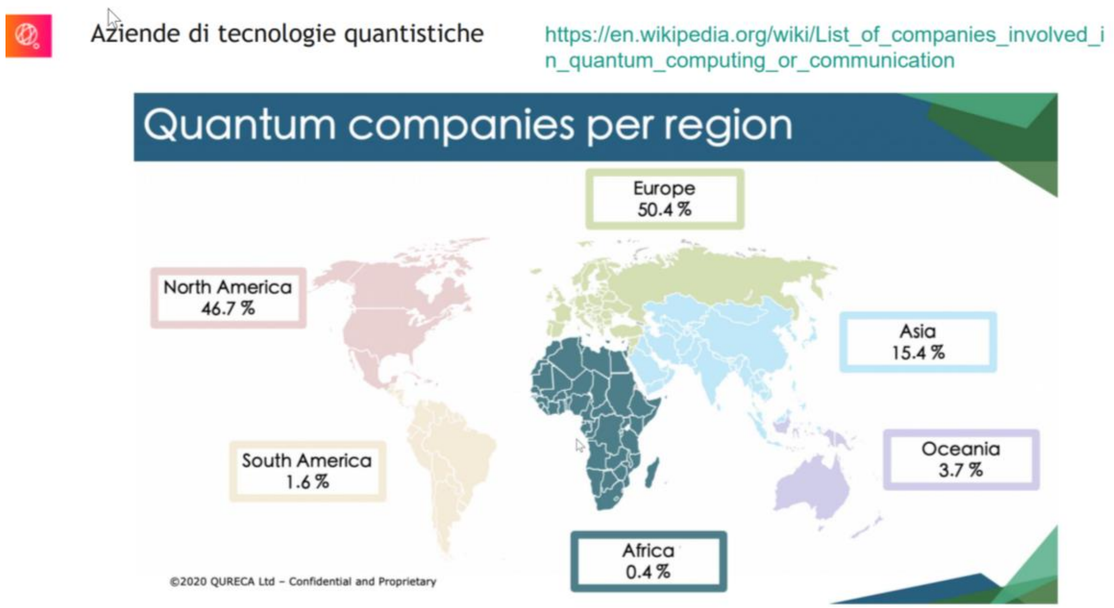


EVALUATION

Several questionnaires and tests were administered to students with the aim of investigating the relationships between their physics identity, their understanding of the concepts and their level of involvement.

The instruments were designed partly from the relevant literature and partly by formulating original items for those fields, such as quantum technologies, where no literature is available.

- Pre- and post-intervention questionnaires
- Short surveys at the end of each introductory lecture were designed to test the understanding of the concepts presented in the lecture
- Disciplinary test at the end of the in-depth lectures including both multiple-choice and open-ended questions were designed with the purpose of testing general understanding of conceptual and computational aspects.

PRE-TEST

students' attitudes → **PHYSICS IDENTITY**

"I am able to help my classmate with physics in the laboratory or in recitation"
"My friends see me as a physics person"
"My physics instructor and/or TA sees me as a physics person."

PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH **15**, 020119 (2019)

Gendered patterns in the construction of physics identity from motivational factors

Z. Yasemin Kalender,[1] Emily Marshman,[2] Christian D. Schunn,[3] Timothy J. Nokes-Malach,[3] and Chandralekha Singh[1]
[1]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[2]*Department of Physics, Community College of Allegheny County, Pittsburgh, Pennsylvania 15212, USA*
[3]*Learning Research and Development Center, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*

Two **multiple-choice tests** were administered before the start of the activities and at the end of the course.

EPISTEMIC VIEWS AND PLAUSIBILITY JUDGEMENTS ABOUT QUANTUM PHYSICS

Literature items

"It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct"

PHYSICAL REVIEW SPECIAL TOPICS - PHYSICS EDUCATION RESEARCH **6**, 020113 (2010)

Refined characterization of student perspectives on quantum physics

Charles Baily and Noah D. Finkelstein

Original items

"Scientists say that quantum communication makes it possible to teleport a particle from one place to another."

DISCIPLINARY TEST

Che cosa implica conoscere lo stato di un sistema quantistico?

