Australian Government

DEFENCE INDUSTRY & INNOVATION
NEXT GENERATION TECHNOLOGIES FUND

Quantum Technologies – Hype or Game Changer?

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What is Quantum?

- Dominant physics at very small scales…atomic, sub-atomic & nuclear scales
  - $10^{-10} - 10^{-15}$ metres
- Arose from theoretical attempts to explain experiments on blackbody radiation & the ‘ultraviolet catastrophe’
  - Thermal electromagnetic radiation emitted by bodies in thermodynamic equilibrium with their environment
  - Classical theory predicts significantly more UV from a black body than is observed
    - UV emissions tend to $\infty \Rightarrow$ matter should radiate away all of its energy!
  - Required the development a new branch of physics to resolve issue…quantum physics!
- Soon became apparent that nature behaved very differently on atomic & sub-atomic scales!

Image Credit: J

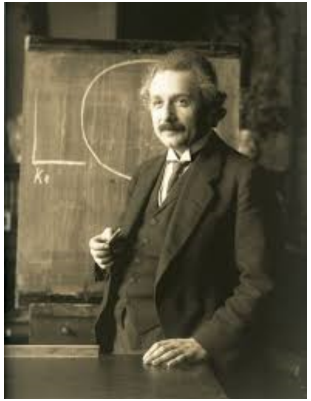
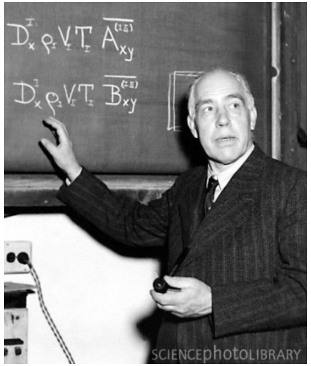


Image Credit: U

Quantization

- Energy is not continuous, but comes in small packets or ‘quanta’
- For example, consider the photoelectric effect
  - The release of electrons when light hits a material
  - Classically, this effect would be attributed to transfer of energy from the light to the electrons in the material…more intense light, more energetic electrons
  - Instead, experiments show that NO electrons are released until the energy of the light reaches a threshold!
  - Einstein proposed that this is because light consists of discrete wave packets or ‘quanta’, & that a photon with energy above a threshold was required to dislodge the electron
- BLUF: Explains atomic energy levels & the periodic table



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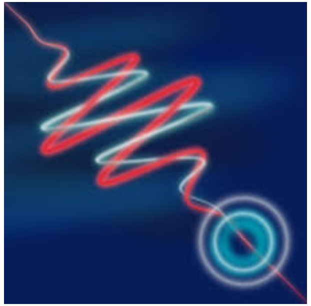


Image Credit: F

Heisenberg's Uncertainty Principal

Image Credit: K

- Macroscopically, we expect to simultaneously measure all properties of matter with arbitrary precision, e.g. position & velocity of a ball
- However, this is NOT the case on quantum scales
  - For example, cannot measure BOTH the position & momentum (velocity) of a particle to arbitrary accuracy at the same time
  - Heisenberg uncertainty relation

$$\Delta x \Delta p \geq \frac{h}{4\pi}, \text{ where } h = 6.62606957 \times 10^{-34}\ \mathrm{m^2\ kg\ s^{-1}} \text{ is Planck's const.}$$

  - Was thought to be a property of the observation disturbing the quantum systems, but is now clear it arises from the matter wave nature of all quantum objects
  - If you improve the accuracy of the position measurement, then you can't measure the velocity of the particle with the same accuracy
  - Comes in a variety of forms involving complementary properties of particles, e.g. energy & time $\Delta E \Delta t \geq \frac{h}{4\pi}$ etc.
- BLUF: Accounts for quantum tunnelling of subatomic particles (electrons) through a potential barrier, that is fundamental for semiconductor devices like flash memory

