From Millimeter-Wave to Quantum Communication: A Call for Cross-Disciplinary Research and Innovation

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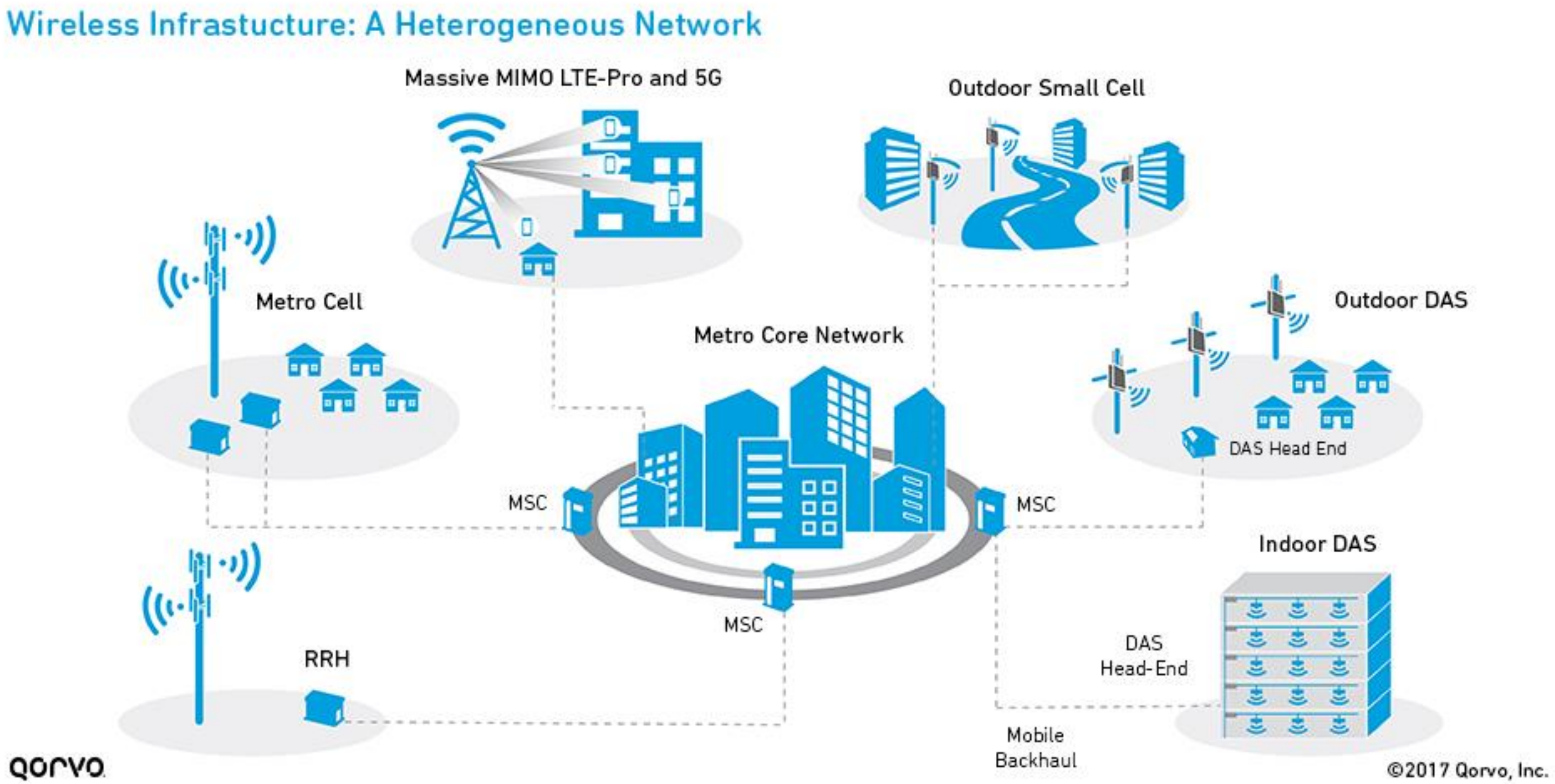
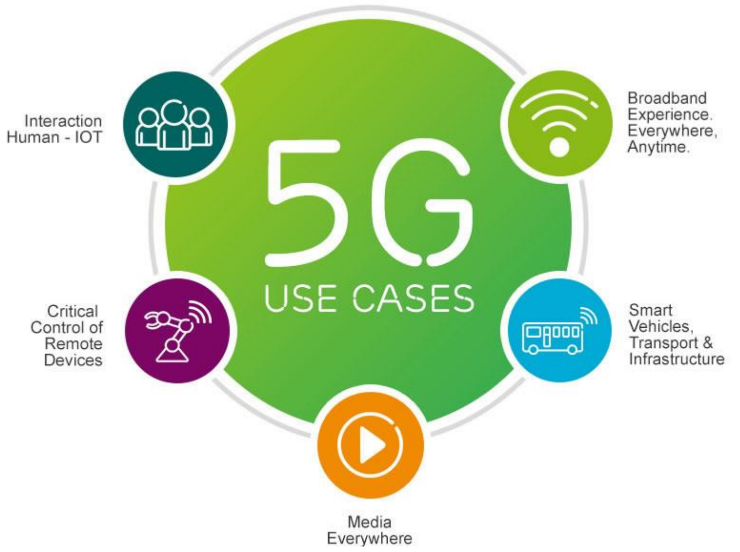
Information Science and Technology

- Communication and computing technology have progressed tremendously in the last 50 years!
- These technological advances have impacted all aspects – social, economic, political – of our lives
  - Cloud, edge, and mobile computing
  - Key enabler: anytime, anywhere wireless connectivity



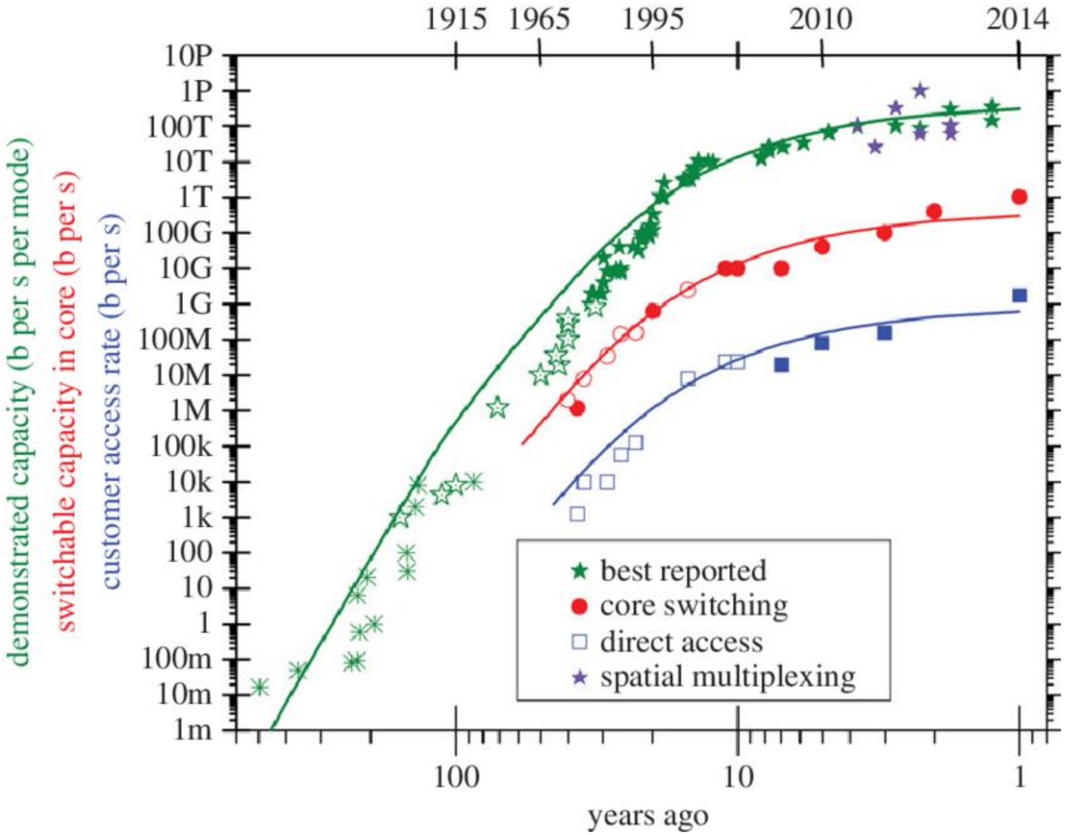


ericsson

Nothing Lasts Forever - Computing and Communication Crunch

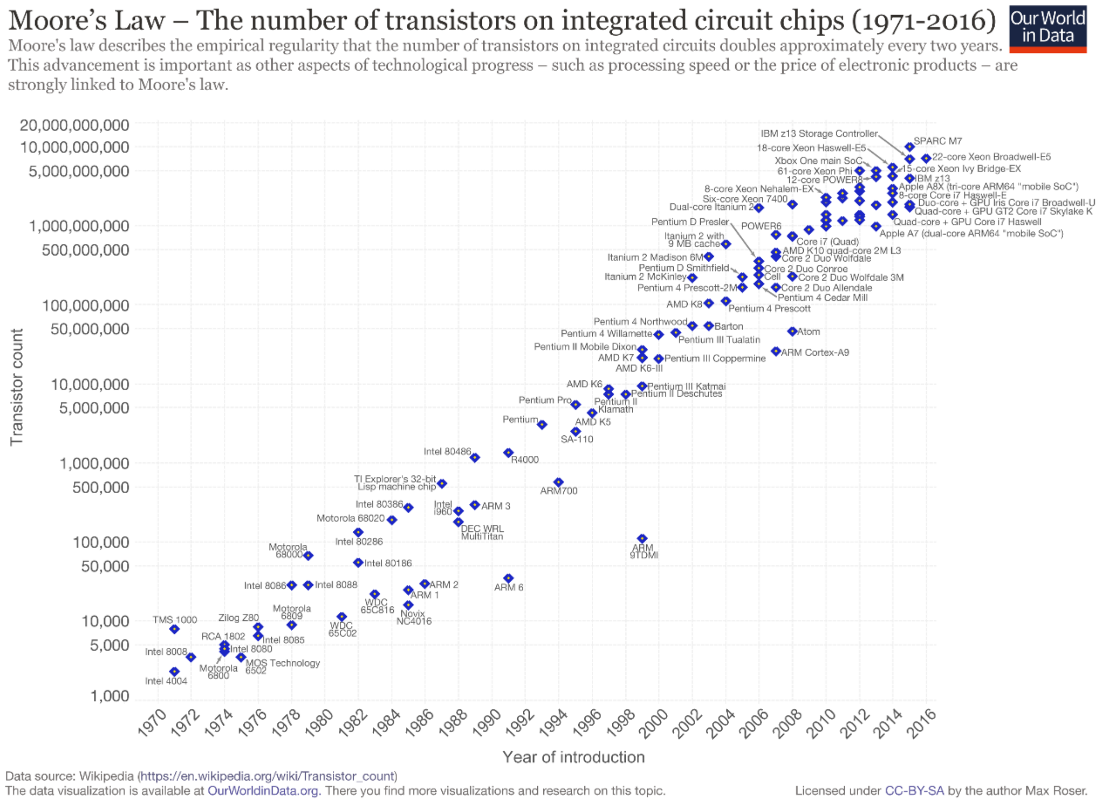
Relentless march of the information technology over the last 50+ years is hitting physical limits

