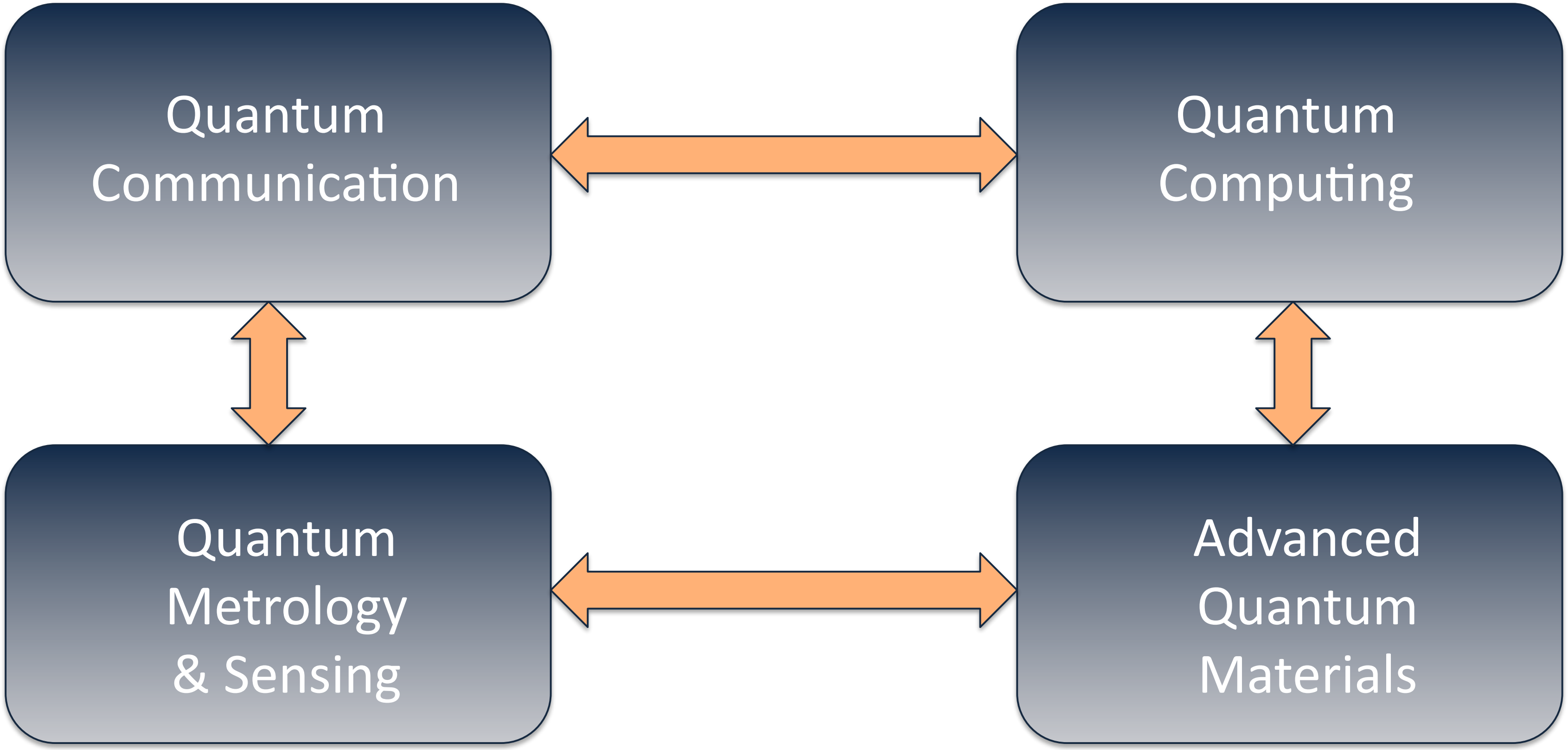
Quantum Bits



Role of superconductivity

Transmon qubits produce microwave photons that could be converted to telecommunication photons for transmission and coupling

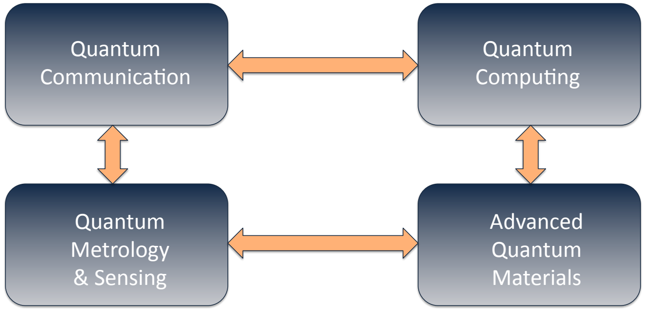
SC qubit platforms useful for quantum processing and error correction

SC devices are leading platforms for qubits technologies

Conventional qubits: non-linearity of the Josephson inductance

Topological qubits: Majorana fermions nucleated in hybrid SC-topological

All: protection from dephasing by energy gap, intrinisic high-frequency scale that enables quantum phenomena, and low temperature operation



