From Electrons to Enzymes

Fifth Visions for Future Communications Summit

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Source: Gemini generated image

From Electrons to Enzymes

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Introduction (i)

As Europe advances toward its +2030 sustainability, sovereignty, and digital transition goals, computing is approaching <u>a fundamental inflection point</u>:

- For decades, progress in information processing has relied on Moore's Law and digital logic miniaturization
- The physical and energetic limits of CMOS scaling are now converging with global constraints on energy production and material availability
- The raise of GenAI has supposed a great challenge in terms on energy consumption and computational resources

Introduction (ii)

The Five Seismic shifts of the Decadal Plan

1	The Analog Data Deluge	Fundamental breakthroughs in analog hardware are required to generate smarter world-machine interfaces that can sense, perceive, and reason.
2	Growth of Memory & Storage Demands	The growth of memory demands will outstrip global silicon supply, presenting opportunities for radically new memory and storage solutions.
3	Communication Capacity vs. Data Generation	Always-available communication requires new research directions that address the imbalance of communication capacity vs. data-generation rates.
4	ICT Security	Breakthroughs in hardware research are needed to address emerging security challenges in highly interconnected systems and AI.
5	Compute Energy vs. Global Energy Prod.	This is creating new risks, and new computing paradigms offer opportunities to dramatically improve energy efficiency.

Introduction (ii)

The Five Seismic shifts of the Decadal Plan

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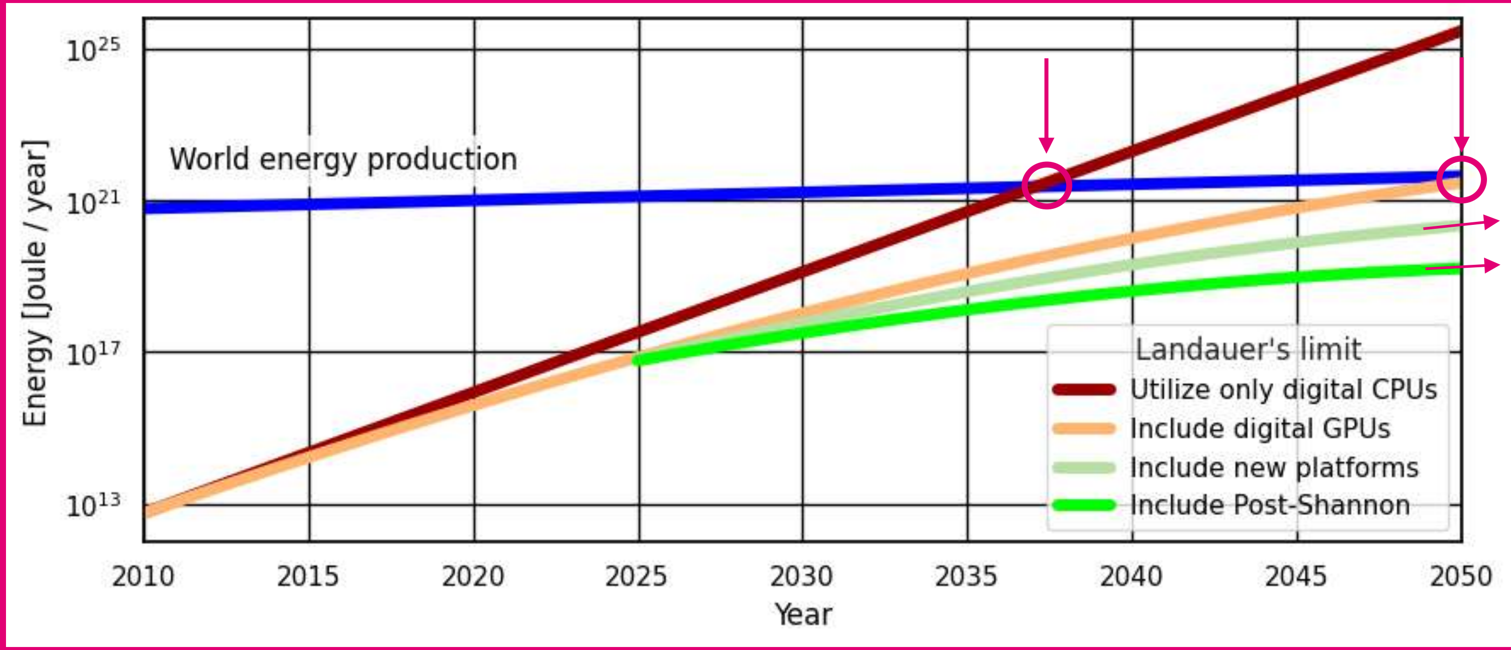
3. Communication Capacity vs. Data Generation — Always-available communication requires new research directions that address the imbalance of communication capacity vs. data-generation rates.
4. ICT Security — Breakthroughs in hardware research are needed to address emerging security challenges in highly interconnected systems and AI.
5. **Compute Energy vs. Global Energy Prod.** — This is creating new risks, and new computing paradigms offer opportunities to dramatically improve energy efficiency.

The Necessity of Extending Computing Paradigms

*"Energy consumption from ICT **already represents between 8–10% of global electricity use** and is projected to rise steeply with the proliferation of AI and immersive services (2022)."*

We are approaching the so called

"Energy-Information singularity."



Source: Ecologic Computing, Product Overview.