Communication capacity crunch: spectrum congestion



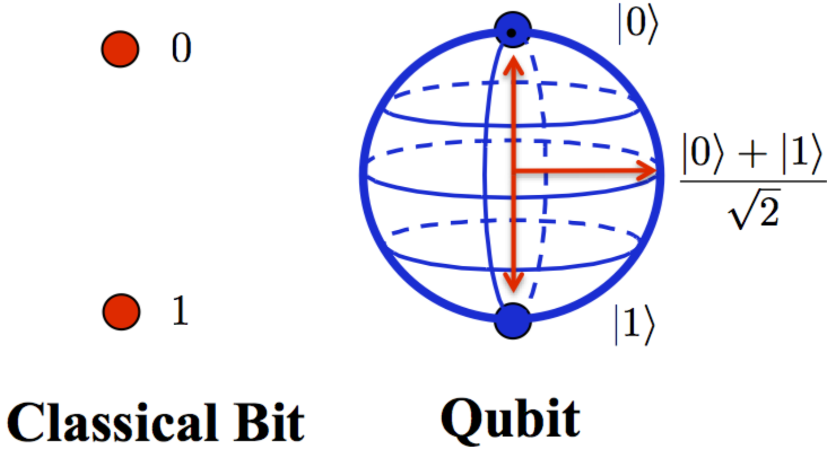
Communication networks beyond the capacity crunch, A. D. Ellis, N. Mac Suibhne, D. Saad and D. N. Payne, Phil. Trans. of the Royal Soc. A, July 2015

Computing capacity crunch: (slow) demise of Moore's law



Challenges Bring Opportunities (Exciting Times for Scientists and Engineers)

Quantum computing: Bits to qubits



Source: towardsdatascience.com

High-Band Communication: Millimeter-wave (mmW) and higher frequencies

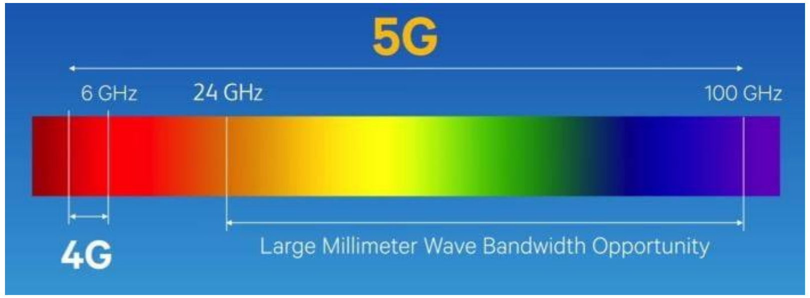
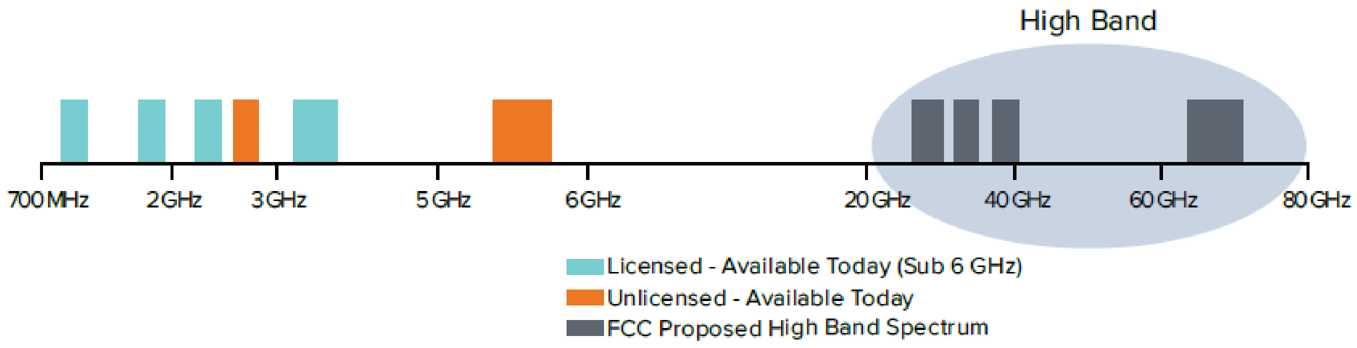


Image courtesy of Qualcomm



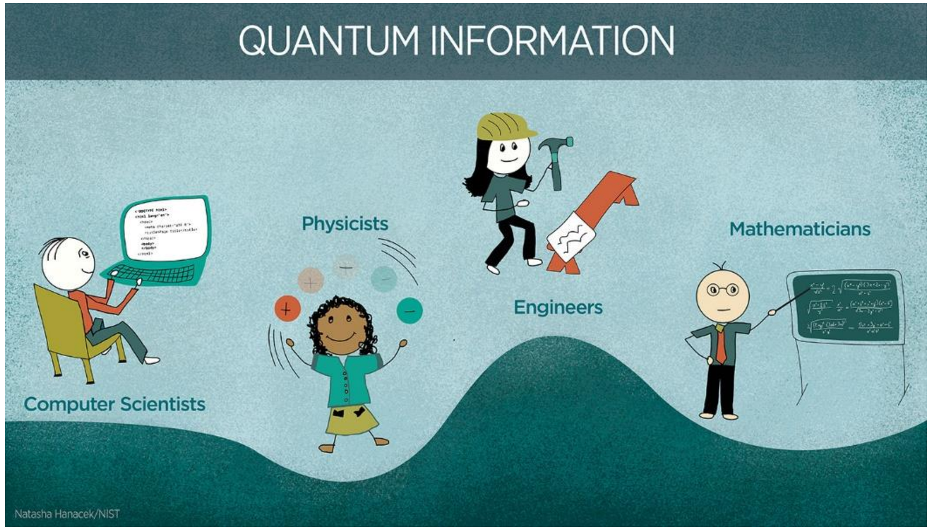
Source: CTIA-5G white paper

Emerging Information Science and Technologies: Key Common Attributes

- Cross-Disciplinary Research
  - Signal processing, communication, networking, hardware, circuits and antenna
  - Physics, math, engineering, computer science
- Experimental testbed development
  - Microcosm of research & technology challenges; workforce training
- Machine learning and artificial intelligence techniques
  - A thoughtful marriage of ML/AI and IS&T would not only benefit IS&T but also benefit ML/AI in terms of explainable/understandable AI
- Optical and photonic principles, techniques and technologies
  - Wireless at higher frequencies (and larger bandwidths)optical; electro-optical methods
  - Microwave and photonic techniques key to quantum information science and engineering

Cross-Disciplinary
Research & Technology Development

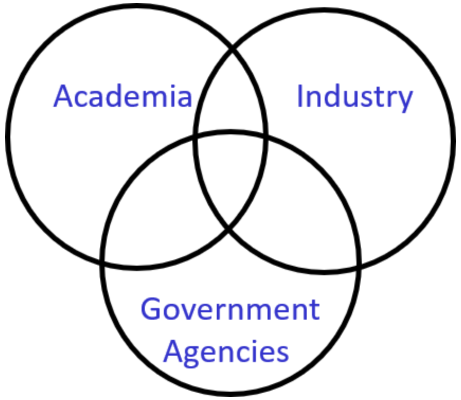
Quantum Information Science and Engineering
QISE

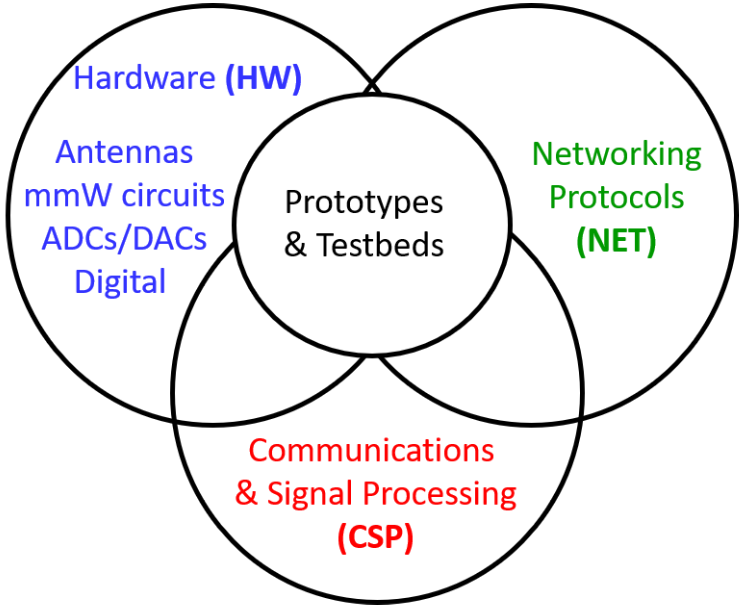


NIST

https://www.nist.gov/topics/quantum-information-science

mmW Wireless
NSF Research Coordination Network





Goal: Cross-fertilization of ideas to guide and accelerate mmW research, innovation and technology development

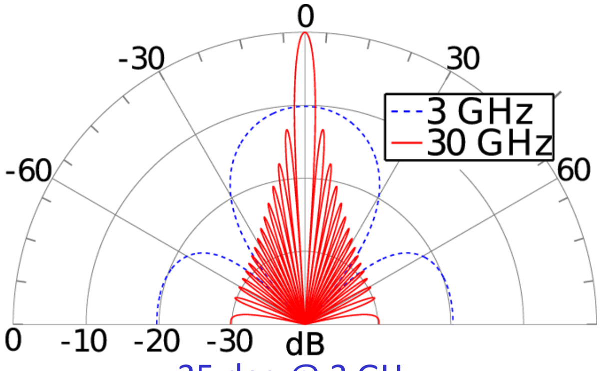
Main takeaway: The key research challenges are at the interfaces: HW-CSP, CSP-NET

https://mmwrcn.ece.wisc.edu/

Two Physical Advantages of mmW

Large bandwidth & narrow beams

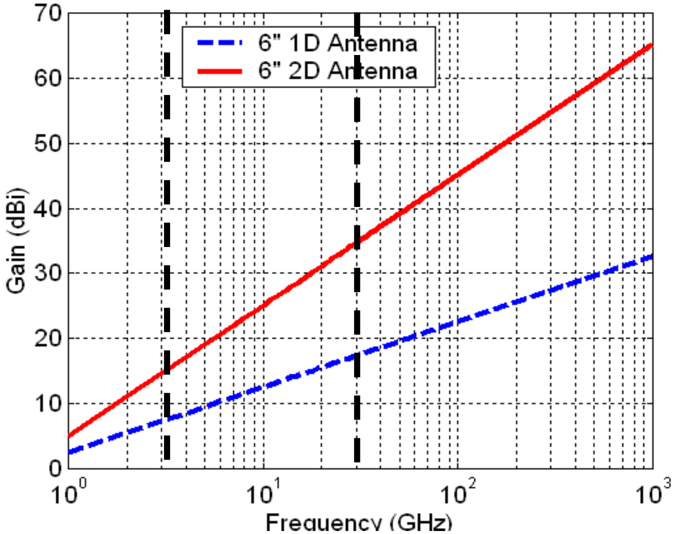
6” x 6” access point (AP) antenna array: 9 elements @3GHz vs 6000 elements @80GHz



