Centre for Doctoral Training in Delivering Quantum Technologies

Open Day 29 January 2014

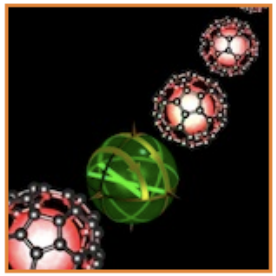
WELCOME!

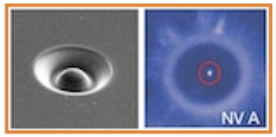
Pioneering research and skills

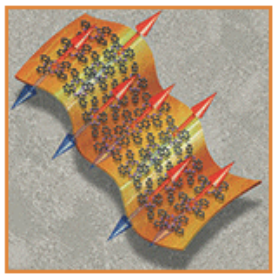
http://blogs.ucl.ac.uk/quantum/cdt

Open Day Schedule

- Welcome
  - Dan Browne
- Introduction to the CDT
  - Andrew Fisher (Director)
- The first year: the MRes
  - Sougato Bose
- Research in the CDT
  - Paul Warburton
- Applying to the CDT
  - Dan Browne





Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Delivering Quantum Technologies

A new Centre for Doctoral Training at UCL

Andrew Fisher
(Director)

Delivering Quantum Technologies

EPSRC
Pioneering research and skills

http://blogs.ucl.ac.uk/quantum/cdt

Outline

- What is a CDT?
- Why in quantum technologies? Why now?
- A student's-eye overview of the CDT

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

What is a CDT?

- A new way of undertaking research training, consisting of
  - An integrated four-year programme
  - A training year giving you key technical and transferable skills
  - Three years of research leading to the award of a PhD

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Advantages of the CDT approach

- The training year gives you the skills, knowledge and confidence to tackle big research challenges
- *You* choose and propose your research project after you have had the chance to learn more about the research groups and supervisors
- You benefit from a supportive network of colleagues in your cohort

Quantum technologies

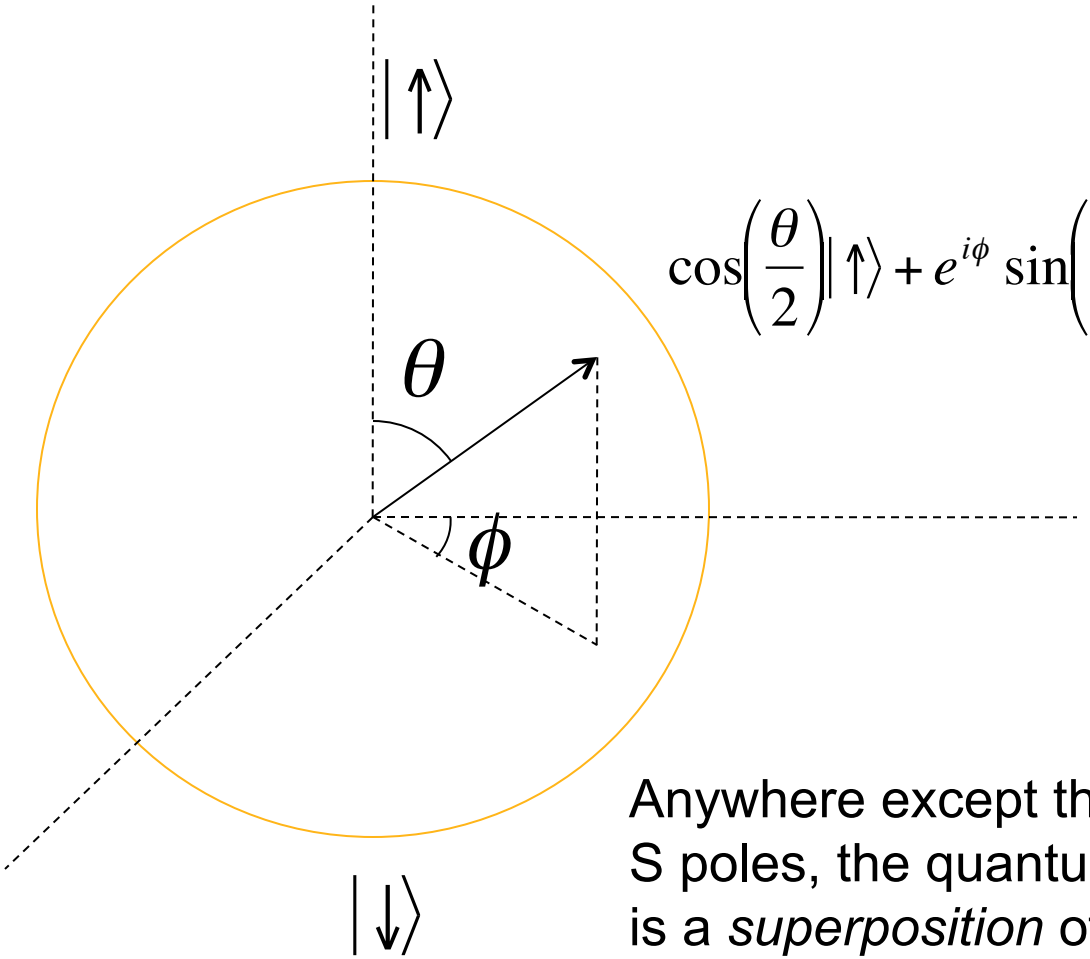
The control and manipulation of quantum states to achieve results not possible with classical matter

Transformative applications on the horizon in

- **Sensing** – beating classical limits on sensitivity
- **Metrology** – new time and current standards
- **Communication** – key exchange with security guaranteed by the laws of physics
- **Simulation** – of other quantum systems or of hard classical optimization problems
- **Computation** – factoring, discrete logarithms, solution of linear systems

Advantages stem from *superposition* and *entanglement*

The Bloch sphere



$$\cos\left(\frac{\theta}{2}\right)|\uparrow\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|\downarrow\rangle$$

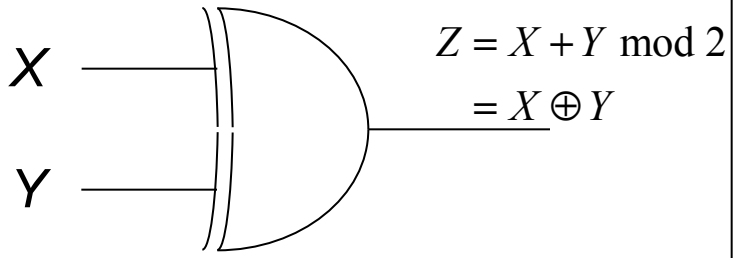
Superpositon

Anywhere except the N and S poles, the quantum state is a *superposition* of up and down

Quantum gates

Quantum bits are conceptually processed by means of logical *gates*

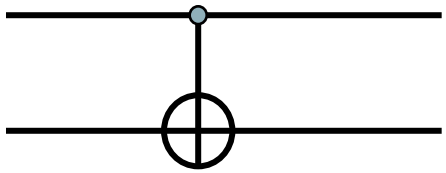
CLASSICAL



"Exclusive or" or "controlled not" gate:

X	Y	Z
0	0	0
1	0	1
0	1	1
1	1	0

QUANTUM



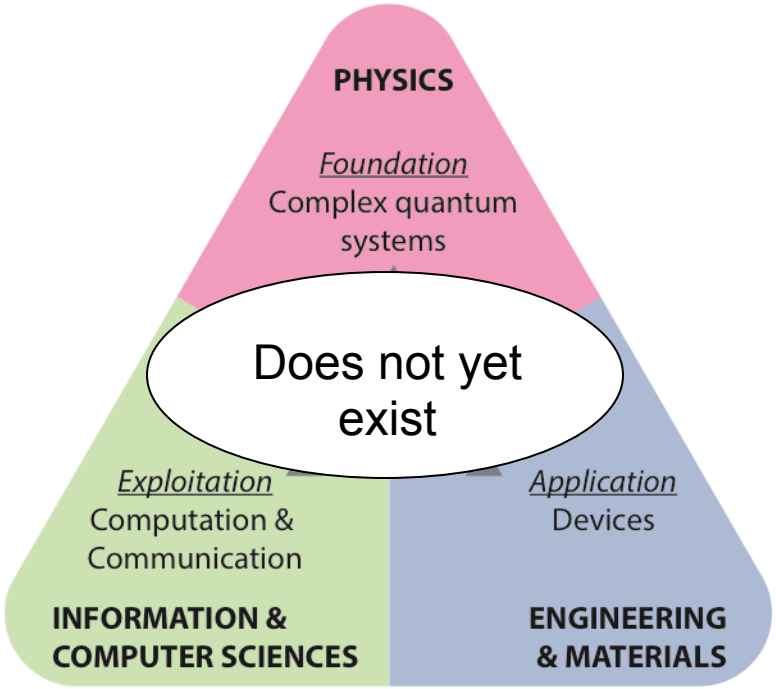
$$|x\rangle|y\rangle \rightarrow |x\rangle|x + y \mod 2\rangle \equiv \begin{cases} |00\rangle \leftrightarrow |00\rangle \\ |01\rangle \leftrightarrow |01\rangle \\ |10\rangle \leftrightarrow |11\rangle \\ |11\rangle \leftrightarrow |10\rangle \end{cases}$$

And…

$$\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \rightarrow \alpha|00\rangle + \beta|01\rangle + \gamma|11\rangle + \delta|10\rangle$$

Entangling gate

The quantum technologist

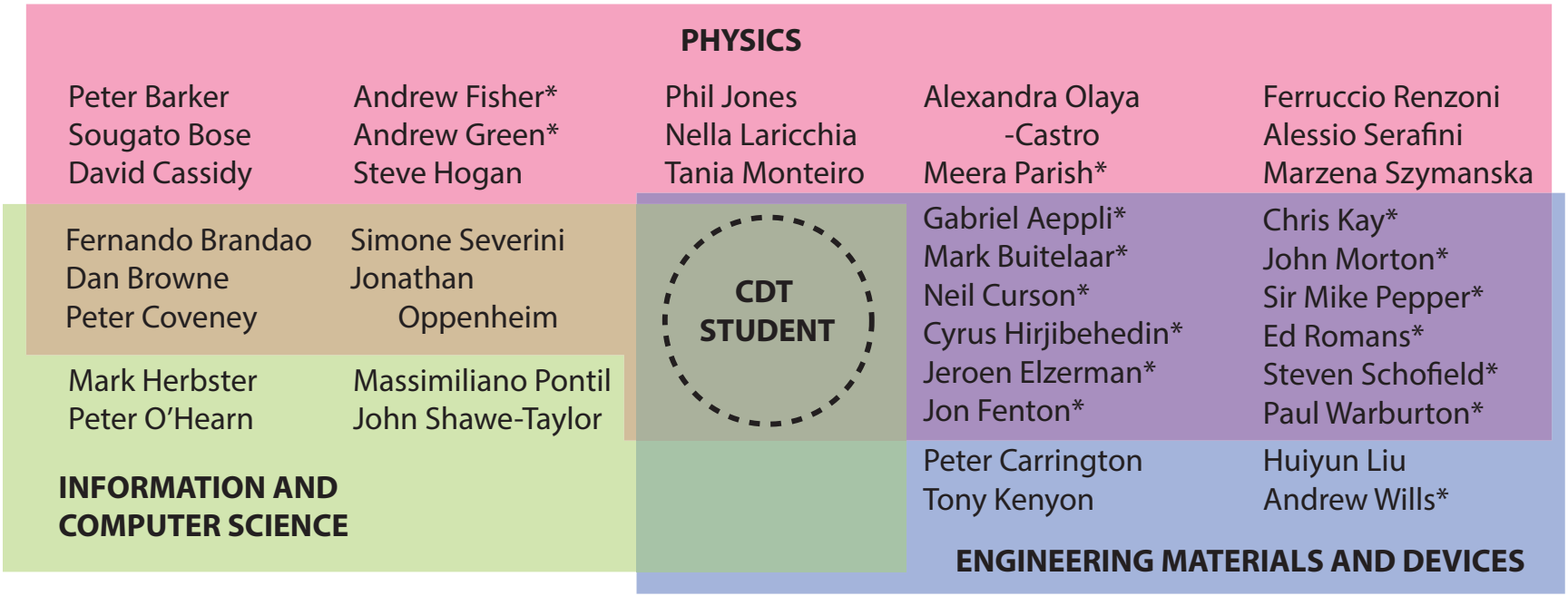


Our aim: to train such people, giving them a broad general background and a world-leading research experience

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

The CDT consortium



* Member of LCN

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Partnerships

- Commercial and government laboratories:
  - Agilent
  - DSTL
  - D-Wave
  - Google
  - Hitachi
  - Lockheed-Martin
  - NPL
  - Nokia
  - Toshiba
- Training partners:
  - Nature Publishing Group
  - DFJ Esprit Venture Capital
- International partners:
  - CQC²T Sydney
  - CQT Singapore
  - IQC Waterloo
  - QSIT Switzerland
  - QuPa Paris

Delivering Quantum Technologies

The programme

- One-year MRes with coverage of all the disciplines underlying quantum technologies
- Three-year PhD research project in one of the centre's groups

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Range of research in the consortium

PHYSICS

INFORMATION AND COMPUTER SCIENCE

ENGINEERING MATERIALS & DEVICES

Quantum Optics
Bose, Browne, Serafini

Rydberg States
Aeppli, Hogan

Quantum Cryptography
Brandao, Oppenheim, *Toshiba*

Quantum Algorithms
Brandao, O'Hearn, Severini

Single Photons
Browne, *Nokia, Toshiba*

Topological Insulators
Bose, Romans, Wills

Superconductor Devices
Fenton, Romans, Warburton, *NPL*

Trapped Ions, Atoms & Molecules
Barker, Cassidy, Hogan, Laricchia, Renzoni, Jones, *NPL*