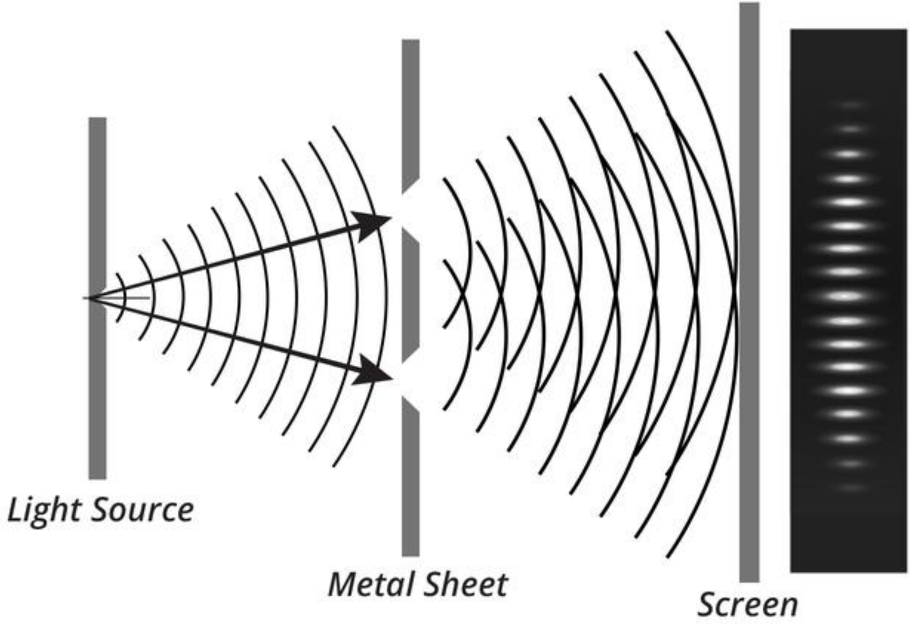
Wave-Particle Duality

Image Credit: O

- Macroscopically, our experience tells us that matter does not behave like a wave & waves need a medium in which to occur…
- Wave-particle duality
  - Sub-atomic particles sometimes behave like waves & photons sometimes behave like particles, i.e. neither ‘particle’ or ‘wave’ descriptions fully describe the behaviour of quantum objects
- Photoelectric Effect ≡ light made up of ‘particles’ or quanta
- BUT light exhibits wave behaviour such as diffraction & interference
  - For example, double slit experiment with light
- However, you can also conduct the double slit experiment with Electrons…
  - Wavelength of matter or de Broglie wavelength, $\lambda = \frac{h}{p}$, where p is the momentum
  - Wavelength is very small for macroscopic objects, but has been observed for molecules containing 810 atoms†

† Sandra Eibenberger *et al*, “Matter–wave interference of particles selected from a molecular library with masses exceeding 10 000 amu”, Phys. Chem. Chem. Phys. (2013) **15**, 14696

Double slit experiment with light



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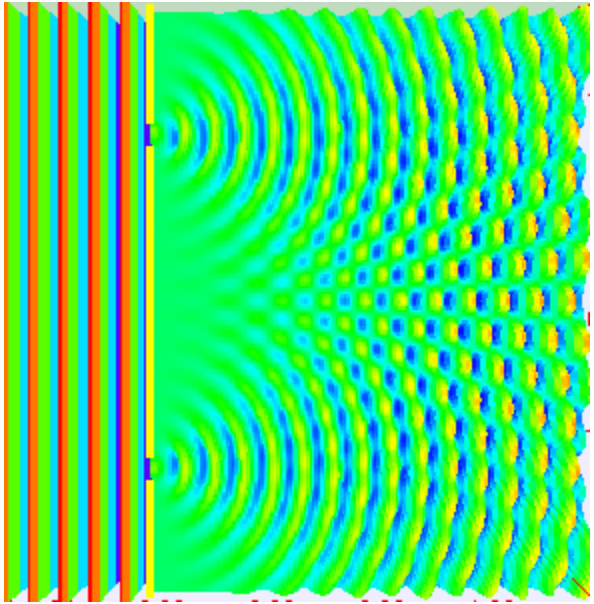