35 deg @ 3 GHz

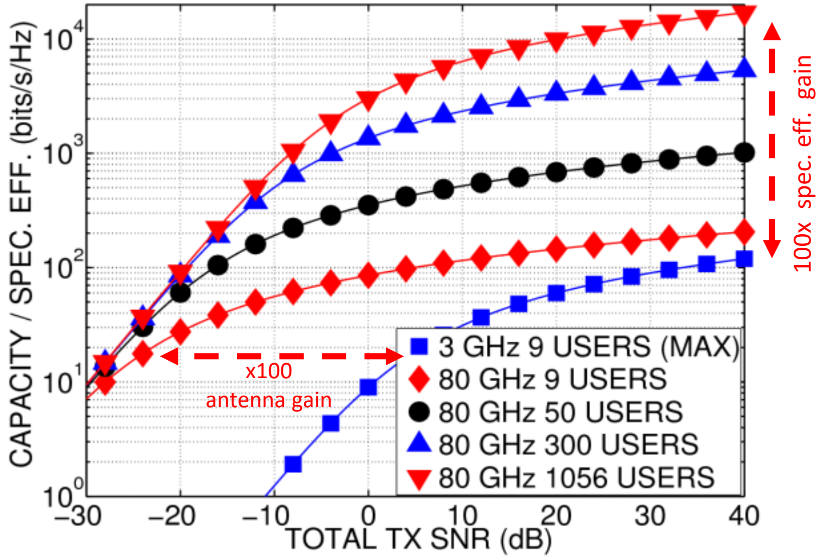
4 deg @ 30 GHz

15dBi @ 3GHz 35dBi @ 30GHz



Potential of beamspace multiplexing

Power & Spec. Eff. Gains over 4G



> 100X gains in power and & spectral efficiency

Key Operational Functionality: Multibeam steering & data multiplexing

Key Challenge: Hardware Complexity & Comp. Complexity (# T/R chains)

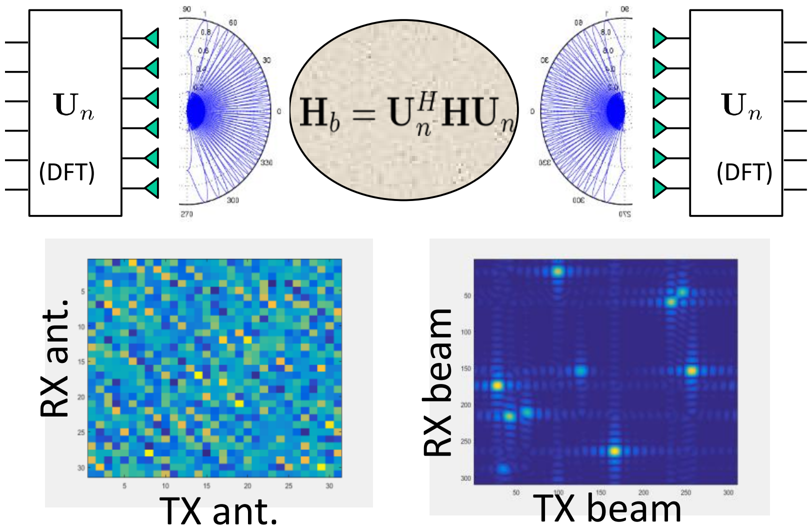
Conceptual and Analytical Framework: Beamspace MIMO

Beamspace Channel Sparsity

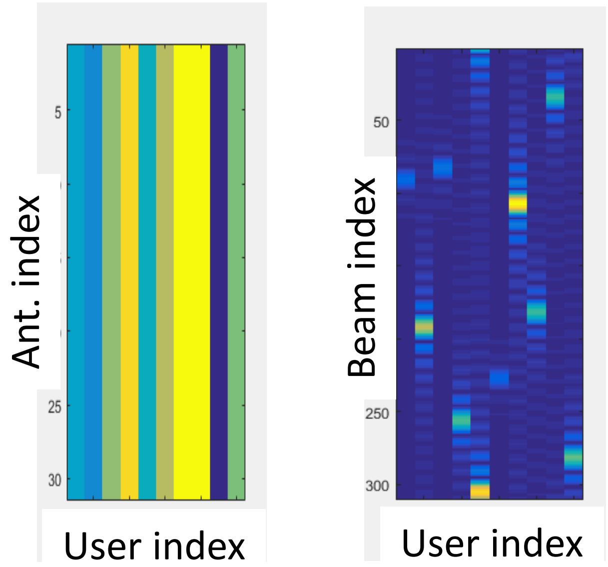
mmW propagation X-tics

- Directional, quasi-optical
- Predominantly line-of-sight
- Single-bounce multipath
- Beamspace sparsity

Point-to-multipoint MIMO link



Point-to-multipoint multiuser MIMO link



high *(n)*-dim. spatial signal space

low *(p)*-dim. comm. subspace

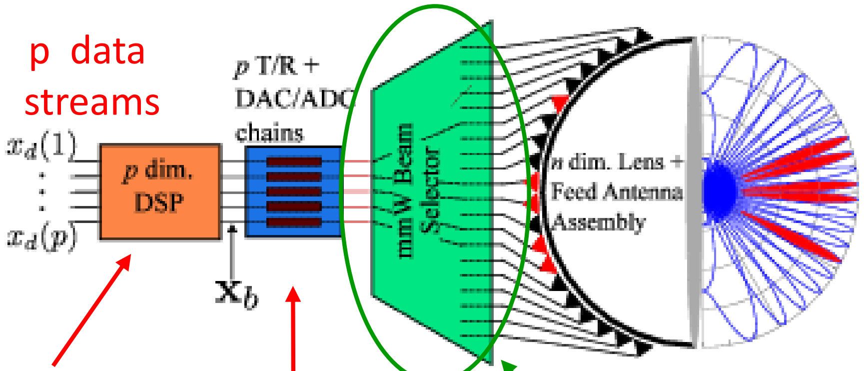
How to access the *p* active beams with the lowest - *O(p)* - transceiver complexity?

(AS & NB Allerton '10; Pi & Khan '11; Rappaport et. al, '13)

Hybrid Analog-Digital Beamforming

Lens Array Hybrid Architecture

p data streams



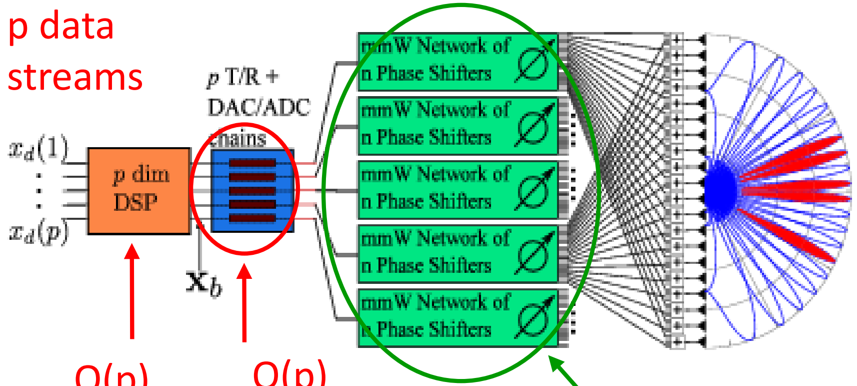
Comp. Complexity: n → p dim. matrix ops

Hardware Complexity: n → p RF chains

p → n Beam selector (switching) network

Phased Array Hybrid Architecture

p data streams

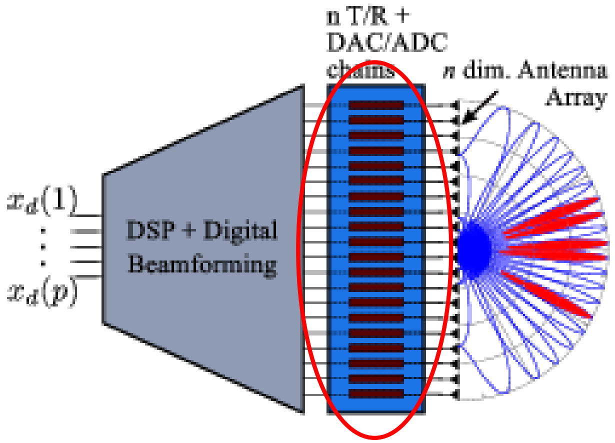


O(p) comp. complexity

O(p) T/R chains

Phase Shifter **(np)** + Combiner Network

Digital Beamforming Architecture



n T/R chains: prohibitive hardware + comp. complexity

$N_{RF} = 1$: Analog beamforming

$N_{RF} = n$: Digital beamforming

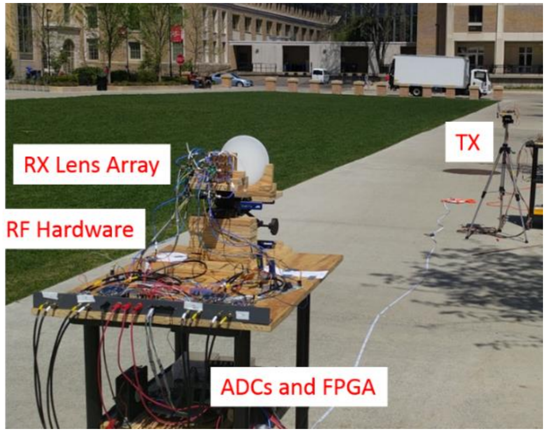
$1 < N_{RF} < n$: Hybrid beamforming

(RH et al., JSTSP 2017)

