Digital Twins

From Hype to Industrial Reality… and Why Applied Mathematics Plays a Key Role

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Professor @ TU Darmstadt

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Digital Twins

From Hype to Industrial Reality… and Why Applied Mathematics Plays a Key Role

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Siemens
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Daniel Berger, Digital Industries, Germany
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Nils Margenberg, Mathematics
Prof. Christian Lessig, Computer Science

KU Leuven
Herman van der Auweraer, Mechanical Engineering

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"We are able to combine the real and digital worlds like no other company!

Dr. Roland Busch,
President and CEO of Siemens AG

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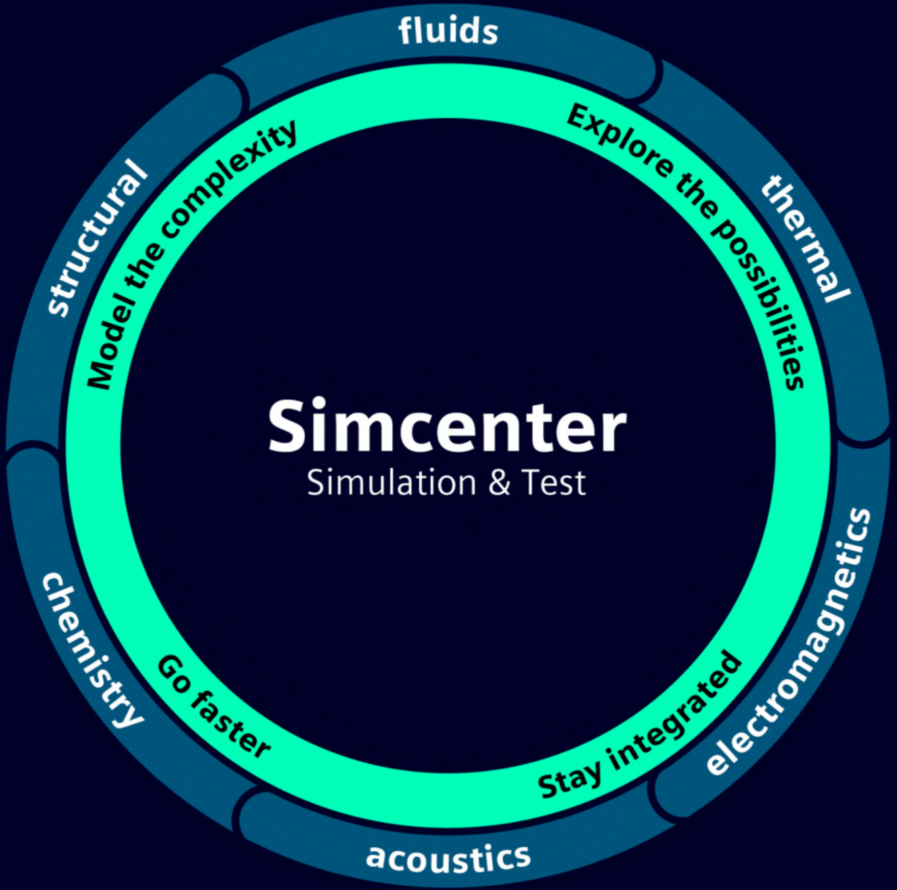
Delivering a comprehensive portfolio for performance engineering



- Multiphysics CFD
- Mechanical simulation
- Systems simulation
- CAD integrated simulation
- Physical testing
- Computational chemistry
- SPDM
- Exploration & analytics
- Materials database
- High frequency electromagnetics
- Fast meshless simulation
- Nonlinear structural analysis
- Automation and scheduling for HPC
- Generative design & topology optimization
- High-fidelity CAE pre-/post-processing
- Data analytics and AI

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Agenda

1. Examples
2. Digital Twins
3. Deep Dive – ML-based Reduced Order Modelling
4. Deep Dive – ML-based Machine Learning
5. Deep Dive – AI-based User Experience
6. Wrap Up

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1

Examples

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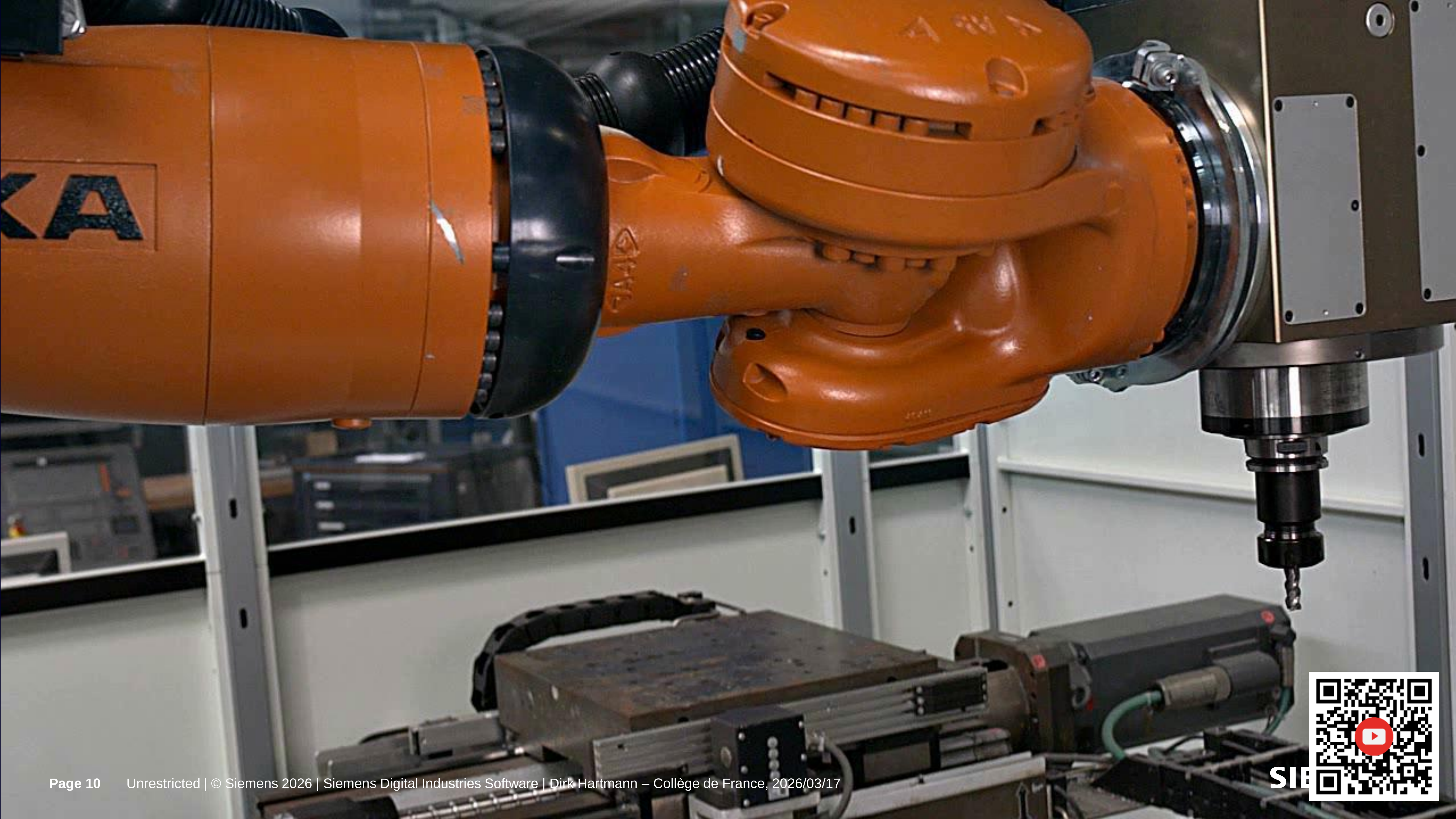
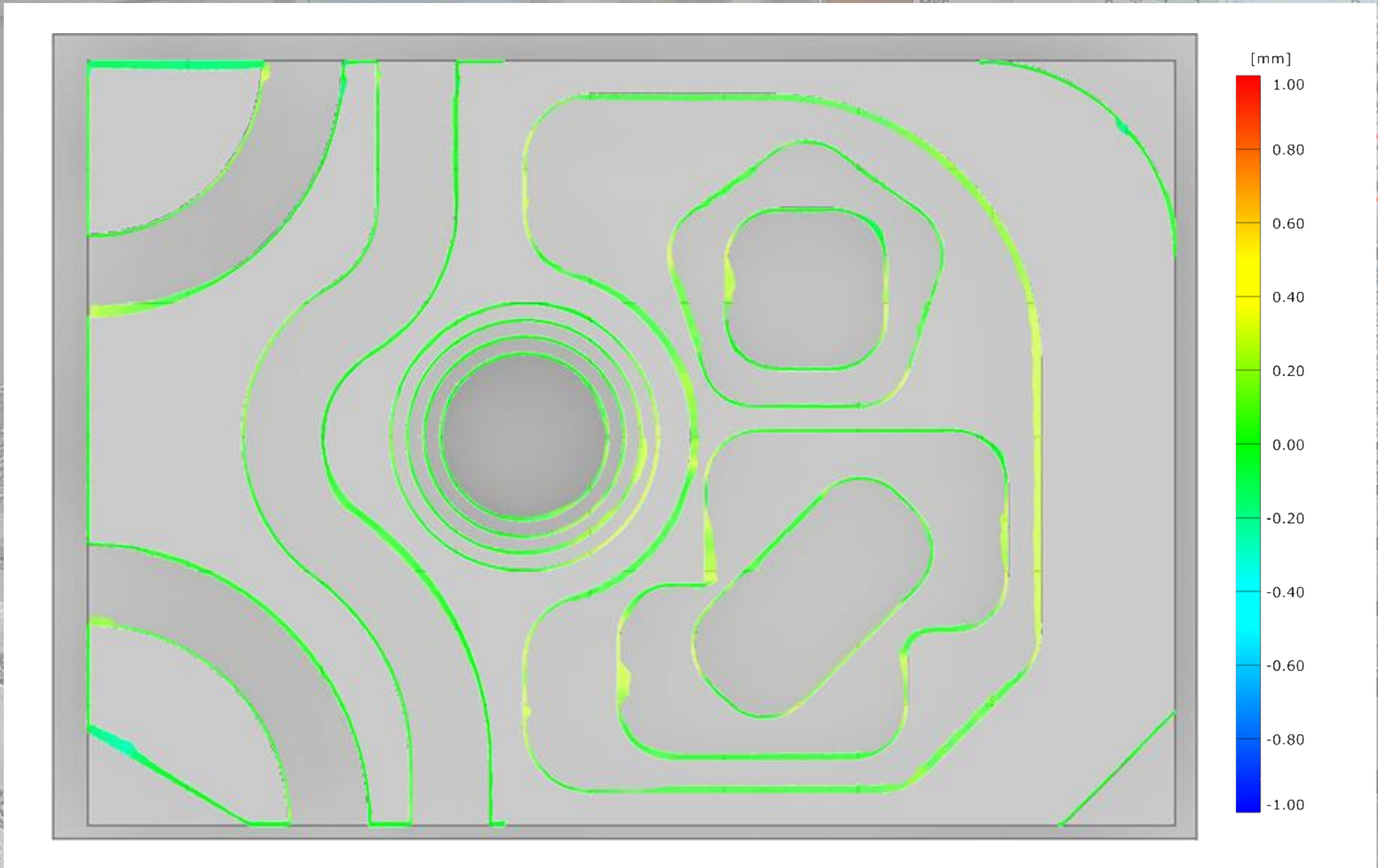
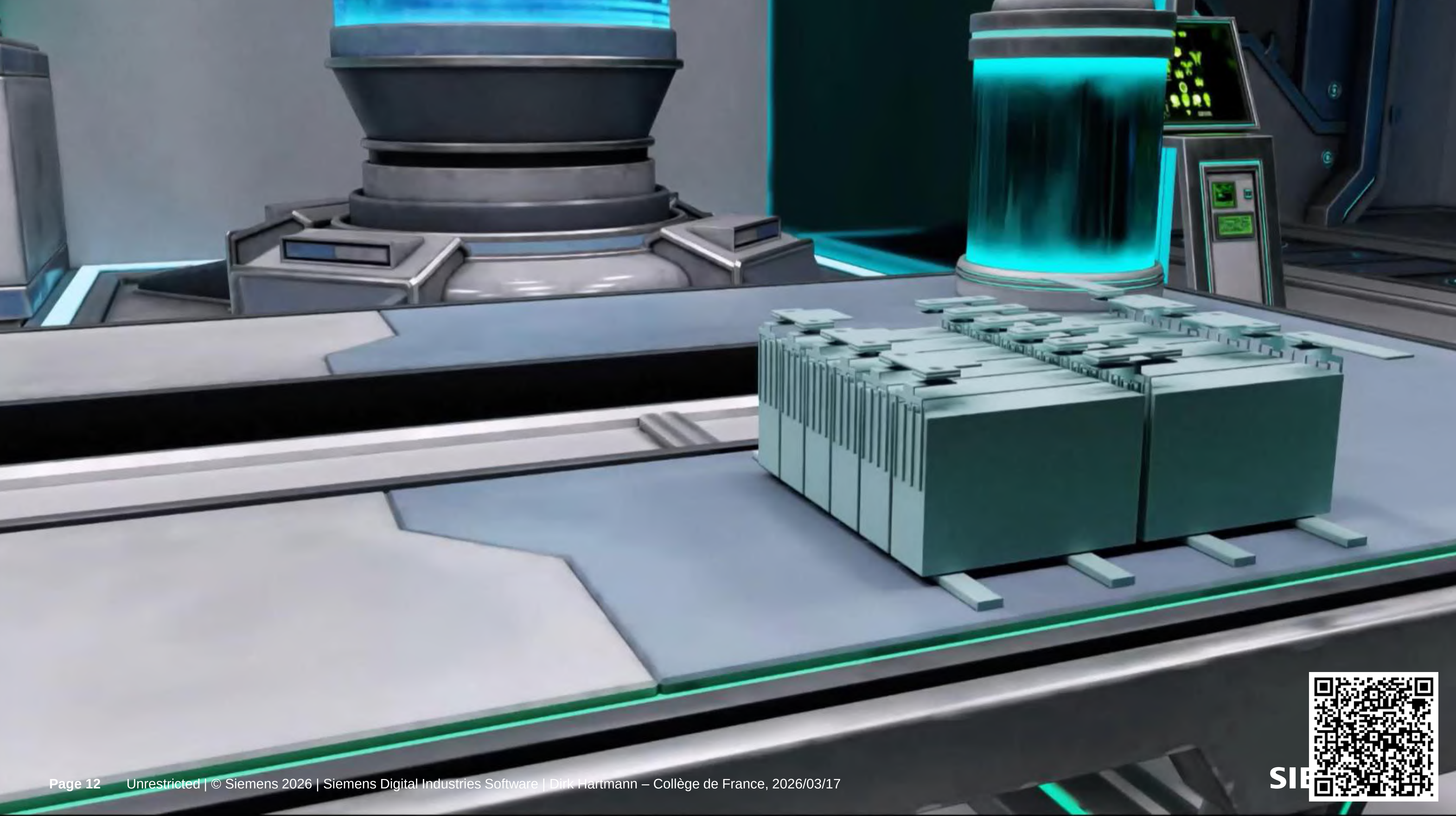
Load File
Deform CADobject
Displacements
2.0