Created by Image Creator, Microsoft

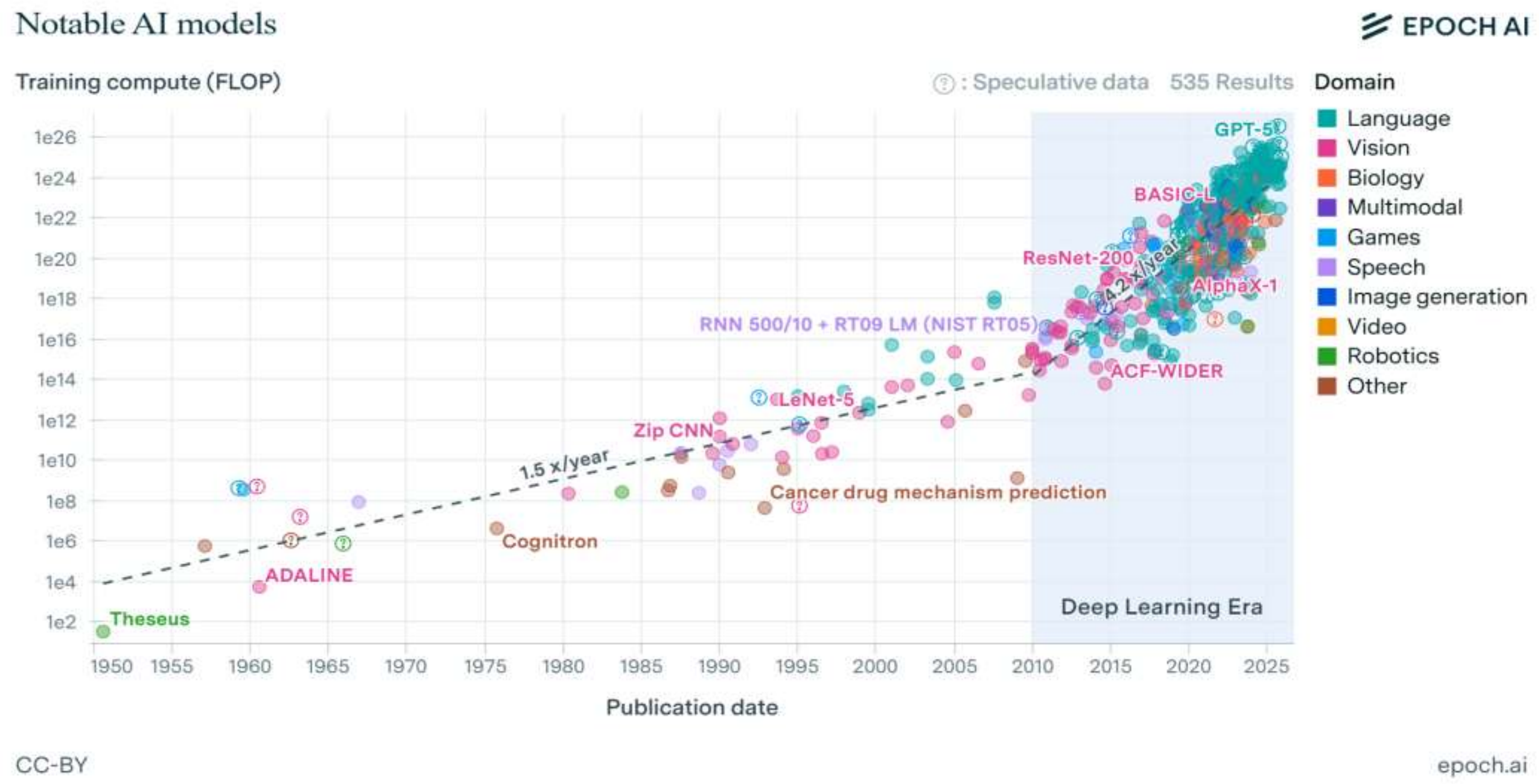
The previous graph was published with data gathered until 2022!

Let‘s dive into the most recent AI energy-related news…

Source: Gemini generated image

The Necessity of Extending Computing Paradigms

Growing number of AI models each year



Source: EPOCH AI - https://epoch.ai/data/ai-models

The Necessity of Extending Computing Paradigms

x4.2 compute resources required every year

Source: EPOCH AI - https://epoch.ai/data/ai-models

The Necessity of Extending Computing Paradigms

How big is 1 Giga Watt?

One Giga Watt could supply **700.000** average **households** with electricity.

That would be a city like **Frankfurt** or **Munich**.

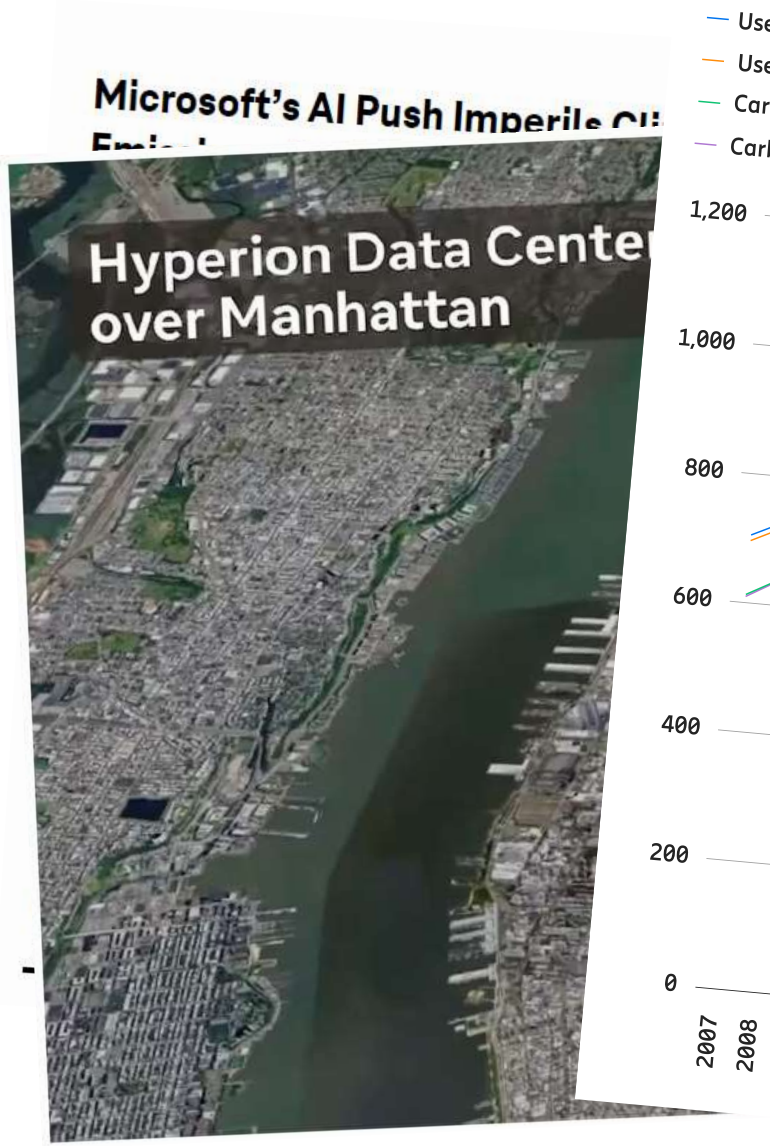
One Giga Watt could supply **100.000.000 LED Light** (10 watt).