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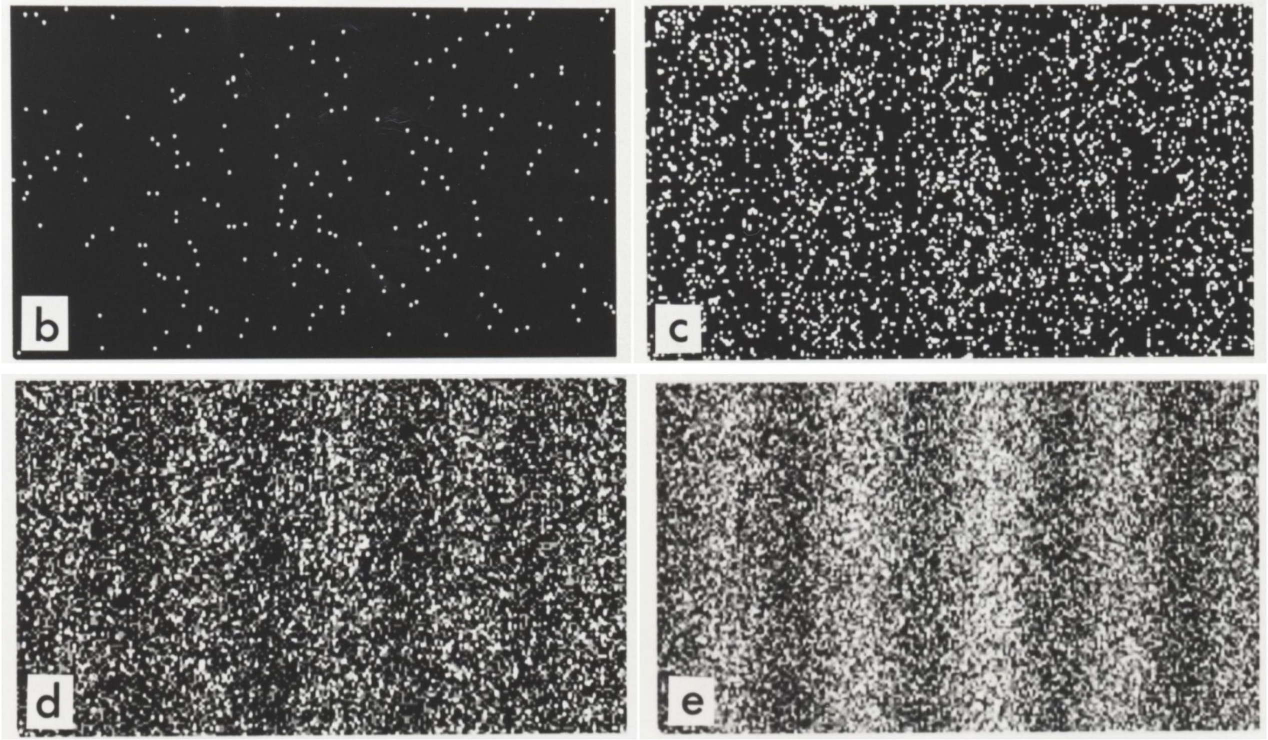
Double slit experiment with Electrons



b = 200 electrons
c = 6000 electrons
d = 40,000 electrons
e = 140,000 electrons

Image Credit: P

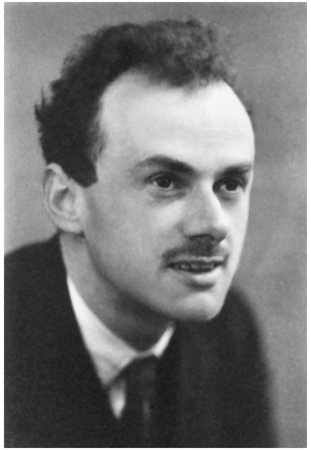
Quantum Superposition

- Any quantum state can be expressed as the sum of two or more other distinct states
- Conversely, any two (or more) quantum states may be added together to form a valid quantum state
- For example, consider a quantum bit or 'qubit' which has an equal chance of outcomes 0 & 1 when measured
  - Until it is measured, the qubit is in a superposition of both states

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

where $|0\rangle$ & $|1\rangle$ are quantum state vector in Dirac notation that give the result 0 & 1 when measured

- BLUF: a quantum computer with n qubits can be in a superposition of up to 2^n different states at any one time (classical computer can only be in one state!)



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Schrödinger's Cat

- Thought experiment to demonstrate how ridiculous the idea of quantum superposition really is…
  - Imagine…a box containing a cat & a radioactive source that triggers the release of a poisonous gas if it decays
  - Assume that during a particular time interval there is a 50% chance of the source decaying
  - The quantum state of the radioactive source may be written as

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|d\rangle + |u\rangle)$$

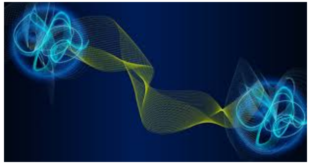
    - where $|d\rangle$ & $|u\rangle$ are quantum state vector that result in the source being decayed or undecayed when measured
  - This makes perfect sense in quantum physics, but what does it mean for the cat?
  - In principle, until the box is opened, the cat is also in a quantum superposition as the release of the poison is linked to the radioactive source…so it is both dead & alive!

