

# 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 a fundamental inflection point:

- 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

The screenshot shows the Semiconductor Research Corporation (SRC) website. At the top, there is a navigation bar with the SRC logo, the text 'Semiconductor Research Corporation', and links for 'Go to SMART USA', 'Mission', 'About', 'Connect', and 'Work'. Below the navigation bar, the breadcrumb 'Home » About » Decadal Plan' is visible. The main heading is 'The Decadal Plan for Semiconductors' with the subtitle 'A PIVOTAL ROADMAP OUTLINING RESEARCH PRIORITIES'. A quote states: 'Semiconductors help shape the way we live. The Decadal Plan for Semiconductors describes the possibilities for semiconductors in the coming decade and defines the challenges to overcome for realizing that vision.' The page is divided into three main columns. The left column, 'The Challenge', discusses the need for innovation in ICT and the physical limits of CMOS scaling. The middle column, 'Semiconductor Technology Leadership Initiative', contains four orange buttons: 'Download the Report Overview', 'Download the Abridged Report', 'Download the Full Report', and 'Download the Spring Tech Forum Summary', each with a brief description. The right column, 'Related Events and News', lists 'SRC-SIA 2022 Webinar Series', 'SRC-SIA 2021 Webinar Series', 'In The News', and 'NIST Microelectronic and Advanced Packaging Technologies (MAPT) Roadmap'. A large pink starburst graphic with the year '2021' is overlaid on the bottom right of the page.

Semiconductor Research Corporation

Go to SMART USA

Mission About Connect Work

Home » About » Decadal Plan

## The Decadal Plan for Semiconductors

A PIVOTAL ROADMAP OUTLINING RESEARCH PRIORITIES

“ Semiconductors help shape the way we live. The Decadal Plan for Semiconductors describes the possibilities for semiconductors in the coming decade and defines the challenges to overcome for realizing that vision. ”

### The Challenge

Innovation in semiconductor technology is needed to advance information and communication technologies (ICT) critical to our economic growth and national security. Advances in semiconductor technology will be needed to manage the exponential amount of data to be moved, stored, computed, secured, and converted to end-user information. As computing systems move into the domain of AI, with cognition and reasoning, the underlying hardware performance is facing constraints by fundamental physical limits. The ICT opportunities of tomorrow are simply unachievable with current hardware technologies. A crisis is at hand, and the current paradigm must shift to create new value propositions with semiconductor technologies as the key driver.

### A Call to Action

We're on the edge of the next industrial revolution. Maintaining and strengthening U.S. leadership in ICT during this new semiconductor era requires tripling federal funding throughout the coming decade—an additional \$3.4B investment per year for large-scale industry-relevant semiconductor research. New public/private partnerships must be initiated to cover a wide breadth of interdependent technical areas and multi-disciplinary teams. Organized and coordinated investments with market-focused goals are needed to support essential technology development.

### Semiconductor Technology Leadership Initiative

[Download the Report Overview](#)

This one-page overview provides a quick summary of the Decadal Plan.

[Download the Abridged Report](#)

A 21-page executive summary that provides added context to the five seismic shifts and their five grand goals.

[Download the Full Report](#)

The final, 150-page report, it illustrates key challenges, trends, and promising technologies and includes all references and calculations.

[Download the Spring Tech Forum Summary](#)

This provides a summary of the Spring Tech Forum.

### Related Events and News

[SRC-SIA 2022 Webinar Series](#)

[SRC-SIA 2021 Webinar Series](#)

[In The News](#)

[NIST Microelectronic and Advanced Packaging Technologies \(MAPT\) Roadmap](#)

2021

# 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

- 1 The Analog Data Deluge**

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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**

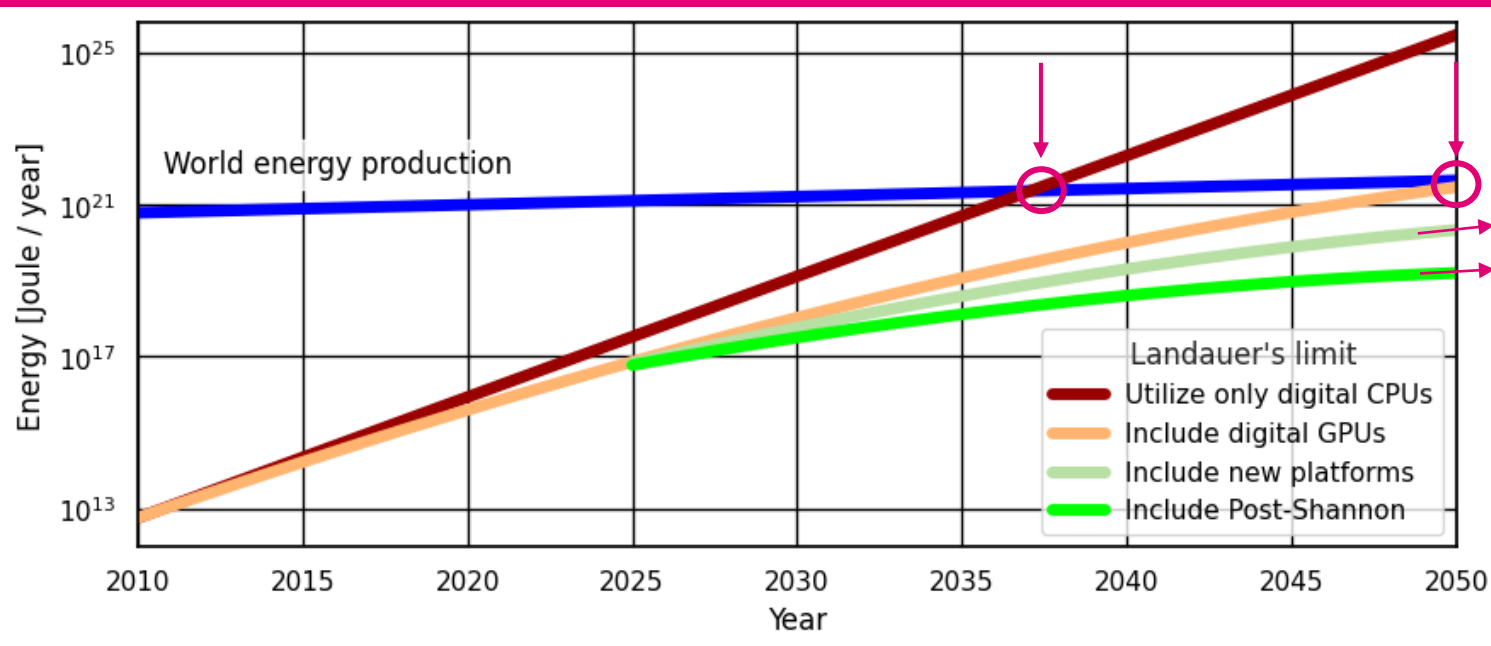
Breakthroughs in hardware research are needed to address emerging security challenges in highly interconnected systems and AI.
- 5 Compute Energy vs. Global Energy Prod.**