Superconducting detectors already offer quantum-limited sensitivity

Improvements possible by incorporating entanglement and squeezed-state techniques

Novel sensors incorporating SQUIDs may be important in dark matter searches for axions and WIMPS

Advanced materials and fabrication techniques are path to reduce dephasing

Topological materials to support Majorana fermions states

Topological materials are promising for computer interconnects

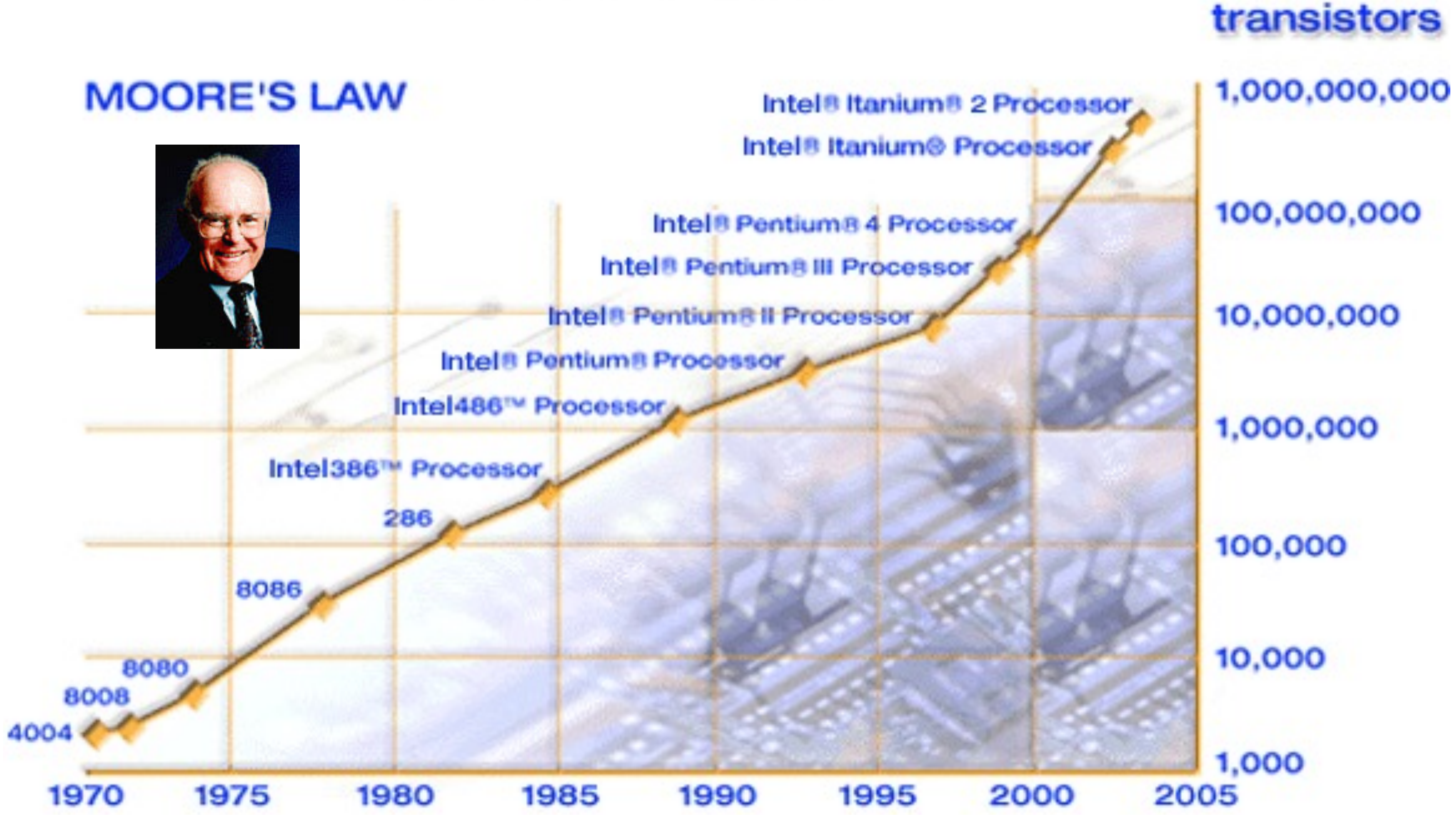
Primary drivers for Quantum information Science