28 GHz Multi-beam CAP-MIMO Testbed (HW-CSP-NET)

P2MP Link

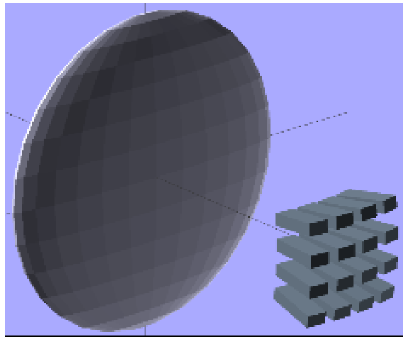
P2P Link

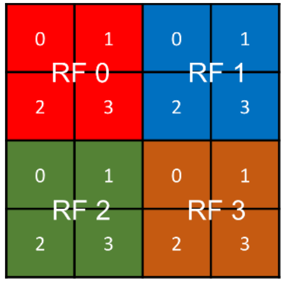


Microcosm of technical challenges

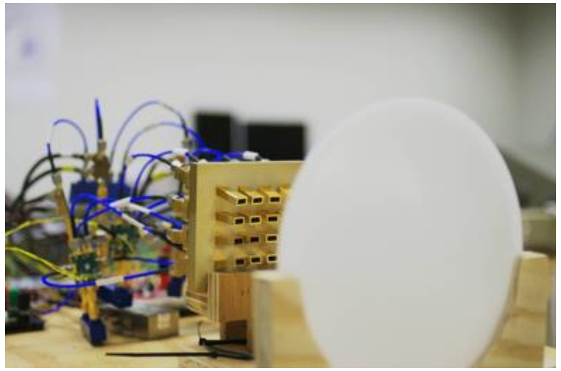
Equivalent to 600-element conventional array!
Beamwidth=4 deg

6” Lens with 16-feed Array





1-4 switch for each T/R chain



Features

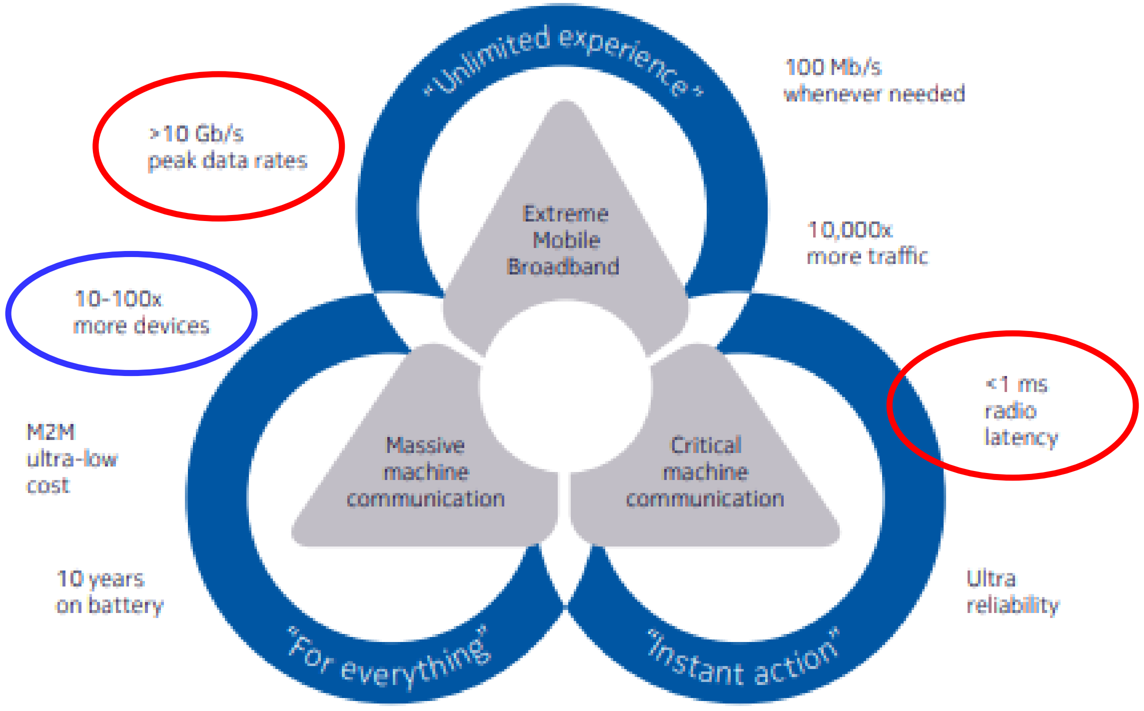
- **Unmatched 4-beam steering & data multiplexing**
- RF BW: 1 GHz, Symbol rate: 370 MS/s -1 GS/s
- Fully discrete mmW hardware
- FPGA-based backend DSP

Use cases

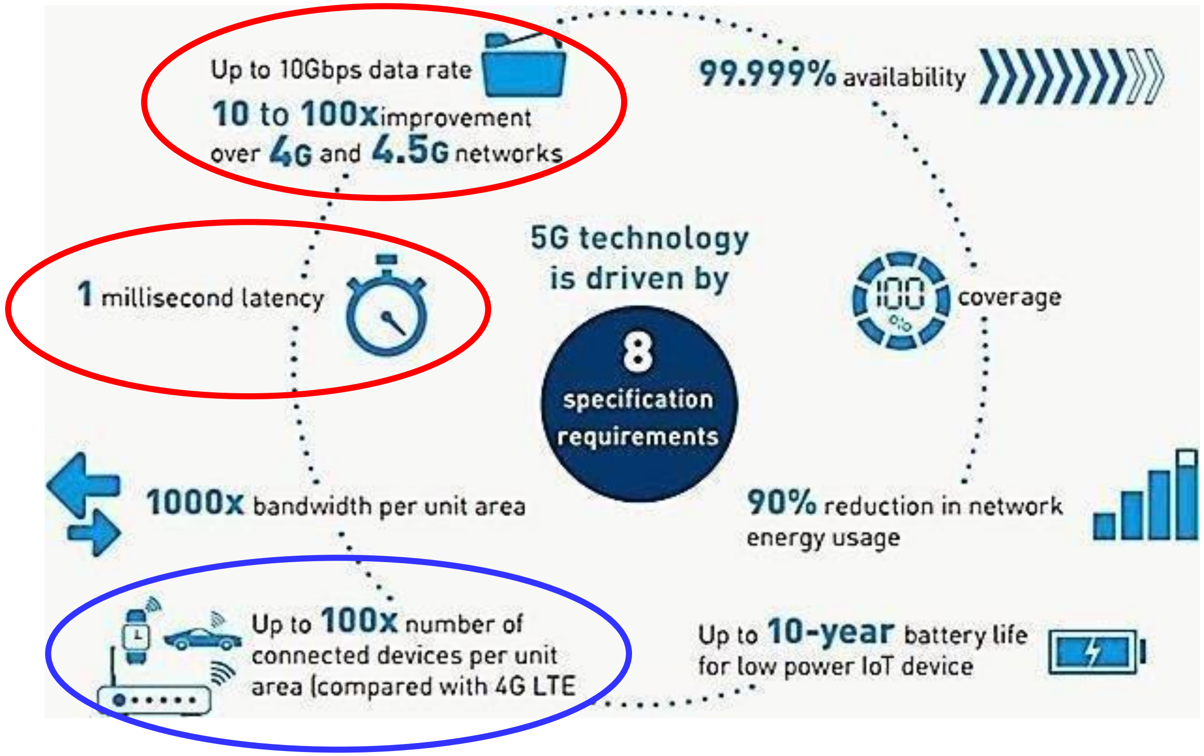
- Real-time testing of PHY-MAC protocols
- Multi-beam channel measurements
- Scaled-up testbed network

(JB, JH, AS, 2016 Globecom wkshop, 5G Emerg. Tech.; AS, CH, YZ, mmNets 2017)

5G Wireless: Key Use Cases and Operational Parameters



nokia

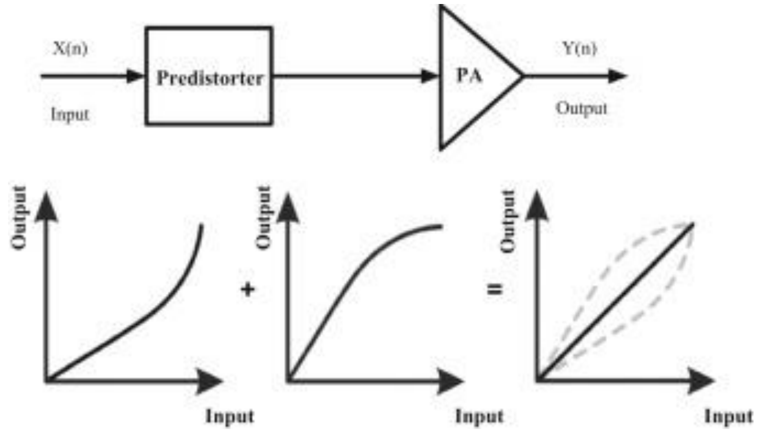


Analyzing 5G: Prospects of Future Technological Advancements in Mobile - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Requirements-of-5G-7_fig2_324941597 [accessed 10 Feb, 2019]

Stringent operational requirements drive x-disciplinary research

e.g. multi-Gigabits/s rates & **millisecond latency**

CSP-HW Challenges



- **Energy-performance-complexity tradeoffs**
- Analog vs Digital Signal Processing:
  - Hybrid beamforming & interference nulling
  - Hybrid temporal signaling/filtering (OFDM)
- PA efficiency – digital predistortion
- Non-ideal device characteristics over large bandwidth:
  - Non-flat frequency response; I/Q mismatch
- New models needed that incorporate non-idealities
- Technology for RF integration (Si, GaAs, InP, GaN, …)
- New methodologies for Over-the-Air (OTA) testing

CSP-NET Challenges

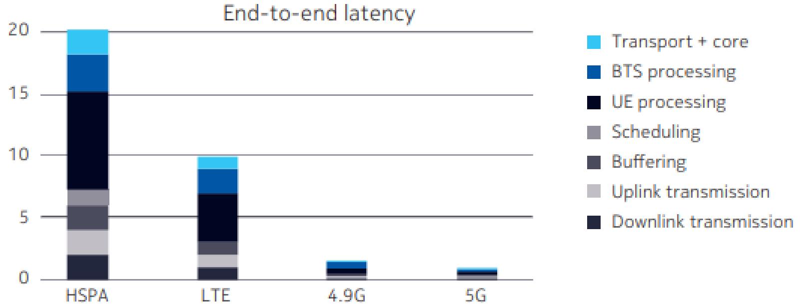


Figure 2. Round trip time evolution from 3G to 5G.

