Quantum Roundabout 2016

Nottingham, 6th-8th July 2016

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Welcome to Quantum Roundabout 2016!

Organising committee

- **Pietro Liuzzo Scorpo**, University of Nottingham
- **Rosanna Nichols**, University of Nottingham
- **Bartosz Regula**, University of Nottingham

with support from **Gerardo Adesso, Katie Gill** and the **Quantum Correlations group** at the University of Nottingham.

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Programme

Tuesday 5th July	
16:00-	Registration
19:00-	Welcome pub trip
Wednesday 6th July	
08:50-09:00	Opening remarks
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10:30-11:00	Tea break
11:00-11:30	**Carlo Sparaciari** A resource theory of work and heat
11:30-12:00	**Alvaro Alhambra** The second law of thermodynamics as an equality
12:00-12:30	**Alexander Pitchford** Quantum Optimal Control in QuTiP
12:30-14:00	LUNCH
14:00-15:00	**Sabrina Maniscalco** Markovian and non-Markovian open quantum dynamics
15:00-15:30	**Filip Wudarski** How to get Markovian semigroup from non-Markovian evolution?
15:30-16:00	**Katarzyna Siudzińska** The non-Markovian evolution of the generalized Pauli channels
16:00-16:30	Tea Break
16:30-17:00	**Caterina Foti** Can the dynamics of a macroscopic environment testify of its entanglement with a quantum companion?
17:00-17:30	**Carlo Maria Scandolo** Entanglement and thermodynamics in general probabilistic theories
17:30-	Round-a-boat
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10:00-10:30	**Joshua Lockhart** Combinatorial entanglement
10:30-11:00	Tea break
11:00-11:30	**Alexander Streltsov** Entanglement and coherence in quantum state merging
11:30-12:00	**Anaelle Hertz** Improved entropic uncertainty relations
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12:30-14:30	LUNCH AND POSTER SESSION

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15:30-16:00	**Sara di Martino** Entanglement measures: monogamous or faithful?
16:00-16:30	**Thomas Bromley** Accessible quantification of multiparticle entanglement
16:30-17:00	Tea Break
17:00-17:30	**Albert Aloy López** Detection of nonlocality with two-body correlation functions
17:30-18:00	**Davide Nuzzi** Entanglement transfer by large-S spin channels
18:00-	Social event: The Dark Room
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10:00-10:30	**Ana Belen Sainz** Postquantum steering
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11:00-11:30	**Sammy Ragy** High-rate device independent randomness generation
11:30-12:00	**Antonella De Pasquale** Quantum correlations transmission via noisy quantum maps
12:00-12:30	**Riccardo Laurenza** General bounds for sender-receiver capacities in multipoint quantum communication
12:30-14:00	LUNCH
14:00-15:00	**Susana Huelga** Quantum metrology in Open Quantum Systems
15:00-15:30	**Giacomo De Palma** Gaussian States Minimize the Output Entropy of the One-Mode Quantum Attenuator
15:30-16:00	**Dominic Branford** Multiple Phase Estimation with Gaussian States
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16:30-17:00	**Alessandro Farace** Building versatile bipartite probes for quantum metrology
17:00-17:30	**Dardo Goyeneche** Multipartite entanglement in heterogeneous systems
17:30-18:00	**Jan Czajkowski** Many-body effects in quantum metrology
18:00	Conference closing & Ye Olde Trip to Jerusalem
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	Departures

Invited Talks - Abstracts

Open Quantum Systems: Prof. Sabrina Maniscalco

Introduction to open quantum systems

In this talk I will give a basic introduction to the dynamics of open quantum systems. After presenting the king and queen of open quantum systems theory, namely the dynamical map and the master equation, I will discuss the projection operator technique to formally derive the equation of motion for the reduced density matrix of the system. Both memory kernel and time-local master equations will be briefly considered and two exemplary solutions will be discussed to illustrate their main properties. Finally, I will shortly present one example of exactly solvable master equation and discussed its main physical phenomena and dynamical regimes.

Markovian and non-Markovian open quantum dynamics

I will introduce the concept of divisibility of the dynamical map and review the main properties of quantum systems interacting with their environment in absence and presence of memory effects, i.e., in the Markovian and non-Markovian regimes, respectively. After discussing the recently introduced information theoretical approach to non-Markovianity, I will focus on three of the most used non-Markovianity measures. I will conclude the talk with a few examples illustrating how reservoir engineering allows to exploit memory effects to enhance certain tasks useful for quantum technologies.

Quantum Entanglement: Prof. Karol Życzkowski

Geometry of quantum entanglement

A geometric approach to investigation of quantum entanglement is advocated. We discuss first the geometry of the (N^2-1)-dimensional convex body of mixed quantum states acting on an N-dimensional Hilbert space. For composed dimensions, $N=K^2$, one considers the subset of separable states and shows that it has a positive measure. Analyzing its properties contributes to our understanding of quantum entanglement, which in this context can be interpreted as the distance of the given quantum state to the closest separable state.

Distinguishing generic quantum states

Properties of random mixed states of dimension N distributed uniformly with respect to the Hilbert-Schmidt measure are investigated. We show that for large N, due to the concentration of measure phenomenon, the trace distance between two random states tends to a fixed number $1/4+1/\pi$, which yields the Helstrom bound on their distinguishability. To arrive at this result we apply free random calculus and derive the symmetrized Marchenko--Pastur distribution. Asymptotic value for the root fidelity between two random states, $\sqrt{F}=3/4$, can serve as a universal reference value for further theoretical and experimental studies. Analogous results for quantum relative entropy and Chernoff quantity provide other bounds on the distinguishablity of both states in a multiple measurement setup due to the quantum Sanov theorem. Entanglement of a generic mixed state of a bi--partite system is estimated.

Quantum Metrology: Prof. Susana Huelga

Foundations of quantum metrology

We will discuss the origin and provide a derivation of fundamental metrological bounds, which characterize the best achievable precision in the local estimation of a phase shift, given certain resources. The problem of phase estimation underlies different forms of metrology, ranging from precision spectroscopy to magnetometry. We will show how quantum metrology protocols allow overcoming precision limits typical to classical statistics, the so-called standard quantum limit (SQL), and achieving Heisenberg resolution using entangled probes.

Quantum metrology in Open Quantum Systems

We will discuss in detail the persistence of Heisenberg scaling for open system dynamics and characterize the best achievable precision in the presence of different forms of noise. We will show that typical forms of uncorrelated noise can constrain the quantum enhancement to a constant factor, and thus bound the error to the SQL. In particular, that is the case of all semigroup (Lindbladian) dynamics that include phase covariant terms, which commute with the system Hamiltonian. Remarkably, the standard scaling can be surpassed when the dynamics is no longer ruled by a semigroup and becomes time-inhomogeneous. We will show that in this case, the ultimate precision is determined by the system short-time behaviour, which when exhibiting the natural Zeno regime, leads to a non-standard asymptotic resolution, albeit below Heisenberg scaling. In particular, we demonstrate that the relevant noise feature dictating the precision is the violation of the semigroup property at short timescales, while genuine non-Markovianity does not play any specific role.