This is creating new risks, and new computing paradigms offer opportunities to dramatically improve energy efficiency.

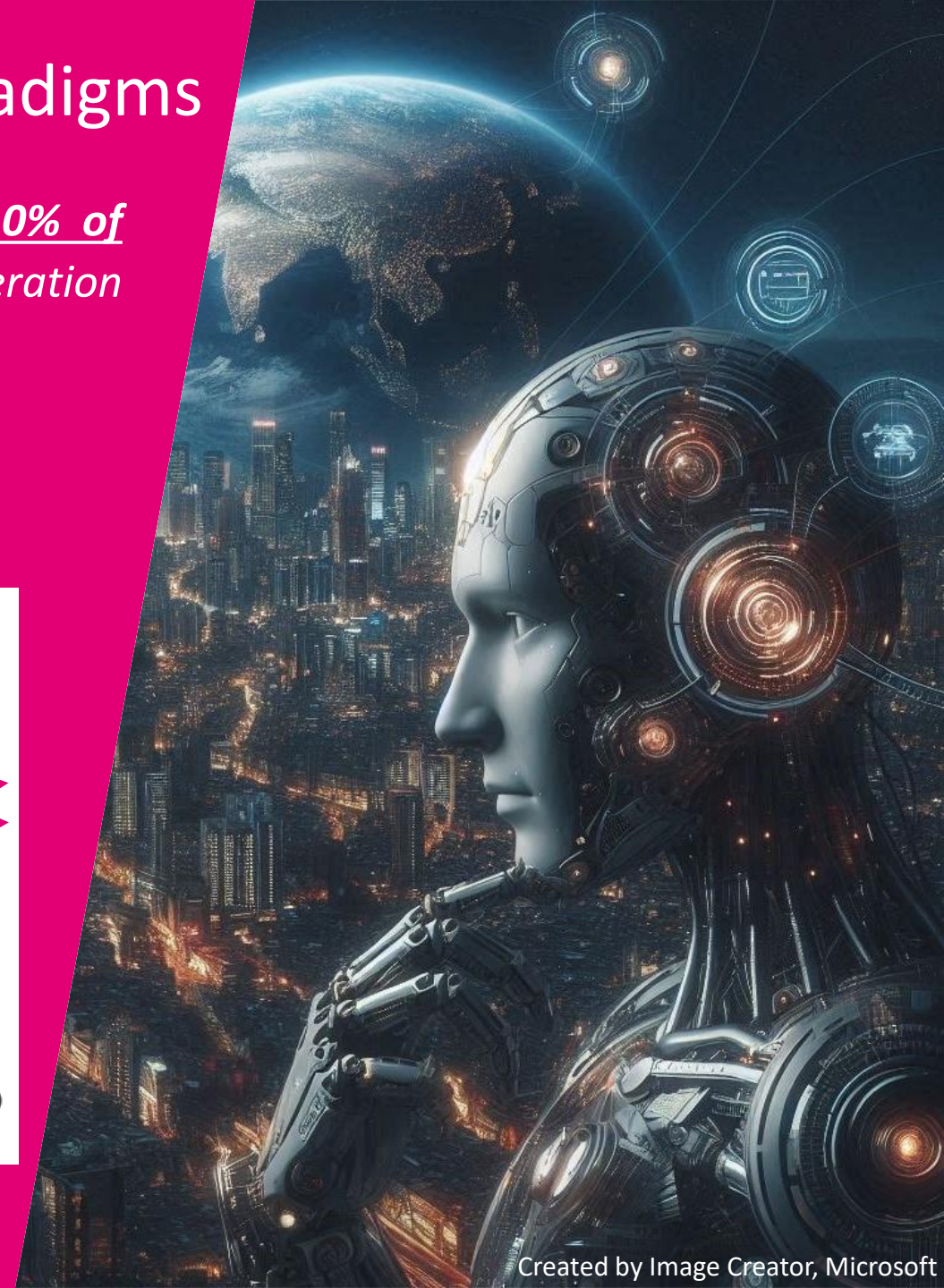
# The Necessity of Extending Computing Paradigms

*“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...



