IBM Research: Science & Technology and Semiconductor Technology Research Overview

Outline

- **IBM Research Division - quick overview**

- **Semiconductor Technology Research (STR)**
  - Business Model
  - Roadmap
  - Collaboration

- **Science & Technology (S&T)**
  - Mission
  - Infrastructure
  - Research Programs
  - Collaboration

IBM Research Worldwide: Established 1945

Twelve Labs with Over 3,000 Researchers Around The World

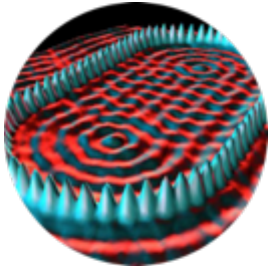
Science & Solution Strategy Labs

Labs Opened Since 2011

A Diversity of Disciplines

From Atoms to Service Science

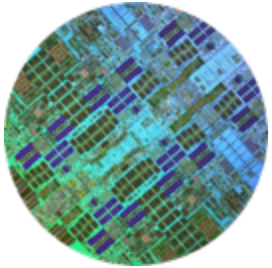
Physics



Chemistry

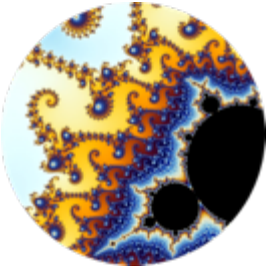
Materials Science

Electrical Engineering



Computer Sci.

Mathematical Sci.

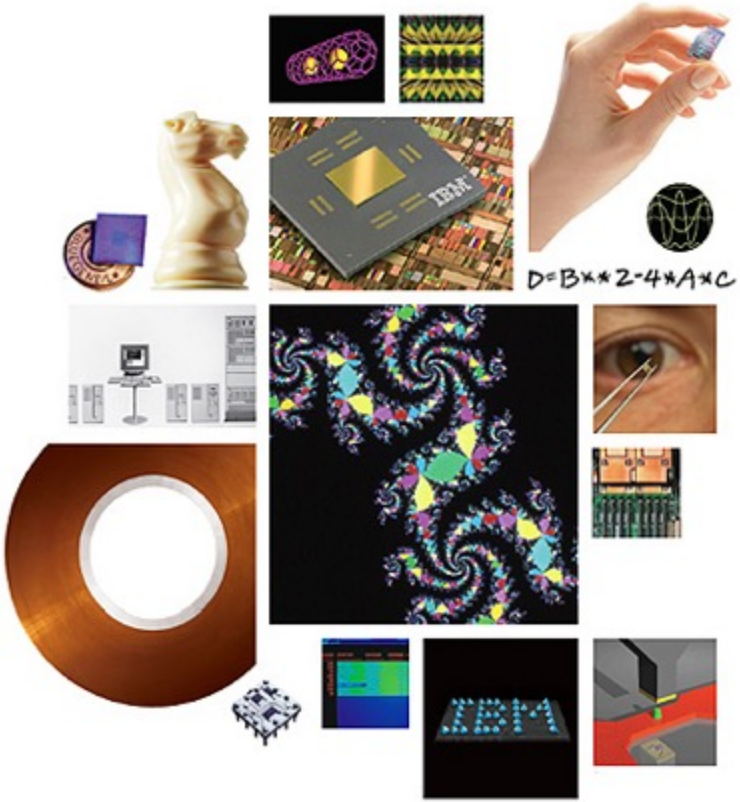


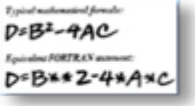
Behavioral Sci.

Service Science

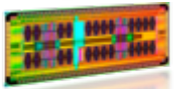
SSME

A Legacy of World-Class Research For 70 Years





2016 Quantum Computing in the Cloud
2015 Quantum Computing: Error Detection
2015 23rd Consecutive Year of Patent Leadership
2012 Atomic Imaging (Charge Distribution, Bond Order)
2011 Watson System
2009 Nanoscale Magnetic Resonance Imaging (MRI)
2008 World's First Petaflop Supercomputer
2007 Web-scale Mining
2005 Cell Broadband Engine
2004 Blue Gene/L
2003 5 Stage Carbon Nanotube Ring Oscillator
2000 Java Performance
1998 Silicon on Insulator (SOI)
1997 Copper Interconnect Wiring
1997 Deep Blue
1994 Design Patterns
1994 Silicon Germanium (SiGe)
1990 Chemically Amplified Photoresists
1987 High-Temperature Superconductivity (Nobel Prize)
1986 Scanning Tunneling Microscope (Nobel Prize)
1980 Reduced Instruction Set Computing (RISC)
1979 Thin Film Recording Heads
1973 Winchester Disk Drive
1971 Speech Recognition
1970 Relational Database
1967 Fractals
1966 One-Device Memory Cell
1957 FORTRAN
1956 Random Access Memory Accounting Machine (RAMAC)

