LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

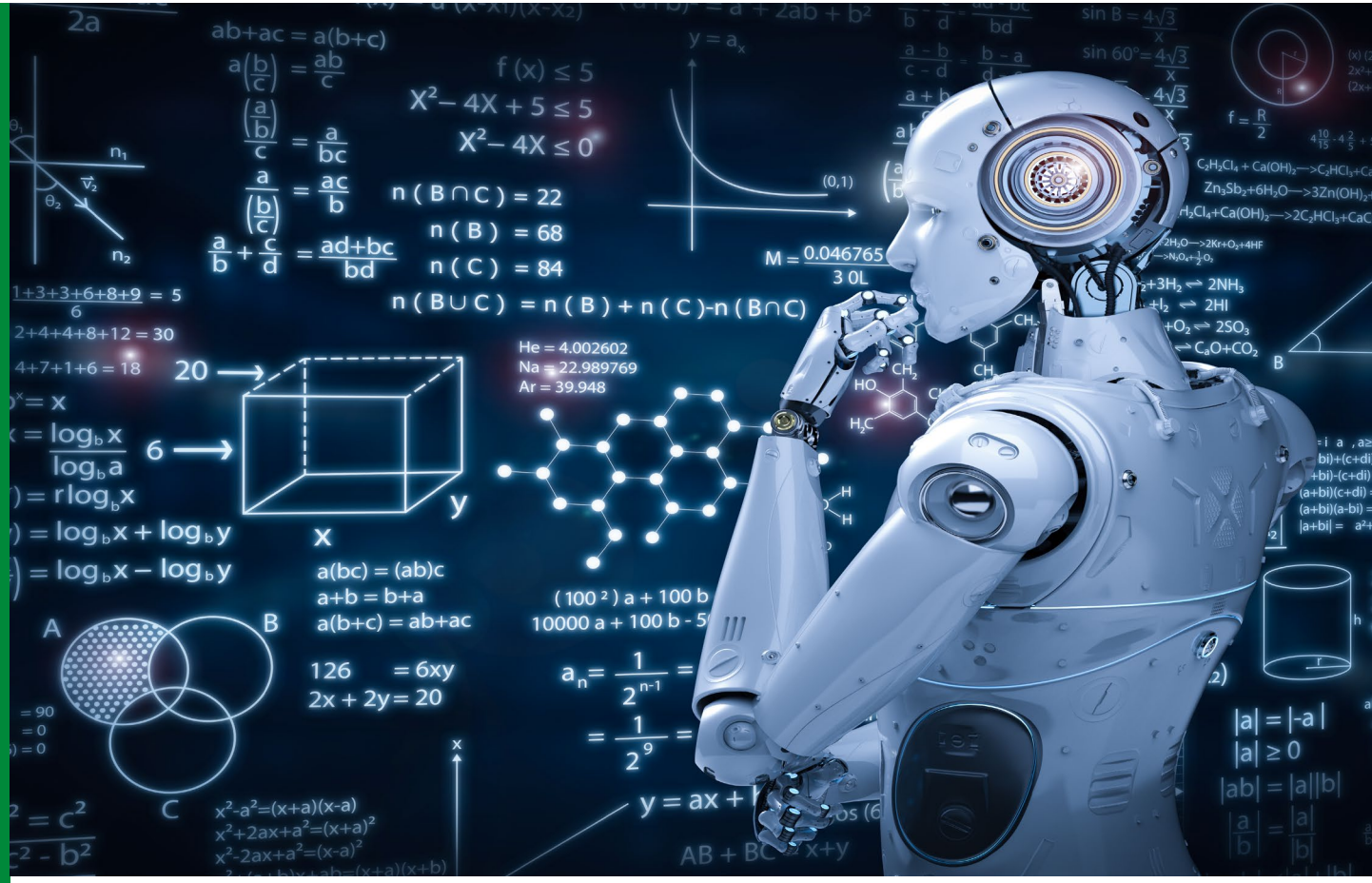
FACULTY FOR MATHEMATICS, INFORMATICS, AND STATISTICS
DEPARTMENT OF MATHEMATICS
BAVARIAN AI CHAIR "MATHEMATICAL FOUNDATIONS OF ARTIFICIAL INTELLIGENCE"

Rethinking Intelligence: Next Generation Computing for a Sustainable AI Future

Prof. Dr. Gitta Kutyniok

Ludwig-Maximilians-Universität München

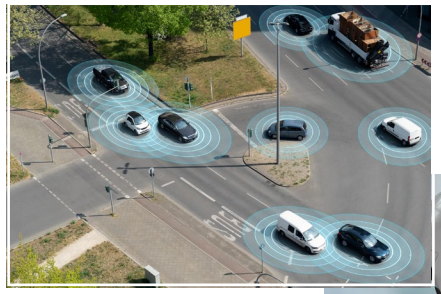
(also DLR – German Aerospace Center
& University of Tromsø, Norway)

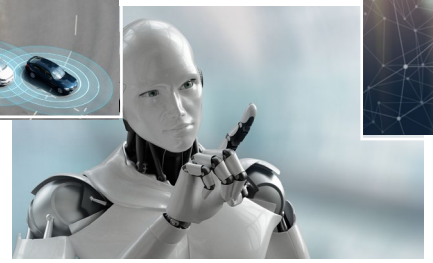


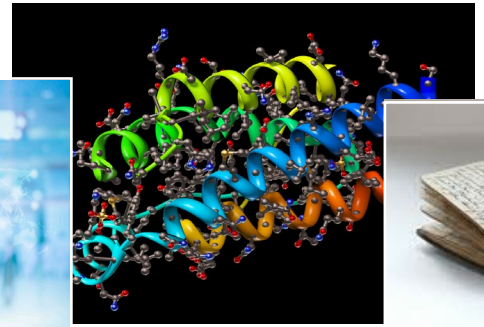
AI for Good Global Summit
Geneva, 8.-11.7.2025

baiosphere the bavarian ai network
DFG Deutsche Forschungsgemeinschaft
Bundesministerium für Bildung und Forschung
relAI Konrad Zuse School of Excellence in Reliable AI
mcml Munich Center for Machine Learning
Bayerisches Staatsministerium für Wissenschaft und Kunst
HIGHTECH Agenda Bayern

Fourth Industrial Revolution by Artificial Intelligence







Radical Change of our Society in its Full Breadth!

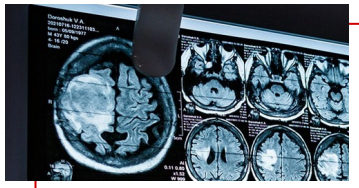
Challenges in Artificial Intelligence: Reliability

Problems with Safety

Example:
Accidents involving robots

Problems with Security

Example:
Risks of hacking into AI systems



Problems with Privacy

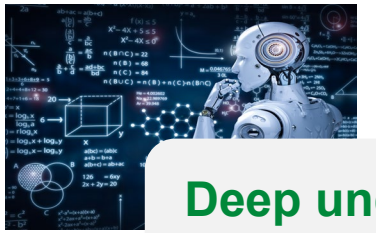
Example:
Privacy violations of health data

Problems with Responsibility

Example:
Black-box and biased decisions

Current major problem worldwide:

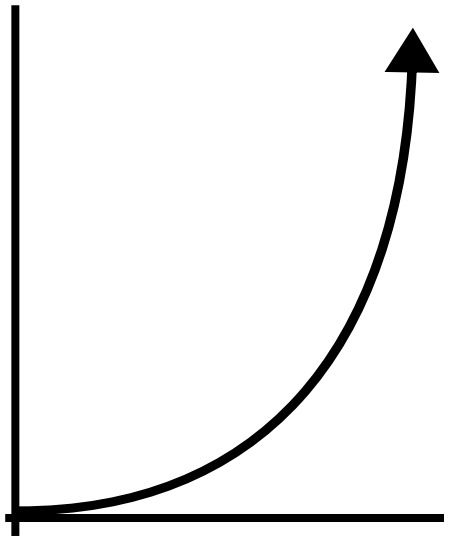
Lack of reliability of AI technology!

