Post Von Neumann Computing

Matthias Kaiserswerth

Hasler Stiftung (formerly IBM Research)
Foundation Purpose
Support information and communication technologies (ICT) to advance Switzerland as a place to work and think.

Mechanisms
1. Education Computer Science as compulsory subject in secondary schools
2. Research Topical research programs (Smart World, MMI, DICS)
3. Innovation Startup funding

Structure
- Foundation board (6 Persons) split into investment and scientific committees
- Offices in Berne
Agenda

1. Von Neumann Computing
2. Big Data
3. Cognitive Computing
4. Post Von Neumann Computing
Von Neumann Computer

- Input Device
- CPU
  - Control Unit
  - Arithmetic/Logic Unit
- Memory Unit
- Output Device
Agenda

1. Von Neumann Computing
2. Big Data
3. Cognitive Computing
4. Post Von Neumann Computing
2.5 quintillion bytes of data created every day.

90% of the data in the world today has been created in the last **two years** alone.

Every minute, **1.7 megabytes** of data is created for every person on the planet. **All 7.3 billion of us.**
Unstructured data — “dark data” — accounts for 80% of all data generated today.
This is expect to grow to 93% by 2020.
Agenda

1. Von Neumann Computing
2. Big Data
3. Cognitive Computing
4. Post Von Neumann Computing
On February 14, 2011, IBM Watson made history
Tabulating Systems Era
1900 - 1940s

Programmable Systems Era
1950s - Present

Cognitive Systems Era
2011 -
Welcome to the dawn of the Cognitive Era
The Future of Computing:
Non-Von Neuman for Next Generation Cognitive Applications

Physics of Nanoscale Systems

Quantum Computing

Neuromorphic Computing
A classical computer makes use of bits to process information, where each bit represents either a 1 or a 0.

A quantum bit (qubit) can represent a 1, a 0, or both at once, which is known as superposition.

This property along with other quantum effects enable quantum computers to perform certain calculations vastly faster than is possible with classical computers.
Three Known Types of Quantum Computing

**Annealer**
Potential applications for optimization problems

**Analog**
First time we will likely see a speed up over conventional computing

**Universal**
50-100 qubits: none of today’s TOP500 supercomputers could successfully emulate it,

YEARS
- Annealer: +0
- Analog: +5
- Universal: +25

Potential applications for optimization problems
Quantum Systems Era

“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.”

Physicist Richard Feynman, Physics of Computation Conference, co-organized by MIT and IBM, May 6-8, 1981

IBM’s Quantum System Milestones: 1970s - Today

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Quantum money (security)</td>
<td>Wiesner/Bennett</td>
</tr>
<tr>
<td>1984</td>
<td>Quantum key distribution (BB84)</td>
<td>Bennett/Brassard</td>
</tr>
<tr>
<td>1993</td>
<td>Quantum teleportation</td>
<td>Bennett et al.</td>
</tr>
<tr>
<td>1996</td>
<td>DiVincenzo Criteria for building a quantum computer</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>Shor algorithm with NMR</td>
<td>Steffen/Chuang/Vandersypen</td>
</tr>
<tr>
<td>2015</td>
<td>Error Correction Demonstration with superconducting qubits (shown at IBM and other groups)</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>IBM Quantum Experience</td>
<td>(5 qubits in the cloud for the general public)</td>
</tr>
</tbody>
</table>

# Quantum Computing Platforms: Status Quo

<table>
<thead>
<tr>
<th>Platform</th>
<th># of controllable qubits</th>
<th>main application</th>
<th>scalability</th>
<th>(2-qubit) gates per coherence</th>
<th>Clock speed</th>
<th>universal set of gates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting Qubits</td>
<td>~ 10</td>
<td>computing</td>
<td>+: micro-/nanofabrication -: qubit size</td>
<td>100-1000</td>
<td>100 MHz</td>
<td>proven</td>
</tr>
<tr>
<td>Trapped Ions</td>
<td>~ 15</td>
<td>computing</td>
<td>surface traps</td>
<td>1000 - 10000</td>
<td>100 kHz</td>
<td>proven</td>
</tr>
<tr>
<td>Ultra-Cold Atoms</td>
<td>~ 5 / 1000</td>
<td>simulation</td>
<td>+: laser lattices -: individual control</td>
<td>1-10</td>
<td>1 MHz</td>
<td>controlled 2-qubit interactions ?</td>
</tr>
<tr>
<td>Quantum Dots</td>
<td>~ 3</td>
<td>computing</td>
<td>+: nanofabrication -: long range coupling</td>
<td>10-100</td>
<td>1 GHz</td>
<td>scalable 2-qubit gates ?</td>
</tr>
<tr>
<td>NV Centers</td>
<td>~ 2</td>
<td>sensing</td>
<td>-: 2-qubit interactions</td>
<td>1-10</td>
<td>1 kHz</td>
<td>2-qubit gates ?</td>
</tr>
<tr>
<td>Photons</td>
<td>~ 10</td>
<td>communication</td>
<td>-: single photon source</td>
<td>n. a.</td>
<td>1 Hz</td>
<td>2-qubit interactions ?</td>
</tr>
</tbody>
</table>
Superconducting Qubit Processor – A Closer Look