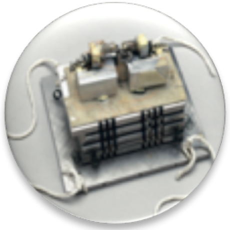


A Culture of Innovation – External Recognition

6 Nobel Laureates

1 Millennium Technology Prize

2 Kavli Prizes



6 Turing Awards

10 US National Medals of Technology

1 Emmy

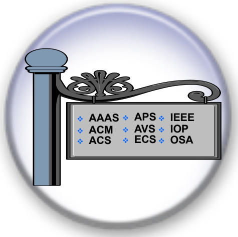
2 U.S. Presidential Medals of Freedom

5 US National Medals of Science

22 Members in National Academy of Sciences

64 Members in National Academy of Engineering

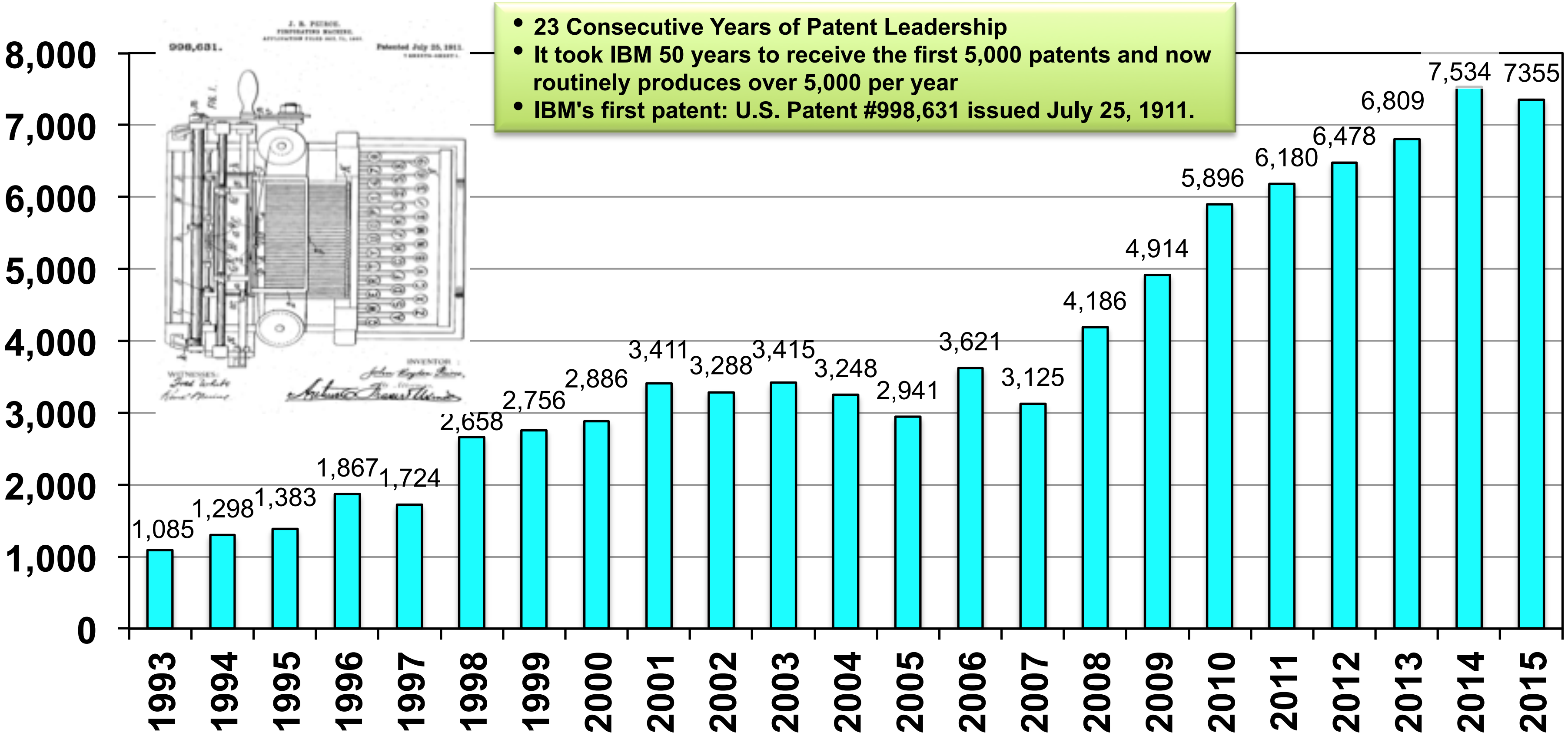
> 400 Professional Society Fellows



20 Inductees in National Inventors Hall of Fame

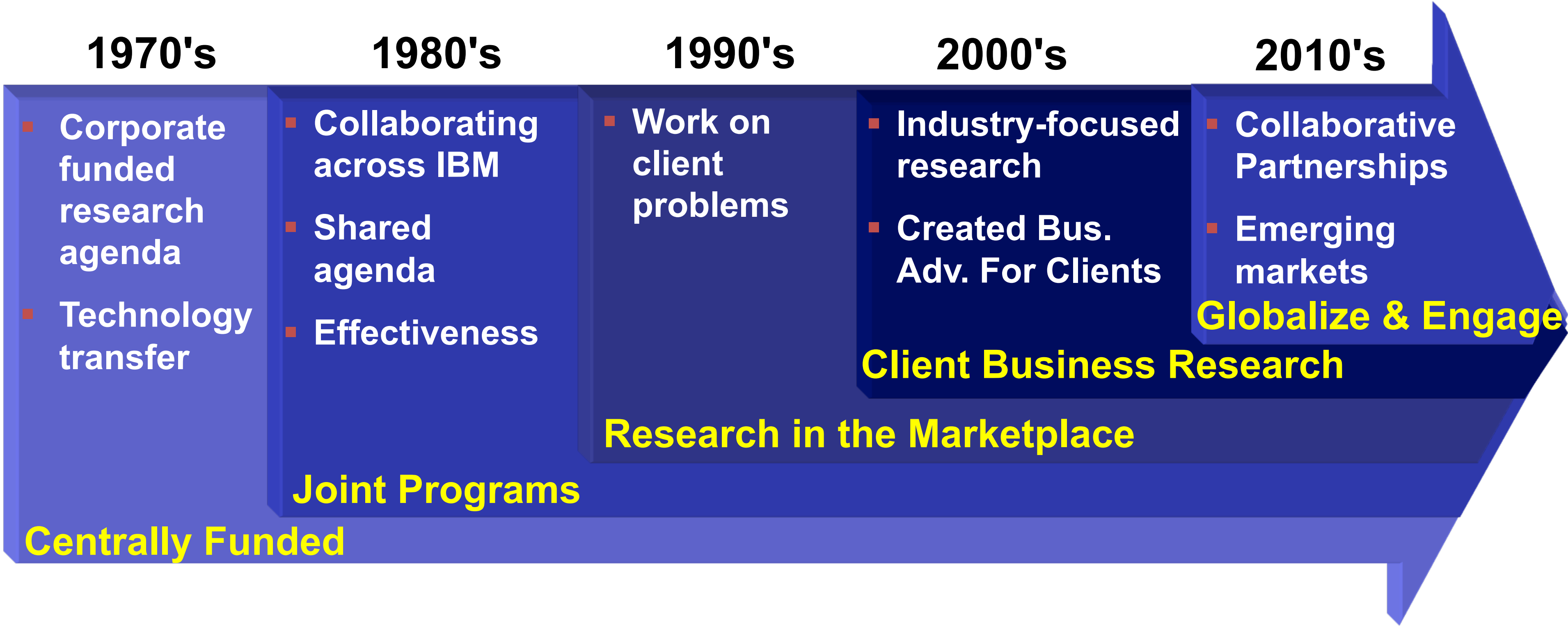
Innovations That Matter Have Enabled an Unprecedented 23 Consecutive Years of IBM Patent Leadership

- 23 Consecutive Years of Patent Leadership
- It took IBM 50 years to receive the first 5,000 patents and now routinely produces over 5,000 per year
- IBM's first patent: U.S. Patent #998,631 issued July 25, 1911.

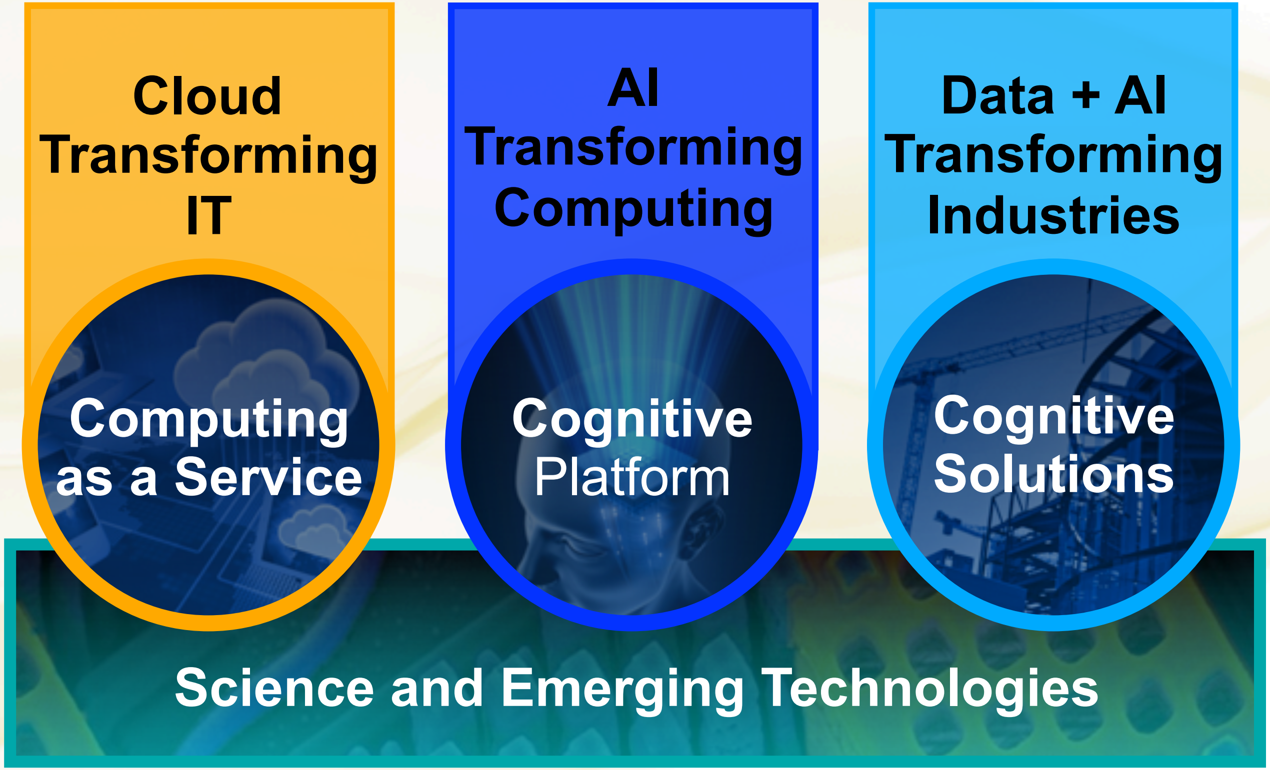


Evolution of IBM Research Business Model

Business Model Evolves as Business Conditions Change In Order for IBM Research to Remain Essential to the IBM Company



IBM Research: Aligned to Growth



IBM Relationship with GlobalFoundries

Acquisition of IBM's Semiconductor Business by GLOBALFOUNDRIES is Completed

Armonk, N.Y. - 01 Jul 2015: IBM (NYSE: IBM) today announced that the acquisition of the company's global commercial semiconductor technology business by GLOBALFOUNDRIES has been completed.

With the closing of this transaction, **GLOBALFOUNDRIES becomes IBM's exclusive semiconductor processor technology provider for the next 10 years**, ensuring a long-term supply of semiconductors for IBM systems. IBM Research will continue its deep focus on fundamental semiconductor and material science research and systems innovation to drive IBM's leadership in mainframe, Power and storage systems as well as future cloud, big data and analytics systems.

"This announcement is the next step in our long-standing relationship with GLOBALFOUNDRIES. IBM continues to invest in systems leadership, innovation and talent for the long-term," said Tom Rosamilia, senior vice president, IBM Systems. "IBM is designing and developing IT systems for the digital era -- including servers, storage and middleware that will empower our clients to drive new workloads and new business models."

IBM expects its unparalleled semiconductor and materials research, which has delivered such breakthroughs as copper chips, silicon germanium and quantum computing research, to continue to advance its capabilities in systems for years to come.

IBM/GF Relationship Is Imperative to Future IBM Systems

GF Must Successfully Manufacture Microprocessors for IBM Mainframes / Systems

IBM is Committed to Hardware *Research & Development*

…let me be clear-we are not exiting hardware. IBM will remain a leader in high-performance and high-end systems, storage and cognitive computing, and we will continue to invest in R&D for advanced semiconductor technology.