1. Quantum computing ---- beyond Moore's Law

2. Secure data communications --- encryption codes

3. Exciting science enabled by quantum computing

Moore's Law

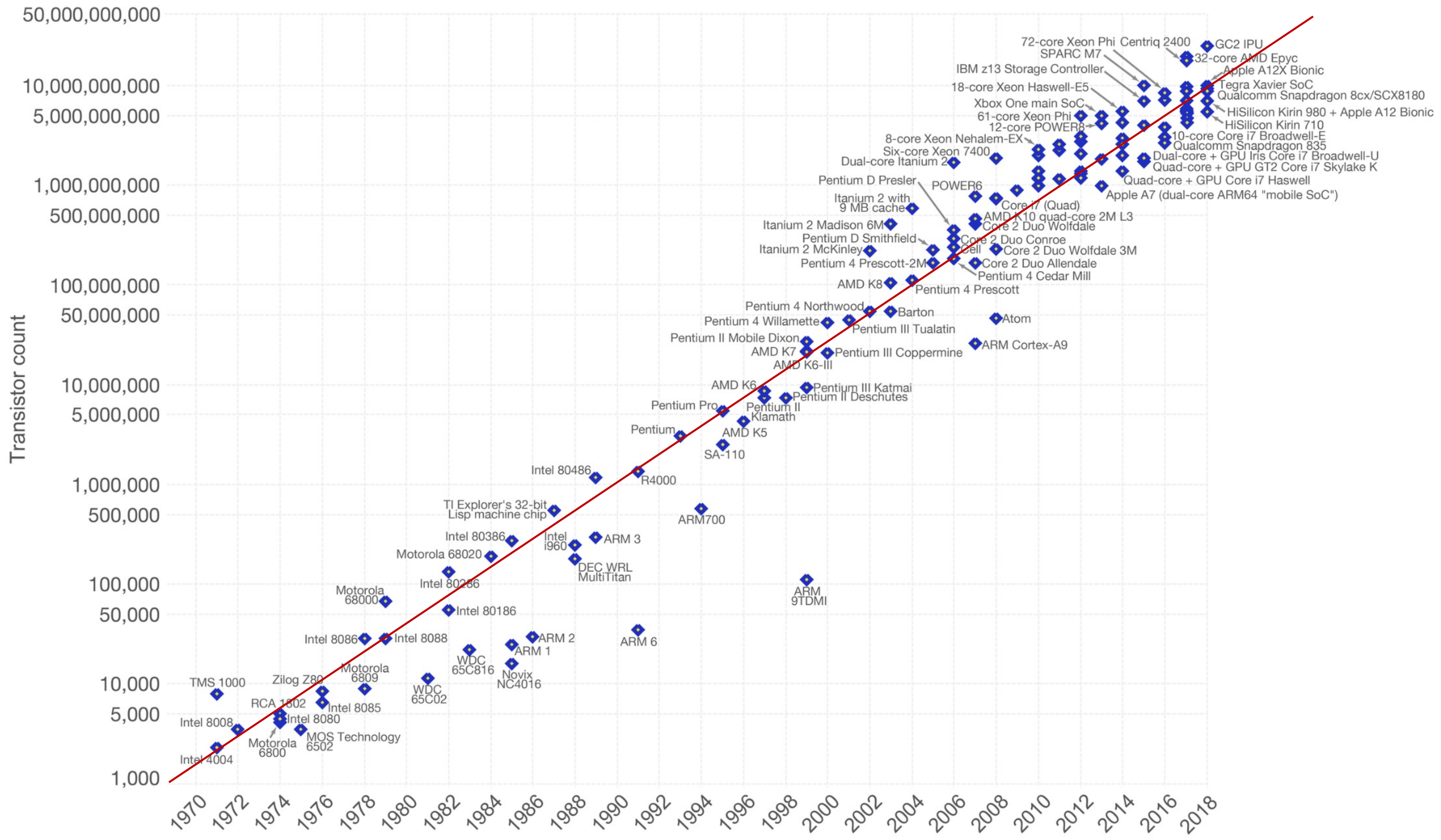


Source: Intel

Moore’s Law – The number of transistors on integrated circuit chips (1971-2018)

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Classic vs. Quantum Logic

CLASSICAL LOGIC: two distinct states "bit"

$$0 \ \ or \ \ 1$$

can do all operations from NOT and exclusive-OR gates

Single-bit operation

Two-bit operation

perform series of operations on bits to get final answer

QUANTUM LOGIC: superposition of two quantum levels "qubit" = quantum bit

$$\Psi = a|0\rangle + b|1\rangle$$

can do all operations from single-qubit and controlled-NOT functions

unitary transformations (e.g. rotations)

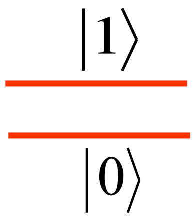
Two-qubit operation

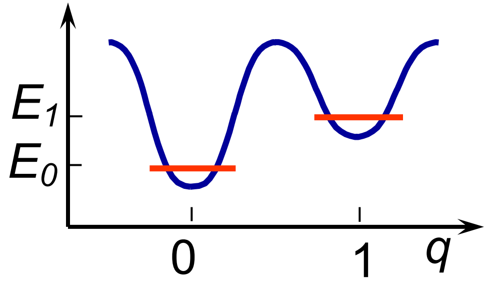
"Entangle" qubits and allow quantum evolution to "project out" answer

Key to quantum computation = entanglement

qubit = quantum two-level system $|0\rangle$ *and* $|1\rangle$

Superposition: $\Psi = a|0\rangle + b|1\rangle$





Entanglement: interference of two qubits $\Psi = A|00\rangle + B|01\rangle + C|10\rangle + D|11\rangle$

Performing logic operations with entangled states allows the quantum evolution to sample multiple states …
effectively massive parallel computation

Quantum mechanically, a register of N entangled qubits can store 2^N states in superposition:

e.g. A 300-qubit register can simultaneously store $2^{300} \sim 10^{90}$ numbers

2037035976334486086268445688409378161051468393665936250636140449354381299763336706183397376

This is more than the total number of particles in the Universe!