Contributed Talks - Abstracts

Wednesday 6th July

Matteo Rossi *Probing the diamagnetic term in light-matter interaction*

Should the Dicke model of light-matter interaction include a diamagnetic term? This question has generated intense debate in the literature, and is particularly relevant in the modern contexts of cavity and circuit QED. We design an appropriate probing strategy to address the issue experimentally. Applying the tools of quantum estimation theory to a general Dicke model, we quantify how much information about the diamagnetic term (or lack thereof) is contained in the ground state of the coupled system. We demonstrate that feasible measurements, such as homodyne detection or photon counting, give access to a significant fraction of such information. These measurements could be performed by suddenly switching off the light-matter coupling, and collecting the radiation that naturally leaks out of the system. We further show that, should the model admit a critical point, both measurements would become asymptotically optimal in its vicinity. We finally discuss binary discrimination strategies between the two most debated hypotheses involving the diamagnetic term.

Carlo Sparaciari *A resource theory of work and heat*

In recent years, the tools of quantum information theory have been successfully applied to the field of thermodynamics. In particular, a key element for extending the thermodynamic theory to the microscopic regime is represented by quantum resource theory. In this talk, we present the main mathematical aspects of resource theories, and we introduce a specific theory for quantum thermodynamics. This theory is characterised by two resources, work and heat, which are represented by pure and thermal states, respectively. We show how the theory allows us to describe asymptotic state transformations, and to quantify the amount of work and heat exchanged. Moreover, we find the monotones of the theory, defined by the relative entropy distance from specific quantum states. The theory we develop allows for a rigorous definition of work and heat in the microscopic regime, and provides information about the size of the thermal bath needed to perform state transformations.

Alvaro Alhambra *The second law of thermodynamics as an equality*

We investigate the connection between resent results in quantum thermodynamics and fluctuation relations. We adopt a fully quantum mechanical and information theoretic description of thermodynamics and include a work system whose energy is allowed to fluctuate. We derive a generalisation of Gibbs-stochasticity, a condition found in the approach to thermodynamics inspired by quantum information theory. We show that this generalisation gives a necessary and sufficient condition for a thermodynamical transition to happen in the case of fluctuation work. The condition serves as a parent equation which can be used to derive a number of results. These include writing the second law of thermodynamics as an equality featuring a fine-grained notion of the free energy. We also obtain a generalisation of the Jarzynski fluctuation theorem which holds for arbitrary initial states. We further show that each of these three relations can be seen as the quasi-classical limit of three fully quantum identities. This allows us to consider the free energy as an operator, and allows one to obtain more general and fully quantum fluctuation relations from the information theoretic approach to quantum thermodynamics.

Alexander Pitchford *Quantum Optimal Control in QuTiP*

Optimal control for quantum systems is introduced, explaining how the amplitude function of an external controlling field can be determined such that a target unitary gate or specific state-to-state transfer can be effected. Examples of optimising control pulses using QuTiP are shown. QuTiP is an open source Python library for simulating the dynamics of quantum systems. The library contains implementations of the GRAPE and CRAB algorithms. The examples cover closed and open quantum systems, and symplectic transformations on Gaussian systems. An overview is included of how quantum optimal control can be used to investigate theoretical questions such as minimum gate time and reachability of gate operations.

Filip Wudarski *How to get Markovian semigroup from non-Markovian evolution?*

We show how to obtain Markovian semigroup as a convex combination of two non-Markovian evolutions. This approach indicates that evolution with non-trivial memory effects may cancel each other to obtain perfectly memoryless dynamics.

Katarzyna Siudzińska *The non-Markovian evolution of the generalized Pauli channels*

Our goal is to analyze the evolution of open quantum systems which is given by the family of time-dependent generalized Pauli channels. These channels are a special case of the random unitary evolution, and they are constructed with the use of the maximal number of mutually unbiased bases. We provide the conditions for the back-flow of information to vanish.

Caterina Foti *Can the dynamics of a macroscopic environment testify of its entanglement with a quantum companion?*

We study a composite bipartite quantum system in such a way that the quantum character of one component is not affected even if the other one becomes macroscopic. In particular, we aim at investigating if the evolution of the macroscopic part can testify the entanglement with its microscopic quantum companion. To accomplish this goal, we refer to a magnetic system with fixed spin S, which exchanges energy with a quantum mechanical oscillator. We then formally introduce a large-S limit to describe how the magnetic environment becomes macroscopic: This allows us to write the propagator as a composition of terms where we single out the back-action effects, i.e. the dynamical effects of the oscillator on the magnet. In order to quantitatively analyze such back-action, we have chosen some specific initial states for the quantum oscillator and described the time evolution that it induces on the magnetic system.

Carlo Maria Scandolo *Entanglement and thermodynamics in general probabilistic theories*

Entanglement is one of the most striking features of quantum mechanics, and yet it is not specifically quantum. More specific to quantum mechanics is the connection between entanglement and thermodynamics, which leads to an identification between entropies and measures of pure-state entanglement. Here we search for the roots of this connection, investigating the relation between entanglement and thermodynamics in the framework of general probabilistic theories. We first address the question whether an entangled state can be transformed into another by means of local operations and classical communication. We then consider a resource theory of purity where free operations are random reversible transformations. Our key result is a duality between the resource theory of entanglement and the resource theory of purity, valid for every physical theory where all processes arise from pure states and reversible interactions at the fundamental level.

Thursday 7th July

Joshua Lockhart *Combinatorial Entanglement*

In an attempt to better understand the phenomena of mixed state entanglement, we consider a family of extremely simple states which emerge in what we call the ``faulty emitter scenario''. We show that such states can be represented using a combinatorial object called a grid-labelled graph.

Graph theoretic approaches to mixed state entanglement have been explored in the past, with demonstrations that the PPT criterion is equivalent to checking vertex degree invariance under a graph operation. We show that imposing a labelling allows for a richer framework: we can ``import'' LOCC and additional entanglement criteria.

Our framework lets us test the limits of certain well known entanglement criteria which have a graphical interpretation, for instance, we can use it to generate entangled states that the matrix realignment criterion cannot detect, as well as new families of bound entangled states.

Alexander Streltsov *Entanglement and coherence in quantum state merging*

Understanding the resource consumption in distributed scenarios is one of the main goals of quantum information theory. A prominent example for such a scenario is the task of quantum state merging where two parties aim to merge their parts of a tripartite quantum state. In standard quantum state merging, entanglement is considered as an expensive resource, while local quantum operations can be performed at no additional cost. However, recent developments show that some local operations could be more expensive than others: it is reasonable to distinguish between local incoherent operations and local operations which can create coherence. This idea leads us to the task of incoherent quantum state merging, where one of the parties has free access to local incoherent operations only. In this case the resources of the process are quantified by pairs of entanglement and coherence. Here, we develop tools for studying this process, and apply them to several relevant scenarios. While quantum state merging can lead to a gain of entanglement, our results imply that no merging procedure can gain entanglement and coherence at the same time. We also provide a general lower bound on the entanglement-coherence sum, and show that the bound is tight for all pure states. Our results also lead to an incoherent version of Schumacher compression: in this case the compression rate is equal to the von Neumann entropy of the diagonal elements of the corresponding quantum state.

See arXiv:1603.07508 for more details

Anaelle Hertz *Improved entropic uncertainty relations*

Uncertainty relations have recently found a revived interest in continuous-variable quantum information as they can be related to entanglement. The Duan-Simon separability criterion, for example, can be interpreted as the result of applying the Schrödinger-Robertson uncertainty relation to the partially transposed state of a two-mode state. It is, however, mostly useful for Gaussian states since the uncertainty principle relies on the second-order moments of the quadrature operators. In our work, we turn instead to the entropic uncertainty relations (EUR) expressed in terms of Shannon differential entropies. These EUR can be shown to be strictly stronger than the Heisenberg uncertainty relations for non-Gaussian states. We will show that an improvement of the EUR can be achieved by taking into account a specific measure of Gaussianity, namely the negentropy. We will derive Gaussianity -bounded EUR that are well behaved under symplectic transformations, and may give rise to stronger entanglement detection for non-Gaussian states.