Virginia Rometty, IBM CEO
IBM 2013 Annual Report
March 8, 2014

IBM is investing $3 billion to push the limits of chip technology

Cloud and big data applications are placing new challenges on systems, just as the underlying chip technology is facing significant physical scaling limits.

IBM News Room
July 10, 2014

IBM Research Alliance Produces Industry's First 7nm Node Test Chips

Partners with GLOBALFOUNDRIES, Samsung and SUNY Polytech to Clear Path For Next Generation Semiconductors

IBM News Room
July 9, 2015

IBM Semiconductor Technology Research

Mission: Industry Leadership in Semiconductor Technology Research

Lithography Materials
Exploratory Physics
Integrated sensors
Intelligent Machines

mmWave Technology
THz passive imaging

Neuromorphic Sciences
Nano/micro systems for low power
IoT device minaturization
Optical Interconnects

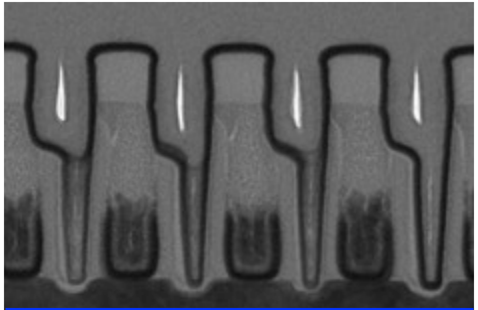
Quantum Computing
Neuromorphic Computing
MRAM & PCM
III-V & Si Photonics
Wearables

Center for Semiconductor Research
10nm / 7nm / Pathfinding
EUV Center of Excellence
New device architectures
III-V, 3DI, MRAM

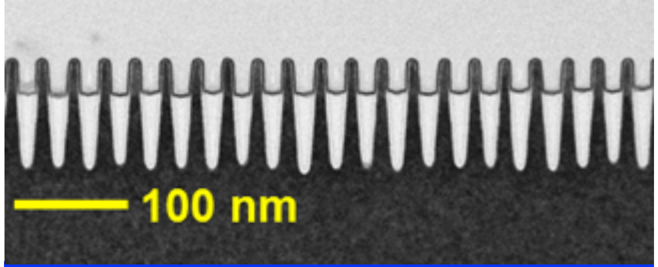
Binnig & Rohrer Nanotechnology Center
III-V & Si Photonics
Low Power technologies
Quantum Technologies
Precision Diagnostics

Industry 1st : IBM Semiconductor Technology Research 7nm Device Demonstration @ Albany with Early R&D Partners

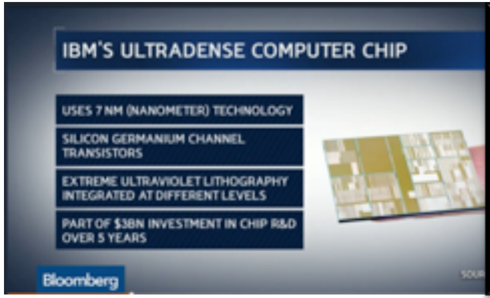
- **Key Features:**
  - Fully Integrated build
  - Sub 50nm gate pitch, 15nm Lpoly
  - Sub 30nm fin pitch, dual channel
  - Sub 40nm BEOL pitch
  - Multiple EUV levels



Sub 50nm gate pitch w/ SA contacts



Sub 30nm pitch, dual channel fins



Will IBM's Ultra-Dense Chip Be A Game Changer?

TECHNOLOGY

IBM Discloses Working Version of a Much Higher-Capacity Chip

By JOHN MARKOFF JULY 9, 2015

The New York Times

IBM's tiniest transistor casts big shadow on Intel

By Pete Carey | pcarey@mercurynews.com

San Jose Mercury News BUSINESS

Moore's Law Lives On: How IBM Chip Pushes the Standard for Computing Power

Jul 10, 2015, 9:45 AM ET

By ALYSSA NEWCOMB via GOOD MORNING AMERICA

abc NEWS

THE BEST THING ABOUT IBM'S SUPER-CHIP? IT'S NOT FROM INTEL

WIRED

IBM Leapfrogs Intel to 7nm

EUV FinFETs Use Germanium Channel

R. Colin Johnson

7/9/2015 00:01 AM EDT

EE Times

TECH

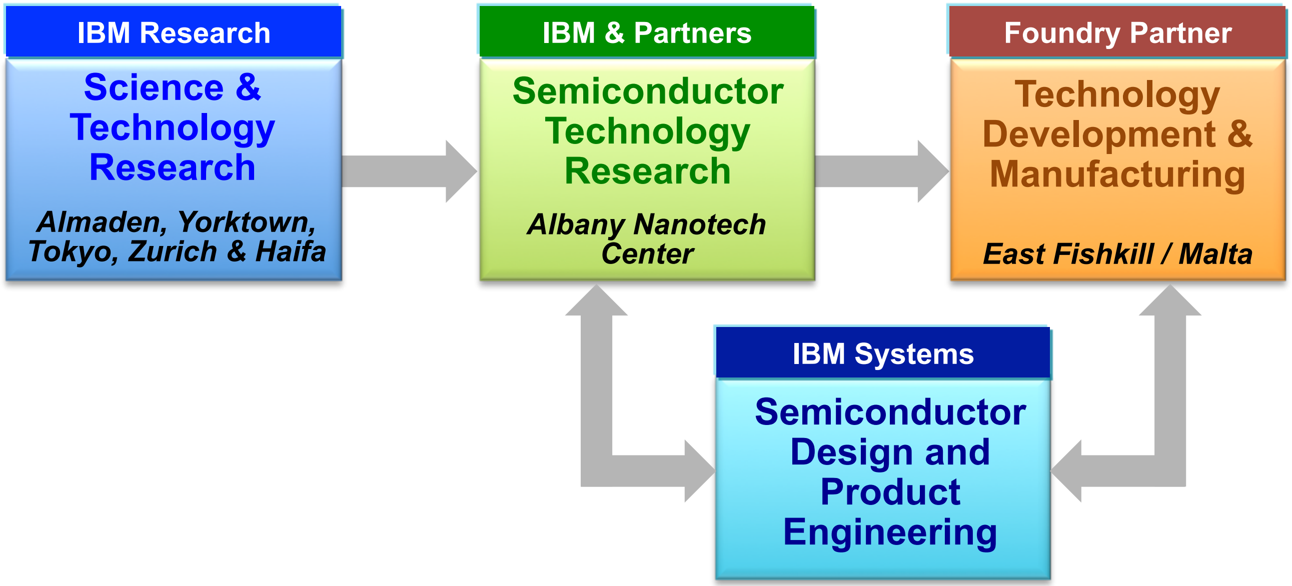
IBM Reports Advance in Shrinking Chip Circuitry

Prototypes signal the industry is continuing to make progress in developing smaller circuitry

THE WALL STREET JOURNAL.

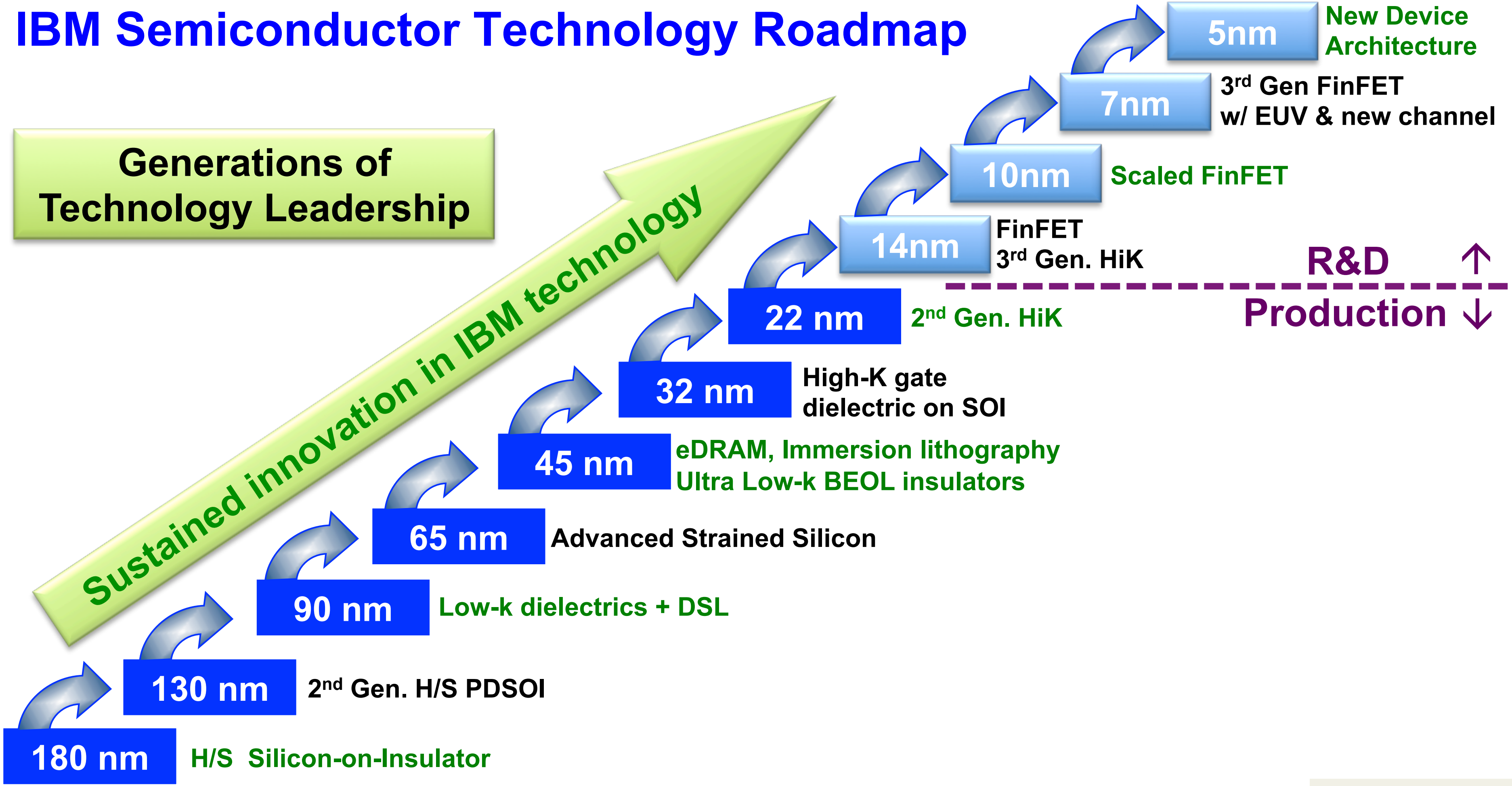
IBM Semiconductor Technology Business Model

