Beyond von Neumann computing

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Geoplanet — Earth and planetary research centre conference
Sopot, 28–29 Nov 2024

Von Neumann computing

Von Neumann Computing I

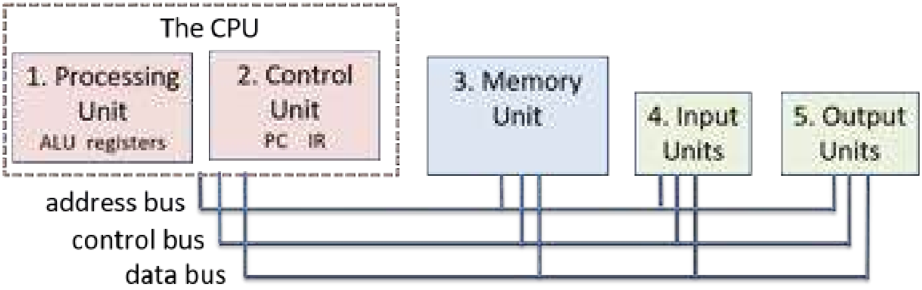


Figure: The von Neumann architecture consists of the processing, control, memory, input, and output units. The control and processing units make up the CPU, which contains the ALU, the general-purpose CPU registers, and some special-purpose registers (IR and PC). The units are connected by buses used for data transfer and communication between the units.

Von Neumann Computing II

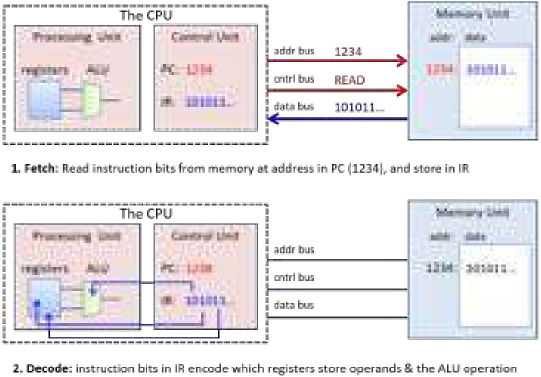


Figure: The fetch and decode stages of execution of the von Neumann architecture for an example addition instruction. Operand, result, and memory addresses are shown as decimal values, memory contents are shown as binary values.

Von Neumann Computing III

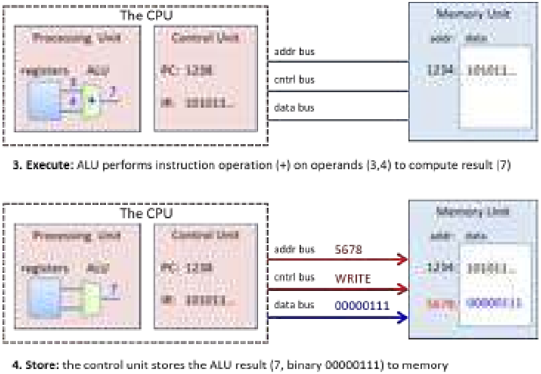
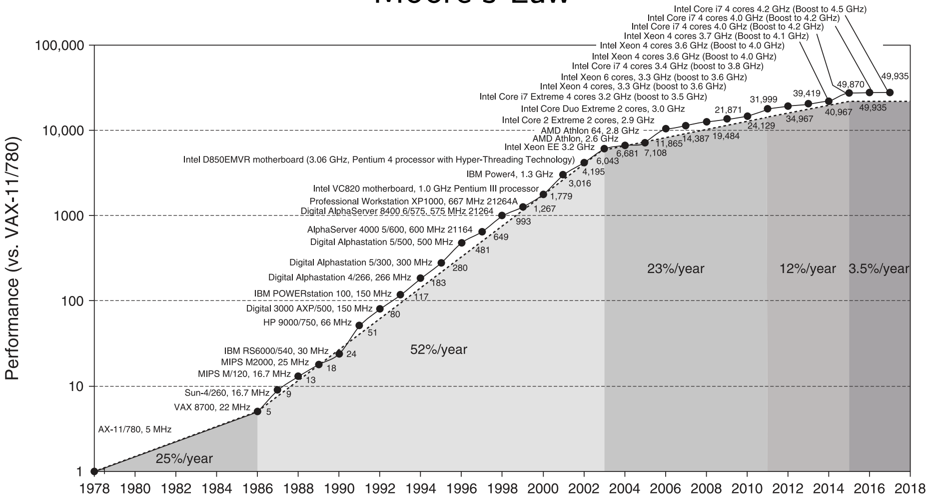