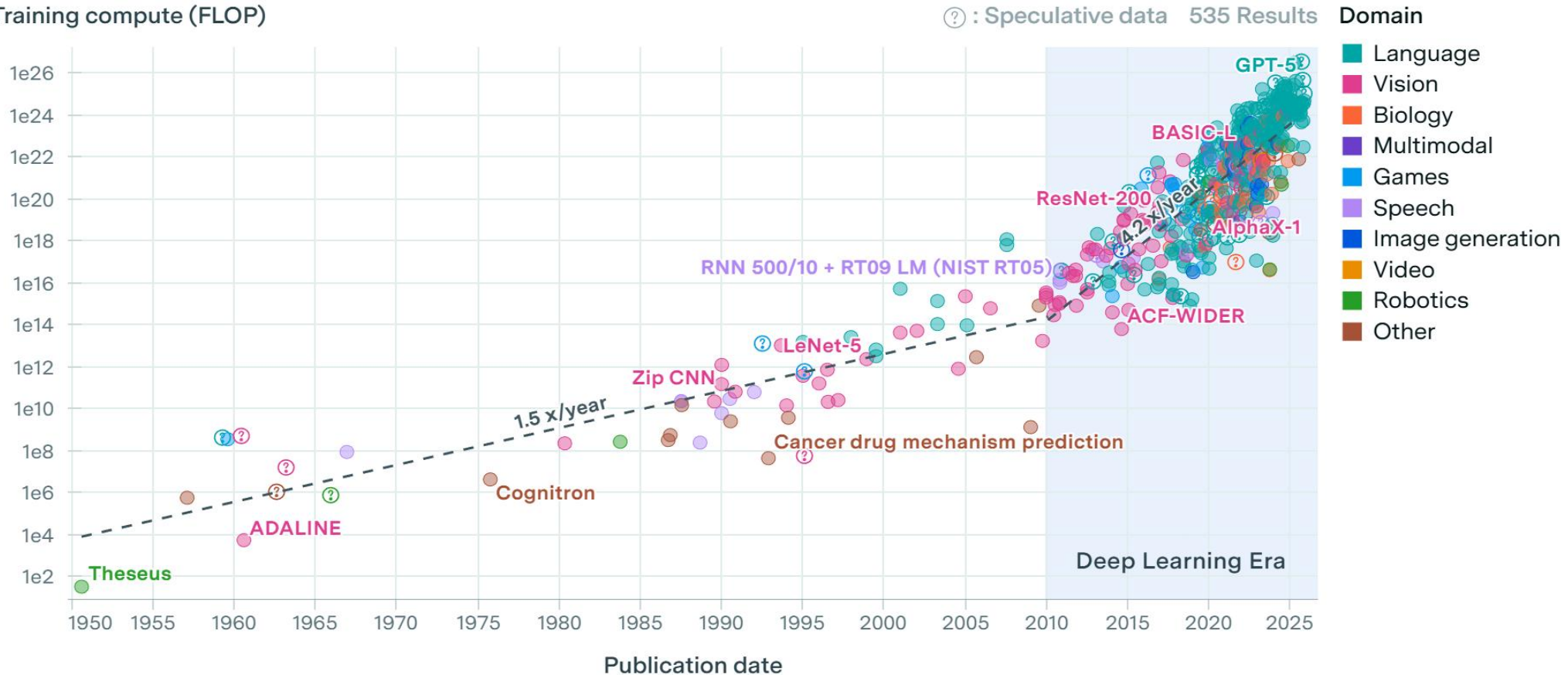
Source: Gemini generated image

# The Necessity of Extending Computing Paradigms

Growing number of AI models each year

## Notable AI models

Training compute (FLOP)