Sara Di Martino *Entanglement Measures: Monogamous or Faithful?*

Given a tripartite system it is easy to see that if two of the parties are maximally entangled neither of the two can share any entanglement with the third party. Moreover we can ask if the entanglement that two parties can share is bounded by the entanglement that they share with the rest of the system. Effectively, monogamy of entanglement gives a relation between the entanglement that different parties of a system can share. The first formulation of the so-called monogamy inequalities was given by Coffman, Kundu and Wootters in 2000. This set of inequalities holds for systems of three qubits and is written in terms of the so-called Concurrence. After some years Osborne and Verstraete found that a set of similar inequalities holds for systems of n qubits: the sum of the entanglement that one qubit shares with each one of the other qubits of the system is bounded from above by the entanglement that this qubit shares with the rest of the system. Anyway, it is well-known that the inequality, as was initially formulated, is no longer satisfied by all measures of entanglement. Starting from this fact we try to answer if it is possible to construct a more general inequality that makes monogamy a property of entanglement itself and not of measures. In particular, we prove that is not possible to create a universal and dimension-independent inequality, for any measure satisfying a set of reasonable axioms (including entanglement of formation, entanglement cost and relative entropy). We thereby provide criteria the measure should satisfy in order to attempt this task. This allows, on the other hand, us to show that it is possible to provide a monogamy inequality, both dimension- and measure-dependent, for measures such as the entanglement of formation or the regularized relative entropy of entanglement.

Thomas Bromley *Accessible quantification of multiparticle entanglement*

Entanglement is a key ingredient for quantum technologies and a fundamental signature of quantumness in a broad range of phenomena encompassing many-body physics, thermodynamics, cosmology, and life sciences. For arbitrary multiparticle systems, entanglement quantification typically involves nontrivial optimisation problems, and may require demanding tomographical techniques. Here we develop an experimentally feasible approach to the evaluation of geometric measures of multiparticle entanglement. Our approach provides analytical results for particular classes of mixed states of N qubits, and computable lower bounds to global, partial, or genuine multiparticle entanglement of any general state. For global and partial entanglement, useful bounds are obtained with minimum effort, requiring local measurements in three settings for any N. For genuine entanglement, a number of measurements scaling linearly with N is required. We demonstrate the power of our approach to estimate and quantify different types of multiparticle entanglement in a variety of N-qubit states recently engineered in laboratories.

Albert Aloy López *Detection of nonlocality with two-body correlation functions*

Nonlocality detection in multipartite quantum systems is of great interest. The most popular tool to detect nonlocality in quantum systems are Bell inequalities. Most of the provided constructions of multipartite Bell inequalities involve correlations between all parties which quickly becomes computationally intractable and hard to test experimentally in many-body quantum systems. In the talk I will show how to derive Bell Inequalities constrained by symmetry and involving only one- and two-body correlation functions that allow for nonlocal detection in multipartite systems. Furthermore, I will also introduce the notion of entanglement depth and show how these inequalities can be turned into Device Independent Entanglement Witness.

Davide Nuzzi *Entanglement transfer by large-S spin channels*

We here follow the idea of using large-S 1-d systems as robust channels for entanglement transfer. Since a full quantum description of a many-body large-S system interacting with some qubits is in general not feasible, we introduce a semi-classical approximation scheme based on single-spin coherent states; this scheme allows us to describe the dynamics of a system made by two distant (and not directly interacting) qubits and a large number of interacting spins, still retaining enough of the system's quantum nature to account for entanglement generation and transmission.

In this way, considering a spin-S chain, we show that, choosing the chain initial state close to a localized classical dynamical configuration (soliton), the entanglement established between the first qubit and the chain can be transferred along the spin-S system through to the second qubit leading to an entangled state of the two distant qubits.

Friday 8th July

Ana Belen Sainz *Postquantum steering*

The discovery of postquantum nonlocality, i.e. the existence of nonlocal correlations stronger than any quantum correlations but nevertheless consistent with the no-signaling principle, has deepened our understanding of the foundations quantum theory. In this work, we investigate whether the phenomenon of Einstein-Podolsky-Rosen steering, a different form of quantum nonlocality, can also be generalized beyond quantum theory. While postquantum steering does not exist in the bipartite case, we prove its existence in the case of three observers. Importantly, we show that postquantum steering is a genuinely new phenomenon, fundamentally different from postquantum nonlocality. Our results provide new insight into the nonlocal correlations of multipartite quantum systems.

Sammy Ragy *High-rate device independent randomness generation*

For cryptographic uses, we need that randomness be private. If we have not built the randomness generation equipment ourselves (or if we have looked away for long enough for someone to interfere with it), then it may be that it is leaking information about our randomness to an adversary. Device independent quantum random number generation (DIQRNG) aims to certify private randomness with minimal assumptions about the equipment used. Thus far, DIQRNG proofs have required some unreasonable measures, such as having a pair of devices per every entangled state present; otherwise, they have abysmal rates of randomness generation. We attempt to prove good rates for a not-so-unreasonable scheme.

Antonella De Pasquale *Quantum correlations transmission via noisy quantum maps*

Quantum correlations represent a key ingredient for efficient quantum commnication between two or more parties. Physical communication lines are formally modelled as completely positive, trace-preserving maps, taking into account unavoidable sources of disturbance. Several protocols, based on local operations and classical communcation, aim to amplify and partially restore the correlations surived in the transmission process. In this context entanglement-breaking channels, mapping every bipartite state into a separable one, are considered useless for quantum communication objectives, as they get rid of all quantum correlations.

In this work we overthrow this statement. We prove both theoretically and experimentally, that is possible to transmit quantum correlations having at disposal ONLY entanglement-breaking maps. We dub the theoretical mechanism underpinning this phenomenon CUT-AND-PASTE, as it consists in cutting and reshuffling the subparts of entanglement-breaking channels. We have successfully tested this mechamism in a quantum optics experiment, by monitoring the transmission of single-photon polarization states.

Riccardo Laurenza *General bounds for sender-receiver capacities in multipoint quantum communications*

We investigate the maximum rates for transmitting quantum information, distilling entanglement and distributing secret keys between a sender and a receiver in a multipoint communication scenario, with the assistance of unlimited two-way classical communication involving all parties. First we consider the case where a sender communicates with an arbitrary number of receivers, so called quantum broadcast channel. Here we also provide a simple analysis in the bosonic setting where we consider quantum broadcasting through a sequence of beamsplitters. Then, we consider the opposite case where an arbitrary number of senders communicate with a single receiver, so called quantum multiple-access channel. Finally, we study the general case of a quantum interference channel where an arbitrary number of senders communicate with an arbitrary number of receivers. Since our bounds are formulated for quantum systems of arbitrary dimension, they can be applied to many different physical scenarios involving multipoint quantum communication.

