**QUANTUM TECHNOLOGY**
An Initiative Seminar by Area of Advance Nanoscience and Nanotechnology

**Enrique Solano**, University of the Basque Country, *Quantum simulations: a quantum theater for quantum technologies*
I will introduce the concept of quantum simulation as a means of reproducing physical models onto another quantum system, which is typically more controllable. From an aesthetic perspective, quantum simulations perform mimicking and role-playing in our quantum theatre, where the actors can be atoms, photons, or superconducting circuits. In more scientific terms, they make use of interdisciplinary analogies as communicating vessels between unconnected fields. As a promising quantum technology, quantum simulations aim at solving complex problems that are impossible for classical computers. Furthermore, I will explain the differences between analog and digital quantum simulators from a wide point of view and will give pedagogical examples in different quantum platforms. Finally, I will discuss the future scope of quantum simulations in fundamental science and disruptive industrial applications to physics, chemistry, biology, materials, engineering, and the unexpected.

**Leo Kouwenhoven**, Delft University of Technology, *Majorana Qubits*
Majoranas in semiconductor nanowires can be probed via various electrical measurements. Tunnel spectroscopy have revealed zero-bias peaks in the differential conductance. New observations include quantum superpositions of Majorana states leading, for instance, to a 4π current phase relation or a fractional Josephson effect. When the existence of Majoranas is firmly established, the next challenge is to build Majorana qubits. We discuss the different qubit schemes and report on our first building blocks. The promise of Majorana qubits is that the error rate is very low yielding a relativistic simple scalable architecture.

**Matthias Troyer**, ETH Zürich, *Quantum High Performance Computing*
Following experimental realizations of small but scalable quantum computers we may soon see the first quantum computers with the potential to outperform the fastest classical computers. It is thus timely to identify application problems that a quantum computer could solve better than any classical supercomputer. Despite the challenges posed by mature classical computing technology we can identify several interesting application areas for quantum computers that can make the efforts to build a quantum computer not only a scientifically but also a commercially interesting endeavor. These include materials science and quantum chemistry as the "native" applications of quantum technology. A closer look at these algorithms reveals that in parallel to the development of quantum computing hardware, a strong effort in quantum software engineering and algorithmic optimization is needed to make quantum computers competitive for a wide range of applications.

**Andrew Cleland**, University of Chicago
*EnCt29676b5614c6c39b30f0a7a91f5291416cadd77, or, Can you read this title?*
Present methods for the secure communication of sensitive information rely on the difficulty of decoding mathematically encrypted messages. How much can these methods be trusted in an era of quantum information? Asymmetric encryption relies on a combination of a public and a private key, and is open to attack by a quantum computer. Symmetric encryption relies on the secure transmission of a shared secret key, so can be attacked by an eavesdropper. Quantum communication is provably secure to both quantum computers and eavesdroppers, but to date has only been deployed in ways that are subject to technical attacks, and are slow and short-range. In this talk, I will first introduce the concept of quantum communication and how it can provide better information security than current methods. I will then describe my group’s progress in developing a quantum repeater, a device that could serve as a fundamental component for a long-range, high speed quantum communication network. The devices we are developing rely on the coherent parametric conversion of signals between microwave and optical frequencies, via the strong interaction between light and mechanics occurring in a mechanically suspended, nanopatterned structure. This device will eventually be coupled to a circuit of quantum bits, which would serve to purify and/or create entangled quantum information. I will include a brief description of our approach and a description of the current status of development. Work is supported by grants from AFOSR, ARO, DOE and NSF.
Stefan Kröll, Lund University, Quantum applications and spin off discoveries in rare earth crystals.

Abstract: Rare earth ion doped crystals are unique among solid state quantum materials due to their ability to maintain quantum properties created by interaction with light over extended times. Because of this they have been an interesting candidate as a part of quantum repeaters for secure long distance quantum communication. The presentation will first address particular properties of rare earth ion doped crystals relevant for quantum technology. It will then describe unexpected potential spin off applications, for example in medicine. These spin off effects were discovered in connection with the preparation of these materials for quantum operations and they build on the somewhat surprising circumstance that the speed of light in these crystals are often reduced ten-thousand or hundred-thousand times as they are prepared for the quantum operation tasks.

Steven Girvin, Yale University, Quantum Error Correction: Building a (Nearly) Perfect Computer from Imperfect Parts

The ‘second quantum revolution’ is well underway. Through careful microwave engineering we have made more than five orders of magnitude improvement in the coherence times of superconducting quantum circuits over the last 15 years. Multi-qubit entanglement, high-fidelity readout and quantum control have become routine. This progress now allows us to enter an important new era of quantum feedback and quantum error correction. The fact that it is possible even in principle to do quantum error correction has to be viewed as a counter-intuitive miracle. This talk will provide an introduction to quantum error correction and recent experiments [1] using Schrödinger cat states of microwave photons to encode quantum information and actively preserve it for times longer than the individual photons live.[1] N. Ofek et al., ‘Demonstrating Quantum Error Correction that Extends the Lifetime of Quantum Information; Nature 536, 441–445 (2016).