Quantum Thermodynamics
Brandao, Olaya-Castro, Oppenheim, Serafini

Quantum Annealing
Aeppli, Green, Warburton, *Google, LM, D-Wave*

Optical-solid state hybrids
Elzerman, Hogan, Kenyon, Morton, Szymanska

Semiconductor Devices
Carrington, Curson, Liu, Schofield, Warburton

Open & Driven Systems
Fisher, Green, Monteiro, Olaya-Castro, Parish

Quantum Computing & Simulation
Bose, Browne, Green

Optimization & Learning
Coveney, Green, Herbster, Pontil, Severini, Shawe-Taylor

Silicon-based Qubits
Aeppli, Curson, Fisher, Morton, Schofield

Spin Detection & Control
Aeppli, Hirjibehedin, Kay, Morton, Monteiro, *Agilent*

Many-body States & Dynamics
Bose, Browne, Fisher, Green

Quantum Information
Brandao, Browne, Oppenheim

Quantum Chemistry & Biology
Coveney, Kay, Olaya- Castro

Quantum Sensors
Aeppli, Morton, Pepper, *DSTL*

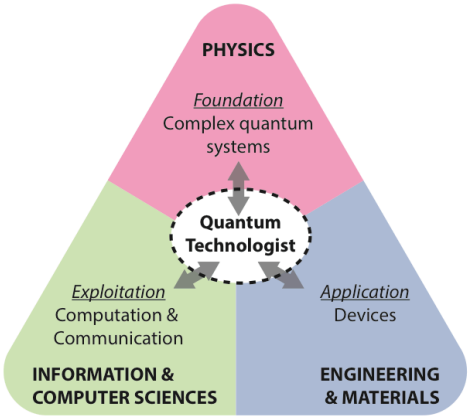
Quantum Standards
Fenton, Pepper, Warburton, *NPL*

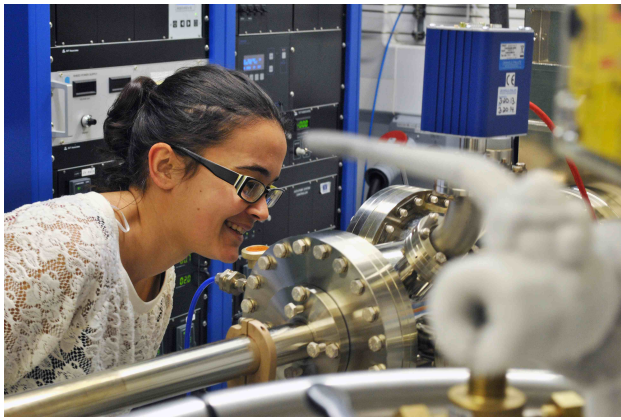
Quantum Dots & Wires
Buitelaar, Elzerman, Liu, Pepper, *Hitachi, Toshiba*

DQT Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Conclusion





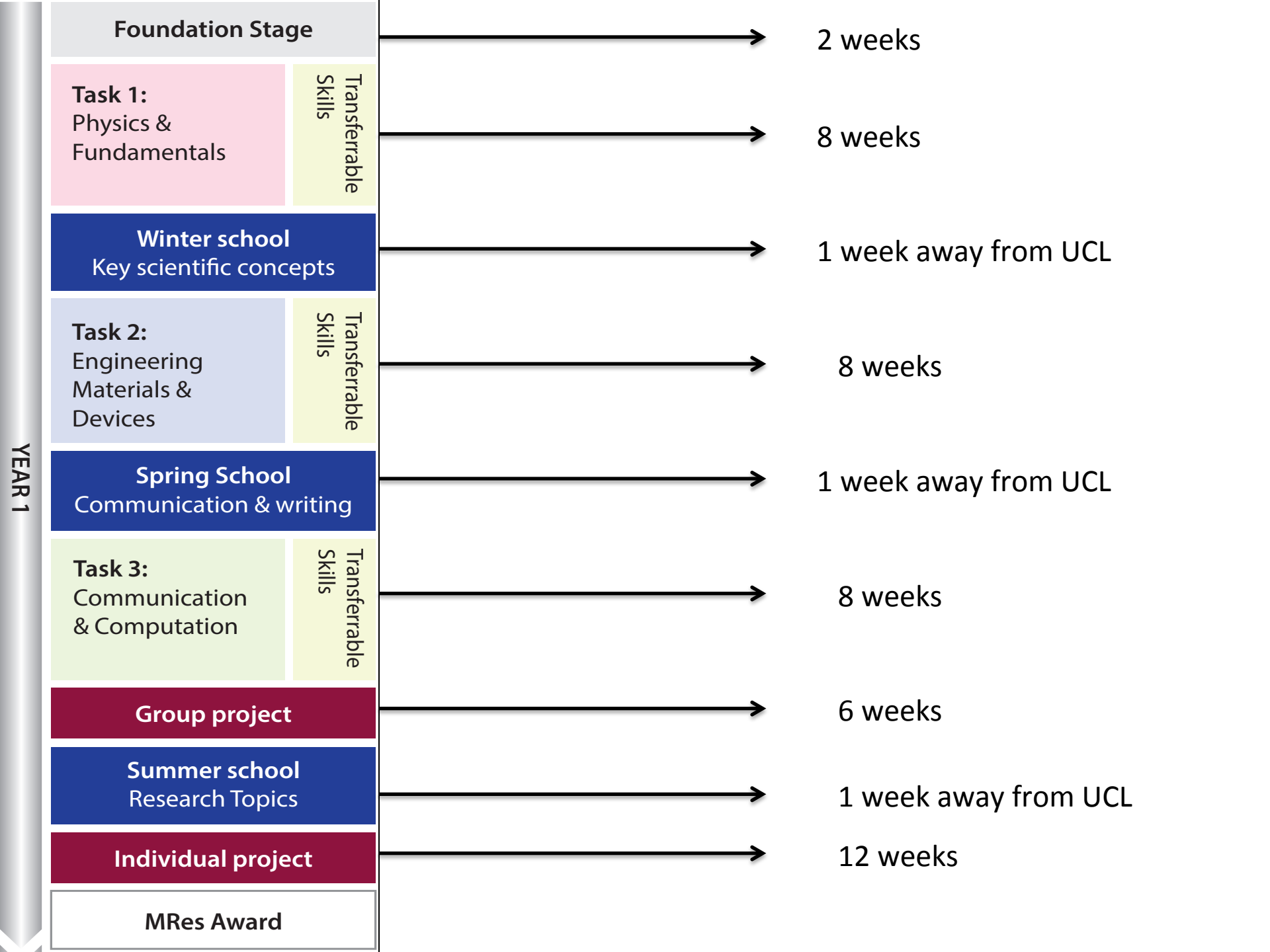
- Critical need for people trained across the combination of disciplines needed for quantum technologies
- Delivering Quantum Technologies is a new CDT at UCL addressing this need

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

The First Year (MRes) & PhD Topic Selection

Sougato Bose


YEAR 1
Foundation Stage
2 weeks
Task 1:
Physics &
Fundamentals
Transferrable Skills
8 weeks
Winter school
Key scientific concepts
1 week away from UCL
Task 2:
Engineering
Materials &
Devices
Transferrable Skills
8 weeks
Spring School
Communication & writing
1 week away from UCL
Task 3:
Communication
& Computation
Transferrable Skills
8 weeks
Group project
6 weeks
Summer school
Research Topics
1 week away from UCL
Individual project
12 weeks
MRes Award

First 2 weeks (Oct 2014)

Foundation stage

Quantum physics: (W) A revision of quantum mechanics & key mathematics (matrices, linear operators)

Device principles: (W) Quantum wells, quantum wires and quantum dots; principles of superconducting devices, basic atomic and optical physics

Computation and information: (W) Computational models and complexity, basic Shannon theory, inference

This part will be adapted according to student requirements and backgrounds: Some degree of peer to peer learning will be encouraged

Late Oct, Nov, Dec 2014

Task 1 - Physics and foundations (25 credits)

Quantum information: (Lec) Entanglement theory, non-locality, quantum Shannon tneory, protocols (teleportation, super-dense coding)

Quantum optics and atoms: (Lec) Quantum light; photons; linear optics; squeezed light; measurement, atom-light interaction; Dicke limit; Cirac-Zoller gate; Atom chips;

Open systems and decoherence: (Lec) Markovian approximation; weak coupling. Master equations in Lindblad form; decoherence; entanglement and entropy

MORNING

State transfer and tomography experiment: (Lab) Initialisation of spin population; high fidelity control; evaluation of fidelity through density matrix state tomography

Research case study (W)

AFTERNOON

Critical assessment of the status of an open problem. New ideas encouraged from the students!