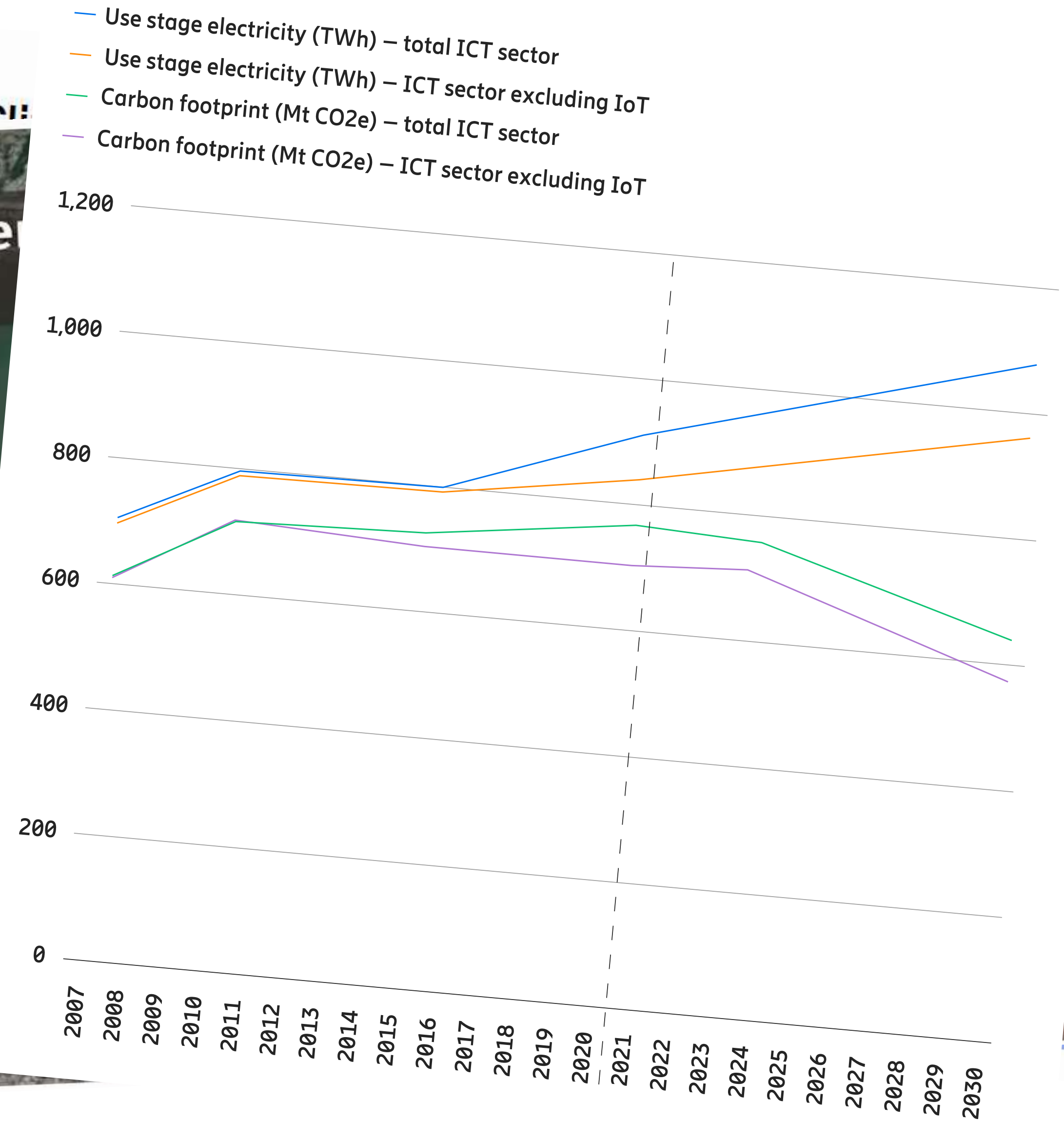
With this, **ALL households in Germany could be supplied with light** (two lamps per household).

Source: Responsible AI for Sustainable Business Success

The Necessity of Extending Computing Paradigms

We might be closer to the singularity than we think ...





Source: Gemini generated image

How to avoid reaching the singularity?

It is clear that:

"Simply improving transistor efficiency or scaling digital logic will not suffice (i.e., every bit processed carries an energy and thermodynamic cost bounded by Landauer's limit)"

Solution

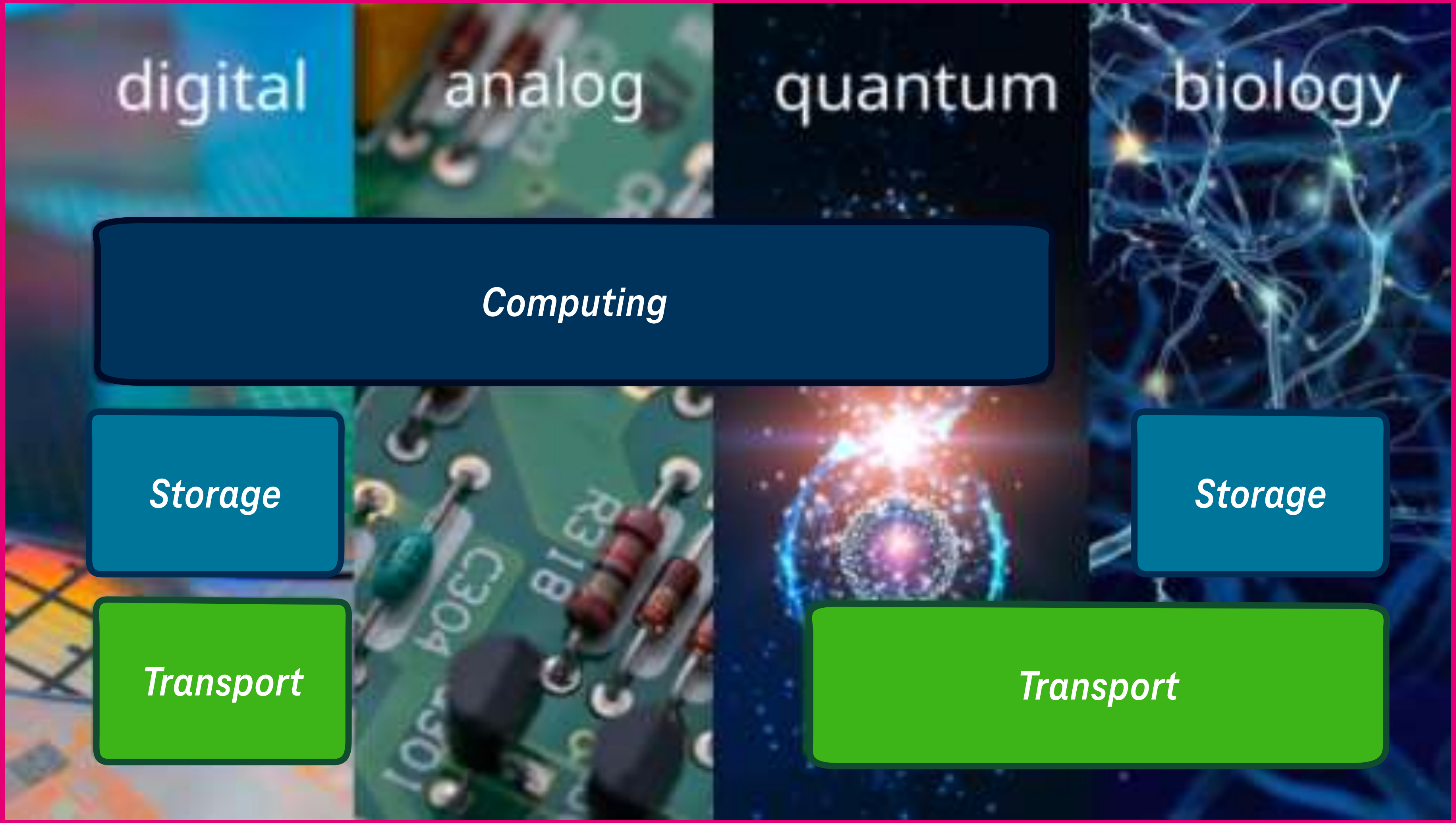
Either we **extend the compute spectrum towards physical, quantum and biological substrates.**