nokia

	HSPA	LTE	4.9G	5G
Downlink transmission	2 ms	1 ms	0.14 ms	0.125 ms
Uplink transmission	2 ms	1 ms	0.14 ms	0.125 ms
Frame alignment	2 ms	1 ms	0.14 ms	0.125 ms
Scheduling	1.3 ms[2]	0-18 ms[1]	Pre-scheduled	Contention based and pre-scheduled
UE processing	8 ms	4 ms	0.50 ms	0.250 ms
BTS processing	3 ms	2 ms	0.50 ms	0.250 ms
Transport + core	2 ms (including RNC)	1 ms	0.1 ms (local content)	0.1 ms (local content)
Total	20 ms	10 – 28 ms	1.5 ms	1.0 ms

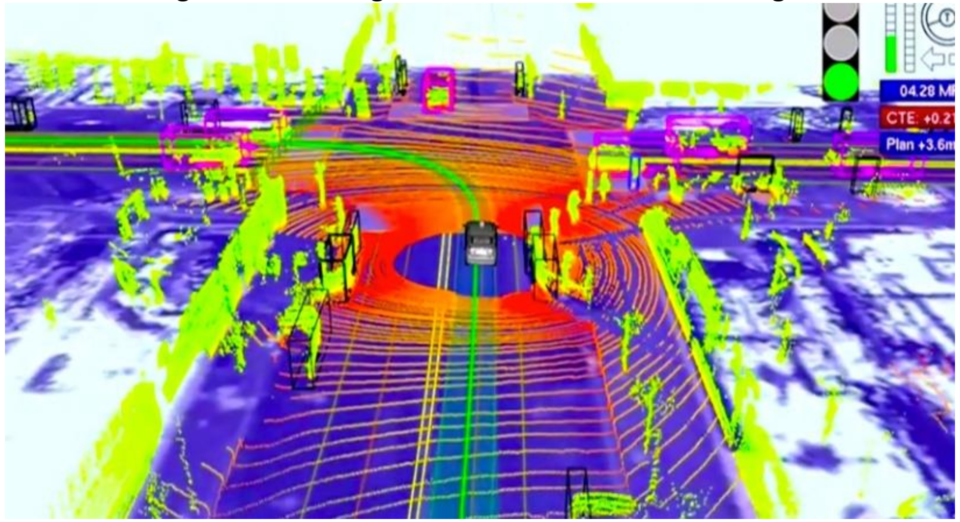
[1] Scheduling period + capacity request + scheduling decision + PDCCH signaling. [2] Just Shared Control Channel (SCCH)

- PHY-MAC and higher layer protocols for exploiting wideband multi-beamforming
- Gb/s speeds and sub-millisecond latency
  - Edge & cloud computing
  - Continuous network monitoring & adaptation
- Accurate network models

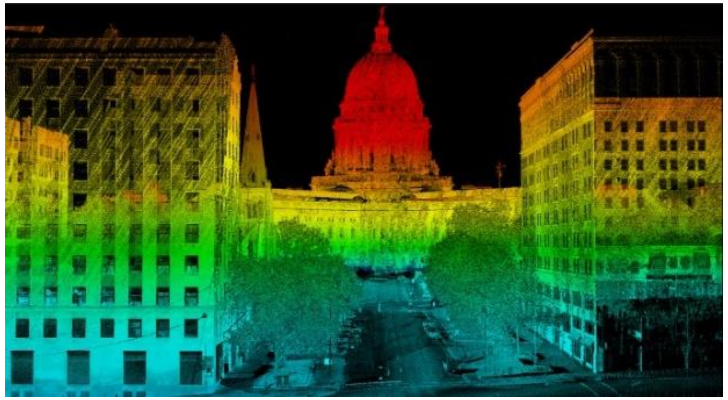
Measurements to Modeling to Network Simulators & Emulators (HW-CSP-NET)

- **Need: Accurate** performance prediction prior to deployment
- Current network models (e.g., ns-3) are limited
  - Need: Multi-beam PHY capabilities
- Current mmW channel models limited
  - Sounders with limited capability
  - Need: models for beam dynamics & blocking
- **Opportunity:** Measurements + computational power
  - Multi-beam sounders & measurements
  - Ray tracing (combined with LIDAR, e.g.)
  - → accurate channel models
- → Accurate Network Simulators & Emulators

Google's self-driving car use lidar to create 3D images



Sebastian Thrun & Chris Urmson/Google (IEEE Spectrum)



(Xconfluence)

Opportunity: machine learning + data analytics

Channel Sounders (HW) → Channel Modeling, Simulators & Emulators (HW-CSP) → Network Simulators & Emulators (CSP-NET)

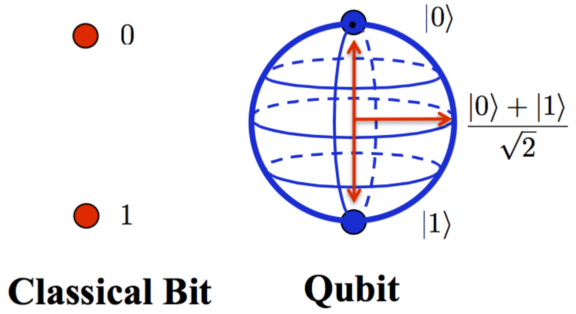
5G channel model alliance, NYU, U. Padova, Bristol, NCSU, CRC, UW, NIST, SIRADEL ….

Quantum Information Science and Engineering (QISE)

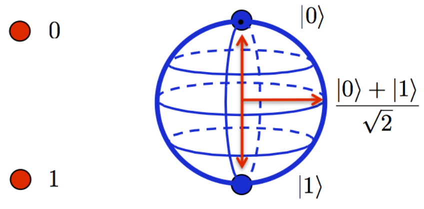
Exploiting the unique (and non-intuitive) aspects of quantum physics to develop new technologies for *sensing, generation, processing and communication of information*

Three key aspects of quantum physics underlying QISE:

- Superposition
- Entanglement (spooky action at a distance)
- Interference (in phase space to ***shape*** the ***probabilities*** of different outcomes)



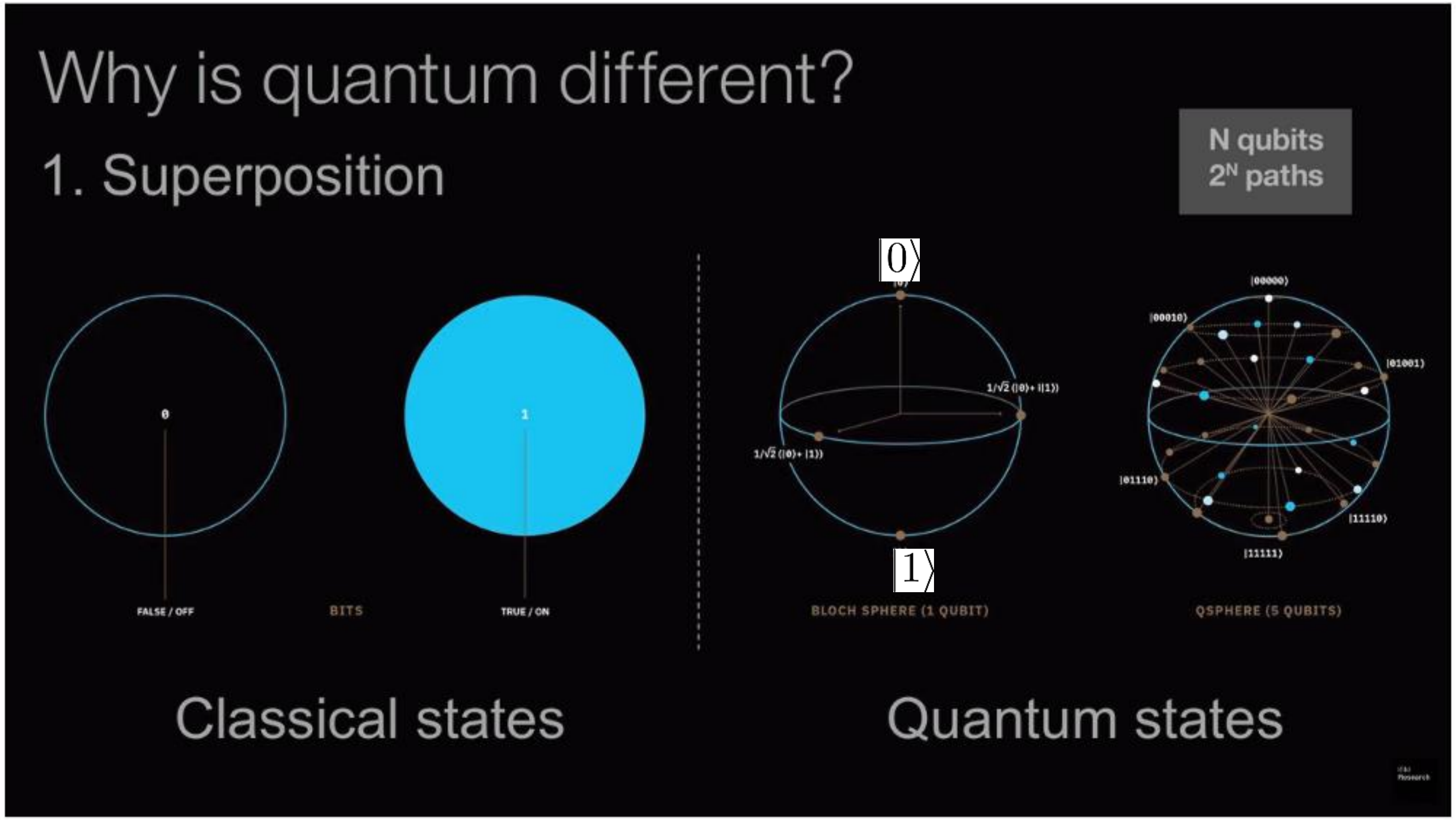
QISE Principle 1: Superposition



Classical Bit **Qubit**

one qubit: $|\psi\rangle = \alpha_0|0\rangle > +\alpha_1|1\rangle$ 2-dim. system

n qubits: $|\psi_1\rangle \otimes |\psi_2\rangle \cdots \otimes |\psi_n\rangle$ 2^n-dim. tensor product space