Sources: D Hartmann , M Herz , M Paffrath , J Rommes , T Tamarozzi , H Van der Auweraer, U Wever (2021): Model order reduction and digital twins. Model Order Reduction - Volume 3





Sources: F Schnös, D Hartmann, B Obst, G Glashagen (2021): GPU accelerated voxel-based machining simulation. Int. J. of Adv. Manufacturing Tech
M Busch, F Schnös, T Semm, MF Zäh, B Obst, D Hartmann (2020): Probabilistic information fusion to model the pose-dependent dynamics of milling robots. Production Engineering
MF Zaeh, F Schnoes, B Obst, D Hartmann (2020): Combined offline simulation and online adaptation approach for the accuracy improvement of milling robots. CIRP Annals



Digital Twins
Very Different Requirements across Different Scales

Use Case		Physics	Models	Scale	Require Accuracy	Required Response	Compute Unit	User
	Design Validation	CFD	FV	~mm - m	~ 1-5%	days	HPC	Simulation Expert
	Design Exploration	Mechanics	FEM	~cm - m	~10-20%	seconds	Single Machine	Designer
	Virtual Sensing	Thermal	ROM	~°C	~ 1%	seconds	Edge Computer	Machine Operator
	“Optimal” Control	Dynamics	Multibody + Lumped Model	~µm - m	~10%	< milli-seconds	Controller	Machine Operator
	Learning Control	Thermal	ROM	~°C	~ 1%	seconds	Cloud	“AI”

2

Digital Twin

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The Digital Twin Paradigm

"A comprehensive set of digital models accepted as full substitutes for reality to understand, predict, and optimize the physical counterpart's performance characteristics for specific purposes. The bidirectional interaction between the digital and the real is central to the digital twin.

Source: D. Hartmann, H. v.d. Auweraer (2025): Digital Twins - a golden age for industrial mathematics. Journal of Industrial Mathematics

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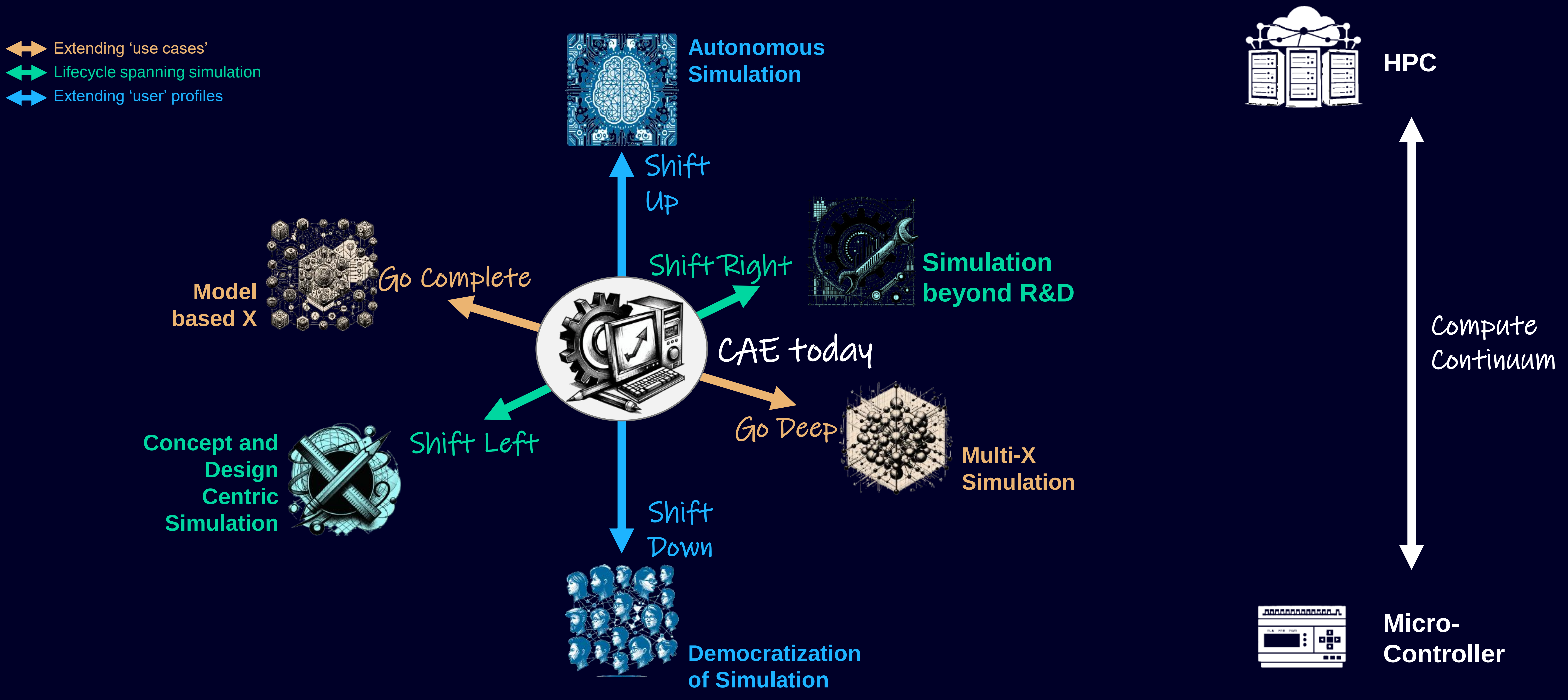
Digital Twins require a massive expansion of the use of simulation technologies along different “scales”



Source: R. Bornoff, D. Hartmann (2024): On the ongoing evolution of industrial simulation. Siemens Blog

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Digital Twin – *State of Industrial Adoption Today*

"Despite […] examples of digital twins providing practical impact and value […] publicity around digital twins […] currently outweighs the evidence base of success."

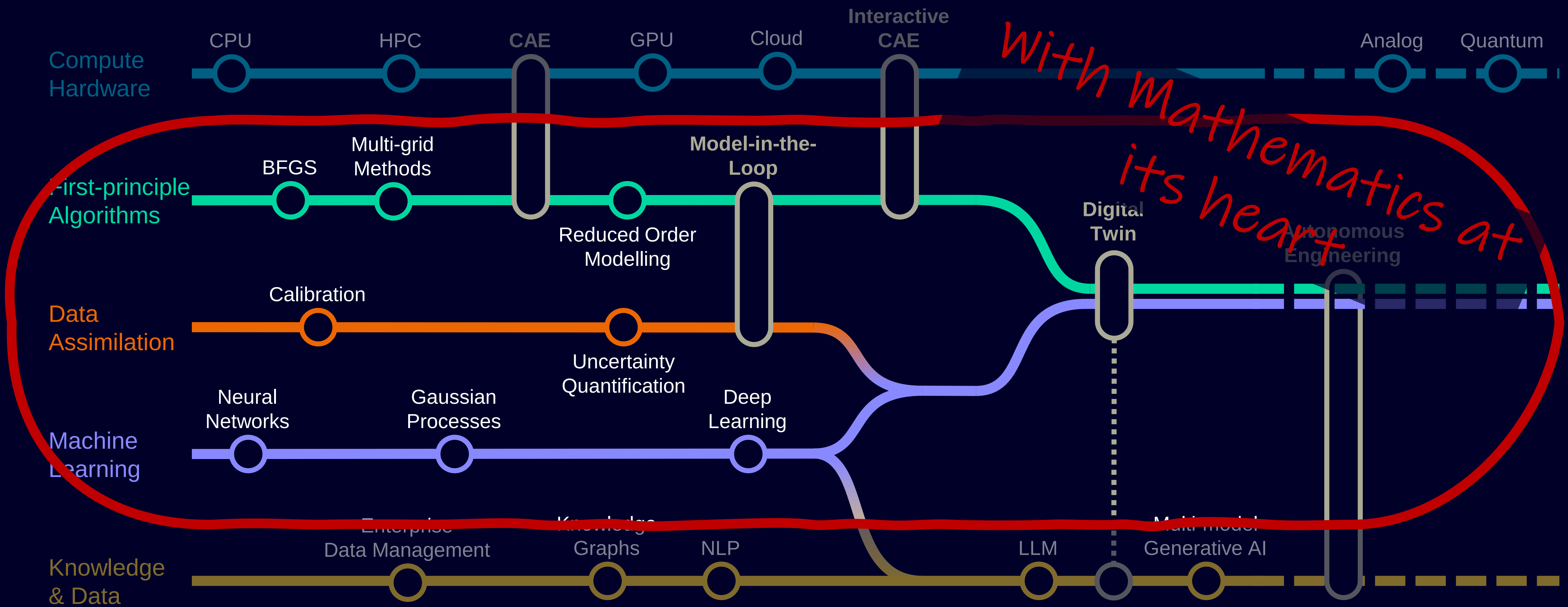
Source: National Academies (2024): Foundational Research Gaps and Future Directions for Digital Twins.

Scalability of simulation is limited by the same obstacles since a decade.
Challenge: This holds also for Digital Twins

Knowledge	48%	Lack of experience and knowledge
Time	45%	Tight deadlines for design don’t allow for simulation
Price	35%	Simulation can be very expensive
Accuracy	27%	Simulation is not sufficiently predictive
Ressources	22%	Computing power required is prohibitive
Automation	15%	Shortage of tools to automate workflows

Source: Engineering.com (2022): Research Report: The State of Simulation, Prototyping and Validation

But there is hope! It is exciting times …
… the evolution and convergence of technologies will make Digital Twins real.



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The Coming Technological Singularity: How to Survive in the Post-Human Era
Vernor Vinge, 1993 – NASA VISION-21 Symposium

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The Coming Technological Singularity:
How to Survive in the Post-Human Era

Vernor Vinge
Department of Mathematical Sciences
San Diego State University

This article was for the VISION-21 Symposium
sponsored by NASA Lewis Research Center
and the Ohio Aerospace Institute, March 30-31, 1993.
It is also retrievable from the NASA technical reports
server as part of NASA CP-10129.
A slightly changed version appeared in the
Winter 1993 issue of _Whole Earth Review_.