Giacomo De Palma *Gaussian States Minimize the Output Entropy of the One-Mode Quantum Attenuator*

We prove that Gaussian thermal input states minimize the output von Neumann entropy of the one-mode Gaussian quantum attenuator for fixed input entropy. The Gaussian quantum attenuator models the attenuation of an electromagnetic signal in the quantum regime. The Shannon entropy of an attenuated real-valued classical signal is a simple function of the entropy of the original signal. A striking consequence of energy quantization is that the output von Neumann entropy of the quantum-limited attenuator is no more a function of the input entropy alone. Our result opens the way to the multimode generalization, that permits to determine both the triple trade-off region of the Gaussian quantum-limited attenuator and the classical capacity region of the Gaussian degraded quantum broadcast channel

Dominic Branford *Multiple Phase Estimation with Gaussian States*

Phase estimation is a common problem in metrology with the aim being to estimate parameters with high precision, making efficient usage of some finite resources. The estimation of single phases with a range of states is well understood, yet applications such as imaging involve measuring a large number of distinct phases. Prior work has shown that by employing strategies which simultaneously measure multiple phases can lead to an improved estimation relative to multiple independent phase measurements. Such states are not easy to make, instead Gaussian states can be produced experimentally and are known to perform well for single phase estimation. We analyse the performance of pure Gaussian states for multiple phase estimation, identifying optimal states for estimation and comparing their performance to strategies which employ fixed number or Gaussian probe states.

Alessandro Farace *Building versatile bipartite probes for quantum metrology*

We consider bipartite systems as versatile probes for the estimation of transformations acting locally on one of the subsystems. We investigate what resources are required for the probes to offer a guaranteed level of metrological performance, when the latter is averaged over specific sets of local transformations. We quantify such a performance via the average skew information (AvSk), a convex quantity which we compute in closed form for bipartite states of arbitrary dimensions, and which is shown to be strongly dependent on the degree of local purity of the probes. Our analysis contrasts and complements the recent series of studies focused on the minimum, rather than the average, performance of bipartite probes in local estimation tasks, which was instead determined by quantum correlations other than entanglement. We provide explicit prescriptions to characterize the most reliable states maximizing the AvSk, and elucidate the role of state purity, separability and correlations in the classification of optimal probes. Our results can help in the identification of useful resources for sensing, estimation and discrimination applications when complete knowledge of the interaction mechanism realizing the local transformation is unavailable, and access to pure entangled probes is technologically limited.

Dardo Goyeneche *Multipartite entanglement in heterogeneous systems*

Heterogeneous bipartite quantum pure states, composed of two subsystems with a different number of levels, cannot have both reductions maximally mixed. We demonstrate the existence of a wide range of highly entangled states of heterogeneous multipartite systems consisting of $N > 2$ parties such that every reduction to one and two parties is maximally mixed. Two constructions of generating genuinely multipartite maximally entangled states of heterogeneous systems for an arbitrary number of subsystems are presented. Such states are related to quantum error correction codes over mixed alphabets and mixed orthogonal arrays.

Jan Czajkowski *Many-body effects in quantum metrology*

One of the most useful tools of quantum metrology is the Quantum Fisher Information (QFI), it gives a bound on achievable precision in experiments estimating some unknown parameter. It is not easy to find optimal experimental setups for estimation but it is feasible to calculate QFI or at least a bound for it. Nonlinear hamiltonians are easily realisable in experiments using cold atoms, allowing for increased rate of phase acquiring in interferometers. I will present a metrological models involving interactions of particles and a bound on precision of estimation in such schemes. To derive the results I used the method of Channel Extension basing on geometry of quantum channels and semi-definite programming. These are new results allowing to better analyse effects of decoherence in nonlinear metrological schemes.

Posters - Abstracts

(Author alphabetical order)

Anirudh Acharya *Statistically efficient tomography of low rank states with incomplete measurements*

The construction of physically relevant low dimensional state models, and the design of appropriate measurements are key issues in tackling quantum state tomography for large dimensional systems. We consider the statistical problem of estimating low rank states in the set-up of multiple ions tomography, and investigate how the estimation error behaves with a reduction in the number of measurement settings, compared with the standard ion tomography setup. We present extensive simulation results showing that the error is robust with respect to the choice of states of a given rank, the random selection of settings, and that the number of settings can be significantly reduced with only a negligible increase in error. We present an argument to explain these findings based on a concentration inequality for the Fisher information matrix. In the more general setup of random basis measurements we use this argument to show that for certain rank r states it suffices to measure in O(rlogd) bases to achieve the average Fisher information over all bases. We present numerical evidence for states upto 8 atoms, supporting a conjecture on a lower bound for the Fisher information which, if true, would imply a similar behaviour in the case of Pauli bases. The relation to similar problems in compressed sensing is also discussed.

Elizabeth Agudelo Ospina *Multimode nonclassicality in phase-space*

Nonclassicality quasiprobabilities (NQPs) are introduced and characterized, we discuss their experimental applicability and relevance. The NQPs are regularized versions of the highly singular Glauber-Sudarshan P-function. They show negativities for any nonclassical state and can be directly obtained from experimental data. Multipartite quantum correlations (QC) of light are revealed by using NQPs, which are necessary and sufficient to visualize any multipartite QC. A bipartite state is investigated, which has classical reduced single-mode states, no entanglement, zero quantum discord, and a positive Wigner function. Our method clearly reveals its QC, even when other methods fail. An experimentally generated squeezed vacuum state was also analyzed by direct sampling of the quantum state, and its nonclassicality was certified. The sampled NQP displays highly significant negativities, even for a rather small amount of data. This direct sampling of NQPs is a powerful and universal method to verify quantum effects of arbitrary quantum states.

Francesco Albarelli *Nonlinearity as a resource for quantum technologies*

I will present the combined results of two papers about nonlinearity. In the first part I will explore how nonlinearity can be a resource to generate nonclassical ground states in anharmonic systems. I will present the results for different exactly solvable anharmonic potentials as well as a generic sixth order potential, treated with perturbation theory. In the second part I will explore how adding a nonlinearity of Kerr type to a quantum optical lossy channel can improve the metrological task of estimating the loss rate of the channel, by using Gaussian input states. The figure of merit for the task is the Quantum Fisher Information, which is enchanced thanks to the nonlinearity, in particular if the interaction time is short (e.g. the sample is small).

Fabiano Andrade *Green's function approach for quantum graphs and quantum walks*

Quantum walks are the quantum version of the classical random walks and constitute important tools in different applications, especially in quantum algorithms. A key aspect to explain different phenomena observed in quantum walks is the interference. So a description emphasizing the path-like character of quantum walks is desirable. In this direction, a Green's function approach is particularly useful and is developed in this work. The exact formula has the form of a sum-over-paths and always can be cast into a closed analytic expression for arbitrary graph topologies. To a great extent the quantum walks usefulness is due to unusual diffusive features, allowing much faster spreading than their classical counterparts. Such behavior, although frequently credited to intrinsic quantum interference, usually is not completely characterized. Using the Green's function approach allows one to explicitly identify interference effects and also explain the emergence of superdiffusivity.

Matthieu Arnhem *Enhancing the quantum measurement of optical phase with squeezed states*

We analyse a measurement scheme of squeezed quantum states which uses both joint measurement and phase conjugation. We see if we can extract more information from joint measurement of two conjugated squeezed vacuum states compared to individual measurements.

Our measurement scheme is built on two main ideas. The first of them is joint measurement. A. Peres and W. K. Wootters conjectured in 1991 that considering a system composed of two 1/2-spins globally can gives us a better knowledge of their orientation in space than measuring them individually. This conjecture was proven for finite quantum systems in 1995 by S. Massar and S. Popescu. We implement this idea of joint measurement of continuous-variable systems by using a 50/50 beamsplitter to entangle our two inputs. The second idea was introduced by N. Gisin and S. Popescu in 1999. They showed that measuring globally a system composed of two antiparallel 1/2-spins gives us more information than two parallel one's. This purely quantum effect exists because of the anti-unitary nature of the spin-flip operation. We use it in our measurement scheme by starting with two phase conjugated squeezed states.