n-dim quantum system

wavefunction

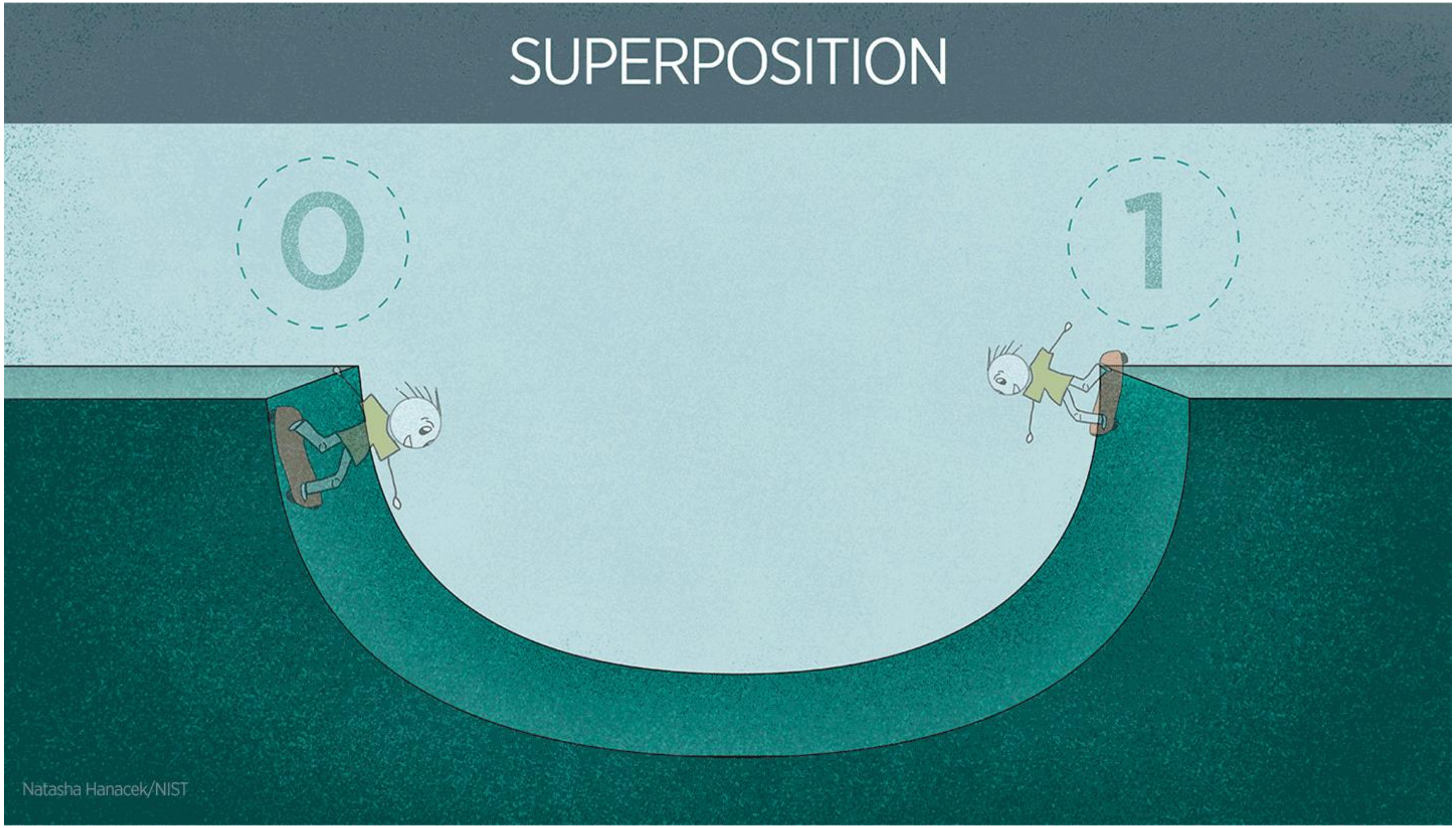
$$|\psi\rangle = \sum_{i=1}^{n} \alpha_i |i\rangle$$

Measurement $\rightarrow$ the system wavefunction $|\psi\rangle$ collapses into state i with probability $p(i) = |\alpha_i|^2$

$$\sum_{i=1}^{n} |\alpha_i|^2 = \sum_{i=1}^{n} p(i) = 1$$

Towards Data Science - Towardsdatascience.com

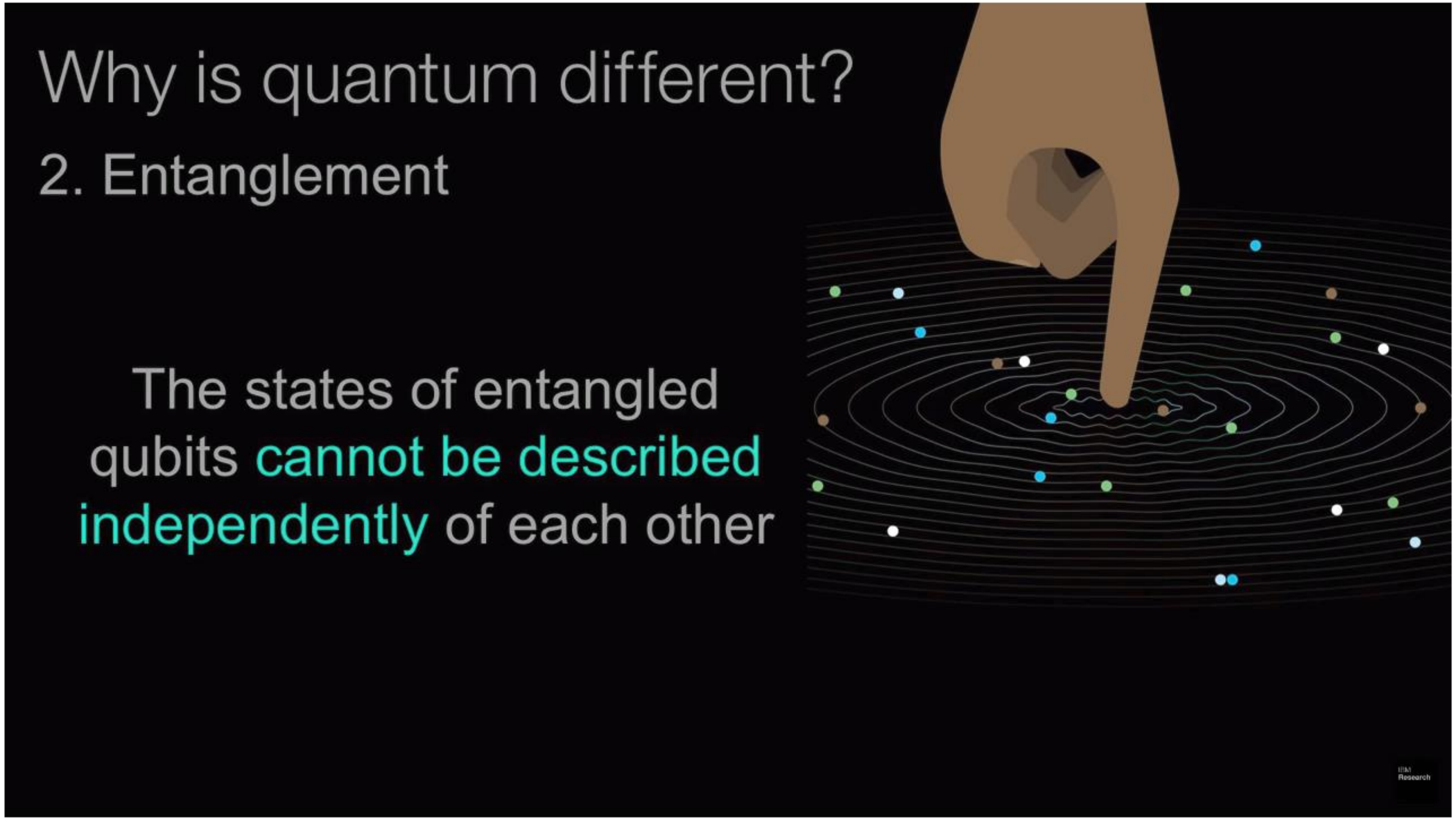
Superposition in Action



Measurement/observation collapses the wavefunction into one definite state

https://www.nist.gov/topics/quantum-information-science

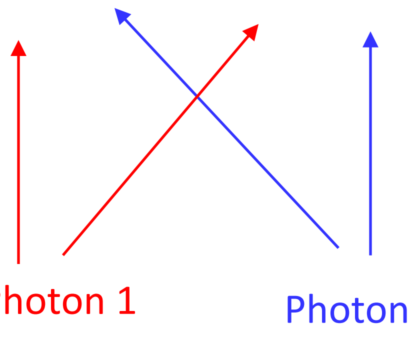
QISE principle # 2: Entanglement



Towards Data Science - Towardsdatascience.com

Wavefunction of two entangled photons

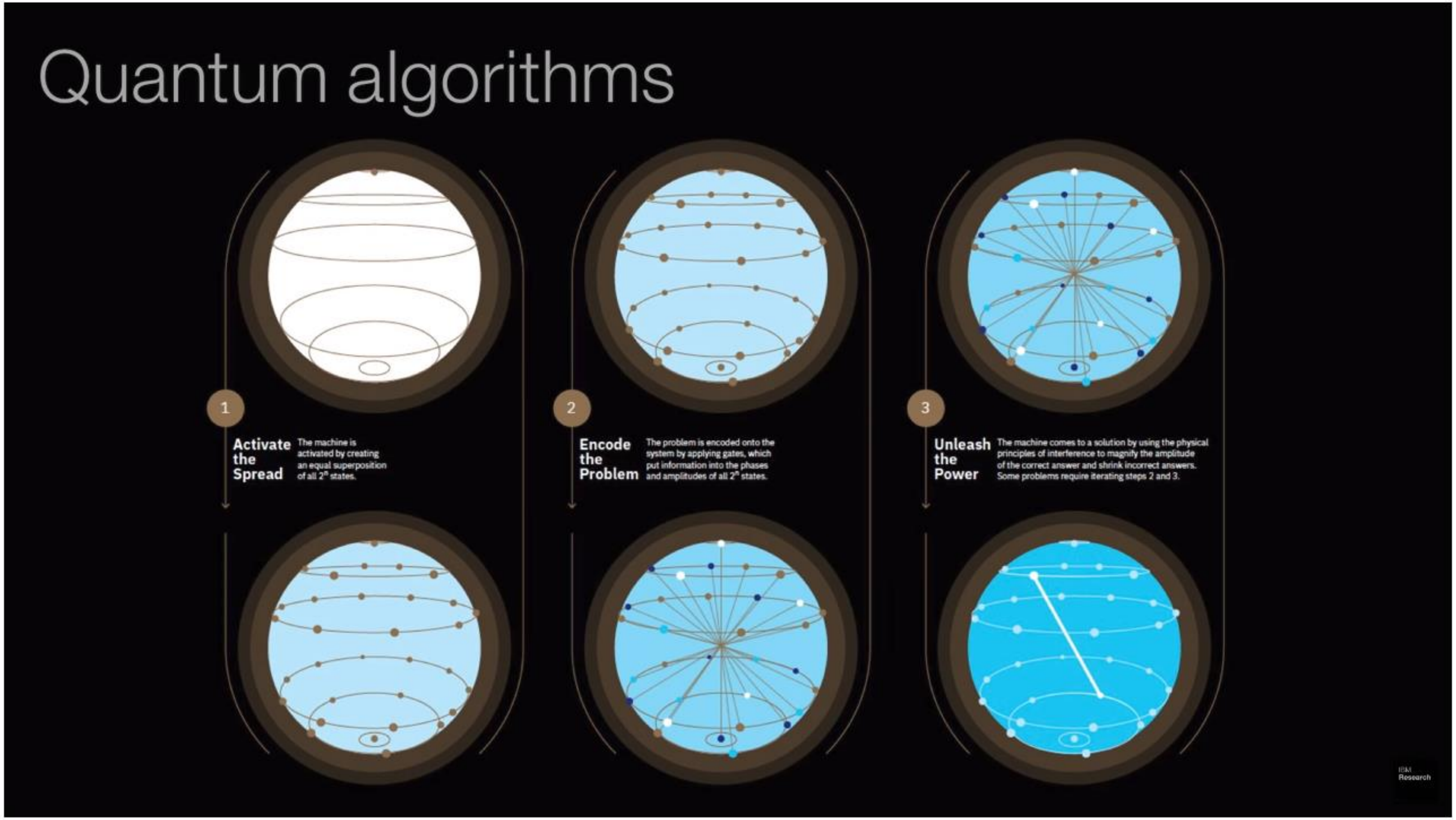
$$\frac{1}{\sqrt{2}}\left[|0\rangle|0\rangle + |1\rangle|1\rangle\right]$$



