Can quantum computers help us achieve human level intelligence?

...Uploading Schrödinger's Cat

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I.) Some important QC concepts
Superposition/Entanglement/Qubits
Case study: The Superconducting Flux Qubit
How do we make them / measure them
What can Quantum Computers DO / NOT DO?

II.) Quantum computing applications

III.) A foray into the metaphysical...
What is intelligence?
QM and the brain
Interpretations of QM
What does QC mean for Transhumanists?
What makes a quantum computer?

Main QC concepts

Superposition
Superposition is the ability of a bit to be in a mixture of two states (e.g. 0 and 1) at the same time

Entanglement
Entanglement is the ability of two or more bits to be 'linked' such that changing or manipulating the state of one of the bits automatically changes the other one. Note: The two bits do not have to be locally connected. Einstein referred to this phenomenon as 'spooky action at a distance'

Decoherence
Any open system will interact with 'degrees of freedom' in the environment. Quantum states will lose their coherence when this happens. Note: This can get (somewhat) around the problem of the observer effect. (More later)
What is a qubit?

- A qubit (or QUantum BIT) is similar in concept to a standard 'bit' - it is a memory element, a bit of information. It can hold not only the states '0' and '1' but a linear superposition of both states, $\alpha|0> + \beta|1>$

- Physicists denote the basis states $|0>$ and $|1>$ respectively.

QUBIT vs. CLASSICAL BIT

Classical bits

Quantum bits
What are qubits made from?

There are lots of different ways to make a device that exhibits quantum behaviour.

A good rule of thumb is: Anything small (and usually cold) that is well isolated from the environment but that can be 'read out' somehow can form a qubit.

- Individual atoms / ions – read out by sending in photons
- Photons – read out using single photon detectors (for example)
- Nuclear Spins in a molecule (read out using an NMR setup)

I'm going to explain qubits using a particular type with which I'm quite familiar and I believe to be a promising candidate for scalable QC:

Superconducting Flux Qubit (SCFQ).
Superconducting Flux Qubit (SCFQ)

This is made from a device called a 'Josephson Junction'.

In a superconductor, the electrons form a coherent state (a bit like photons in a laser beam) which means that they can be described quantum mechanically.

**ELECTRONS BECOME WAVES**

Where does the 'quantumness' come from? The electron wave obeys quantum mechanics and exhibits superposition and entanglement.

You can control the wave by applying a magnetic field.
Getting it to be quantum...

- A discontinuity in Phase makes a current flow around the loop.
- This can be controlled by applying magnetic fields

The qubit can support currents flowing in both directions at once!
- We can encode our data, $|0\rangle$ and $|1\rangle$, into these two states.

- Both flux states are equally favourable. They become quantum mechanically 'linked' through the barrier!
- No longer considered separate states
Why SCFQ?

SCFQ compatible with existing process technology

SCFQ is scalable and can be made compatible with Josephson Logic (RSFQ)

Unique because they contain a Macroscopic quantum superposition – a large number of electrons (this will have interesting consequences as discussed later).

Disadvantages:
Cooling required (although cooling techniques are arguably improving faster than QC so this may not be an issue!)

Solid state systems are more prone to decoherence (more later)
How are they made?

Use material deposition techniques to place a layer of superconductor.

Pattern a ramp into the superconductor.

Oxidise the surface of the superconductor (or deposit an insulating layer on top) to form the Josephson barrier.

Make a via (hole) into the insulating layer and attach electrodes to each side of the junction.

Different superconductors can be used for the two layers, to investigate interesting effects.

Josephson junction Technology

Superconductor (Niobium or Aluminium)

Gold Electrodes

Insulating barrier
Testing and measuring qubits?

What temperatures do the qubits operate at?

- They need to be in the superconducting regime
- They need to be cold enough that thermal fluctuations are unimportant.
- So in the energy well diagram, the energy of the system is unlikely to be accidentally 'excited' over the barrier.

The qubit sits in a copper box, which reaches the lowest temperatures – here approx. 30mK, (or 0.03 of a degree above absolute zero!)

DISPELLING A QUBIT MYTH...
Even if you had Room Temperature Superconductors, qubits would still need to be refrigerated down to very low temperatures.
What can Quantum Computers DO?

The power of the QC comes from the fact that it can exploit entanglement and superposition.

Because qubits can be put into superpositions, they can 'explore' several 'calculation possibilities' at the same time.

They can natively store the states of quantum objects (useful for simulation e.g. quantum chemistry).
What can they NOT do?

You can never 'see' a superposition of states. So you need an algorithm that uses the quantum superpositions to calculate a classical answer without 'disturbing it'. You can only read out a CLASSICAL answer (Quantum Measurement problem).

