If only we could control them:

Challenges and Opportunities in Scaling-up Quantum Computers

David Reilly

www.microsoft.com/quantum/
Light waves

Light particles (photons)
Louis-Victor-Pierre-Raymond, 7th duc de Broglie

“He has lifted a corner of the veil that shrouds the Old One.” –Einstein (Thesis Report).

Ph.D Awarded 1924.

Experimentally demonstrated in 1927. Nobel Prize for Physics 1929.
Quantum Technologies

Sensing & Imaging
Computing
Simulation
Metrology
Secure communication
New Physics
Convergence of Qubit Platforms

- **Superconducting qubits**
- **Surface Ion Trap**
- **Topological Qubits**
- **Spin Qubits**
- **Photonic Qubits**

- Control via microwave pulses.
- Readout via detection of amplitude / phase of microwaves.
- Cryogenic operation.
Quantum-Classical Interface

Control

Oscillating Electric
Oscillating Magnetic
Laser Light
Quasi-particle

Readout

$|1\rangle$

However, all these functions suffer from what has been called 'the tyranny of numbers.' Such systems, because of their complex digital nature, require hundreds, thousands, and sometimes tens of thousands of electron devices.

— Jack Morton, VP Bell Labs (June 1958).
Brute force scaling...

Google’s Bristlecone 72 Qubits, 2 control lines per qubit... Impressive!
Integration and Abstraction are Essential

Intel Ivy-Bridge: 2 billion transistors. 340 wires on a BGA
IO Management in Classical VLSI

Rent’s Rule: $T = t \cdot g^a$

- $T =$ number of IOs
- $g =$ number of gates
- $t, a$ are constants

Fan-out: “Output of one gate feeds the input of another”
Quantum Circuits are Different!

*Each qubit requires a unique, independent set of IO channels...*

*Leads to an IO - Bottleneck at the Quantum-Classical Interface*
Challenges at the Quantum-Classical Interface

- IO Management
- Footprint / interconnect density
- Heat and Power
- Distributed verse integrated systems
  (synchronicity, latency, wavelength effects...).
- Noise, crosstalk, interference
- Bandwidth / rise-time

*All aspects can be addressed by moving the interface electronics into the cold*

100,000 transistors, operating at 100 mK

Frequency multiplexing for readout of spin qubits

J. M. Hornibrook,1 J. I. Colless,1 A. C. Mahoney,1 X. G. Croot,1 S. Blanvillain,1 H. Lu,2 A. C. Gossard,2 and D. J. Reilly1,a)
1ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Sydney, Sydney, NSW 2006, Australia
2Materials Department, University of California, Santa Barbara, California 93106, USA

(Received 24 December 2013; accepted 26 February 2014; published online 12 March 2014)
New physics leads to new technologies

\[
\begin{align*}
    dS &= \delta Q / T \\
    dS &\geq 0
\end{align*}
\]

\[
\begin{align*}
    \nabla \cdot \vec{D} &= \rho \\
    \nabla \cdot \vec{B} &= 0 \\
    \nabla \times \vec{H} &= \vec{j} + \frac{\partial \vec{D}}{\partial t} \\
    \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t}
\end{align*}
\]
Nitrogen fixation
Carbon capture
Materials science
Machine learning
“The projected device, or rather the species of devices of which it is to be the first representative, is so radially new that many of its uses will become clear only after it has been put into operation,”

“These uses which are not, or not easily, predictable now, are likely to be the most important ones. Indeed they are by definition those which we do not recognize at present because they are farthest removed from... our present sphere.”