Image Credit: N

Image Credit: G

Quantum Entanglement

- Physical phenomenon that occurs when pairs of particles or photons are generated such that their quantum states cannot be described independently of each other
  - Even when particles or photons are separated by large distances
  - Measurement of physical properties, such as position, momentum, spin and polarisation, are perfectly correlated for entangled particles
    - For example, if particles are produced with a total spin of zero, then if one particles is measured to be spin up, the other will be spin down
    - Implies that the measurement of one particle impacts the whole entangled system $\Rightarrow$ properties of quantum particles are non-local
    - AND it occurs instantaneous, even if separation of particles is very large!
- BLUF: used in quantum cryptography to detect the presence of an interceptor & likely to be important for quantum computing



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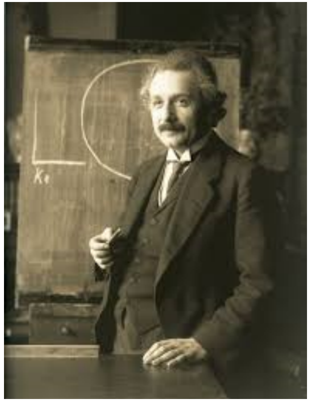


Image Credit: U

Second Quantum Revolution

- Heralded by Jonathon Dowling & Gerard Milburn in 2002†
- Actively using the new rules of quantum science to manipulate the physical world & develop new technologies
  - Create new artificial atoms to have electronic & optical properties of our choosing e.g. quantum dots etc.
  - Create new states of entangled or quantum coherent matter & energy with novel properties
- Moving from the science of quantum mechanics, to quantum technologies & quantum engineering

Image Credit: K


Image Credit: **B**

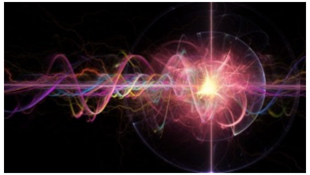
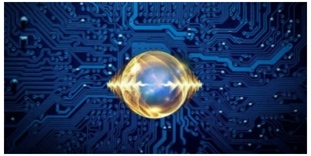


Image Credit: E

† Jonathon P Dowling & Gerard Milburn, "Quantum Technology: The Second Quantum Revolution", Phil. Trans. R. Soc. Lon. (2003) **361**, 1655-1674

Quantum Technology

- Imperatives
  - Ongoing miniaturisation of technology will ultimately lead to devices on the nanometre scale…design must be based on quantum principles
    - Semiconductor process at ~5 nm…lines just a few atoms wide
  - Quantum technologies also promise vastly improved performance compared to classical technologies
    - Small sensors of unprecedented sensitivity
      - Magnetometers, gravimeters, accelerometers…
    - Small clocks of unprecedented accuracy
    - Communications with unprecedented security…in principle!
    - Computers of unprecedented power…for some problems!



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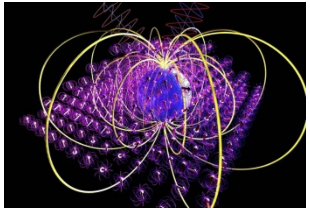

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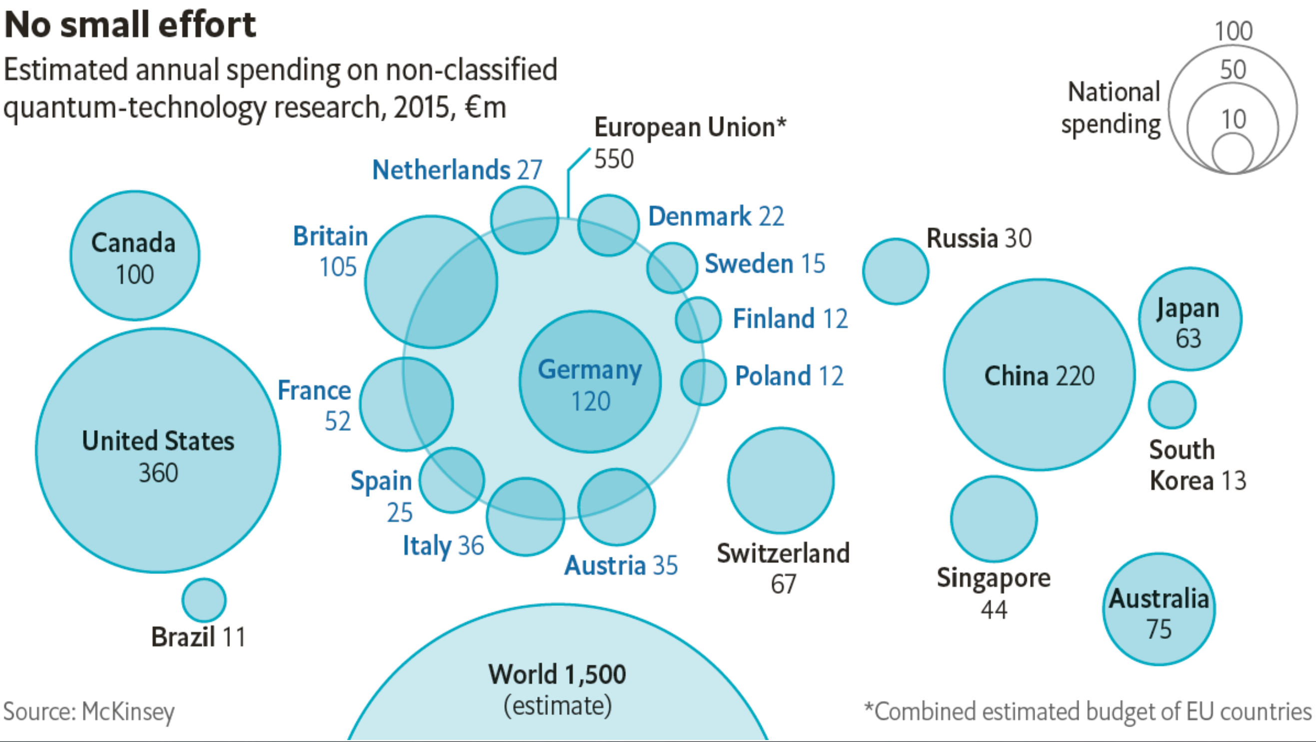
Quantum Technology – Research Investment