(Google SC quantum computer has 57 qubits = only 144,115,188,075,855,872 states)

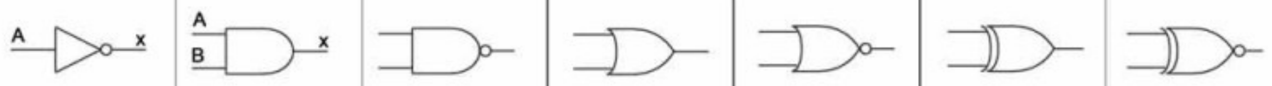
Some problems benefit from this exponential scaling, enabling solutions of otherwise insoluble problems.

Classical vs. Quantum logic --- gates and algorithms (cont'd)

Because the bits are different, the logic operations are different also

CLASSICAL LOGIC

Classic logic gates operate on discrete binary bits --- there are 7 types of logic gates:

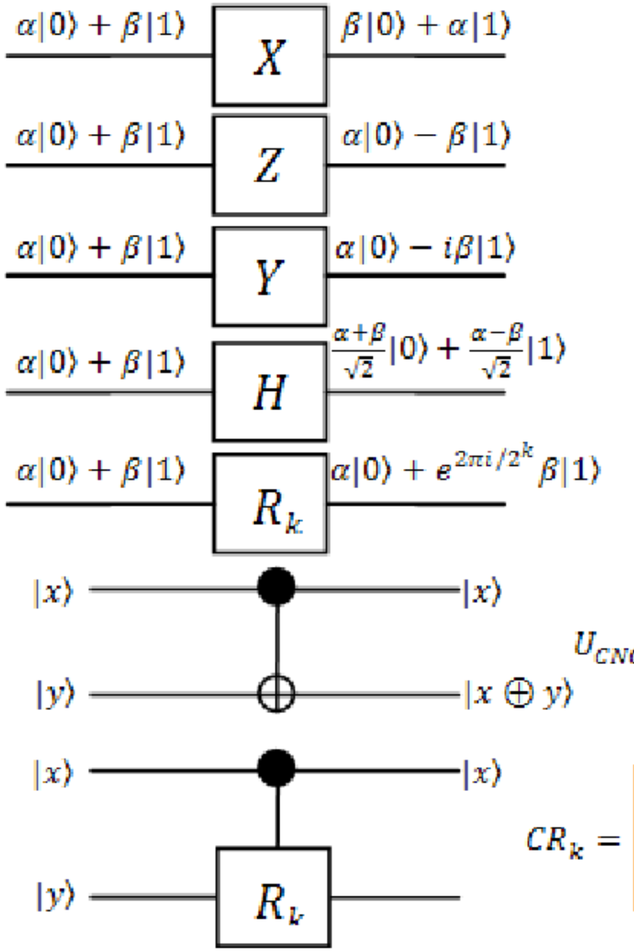
Name	NOT	AND	NAND	OR	NOR	XOR	XNOR
Alg. Expr.	$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A\oplus B$	$\overline{A\oplus B}$
Symbol							
Truth Table	A X 0 1 1 0	B A X 0 0 0 0 1 0 1 0 0 1 1 1	B A X 0 0 1 0 1 1 1 0 1 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 1	B A X 0 0 1 0 1 0 1 0 0 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 0	B A X 0 0 1 0 1 0 1 0 0 1 1 1

Classical algorithms consist of sequences of these logic operations, sometimes performed in parallel in large computers

Classical vs. Quantum logic --- gates and algorithms (cont'd)

QUANTUM LOGIC

Quantum logic gates operate on single qubits and pairs of qubits



$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

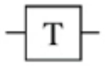
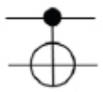
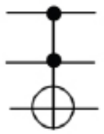
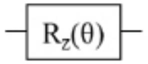
$$Y = \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix}$$

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$R_k = \begin{bmatrix} 1 & 0 \\ 0 & e^{2\pi i/2^k} \end{bmatrix}$$

$$U_{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$CR_k = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{2\pi i/2^k} \end{bmatrix}$$