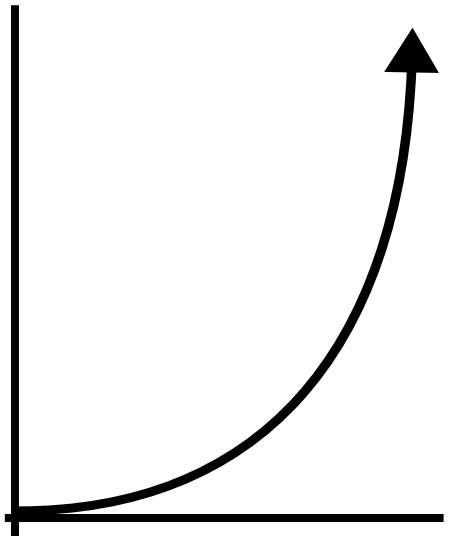


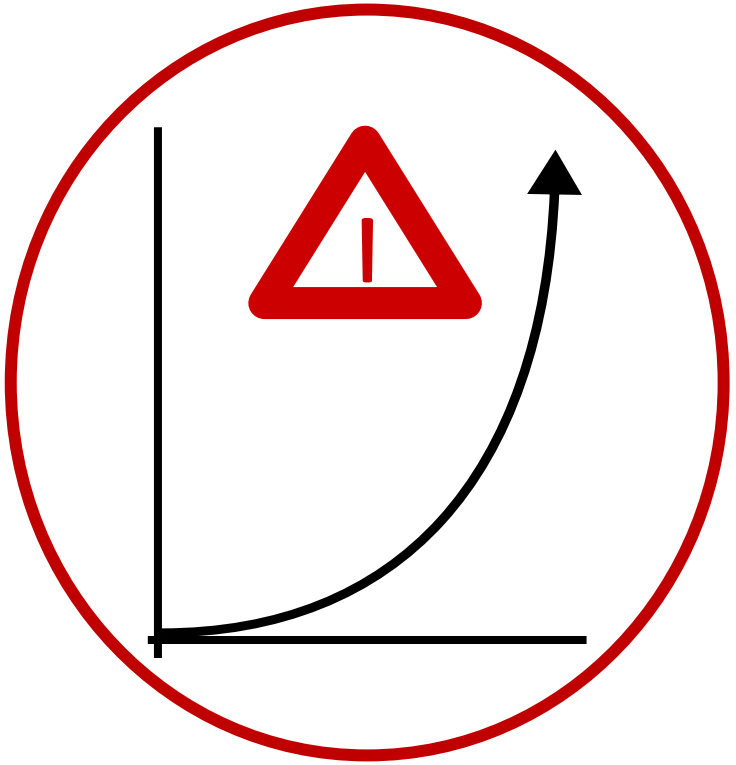
Deep understanding from a mathematical perspective!