CC-BY

epoch.ai

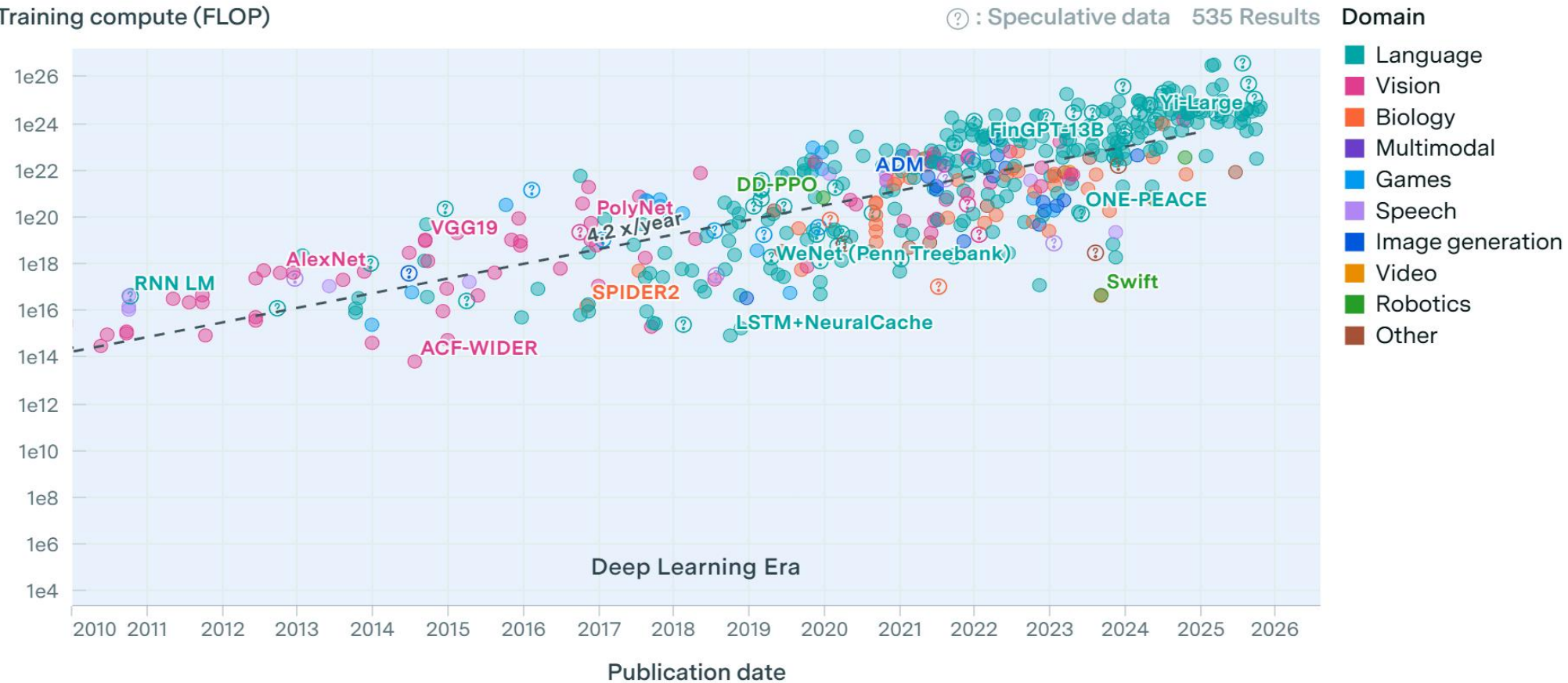


# The Necessity of Extending Computing Paradigms

x4.2 compute resources required every year

## Notable AI models

### Training compute (FLOP)



CC-BY

epoch.ai

# 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**.



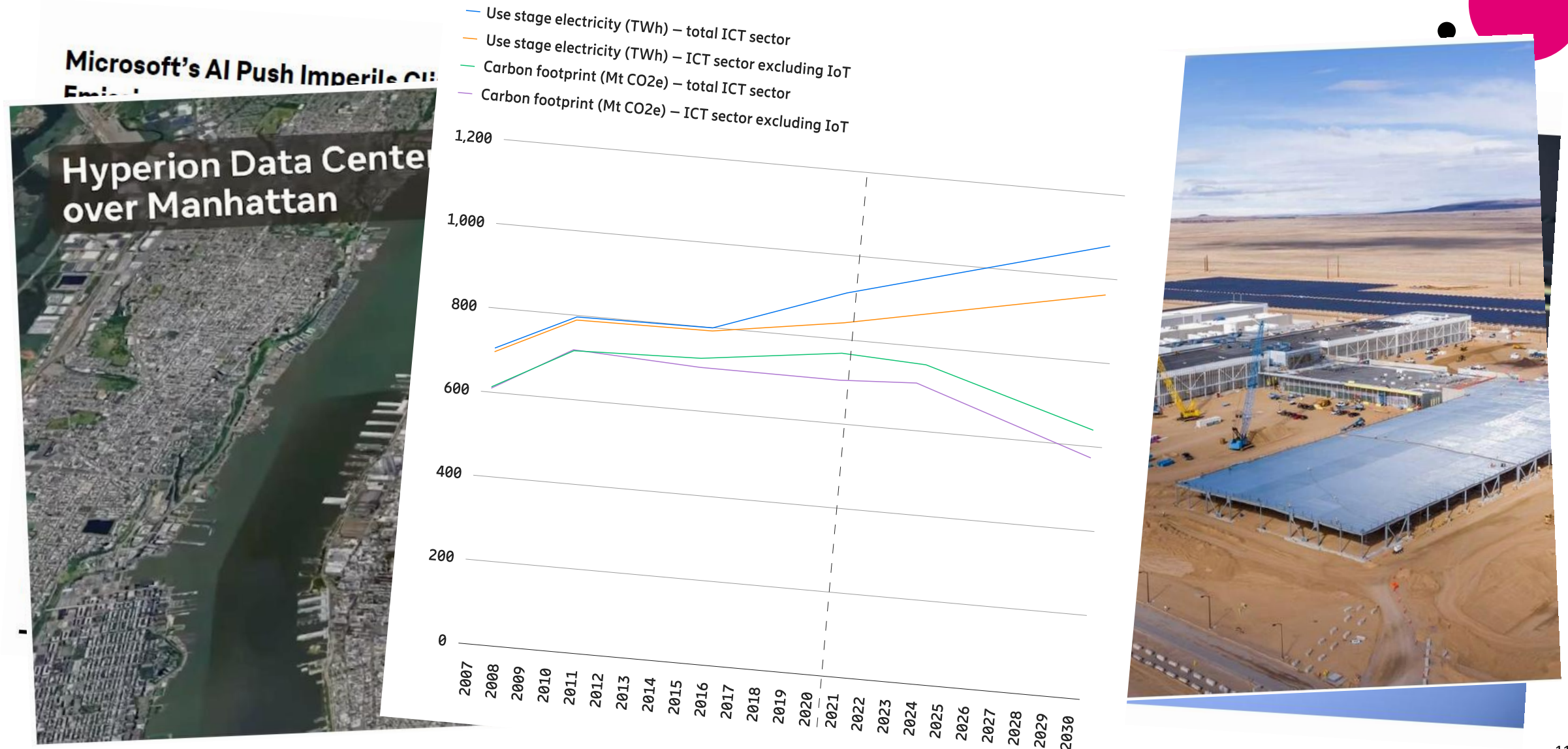
**One Giga Watt** could supply **100.000.000** LED Light (10 watt).