In order to enhance the optical phase measurement, we use phase-squeezed states that are the non-classical quantum states which suits the best for our goal. Our global measurement scheme is decomposed in three steps and has already shown his advantages for the measurement of two coherent states. First, we consider two vacuum squeezed states which are conjugated one to the other. Then, we input these states in a 50/50 beamsplitter to entangle the two squeezed states. Finally, we make homodyne detections on the correlated quadratures of the two different output modes.

We analyse if the joint measurement scheme provides us with more information on the initial phase of the squeezed vacuum states compared to individual measurements by considering statistical moments and Fisher information.

Marco Cianciaruso *Generalized Geometric Quantum Speed Limits*

The attempt to gain a theoretical understanding of the concept of time in quantum mechanics has triggered significant progress towards the search for faster and more efficient quantum technologies. One of such advances consists in the interpretation of the time-energy uncertainty relations as lower bounds for the minimal evolution time between two distinguishable states of a quantum system, also known as quantum speed limits. We investigate how the non uniqueness of a bona fide measure of distinguishability defined on the quantum state space affects the quantum speed limits and can be exploited in order to derive improved bounds. Specifically, we establish an infinite family of quantum speed limits valid for unitary and nonunitary evolutions, based on an elegant information geometric formalism. Our work unifies and generalizes existing results on quantum speed limits, and provides instances of novel bounds which are tighter than any established one based on the conventional quantum Fisher information. We illustrate our findings with relevant examples, demonstrating the importance of choosing different information metrics for open system dynamics, as well as clarifying the roles of classical populations versus quantum coherences, in the determination and saturation of the speed limits.

Francesco Maria Di Lena *Correlation Plenoptic Imaging*

Plenoptic imaging is a promising optical modality that simultaneously captures the location and the propagation direction of light in order to enable tridimensional imaging in a single shot. However, in classical imaging systems, the maximum spatial and angular resolutions are fundamentally linked; thereby, the maximum achievable depth of field (DOF) is inversely proportional to the spatial resolution. Our idea is to exploit the second-order spatio-temporal correlation properties of light to overcome this fundamental limitation. The proposed technique is called Correlation Plenoptic Imaging (CPI): using two correlated beams, from either a chaotic or an entangled photon source, it is possible to perform imaging in one arm, and simultaneously obtain the angular information in the other one.

We demonstrate, both theoretical and experimentally, that the second order correlation function possesses plenoptic imaging properties, and is thus characterized by a key tridimensional imaging capability.

Felipe Fanchini *Quantum Correlations and Coherence in Spin-1 Heisenberg Chains*

Exploiting the tools of quantum information theory, as quantum discord, quantum mutual information and three recently introduced coherence measures, we investigate the quantum phase transitions and special symmetry points in the one-dimensional XXZ model and the one-dimensional bilinear biquadratic model. We point out the relative strengths and weaknesses of correlation and coherence measures as figures of merit to witness the quantum phase transitions and symmetry points in the considered spin-1 Heisenberg chains. In particular, we demonstrate that as none of the studied measures can detect the infinite order Kosterlitz-Thouless transition in the XXZ model, they appear to be able to signal the existence of the same type of transition in the bilinear biquadratic model. However, we argue that what is actually detected by the measures here is the SU(3) symmetry point of the model rather than the infinite order quantum phase transition. Moreover, we show in the XXZ model that examining even single site coherence can be sufficient to spotlight the second-order phase transition and the SU(2) symmetry point.

David Hurst *Cavity QED for Quantum Information Processing*

We use a simplified cavity QED model to determine the possibility of entanglement generation between stationary qubits through their mutual interaction with two-mode squeezed light. Although promising, these results were obtained under the assumption of fully suppressed spontaneous emission and perfectly transmissive cavities. In order to free our system of these constraints, we investigate more sophisticated methods of modelling the cavity-qubit systems.

Nikolaos Kollas *A new measure for quantum resources*

A new measure for quantum resources is introduced which is physically related to possible constraints present on a system reflected as the restriction on the set of possible measurements. For pure entangled states it is shown that this "residual information" is equal to the entropy of entanglement. Finally some simple examples are given for mixed entangled as well as separable states.

Matthew Levitt *Power Spectral System Identification for SISO Quantum Linear Systems*

In this poster we investigate system identification for general SISO quantum linear systems (QLSs). For a given input we would like to understand the following questions: (1) What parameters can be identified? (2) How can we construct the system from sufficient input-output data? There are two parallel approaches, which are the use of time-dependent inputs or stationary inputs. The first has only been understood previously for a subclass of QLSs called passive systems. Here we extend those results to general QLSs; we find equivalent minimal systems are related by a symplectic transformation on the space of system modes. In the stationary regime we define the notion of global minimality, which turns out to be central; providing necessary and sufficient conditions for complete identifiability of the system (up to the symplectic equivalence class in the time- dependent approach). We give an algorithm for constructing a globally minimal subsystem direct from the power spectrum, which is the maximum that one could hope to identify from the power spectrum. Restricting to passive systems the analysis simplifies so that identifiabilility may be completely understood from the eigenvalues of a particular system matrix.

Patryk Lipka-Bartosik *Quantum Error Correction Codes for non-unitary noise*

We introduce a notion of nuclear numerical range as a generalization of the ordinary numerical range and emphasise its application to quantum error correction by considering a quantum noise model with block-diagonal structure of Kraus operators. Using the algebraic compression formalism and nuclear numerical range we show that the problem of finding a suitable quantum error correcting code for this noise model can be restated as a geometric problem of finding intersection points of two ellipses in the complex plane (which can be degenerated to a line segment). We prove this statement for two 4x4 (two-qubit) complex-valued Kraus operators.

Michael Lynch-White *Holographic codes in the continuous variable regime*

Recent work has shown that a key problem with the AdS/CFT correspondence, regarding the reconstruction of operators deep within the bulk, may be resolved if we treat the boundary system as a quantum error correcting code (QECC). This remarkable resolution has opened up a new avenue of research, out of which holographic codes have been born. These codes recreate many aspects of AdS/CFT (such as having the true physical system living on the boundary), as well as improving our understanding of the correspondence itself.

I am looking to generalise a holographic code to the continuous variable regime, for if we want these codes to be representative of reality it must be capable of working in this regime. Though this work is at a very early stage, it has the potential for both physical insight as well as applications to our own QECCs.

Liubov Markovich *Nonnegativity of Quantum Information and Photon Distributions Versus Quadrature Uncertainty Relation*

A photon distribution for one-, two- and multi-mode field states can be represented by special functions. Hermite, Laguerre, Legendre and Gauss' hypergeometric functions are used to represent photon distributions for the mixed light with a generic Gaussian Wigner function.

These representations can be used to construct the Shannon entropies which satisfy the subadditivity condition. The entropic inequalities for bipartite systems are used in the framework of the tomographic probability representation of quantum mechanics to characterize two degrees of quantum correlations in the systems. The subadditivity condition can be applied when the set of nonnegative functions with the unity sum is arisen.

We consider the polynomial representation of the photon distributions to construct new polynomial relations and investigate the dependence between the nonobservance of the quadrature uncertainty relation and the existence of the photon distribution function. The violation of the quadrature uncertainty relation leads to complex values of the probability.