- IBM is focusing on *Industry Leadership in Semiconductor Technology Research*, and will transfer the results to *manufacturing partner* with a leading edge, *at-scale fab*



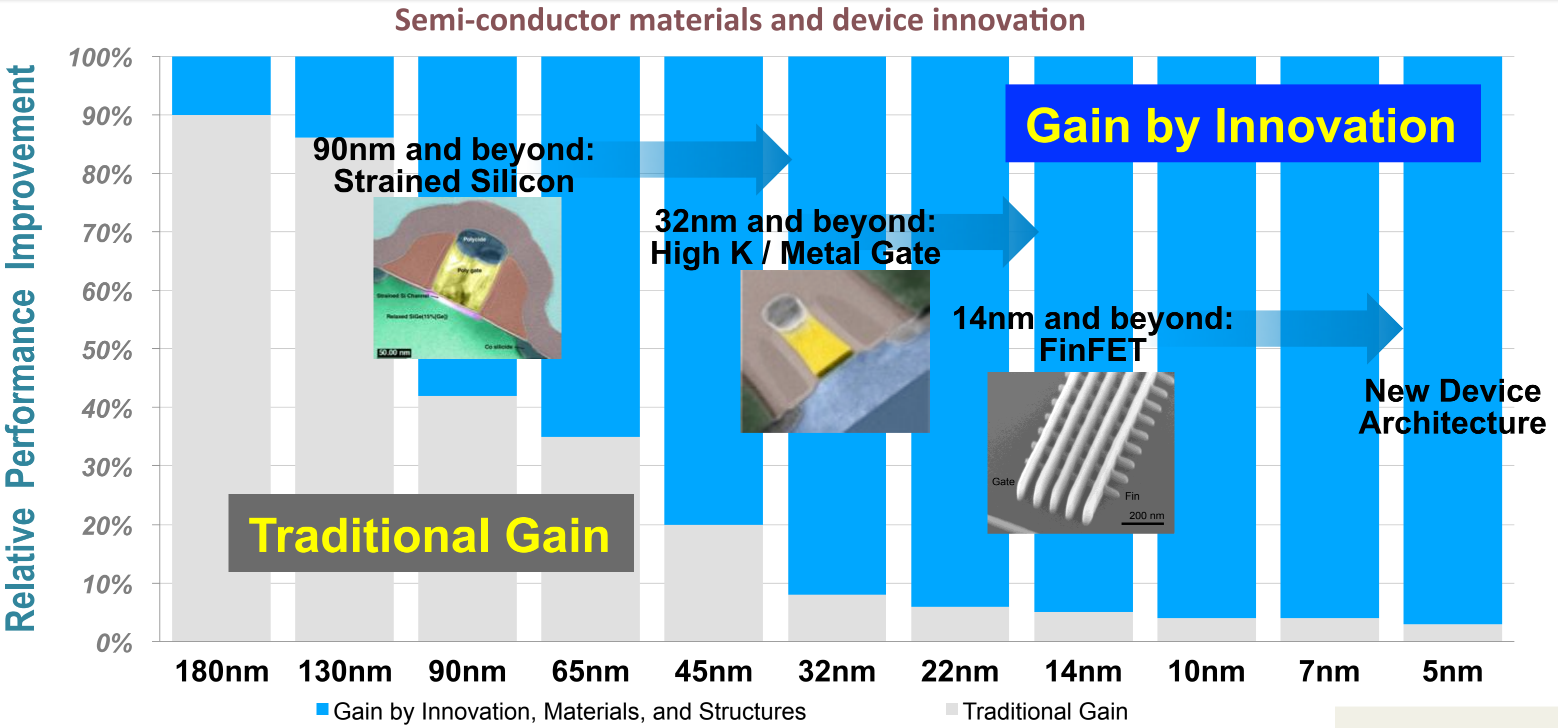
NET: Path for IBM Research Technologies to Market Through Manufacturing Foundry Partner

IBM Semiconductor Technology Roadmap



Scaling vs. Innovation

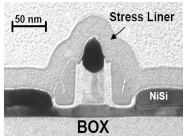
Driving the innovation pipeline is critical as the benefits from traditional scaling decline



***Prior to 90nm:* performance improvement was from scaling … *Now:* innovation, materials and structures are key**

Semiconductor Roadmap: Technology Innovations Continue Performance Gains

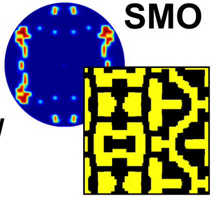
Extending Si CMOS



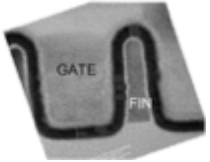
Strain Layers

High-k / Metal Gate

Interconnects / ULK Dielectric

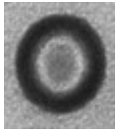


SMO



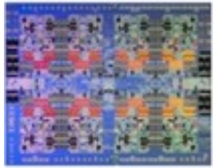
FINFETs

Si Nano-wires

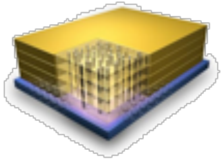


Subsystem Integration

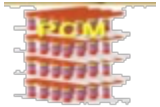
eDRAM



3Di



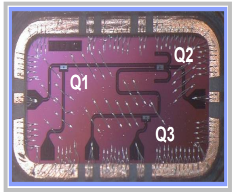
MRAM, PCM for SCM



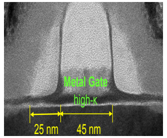
Silicon Photonics

Non-Si FET

Beyond FET



Beyond Von-Neumann Architectures



III/V

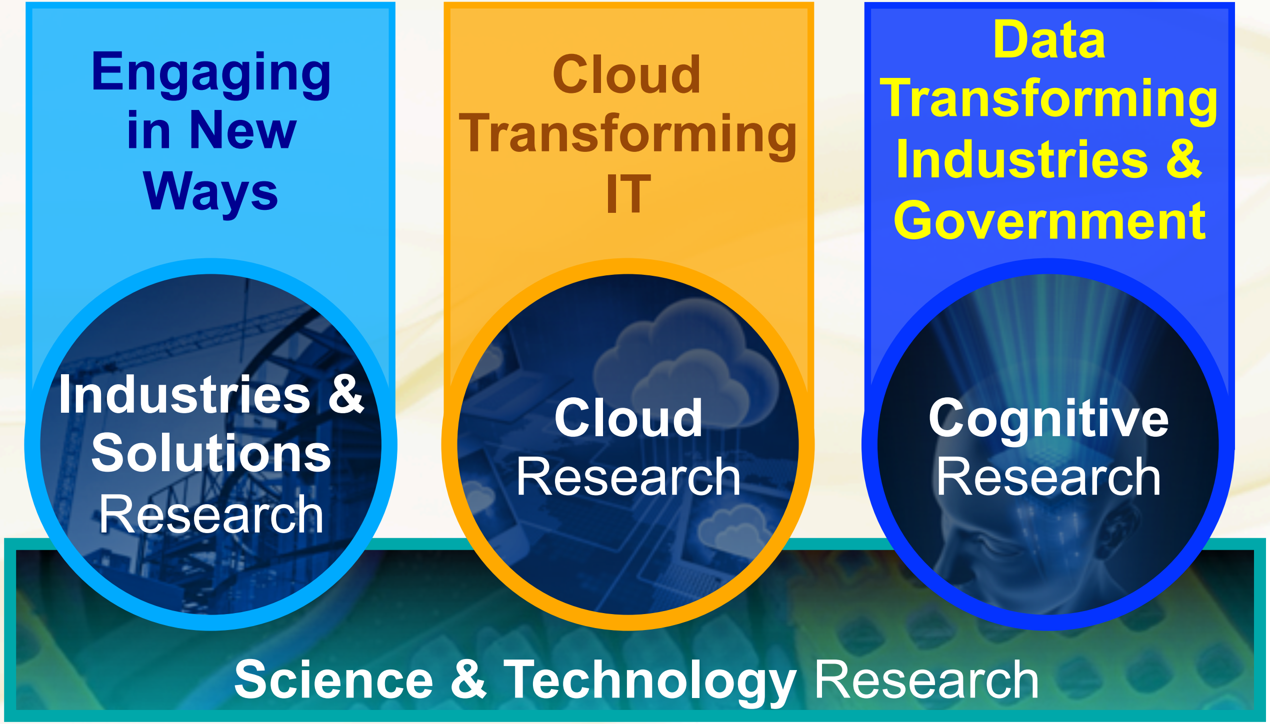
Carbon Electronics

Outline

- **Semiconductor Technology Research (STR)**
  - Business Model
  - Roadmap
  - Collaboration