Yoshihisa Yamamoto, Japan Science and Technology Agency, Stanford University, Combinatorial Optimization and Boltzmann Sampling by Coherent Ising Machines.

We present the principle, implementation and performance of the coherent Ising machines based on degenerate optical parametric oscillator network. Exact solutions are obtained with short computation times (less than or equivalent to 1 msec) and reasonable probabilities (>20%) for NP-hard MAX-CUT problems with a problem size up to N = 100. Approximate solutions with an accuracy better than 87.8% are obtained with a computation time of ~70 μsec for N = 2048 complete graph MAX-CUT problems. We will also discuss the future applications of the machines in the combinatorial optimization and Boltzmann sampling.

Jacqueline Bloch, CNRS / Paris Sud University, Quantum fluids of light in semiconductors

The progress in Nanotechnologies enables confining both light and electronic excitations in tiny volumes, and build cavity lattices with strong light matter coupling. Because of the dressing of photons with matter excitations, light behaves as a quantum fluid and exhibits fascinating properties such as superfluidity. I will review recent progress in the emerging research field on quantum fluids of light in semiconductor microcavities. This non-linear photonic platform enables implementing a large variety of Hamiltonians, emulating the physics of quantum particles with zero mass (Dirac particles), with infinite mass (flat band physics), emulating acoustic black holes or unraveling dissipative quantum phase transitions.

John Martinis, Google and UC Santa Barbara, Roadmap for building a quantum computer

I will overview the basic strategy and roadmap for the quantum-AI project at Google, which has the goal of building a useful quantum computer. For hardware, the key metric is building scalable qubits with 2-qubit gate errors below 0.1-0.2% [J.M.Martinis, NPQI 1, 15005 (2015)]. For software, I will describe a new “quantum-supremacy” test that can demonstrate the exponential power of a quantum processor by checking its output with a classical computer, which is intractable for even the world’s most advanced classical supercomputer beyond 42-50 qubits. We are working to perform this experiment in the next 2 years.
Stefan Filipp, IBM Research Zurich, *Quantum computing on a scalable superconducting qubit platform*

The rapid improvement of quantum technology brings the coherent control of dozens of qubits within the reach of next-generation quantum computing platforms. This will provide the ability to tackle problems in molecular chemistry, condensed matter physics or mathematical optimization more efficiently than classical computers could do. Superconducting qubits are ideally suited as there exists a clear path towards a scalable architecture to realize the building blocks of a future universal quantum computer and for practical quantum simulation applications. At IBM, we have demonstrated full error detection and multi-qubit parity measurements for the surface code on a five-qubit chip. A quantum computing platform, the ‘IBM Quantum Experience’, has been made publicly available as a cloud service where everyone can implement quantum algorithms with up to five qubits. For quantum simulations of small molecular systems, we explore longitudinal and transverse coupling mechanisms based on the parametric modulation of an auxiliary bus frequency. The potential to realize different interaction terms makes this method well suited for analog quantum simulations and may serve as a scalable coupling bus in surface-code architectures.

Lisa Barsotti, MIT, *The quantum side of gravitational wave detectors*

The recent discovery of gravitational waves has been enabled by the new generation of Advanced LIGO detectors, the most sensitive laser interferometers ever built. Gravitational wave interferometers are limited by quantum noise across their entire detection band, and can benefit from quantum technology to further extend their astrophysical reach. In my talk I will describe the Advanced LIGO detectors and prospects for surpassing the quantum limit by using squeezed states of light.

David DiVincenzo, Forschungszentrum Juelich GmbH, *Hall Effect Gyrators and Circulators*

I will begin by explaining the very important role that microwave circulators play in current microwave quantum optics work. The Faraday-effect circulator was invented in the 1950’s, at which time circulators using the Hall effect were also considered. It was “proved” then that a Hall bar cannot make a good gyror (a close cousin to the circulator). This proof is flawed, and we have shown that good gyroras are possible for Hall angle > 90 degrees (aka “quantum Hall state”) if the device is contacted capacitively. We predict that the resulting Hall circulator can be much more miniaturized than the Faraday kind. We will discuss the relation of this device functionality to the physics of chiral edge magnetoplasmons in the Hall conductor.