OR

Singularity is coming...

Source: Gemini generated image

New computing substrates



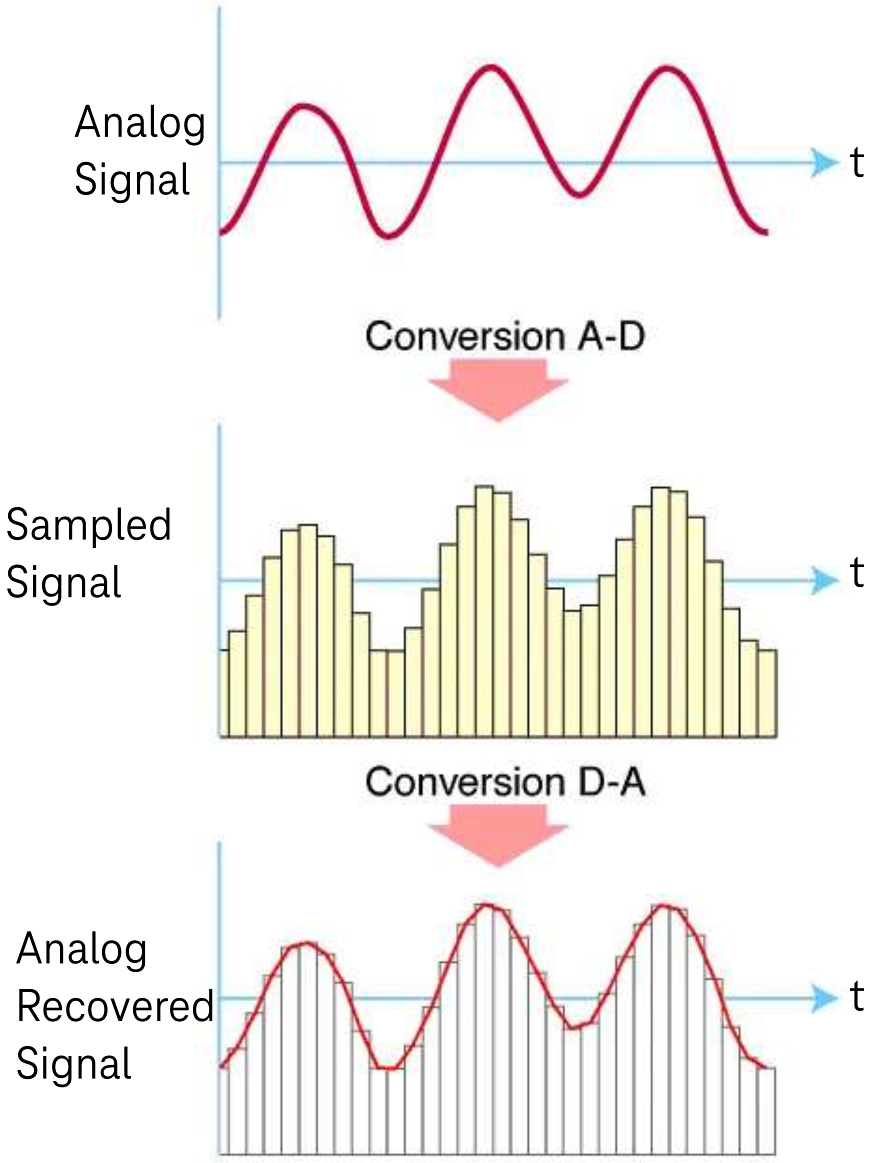
Source: Ecologic Computing, Product Overview.

Analog computing

An existing technology – reborn

- Analog computation became an old technology when digital systems started to araise but is being reborn in the AI and sensor era.

- Rather than converting physical phenomena into digital form, analog systems perform computation directly in the physical domain using currents, voltages, or wave interference as computational substrates.



Analog computing

An existing technology – reborn

Antikythera – 200 B.C.

1. In-memory analog processing for neuromorphic inference, using resistive memory crossbars (RRAM, FeFETs) as matrix-

2.