Saulo Moreira *Modeling Leggett-Garg inequality violation*

The Leggett-Garg inequality is a widely used test of the "quantumness" of a system and involves correlations between measurements realized at different times. According to its widespread interpretation, a violation of the Leggett-Garg inequality disproves macroscopic realism and noninvasiveness. Nevertheless, recent results point out that macroscopic realism is a model-dependent notion and that one should always be able to attribute to invasiveness a violation of a Leggett-Garg inequality. This opens some natural questions: How do we provide such an attribution in a systematic way? How can apparent macroscopic realism violation be recast into a dimensional-independent invasiveness model? The present work answers these questions by introducing an operational model where the effects of invasiveness are controllable through a parameter associated with what is called the measurability of the physical system. Such a parameter leads to different generalized measurements that can be associated with the dimensionality of a system, to measurement errors, or to back action.

Carmine Napoli *Towards quantum super-resolution imaging: limitations and resources*

The imaging and sensing of micro- and nano-systems have a vast range of applicability, from quantum cosmology to information technology, from biomedical science to manufacturing industry. Motivated by these aspects, scientists and engineers have investigated how to improve the sensitivity and how to overcome the fundamental resolution limits in the detection process. The term "super-resolution" refers to all optical imaging techniques for which the precision achievable exceeds the Abbe diffraction limit. On a fundamental level, optics is governed by the quantum theory of electromagnetic radiation, and the exploration of fundamental quantum limits is still an open challenge. We will present some progress in elucidating the role of quantum correlations and other quantum mechanical resources to enhance the imaging formation and detection process.

Sofia Qvarfort *Resource theory of asymmetry applied to time-energy measurements*

The quantum resource theory of asymmetry, also known as the resource theory of quantum reference frames, allow for operations that would otherwise violate the conservation law that follows from an imposed symmetry. We show how the resource theory of asymmetry can be applied to time-energy measurements such that information about the phase of a qubit can be extracted without violating energy conservation.

Luca Rigovacca *Using susceptibility under local unitaries to quantify correlations in a Gaussian framework*

One of the ways used to quantify the non-classicality of a quantum state is based on the minimum change induced by a local unitary operation. The optimization set plays a crucial role, and typically it is defined by fixing a non-degenerate spectrum for the unitary operations. Here we show how the non-degeneracy condition is changed within the Gaussian scenario, and we use it to explicitly study the Gaussian version of the Discriminating Strength, a quantifier of discord-like correlations based upon the Quantum Chernoff bound.

Dominic Rose *Metastability in the open quantum Ising model*

We apply a recently developed theory for metastability in open quantum systems to a one-dimensional dissipative quantum Ising model. This system is known to have a non-equilibrium phase transition where the stationary state changes from paramagnetic to ferromagnetic. We show that for a range of parameters close to this transition point the dynamics displays pronounced metastability, i.e., the system relaxes first to long-lived metastable states, before eventual relaxation to the true stationary state. From the spectral properties of the quantum master operator we are able to characterise the low-dimensional manifold of metastable states. We also show that for long times the dynamics can be approximated by a classical dynamics on this manifold. We discuss how metastability is related to the intermittent dynamics of quantum trajectories.

Luigi Seveso *Quantum Galileo's experiments and mass estimation in a gravitational field*

We address the problem of estimating the mass of a (quantum) particle interacting with a classical gravitational field. In particular, we analyze in details the ultimate bounds to precision imposed by quantum mechanics and study the effects of gravity in a variety of settings. Our results show that the presence of a gravitational field generally leads to a precision gain, which can be significant in a regime half-way between the quantum and classical domains. We also address quantum en- hancement to precision, i.e. the advantages coming from taking into account the quantum nature of the probe particle, and show that non-classicality is indeed a relevant resource for mass estimation. In particular, we suggest schemes for mass-sensing measurements using quantum probes and show that upon employing non-classical states like quantum coherent superpositions one may improve precisions by orders of magnitude. In addition, we discuss the compatibility of the weak equivalence principle (WEP) within the quantum regime using as a guide the notion of Fisher Information. We find that the information on the probe's mass that can be extracted through position measurements is unchanged by turning on a uniform gravitational field. This conclusion is somehow at variance with certain views expressed in the literature that the WEP cannot hold in the quantum regime. In fact, our results show that in an information-theoretic framework, no clash occurs between quantum mechanics and the WEP.

Uther Shackerley-Bennett *The reachable set of single-mode unstable quadratic Hamiltonians*

We consider open-loop control of the subset of continuous variable systems described by Gaussian states. The problem we study consists of finding which Gaussian unitary transformations can be enacted by turning on and off a set of quadratic Hamiltonians. The group of Gaussian unitary transformations is essentially the symplectic group and so we look to Lie group control theory for answers. Here the problem has been solved for compact groups by the Lie algebra rank criterion but not for non-compact groups like the symplectic group. We explore single mode control systems that satisfy this criterion and yet in which not all symplectic operations are obtainable. This is hoped to provide intuition into why the criterion is not sufficient for non-compact groups. We find that in such systems 'energy preserving' symplectics are not enactable which creates new avenues for conjectured resolutions to the broader problem.

Serban Suciu *Quantum Coherence of Gaussian two-mode open systems*

Coherence plays a central role in physics and is a necessary condition for quantum correlations such as entanglement and discord.

Recently, a framework for the quantification of coherence has been established, in which quantum coherence is considered to be a resource in a manner similar to quantum entanglement.

The main results so far apply mostly to the finite dimensional setting and do not describe many physical relevant situations. For example, quantum optics requires quantum states in infinite dimensional systems, mainly Gaussian states. We address the quantification of coherence for Gaussian states of continuous variable systems from a geometric perspective. By tracing the distance between our state and the closest incoherent Gaussian state, we can calculate the evolution in time of the coherence under the influence of the environment. For this purpose we take as a choice of distance the Hellinger distance, as it provides a good measure for quantum coherence.

Szilárd Szalay *Multipartite entanglement and correlation*

First, we give the three level lattice-theoretic structure of multipartite entanglement/correlation. It turns out that the structure of the entanglement classes (Level III) is the up-set (order-ideal) lattice of the structure of the different kinds of partial separability (level II), which is the down-set (order filter) lattice of the lattice of the partitions of the subsystems (level I). This structure is related to the LOCC convertibility: If a state from a class can be mapped into another one, then that class can be found higher in the hierarchy. A simplified structure arises if only correlations are considered.
Second, we introduce the notion of multipartite monotonicity, expressing that a given set of faithful entanglement/correlation measures, while measuring the different kinds of partial entanglement/correlation (level II), shows also the same hierarchical structure as those. We also construct the proper multipartite generalization of the entanglement of formation, based on the entanglement entropy. Using the quantum relative entropy provides the point of view from which the new measures (and also the original bipartite ones) have a unified meaning. The multipartite monotonicity shown by this set of measures motivates us to consider these measures to be the different manifestations of some "unified" notion of entanglement. Third, illustrating the correlation part of the theory, we evaluate measures of correlations in molecules. The chemical bonds can nicely be seen in the correlation picture. We also investigate the structure of correlations, and formulate an algorithm for a clustering method, based on multipartite correlations. From this point of view, a definition of hidden correlations arise, which are multipartite correlations which couldn't be "explained" by bipartite ones.

Konrad Szymański *Joint numerical range of three hermitian matrices of size three*

The joint numerical range of three hermitian matrices of order three is a convex and compact subset $W \subset R^3$ which is an image of the unit sphere of pure states $S^5 \subset C^3$ under the hermitian form defined by the three matrices. It is therefore range of quantum averages of three hermitian operators acting on a qutrit. In this work, we label classes of the analysed set W by pairs of numbers counting the exposed faces of dimension one and two. Assuming dim(W)=3, the faces of dimension two are ellipses and only ten classes exist. Generically, W belongs to the class of ovals. We present objects belonging to each class as 3–D printouts.