Seminars defined by student needs

Jan – Mar 2015

Task 2 - Engineering materials and devices (25 credits)

Quantum dots and wires: (Lec) Materials systems, lithography and self-assembly; confined states; quantum transport; light-matter interaction

Superconductors and superfluids: (Lec) Phenomonology; BCS theory and Landau-Ginzburg model; broken gauge symmetry; Josephson effect; SQUIDs; flux and phase qubits

Quantum sensors and metrology: (Lec) Classical and quantum limits in measurement sensitivity; atomic clocks; scanning probes

Cleanroom training: (Lab) Etching and lithography steps; fabrication of basic devices (diodes, capacitors); introduction to electron beam lithography and focused ion beam (FIB)

Research case study (W)

Apr – June 2015

Task 3 - Communication and computation (25 credits)

Quantum cryptography: (Lec) Cyphers, Vernam cypher, RSA, quantum cryptography, security and verification.

Quantum computation and algorithms: (Lec) Searching algorithms, hidden-subgroup problems, phase estimation, quantum compuation and communication complexity; classical simulatibility. Adiabatic computation, optimization and annealing.

Error correction: (Lec) Stabiliser codes; error correction; dynamical decoupling; decoherence-free subspaces

Quantum cryptography experiment: (Lab) Optical realisation of BB84 protocol

Research case study (W)

Winter School

Research highlights: Current research results from CDT members and partners.
Team research pitch challenge: In groups of 4, students write a pitch for a research grant. Pitches evaluated by all. Best pitch wins prize.

Hitachi – IP,
NPL – Advanced Instrumentation

Spring School

Excellence in scientific writing: Technical writing with clarity and precision, structuring a scientific paper, structuring an academic thesis. (Project partner, Nature Publishing Group)
Public engagement: How to engage a lay audience, finding good analogies, props and demonstrations, practical tips
IP and entrepreneurship: Intellectual property, patents, commercialisation of novel ideas, moving from vision, to development of a business-plan, how to raise finance, effective Marketing and Sales. (Project partner DFJ Venture Capital)
Team entrepreneurship challenge: Teams given a starting budget of £20, aim to make as big a profit as possible in 24 hours.

Lockheed, Toshiba, Nokia, Agilent and Google, DSTL
-- Training Seminars

Summer School

Project Fair: Potential supervisors (from UCL and external) give presentations on potential project topics
Outreach Challenge: Teams must create a demonstration and take it onto the streets of London.

→ Cohort visit to D-Wave

Group Project (30 credits)

A 6 week research project targeting project planning skills, literature skills, teamwork and presentation skills in the context of a team approach to a research problem

MRes Project (90 credits)

A 12-week original research project. Students will choose their project from a pool offered by CDT supervisors and partners.

Transferable skills (15 credits)

Project management and time planning (W): Effective structuring of research projects, realistic goal setting, identifying subtasks and timescales; prioritisation, working to deadlines, procrastination avoidance.

Speaking and presentation skills (W): Large-group speaking skills, adapting your presentation to the audience, effective presentation of technical results, use of visual aids, practice and feedback

Laboratory, simulation and scripting software (W): Introduction to Python, Labview, Matlab

Generation of thesis topics (end of 1st year)

Background: (a) First-year training, (b) Web resource; (c) MRes project; (d) Contact with other students and, (e) Science fair during the summer school

Stage 1: student preference and pre-sift

Principal topic, Reserve topic(s) and supervisor(s)

Stage 2: collaborative preparation, presentation and selection

Proposal Writing and Proposal Presentation

Join your supervisor's group & start your PhD research

Delivering Quantum Technologies

The Research Environment

Paul Warburton
(Co-Director)

Delivering Quantum Technologies

EPSRC
Pioneering research and skills

http://blogs.ucl.ac.uk/quantum/cdt

How to choose a PhD…

Research Project	Theory / Experiment Blue skies / Application-oriented National facilities / Lab at university
Supervisor	Junior Lecturer / Prof. Sir FRS Good personal relationship
Research Group	Other students / postdocs Facilities: high-performance computing fabrication measurement

Open Questions in Quantum Technologies

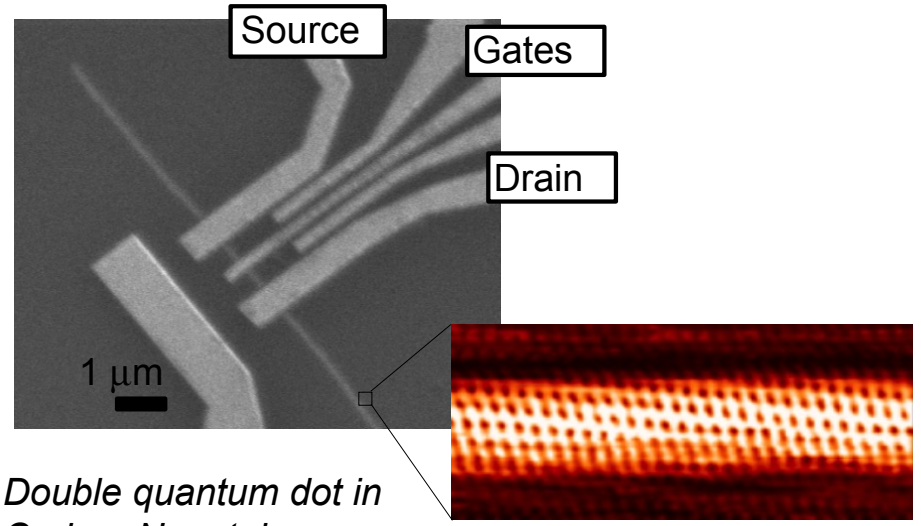
Decoherence Lifetimes

Scaling to hundreds / thousands of qubits

Which technology platform(s)?