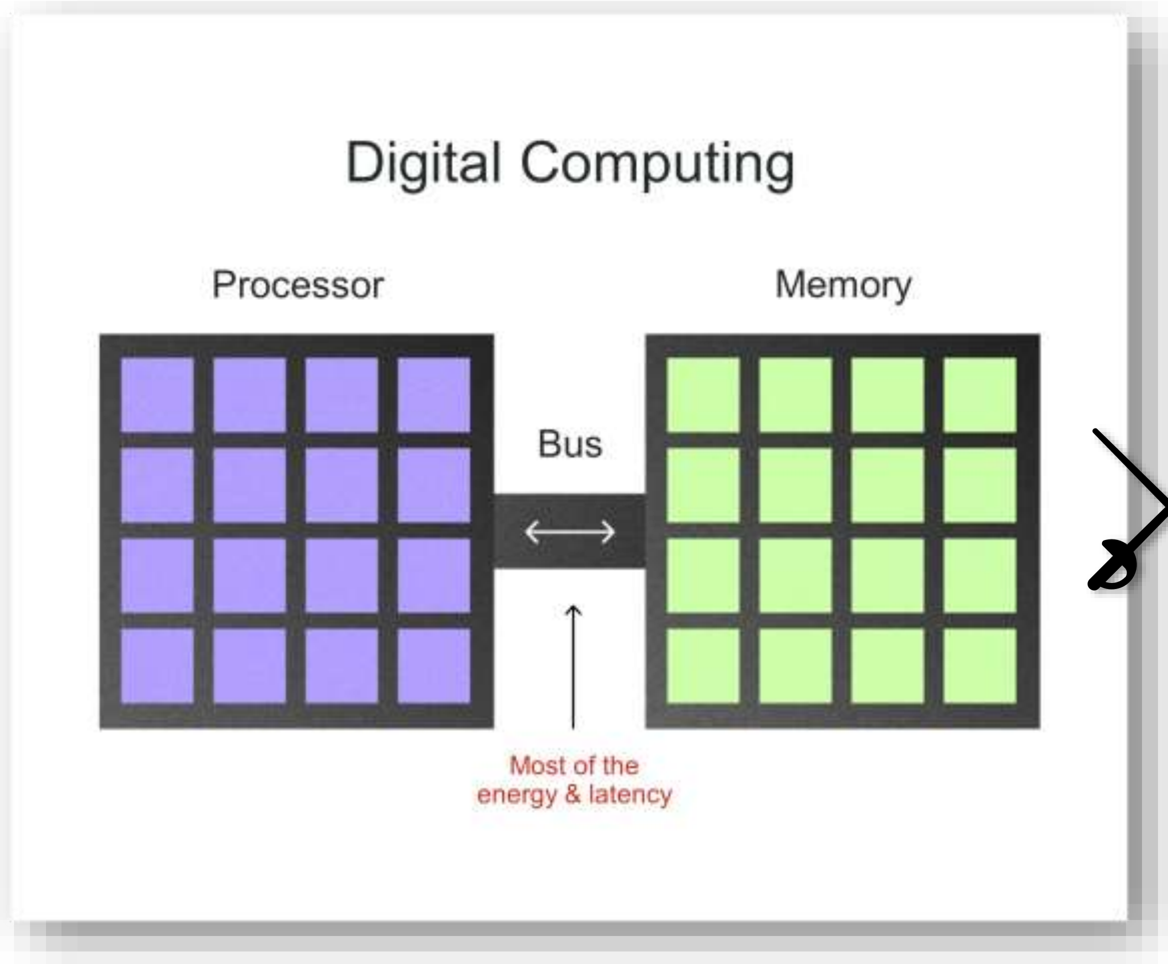
1. systems, aligning with the Decadal Plan's concept of 100.000:1 data-to-information compression.

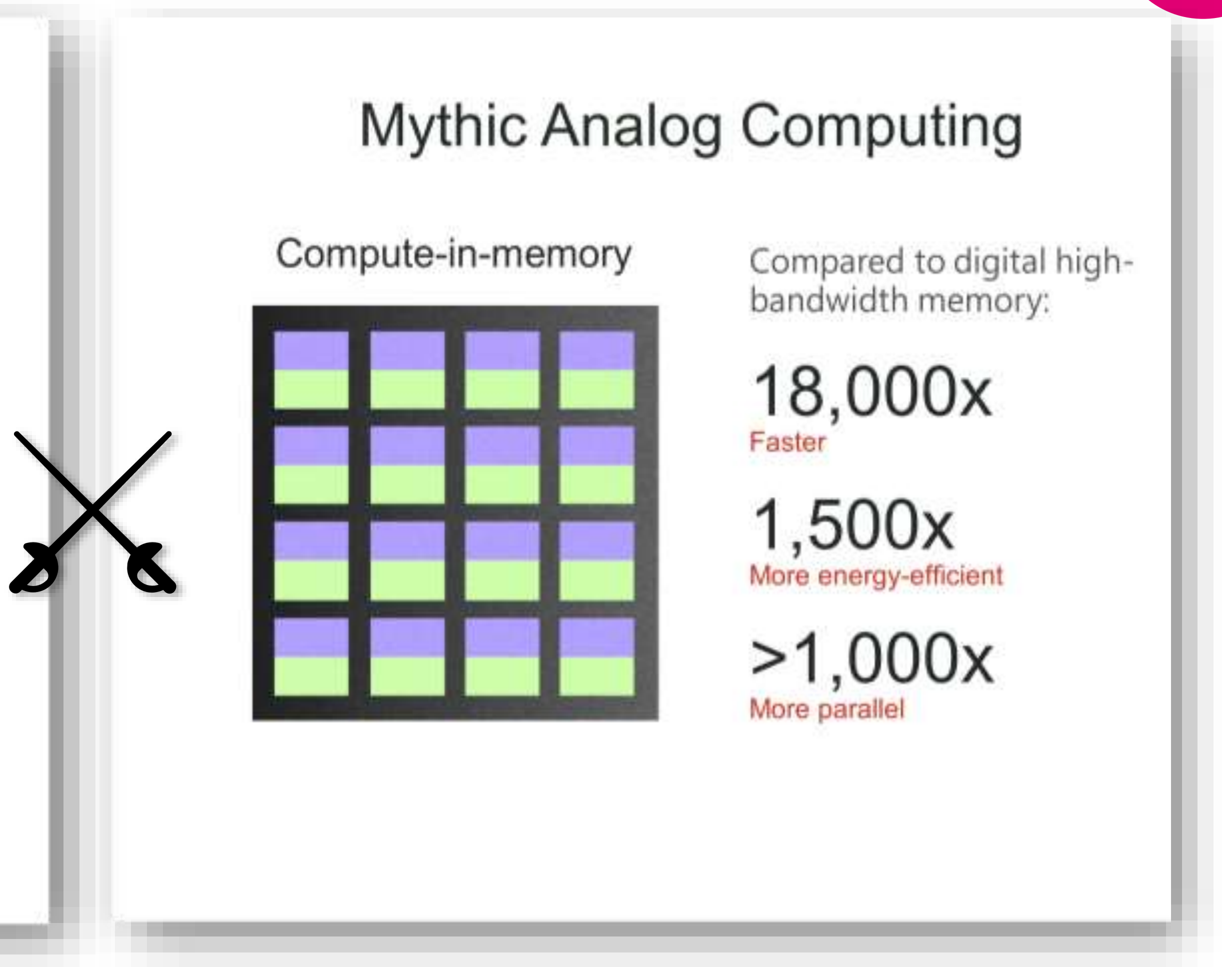
- *10x more affordable*
- *3.8x less power*
- *2.6x faster**

·Mythic MM1076 chip compared to an industry-standard AI inference digital chip, independently tested for batch-1 yolov8s at 1408x1408.