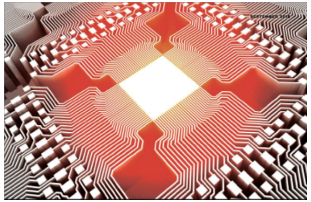


Quantum Technologies – Strategic Investment

- UK National Quantum Technologies Program
  - £270M over 5 years from 2015…anticipate a £1B quantum industry over time
- European Commission's Quantum Technologies Flagship
  - €1B over 10 years from 2018, focus on quantum sensing, communication, simulation & computing
- US National Quantum Initiative Act
  - USD1.2B over 5 years from 2018, focus appears to be on quantum information science & technology
- China's Quantum Science Program
  - Recent estimates put the value of the program as high as $5-10B, although this probably includes elements of the space segment of the 'quantum internet'

Image Credit: N

Image Credit: O



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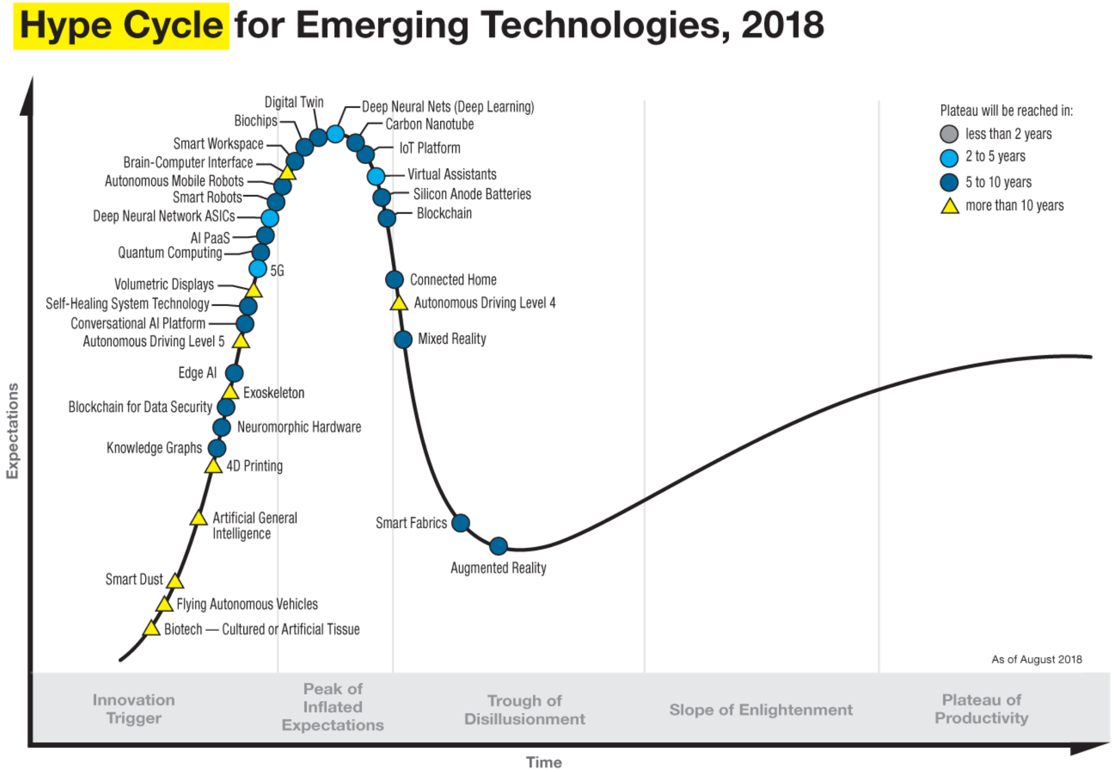
Quantum Technologies Hype Cycle