- **Science & Technology (S&T)**
  - Mission
  - Infrastructure
  - Research Programs
  - Collaboration

Science & Technology (S&T) is the Foundation for IBM Research



IBM Research Science & Technology Mission

Provide *IBM Systems & Cloud* with competitive advantages delivered through leadership in materials and processes, packaging, logic and memory devices, I/O and computation subsystems

Create *new growth opportunities* for IBM and our partners by advancing the frontiers of information technology through the physical sciences and hardware innovations

Yorktown, NY USA

Almaden, CA USA

Zurich Switzerland

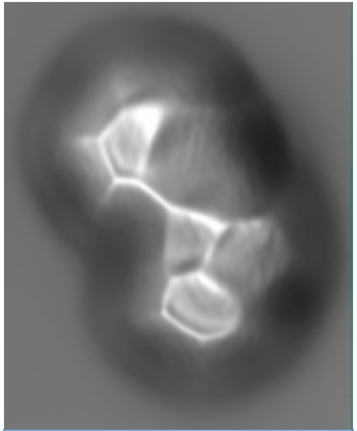
Tokyo Japan

Haifa Israel

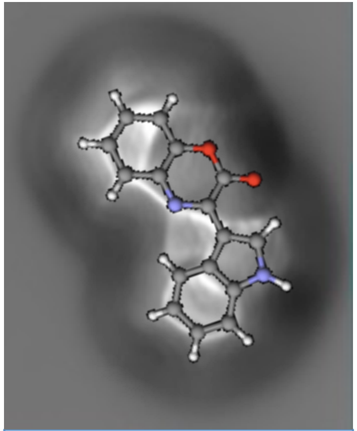
Structural Analysis of New Organic Molecules

Providing the Ability to Rapidly and Directly Determine Structures of New Molecules Not Determinable by Other Analysis Methods

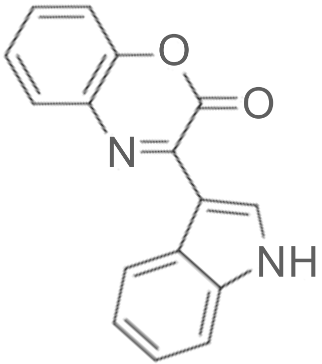
- **Molecules: Metabolite from *Dermacoccus abyssi* collected in the Mariana Trench at 10898 m depth**
  - Composition determined from mass spectrometry: $C_{16}H_{10}N_2O_2$
  - Structure not known (x-ray crystallography not possible due to lack of material)



AFM Measurement, Constant Height, 3D Representation



AFM Measurement, Molecular Model Overlaid

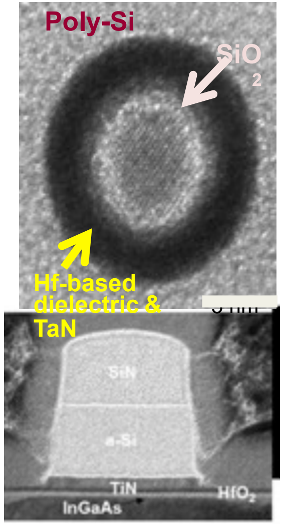


Proposed Molecular Structure: Cephalandole A

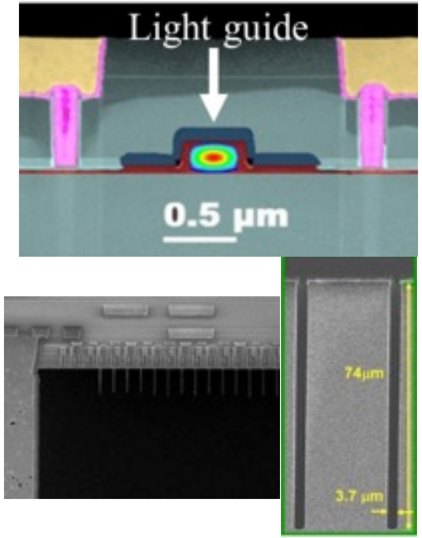
L. Gross et al., Nature Chem. 2(10), 821 (2010)

Microelectronics Research Laboratory (MRL)

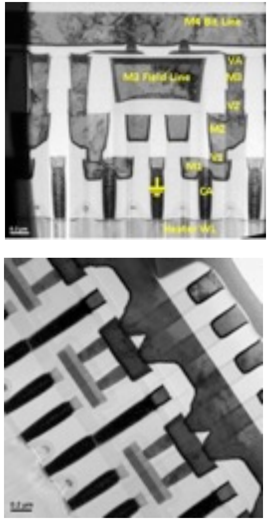
MRL offers state of the art processing and the unique opportunity to utilize existing CMOS technology and further integrate novel processes to build nanofabrication capabilities not available anywhere else



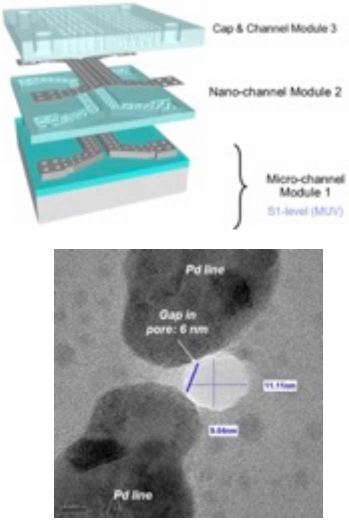
Silicon nanowires, III-V devices



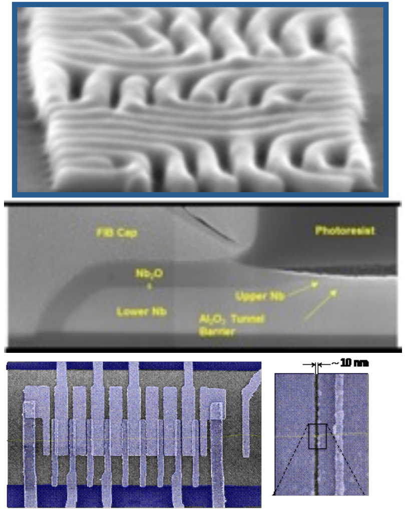
Photonics, 3D integration (TSV)



Non volatile memory (PCM, MRAM)-integration of new materials



Nanochannel electrodes for sensing biomolecules



CNT Ring Oscillator demonstrated in Research

New devices and nanopatterning: Directed self assembly, CNT, QUBIT

A sample of MRL Capabilities…

Science & Technology Strategic Imperatives

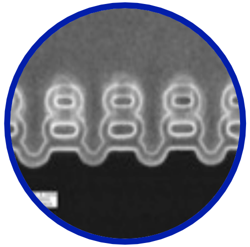
IBM is investing $3 billion to push the limits of chip technology

10 July 2014

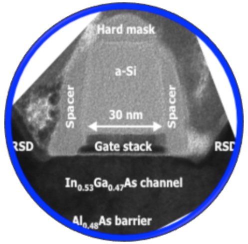
Cloud and big data applications are placing new challenges on systems, just as the underlying chip technology is facing significant physical scaling limits.