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



# 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

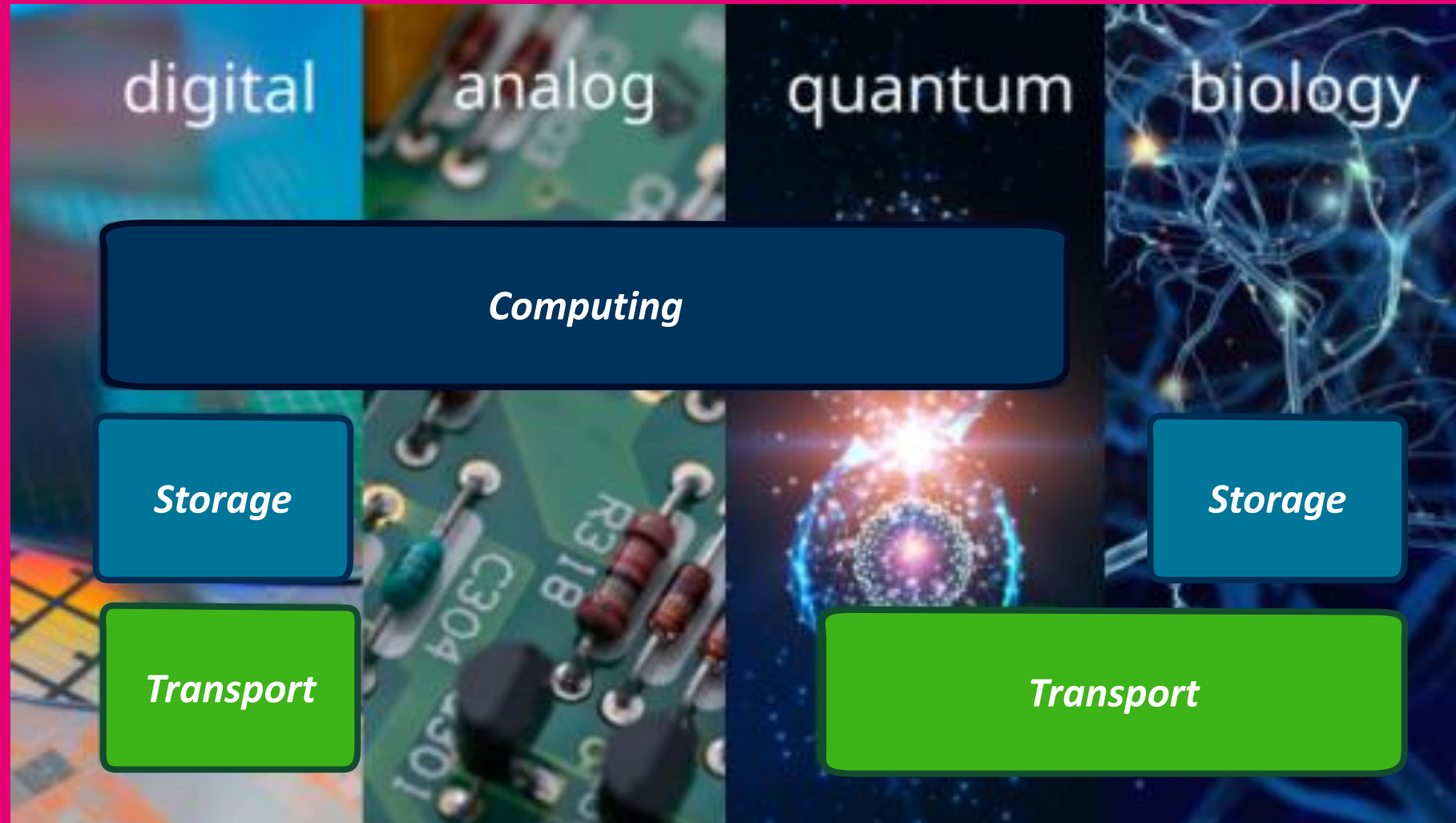
Either we **extend the compute spectrum towards physical, quantum and biological substrates.**