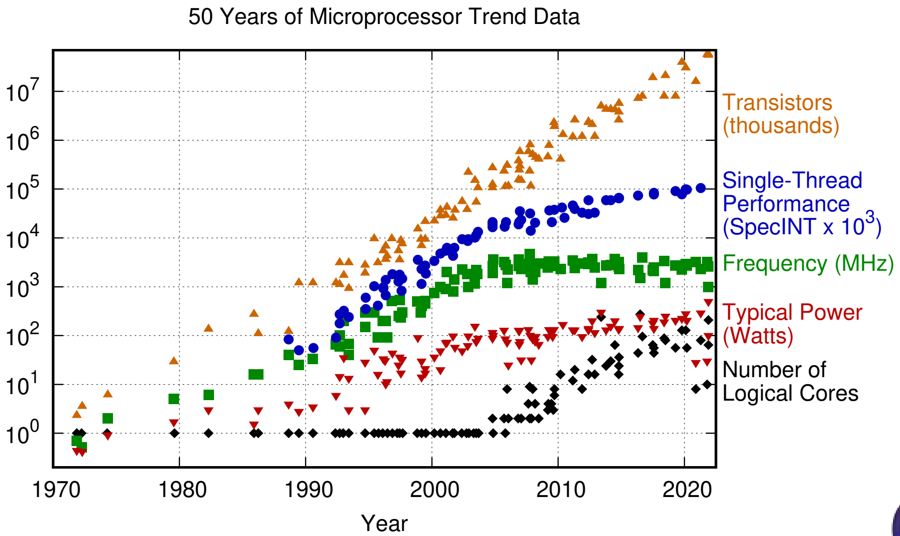
Figure: The execute and store stages of execution of the von Neumann architecture for an example addition instruction. Operand, result, and memory addresses are shown as decimal values, memory contents are shown as binary values.

Source: Suzanne J. Matthews, Tia Newhall, and Kevin C. Webb. *Dive Into Systems: A Gentle Introduction to Computer Systems*. English. New York: No Starch Press, Sept. 2022. ISBN: 978-1-7185-0136-2