- **Continue silicon scaling**

Scaling: 22, 14, 10, 7, 5 nm Nodes

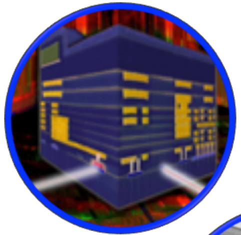


Gate All Around Devices



III/V Devices

- **New materials and devices to extend core logic, memory & I/O technology roadmaps**

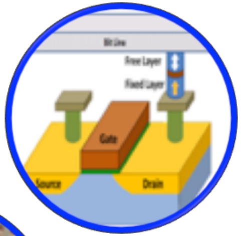


Silicon Photonics

PCM

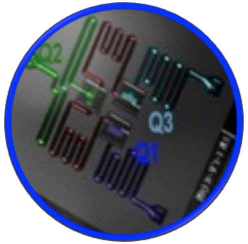
Carbon Devices

3D

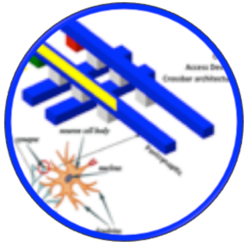


MRAM

- **New computing devices and architectures**



Quantum Computing

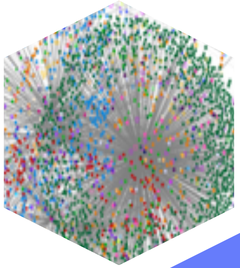


Cognitive Computing

Architectures, Circuits & Devices – Roadmap For Cognitive Computing

Kailash Gopalakrishnan

Cognitive Roadmap and The Need for New Architectures & Technologies



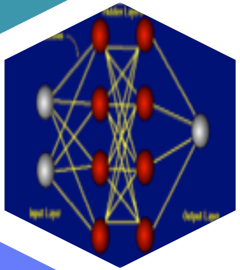
Graph Analytics

Security, Fraud Detection
Genome Analysis
Social Network Analytics
Knowledge Graphs

$> 10^{18}$ Flops
for Image Classification

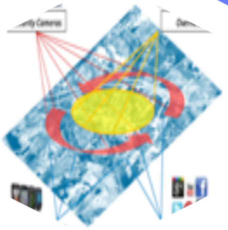
Watson Health
Watson Analytics
Robotics
Education

Machine Learning



100x
size increase
in past 5 years

$> 10^{7}$ hrs
For Speech Training
In 1000's of languages



Video Analytics

Multimodal Analytics
- Object recognition
- Complex video analytics
- Correlation and stitching

> 100 MW
to process
YouTube videos
from a single day

- **Cognitive Workload computational requirements growing significantly.**
- **Saturation in Silicon technology, circuit & architectural performance**

Challenging Assumptions of the past era: Accelerators & Approximations

Cognitive Application Analysis
- Deep Learning, Machine Learning, Robotics

Exploitation of Current Accelerators
- FPGA, GPU, Synapse

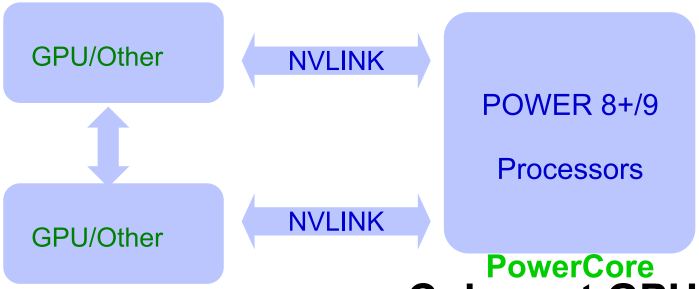
Design of New Accelerators for the Cognitive Era

Approximate Architectures

Approximate Circuits, Devices & Memory

- Application analysis & profiling is the first step towards understanding bottlenecks in today's (optimized) implementations.
- Exploitation of commercially available accelerators – FPGA, GPU etc – to get ~ 5-20X in performance over CPU.
- Design of new accelerator microarchitectures that overcome the bottlenecks & programming-model challenges of today's accelerators.
- Further 10-100X improvement – exploiting approximations in synchronization, precision & perforation over current accelerators.
- Extending approximations down to the circuits & device level – analog computing, computing-in-memory, approximate circuit design & synthesis.

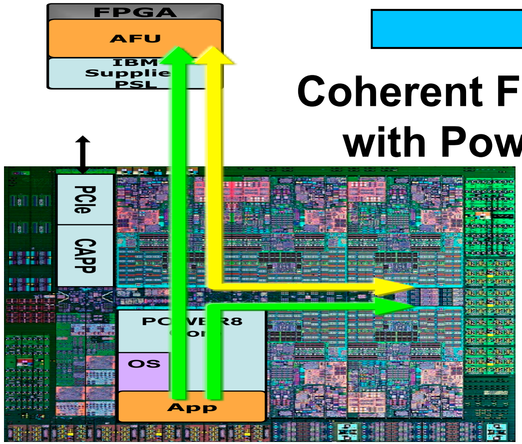
Exploitation & Challenges with FPGAs & GPUs



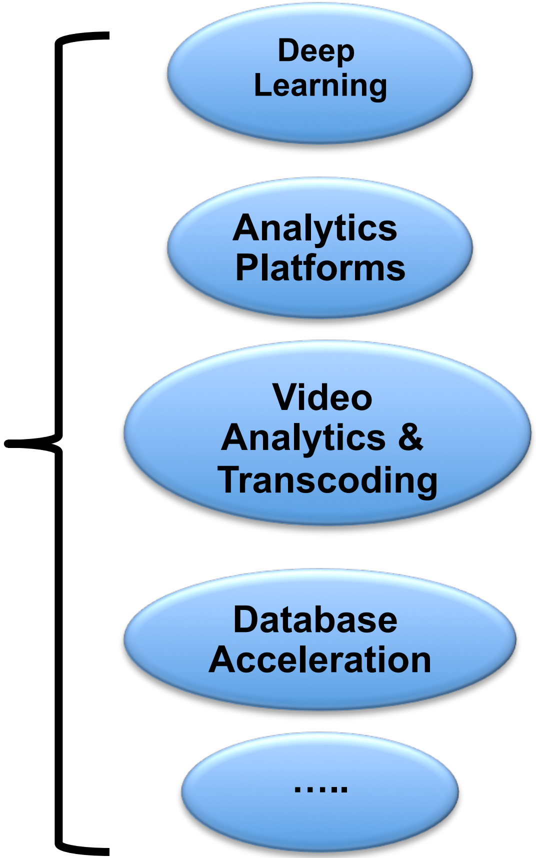
PowerCore

Coherent GPUs with Power9

Coherent FPGAs with Power8



POWER8 Processor



Advantages:

- 5-20X Improvement in performance

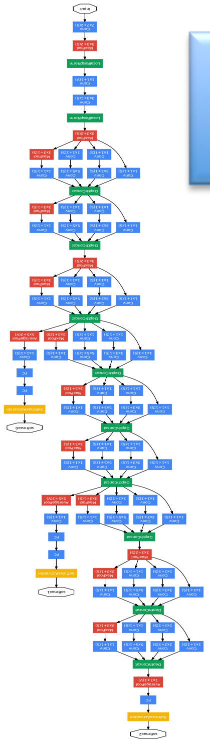
Challenges:

- Works only for simple applications (not fragmented code)
- Programming Model Challenges
- Cost of Offload
- SW Debug / Development

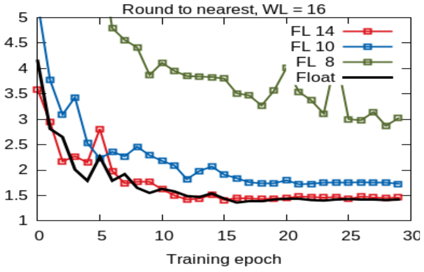
Approximate Computing Stack for Cognitive Applications

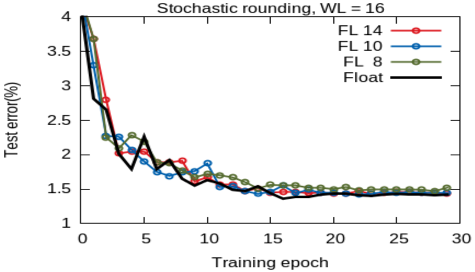
Stack layer	Research focus	Term
Cloud enabled **Cognitive Systems**	• **Novel data ingestion** mechanisms designed for stochastic sensory inputs	Near Term
Approximate and error tolerant **Algorithms**	• **Stochastic Programming Models** • **Real time algorithms** • **Compilers**	
Approximate and Stochastic **Chip Architectures**	• **Automatic synthesis of Approximate and error resilient circuits**	Medium Term
Approximate and error resilient **Circuits**		
Approximate and Stochastic **Devices**	• **Modeling of Approximate and Stochastic logic and memory devices**	Long Term

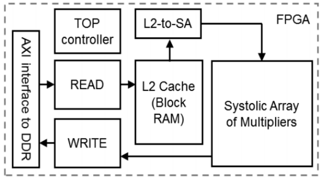
Approximate Computing for Deep Learning



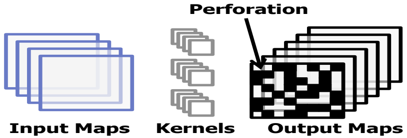
Role of Reduced Precision

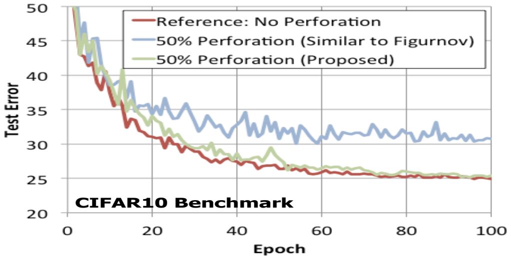




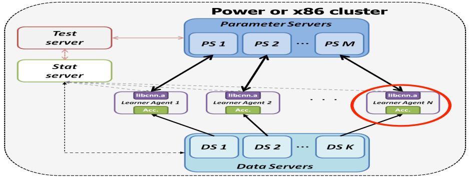


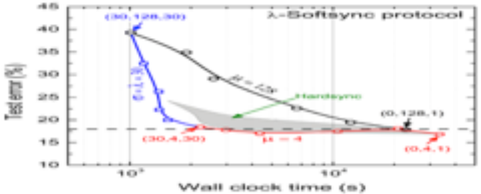
Role of Loop Perforation





Role of Relaxed Synchronization





- **Overall 10-100X Performance gains possible by exploiting approximations across the stack**
- **Robotics, Graph and other Applications currently being studied**

Going Deeper In the Stack with Approximations…
There is plenty of room at the bottom – for exploitation!