Abstract

Within thirty years, we will have the technological means to create superhuman intelligence. Shortly after, the human era will be ended.

Is such progress avoidable? If not to be avoided, can events be guided so that we may survive? These questions are investigated. Some possible answers (and some further dangers) are presented.

What is The Singularity?

The acceleration of technological progress has been the central feature of this century. I argue in this paper that we are on the edge of change comparable to the rise of human life on Earth. The precise cause of this change is the imminent creation by technology of entities with greater than human intelligence. There are several means by which science may achieve this breakthrough (and this is another reason for having confidence that the event will occur):

o The development of computers that are "awake" and superhumanly intelligent. (To date, most controversy in the area of AI relates to whether we can create human equivalence in a machine. But if the answer is "yes, we can", then there is little doubt that beings more intelligent can be constructed shortly thereafter.
o Large computer networks (and their associated users) may "wake up" as a superhumanly intelligent entity.
o Computer/human interfaces may become so intimate that users may reasonably be considered superhumanly intelligent.
o Biological science may find ways to improve upon the natural human intellect.

The first three possibilities depend in large part on improvements in computer hardware. Progress in computer hardware has followed an amazingly steady curve in the last few decades [16]. Based largely on this trend, I believe that the creation of greater than human intelligence will occur during the next thirty years. (Charles

The Coming Technological Singularity: How to Survive in the Post-Human Era

Vernor Vinge, 1993

Abstract:

Within thirty years, we will have the technological means to create superhuman intelligence. Shortly after, the human era will be ended.

Is such progress avoidable? If not to be avoided, can events be guided so that we may survive? These questions are investigated. Some possible answers (and some further dangers) are presented.

Source: Vernor Vinge (1993): The Coming Technological Singularity: How to Survive in the Post-Human Era, NASA CISION-21 Symposium

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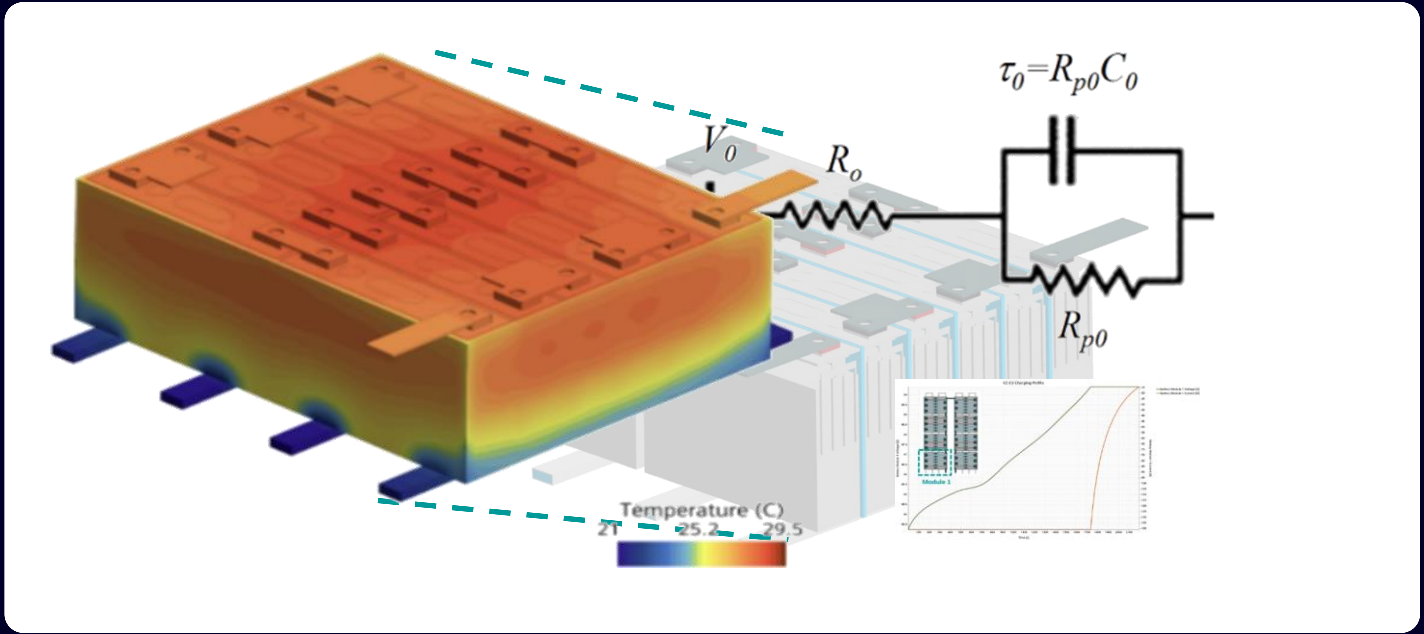
3

Deep Dive

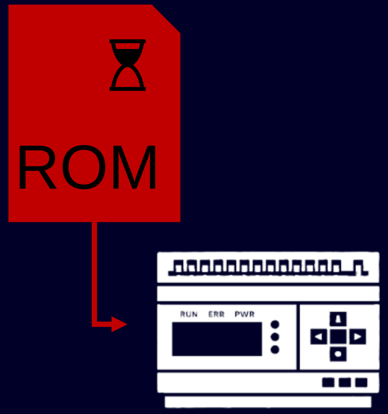
ML-based Reduced Order Modelling

ML-based Reduced Order Modelling
Challenge



Battery Thermal Management

Complex multi-physics model:
- Turbulent fluid flow
- Battery electrochemistry
- Electrical modeling
- ~ 1 million cells



Challenge:

Real-time model running within a system simulation or a controller

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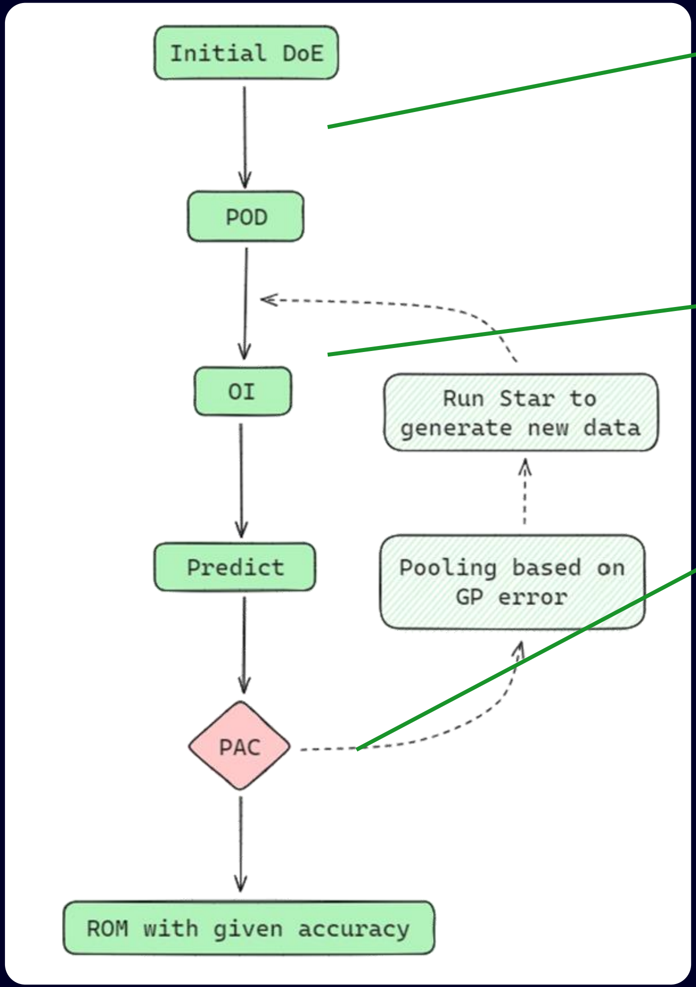
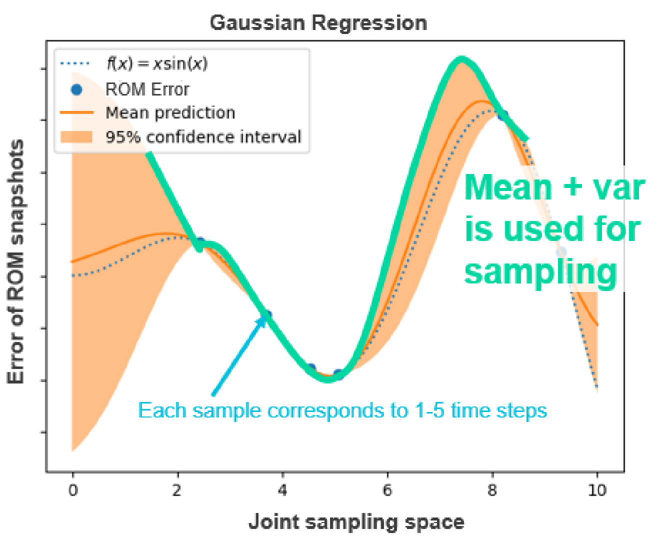
ML-based Reduced Order Modelling
Concept



Latent Dimension Identification, e.g., Autoencoder, Diffusion Maps, Dynamic Mode Decomposition, Proper Orthogonal **Decomposition (POD)**

Reduced Model Discovery, e.g., Discrete Empirical Interpolation, Neural Networks, **Operator Inference (OI)**

Active Learning, e.g., classical Design of Experiments



Source: Q Zhuang, D Hartmann, HJ Bungartz, JM Lorenzi (2023): Active-learning-based nonintrusive model order reduction; Data-centric Eng
Q Zhuang, JM Lorenzi, HJ Bungartz, D Hartmann (2021): Model order reduction based on Runge–Kutta neural networks; Data-centric Eng

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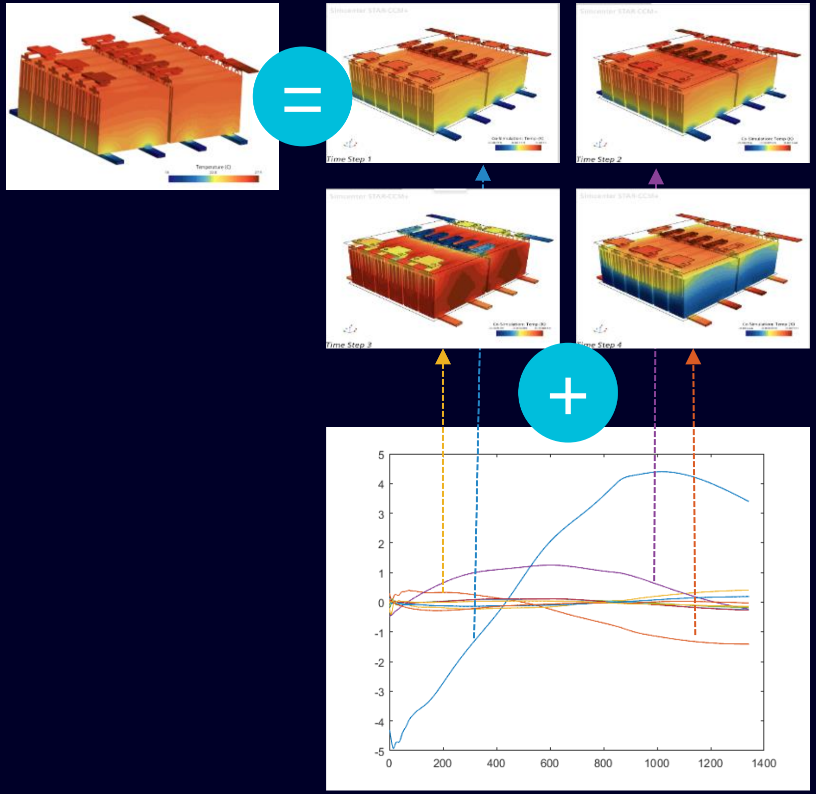
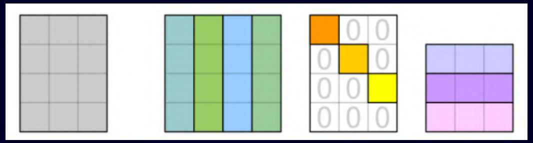
ML-based Reduced Order Modelling
Proper Orthogonal Decomposition and Differential Operator Inference



Proper Orthogonal Decomposition:



$$\underset{n\times m}{\boldsymbol{\Phi}} = \underset{n\times n}{\boldsymbol{U}} \cdot \underset{n\times m}{\boldsymbol{\Sigma}} \cdot \underset{m\times m}{\boldsymbol{V}^*}$$

- Fast and robust
- Parallelization allows up to 10+M cells

Differential Operator Inference (OI):