- Super-dense coding
- Secure communication
- Quantum computing
- Enhanced measurement

Spooky action at a distance

Quantum Algorithms

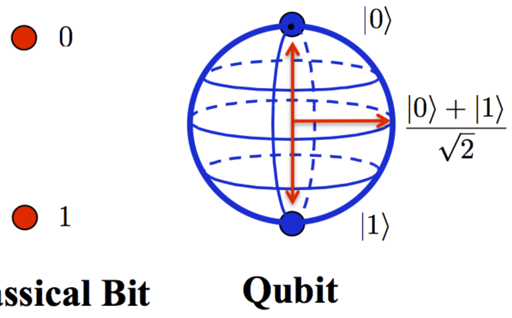


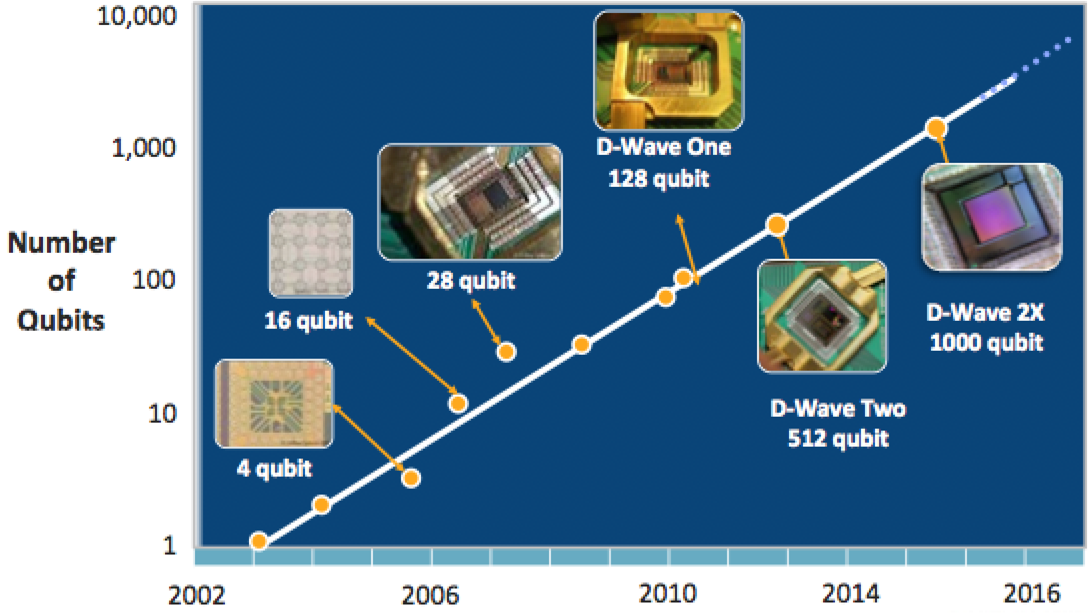
IBM Research

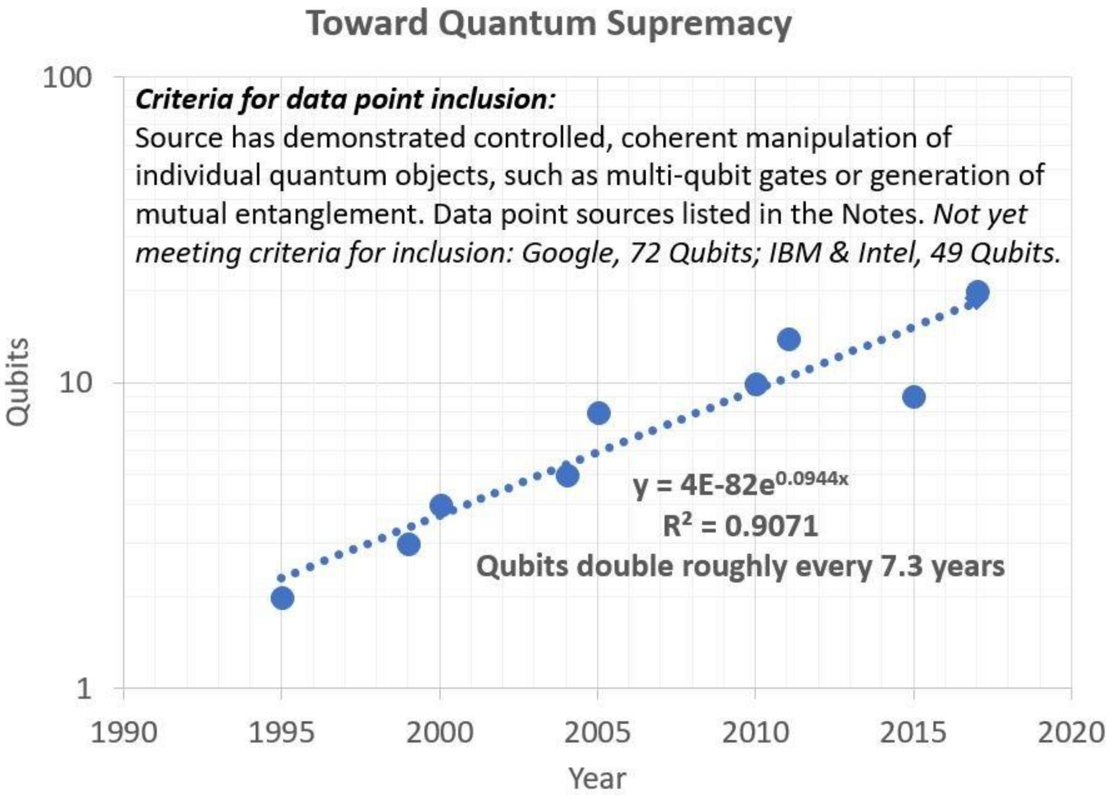
Quantum Computing

Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical – Richard Feynman (1981)