Challenges in Artificial Intelligence: Sustainability

AI =





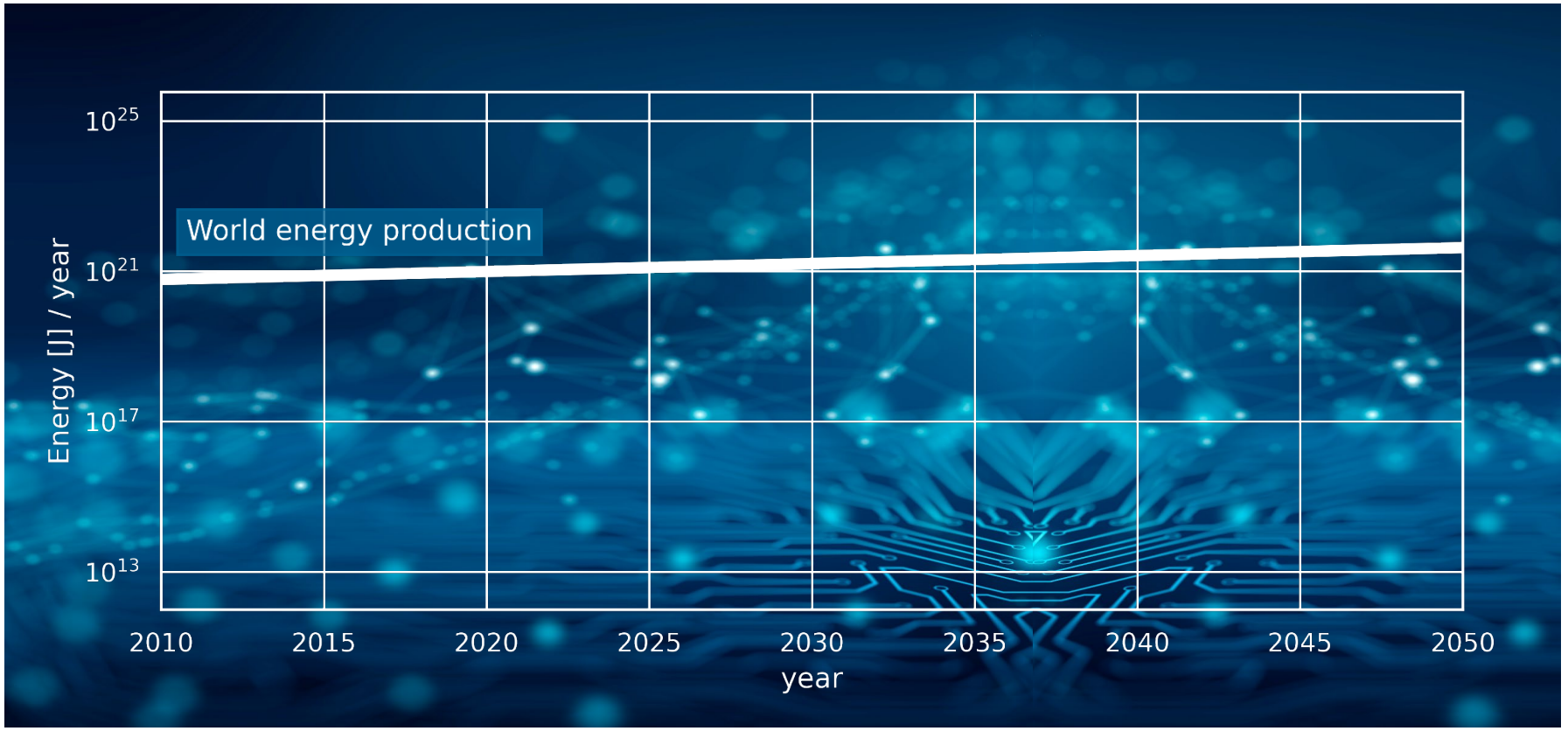


DATA

COMPUTE

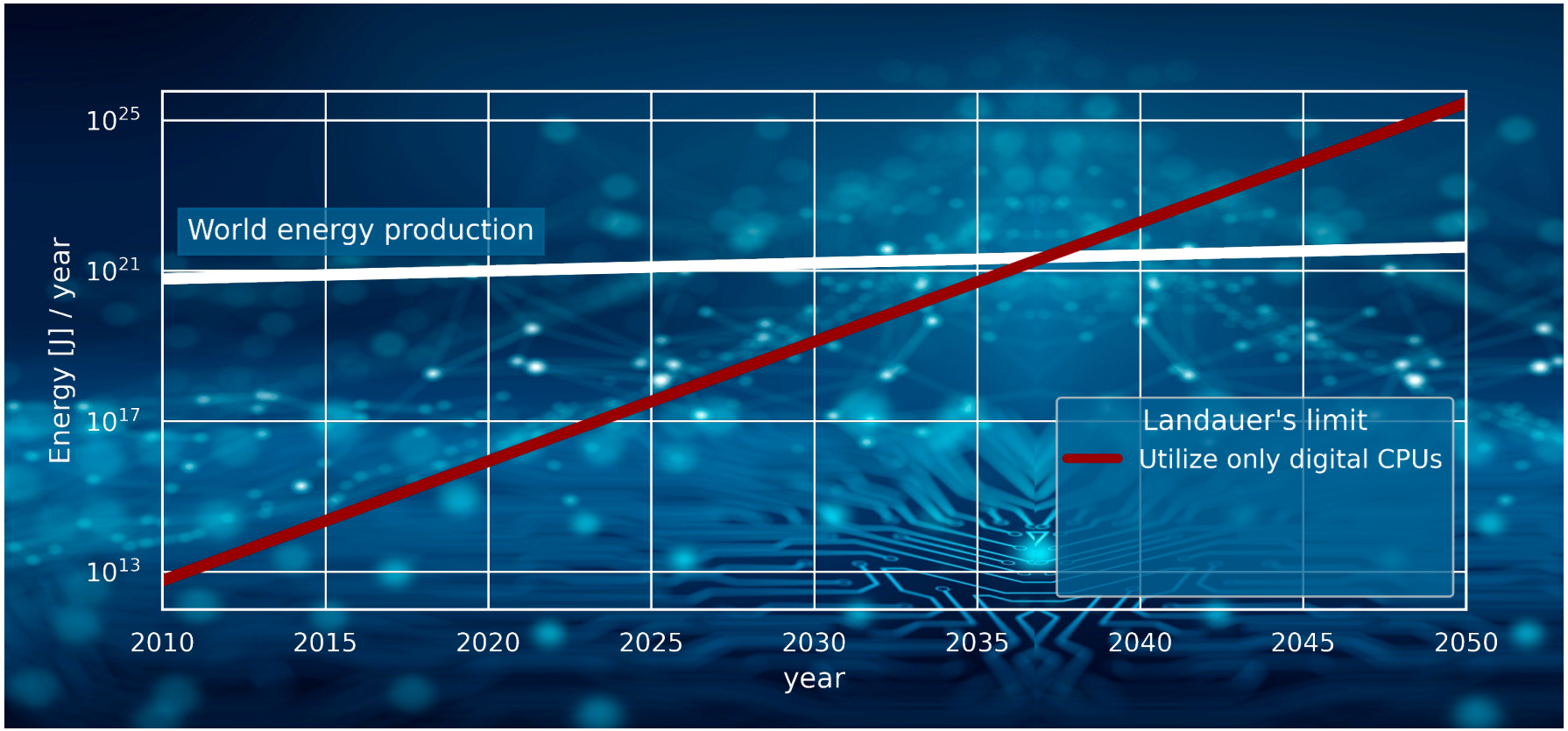
ENERGY

The Energy Problem is even more serious!



Source: Decadal Plan of the Semiconductor Research Corporation for the Biden (US) Administration, 2021

The Energy Problem is even more serious!



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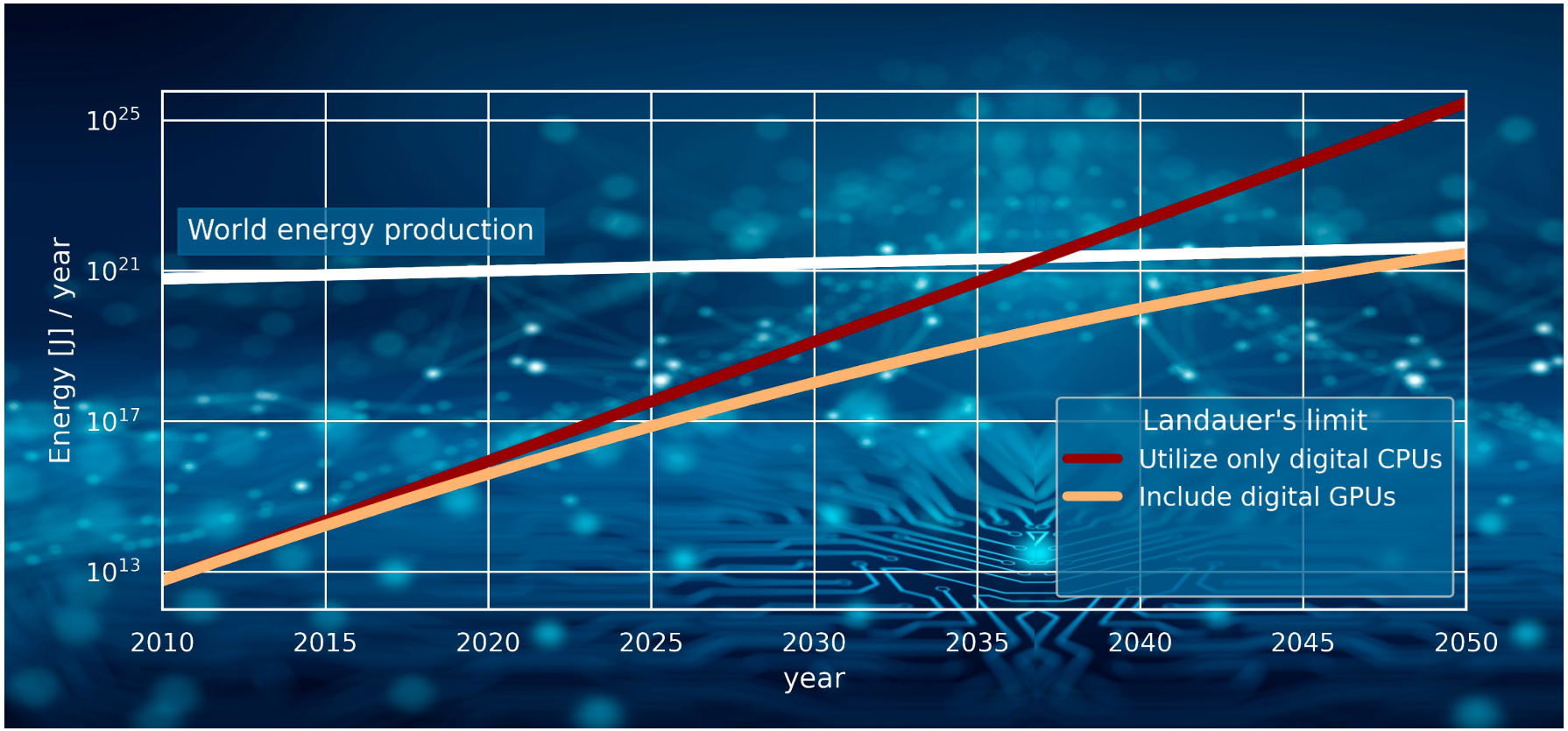


Source: Decadal Plan of the Semiconductor Research Corporation for the Biden (US) Administration, 2021