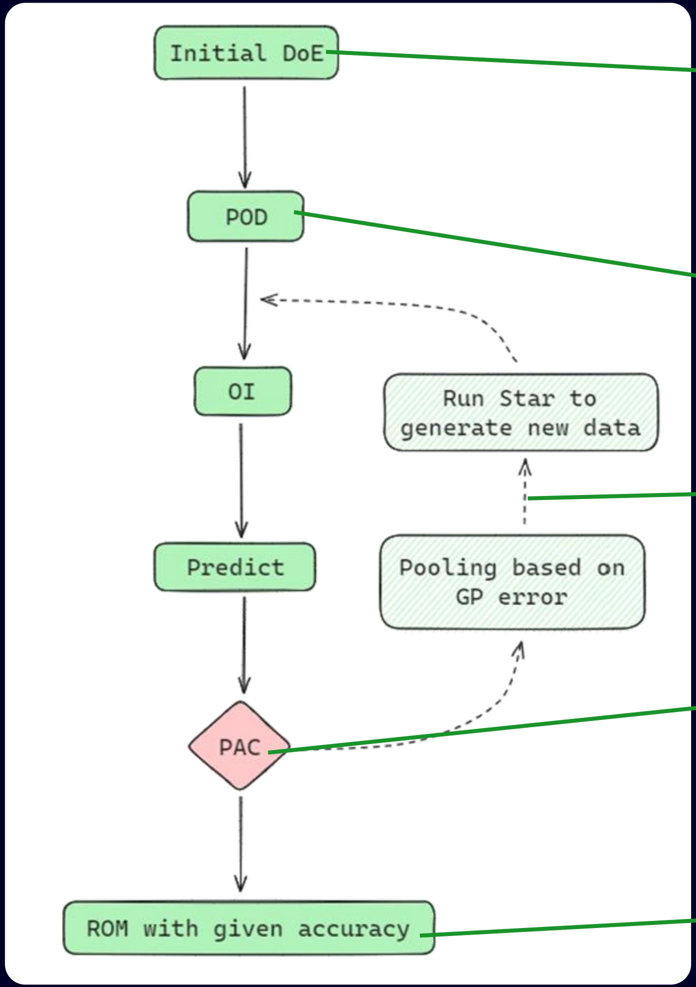
$$w^\star = \underset{A,H,B}{\operatorname{argmin}} \sum_{j=1}^{N\_S} \sum_{i=0}^{N_T-1} \left\| \hat{y}_{i+1}^j - y_i^j \right\|^2$$

$$\text{s.t. } y^j(t_i) = y_{i-1}^j + (t_i - t_{t-1}) \cdot [A\ H\ B] \cdot \begin{bmatrix} y_{i-1}^j \\ y_{i-1}^j * y_{i-1}^j \\ \hat{u}_{i-1}^j \end{bmatrix}$$

- More robust and stable than classical OI
- Computationally feasible due to low-dimensionality

Source: WIT Uy, D Hartmann, B Peherstorfer (2023): Operator inference with roll outs for learning reduced models from scarce and low-quality data. Computers & Mathematics with Applications, 145, 224-239
D Hartmann, L Failer (2021): A differentiable solver approach to operator inference. arXiv preprint arXiv:2107.02093.

ML-based Reduced Order Modelling
Results – "Performance" metrics



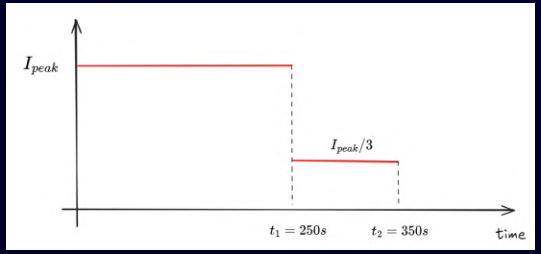
15 long simulations[1] for different parameters
[Time: **4h |** Size on disk: **4.1 GB**]

POD on initial DoE data
[Time: **20' |** Size on disk: **0.7 GB**]

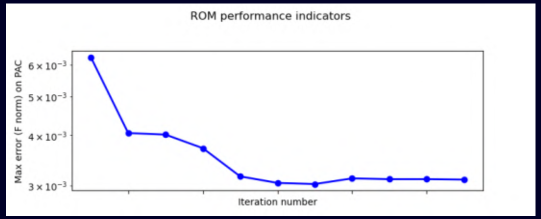
AL loop, 11 iterations with 5 short[2] sim. each
[Time: **2h 20' |** Size on disk: **3.4 GB**]

PAC based on 58 short simulations[2]
[Time: **2h 30' |** Size on disk: **3.6 GB**]

Real-time capable ROM (20 ODEs)



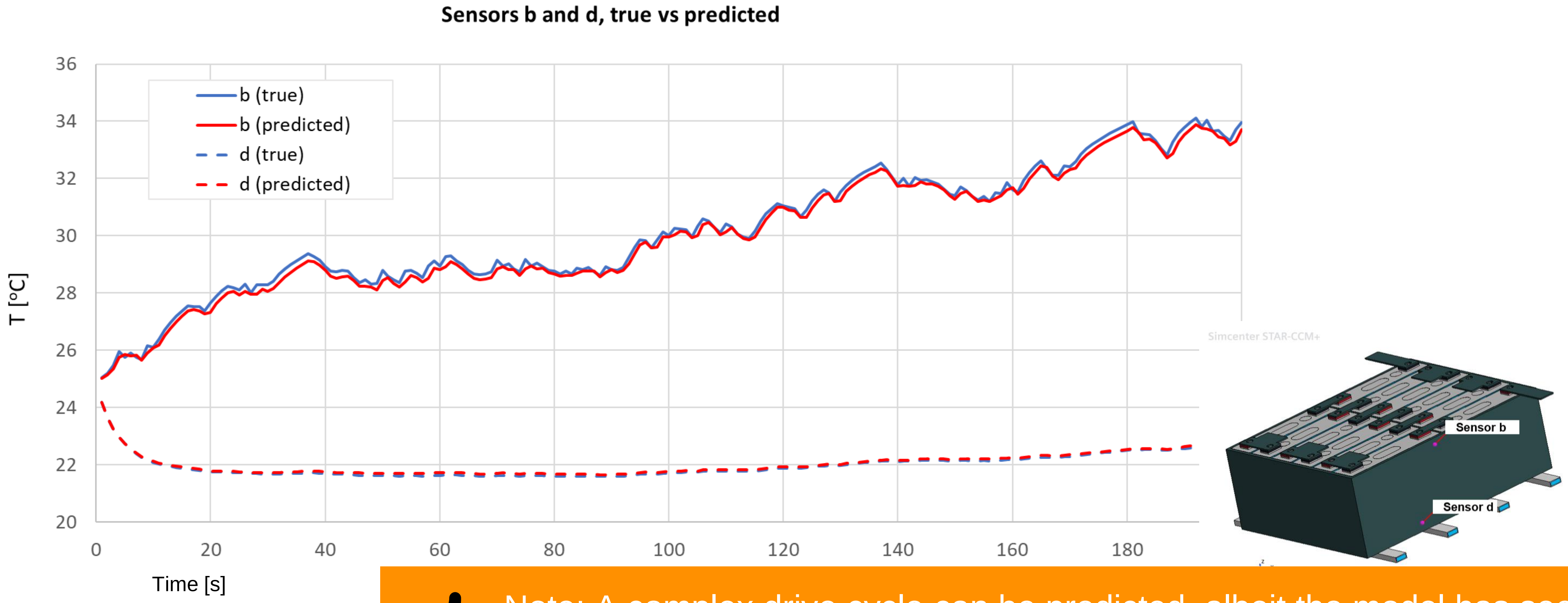
Heating Profile



Error improvement

1) 350 time steps per simulation 2) 5 time steps per simulation

ML-based Reduced Order Modelling
Results



Note: A complex drive cycle can be predicted, albeit the model has seen only simple step functions in the training phase.

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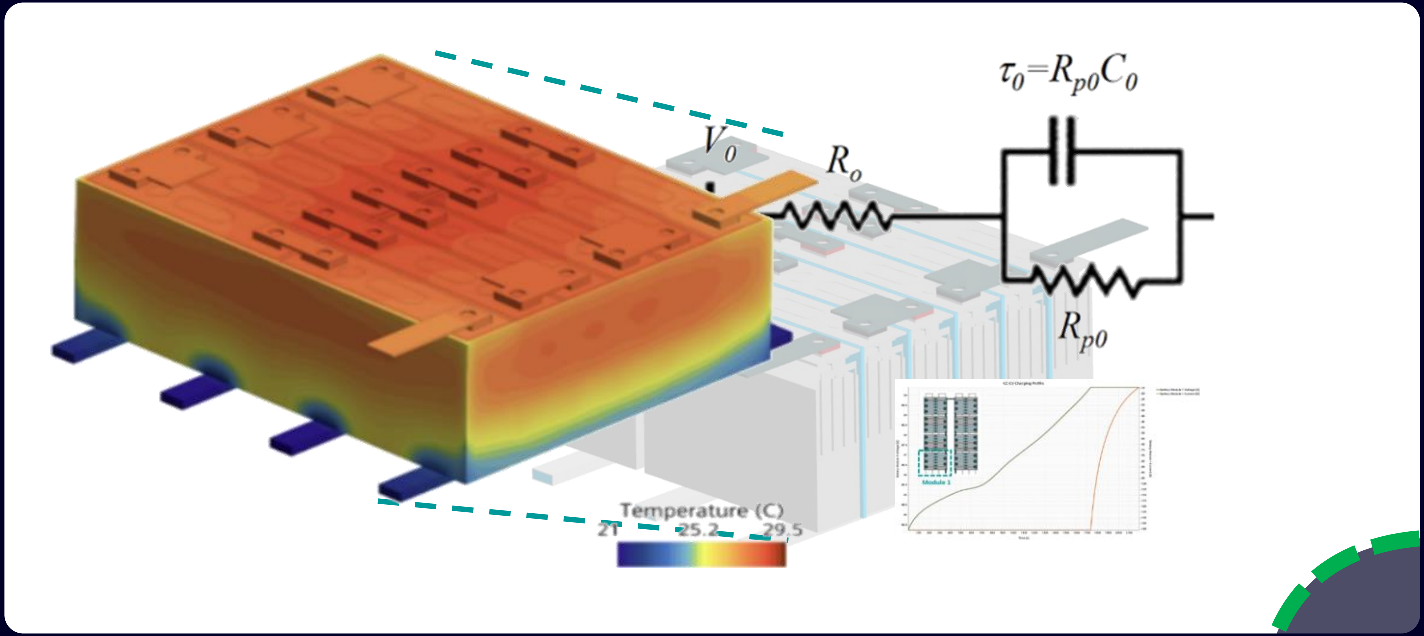
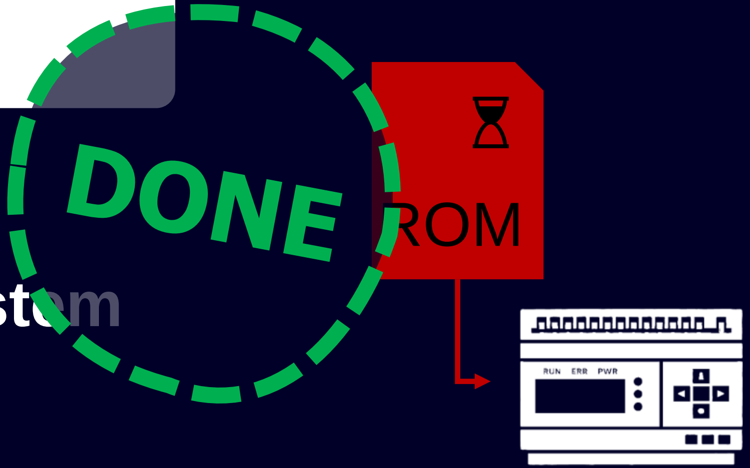
ML-based Reduced Order Modelling
Challenge



Battery Thermal Management

Complex multi-physics model:
- Turbulent fluid flow
- Battery electrochemistry
- Electrical modeling
- ~ 1 million cells



Challenge:
Real-time prediction running within a system simulation or a controller