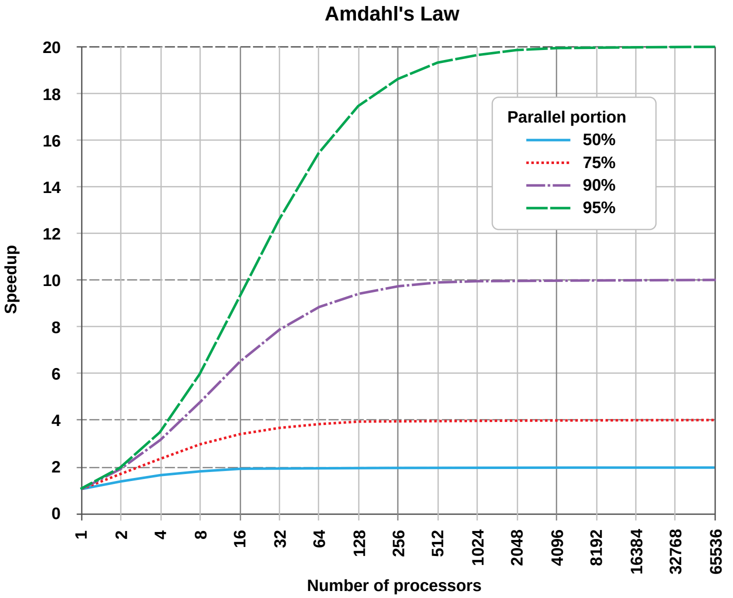
Moore's Law



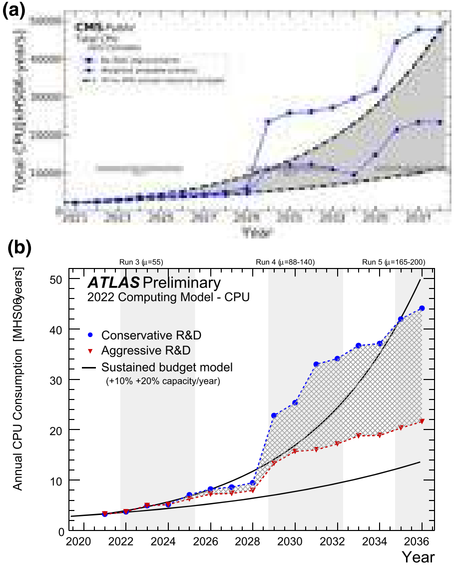
Source: Hennessy, John L., and David A. Patterson. Computer architecture: a quantitative approach. Elsevier, 2011. 6th edition.



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2021 by K. Rupp


Amdahl's Law
Speedup
20
18
16
14
12
10
8
6
4
2
0
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
Number of processors
Parallel portion
50%
75%
90%
95%

Demand for computation in High Energy Physics



Jonas Eschle et al. "Potential of the Julia Programming Language for High Energy Physics Computing". en. In: *Computing and Software for Big Science* 7.1 (Dec. 2023), p. 10. ISSN: 2510-2036, 2510-2044. DOI: 10.1007/s41781-023-00104-x

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Demand for computation in High Energy Physics

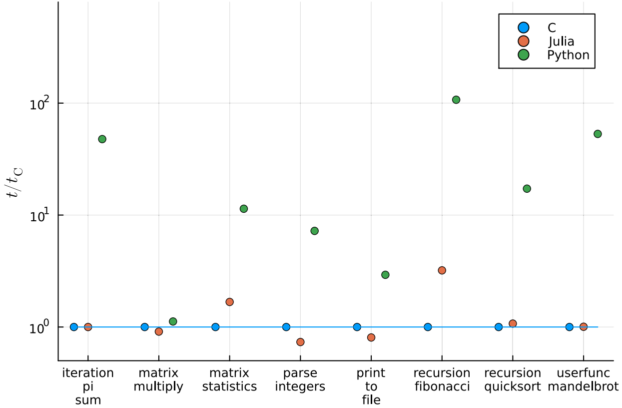
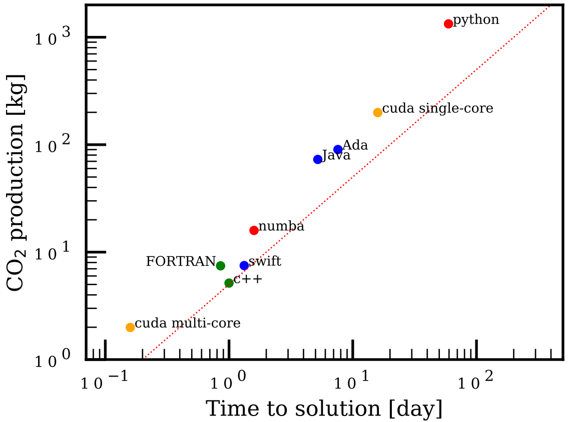


Fig. 3 Comparison of C/C++, Python and Julia language performance for a set of short algorithms. OpenBLAS, together with `NumPy` in the Python case are used for matrix operation. The score is defined as the time to run the algorithm divided by the time to run the C version of the same algorithm

