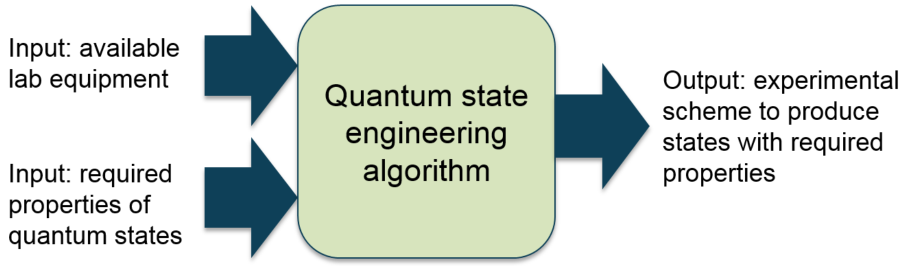
Employing computer algorithms to automate the engineering of quantum states

The ultimate goal of this project is shown in the figure: I will develop a computational toolbox that allows researchers working on a range of quantum systems to input the details of their lab equipment and noise sources, and the specific quantum states they require; the computational toolkit will then output optimal experimental setups to produce the desired states. I first pioneered this technique specifically for quantum metrology in optical systems – my *quantum state engineering algorithm* (QSEA) efficiently found a number of novel quantum states with significant improvements over the previous results in the literature [1]. This project will go far beyond my initial work and achieve the goal introduced above via three Work Packages (WPs): WP1 will find quantum states for a range of applications and develop more advanced QSEAs; WP2 will experimentally produce the quantum states found by the algorithms; and WP3 will extend this method to a range of physical systems.



<u>Work Package 1:</u> Develop a QSEA to find methods of producing optical quantum states for a wide range of applications. (Months (M) 1-12)

A novel QSEA will be developed to find quantum states for quantum computing [2], fundamental experiments [3], quantum metrology [1], highly entangled states, and so called “Schrödinger’s Cat states” [4]. These states will be searched for simultaneously by the QSEA (traditional methods involve painstaking calculations for each state). The state space being explored will be immense, and a simple search algorithm will not suffice: to overcome this I will incorporate evolutionary algorithms, machine learning, and further techniques from artificial intelligence. Previous results suggest that the QSEA will produce new classes of unintuitive and unexpected quantum states [1,3]; I will perform detailed characterisation and analysis of these states, helping develop a deeper understanding of quantum state engineering.

<u>Work Package 2:</u> With Dr Jonathan Matthews’s group at the Centre for Quantum Photonics (CQP) in Bristol, model experimental imperfections and collaborate to produce the states in WP1. (M 13-30, following WP1)

I will extend the QSEA toolbox to include all the optical elements available at CQP; the relevant experimental parameters available in their labs; and the biggest sources of error in their equipment (e.g. photon losses and imperfect detectors). I will then work closely with experimentalists to produce the states in WP1 to a high fidelity.

<u>Work Package 3:</u> Find quantum states and preparation schemes for quantum metrology in spin systems [5], linear optical circuits [6], and further emerging quantum technologies.

<u>WP3.1</u> (M 13-36, largely independent of other WPs.) In collaboration with Dr William Munro and Dr Yuichiro Matsuzaki at NTT BRL, Tokyo, Japan, I will apply my methods to spin systems (e.g. electrons) [5]. We will search for the optimal states for measuring magnetic and electric fields

(including vector fields [7]) and for *mapping* fields using sensor networks, all under realistic conditions. We will create a spin version of the optical QSEA in WP1&2, specifically tailored to NTT's equipment (e.g. flux qubits & NV centres).

WP3.2 (M 4-18, largely independent of other WPs.) In collaboration with Dr Jacques Carolan and Prof. Dirk Englund at MIT, USA, I will develop algorithms for linear optical circuits to find highly entangled states and quantum gates that can be used for linear optical quantum computation [6]. We will also explore *in situ* optimisation on-chip.

WP3.3 (M 19-36, building upon all other WPs.) QSEAs in additional physical systems will be developed, including the following: algorithms for designing states and experiments in optomechanics and optical cavities; finding optimal measurements in multi-parameter estimation [8]; and engineering a STIRAP laser pulse for shaping photons (I have discussed these projects with relevant experimentalists). More avenues for exploration will arise, particularly through Nottingham's links with the quantum technology hubs.

Physics art I will continue my collaboration with artist Joseph Namara Hollis (http://josephhollis.com/) to produce "quantum physics artwork" (1 piece per WP). The works will be showcased on my website, and we aim to exhibit them at Nottingham University's Djanogly Gallery.

Host Department

My two main challenges will be: (i) utilising *theoretical* quantum state engineering research to develop the QSEAs and ii) incorporating *experimental* imperfections into the QSEAs. For (i), Nottingham hosts numerous experts in quantum metrology, quantum correlations, and optical quantum information: Prof. Adesso (my proposed mentor), his quantum correlations group, others in the Quantum Information group (e.g. Guta, Tufarelli) and at CQNE (e.g. Lesanovsky, Garrahan). For (ii), Nottingham hosts a variety of experiments such as in the Cold Atoms and Quantum Optics Group (e.g. Fromhold), the Midlands Ultracold Atoms Research Centre (e.g. Fernholz, Hackermüller, links to Birmingham), and Nottingham's Quantum Systems and Technologies priority area.

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