Dramatic Consequences

Forbes

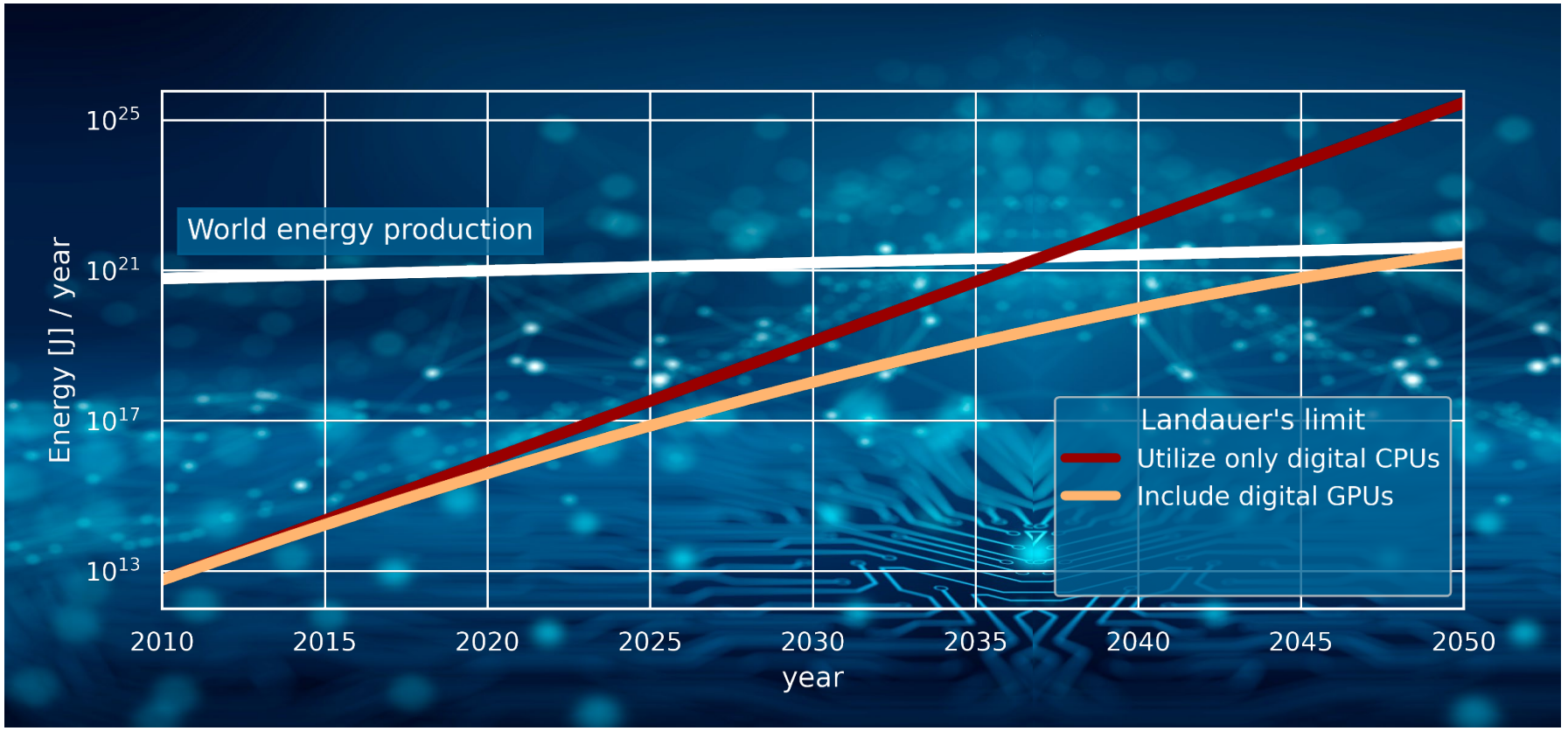
AI Is Pushing The World Toward An Energy Crisis

Further Problematic Environmental Impacts:

- Carbon emissions
- Water usage
- Resource depletion such as rare earth elements
- E-Waste
- Loss of biodiversity
- New power plants
- …

Disruptive Novel Ideas are needed!

Be smart: Develop disruptive new hard-software combinations!



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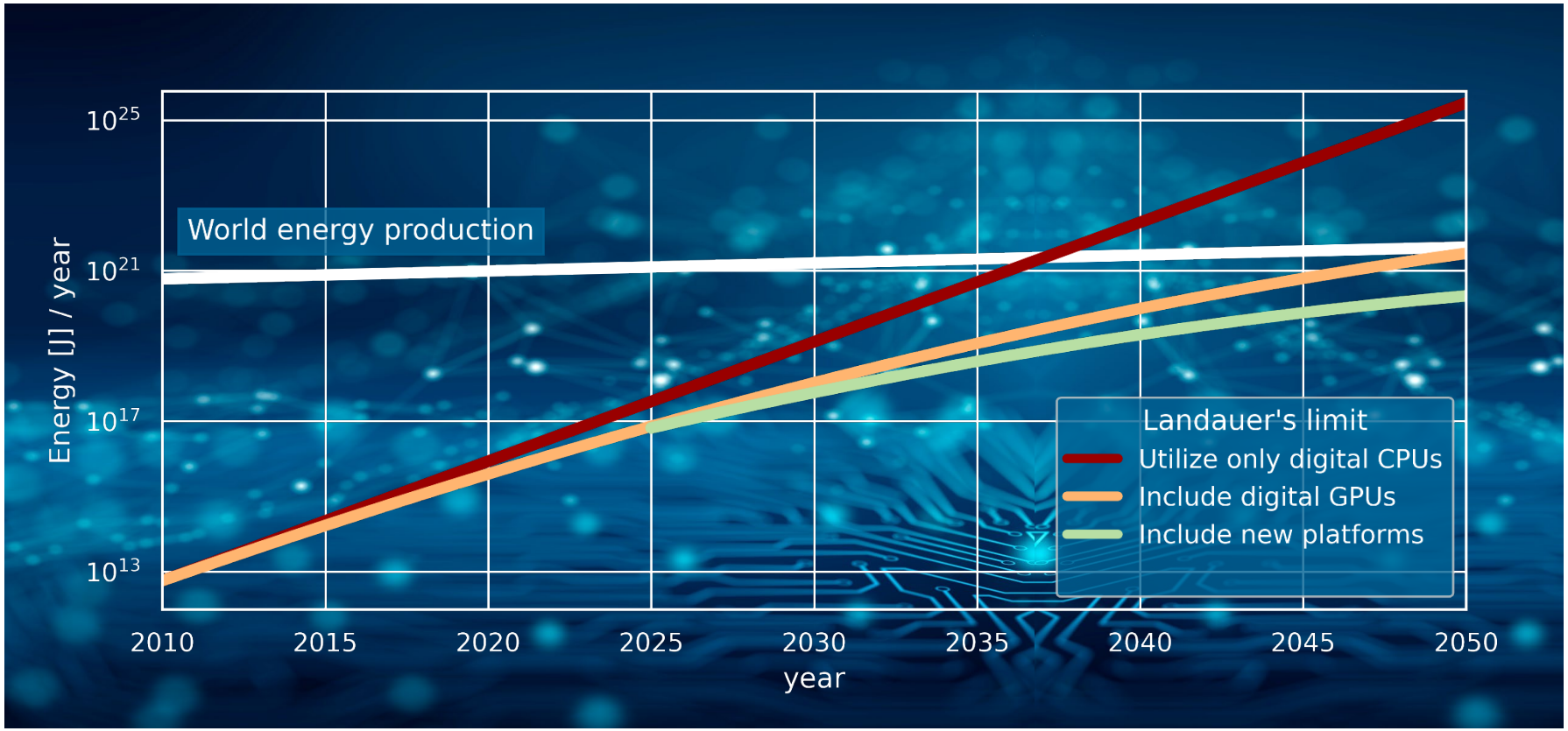
Be smart: Develop disruptive new hard-software combinations!