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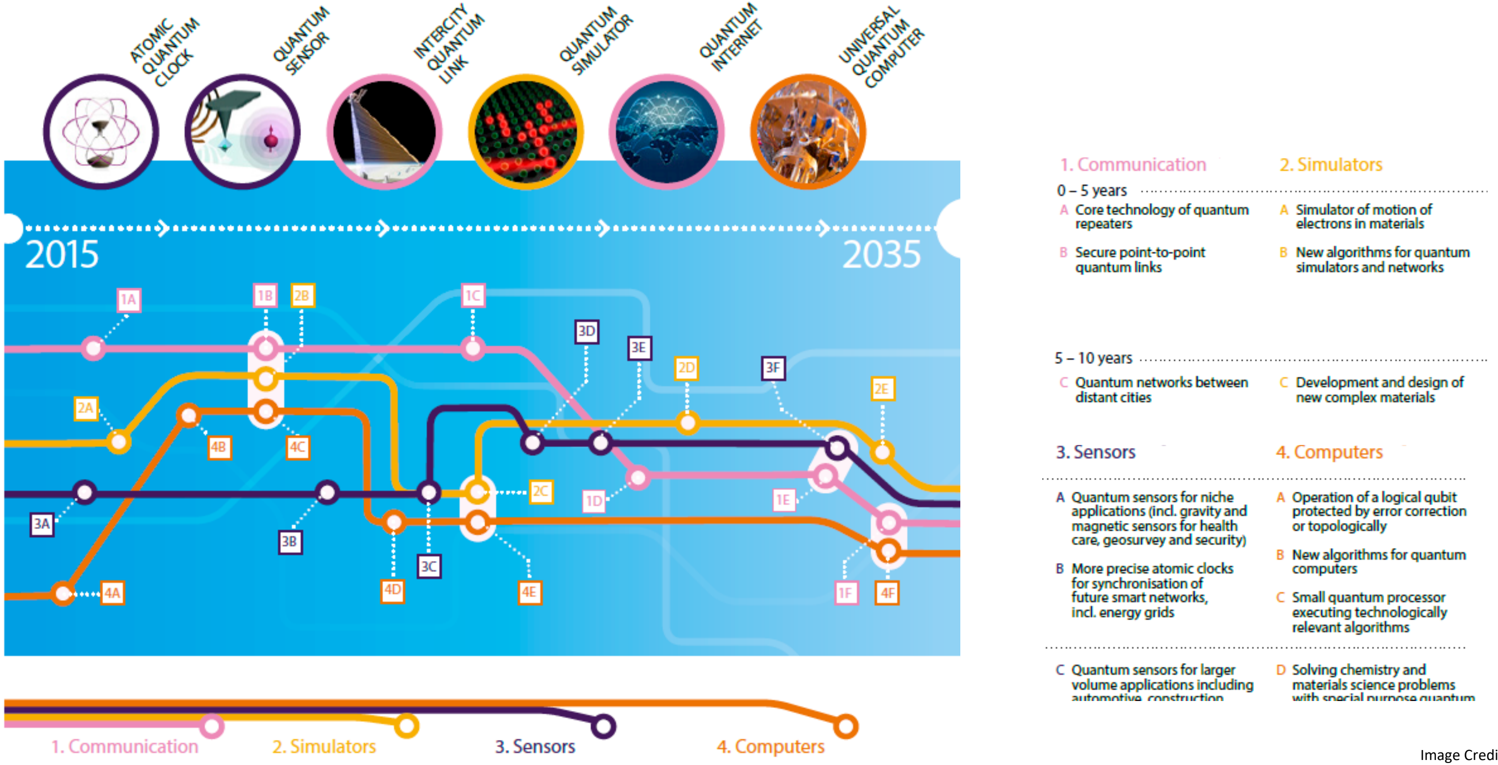
Quantum Technologies Timeline (*c.* 2015)