OR

**Singularity is coming...**



# *New computing substrates*

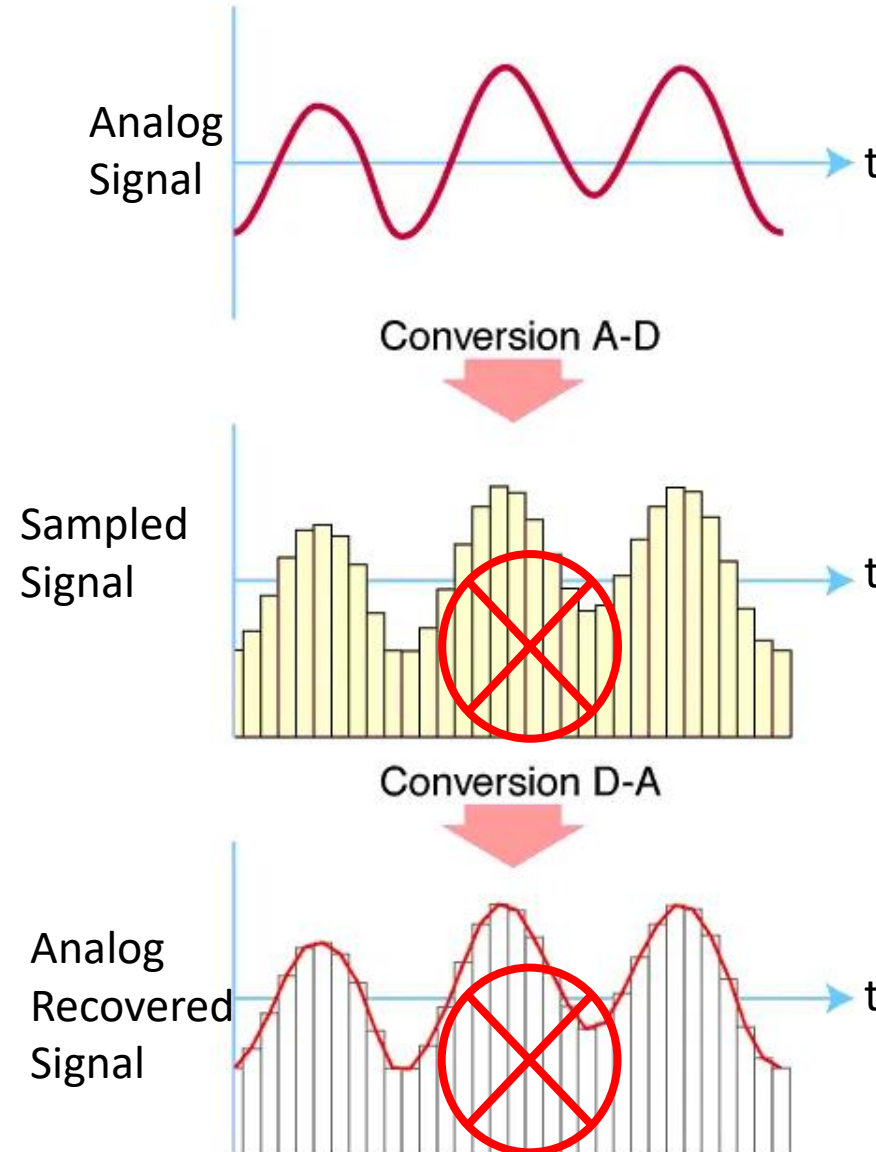




# Analog computing

An existing technology – reborn

- Analog computation became an old technology when digital systems started to arise 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.

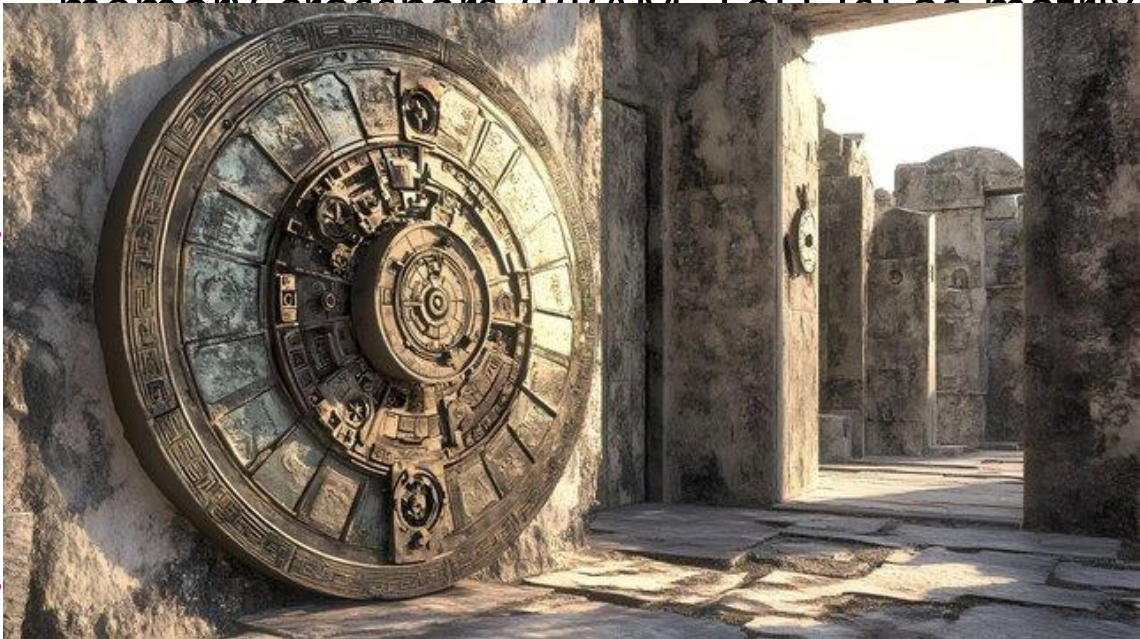


# Analog computing

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



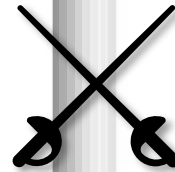
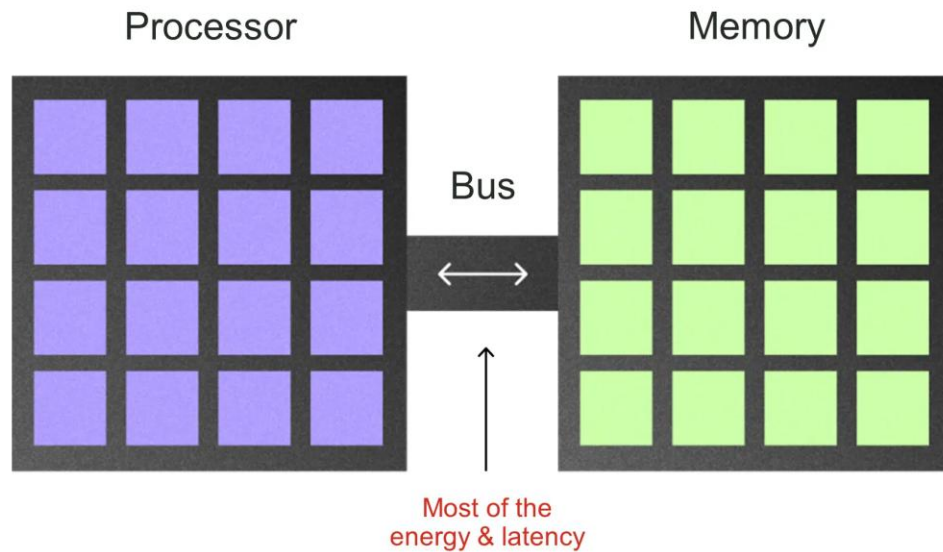
- 10x more affordable
- 3.8x less power
- 2.6x faster\*