Erika Andersson, Heriot-Watt University, Edinburgh, *Secure signatures - a practical quantum technology.*

Modern cryptography encompasses much more than encryption of secret messages. Signature schemes are widely used to guarantee that messages cannot be forged or tampered with, for example in e-mail, software updates and electronic commerce. Messages are also transferrable, which distinguishes digital signatures from message authentication. Transferability means that messages can be forwarded; in other words, that a sender is unlikely to be able to make one recipient accept a message which is subsequently rejected by another recipient if the message is forwarded. Similar to public-key encryption, the security of commonly used signature schemes relies on the assumed computational difficulty of problems such as finding discrete logarithms or factoring large primes. With quantum computers, such assumptions would no longer be valid. Partly for this reason, it is desirable to develop signature schemes with unconditional or information-theoretic security. Quantum signature schemes are one possible solution. Similar to quantum key distribution (QKD), their unconditional security relies only on the laws of quantum mechanics. Quantum signatures can be realized with the same system components as QKD, but are so far less investigated. This talk aims to provide an introduction to quantum signatures and to review progress so far.
Nicolas Gisin, University of Geneva, *Quantum Communication*
Quantum communication is the art of transferring a quantum state from one location to a distant one. Commercial applications cover Quantum Random Number Generators (QRNG) and Quantum Key Distributions (QKD). Academic research focuses mostly on two topics. First, quantum repeaters that should allow one to break the 500 Km distance limit of direct QKD; the grand challenge is second-long quantum storage with 90% efficiency. A second topic is Device Independent Quantum Information Processing, another intellectually fascinating prospect.

Paola Cappellaro, MIT, *Coherent feedback of a single qubit in diamond*
The most common approach to engineering desired operations on qubits subjected to the deleterious effects of their environment relies on open-loop control techniques. Feedback control, an alternative strategy inspired by the success of classical control, is less pervasive in the quantum setting because of complications introduced by quantum measurement. I will present the experimental implementation of a feedback-control algorithm with a solid-state spin qubit associated with the nitrogen vacancy center in diamond. The feedback algorithm can protect the qubit against intrinsic dephasing noise for milliseconds (orders of magnitude larger than its dephasing time) by exploiting a long-lived ancillary qubit. In addition, it protects the qubit coherence while performing two essential qubit gates—NOOP and NOT gates—during the protection time.

Mohamed Bourenanne, Stockholm University, *Photonic Multipartite Entanglement*
Quantum entanglement leads to the most counterintuitive effects in quantum mechanics and it plays a central role in the field of quantum information and quantum computing. The entanglement quantitative and qualitative characterization for mixed and multipartite systems is still under intense research. An important and crucial question is to know which of mixed states can be distilled to maximally entangled states with help of local operations and classical communication. The Horodecki group has made an important discovery by predicting theoretically existence of quantum entangled states where no entanglement can be distilled. This peculiar entanglement has been called bound entanglement. This new class of states lies between separable and “free” entangled. In my talk, I will present our results on experimental demonstrations of three and four qubits bound entangled states and fully characterize their entanglement properties. I will also show our results on unlocking and activation protocols of bound entanglement.
Patrice Bertet, CEA Saclay, Magnetic resonance at the quantum limit and beyond
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The detection and characterization of paramagnetic species by electron-spin resonance (ESR) spectroscopy has numerous applications in chemistry, biology, and materials science [1]. Most ESR spectrometers rely on the inductive detection of the small microwave signals emitted by the spins during their Larmor precession into a microwave resonator in which they are embedded. Using the tools offered by circuit Quantum Electrodynamics (QED), namely high quality factor superconducting micro-resonators and Josephson parametric amplifiers that operate at the quantum limit when cooled at 20mK [2], we report an increase of the sensitivity of inductively detected ESR by 4 orders of magnitude over the state-of-the-art, enabling the detection of 300 Bismuth donor spins in silicon with a signal-to-noise ratio of 1 in a single echo [3,4]. We also demonstrate that the energy relaxation time of the spins is limited by spontaneous emission of microwave photons into the measurement line via the resonator [5], which opens the way to on-demand spin initialization via the Purcell effect. Finally, we show that the sensitivity can be enhanced beyond the quantum limit by using quantum squeezed states of the microwave field [6].


Immanuel Bloch, Max-Planck Institut für Quantenoptik & Ludwig-Maximilians Universität, Controlling and Exploring Quantum Matter Using Ultracold Atoms in Optical Lattices
More than 30 years ago, Richard Feynman outlined the visionary concept of a quantum simulator for carrying out complex physics calculations. Today, his dream has become a reality in laboratories around the world. In my talk I will focus on the remarkable opportunities offered by ultracold quantum gases trapped in optical lattices to address fundamental physics questions ranging from condensed matter physics over statistical physics to high energy physics with table-top experiment. For example, I will show how it has now become possible to image and control quantum matter with single atom sensitivity and single site resolution, thereby allowing one to directly image individual quantum fluctuations of a many-body system or directly reveal antiferromagnetic order in the fermionic Hubbard model. I will also show, how recent experiments with cold gases in optical lattices have enabled to realise and probe artificial magnetic fields that lie at the heart of topological energy bands in a solid. Using a novel ‘Aharonov-Bohm’ type interferometer that acts within the momentum space, we are now able to fully determine experimentally the geometric structure of an energy band. Finally, I will discuss our recent experiments on novel many-body localised states of matter that challenge our understanding of the connection between statistical physics and quantum mechanics at a fundamental level.