Tatiana Mihaescu *Gaussian quantum steering of two bosonic modes in a thermal environment*

We describe the time evolution of a recently introduced measure that quantifies steerability for arbitrary bipartite Gaussian states in a system consisting of two bosonic modes embedded in a common thermal environment.

We work in the framework of the theory of open systems. If the initial state of the subsystem is taken of Gaussian form, then the evolution under completely positive quantum dynamical semigroups assures the preservation in time of the Gaussian form of the state.

We study Gaussian quantum steering in terms of the covariance matrix under the influence of noise and dissipation and find that the thermal noise introduced by the environment destroys the steerability between the two parts.

We make a comparison with other quantum correlations for the same system, and show that, unlike Gaussian quantum discord, which is decreasing asymptotically in time, the Gaussian quantum steerability suffers a “sudden death” behaviour, like quantum entanglement.

Jacopo Trapani *Optimized protocols for discrimination of collective decoherence for classical environments*

We address the problem of distinguishing collective decoherence phenomena from local decoherence of quantum systems interacting with a classical environment. We probe the environment with a two-mode bosonic system, look for the optimal discrimination protocol and present an overview of results, focusing particularly on the performance of states of the probe easy to implement in experimental realizations.

Scott Vinay *High-Fidelity Quantum Repeaters*

We present a protocol for generating long-range entanglement based on double-heralded entanglement generation, which produces very high fidelity Bell pairs. The use of photonic cluster states allows for entanglement swapping at much higher rates than the 50% allowed by passive, linear optical Bell measurements.

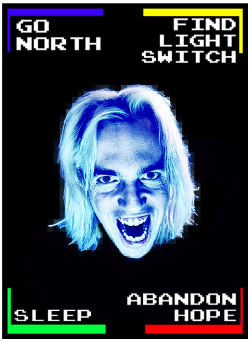
Social programme

Welcome event Tuesday 5th July

We will go to a selection of local pubs for dinner. Note, participants must pay for food and drink.

The Round-a-boat Wednesday 6th July

The social event will be a scenic river cruise down the Trent River. The conference dinner will be served during the cruise. Taxis will transport participants from the conference to the marina.



The Dark Room Thursday 7th July

We will be host to The Dark Room - the world's only live-action videogame! Originally a hit Youtube series, the show combines comedy with a near-impossible interactive text-based adventure game.

“NOT TO BE MISSED!” - The Guardian

This will be preceded by a Chinese buffet and drinks

Ye Olde Trip To Jerusalem Friday 8th July

After conference closing there will be a chance to go to The Trip To Jerusalem for dinner. This is a pub in central Nottingham set into the rock be-neath the castle with a claim to be the oldest inn in England (established 1189).

Connecting to the Wi-Fi

Eduroam is available for those with access. Otherwise please follow these instructions

<u>Connecting to UoN-guest</u>

1. Make sure the wireless network adapter is activated on your device
2. If you are in range, your device should automatically connect to the UoN-guest network. If not, find 'UoN-guest' in the list of wireless connections available and select this network. If it is not listed you are not within range of the hotspot. Please move the device until you are in range
3. Open your web browser, then browse to any unsecure website such as www.bbc.co.uk.
4. The UoN-guest wireless login page will appear
5. Follow the on-screen instructions to register for an account.
6. You will be sent two emails: one asking you to confirm your request and another with your username and password. You have 10 minutes grace time to read and confirm your access. *If you do not validate your account, then it will be deleted and your device will disconnect once its 10 minutes grace period expires.*
7. Once you have confirmed your account, disconnect and reconnect, logging in with your account details. You can log in and use the service for 7 days before you will need to re-register.

Notes:

- 'UoN-guest network' is an open network and does not provide encryption for traffic transmitted or received by connected devices.
- Security for connections made using the UoN-guest network remains the responsibility of the user and the service is used at your own risk. Please do not enter passwords online when using this network.
- If you do not validate your account within the 10 minutes grace period you will be disconnected and need to re-register.

Venue information

The conference will be held at the **Keighton Auditorium** in the **University Park Campus**, a few miles away from the centre of Nottingham. Participants will be accommodated in **Hugh Stewart Hall**, only 300 metres away from the auditorium. A detailed campus map is shown overleaf.

<u>From Nottingham Train Station or Bus Station (Broadmarsh):</u>

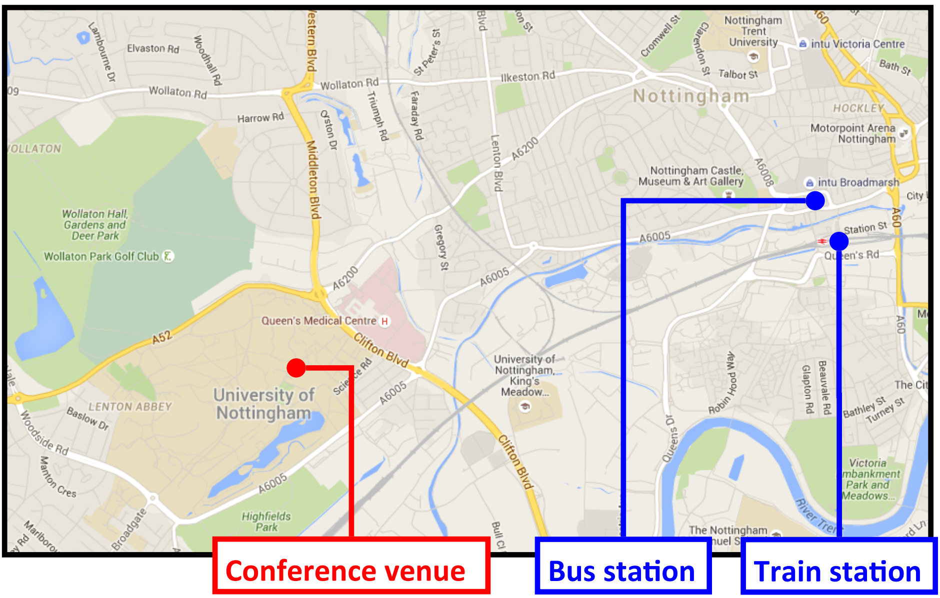
From the **bus stop C7 on Collin St.**, take the **NCT 34** (Orange Line) to the Nottingham University Main Campus. The **George Green Library stop (UN31)** is just 60 metres from the conference venue