Open quantum systems

Quantum thermodynamics



Double quantum dot in Carbon Nanotubes

Range of research in the consortium

PHYSICS

INFORMATION AND COMPUTER SCIENCE

ENGINEERING MATERIALS & DEVICES

Quantum Optics
Bose, Browne, Serafini

Rydberg States
Aeppli, Hogan

Quantum Cryptography
Brandao, Oppenheim, *Toshiba*

Quantum Algorithms
Brandao, O'Hearn, Severini

Single Photons
Browne, *Nokia, Toshiba*

Topological Insulators
Bose, Romans, Wills

Superconductor Devices
Fenton, Romans, Warburton, *NPL*

Trapped Ions, Atoms & Molecules
Barker, Cassidy, Hogan, Laricchia, Renzoni, Jones, *NPL*

Quantum Thermodynamics
Brandao, Olaya-Castro, Oppenheim, Serafini

Quantum Annealing
Aeppli, Green, Warburton, *Google, LM, D-Wave*

Optical-solid state hybrids
Elzerman, Hogan, Kenyon, Morton, Szymanska

Semiconductor Devices
Carrington, Curson, Liu, Schofield, Warburton

Open & Driven Systems
Fisher, Green, Monteiro, Olaya-Castro, Parish

Quantum Computing & Simulation
Bose, Browne, Green

Optimization & Learning
Coveney, Green, Herbster, Pontil, Severini, Shawe-Taylor

Silicon-based Qubits
Aeppli, Curson, Fisher, Morton, Schofield

Spin Detection & Control
Aeppli, Hirjibehedin, Kay, Morton, Monteiro, *Agilent*

Many-body States & Dynamics
Bose, Browne, Fisher, Green

Quantum Information
Brandao, Browne, Oppenheim

Quantum Chemistry & Biology
Coveney, Kay, Olaya- Castro

Quantum Sensors
Aeppli, Morton, Pepper, *DSTL*

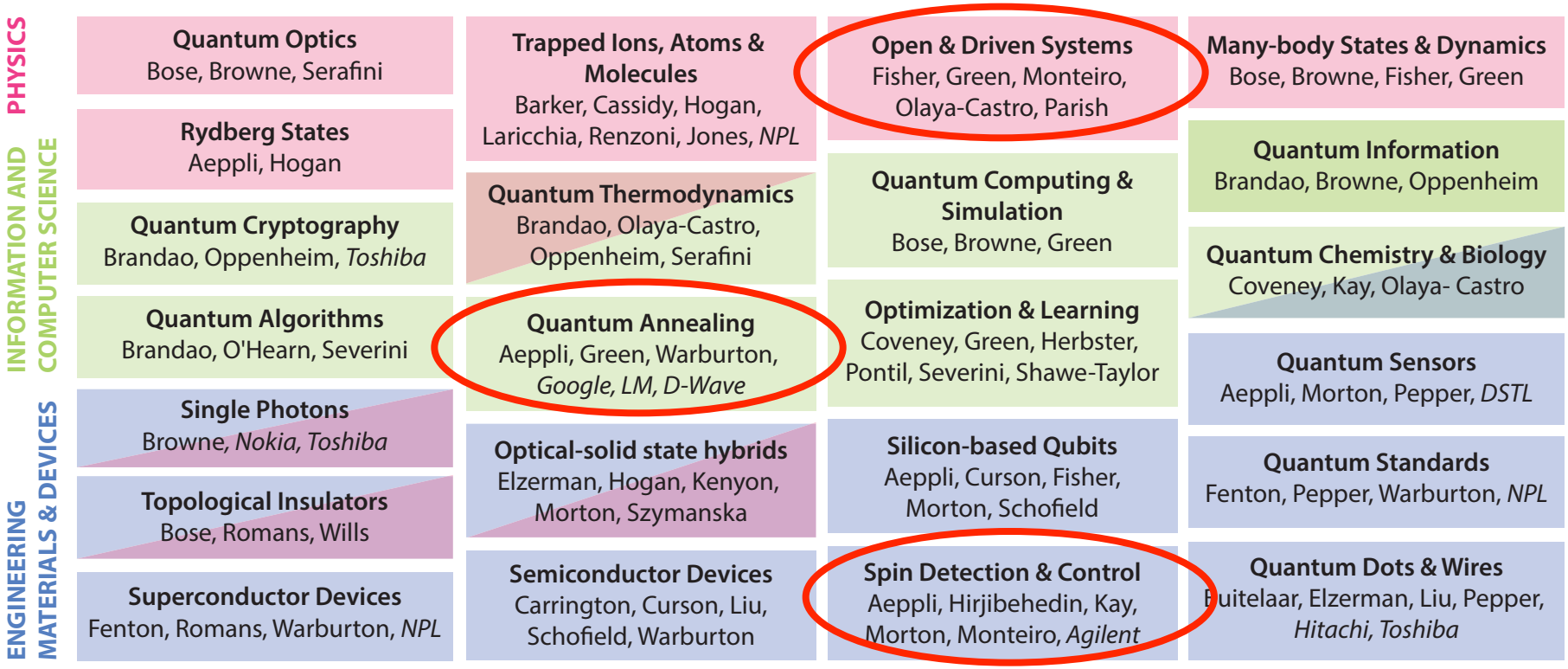
Quantum Standards
Fenton, Pepper, Warburton, *NPL*

Quantum Dots & Wires
Buitelaar, Elzerman, Liu, Pepper, *Hitachi, Toshiba*

DQT Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Range of research in the consortium



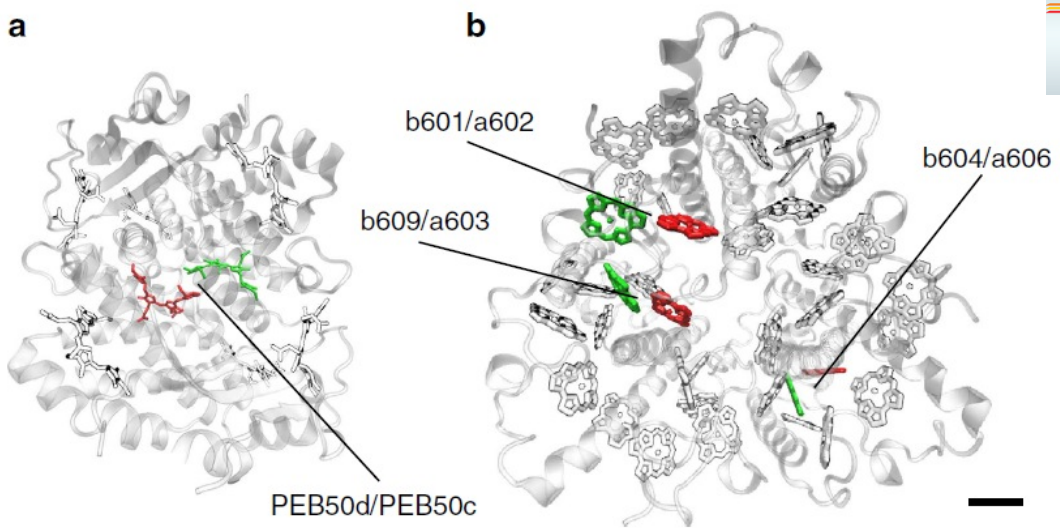
Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Open System Quantum Mechanics: Theory