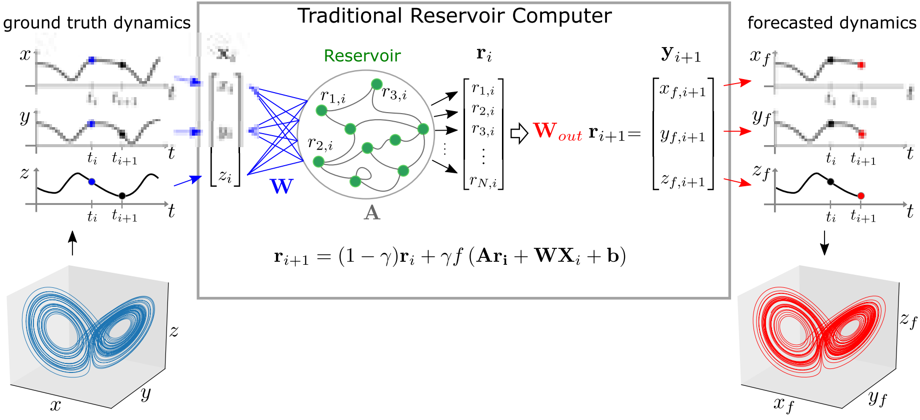
CO_2 cost of scientific computing per language



Source: Simon Portegies Zwart. "The ecological impact of high-performance computing in astrophysics". en. In: *Nature Astronomy* 4.99 (Sept. 2020), pp. 819–822. ISSN: 2397-3366. DOI: 10.1038/s41550-020-1208-y

Alternative computing paradigms

Reservoir Computing



Source: Daniel J. Gauthier et al. "Next generation reservoir computing". en. In: *Nature Communications* 12.11 (Sept. 2021), p. 5564. ISSN: 2041-1723. DOI: 10.1038/s41467-021-25801-2

Neuromor

Spiking neural networks

www.nature.com/scientificreports/

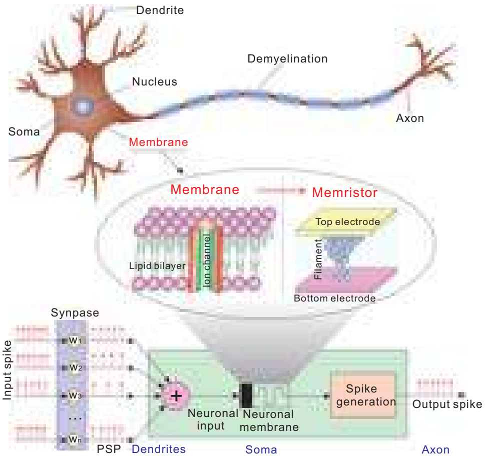
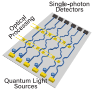
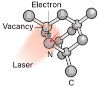
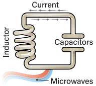
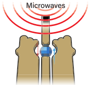
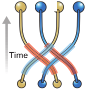


Figure 1. An artificial neuron based on a HfO_2 memristor. Schematic of an artificial neuron that consists of the dendrites (inputs), the soma (which comprises the neuronal membrane and the spike event generation) and the axon (output). The dendrites may be connected to synapses in a network. The input spikes are modulated by synapse in frequency domain having the same amplitude.

Source: J. J. Wang et al. "Handwritten-Digit Recognition by Hybrid Convolutional Neural Network based on HfO2 Memristive Spiking-Neuron". en. In: *Scientific Reports* 8.1 (Aug. 2018), p. 12546. ISSN: 2045-2322. DOI: 10.1038/s41598-018-30768-0

Quantum Computing

		Qubit Coherence Time (sec)	Two-qubit Gate Fidelity	Qubits Connected	Companies	Pros	Cons
	**Trapped Ions** Electrically charged atoms, or ions, are held in place with electric fields. Qubits are stored in electronic states. Ions are pushed with laser beams to allow the qubits to interact.	>1000	99.9%	High	IonQ, Quantinuum, AQT Oxford Ionics, Universal Quantum	Very stable. Highest achieved gate fidelities.	Slow operation. Many lasers are needed.
	**Neutral Atoms** Neutral atoms, like ions, store qubits within electronic states. Laser activates the electrons to create interaction between qubits.	1	99.5%	Very high; low individual control	Infleqtion, Atom Computing, QuEra, Pasqal, Planqc, M²	Many qubits, 2D and maybe 3D.	Hard to program and control individual qubits; prone to noise.
	**Photonics** Photonic qubits are sent through a maze of optical channels on a chip to interact. At the end of the maze, the distribution of photons is measured as output.	–	–	–	PsiQuantum, Xanadu	Linear optical gates, integrated on-chip.	Each program requires its own chip with unique optical channels. No memory.
	**Diamond Vacancies** A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.	10	99.2%	Low	Quantum Diamond Technologies, Quantum Brilliance	Can operate at room temperature.	Difficult to create high numbers of qubits, limiting compute capacity.