Superconducting Qubit:
- non-linear Josephson Junction (Inductance)
- anharmonic energy spectrum => qubit
- nearly dissipationless => $T_1, T_2 \approx 70 \mu s$

Microwave Resonator as:
- read-out of qubit states
- multi-qubit quantum bus
- noise filter

$E_{01} \approx 5 \text{ GHz} \approx 240 \text{ mK}$
Welcome to the IBM Quantum Experience

If quantum physics sounds challenging to you, you are not alone. The intuitions we all have, based on our day-to-day experiences, are defined by classical physics -- so most of us find the concepts in quantum physics counterintuitive at first. If you try to interpret quantum mechanics with a classical physics mindset, you'll find it is not only a hindrance — It is impossible to do so. In order to comprehend the quantum world, you must let go of your beliefs about our physical world, and develop an intuition for a completely different (and often surprising) set of laws.

Our goal with the IBM Quantum Experience is to introduce this world through a set of tutorials, and by providing the hands-on opportunity to experiment with operations on a real quantum computing processor. In this way, we hope to foster a quantum intuition for the community at large, and spark interest in those who are curious. By making quantum concepts more widely understood—even on a general level— we can more deeply explore all the possibilities quantum computing offers, and more rapidly bring its exciting powers to a world that thinks it is limited to the laws of classical physics.

We have developed five short tutorials that explain how the IBM Quantum Experience and the quantum world works.

Section I
The IBM Quantum Experience
Introducing the world's first cloud-based quantum computer built for and useable by everyone!

Section II
The Weird and Wonderful World of the Qubit
Industry Applications in Quantum Computing

- **Chemistry**, e.g. for catalyst design
- **Material Science**, e.g. for energy efficient devices
- **Life Sciences**, e.g. for drug development
- **Optimization**, e.g. for cognitive computing and business processes
- **Cryptography**, e.g. for secure communication and information processing
- **Education**, e.g. to train engineers for the future quantum industry
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>First integrated circuit</td>
</tr>
<tr>
<td></td>
<td>Size ~1cm²</td>
</tr>
<tr>
<td></td>
<td>2 Transistors</td>
</tr>
<tr>
<td>1971</td>
<td>Moore’s Law is Born</td>
</tr>
<tr>
<td></td>
<td>Intel 4004</td>
</tr>
<tr>
<td></td>
<td>2,300 transistors</td>
</tr>
<tr>
<td>2014</td>
<td>IBM P8 Processor</td>
</tr>
<tr>
<td></td>
<td>&lt;650 mm²</td>
</tr>
<tr>
<td></td>
<td>22 nm feature size</td>
</tr>
<tr>
<td></td>
<td>16 cores</td>
</tr>
<tr>
<td></td>
<td>&gt; 4.2 Billion Transistors</td>
</tr>
</tbody>
</table>

Choose a Side: Naysayers or Feynman?
Choose a Side: Naysayers or Feynman?

1958
First integrated circuit
Size ~1cm²
2 Transistors

1971
Moore’s Law is Born
Intel 4004
2,300 transistors

2014
IBM P8 Processor
<650 mm²
22 nm feature size
16 cores
>4.2 Billion Transistors

We are here
Neuromorphic Computing

Brain-inspired computing

Biological neurons and synapses

"Memelements": artificial neural components

Networks of neurons and synapses

Input modalities

Sensory data

Scientific computing

Social computing

In-silico neural hardware

Small-scale prototypes of neural hardware

Cognitive Systems
<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programmable Neurons</td>
<td>256</td>
<td>1 million</td>
</tr>
<tr>
<td>Programmable Synapses</td>
<td>262,144</td>
<td>256 million</td>
</tr>
<tr>
<td>Neurosynaptic Cores</td>
<td>1</td>
<td>4096</td>
</tr>
</tbody>
</table>
Detecting Correlations with a Spiking Neural Network
Brain Inspired Computing: Electronic Blood

- 98% of the energy of a computer is for cooling
- Liquid removes heat 4000x more efficiently than air
- The brain is powered & cooled using liquid, can we do the same for computers?
- The result: a 1 PetaFlop supercomputer in 10 liters
Summary

Non-Von Neumann Architectures

Von Neumann Architectures

Computing Without Programming:
- Accelerators
- High-k
- Subsystem Integration (3D, SCM, Photonics)

Computing with Programs:
- Fetch Instructions, Decode, Execute & Repeat.

Today

Time

- FPGA's
- Reconfigurable Logic
- InAs
- Carbon Electronics
- Spintronic & Magnetic

Low V Devices

Low V Circuits & Architecture

Neuromorphic & Quantum Devices

- Neuromorphic Devices & Circuits
- Quantum Devices & Circuits

New Devices, Architectures & Computing Paradigms

New Architectures Leveraging 100's of Billions of Low-Voltage Devices

Existing Architectures