Source: https://mythic.ai/

Analog computing
Analog processor architectures





Source: https://mythic.ai/

Analog computing
Conclusions

ANALOG	DIGITAL
Calculation using varying values	Calculation using binary code
Often built for one task	Programmable
No memory	Storage for programs and data
Physically large	Can be miniaturized
Power hungry	Uses less power
Immediate result	Processing time required
Approximate output	Precise output

OLD ANALOG COMPUTER	NEW ANALOG CHIP
Calculation using varying values	Can cohabit with a digital computer
Often built for one task	Programmable
No memory	Storage for programs and data
Physically large	Tiny
Power hungry	Very low power consumption
Immediate result	Immediate results
Approximate output	Output can be refined digitally

Source: Wired/science/analog-computing

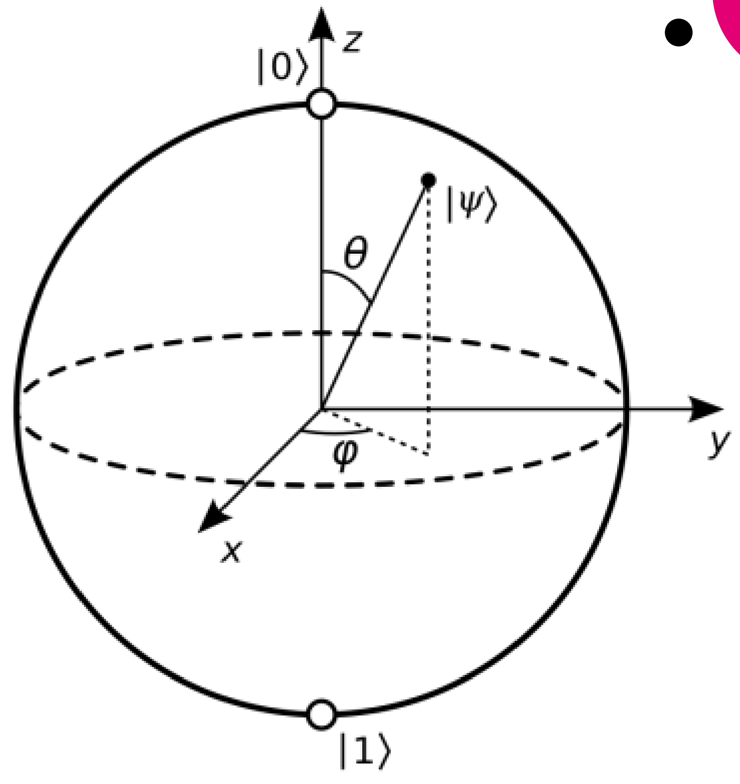
Quantum computing

The Qubit paradigm

- Quantum computing introduces a computational fabric based on qubits, whose states are described by probability amplitudes rather than binary logic.

- Quantum superposition and entanglement allow certain classes of problems (i.e., molecular modeling, optimization, and cryptography) to be solved exponentially faster than by digital machines.

- The true value of quantum computing lies not only in speed, but in energy-information density: a single cryogenic quantum processor could replace thousands of high-power digital clusters for specific workloads.

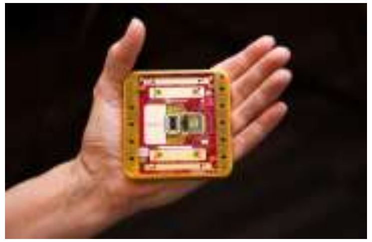


Bloch Sphere

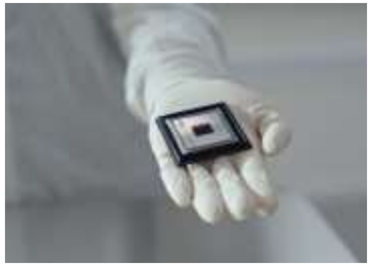
Quantum computing

The Quantum race

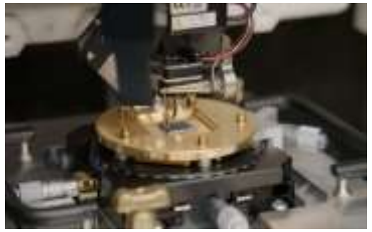
- **Microsoft:**
  - **Approach:** Topological qubits
  - **Processor:** Majorana 1
  - **Qubits:** 8



- **Google:**
  - **Approach:** Superconducting qubits
  - **Processor:** Willow
  - **Qubits:** 105



- **Amazon:**
  - **Approach:** Superconducting qubits
  - **Processor:** Ocelot
  - **Qubits:** 9 (CAT & transmon)



- **IBM:**
  - **Approach:** Superconducting qubits
  - **Processor:** Condor
  - **Qubits:** 1121

Quantum computing
Applications & Challenges

Application Area	Description and Rationale	Key Challenge
Information Exchange	Integrates **quantum accelerators with neuromorphic and analog units** to form energy-heterogeneous compute fabrics. This is key to task-based orchestration.	**The No-Communication Theorem:** Prevents instantaneous data transfer via entanglement alone; limits apply to FTL (faster-than-light) communication.
Enhanced Security	**Quantum Key Distribution (QKD)** provides intrinsically secure cryptographic key exchange by leveraging quantum mechanics to detect any eavesdropping attempt.	**Scalability and Hardware Complexity:** Requires complex, stable, and often cryogenic hardware, making large-scale deployment challenging.
Information Density	Utilizes **qubits** to solve exponentially complex problems (e.g., molecular modeling and optimization) with potentially lower thermodynamic cost per logical operation.	**Decoherence:** Qubits are highly fragile; environmental noise leads to the loss of quantum states, which compromises computational fidelity.
Transport Network	**Optical Distributed Quantum Systems** enable entanglement-assisted Networking, linking quantum nodes to form a cohesive quantum communication and compute infrastructure.	**Signal Loss and Entanglement Distribution:** Maintaining quantum states over long distances in optical fibers is difficult, requiring quantum repeaters and efficient distribution protocols.