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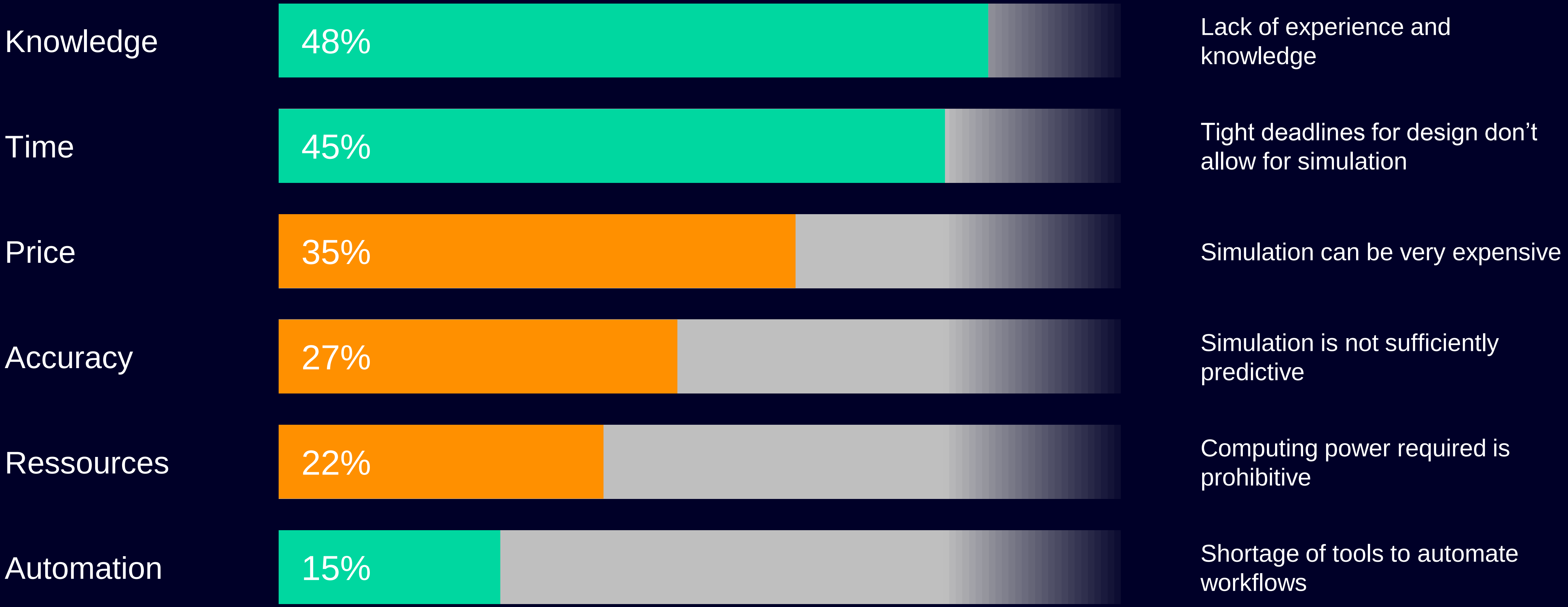
Scalability of simulation is limited by the same obstacles since a decade.

Challenge: This holds also for Digital Twins



Source: Engineering.com (2022): Research Report: The State of Simulation, Prototyping and Validation

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Deep Dive

ML-based Multiscale Modelling

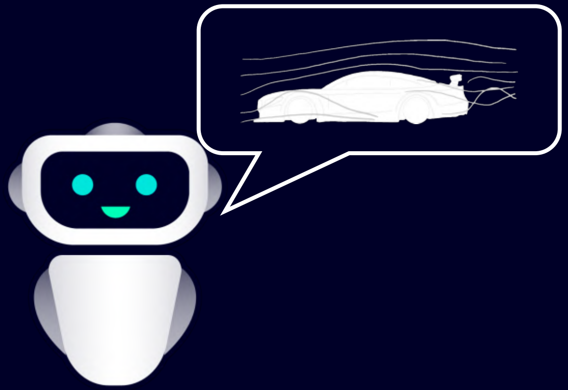
ML-based Multiscale Modelling
Challenge: Real-time Computational Fluid Dynamics (CFD)

Internal or External Flows

Complex multi-scale physics

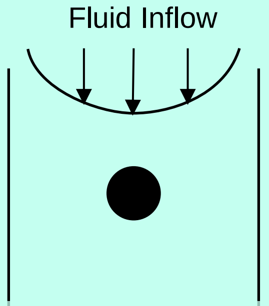
- Changing geometries
- Turbulent fluid flow
- ~ 1-100 million cells

Challenge:
Flexible real-time simulation running on a workstation for powering an engineering agent



ML-based Multiscale Modelling
Challenge: Acceleration of High-Fidelity Simulations

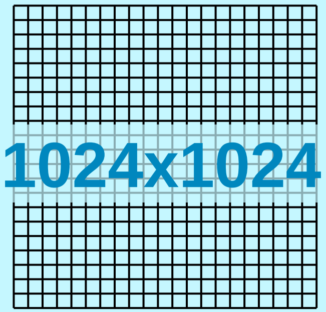
Simulation Task

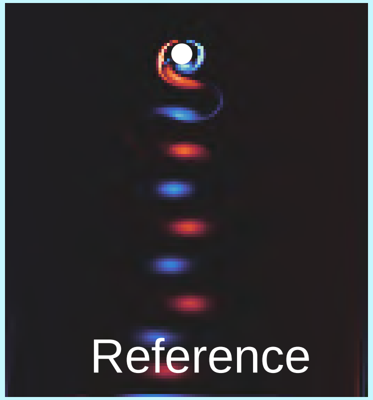


$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \mu \Delta \vec{V}$$

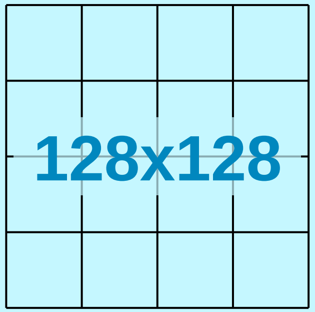
$$\nabla \cdot \vec{V} = 0$$

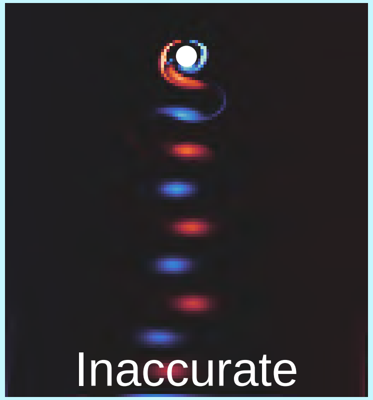
HiFi Simulation





LoFi Simulation





Using a coarser mesh allows a significant acceleration

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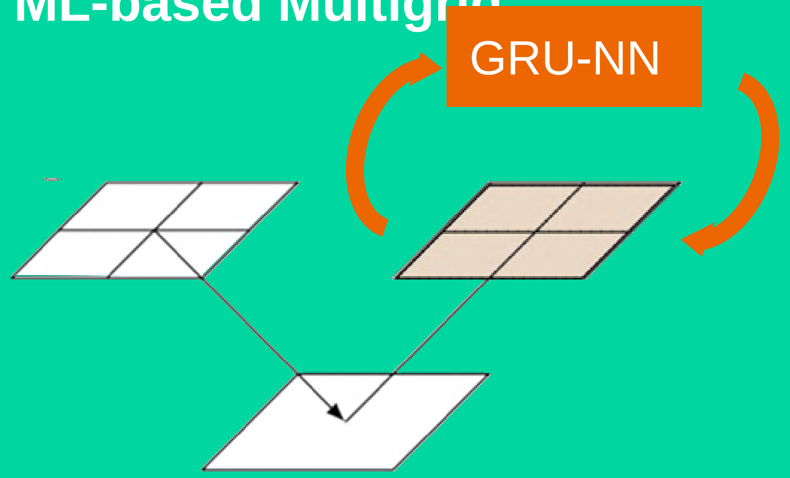
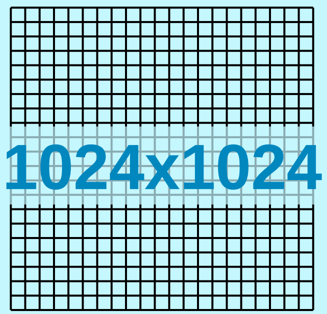
ML-based Multiscale Modelling
Core Idea

Approach A:
ML-based Multigrid

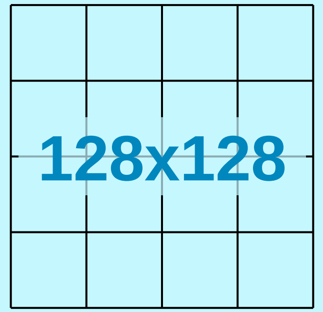


- ▶ **Geometric multi-grid method**
- ▶ **NN-based smoother**

HiFi Simulation



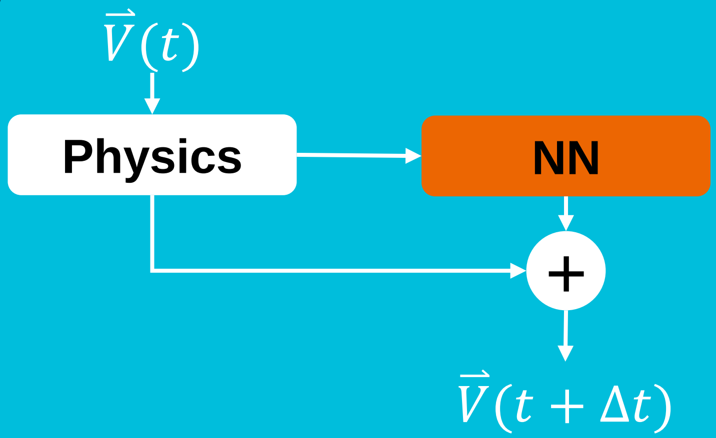
LoFi Simulation



Approach B:
ML-based Hybrid Modelling

$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \mu \Delta \vec{V} + NN(\vec{V}, \omega_i)$$

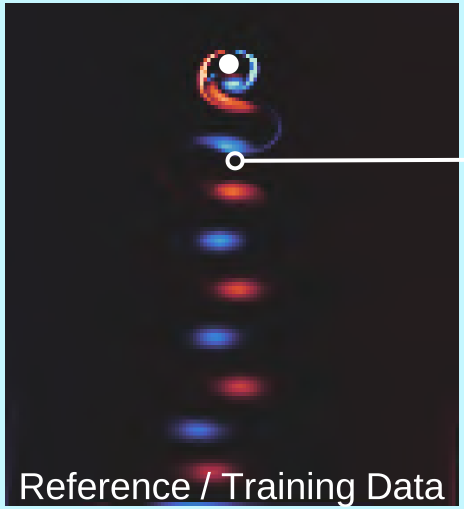
$$\nabla \cdot \vec{V} = 0$$



Source: N Margenberg, D Hartmann, C Lessig, T Richter (2020): A neural network multigrid solver for the Navier-Stokes equations; J. Comp. Phys.
G Jouan, M Schulz, D Berger, S Gavranovic, D Hartmann (2025): Hybrid solver with local correction using Lagrangian latent memory. Eurips Workshope– Diff Systems