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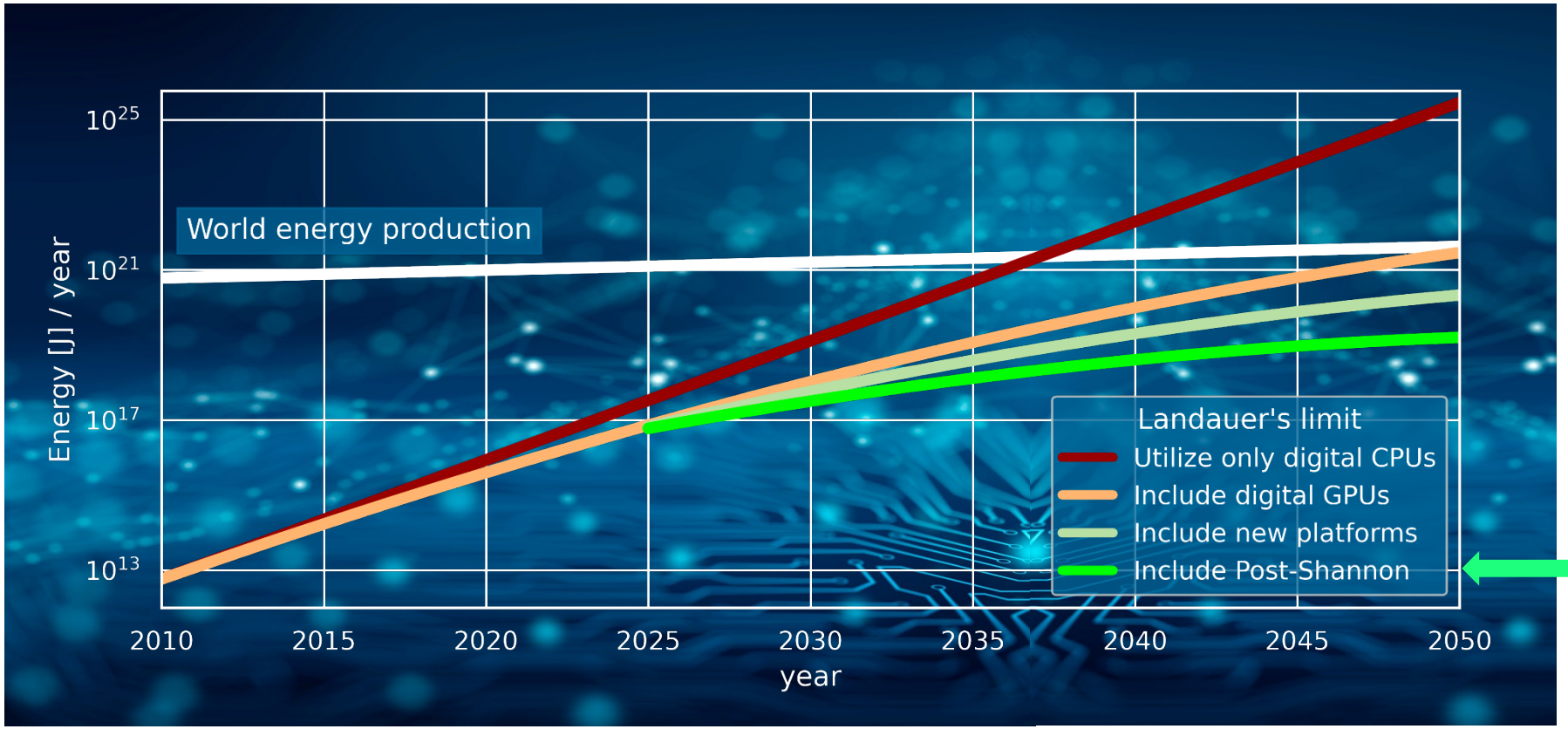
Be smart: Develop disruptive new hard-software combinations!



Novel Mathematical Method!

Source: Decadal Plan of the Semiconductor Research Corporation for the Biden (US) Administration, 2021

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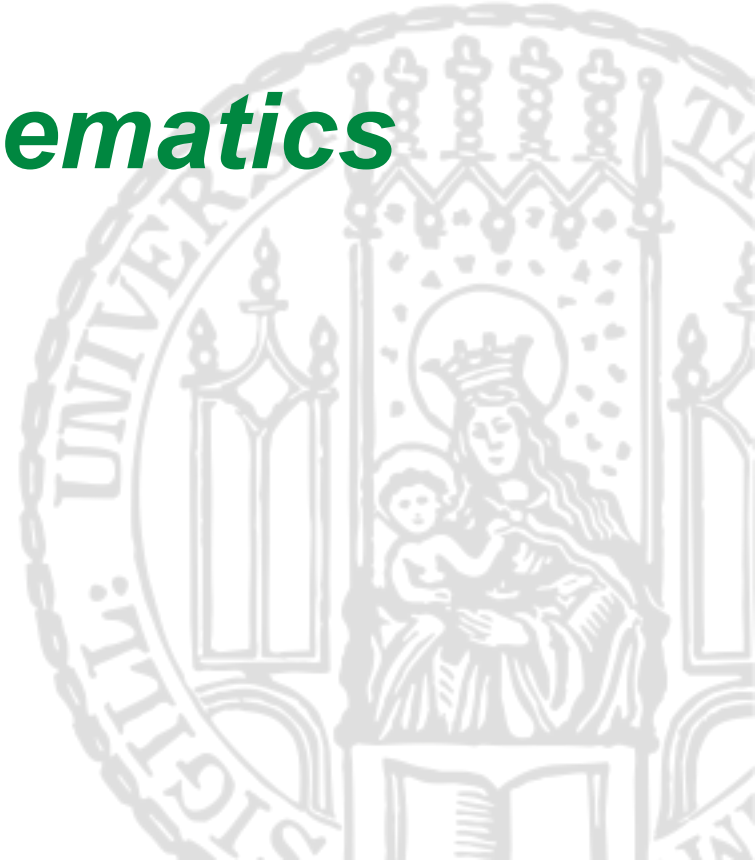
AI Through the Lens of Mathematics



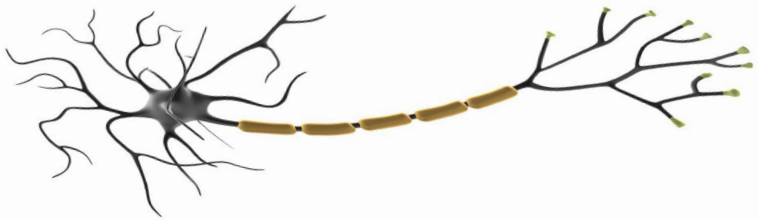
Deep Neural Networks

Key Goal of McCulloch and Pitts (1943):

→ Introduce *artificial Intelligence!*

Artificial Neurons:

$$f(x_1, \dots, x_n) = \rho\left(\sum_{i=1}^{n} x_i w_i - b\right)$$



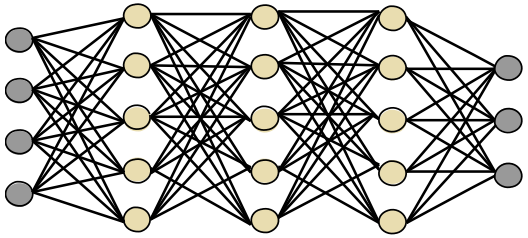
Definition of a Neural Network:

A *deep neural network* is a function $\Phi\colon \mathbb{R}^d \to \mathbb{R}^{N_L}$ of the form

$$\Phi(x) = T_L \rho(T_{L-1}\, \rho(\dots \rho(T_1(x)) \dots)), \quad x \in \mathbb{R}^d,$$

with

$$T_l\colon \mathbb{R}^{N_{l-1}} \to \mathbb{R}^{N_l},\ l = 1, \dots, L, \text{ where } T_l(x) = W^{(l)} x + b^{(l)}.$$



