Quantum Simulations:
A quantum theatre for quantum technologies

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Quantum technologies

- Quantum communication, quantum simulation, quantum sensors & quantum computing

- In quantum technologies there is room for arts, science, engineering, and societal interest
Quantum simulations
Quantum simulation is the intentional reproduction of the quantum aspects of a physical or unphysical model onto another quantum system that is typically more controllable.

Richard Feynman

Let nature calculate for us
Quantum Models simulated in Quantum platforms

- Novel arts
- Novel science

Simulated models \(\iff\) Simulating systems

- Novel materials
- Novel chemicals
- Quantum materials

- Optical lattices
- Trapped ions
- Superconducting circuits
- Photonics
- NV centers in diamond
Analog Quantum Simulators

- Analog quantum simulation (AQS) aims at a close imitation of the original quantum model, with a simulating system that evolves while accumulating errors that cannot be corrected.

- Analog quantum simulators require creative artists and versatile platforms.
Analog quantum simulator at Innsbruck (2010)
First AQS of the Dirac equation in a nonrelativistic trapped ion

Trapped ions

Analog quantum simulator at Karlsruhe (2016)
First AQS of the quantum Rabi model in circuit quantum electrodynamics

Superconducting circuits
Digital Quantum Simulators

- Digital quantum simulation (DQS) is an algorithmic imitation that digitizes the original quantum model into a series of quantum gates. It is universal and allows error correction.

- At hardware level, digital quantum simulators & digital quantum computers are equivalent.
Digital quantum simulator at ETH Zurich (2015)

First DQS of spin models in superconducting circuits
Digital quantum simulator at Google (2015)

First DQS of electronic models in superconducting circuits

DQS of 2-4 fermionic modes
More than 300 quantum gates
Digital quantum computer at Google (2016)

First digitization of analog quantum computation

Quantum computer with 9 qubits
More than 1000 quantum gates
Digital-analog quantum simulations

• Digital-analog quantum simulation (DAQS) merges digital and analog concepts: *analog blocks* combine sequentially with *digital steps* to enhance quantum simulators.

Analog blocks are built upon the natural larger complexity of a quantum platform, while digital steps enhance the flexibility of the simulated models.
Digital-analog quantum simulator at TU Delft (2016)

First DAQS of full-fledged light-matter interaction in superconducting circuits

More than 90 digital steps and a dimension comparable to 6-7 qubits
Further works involving DAQS concepts

Quantum Field Theory models
Casanova et al., PRL 2011

Holstein Models
Mezzacapo et al., PRL 2012

Quantum field theory models
L. García-Álvarez et al., PRL 2015

Quantum chemistry models

Trapped ions

Superconducting circuits

Fig. 2: The first and second ion are driven with two frequencies (detunings set of lasers detuned close to a second mode of frequency) to drive the first two ions (detunings than two ions, one must be careful in designing an ap-
Perspectives and Future scope
Aesthetic perspective on quantum simulation

- Because we tend to be unhappy with reality, we enjoy arts and fiction in all forms: literature, music, theatre, painting, quantum simulations

Richard Feynman

Let nature calculate for us

Greek theatre

Mimesis or imitation is always partial, this is the origin of creativity in science and arts

Quantum simulation <=> Quantum theatre

Quantum simulation of unphysical operations
**Scientific perspective on Quantum simulation**

- Because we can discover analogies between unconnected fields, yielding a flood of knowledge in both directions, e.g. black hole physics and cold atoms in the lab.

- Because we can study phenomena that are difficult to access in nature or in the lab, e.g. relativistic effects, biochemistry problems, high-energy physics, astrophysical problems, among others.
Technological perspective on Quantum simulation

- Because we can study and predict novel physics without manipulating the original systems, while some experiments may reach quantum supremacy: CM, QChem, QFT, ML, AI & AL

- Because we can contribute to the development of novel quantum technologies via the use of scalable quantum simulators and their merge with quantum computing
Will we soon display classical computers in museums?
Will we have quantum simulators or quantum computers on our mobile phones?
Do quantum technologies raise ethical issues?

Quantum technologies looked, up to now, as harmless as toy models or artistic views.

At most QTs may kill kittens.

Quantum security.
Quantum biomimetics

It is the reproduction of features of living systems in controllable quantum platforms:

- Biomimetic partial cloning of quantum bits of quantum information
- Quantum artificial life in quantum technologies

And there is also quantum machine learning and quantum artificial intelligence arriving
Quantum memristors

Classical memristors
- history-dependent response/resistance
- processing and storage in the same device
- applications in neuromorphic computing, learning circuits, memcomputing

Quantum memristors
- memory feature in quantized circuits
- interplay of memory & quantum properties
- memristor as a role model in quantum technologies

Hodgkin-Huxley model of neuron membrane

Cooper Pair Box

**Bilbao Quantum Roadmap**

**Digital-Analog Quantum Simulation (DAQS)**
- Analog blocks provide complexity
- Digital steps provide versatility

**Digital-Adiabatic quantum computing (DAQC)**
- Adiabatic blocks provide complexity
- Digital steps provide versatility

**Complexity Simulating/Computing Complexity**

**DQS + AQS + AQC**

**Neuromorphic Quantum Computing (NQC)**
- Quantum memristors provide complexity

**Embedding Quantum Simulators (EQS)**

**Optimal Quantum Control (OQC)**

**Quantum Machine Learning (QML)**

**Quantum Artificial Intelligence (QAI)**