- **Approximate Systems Topologies**
  - Approximate accelerators.
  - Relaxed Cache Coherency & Consistency

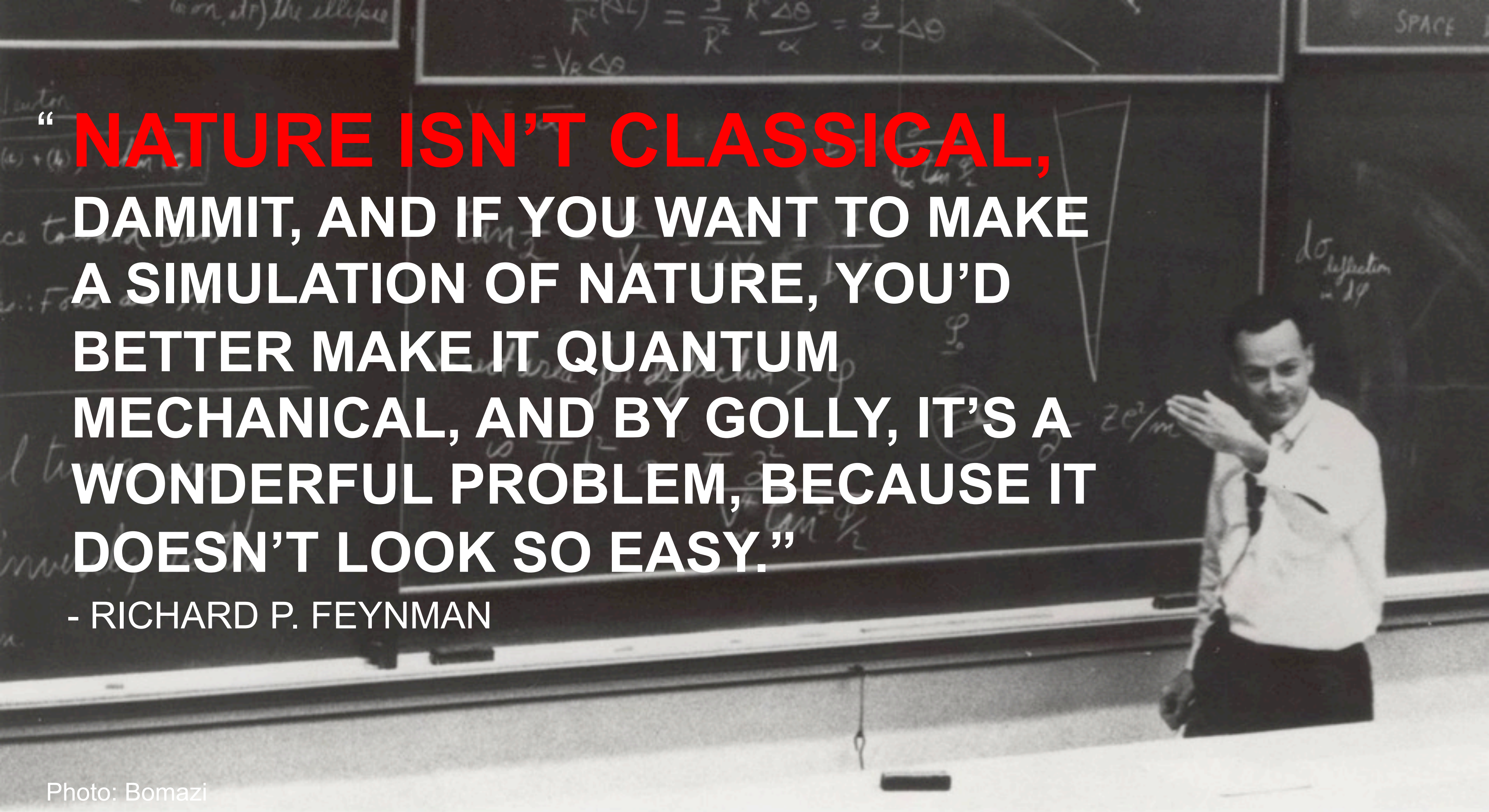
- **Approximate Systems & Circuit Topologies**
  - Approximate Multipliers & Adders
  - Approximate Circuit Topologies
  - Synthesis of Approximate Circuits

- **Approximate Computing Mechanisms**
  - Approximate (Analog) Computing & other logic devices
  - Approximate memory cells (SRAM / DRAM / PCM)
  - Approximate Storage
  - Stochastic Computing techniques
  - Neuromorphic Computing

- **Stochastic Information Processing Fabrics**
  - CNT
  - RRAM / PCM etc

IBM Quantum Computing

T.J. Watson Research Center, Yorktown Heights



“ **NATURE ISN’T CLASSICAL,** DAMMIT, AND IF YOU WANT TO MAKE A SIMULATION OF NATURE, YOU’D BETTER MAKE IT QUANTUM MECHANICAL, AND BY GOLLY, IT’S A WONDERFUL PROBLEM, BECAUSE IT DOESN’T LOOK SO EASY.”

- RICHARD P. FEYNMAN

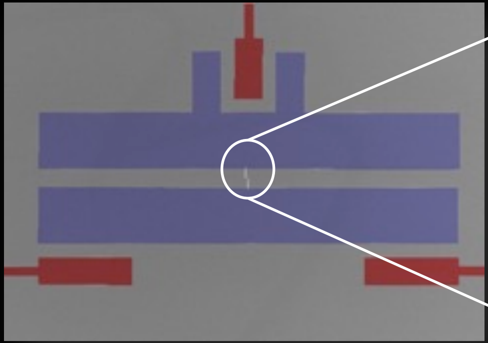
Photo: Bomazi

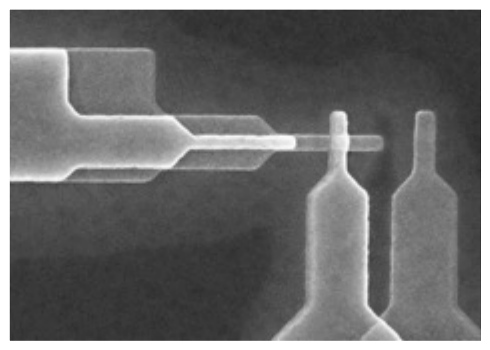
The two quantum principles

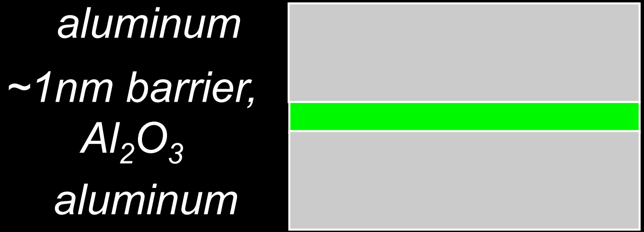
1. **Quantum measurement**: observing a state disturbs it, and returns only partial information about the state (**uncertainty principle**).

2. **Quantum entanglement**: Two systems can exist in an ***entangled*** state, causing them to behave in ways that cannot be explained by supposing that each particle has some state of its own.