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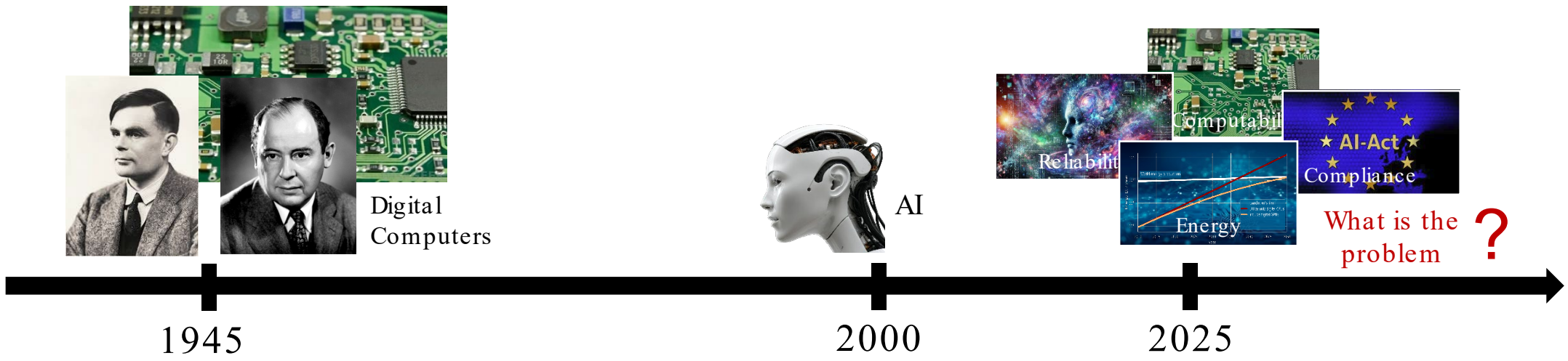
The Evolution of AI



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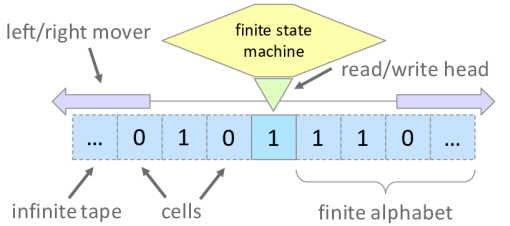
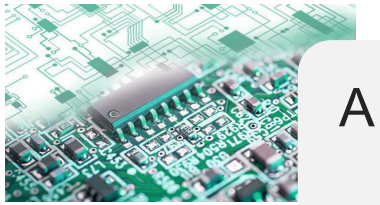
Toward the Core of the Problem…

Delving Deeper

What can actually be *computed on digital hardware*?



Turing-Machine



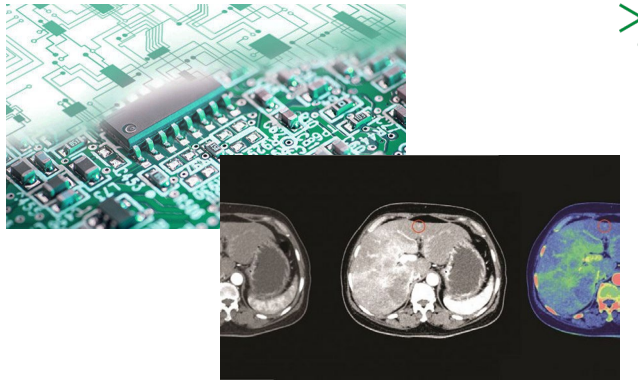
A *computable problem (function)* is one for which the input-output relation can be computed on a digital machine for any given accuracy.

What about Non-Computability?

Non-computable problems can be tackled successfully in practice, if limited precision succeeds!

But we have no guarantees of correctness, hence no reliability!

Very Disappointing News: Theoretical View



Theorem (Boche, Fono, Kutyniok; 2024):
The solution of a finite-dimensional inverse problem is *not (Turing-)computable* (by a deep neural network).

Solution Set: For $A \in \mathbb{C}^{m\times \mathrm{N}}$ and $y \in \mathbb{C}^m$ let

$$\Psi(A,y) := \underset{x \in \mathbb{C}^N}{\arg\min} \|x\|_1 \text{ such that } \|Ax - y\|_2 \leq \epsilon.$$

Theorem (Boche, Fono, Kutyniok; 2024):

Fix parameters $\epsilon \in \left(0, \frac{1}{4}\right)$, $N \geq 2$, and $m < N$. There does *not exist a (Turing-) computable function* $\widehat{\Psi} : \mathbb{C}^{m\times \mathrm{N}} \times \mathbb{C}^m \to \mathbb{C}^N$ such that

$$\sup_{(A,y) \in \mathbb{C}^{m\times \mathrm{N}} \times \mathbb{C}^m} \left\|\Psi(A,y) - \widehat{\Psi}(A,y)\right\|_2 < \frac{1}{4}.$$

Very Disappointing News: Practical View

2024 Asilomar Conference on Signals, Systems & Computers

Deep-Unrolling Multidimensional Harmonic Retrieval Algorithms on Neuromorphic Hardware

Vlad C. Andrei*, Alexandru P. Drăguțoiu*, Gabriel Béna†‡, Mahmoud Akl†, Yin Li*,
Matthias Lohrmann†, Ullrich J. Mönich*, Holger Boche*
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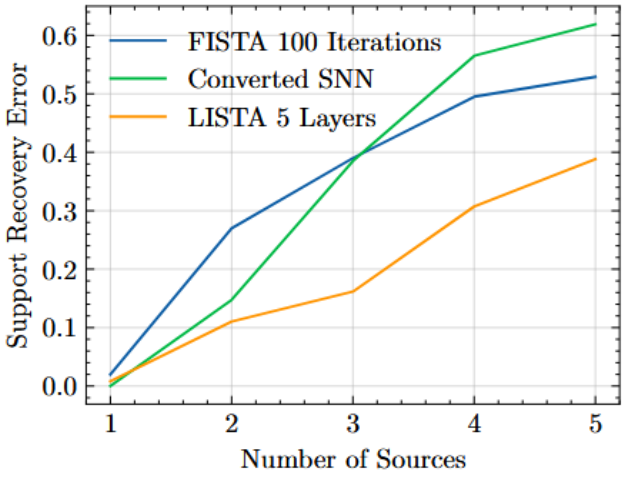
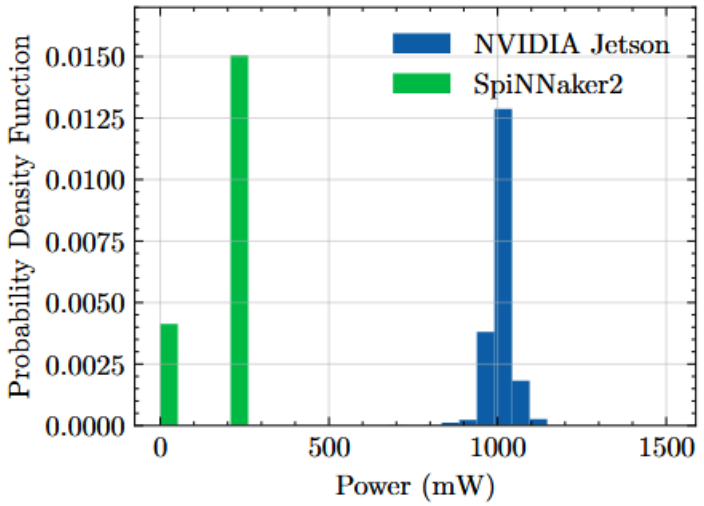
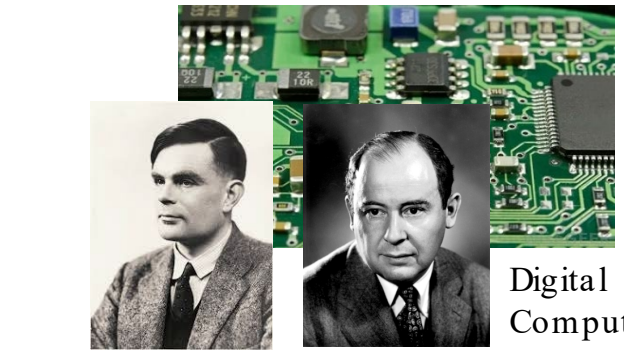
†{gabriel.bena, mahmoud.akl, matthias.lohrmann}@spinncloud.com,