Coupled to classical (decoherent) environment

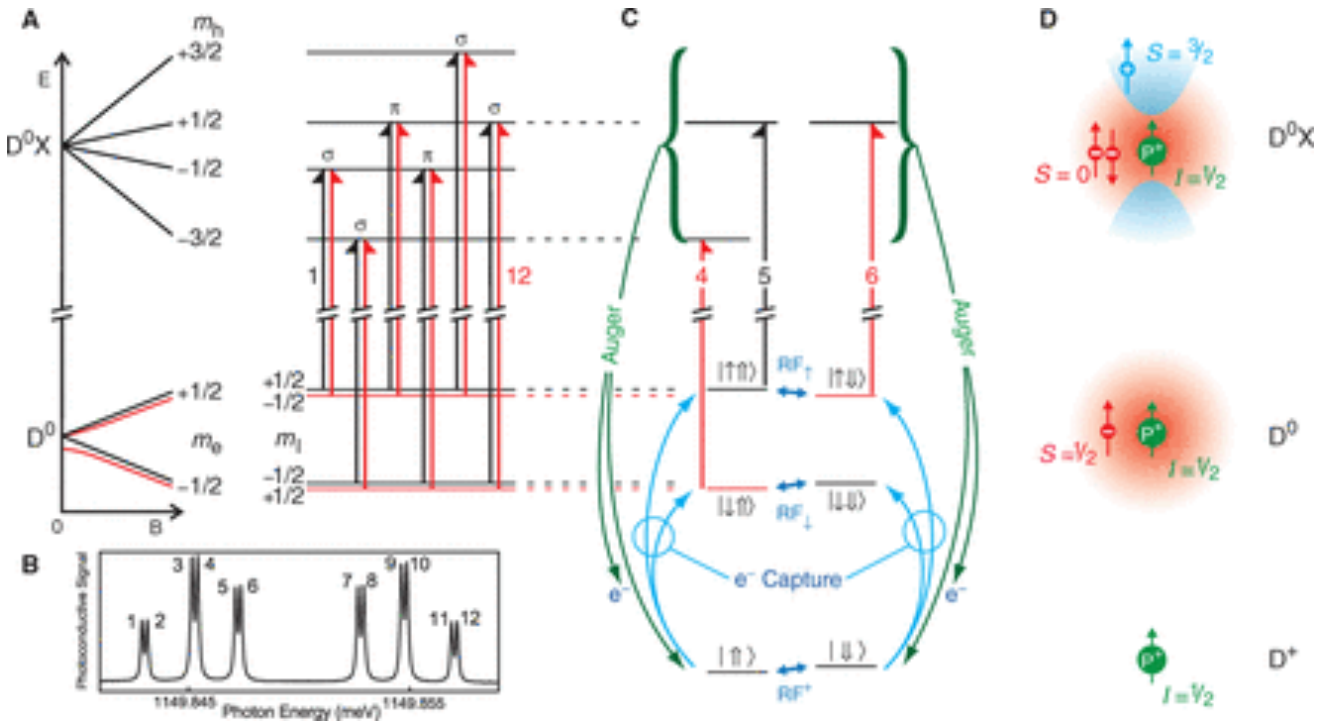
e.g. photosynthesis

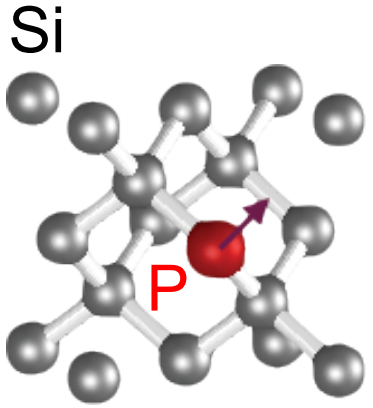


algae protein *spinach protein*

nature COMMUNICATIONS
DOI: 10.1038/ncomms4012

Optical detection of nuclear spins: Experiment





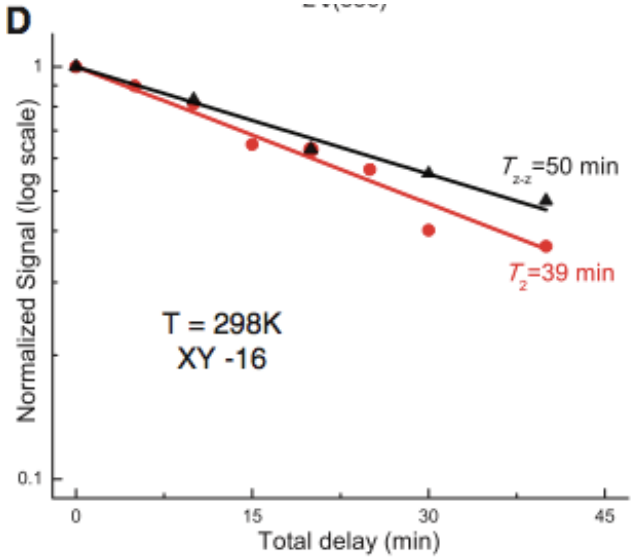
Science
AAAS
DOI: 10.1126/science.1239584

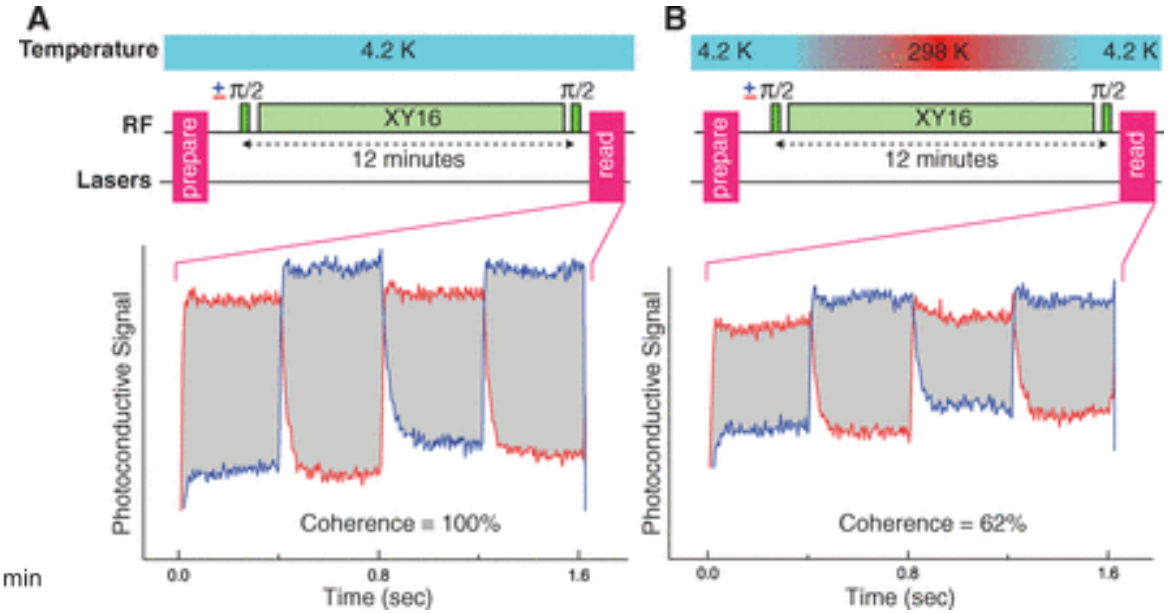
Delivering Quantum Technologies

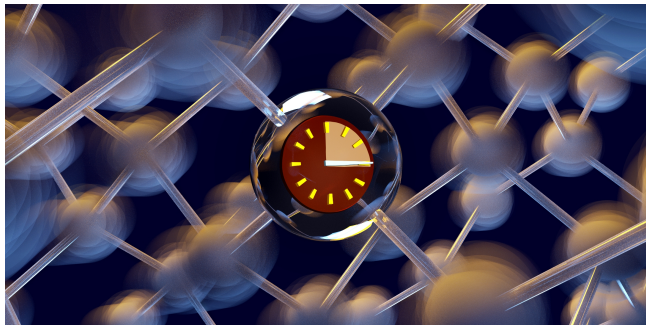
http://blogs.ucl.ac.uk/quantum/cdt

…. Very long spin coherence lifetimes

Very long-lived spins, even at room temperature!