This is the tricky bit – the algorithm must be able to find and somehow 'amplify' the correct answer amongst the superpositions, so that when you take a measurement you are likely to get the right answer.

They can't solve all problems exponentially faster than classical computers. For most computational tasks they are useless!

Examples:
- **Shor's algorithm** for factoring has an exponential speedup
- **Grover's algorithm** for searching only has a Quadratic speedup

But this can still help for large problem sizes.

But they might not always be so specialised – New quantum algorithms are being developed too.
A whole family of Quantum Computers

There is more than one way to make a quantum computer. Depending upon which way you make it determines what problems it can solve.

Lots of people ask questions like:

How many qubits?
What decoherence time?

Think about an analogue computer vs. a digital one, or a programmable logic chip vs. a general purpose computer.

- Gate model - 'Standard' model
- Adiabatic Quantum Computation – a close contender
- Cluster state (measurement based) – slightly more obscure
- Topological quantum computing – slightly more obscure
'Standard' Gate model QC

With two coupled qubits you can make a CNOT gate!

\[ M_{\text{CNOT}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \]

Grajcar et al., PRL 96 (2006)

Checking for quantum behaviour

Mostly $|1\rangle$

Mostly $|0\rangle$
Adiabatic Quantum Computing (AQC)

Another popular method

So far the methods discussed transfer quantum information between qubits, or gates. Similar to conventional computing with transistor logic. For this reason it is quite intuitive.

AQC is a more 'natural' way of computing

It works by finding the minimum energy of a system

A lot of problems can be solved by 'mapping' them onto the minimum energy technique. (Examples later)

WORKS LIKE SIMULATED ANNEALING
AQC - Simulated Annealing

First need to describe how it would be done in a non-quantum way.

System is disordered

Set system to a finite temperature and wait

Ground State

System finds global minimum in time $t_S$
A quantum fluctuation!

System finds global minimum in time $t_Q$

It is less likely for the fluctuations to cause the system to go backwards. Hence the global minimum is found more quickly! So this is why you need a quantum system.
AQC - Lots of qubits

AQC advantage:

Because you do not need to control each qubit individually (they interact naturally), you can quickly scale this model up to lots of qubits.

D-wave's 16 qubit device (they now have 128)

An array of 16 qubits, each coupled to their nearest neighbours.

This is the most advanced qubit coupling scheme implemented by anyone so far.

..Is it truly quantum?
Decoherence – Know your enemy

The main reason that quantum computing technology is progressing slowly is that the delicate quantum states are prone to DECOHERENCE.

The input of any energy at a level similar to the scales discussed earlier 'knocks' the quantum state. (It acts like a type of measurement)

Sources of decoherence:
- EMI from surroundings (Radio 1)
- Thermal noise (already discussed)
- Defects in the materials (e.g. dislocations)
- Electrical Control lines nearby

Most sources are now intrinsic to the junction - The qubits are now limited by the materials technologies.

Martinis et al., PRL 95 (2005)
Quantum computing applications and technology
Quantum Computer complexity

Complexity class: NP-Complete

There is an ongoing debate about whether or not NP-Complete problems can be solved by Quantum Computers in Polynomial Time.

But if they can...

There are lots of NP-complete problems in nature, our environment and in our technological culture. NP-Complete – just making conventional computers faster can only help you up to a point

Exponential explosion of problem size with number of variables. Think of problems with large data sets.
Applications

Engineering:

Circuit routing
Microprocessor/ASIC design
Product and component placement
Traveling Salesman problem
Network Routing
Congestion simulation
Applications

Systems Biology:
Metabolomic pathways
Metabolite databases
Bioinformatics

Genetics Biochemistry
Matching gene sequences
Searching sequence and databases
Protein folding

Nano-Physics:
Spin system modeling
Molecular manufacturing

Chemistry/Physics
Simulating energy levels
Quantum systems
Applications

Security and Internet
Cryptography
Biometrics
Image recognition & processing
Database and www searching
Fast scanning of network traffic

AI
Machine learning
Neural networks
Examples of Apps running on a QC

D-Wave's quantum computer solving some small problems:

Finding a match for a small piece of a molecule in a larger one
Solving a simple sudoku problem

At this point the quantum computer does not have enough 'bits' to be able to see a speedup over a classical machine – but it demonstrates that the problems can indeed be mapped successfully onto this architecture. With ~200qubits, a speedup should be achieved.
Quantum computing and the brain?
(Disclaimer: This is a very new area of research)

AQC is naturally suited to QNN - A 'physical' way of simulating neurons. 1 qubit = 1 artificial neuron (but they are entangled such that they can encode more than one potential neural state at any one time.

By encoding several states, if machine learning algorithms can be mapped onto energy minimisation (which they can), a collection of quantum neurons can 'learn' much faster than a classical neural net.
An even more exotic idea...