		Qubit Coherence Time (sec)	Two-qubit Gate Fidelity	Qubits Connected	Companies	Pros	Cons
	**Superconducting Circuits** A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	0.00005	99.9%	High	Google, IBM, QCI, Rigett, Oxford Quantum Circuits	Can lay out physical circuits on chip.	Must be cooled to near absolute zero. High variability in fabrication. Lots of noise.
	**Silicon Quantum Dots** These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	0.03	~99%	Very Low	HRL, Intel, SQC, Oxford Quantum Ocean, DIRAQ, Quantum Motion, EeroQ	Borrows from existing semiconductor industry.	Only a few connected. Must be cooled to near absolute zero. High variability in fabrication.
	**Topological Qubits** Quasiparticles can be seen in the behavior of electrons channeled though semiconductor structures. Their braided paths can encode quantum information.	–	–	–	Microsoft	Designed to be more robust to environmental noise.	Existence not yet confirmed.

Source: Kenneth Brown et al. "5 Year Update to the Next Steps in Quantum Computing". In: arXiv:2403.08780 (Jan. 2024). arXiv:2403.08780. DOI: 10.48550/arXiv.2403.08780. URL: http://arxiv.org/abs/2403.08780

Number of DOCDB patent families per earliest publication year in the field of quantum computing

joint patent families with an applicant from an EPC state, a second applicant from North America is observed. These results suggest relatively close cooperation within the same region and weaker cooperation between applicants on different continents. A similar picture results from the

shows that European applicants from one sector tend to cooperate more frequently with other European patent applicants from the same sector. However, there is also cooperation with European patent applicants from other sectors.

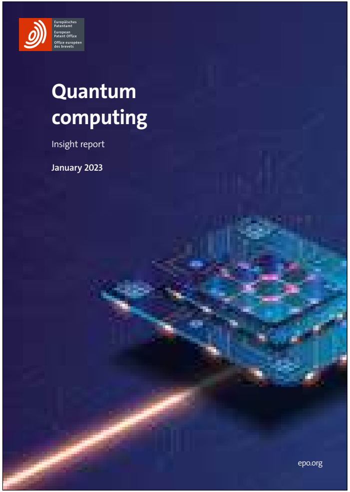
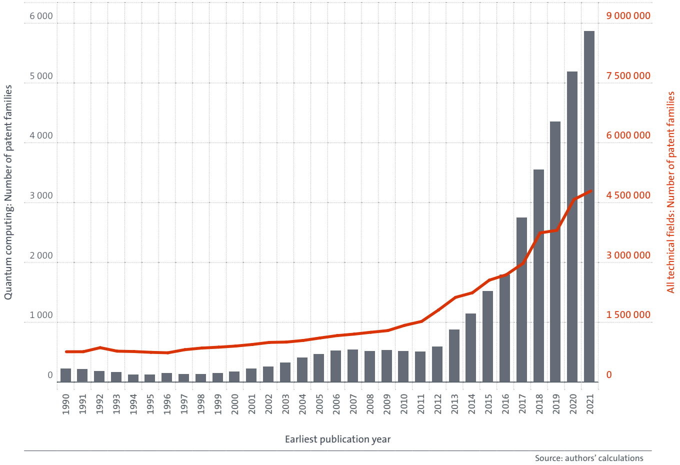


Figure 2

Number of DOCDB patent families per earliest publication year in the field of quantum computing



Projects

Quantum Advantage for Earth Observation

Report commissioned by ESA

QA4EO

Quantum Advantage for Earth Observation

Soronzonbold Otgonbaatar[1,2], Olli Nurmi[3], Mikael Johansson[4], Jarmo Mäkelä[4], Tadeusz Kocman[5], Piotr Gawron[6,7], Zbigniew Puchała[7], Łukasz Pawela[7], Jakub Mielczarek[8], and Artur Miroszewski[8]