1994 – Shor's algorithm

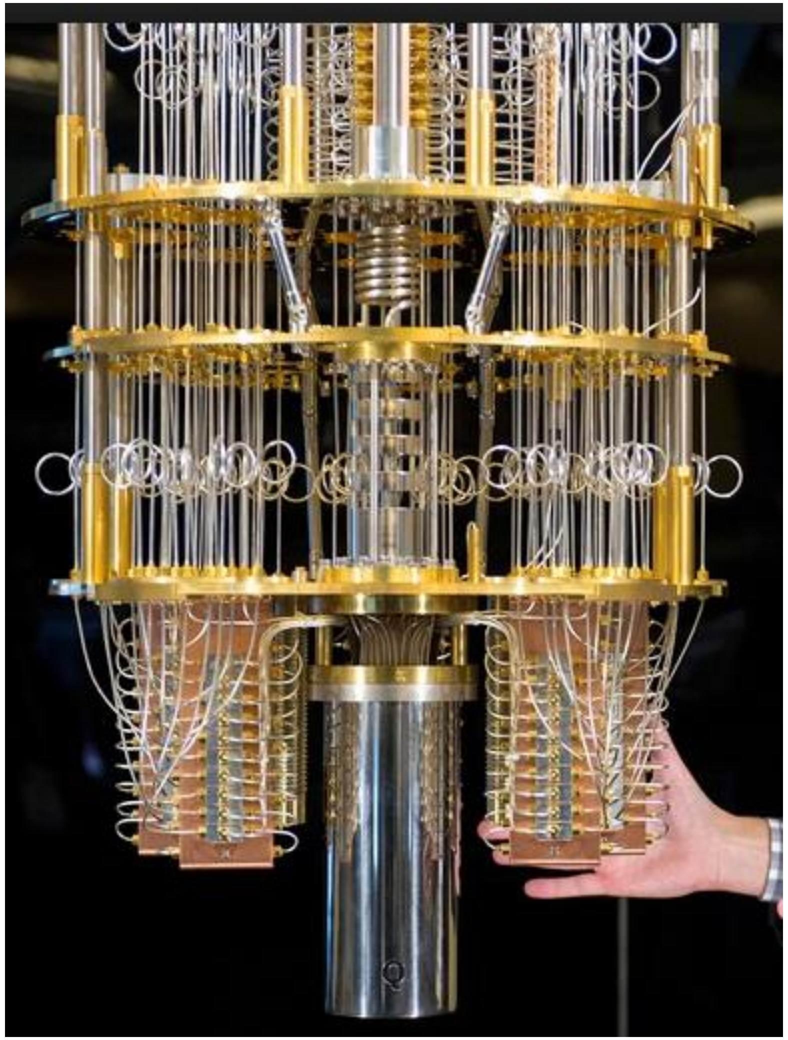




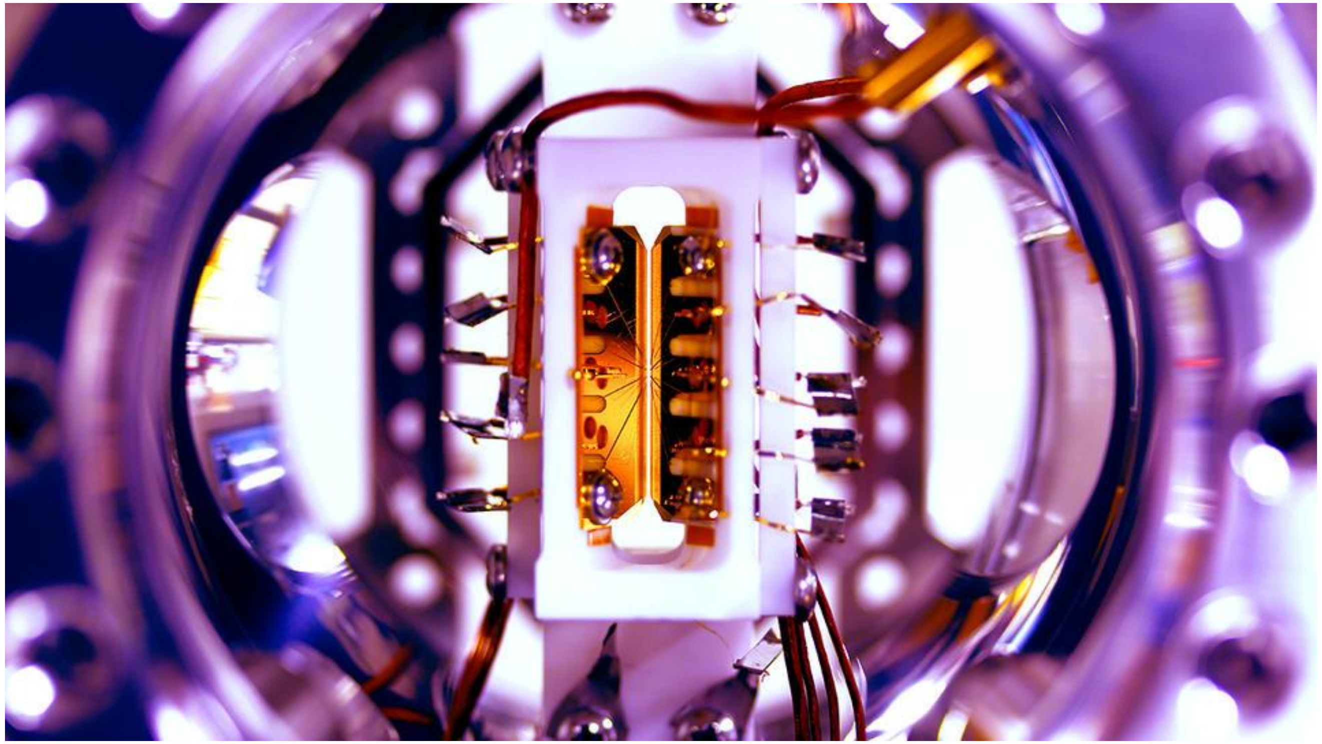


Futuregrasp, LLC

Two Leading Qubit Technologies



Superconducting qubit/IBM Q



Photonic Ion Traps/IonQ

RF, microwave and/or optical signals play a key role in the control and manipulation of qubits

The Bigger Picture of QISE

- Quantum Computation
- Quantum Communication
- Quantum Sensing
- Quantum Simulation

Fathers of Quantum
Planck, Bohr, Heisenberg, Shrodinger

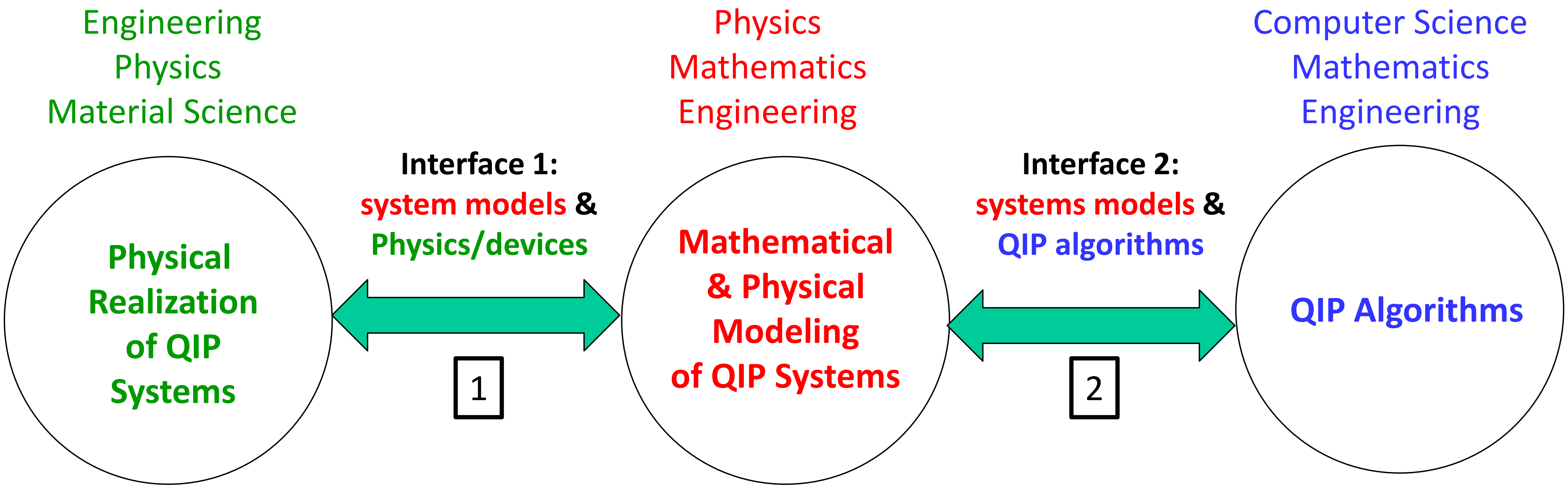
Pan Jianwei

Opportunities for Signal Processing, Communications and Information Science Communities

- **Encoding, entanglement, decoding** – intrinsically signal processing/communications operations
  - **Encoding (TX):** modulation and coding of information into qubits
  - **Decoding (RX):** measurements and processing to recover transmitted qubits
  - **Entanglement**: coupling between input and output Hilbert (vectors) spaces
  - **System model:** interacting tensor product (input x output) Hilbert spaces

- **A Vital Role for Signal Processing, Communications and Information Science Communities**
  - **Mathematical modeling and analysis of Quantum Information Processing (QIP) Systems**
  - Input Qubits, Output Qubits, Quantum Channels

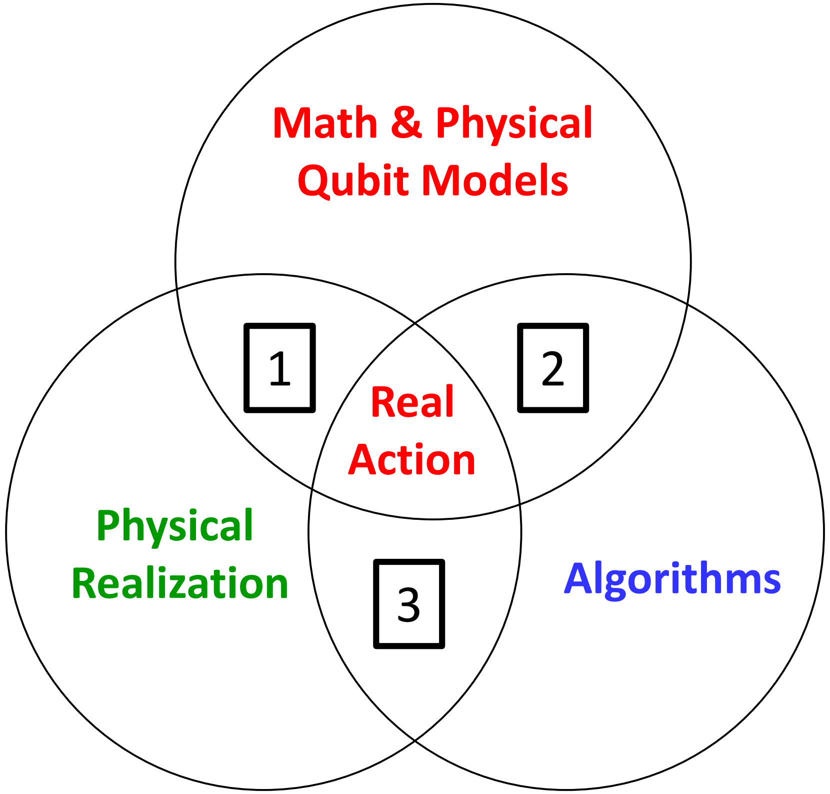
Cross-Disciplinary Challenges & Opportunities for the Fearless (and Inspired)



*If you think you understand **quantum** mechanics, you don't understand **quantum** mechanics* – Feynman/Bohr

Serendipitous (Random Walk) Innovation

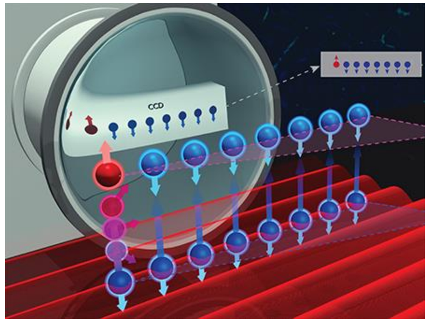
Future QISE Research Framework: Cross-Disciplinary & Convergent



Accelerated (Directed) Innovation

NSF’s 10 Big Ideas

Harnessing the Data Revolution

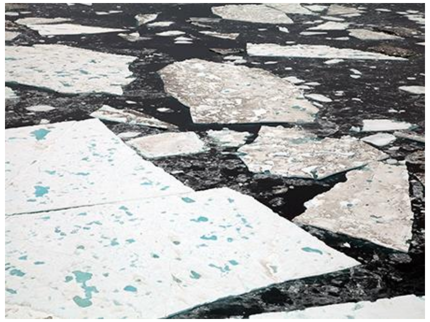


The Quantum Leap: Leading the Next Quantum Revolution

The Future of Work at the Human-Technology Frontier

Mid-scale Infrastructure

Understanding the Rules of Life: Predicting Phenotype

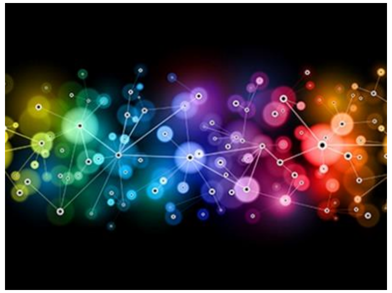


Navigating the New Arctic

Windows on the Universe: The Era of Multi-messenger Astrophysics

NSF INCLUDES: Enhancing STEM through Diversity and Inclusion

NSF 2026: Seeding Innovation



Growing Convergence Research at NSF

Concluding Remarks

- QISE is a major national (and international) priority in science and technology
- The opportunities are enormous and the challenges equally daunting
- **Necessitate a truly cross-disciplinary approach**
  - Signal processing, communication, networking, hardware, circuits and antenna
  - Physics, math, engineering, computer science
  - We all need to roll up our sleeves and get our hands dirty!
- Unique x-disciplinary opportunities for signal processors, communication engineers, information scientists & engineers, computer scientists & engineers
- **Design and development of prototypes and testbeds**
  - A microcosm of technical challenges
  - An unmatched training opportunity
- **Need a fresh approach for research collaboration and coordination**
  - Academia, industry, and national labs

Accelerated Discovery & Innovation