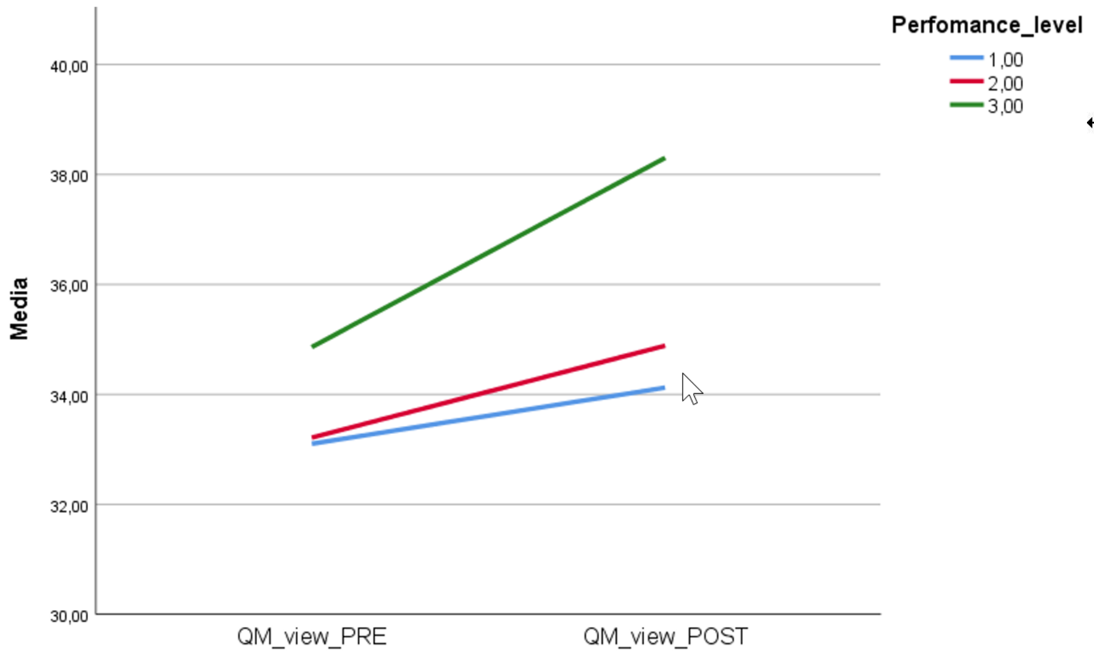
A. Poter prevedere con certezza l'esito di una qualsiasi misura sul sistema.
B. Poter prevedere il risultato di una singola misura di una qualsiasi osservabile entro i limiti posti dal principio di indeterminazione.
C. Poter prevedere la probabilità con cui si avranno i diversi esiti di una qualsiasi misura sul sistema.
D. Poter prevedere con certezza lo stato in cui si troverà un sistema in seguito ad un qualsiasi processo di misura.

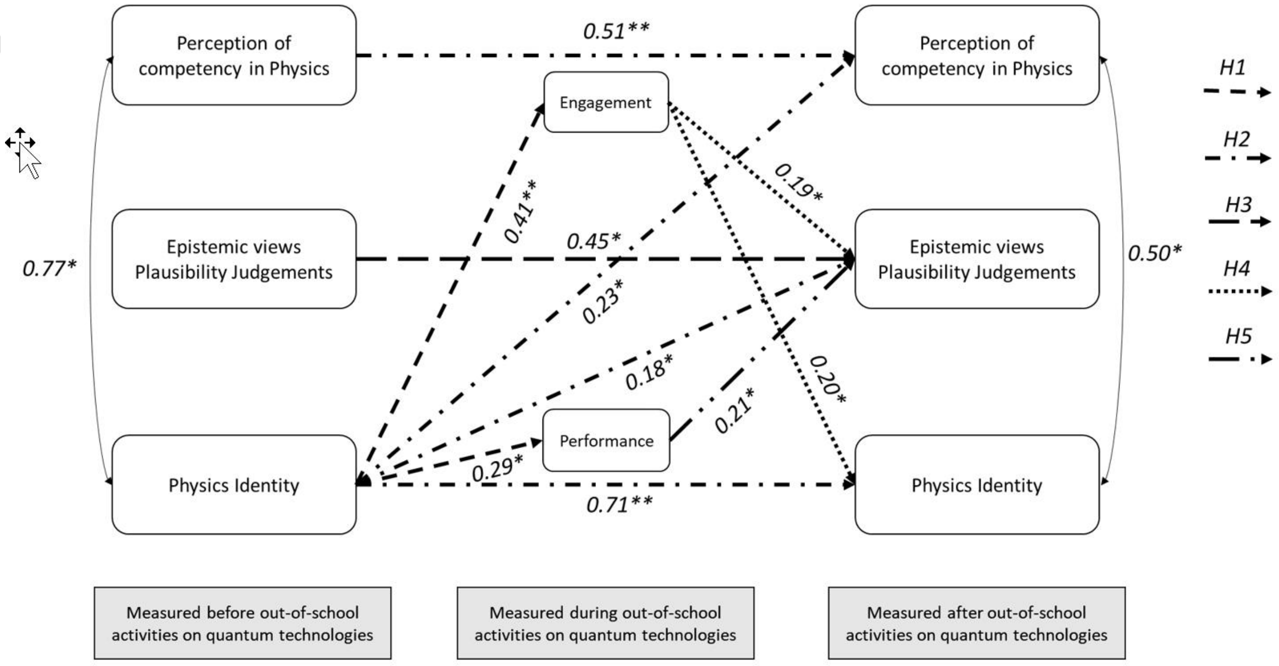
Dati i due stati a due qubit $|\psi_1\rangle = \frac{1}{\sqrt{2}}(|0\rangle|1\rangle + |1\rangle|0\rangle)$ e $|\psi_2\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle - |1\rangle|0\rangle)$:

A. $|\psi_1\rangle$ è separabile (fattorizzabile), $|\psi_2\rangle$ è entangled;
B. $|\psi_2\rangle$ è separabile (fattorizzabile), $|\psi_1\rangle$ è entangled;
C. sono entrambi separabili;
D. sono entrambi entangled.

Antonio dice: "io non capisco la meccanica quantistica. Si scrivono gli stati con dei coefficienti, ma poi sembra che conti solo il quadrato di questi coefficienti. La somma dei quadrati deve fare uno, e le probabilità corrispondono ai quadrati dei coefficienti. Ma allora, non si potrebbero scrivere direttamente i quadrati? Per esempio potrei scrivere $|\psi\rangle = \frac{1}{3}|0\rangle + \frac{2}{3}|1\rangle$; in questo modo avrei già le probabilità, e inoltre potrei controllare più facilmente che la somma faccia 1."
Cosa potresti rispondere ad Antonio? (o se sei d'accordo con lui, scrivilo)

PRELIMINARY RESULTS

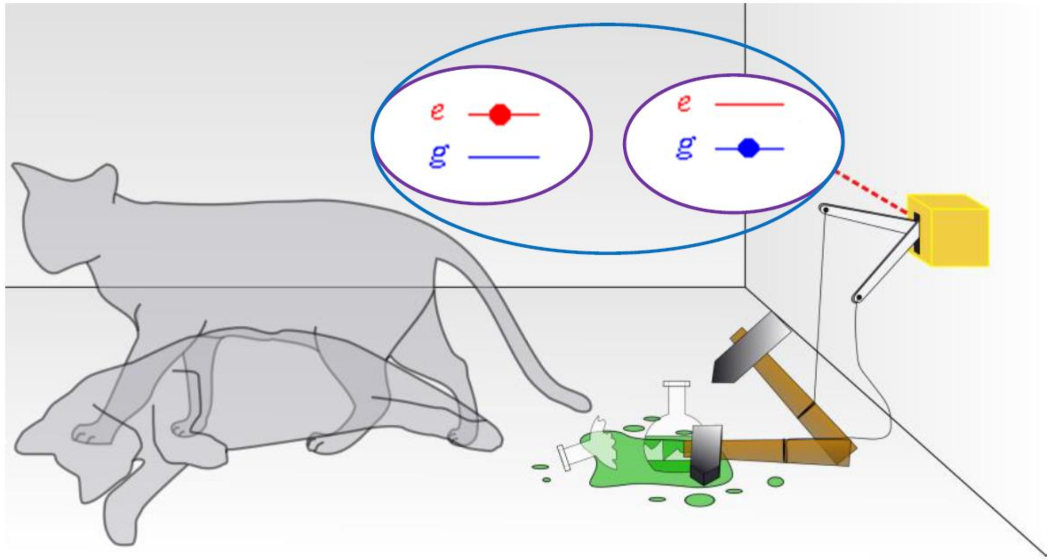




"Investigating upper secondary students' epistemic views and plausibility judgements about quantum physics: the role of physics identity, perception of competency, and engagement in extracurricular activities on quantum technologies".
Manuscript in preparation.

FUTURE PERSPECTIVES

- Further data analysis
- New edition of the PCTO possibly in presence with less and more motivate students
- Coordinated Local PLS laboratories with common activities and evaluation



Thank you for your attention!