[1]German Aerospace Center (DLR) Oberpfaffenhofen
[2]Ludwig-Maximilians-Universitaet Muenchen
[3]VTT-Technical Research Centre of Finland Ltd.
[4]CSC–IT Center for Science Ltd.
[5]SYDERAL Polska sp. z o.o.
[6]AstroCeNT, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
[7]Etos Centrum Edukacji i Doradztwa Służby Zdrowia sp. z o.o.
[8]Jagiellonian University

ESA Contract No. 4000140122/22/I-DT

Quantum Computing for EO Use-Cases

- Use-Case I: Climate Adaptation Digital Twin HPC+QC Workflow
- Use-Case II: Uncertainty Quantification for Remotely-Sensed Datasets
- Use-Case III: Quantum Algorithms for Earth Observation Image Processing
- Use-Case IV: Feature Selection and Feature Extraction for Satellite Hyperspectal Imagery Data

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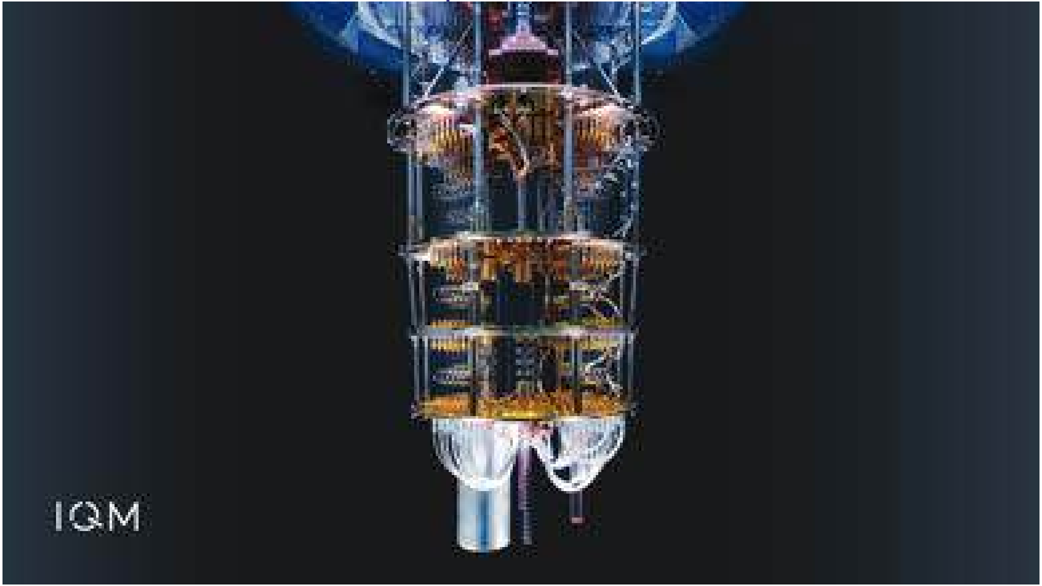
LUMI-Q — IQM Quantum Computer



EuroQHPC-Integration / LUMI-Q

(To be) funded by EuroHPC JU

LUMI-Q

Figure 2. LUMI-Q consortium, with the planned LUMI-Q quantum computer and the distribution of supercomputers and quantum computers inside the consortium.

The hosting site is described in detail within section III.4, while the network of EuroHPC supercomputers and their integration into the LUMI-Q ecosystem is detailed in sections III.1.2, III.1.3 and III.1.4.

The LUMI-Q Consortium consists of the hosting entity (IT4I Innovations from the Czech Republic) and several

Objective of LUMI-Q

Acquisition of a quantum computer and its integration into the HPC environment associated with LUMI.

Objective of EuroQHPC-Integration

Integration of quantum computers and HPC in Europe.
(Applications of QML for EO data processing — as a use-case)

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Thank you for your attention

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CAMK PAN