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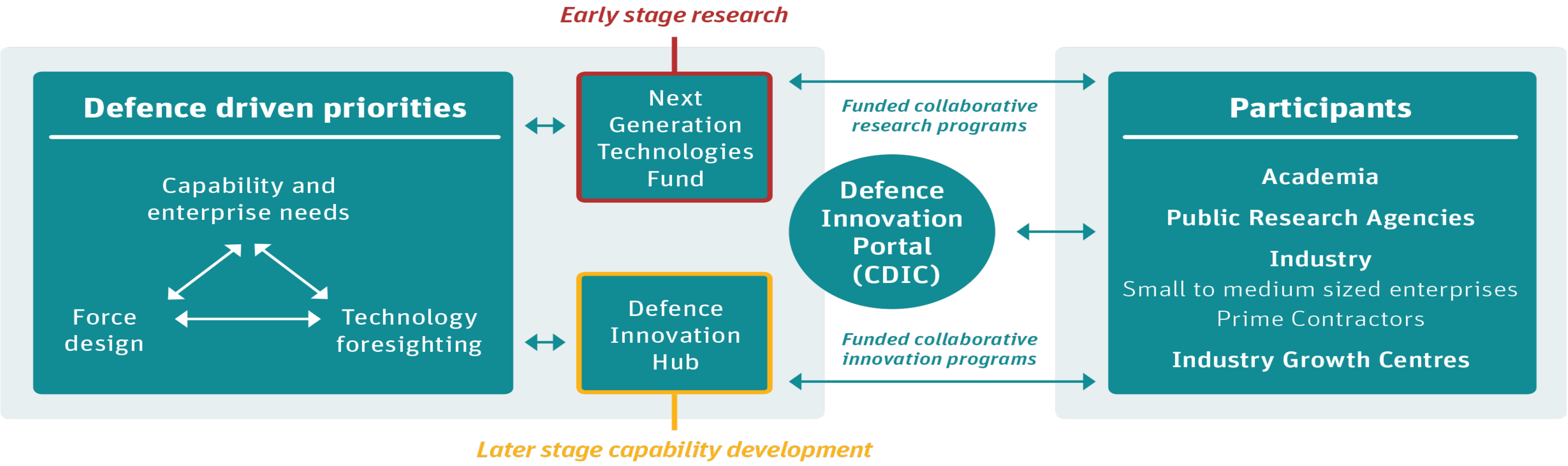
Australian Defence Innovation System



Next Generation Technologies Fund priorities

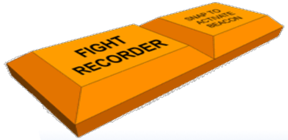
A NATIONAL PARTNERING PROGRAM

Counter Improvised Threats
Grand Challenge
$19M

AUS MURI
up to $25M over 10 yrs

UNSW AUSTRALIA
Griffith UNIVERSITY
UTS UNIVERSITY OF TECHNOLOGY, SYDNEY

SBIRD up to $10M
over 10 yrs



Emerging & Disruptive
Technologies Assessment
Symposia

- Grand Challenges
- Defence Cooperative Research Centres
- University Research Networks
- Strategic Research Program
- Small Business Innovation Research for Defence
- Defence Research Accelerator
- Technology Foresighting

AGILITY ACROSS THE PORTFOLIO, INDEPENDENT OF SCALE

TRUSTED AUTONOMOUS SYSTEMS DEFENCE CRC

$50M over 7 yrs

DATA 61

$10M over 3 yrs

CSIRO
On Prime:Defence
Accelerator

SILENTIUM DEFENCE

Quantum Technologies Theme

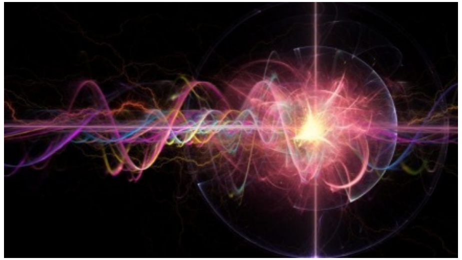
- Currently, a $6M project over three years
  - DST currently working on programing the rest of the NGT program
- Strategic Approach
  - Initially, focus on
    - Quantum Sensing, Navigation & Timing
    - Quantum Communications
- Quantum Computing
  - Significant public & private investments globally in several quantum computing technologies
    - Hard to pick a winning technology…at least 5 qubit technologies being researched
    - Any Defence investment would be dwarfed by global investment!
  - Defence to develop strategic approach to Quantum Computing & focus on potential applications of Quantum Computers
    - Architecture, sub-systems, operating system, algorithms etc.