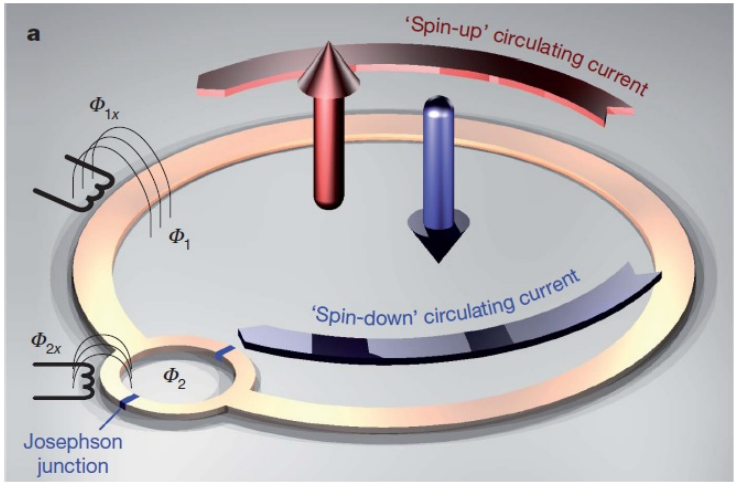




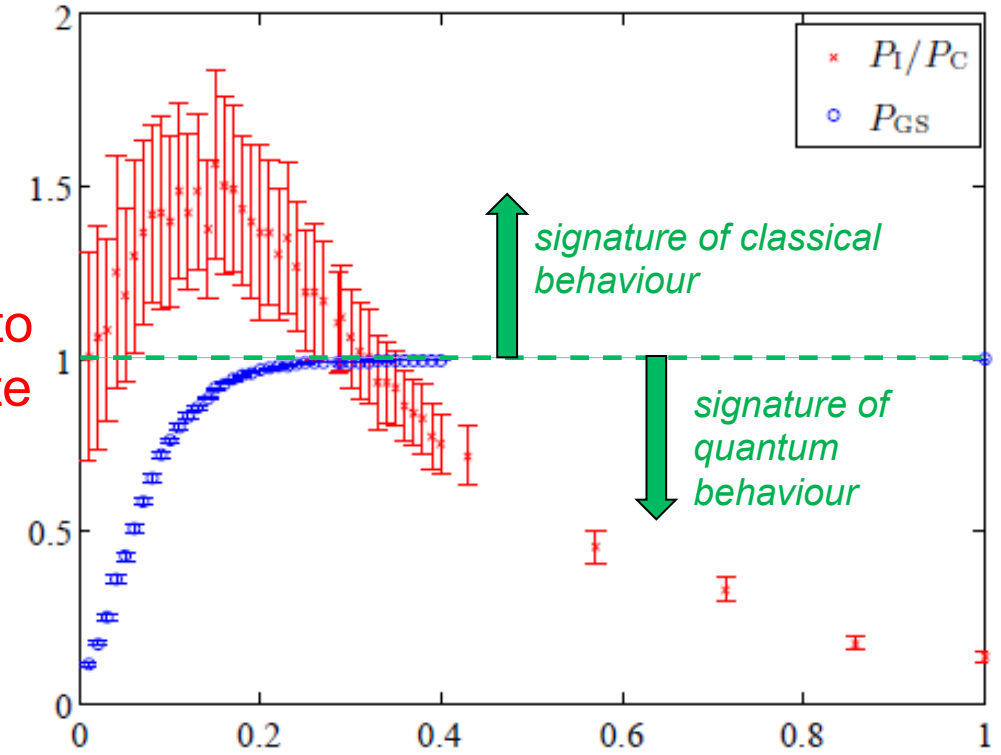
Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Quantum Annealing with "D-Wave" SQUIDs



8 coupled SQUIDs:



Relative probability to find isolated state

"hot" inverse "temperature" "cold"

Theory and experiment

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

Partnership Possibilities

PhD definition by partner

Short-term visits to partner's lab

Scientific collaboration

Applications and technology transfer

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

How to apply

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

How to apply

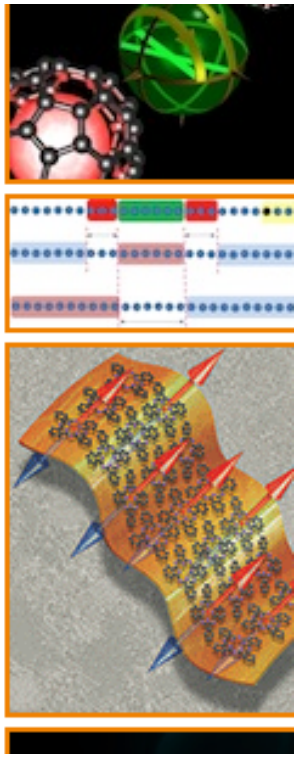
- **Our website:**

ictionary
Mathematical and
ciences
Engineering

UCL has been selected by EPSRC to host a new Centre for Doctoral Training (CDT) in Delivering Quantum Technologies. The first students will be admitted in Autumn 2014.

- About our CDT
- Training and research
- How to apply
- Application form

Quantum technologies involve the control and manipulation of quantum states to achieve results not possible with classical matter; they promise a transformation of measurement, communication and computation. The highly-skilled researchers who will be the future leaders in this field must be equipped to function in a complex research and engineering landscape