Topological neuron information can be encoded into the time-correlations of a low number of qubits.

Reversible computing and quantum superposition means that the qubits 'remember' which path they had to take to get to the current state, so a large amount of information is preserved in a pattern in time.

In the QM equations, you can swap time and space co-ordinates – so use qubit time correlations rather than spatial ones to represent information patterns.

If you can run your QC very fast, you can compute time correlations between a large number of neurons faster than a real brain would run, with fewer physical neurons.

2 qubits can potentially represent 8 quantum neurons, etc. - A form of data compression
The problem of Whole Brain Emulation

Can you...

Simulate a human brain with a classical (digital or analogue) computer?
Simulate it with a quantum computer?
Simulate it with any type of computer!?

What IS human level intelligence?
What IS Intelligence / self awareness / consciousness?

We quickly run into problems here as we don't know what we're trying to simulate!

- Zombie arguments
- Qualia
- Materialism vs. idealism
- Emergent phenomena
Try these out on your friends

The 4 different viewpoints (Penrose, Shadows of the Mind, 1994):

- A.) STRONG AI – all thinking is computation
- B.) WEAK AI - Computation by itself cannot evoke awareness
- C.) Physical processes DO underlie consciousness, but we cannot computationally simulate all physical processes*
- D.) No Physical process underlies consciousness, it is outside of the physical realm.

* Caveat – with our current computational technologies
What about Viewpoint C?

Roger Penrose and Stuart Hameroff
ORCH OR model of the brain
They basically say that consciousness arises due to controlled 'collapse of the wavefunction' within the brain – we have evolved to be able to do this

The brain will have to have evolved a way to combat decoherence.

Quantum computing occurs within microtubules.

I do not believe this to be the case for 2 reasons

1.) The brain is hot and full of stuff, very good conditions for decoherence. Very bad conditions for macroscopic quantum coherence.

2.) I don't think that you need quantum effects to explain consciousness (STRONG AI viewpoint)
Quantum Consciousness...

Even if the brain IS classical, could we potentially build a quantum brain? What type of consciousness would it have?

What are the limitations? - There are no fundamental limitations to the size of Macroscopic Quantum Object that you can create.

However, in the real world we have decoherence. We need large, isolated systems to combat this problem SCFQ are useful here (large numbers of electrons).

Some proposed limitations involve the role of mass and gravitational interactions as a source of 'wave-function collapse'

Limit on the Mass of a quantum system? - Quantum gravity theories, Penrose Hypothesis. $\sim (10^{-7} g)$
Towards quantum superposition of organisms...

Experiments proposed to put objects such as viruses into quantum superpositions.
But quantum computers can help us either way...

Either:

1.) Penrose is correct, (we cannot simulate the brain with a digital computer) – then we can do it with a quantum computer

Or:

2.) Penrose is wrong – (we can simulate it with a classical computer) - we can potentially still simulate it with a quantum one faster, or find new and exciting applications for quantum brains

WIN WIN!

Note I'm not considering D.) to be a sensible argument here!!
Quantum Mechanics foundations... A crash course

What else can QC help us with?
Interpretations of Quantum Mechanics are a problem

- Many Worlds – 'Not the most concise interpretation'
- Copenhagen interpretation – 'The observer plays a role in Physics-?!'
- De-Broglie-Bohm interpretation – 'Passing the quantum buck'

None of these are ideal

Physicists get around this problem by invoking decoherence. It does not make the problem go away completely.

We do NOT fundamentally understand the nature of REALITY!

Quantum Computers may help us understand some of these problems... Perhaps differentiate between the interpretations
How to proceed?

So many interesting questions await an answer!
What can we do?

Tackle the problem from several different angles

• Fundamental junction research (improving hardware)
• Algorithm and theory research
• Commercialization for current algorithms and techniques
• Merging of QC with new technologies (QNNs / AI) <-for future work

Increase awareness and funding!

Commercialisation – nearly none. None in the UK (To my knowledge)
How far away is this technology?

Difficult to estimate – 20 years ago people were projecting the rise of quantum computing as a near-term goal.

We still only have very small systems at the moment.

I personally believe that we will start to see applications of quantum computing in 5-10 years time (funding and result dependent).

It should however get easier as we demonstrate more and more systems working, and potentially more funding when results start looking promising.

The other advantage of a young research field is that there may be previously unconsidered applications discovered along the way.
Why should the H+ community care?

QC could be of great use in areas involving accelerating technologies.

Specifically Kurzweils' 'Epoch 5'
The merging of Technology and Human Intelligence.

QC has potential applications in areas such as Biogerontology, Managing increasingly large data sets, AI and the simulation of nanotech systems.

It can also hopefully answer some very important questions about the nature of consciousness and metaphysics along the way!
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