Image Credit: A

Image Credit: B

Quantum Research Network

- First Call in 2018
  - 80 proposals received & assessed by a panel including UK SME
  - 11 proposals recommended for funding
    - 10 from universities, 1 from industry
  - All contracts now in place & progressing
- Subsequent Calls?
  - Some worthy proposals did not receive funding!
  - Recent business intelligence activities indicate that there remains significant untapped Defence Quantum Technologies potential in Australia
  - DST plans for at least one further call, but is still to determine the focus areas…



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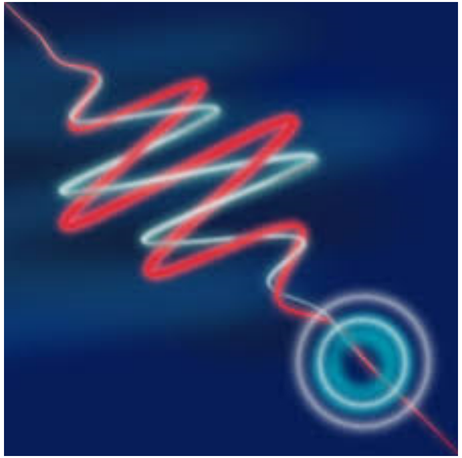

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AUSMURI

- MURI ≡ Multidisciplinary University Research Initiative
  - Australia now partnering with the US on joint projects
- Successful 2017 Round Project in Quantum
  - Quantum control based on real-time environmental analysis by spectator qubits
    - aka “Noise cancelling headphones for quantum computers”
    - https://www.youtube.com/watch?v=dxQCmm5OMZQ
  - Participants
    - Duke University, Louisiana State University, UC Berkeley, MIT, Johns Hopkins University Applied Physics Laboratory, University of Oregon
    - Griffith University (Paz Silva & Wiseman), University of Technology Sydney (Ferrie), University of New South Wales (Morello)

Strategic Engagement – ARC Centres of Excellence

- Quantum Technologies Theme engaging with
  - Centre for Engineered Quantum Systems (EQuS)
  - Centre for Quantum Computing & Communications Technology (CQC2T)
- EQuS Projects
  - 2018 - A theoretical study into the role of dynamical decoupling for correcting systematic errors that degrade the performance of an atomic beam clock (PI: Professor Tom Stace)
  - 2019 - A demonstration of the feasibility of performing frequency conversion of light pulses from 795nm to 1530nm with application to quantum communication & memories (PI: Dr Till Weinhold)
  - 2019 - Quantum computing for Defence applications of quantum chemistry (PI: Dr Cornelius Hempel)

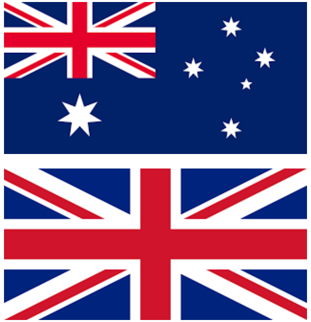
EQUS

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

THE UNIVERSITY OF QUEENSLAND

THE UNIVERSITY OF SYDNEY

AUS-UK Collaborative PhD Program



- AUS & UK seeking to address the workforce pipeline by sponsoring a collaborative PhD Program
  - Aiming for 6 scholarships sponsored by UK, 6 scholarships sponsored by AUS
    - Aim to align PhD topics with national programs, e.g. Quantum Technologies Theme
    - Plan joint Summer Schools bringing together all of the PhD candidates
      - Address topics such as Introduction to the Military, Systems Engineering etc.
- Progress
  - UK: Eighteen PhD projects selected, however process delays have resulted in not all PhD candidates being in place by October 2019
  - AUS: Eight PhD Projects selected, contracts being put in place for candidature to start in Q1 2020

Summary

- We are in the midst of the Second Quantum Revolution
- Quantum Technologies will outperform classical technologies in niche areas
- Significant strategic investments in Quantum Technologies globally
- Australian Department of Defence is investing in niche Quantum Technologies via the Next Generation Technologies Fund
  - Focussing on applications in sensing, timing, communications etc.

Quantum Technologies will deliver game changing capabilities, but there's a lot of hype!

QUESTIONS?


HOW'S YOUR QUANTUM COMPUTER PROTOTYPE COMING ALONG?
GREAT!
Dilbert.com DilbertCartoonist@gmail.com
THE PROJECT EXISTS IN A SIMULTANEOUS STATE OF BEING BOTH TOTALLY SUCCESSFUL AND NOT EVEN STARTED.
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CAN I OBSERVE IT?
THAT'S A TRICKY QUESTION.

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A. https://www.bmbf.de/de/quantentechnologien-7012.html
B. http://marconisociety.org/quantum-communications/
C. https://www.dailygrail.com/2017/03/mental-illness-treatment-may-offer-evidence-for-quantum-effects-in-the-brain/
D. https://www.parliament.uk/business/committees/committees-a-z/commons-select/science-and-technology-committee/news-parliament-2017/quantum-technologies-inquiry-launch-17-19/
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