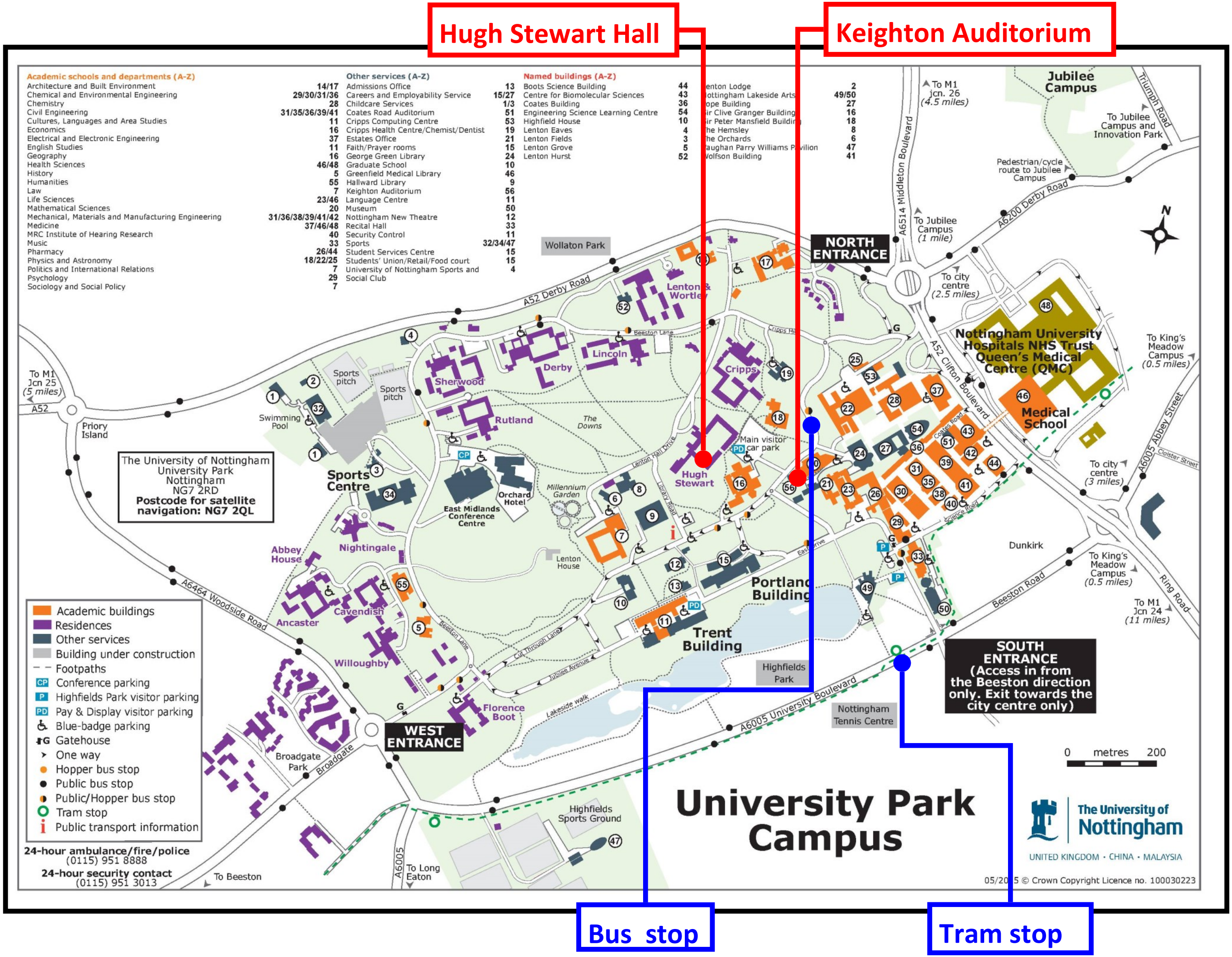
You can also take **the tram** to Toton Lane directly from the train station.
The **University of Nottingham stop** (South Entrance) is a 10-minute walk from the Keighton Auditorium.

Alternatively, take one of the buses at the **Broadmarsh Bus Station**, a short walk from the train station. You can take the **Indigo** line which stops at **Queen's Medical Centre Main Entrance**, and the **Skylink** bus to East Midlands Airport which stops at **Nottingham University Main Campus South Entrance.** Both stops are a 10-minute walk from the Keighton Auditorium.

<u>From the East Midlands Airport:</u>

The [Skylink bus] runs regularly from East Midlands Airport to Nottingham, stopping at the **Nottingham University Main Campus South Entrance**.





Hugh Stewart Hall
Keighton Auditorium
Bus stop
Tram stop
University Park Campus
Academic schools and departments (A-Z)
Architecture and Built Environment 14/17
Chemical and Environmental Engineering 29/30/31/36
Chemistry 28
Civil Engineering 31/35/36/39/41
Cultures, Languages and Area Studies 11
Economics 16
Electrical and Electronic Engineering 37
English Studies 11
Geography 16
Health Sciences 46/48
History 5
Humanities 55
Law 7
Life Sciences 23/46
Mathematical Sciences 20
Mechanical, Materials and Manufacturing Engineering 31/36/38/39/41/42
Medicine 37/46/48
MRC Institute of Hearing Research 40
Music 33
Pharmacy 26/44
Physics and Astronomy 18/22/25
Politics and International Relations 7
Psychology 29
Sociology and Social Policy 7
Other services (A-Z)
Admissions Office 13
Careers and Employability Service 15/27
Childcare Services 1/3
Coates Road Auditorium 51
Cripps Computing Centre 53
Cripps Health Centre/Chemist/Dentist 19
Estates Office 21
Faith/Prayer rooms 15
George Green Library 24
Graduate School 10
Greenfield Medical Library 46
Hallward Library 9
Keighton Auditorium 56
Language Centre 11
Museum 50
Nottingham New Theatre 12
Recital Hall 33
Security Control 11
Sports 32/34/47
Student Services Centre 15
Students' Union/Retail/Food court 15
University of Nottingham Sports and Social Club 4
Named buildings (A-Z)
Boots Science Building 44
Centre for Biomolecular Sciences 43
Coates Building 36
Engineering Science Learning Centre 54
Highfield House 10
Lenton Eaves 4
Lenton Fields 3
Lenton Grove 5
Lenton Hurst 52
enton Lodge 2
ottingham Lakeside Arts 49/50
ope Building 27
ir Clive Granger Building 16
ir Peter Mansfield Buildin 18
he Hemsley 8
he Orchards 6
aughan Parry Williams P vilion 47
Volfson Building 41
Jubilee Campus
To Jubilee Campus and Innovation Park
Pedestrian/cycle route to Jubilee Campus
Triumph Road
A6200 Derby Road
To M1 jcn. 26 (4.5 miles)
A6514 Middleton Boulevard
To Jubilee Campus (1 mile)
To city centre (2.5 miles)
NORTH ENTRANCE
Wollaton Park
A52 Derby Road
A52 Clifton Boulevard
Nottingham University Hospitals NHS Trust Queen's Medical Centre (QMC)
Medical School
To King's Meadow Campus (0.5 miles)
A6005 Abbey Street
Cloister Street
To city centre (3 miles)
Dunkirk
Beeston Road
To King's Meadow Campus (0.5 miles)
Ring Road
To M1 Jcn 24 (11 miles)
SOUTH ENTRANCE (Access in from the Beeston direction only. Exit towards the city centre only)
Nottingham Tennis Centre
A6005 University Boulevard
Highfields Park
Trent Building
Portland Building
Lenton & Wortley
Lincoln
Derby
Sherwood
Rutland
Cripps
Hugh Stewart
Main visitor car park
The Downs
Millennium Garden
Lenton House
East Midlands Conference Centre
Orchard Hotel
Sports Centre
Sports pitch
Sports pitch
Swimming Pool
Nightingale
Abbey House
Ancaster
Cavendish
Willoughby
Florence Boot
WEST ENTRANCE
Broadgate Park
Broadgate
A6464 Woodside Road
Lakeside walk
Highfields Sports Ground
To Beeston
To Long Eaton
A6005
To M1 Jcn 25 (5 miles)
A52
Priory Island
The University of Nottingham
University Park
Nottingham
NG7 2RD
Postcode for satellite navigation: NG7 2QL
Academic buildings
Residences
Other services
Building under construction
Footpaths
Conference parking
Highfields Park visitor parking
Pay & Display visitor parking
Blue-badge parking
Gatehouse
One way
Hopper bus stop
Public bus stop
Public/Hopper bus stop
Tram stop
Public transport information
24-hour ambulance/fire/police (0115) 951 8888
24-hour security contact (0115) 951 3013
0 metres 200
The University of Nottingham
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