Gate name	# Qubits	Circuit Symbol	Unitary Matrix	Description
Hadamard	1		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	Transforms a basis state into an even superposition of the two basis states.
T	1		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$	Adds a relative phase shift of $\pi/4$ between contributing basis states. Sometimes called a $\pi/8$ gate, because diagonal elements can be written as $e^{-i\pi/8}$ and $e^{i\pi/8}$.
CNOT	2		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$	Controlled-not; reversible analogue to classical XOR gate. The input connected to the solid dot is passed through to make the operation reversible.
Toffoli (CCNOT)	3		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$	Controlled-controlled-not; a three-qubit gate that switches the third bit for states where the first two bits are 1 (that is, switches $\|110\rangle$ to $\|111\rangle$ and vice versa).
Pauli-Z	1		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	Adds a relative phase shift of π between contributing basis states. Maps $\|0\rangle$ to itself and $\|1\rangle$ to $-\|1\rangle$. Sometimes called a "phase flip."
Z-Rotation	1		$\begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$	Adds a relative phase shift of (or rotates state vector about z-axis by) θ.
NOT	1		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	Analogous to classical NOT gate; switches $\|0\rangle$ to $\|1\rangle$ and vice versa.

Classical vs. Quantum logic --- gates and algorithms (cont'd)

A few other important differences:

1. Quantum gates are reversible --- classical gates are not.

   That means that the input data is destroyed in the classical operations
   but is retained in the quantum system

2. Classical gates (if they work) give an exact result --- quantum gates give superpositions of states which are characterized by probabilities

   That means (1) that you need "high-fidelity" readouts of the state that can distinguish which state the system is in after an operation, and (2) even with perfect fidelity that you need to work with ensembles and do enough measurements to get the final state

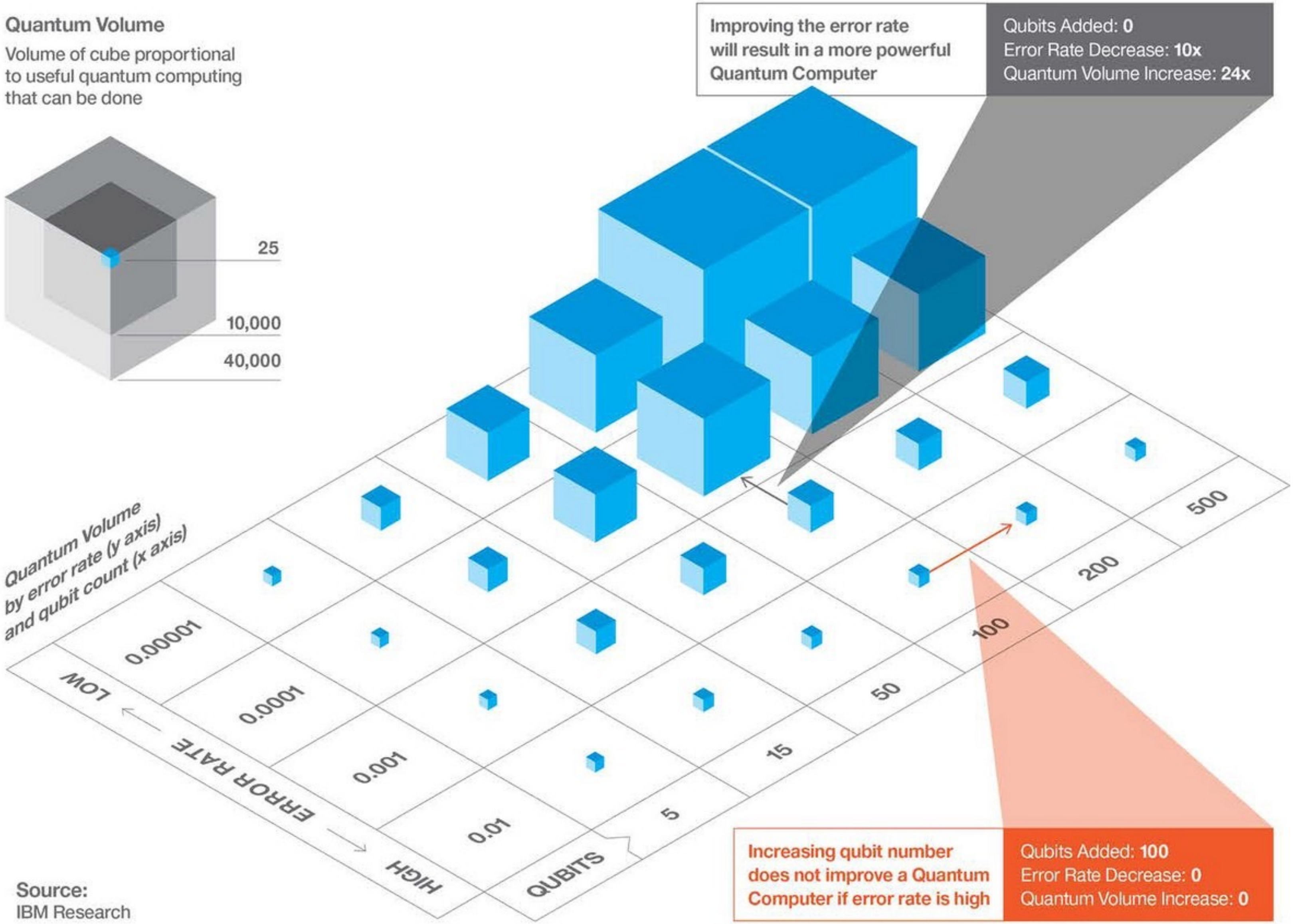
3. You need to implement "error-correcting codes" to mitigate accumulated measurements