Quantum computing

Main EU research drivers

Quantum Flagship

A major European Union scientific research initiative launched in 2018 with a budget of at least €1 billion over ten years.

OpenSuperQ

The project, coordinated by Saarland University and involving 10 international partners from academia and industry at its inception, aimed to develop a hybrid high-performance quantum computer based on superconducting integrated circuits, with a target of up to 100 qubits.

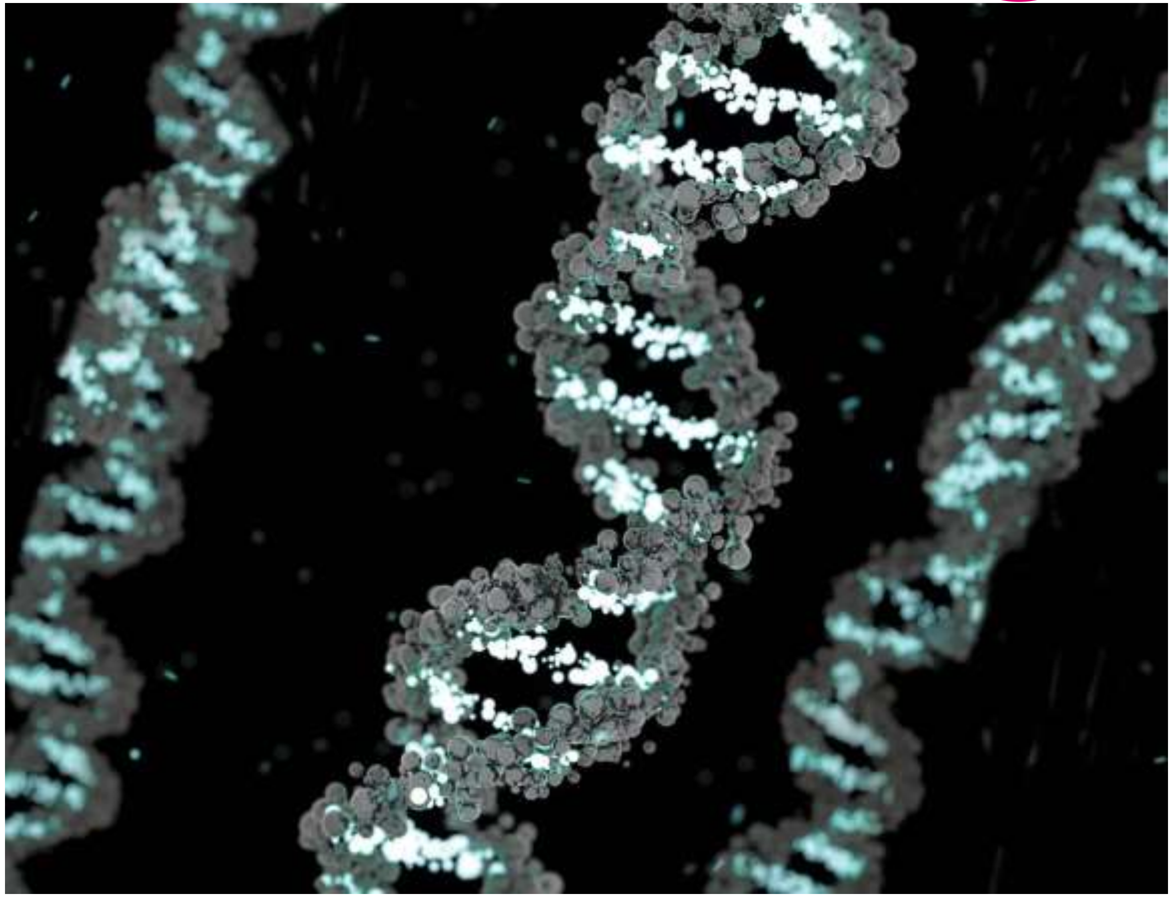
OpenSuperQPlus

OpenSuperQPlus (Open Superconducting Quantum Computers) is funded by the European Union with 20 million euros from a specific quantum grant within the Horizon Europe framework programme. Continues the work carried out in OpenSuperQ.

Biological computing

Nature as an ICT technology

- Extends computation to the molecular and cellular scale, exploiting DNA, RNA, proteins, and even bacteria as information carriers and storage.
- Synthetic biology now enables programmable circuits inside living organisms, capable of sensing, memory, and logic operations.
- The shift to biological computing architectures offers profound energy benefits, moving computation closer to the theoretical thermodynamic limits of information processing.
- This enables a path toward a sustainable future for ICT, featuring systems that are biodegradable, require minimal standby power, and dramatically reduce the overall e-waste and energy footprint of computation, directly challenging the threat of the energy-information singularity.



Source: https://spectrum.ieee.org/exabytes-in-a-test-tube-the-case-for-dna-data-storage

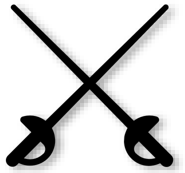
Biological storage
Exabytes in a test tube

- **Sloan Digital Sky Survey:** 73000 GB (73 TB) per year
- **Large Hadron Collider:** 50 million GB (50 PB) per year
- **Worlwide genomics field:** 1 ZB per year
- **Australian Square Kilometre Array Pathfinder:** 750 TB per second (25ZB per year)

Unit	Shortened	Capacity
Bit	b	1b
Byte	B	8 bits
Kilobyte	KB	1024 bytes
Megabyte	MB	1024 kilobytes
Gigabyte	GB	1024 megabytes
Terabyte	TB	1024 gigabytes
Petabyte	PB	1024 terabytes
Exabyte	EB	1024 petabytes
Zettabyte	ZB	1024 exabytes
Yottabyte	YB	1024 zettabytes

Biological storage

Exabytes in a test tube



- **Physical limit:** 1 TB per square inch.
- **Energy demand:** 6-9 watts per drive
- **Lifespan:**
    - **Laptop HDD:** 3-5 years
    - **Server HDD:** 6-7 years
    - **SDDs:** 5-7 years
    - **SD Card:** 5-10 years
    - **CD/DVDs:** +20 years
    - **Magnetic tape:** 30-100 years

- **Physical limit:** 100 trillion GB per gram (1000 YB)
- **Energy demand:** None as far as it is stored in a controlled environment.
- **Lifespan:** ~100.000 years*
- **Example:** Escherichia coli has a storage density of 10^{19} bits of data per cubic centimeter, meaning 1.7 Tbits can be stored in just 1 gram of DNA. (1-2 micrometers length)**

*https://www.csmonitor.com/Science/2013/0626/Straight-from-the-horse-s-toe-the-world-s-oldest-genome

**https://pmc.ncbi.nlm.nih.gov/articles/PMC10296570/

Source: https://spectrum.ieee.org/exabytes-in-a-test-tube-the-case-for-dna-data-storage

Biological networks
Mushrooms!?