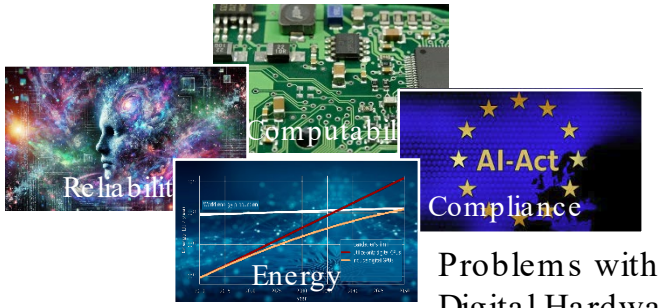


Digital Hardware is a Major Problem!



Digital Computers

AI



Problems with Digital Hardware !

1945 2000 2025

What now?

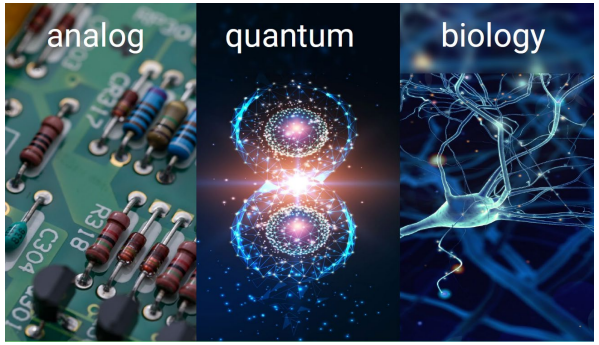
Theory tells us…

Theorem (Boche, Fono, Kutyniok; 2024):
The solution of a finite-dimensional inverse problem is *computable* (by a deep neural network) on an *analog (Blum-Shub-Smale) machine*!

Reliability for certain problem settings requires novel hardware!

Exciting Future Developments:

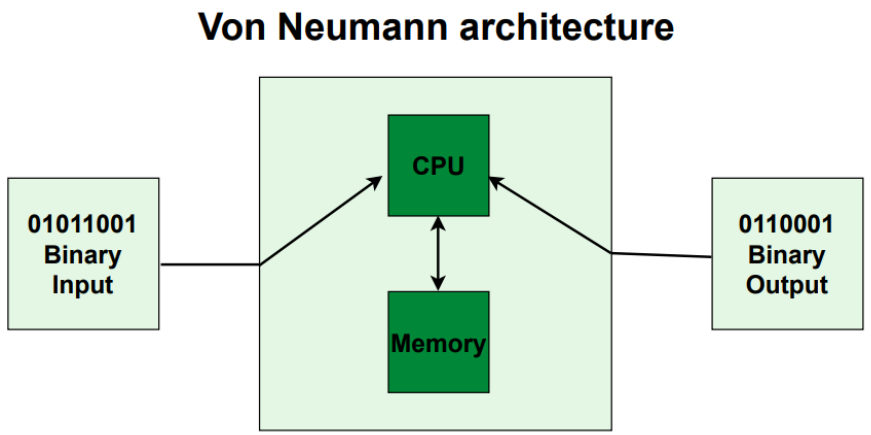
- → Neuromorphic computing
- → Biocomputing
- → Quantum computing



EcoLogic Computing

https://www.ecologic-computing.com

Neuromorphic Hardware

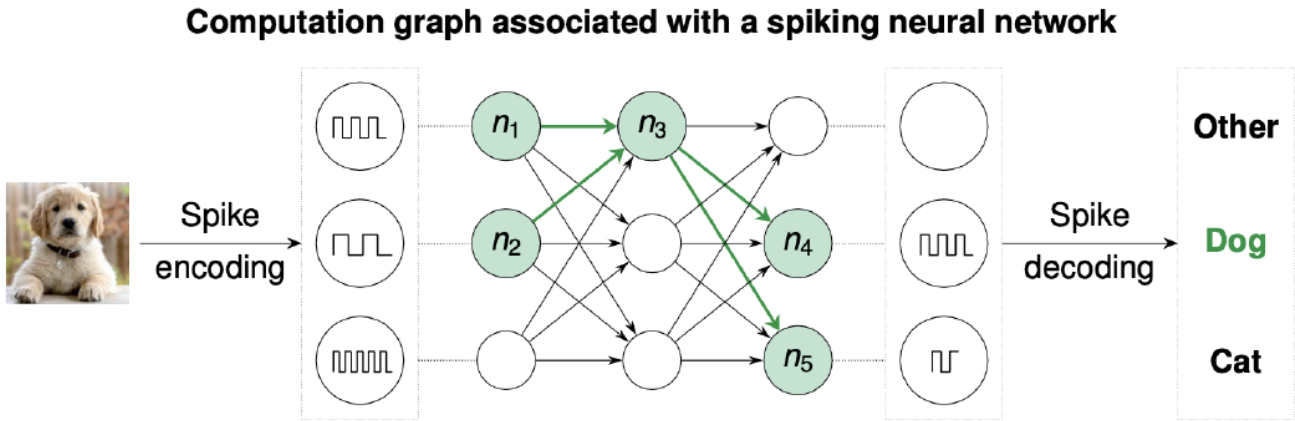


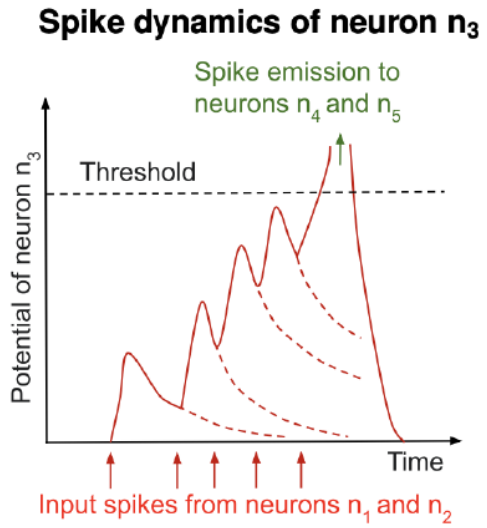
Features of Neuromorphic Hardware:

- → Closer to the human brain.
- → Energy efficiency.
- → Execution speed.
- → Robustness.
- → ….

Computations with 20 W & enormously flexible!