SUPERCONDUCTING QUBIT HARDWARE AT IBM



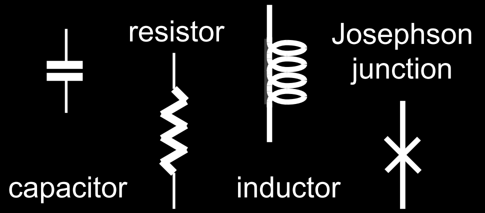




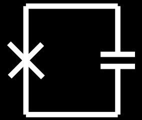
Optical micrograph of a “transmon” superconducting qubit fabricated at IBM

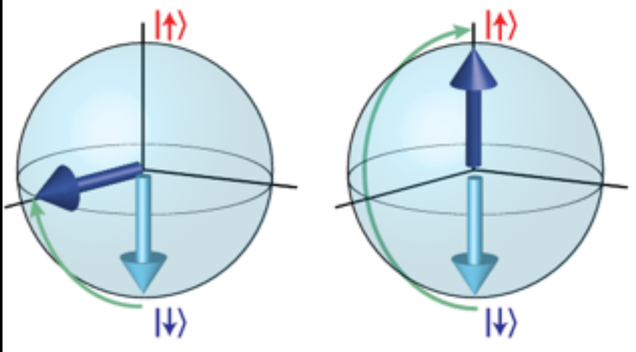
Josephson junction is a non-linear inductor circuit element

Circuit elements



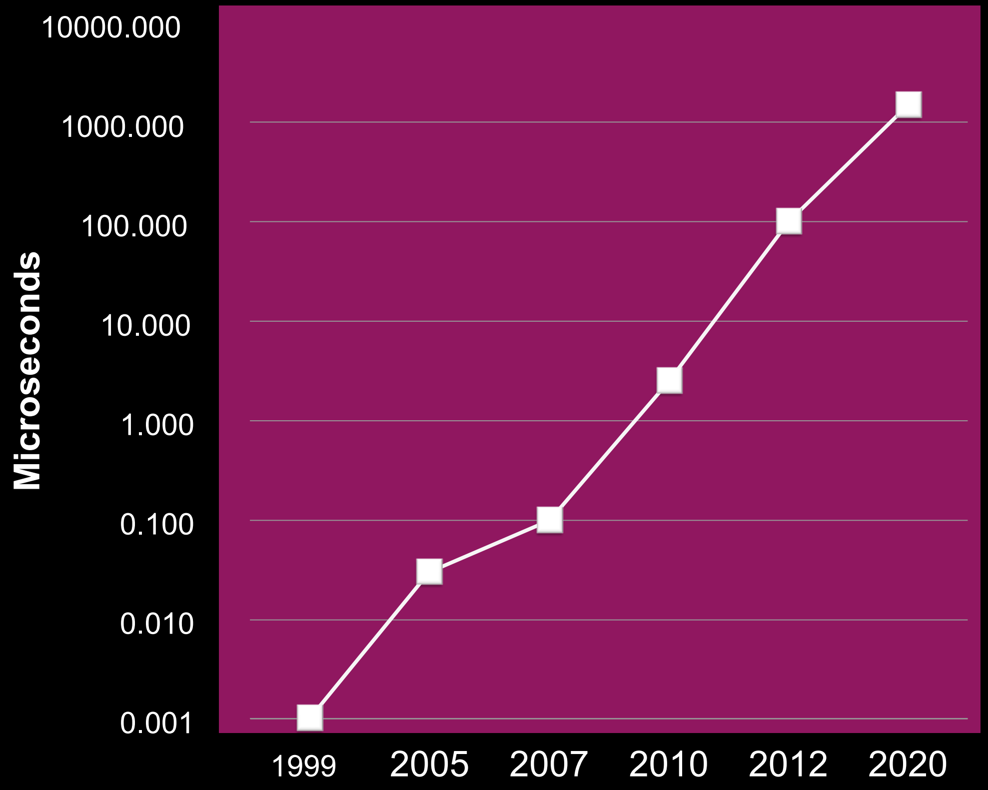
‘anharmonic’ oscillator

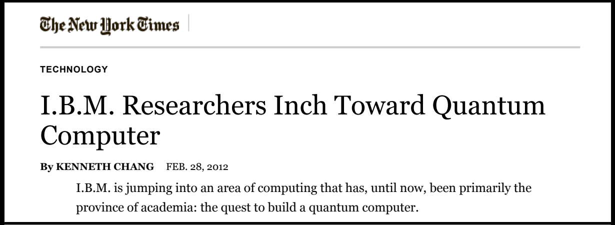




Use microwaves (5 Gigahertz) to control and operate

COHERENCE PROGRESSION





The New York Times

TECHNOLOGY

I.B.M. Researchers Inch Toward Quantum Computer

By KENNETH CHANG FEB. 28, 2012

I.B.M. is jumping into an area of computing that has, until now, been primarily the province of academia: the quest to build a quantum computer.

CADE METZ BUSINESS 02.28.12 6:30 AM

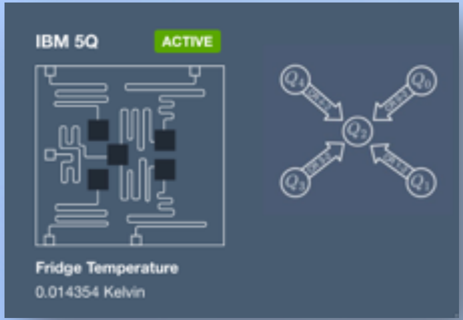
IBM BUSTS RECORD FOR 'SUPERCONDUCTING' QUANTUM COMPUTER

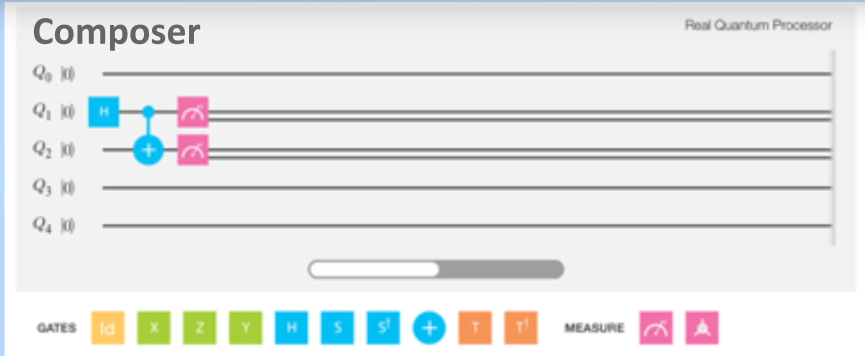
The IBM Quantum Experience

Launched May 4, 2016

Users from 113 countries around the world

5 qubit processor on the cloud

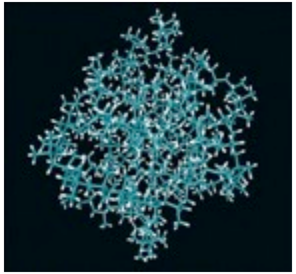




Near-term applications in a post-quantum world

Fully fault-tolerant universal quantum computers are still a long way away, but soon beyond 50 qubits, we will be in a post-quantum world

Quantum Chemistry

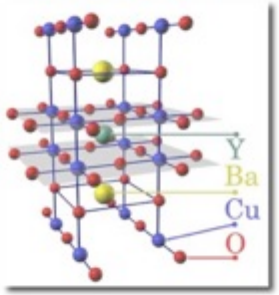


Molecule simulation, bond properties, electronic structure

Quantum Chromodynamics

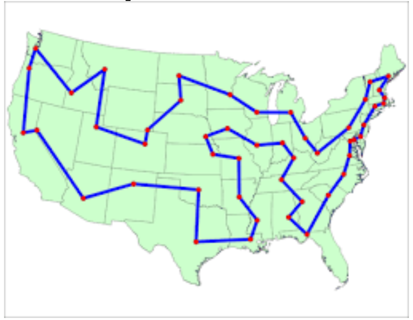
Hadron simulation, high energy physics, nuclear physics

Condensed Matter Physics



High Tc superconducting materials

Quantum enhanced optimization



e.g. Travelling salesman-like problems (constrained satisfaction)

Through IBM enabled by the Quantum Experience, become a part of this new age of discovery

QUANTUM APPLICATIONS

Cryptography

Designing Better Drugs
& New Materials

Machine Learning

Searching Big Data

The three known types of quantum computing and their applications, generality, and computational power.

A very specialized form of quantum computing with unproven advantages over other specialized forms of conventional computing.

DIFFICULTY LEVEL

The most likely form of quantum computing that will first show true quantum speedup over conventional computing. This could happen within the next five years.

DIFFICULTY LEVEL

The true grand challenge in quantum computing. It offers the potential to be exponentially faster than traditional computers for a number of important applications for science and businesses.

DIFFICULTY LEVEL

Quantum Annealer

The quantum annealer is least powerful and most restrictive form of quantum computers. It is the easiest to build, yet can only perform one specific function. The consensus of the scientific community is that a quantum annealer has no known advantages over conventional computing.

APPLICATION
Optimization Problems

GENERALITY
Restrictive

COMPUTATIONAL POWER
Same as traditional computers

Analog Quantum

The analog quantum computer will be able to simulate complex quantum interactions that are intractable for any known conventional machine, or combinations of these machines. It is conjectured that the analog quantum computer will contain somewhere between 50 to 100 qubits.

APPLICATIONS
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics

GENERALITY
Partial

COMPUTATIONAL POWER
High

Universal Quantum

The universal quantum computer is the most powerful, the most general, and the hardest to build, posing a number of difficult technical challenges. Current estimates indicate that this machine will comprise more than 100,000 physical qubits.

APPLICATIONS
Secure computing
Machine Learning
Cryptography
Quantum Chemistry
Material Science
Optimization Problems
Sampling
Quantum Dynamics
Searching

GENERALITY
Complete with known speed up

COMPUTATIONAL POWER
Very High

Thank You!