Biological networks

WWW - Wood Wide Web

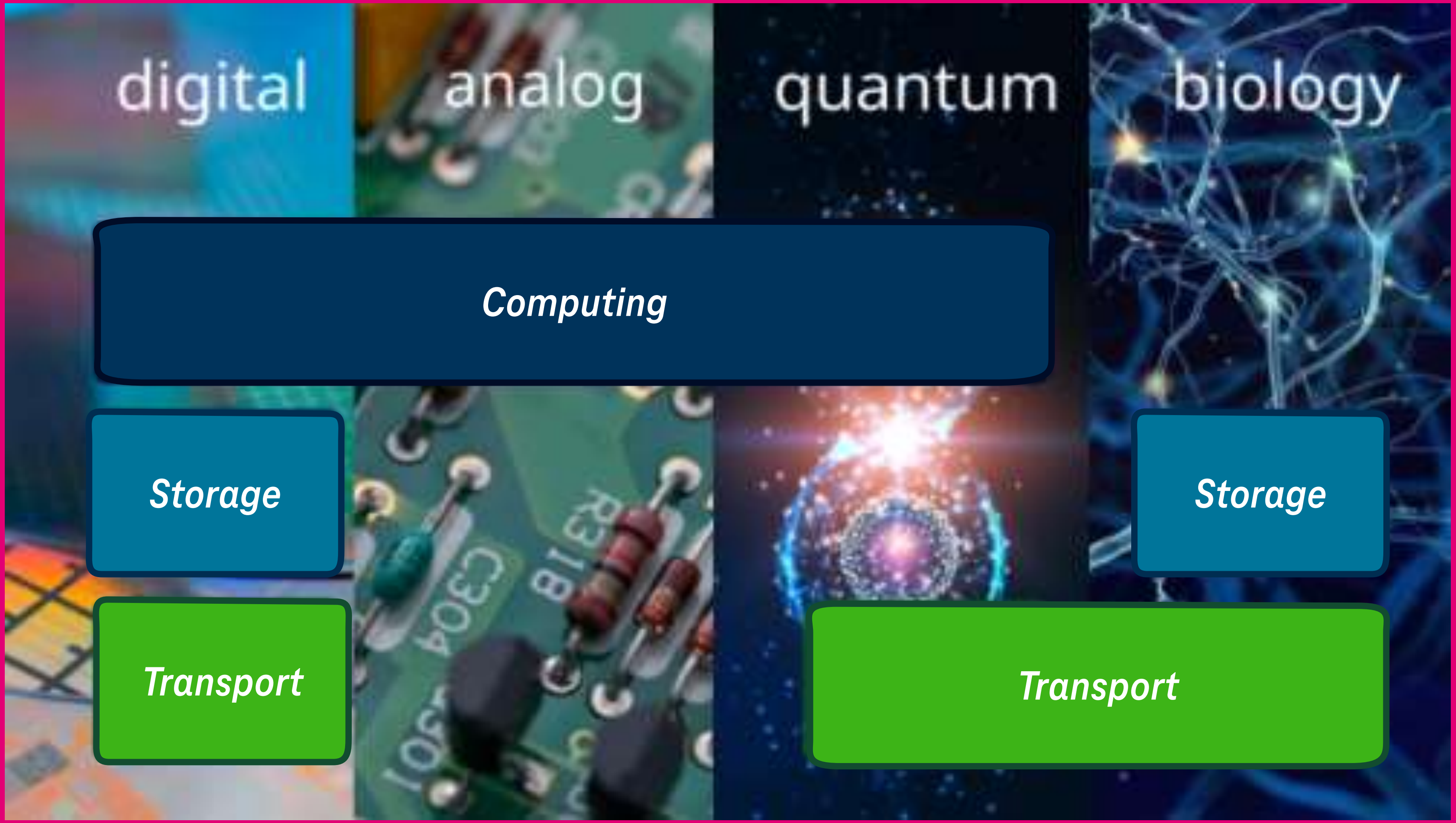
Mycelium Networks - Decentralized Biological Processors

- **Function as Wetware:** The vast, fibrous network of fungal mycelium is being explored as a substrate for *unconventional computing*. Researchers have successfully demonstrated that the bio-electrical activity of mycelium can be harnessed to implement logical gates and circuits, effectively acting as a biological processor or volatile memory ("RAM").

- **Distributed Architecture:** Mycelial growth naturally forms an efficient, distributed network, often dubbed the "wood wide web." This structure is intrinsically suited for decentralized computation, pattern recognition, and large-scale environmental sensing systems.

- **Sensing**: Mycelium networks react to physical, environmental and chemical stimuli i.e., pressure, temperature, humidity, bacteria, etc.

New computing substrates



Source: Gemini generated image

Post-Shannon

Shannon's theory defined the limits of reliable digital communication through discrete bits and entropy. However, future hybrid computing fabrics, where information may exist in analog, quantum, or biochemical forms, demand post-Shannon frameworks.

Post-Shannon communications explore:

- **Semantic and goal-oriented transmission:** Only *meaningful* or *actionable* information is communicated.
- **Analog and biological signaling channels:** such as chemical or optical gradients in intra-body or environmental networks.

By co-designing communication and computation under unified thermodynamic and informational principles, post-Shannon architectures can drastically reduce global data movement energy.

Source: Gemini generated image

Feedback and supporting ideas are highly appreciated!

Source: Gemini generated image

Q&A

Source: Gemini generated image

Disclaimer

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Source: Gemini generated image