Spiking Neural Networks



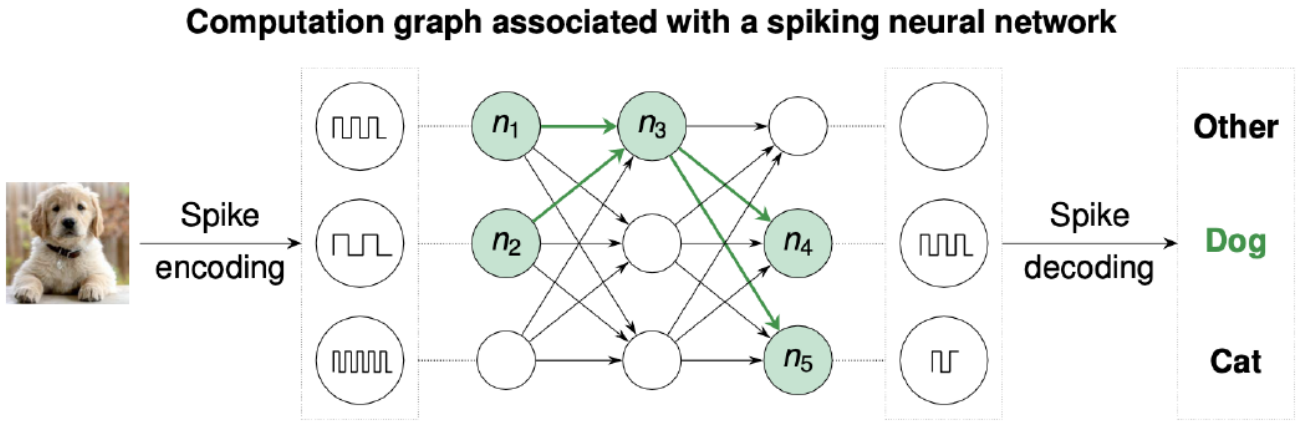


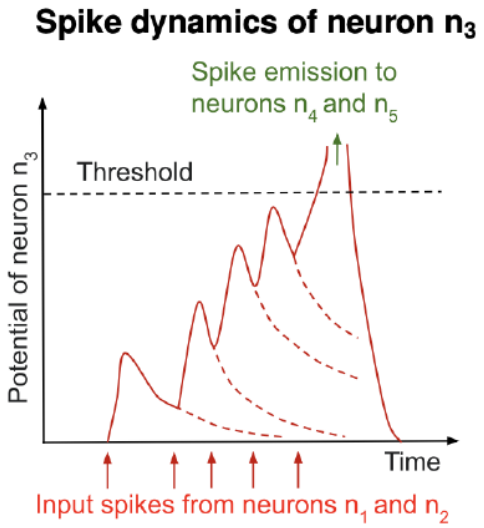
Remarks:

- *More biologically realistic* than first and second generation artificial neurons.
- Information is encoded in the *timing of individual spikes.*
- Numerous models for spiking neurons exist; one of those is the *Spike Response Model.*

Time is one crucial factor in this model!

Spiking Neural Networks

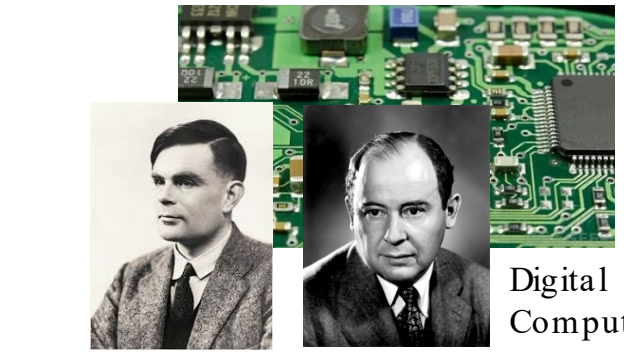




Meta-Result (Singh, Fono, Kutyniok; 2025):

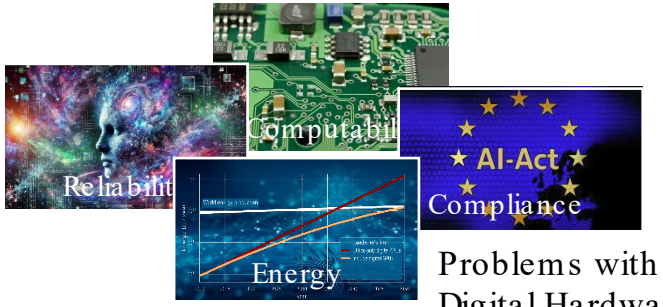
"Spiking neural networks can be emulated by classical artificial ReLU-neural networks, but in many cases, they can be shown to *perform better concerning (energy) efficiency*."

Digital Hardware is a Major Problem!



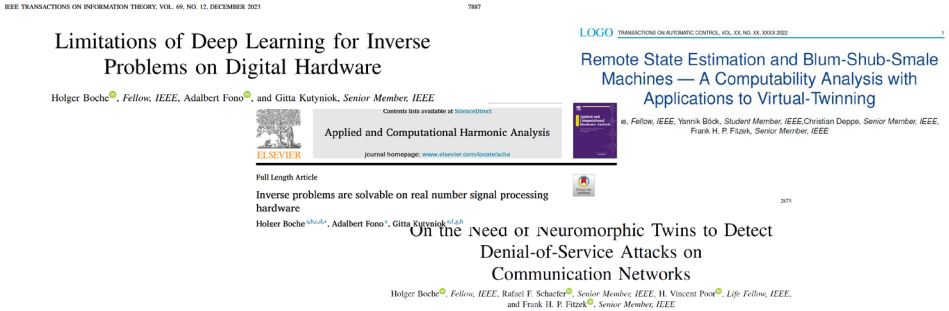
Digital Computers

AI



Problems with Digital Hardware !

1945 2000 2025



Limitations of Deep Learning for Inverse Problems on Digital Hardware

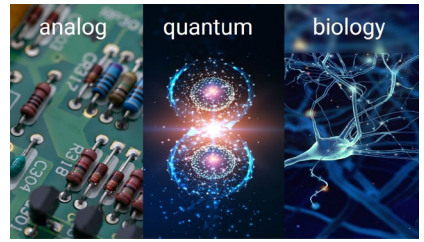
Holger Boche, *Fellow, IEEE*, Adalbert Fono, and Gitta Kutyniok, *Senior Member, IEEE*

Remote State Estimation and Blum-Shub-Smale Machines — A Computability Analysis with Applications to Virtual-Twinning

Applied and Computational Harmonic Analysis

Inverse problems are solvable on real number signal processing hardware

On the Need of Neuromorphic Twins to Detect Denial-of-Service Attacks on Communication Networks



We need to completely rethink AI-Computing!

Vision of our Project

gAIn Next Generation AI Computing

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G. Kutyniok


H. Boche

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TUM


S. Speidel


F. Fitzek

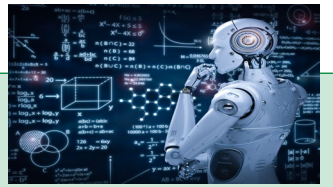
TECHNISCHE UNIVERSITÄT DRESDEN

Comprehensive theory-driven framework for next generation (Green) AI-systems: Optimally application-adapted hard-software combinations for maximal energy-efficiency and reliability!

Provably reliable AI-based *communication* systems which comply with the EU AI Act!

Low cost, trust-worthy *medical* AI-devices for diagnosis and therapy!

Next generation *robotics* with reliable robot brains and life-long learning capabilities!



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Next Generation AI Computing for a Sustainable Future

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Rethinking Intelligence — From Foundational Principles!

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AI HUB LMU

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Thank you very much for your attention!

References available at:

www.ai.math.lmu.de/kutyniok

Survey Papers:

Berner, Grohs, Kutyniok, Petersen, The Modern Mathematics of Deep Learning, 2021
Fono, Singh, Araya, Petersen, Boche, Kutyniok, Sustainable AI: Mathematical Foundations of Spiking Neural Networks, 2025

Related Book:

Grohs and Kutyniok, eds., Mathematical Aspects of Deep Learning, Cambridge University Press, 2022.