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

# Analog computing

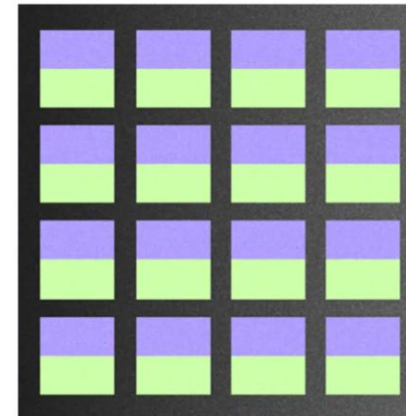
## Analog processor architectures

### Digital Computing



### Mythic Analog Computing

#### Compute-in-memory



Compared to digital high-bandwidth memory:

**18,000x**  
Faster

**1,500x**  
More energy-efficient

**>1,000x**  
More parallel



# Analog computing

## Conclusions

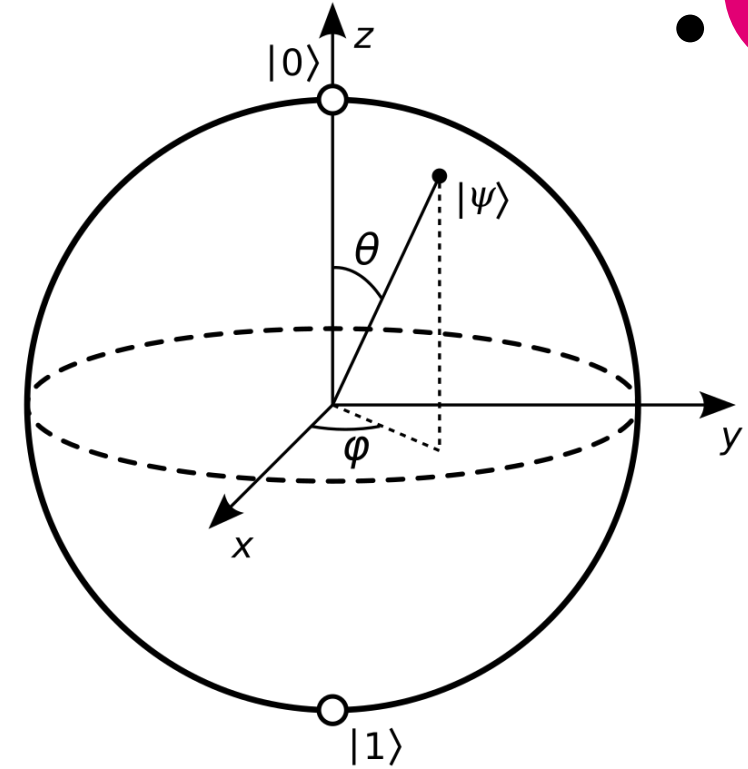
ANALOG	DIGITAL
Calculation using varying values	Calculation using binary code
Often built for one task	Programmable
No memory	Storage for programs and data
Physically large	Can be miniaturized
Power hungry	Uses less power
Immediate result	Processing time required
Approximate output	Precise output

