Simulator

It is used in many contexts, such as simulation of technology for performance optimisation …

The act of simulating something first requires that a **model be developed** …

…it can be used to show the eventual **real effects** of **alternative conditions** …

…it is also used when the real system **cannot be engaged**, because it may not be accessible, or it may be dangerous or …

… or it is being designed but not yet built, **or it may simply not exist**.
One can use machines and/or computers as simulators or **physical systems as simulators**

**Buffon’s needle**

Buffon’s needle is an experiment described by Georges-Louis Leclerc, Comte de Buffon, which can be used to estimate the value of π. The experiment involves dropping a needle of length $l$ onto a lined sheet of paper where the lines are $d$ units apart. The probability of the needle crossing a line depends on the ratio $l/d$, allowing the calculation of π through statistical methods.
Simulator

It is a device that allows the imitative representation of the functioning of one system or process by means of the functioning of another…

…It allows the imitation of the operation of a real-world process or system over time
A quantum simulator …

…for exploring reality and …

…for making “fantasy” real
What is a quantum simulator?
Controlled quantum systems that allow to study specific difficult quantum problems (Feynman 1982)

Why do we need it?
Classical computation may not be able to offer required performances.
Explore “new” phenomena difficult to study elsewhere

How do we realise it?
Several experimental platforms are already available

Where do we stand at present?
Few examples
Many-body systems ... “hard to understand”:

- Frustrated quantum magnets
- High-Tc superconductors

**What & Why**

Quantum simulator: an experimental *controllable* system that reproduces the physics of a given model Hamiltonian

Questions not accessible via classical computation because the exp-large dimension of the Hilbert space (e.g. complex quantum ground states or dynamics in solid state systems)

Questions that are not directly “tractable/identified” in “nature” (e.g. thermalisation, defect formation, ...)

Refine our control on many-body systems

New states of matter (e.g. time-crystals, exotic qp, ...)

Detailed microscopic knowledge
Initial state preparation
Highly tuneable
High level of coherence over large time scales
Good access for measurements
Experimental platforms (prehistory)

Josephson junction arrays in the quantum regime

J.E. Mooij group
(TUDelft)
Exp platforms

- Trapped ions
- Photonic quantum simulators
- Rydberg atoms
- Optical lattices
Exp platforms

Superconducting & semiconducting nanostructures
**Bose-Hubbard model**

Bosons hopping on a d-dimensional lattice

\[ \mathcal{H} = \sum_{\langle ij \rangle} -J (a_i^\dagger a_j + \text{h.c.}) + \sum_i U n_i (n_i - 1) \]

- \( J \gg U \) superfluid
- \( J \ll U \) Mott insulator
Bose-Hubbard model


Fermi-Hubbard model

Different ingredients:
- fermions
- synthetic dimension
- frustration

...from ground state
... to dynamics
The entanglement entropy grows linearly with time saturating to a volume law

\[ S(\rho_L) \equiv -tr(\rho_L \log \rho_L) \]

Our ability to simulate the system with a classical computer is spoiled

Intimate connections between cond-mat stat-mech and quantum-info

Calabrese & Cardy 2005

G. Vidal 2003 - 2004
...from ground state to dynamics

\[ |\Psi(t)\rangle = U(t) |\Psi(0)\rangle \]

Following the dynamics, by means of numerical simulation, of a many-body quantum system becomes increasingly hard.

Thermalisation
Ergodicity and thermalisation in quantum systems is one of the most intriguing problems in quantum physics.

An isolated many-body system should be able to reach at long times a thermal steady state compatible with the initial energy density *as far as local observables* are concerned. *A large system acts as its own environment*

Integrable systems: appear to relax to a non-thermal steady state that keeps track of all the constants of motion: the generalised Gibbs ensemble

Many-body localisation

Breakdown of ergodicity in a generic, disordered many-body quantum system - no part of it acts as reservoir for the rest of the system.

Transport of mass/spin/energy is frozen

Quantum correlations (entanglement) can still propagate in the MBL phase

Existence of an extensive number of local integrals of motions (an effective “l-bit” Hamiltonian)

Many-body localisation

Absence of thermalisation through a measurement of imbalance in a one-dimensional interacting Fermi system in the presence of “pseudo-random” potential


The imbalance indicates the failure of the system to thermalise. It is not a direct indication of the many-body dephasing taking place in the MBL phase.
“even more” exotic
Can time-translational invariance be spontaneously broken?

Wilczek 2013

Time-crystal
Time-crystals

Can time-translational invariance be spontaneously broken?

Wilczek 2013

A no-go theorem lead to the conclusion that systems in thermal equilibrium cannot manifest any time-crystalline behaviour.

Floquet time crystals: The time-translation symmetry breaking appears as the response of an observable which oscillates with periodicity that is a multiple of the imposed drive.

Boundary time crystals: Time-translational symmetry breaking occurs only in a fraction of the sample.

Floquet time crystals (TTSB in periodically driven systems)

\[ \mathcal{H}(t + T) = \mathcal{H}(t) \]

\[ f(t) = \lim_{N \to \infty} \langle \psi | \hat{O}(t) | \psi \rangle \]

\[ f(t + \tau_B) = f(t) \quad \tau_B = nT \]

Else et al 2016
Khemani et al 2016
Trapped ions

\[ H = \sum J_{ij} S_i^z S_j^z - \hbar \sum S_i^x \]

\[ J_{ij} \sim \frac{1}{|i - j|^\alpha} \]
Time-crystals

Experimental realisation of Floquet time-crystals
Choi et al 2016
Zhang et al 2016

Trapped ions
Is it possible to have a Floquet time-crystal in the absence of disorder?

How to observe direct transitions between different crystalline phases

Floquet time-crystals in infinite-range models

F. Surace et al, in preparation
...where do we stand at present?

51 vs 53 qubits

Observation of a Many-Body Dynamical Phase Transition with a 53-Qubit Quantum Simulator

A quantum simulator is a restricted class of quantum computer that controls the interactions between quantum bits in a way that can be mapped to certain difficult quantum many-body problems. As more control is exerted over larger numbers of qubits, the simulator can tackle a wider range of problems, with the ultimate limit being a universal quantum computer that can solve general classes of hard problems. We use a quantum simulator composed of up to 53 qubits to study a non-equilibrium phase transition in the transverse field Ising model of magnetism, in a regime where conventional statistical mechanics does not apply. The qubits are represented by trapped ion spins that can be prepared in a variety of initial pure states. We apply a global long-range Ising interaction with controllable strength and range, and measure each individual qubit with near 99% efficiency. This allows the single-shot measurement of arbitrary many-body correlations for the direct probing of the dynamical phase transition and the uncovering of computationally intractable features that rely on the long-range interactions and high connectivity between the qubits.