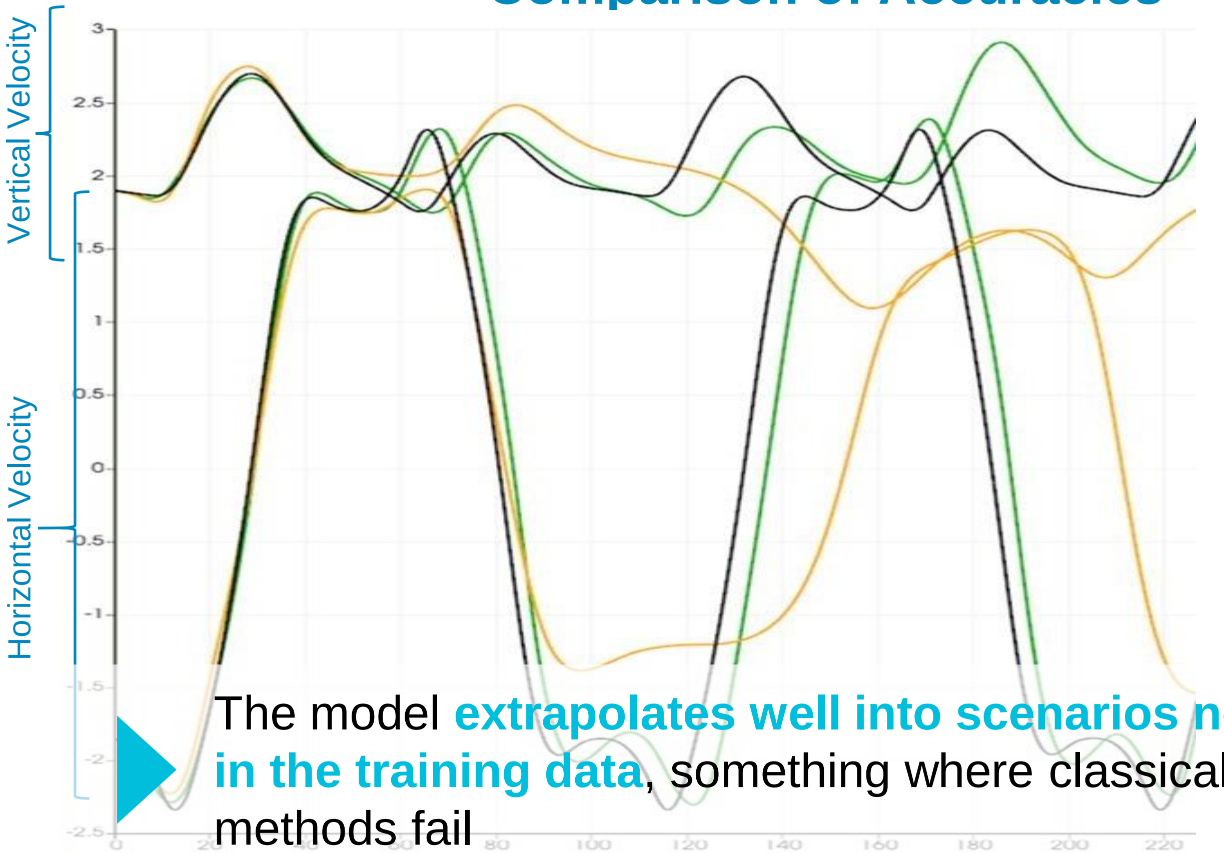
B ML-based Hybrid Modelling
Results

HiFi Simulation



Grid: 1024 x 1024
Solver: Industry-grade solver

Comparison of Accuracies



HiFi Simulation:
Reference & Training Data

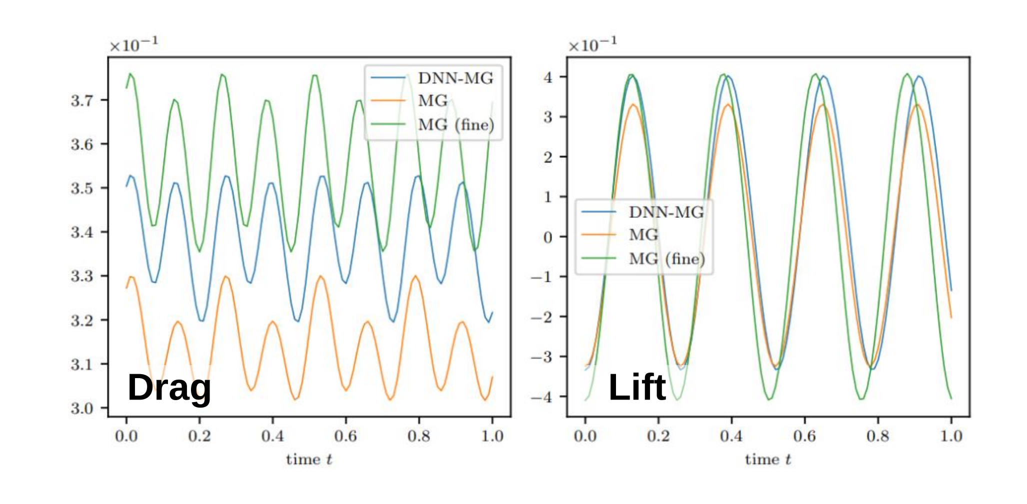
LoFi Simulation:
128 x 128 grid
40x speedup

ML-augmented Simulation:
128 x 128 grid
+ NN augmentation
18x speedup

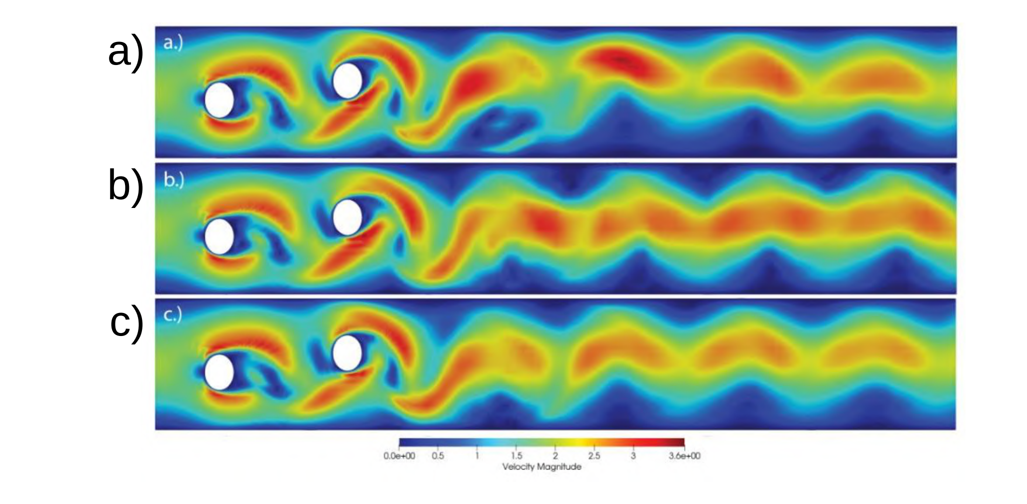
The model **extrapolates well into scenarios not seen in the training data**, something where classical ML methods fail

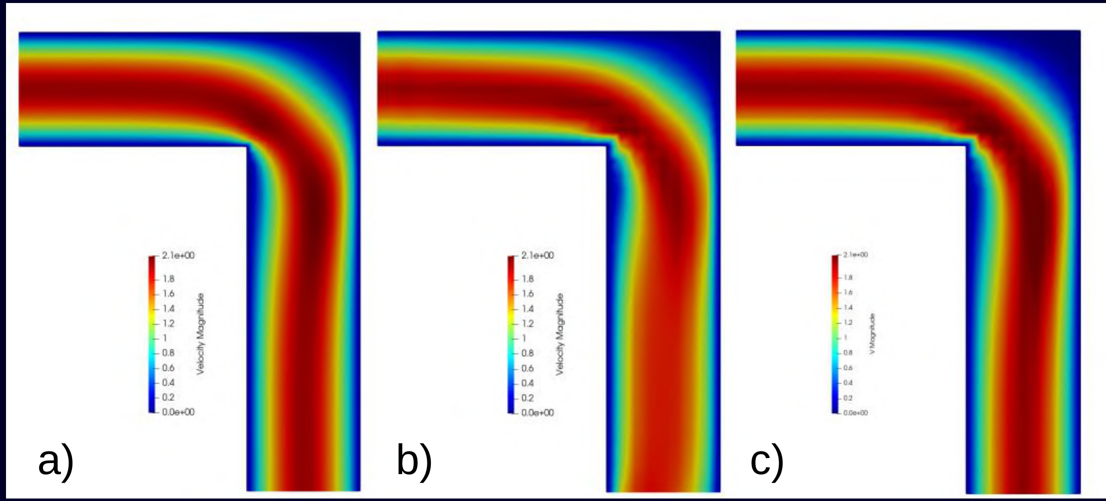
Source: G Jouan, M Schulz, D Berger, S Gavranovic, D Hartmann (2025): Hybrid solver with local correction using Lagrangian latent memory. Eurips Workshop - Differentiable Systems and Scientific Machine Learning

NN-based Multigrid Method
Results



a) $\mathrm{MG}\ (L+1)$
b) $\mathrm{DNN\text{-}MG}\ (L+1)$
C) $\mathrm{MG}\ (L)$





Source: N Margenberg, D Hartmann, C Lessig, T Richter (2020): A neural network multigrid solver for the Navier-Stokes equations; J. Comp. Phys.

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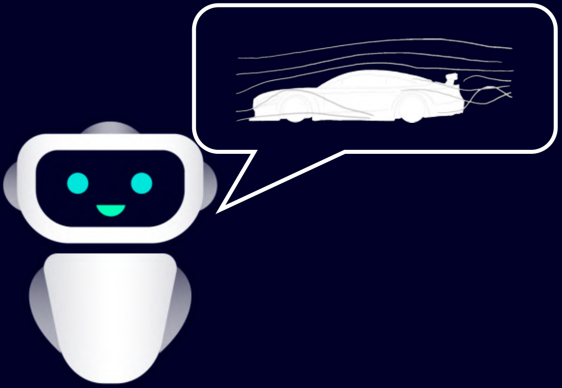
ML-based Multiscale Modelling
Challenge: Real-time Computational Fluid Dynamics (CFD)

Internal or External Flows

Complex multi-scale physics
- Changing geometries
- Turbulent fluid flow
- ~ 1-100 million cells

Work in Progress



Challenge:

Flexible real-time simulation running on a workstation for powering an engineering agent

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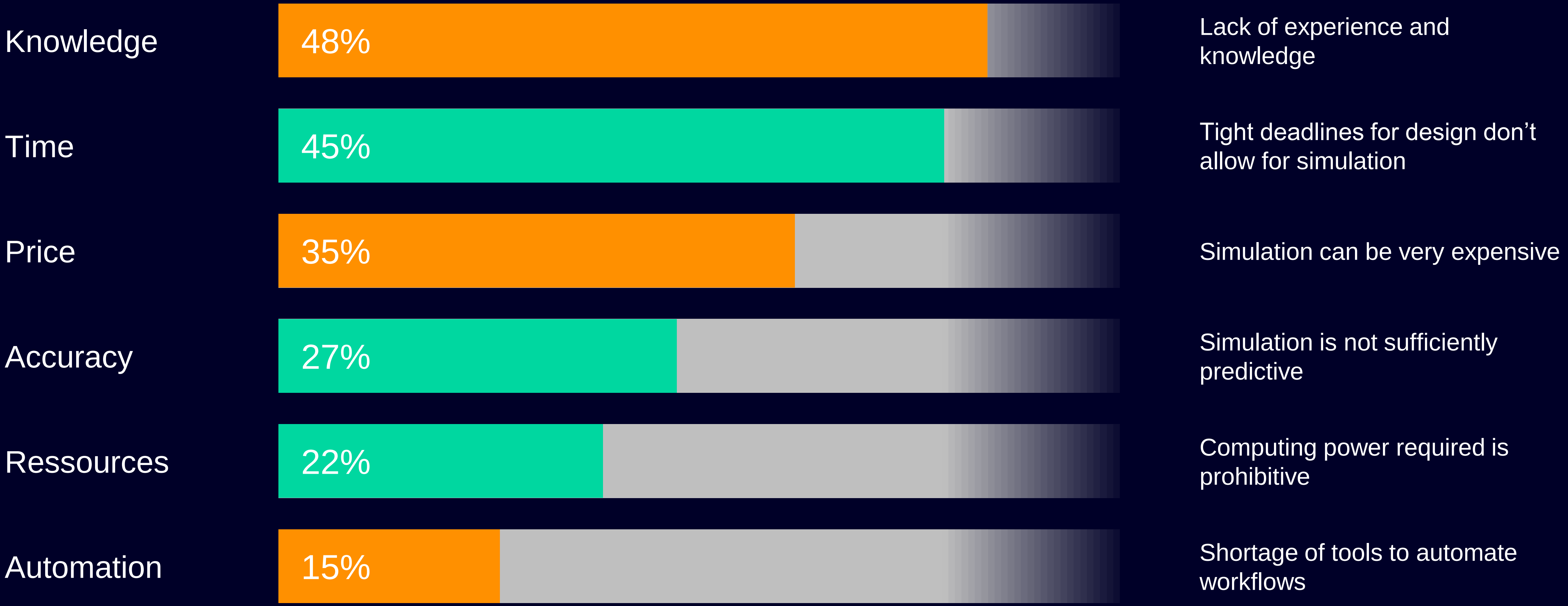
Scalability of simulation is limited by the same obstacles since a decade.
Challenge: This holds also for Digital Twins



Source: Engineering.com (2022): Research Report: The State of Simulation, Prototyping and Validation

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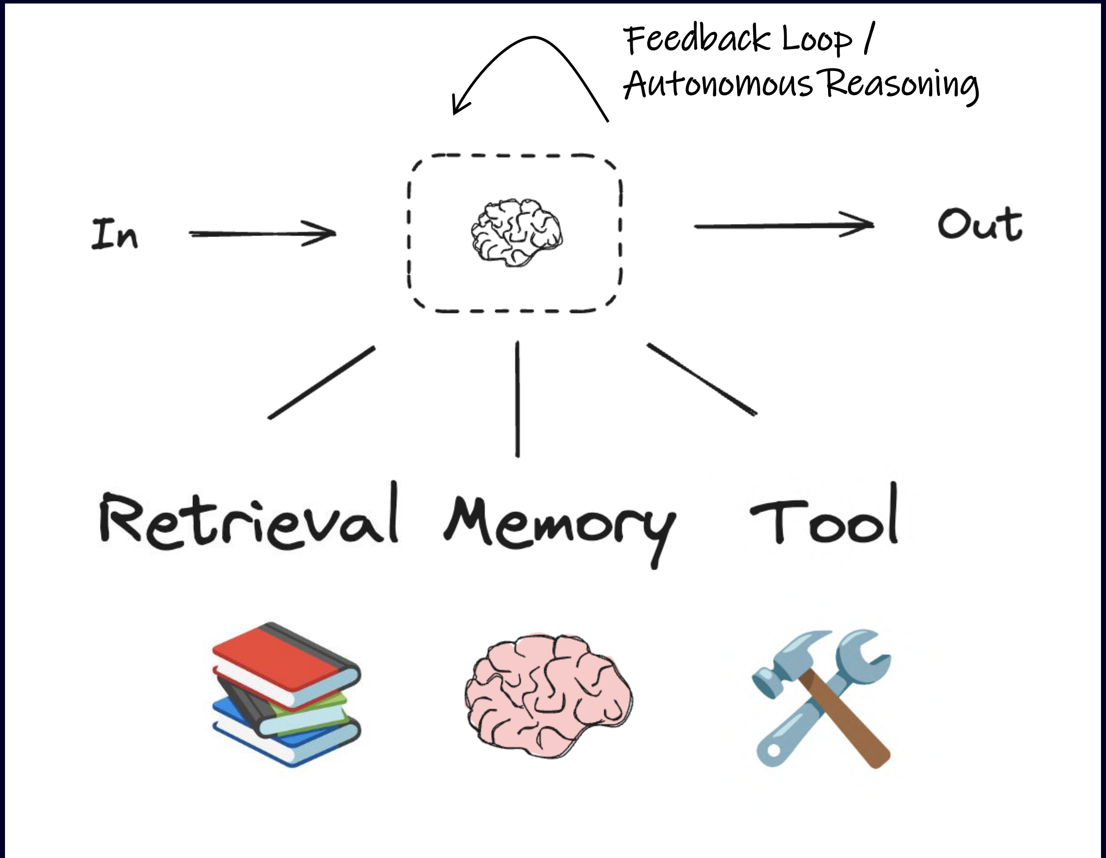
Deep Dive

AI-based User Experience

AI-based User Experience
What are AI Agents?