   That means that there is an "overhead cost", i.e. to make N functioning qubits, you may need many more physical qubits --- that overhead depends on the system but can be 10-1000 times*

** This is one of prime motivations of topologically-protected qubit platforms since it is proposed that these give error-free operations that will eliminate the need for error-corrections (that is only partially true)*

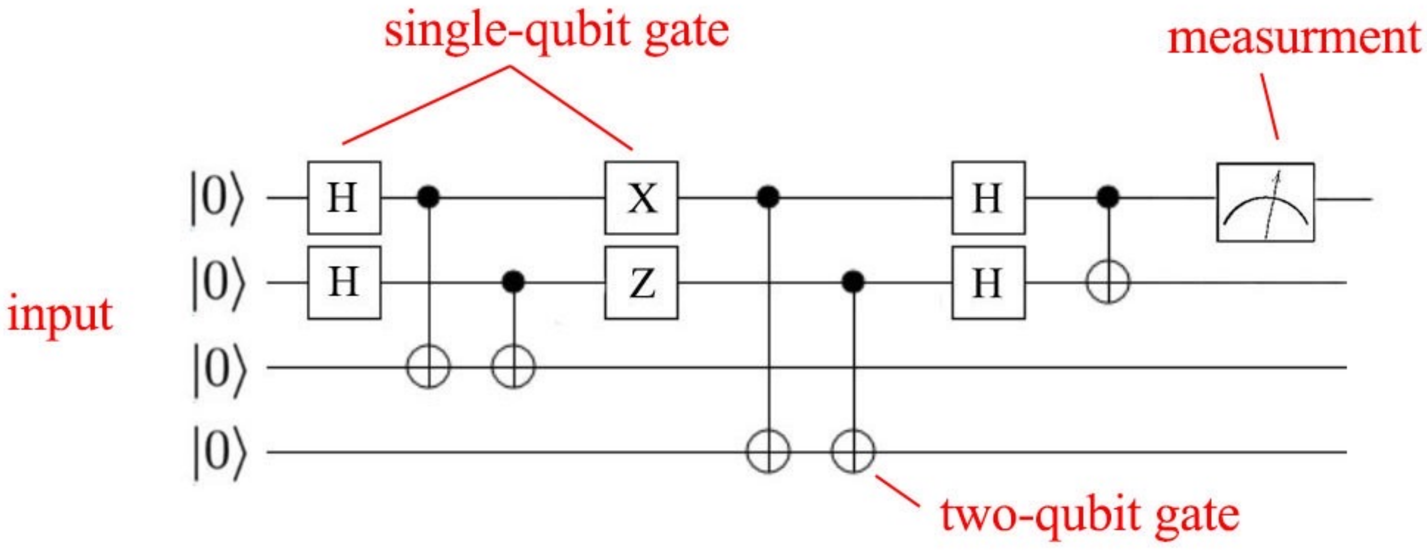
A Quantum Computer's power depends on more than just adding qubits

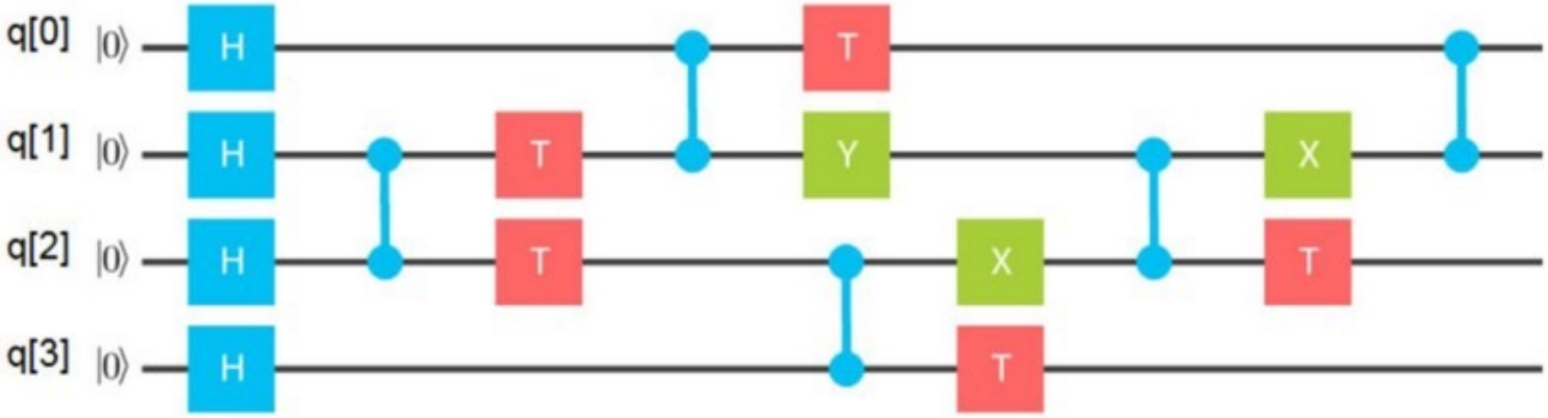
If we want to use quantum computers to solve real problems, they will need to explore a large space of quantum states. The number of qubits is important, but so is the error rate. In practical devices, the effective error rate depends on the accuracy of each operation, but also on how many operations it takes to solve a particular problem as well as how the processor performs these operations. Here we introduce a quantity called **Quantum Volume** which accounts for all of these things. Think of it as a representation of the problem space these machines can explore.