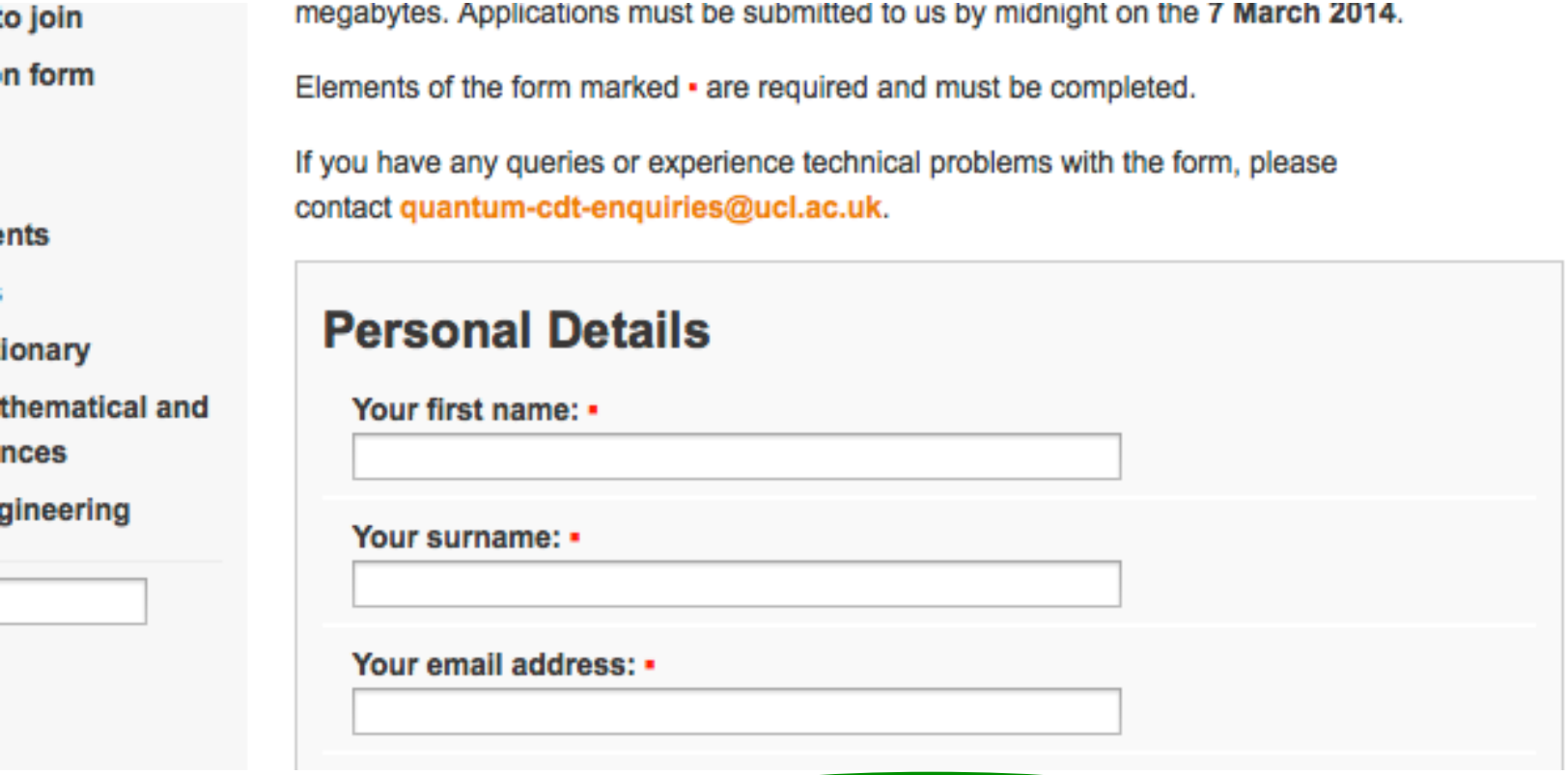


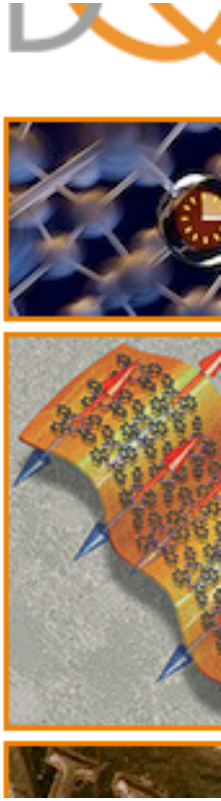
DQT Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

How to apply

- **Application form:**





Delivering Quantum Technologies

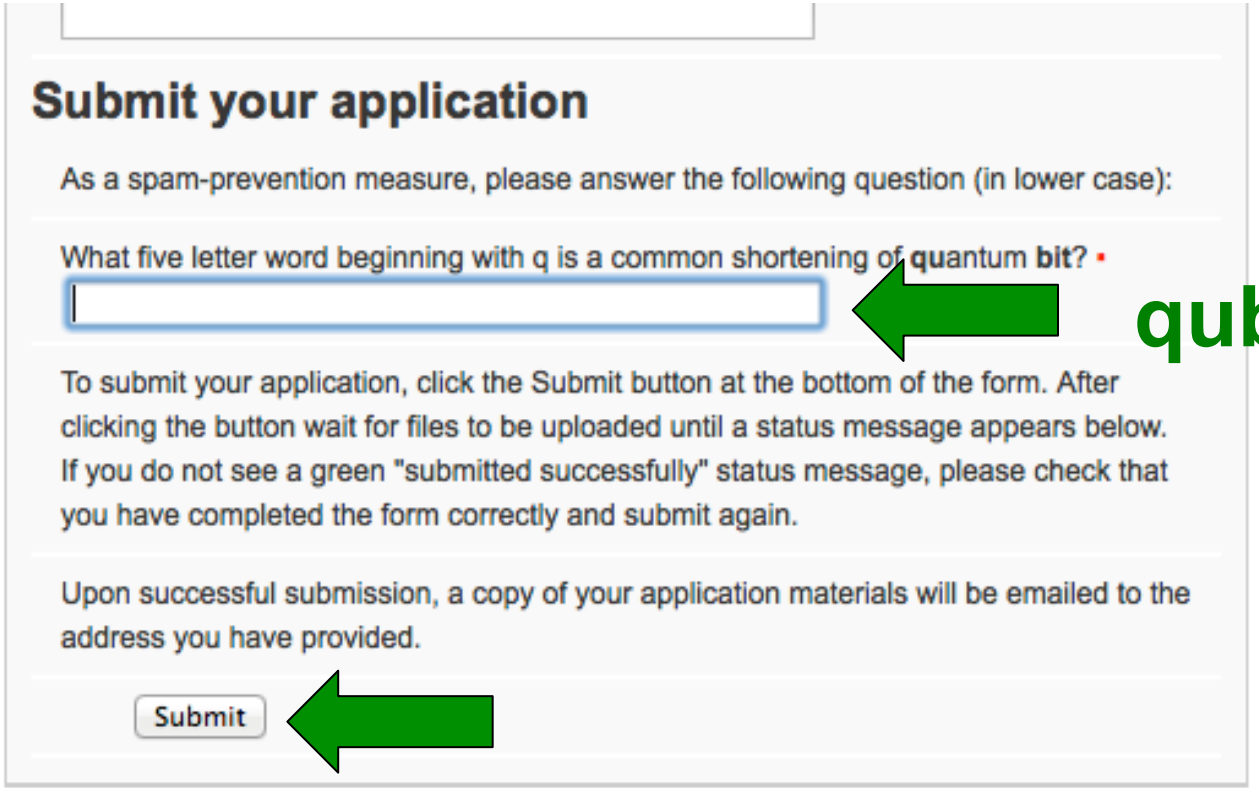
http://blogs.ucl.ac.uk/quantum/cdt

How to apply

- **Application form:**
  - Personal Details
  - Personal statement (2000 chars)
  - Short CV (PDF)
  - Mark Transcript (PDF)
  - 2 Referees

How to apply

- **Application form:**



qubit

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

How to apply

- **Important points**
  - The CDT admissions system is **independent** to departmental admissions.
  - If you apply at a department via PRISM or UCL grad. admissions, we will **not** receive your application.
  - To be considered for the CDT you **must** apply via our CDT form on our website.

- Any queries: *quantum-cdt-enquiries@ucl.ac.uk*

Delivering Quantum Technologies

http://blogs.ucl.ac.uk/quantum/cdt

How to apply

- **Key dates:**
  - Applications open: *Today!*
  - Deadline for applications: *March 7th Midnight*
    - Please don't leave it to the last minute!
  - Shortlisted candidates called to interview: *by 17th March*
  - Interviews: Week beginning *31st March*
  - Offers made: Week beginning *7th April*
  - New students begin: *September 2014*

Today's schedule – LCN

- **5:00** Walk to LCN
- **5:00** – **5:30** Refreshments (Levels 2, 3 and 4, LCN)
- **5:30** onwards:
  - Lab tours + Discussions
    - 5 groups A, B, C, D, E (Follow your group timetable)
  - Potential supervisors + Current Students (Levels 2, 3, 4 in LCN – see handout)

Q & A

- **Any questions?**