- An **agent is a piece of software program** built on top of an augmented Large Language Model (LLM).
- Augmented LLMs can retrieve **knowledge** and access **tools**.
- Agents are **autonomous**, i.e., they can plan and reflect themselves (as well as have memory).
- AI agents are similar to **AI Workflows** which are often used synonymously but are not autonomous.

Source: https://langchain-ai.github.io/langgraph/tutorials/workflows/#building-blocks-the-augmented-llm

AI-based User Experience
Demo: An AI Companion for Design and Engineering

Source: GradCad (2013): GE jet engine bracket challenge

Aircraft Engine Bracket - Technical Specification

Maximum Size (width x depth x height): 10in x 5in x 3in

Iterface 1: 0.75 inch diameter pin.

Fixation / Inteface 2-5: 4 0.375-24 AS3239-26 machine bolt: Nut face 0.405 in. max ID and 0.558 in. min OD

Minimum material feature size (wall thickness): 0.050 in.

Material: Ti-6Al-4V

Service Temperature: 75 F

Load Conditions:

1. Max static linear load of 8,000 lbs vertical up.

Design Goal

- Maximum yield stress below 131 ksi
- Minimum weight

bracket.md

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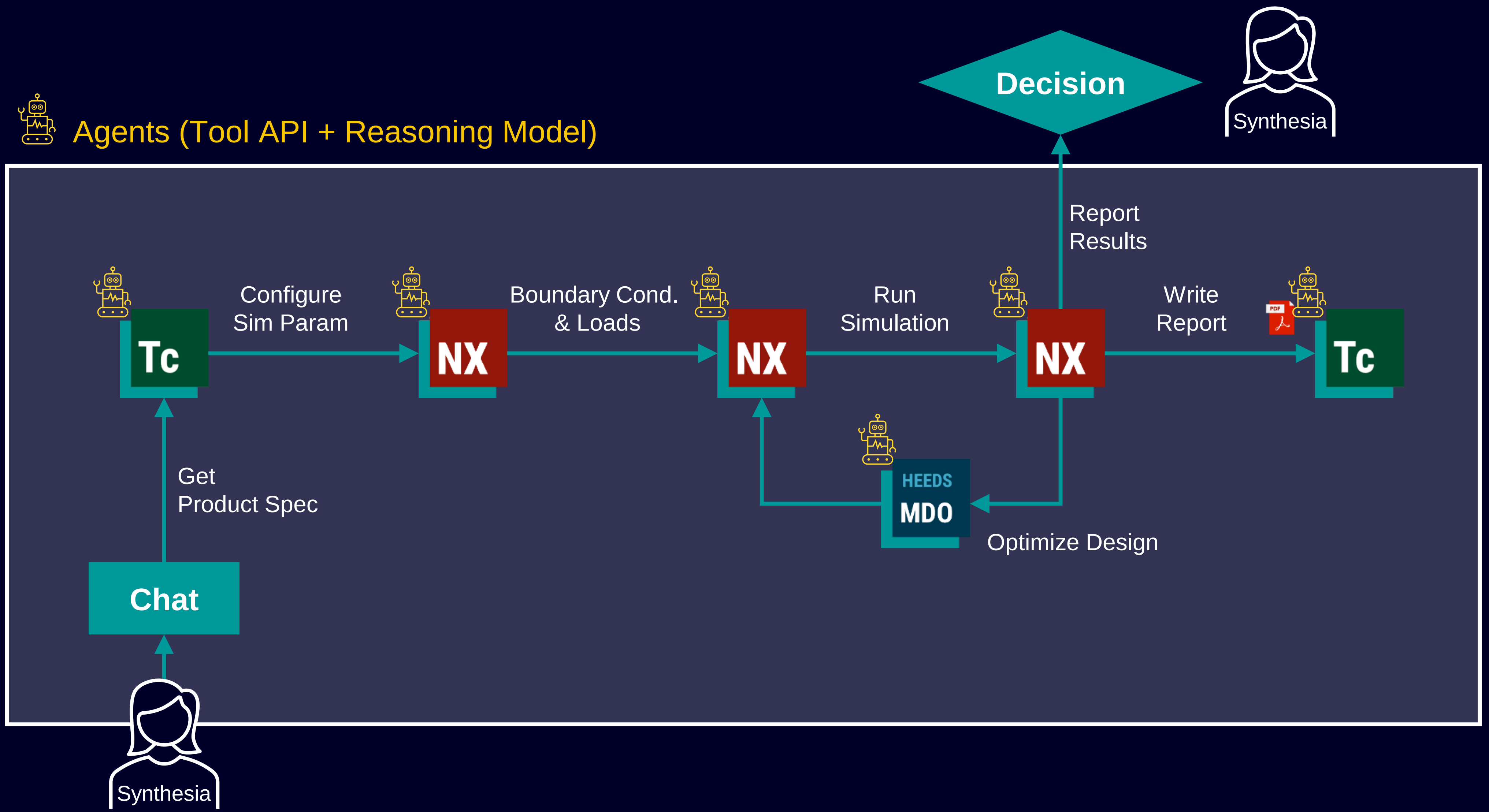
AI-based User Experience
“Architecture”



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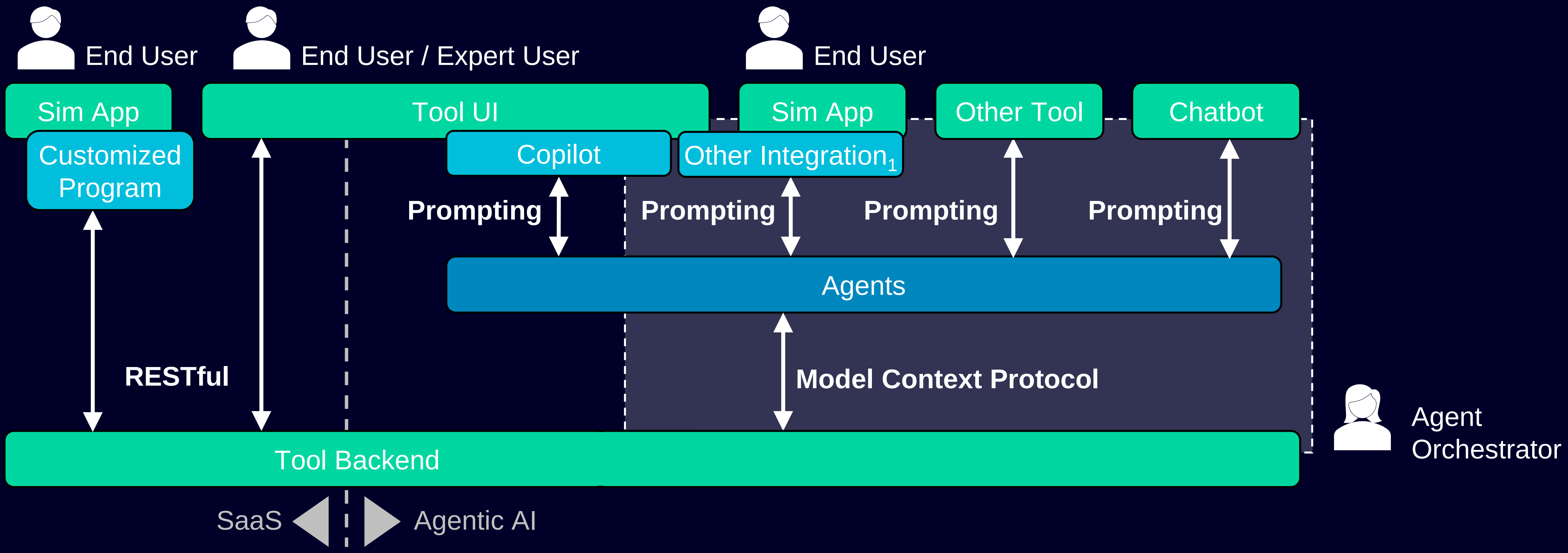
AI-based User Experience
"Architecture"



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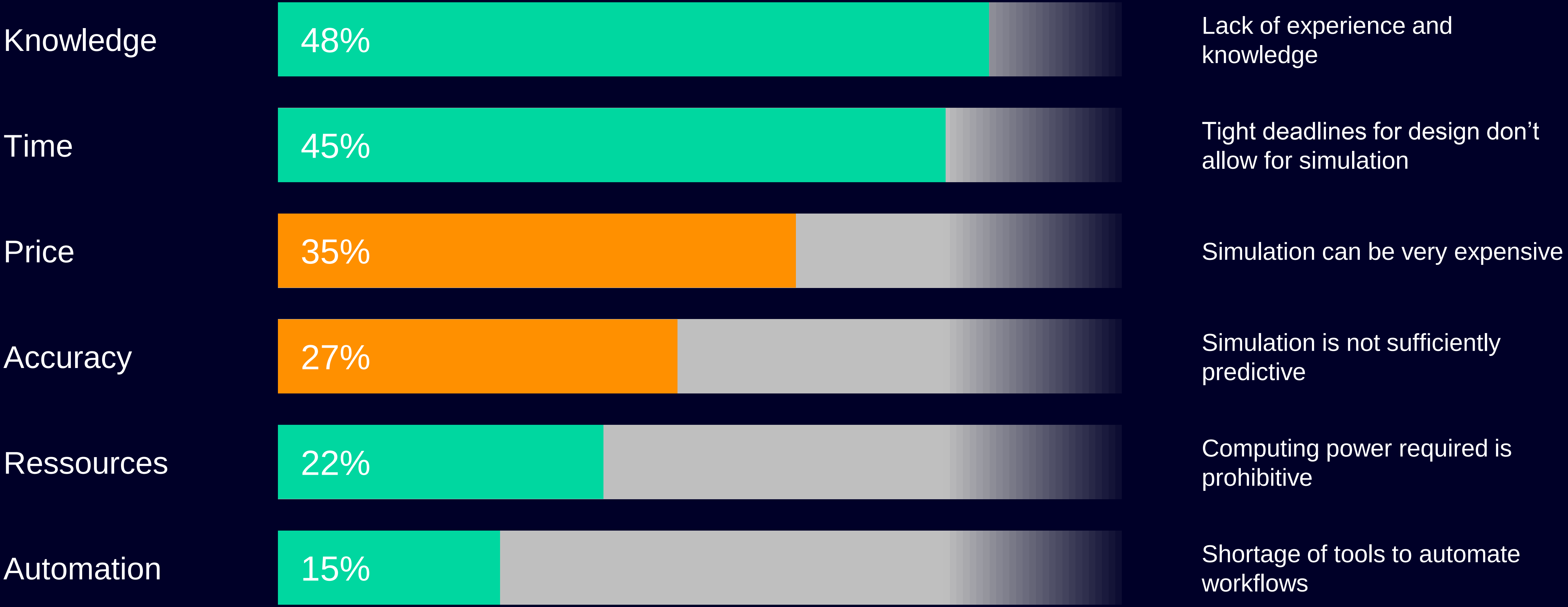
Scalability of simulation is limited by the same obstacles since a decade.
Challenge: This holds also for Digital Twins



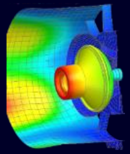
Source: Engineering.com (2022): Research Report: The State of Simulation, Prototyping and Validation

6

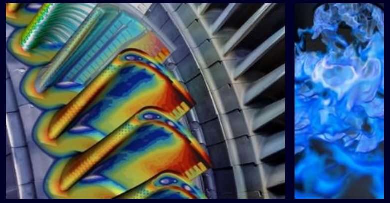
Wrap Up

Digital Twin - *A new age of computational paradigms*

Model Pioneers



CAx Sunrise



R&D Pervasion

Digital Twin Era

~1985 **~2000** **~2015**

CAx: Computer Aided Design, Engineering, & Manufacturing

Engineering AI
in the News

Neural Concept Closes $100M Funding Round Led by Growth Equity at Goldman Sachs Alternatives to Sc... Native E...