Source:
IBM Research

Quantum algorithms consist of sequences of these logic operations, followed by measurements of the resulting quantum states





Requirements for quantum computation *(DiVincenzo criteria)*

1. Scalable physical system of qubits

qubit = quantum two-level system

$$|0\rangle \ \ \textit{and} \ \ |1\rangle$$

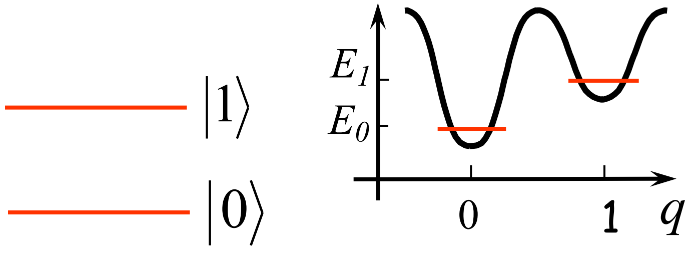
bit = classical two-level system

$$0 \ \ \textit{or} \ \ 1$$

Superposition: $\Psi = a|0\rangle + b|1\rangle$

Two qubits --- *entanglement* :

$$\Psi = A|00\rangle + B|01\rangle + C|10\rangle + D|11\rangle$$



2. Ability to initialize qubits into a particular quantum state

initialization at the start of computation

supply of qubits in low entropy state for quantum error correction

3. Universal set of quantum gates

Classical computer → all operations from NOT and exclusive-OR

Quantum computer → all operations from single qubit rotations and the two-qubit controlled-NOT

Quantum algorithm = sequence of unitary transformations $U_j = e^{iH_j t/\hbar}$

4. Qubit-specific measurement capability

Quantum measurement: $\Psi = a|0\rangle + b|1\rangle$

probability of $|0\rangle = |a|^2$ probability of $|1\rangle = |b|^2 = 1 - |a|^2$

Need to measure the state of each qubit without perturbing the state of the others

Ideal if the measurement does not destroy the quantum state of the measured qubit also → *non-demolition*

Figure of merit = quantum efficiency (<100%)

5. Long decoherence times

Effect of the environment → entangles system with the environment (bad) … or, makes a measurement on the system

Decoherence time criterion is hard to define … depends on specific system and type of measurement to be made, but must be:

"long enough that the uniquely quantum features of the computation have a chance to come into play"

System must maintain phase coherence during the execution of sequences of logic operations ($\sim 10^4 - 10^5$) , but not for the duration of the entire calculation

Quantum error correction (Shor, 1996)

Implications:

reduce internal dissipation of the system

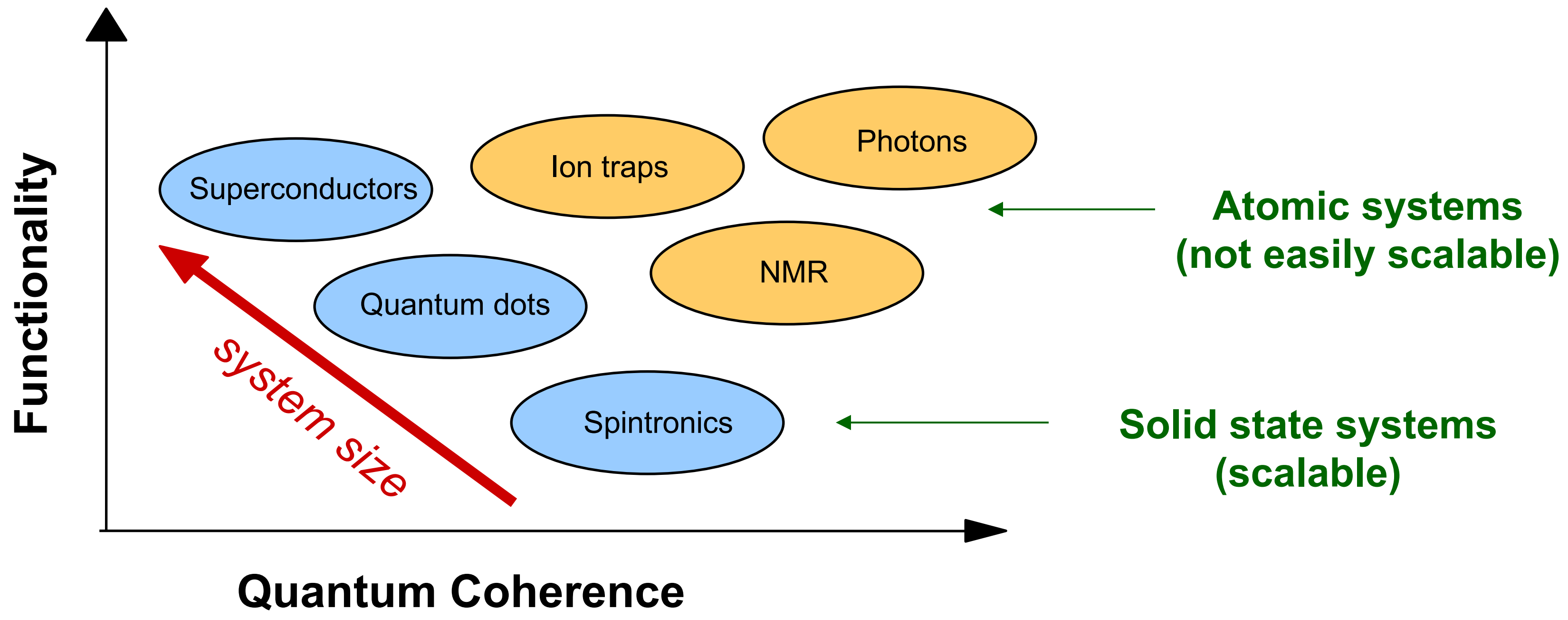
isolate system as much as possible from the environment

QUBIT implementation

1. Must be able to entangle, manipulate, and readout quantum states
   Functionality

2. Must be able to isolate system from the environment
   Quantum coherence

3. Develop architecture that allows coupling of multiple qubits
   Scalability



Comparison of qubit technologies

Organization	Adiabatic/Annealing	Superconducting	Trapped Ion	Cold/Neutral Atom	Spin/Quantum Dot	Photonic	NV Diamond	Topological
Total Number = 97	**7**	**23**	**17**	**9**	**12**	**16**	**6**	**7**
Alibaba/CAS		X						
Alpine Quantum Technologies			X					
Archer Exploration					X			
Atom Computing				X				
Bleximo		X						
CEA-Leti / Inac					X			
Centre for Quantum Computation & Communication Technology					X	X		
Chalmers University of Technology		X						X
ColdQuanta				X				
Duke University			X			X		
D-Wave	X							
EeroQ				X				
Google	X	X						
Griffith Univ./Univ. Of Queensland						X		
Honeywell			X					
IBM		X						
ID Quantique						X		
Institut d'Optique				X				
Intel		X			X			
IonQ			X					
IQM Finland		X						
Korea Institute of Science & Technology							X	
MDR	X	X						
Microsoft								X
MIT Lincoln Lab	X	X	X				X	
MIT/Univ. of Innsbruck			X					
NEC	X							
NextGenQ			X					
Niels Bohr Institute								X
Nokia Bell Labs								X
Northrop Grumman	X							
NQIT			X					
NTT/Japan NII/Univ. of Tokyo						X		
Origin Quantum Computing		X			X			
Oxford		X	X			X	X	
Oxford Quantum Circuits		X						
Pasqal				X				
Penn State University				X				
PsiQuantum						X		
Qilimanjaro	X							
Quantic		X						
Quantum Circuits Inc		X						
Quantum Factory			X					
Quantum Motion Technologies					X			
Qubitekk						X		
QuiX						X		
QuTech		X			X		X	X
Raytheon BBN		X						
Rigetti		X						
RWTH Aachen					X			
Sandia National Laboratories			X	X	X			
SeeQC.EU		X						
SeQureNet						X		
Simon Fraser University					X			
Sparrow Quantum						X		
Toshiba						X		
TundraSystems Global						X		
TU Wein/NII Tokyo/NTT							X	
Universal Quantum			X					
Universitat Duisburg-Essen							X	
University of Bristol						X		
University of California Santa Barbara		X						X
Joint Quantum Institute / University of Maryland			X					X
University. of Science & Technology of China (USTC)		X						
University of Basel					X			
University of Sussex			X					
University of Washington			X					
University of Waterloo - IQC		X	X			X		
University of Wisconsin		X		X	X			
Weizmann Institute			X					
Wuhan Inst. Of Physics & Mathematics, Chinese Academy of Sciences				X				
Xanadu						X		
Yale Quantum Institute		X						