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

# 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.



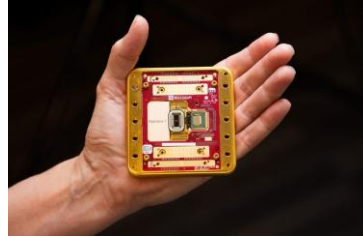
Bloch Sphere

# Quantum computing

## The Quantum race

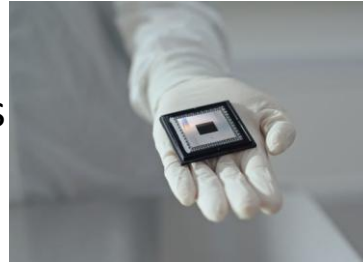
- **Microsoft:**

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



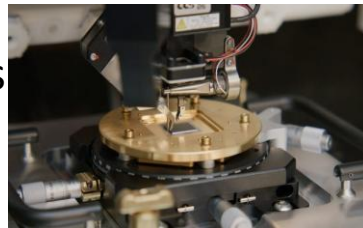
- **Google:**

- **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

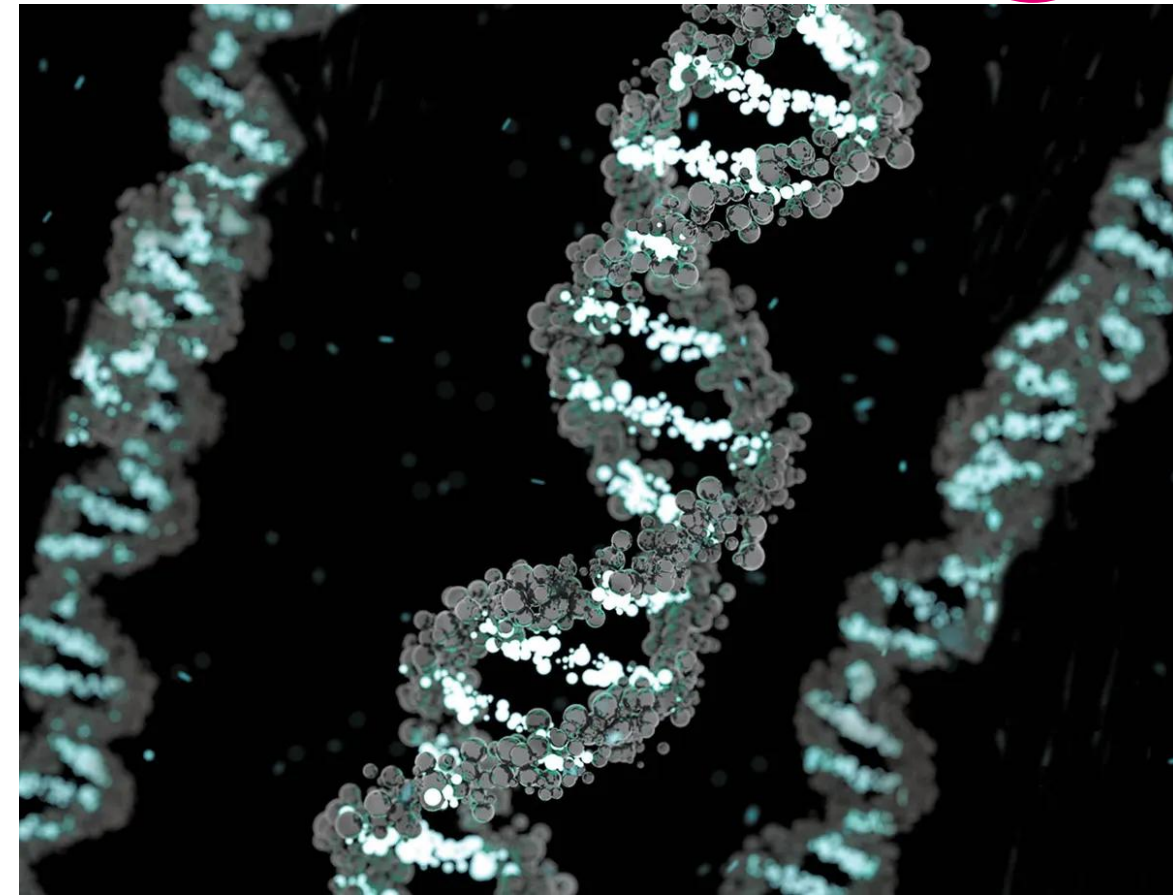
## Applications & Challenges

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

# 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

500

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

© Statista 2024

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  $10^{20}$  bits of data per cubic centimeter, meaning 1.28 Pbits can be stored in just 1 gram of DNA (1.8 bits per DNA nucleotide).\*\*

\*<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

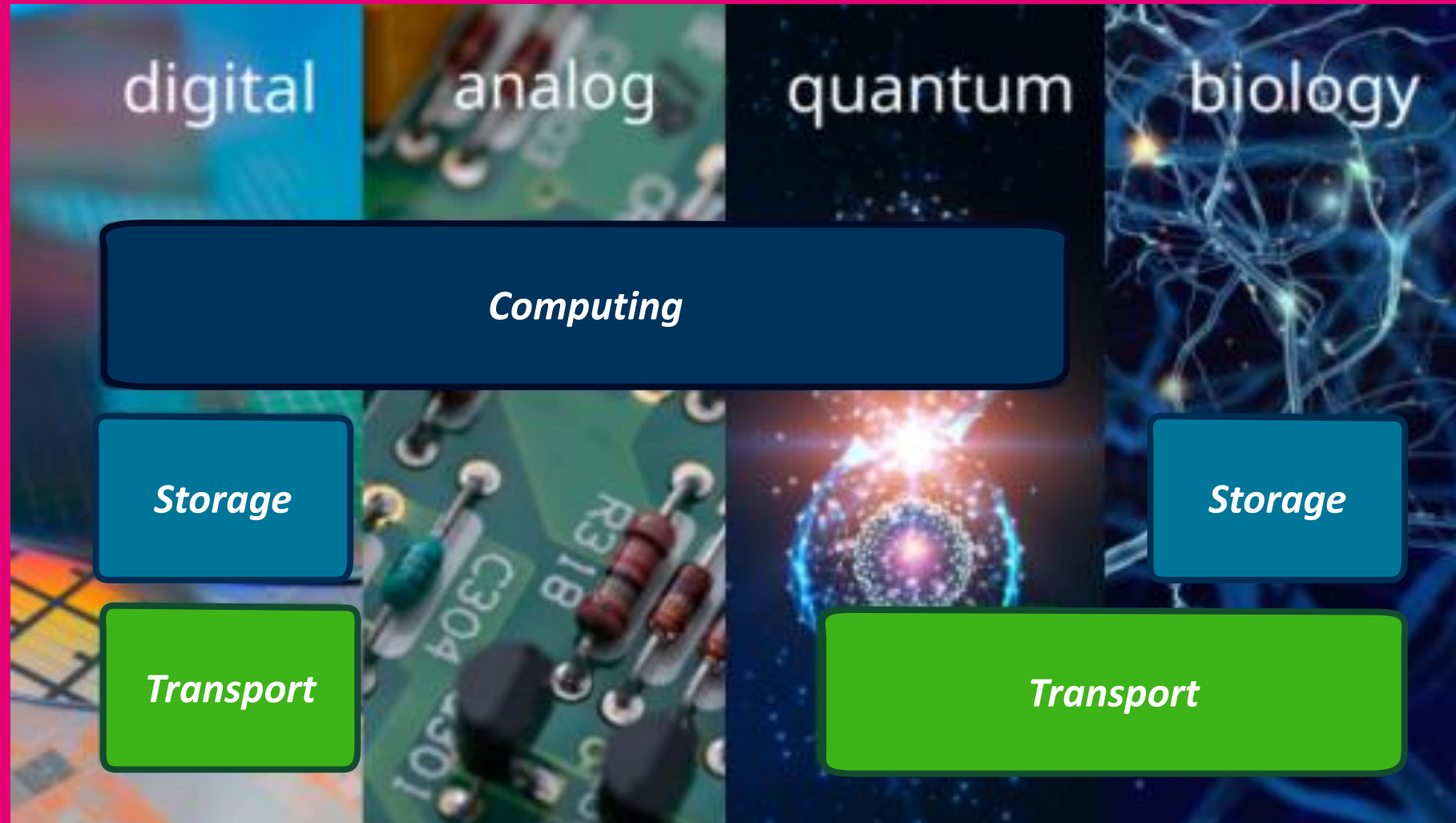
WWW - Wood Wide Web

## 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.





Feedback and supporting  
ideas are highly  
appreciated!





# Q&A



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# Disclaimer



Co-funded by  
the European Union

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