On the brink of a revolution? Engineering simulation in the age of AI

February 12, 2025 | McKinsey Direct

Dassault Systèmes Reveals "3D UNIV+RSES" and Related AI-Based Services

PRESS RELEASE

Siemens & PhysicsX collaborate to build AI-based deep physics simulation

December 4, 2024
Plano, Texas, USA

Synopsys Completes ... n of Ansys

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These New AI Models Are Trained on Physics, Not Words, and They're Driving Discovery

Business Tech News: Zuckerberg Says AI Will Replace Mid-Level Engineers Soon

By Gene Marks, Contributor. ⓘ I write about tech that impacts my small busin...

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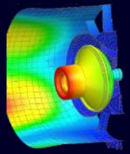
Jennifer Chu | MIT News
December 5, 2024

Volkswagen and IQM Quantum Computers release study on battery simulation

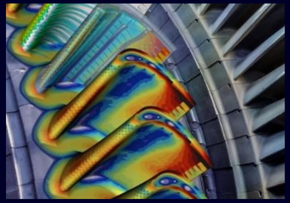
15 Nov 2024

Digital Twin - *A new age of computational paradigms*

Model Pioneers



CAx Sunrise



R&D Pervasion

Digital Twin Era

Physical AI

~1985 **~2000** **~2015** **~2025**

CAx: Computer Aided Design, Engineering, & Manufacturing

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Physical AI
in the News

engineering.com

Beyond digital twins: NVIDIA and Dassault bet on industry …

…l platform means for engineering

Automatisierung

Handelsblatt

ABB Robotics verbündet sich mit Nvidia – „Endgame hat begonnen“

Das Training von intelligenten Robotern … Herausforderungen in der Industrie. Eine … Durchbruch bringen.

Axel Höpner
09.03.2026 - 13:00 Uhr

AI pioneer Fei-Fei Li's World Labs raises $1 billion in funding

By Reuters

February 18, 2026 8:22 PM GMT+1 · Updated February 18, 2026

REUTERS

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Published on October 6, 2025

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Acquisition Strengthens CoreWeave's Position in Manufacturing, Automotive, Aerospace, and Other Industrial Sectors

Jeff Bezos Creates A.I. Start-Up Where He Will Be Co-Chief Executive

Called Project Prometheus, the company is focusing on artificial intellige… for the engineering and manufacturing of computers, … automo… …craft…

$6.2B funding

TECHNOLOGY

Inc.

Why Nvidia's Jensen Huang Is So Bullish on 'Physical AI' and Robots 'The ChatGPT moment for robotics is … said. Here's why

Ex-Meta AI chief Yann LeCun's AMI raises $1.03 billion for alternative AI approach

By Katie Paul and Anhata Rooprai

March 10, 2026 6:01 AM GMT+1 · Updated March 10, 2026

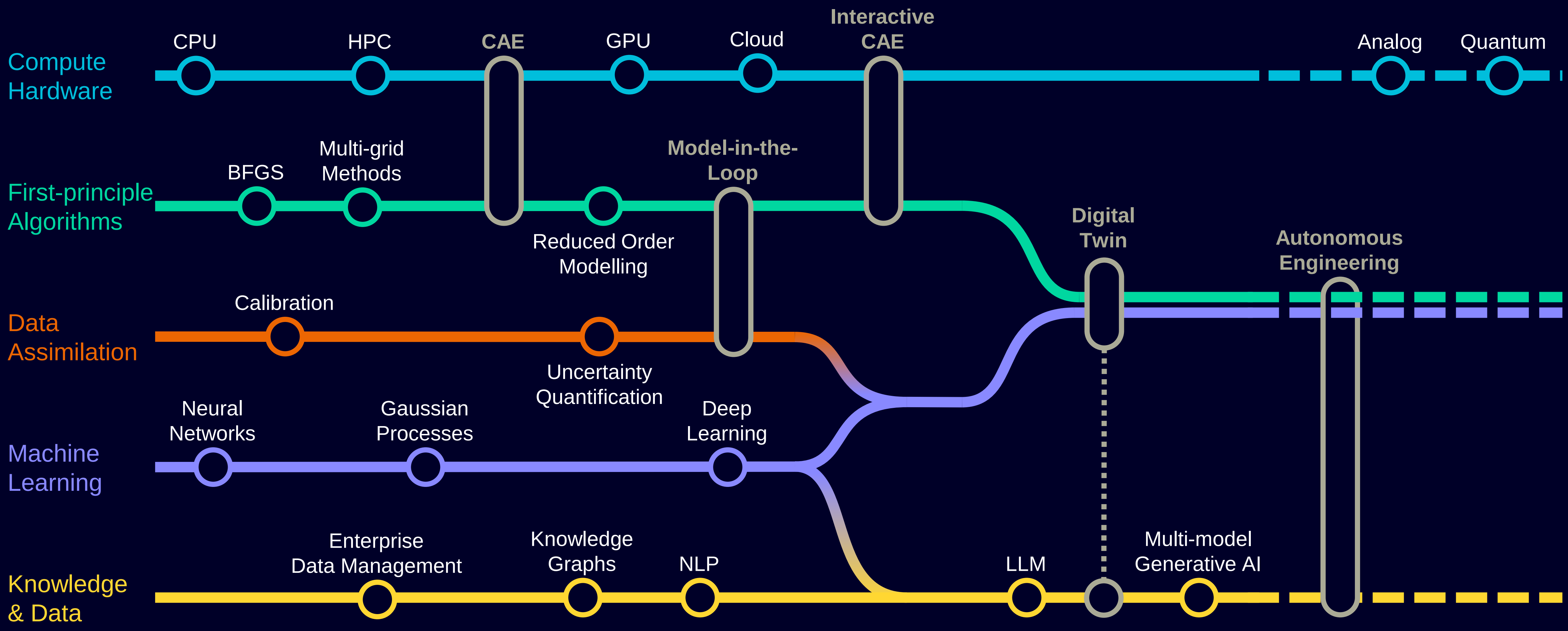
REUTERS

UNITE.AI

The Rise of Physical AI: Why the Boston Dynamics–Google DeepMind Alliance Changes Everything

AI Pioneer Fei-Fei Li Ushers In Next Frontier Of Artificial Intelligence

It is exciting times …
… the evolution and convergence of technologies will make Digital Twins real



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It is exciting times …
… however, without caution we will be lost

Source: OpenAI - ChatGPT

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One is sure, without caution and rigorous research we will be lost!
Overoptimism and weak baselines call for more rigor and clarity!


Weak baselines and reporting biases lead to overoptimism in machine learning for fluid-related partial differential equations

McGreivy, N., & Hakim, A. (2024). Weak baselines and reporting biases lead to overoptimism in machine learning for fluid-related partial differential equations. *Nature machine intelligence*, *6*(10), 1256-1269.


Defining Foundation Models for Computational Science: A Call for Clarity and Rigor

Y Choi, SW Cheung, Y Kim, PH Tsai, AN Diaz, I Zanardi, ... M Heinkenschloss (2025): Defining Foundation Models for Computational Science: A Call for Clarity and Rigor. *arXiv preprint arXiv:2505.22904*.


Fluid Intelligence: A Forward Look on AI Foundation Models in Computational Fluid Dynamics

N Ashton, J Brandstetter, S Mishra (2025): Fluid Intelligence: A Forward Look on AI Foundation Models in Computational Fluid Dynamics. *arXiv preprint arXiv:2511.20455*.


What Has a Foundation Model Found? Using Inductive Bias to Probe for World Models

K Vafa, PG Chang, A Rambachan, S Mullainathan (2025): What has a foundation model found? using inductive bias to probe for world models. arXiv preprint arXiv:2507.06952.

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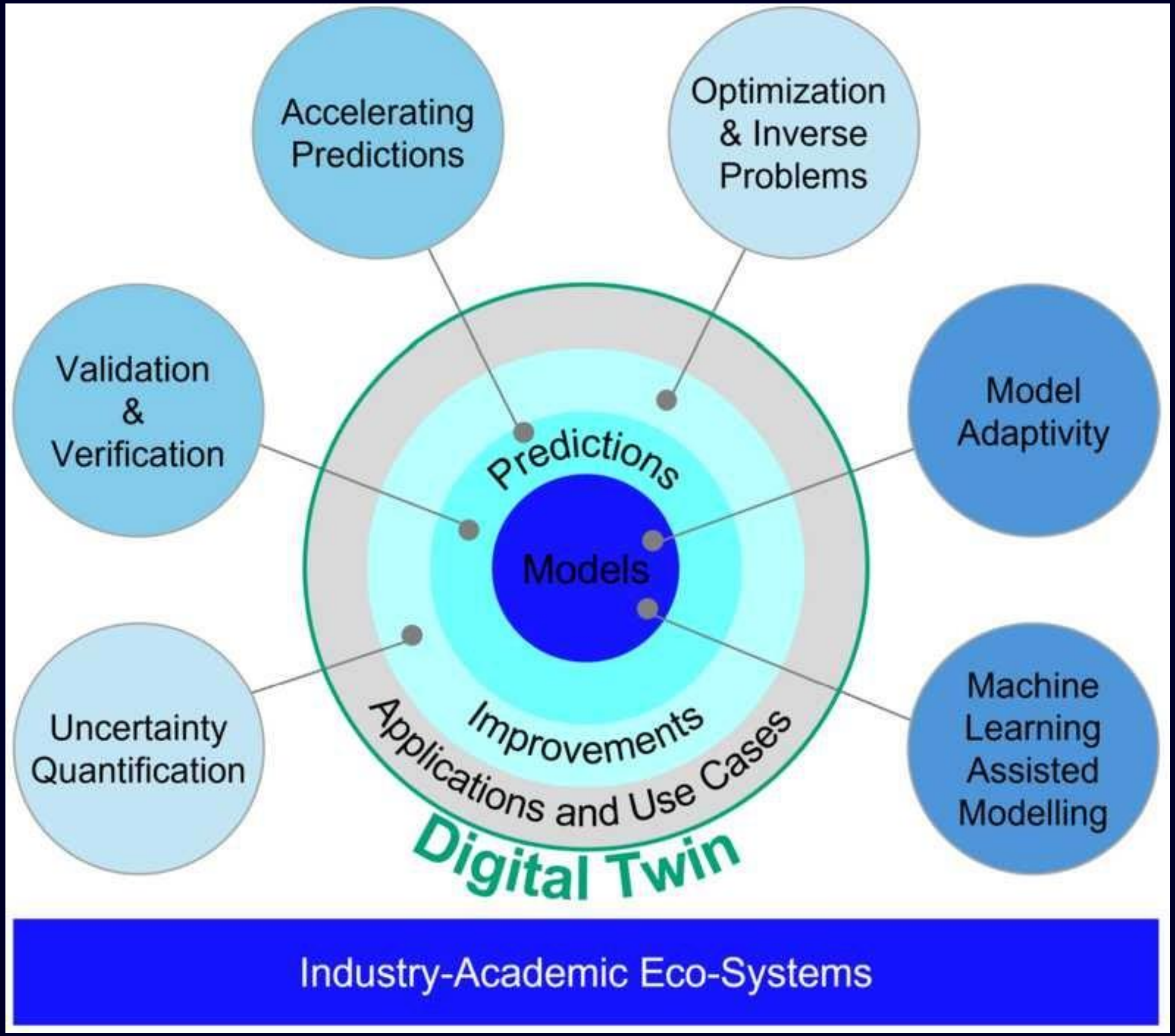
Mathematics is crucial to make Digital Twins real!



Digital Twins - a golden age for industrial mathematics

Source: D Hartmann, H Van der Auweraer (2025) Digital Twins - a golden age for industrial mathematics. Journal of Mathematics in Industry

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