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Artificial Intelligence and Digital Engineering as Enablers for System Engineering in the Energy Sector

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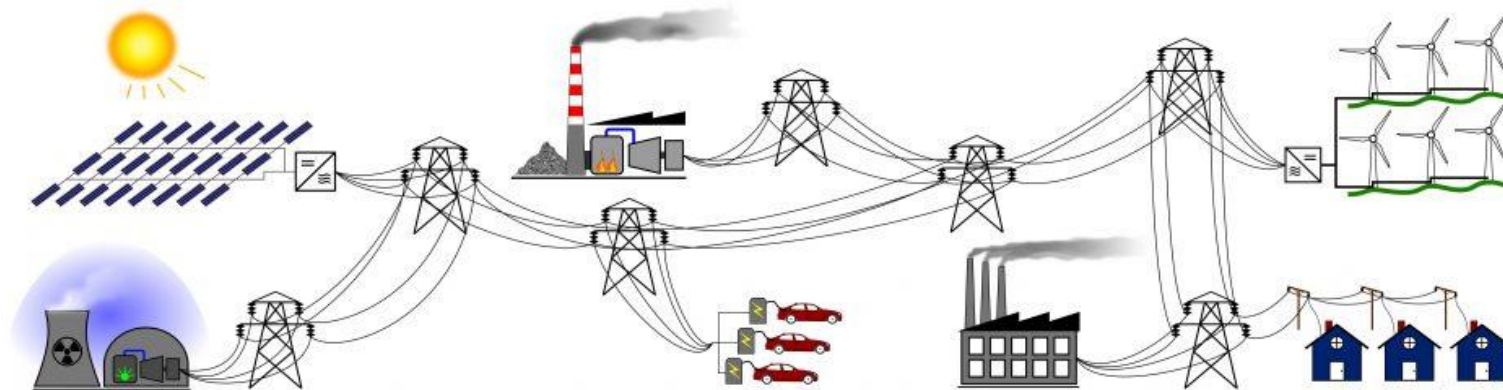
Overview: Energy Sector



Courtesy: US EPA



Courtesy: evgenii_v, Adobe Stock



Courtesy: Dennice F. Gayme

- Complex, expensive megaprojects.
- Often over budget and behind schedule.
- Needs rigorous systems engineering!

Resistance to Traditional SE

- **Systems engineering:**
 - Often characterized as “labor-intensive” and “time-consuming.”
 - Traditionally document-based → Workflows difficult to trace, especially for complex projects.
- **Current needs of the energy sector:**
 - AI data centers, manufacturing, domestic consumption → Rising energy demand.
 - Requires quick deployment of new facilities and sustained, efficient operation of existing ones.
 - Traditionally slow-paced industry but now needs speed and agility.

Solution: Digital Engineering + AI

Digital Engineering

Use of digital models and data for lifecycle management of engineered systems

Flexibility, modularity, traceability, efficiency

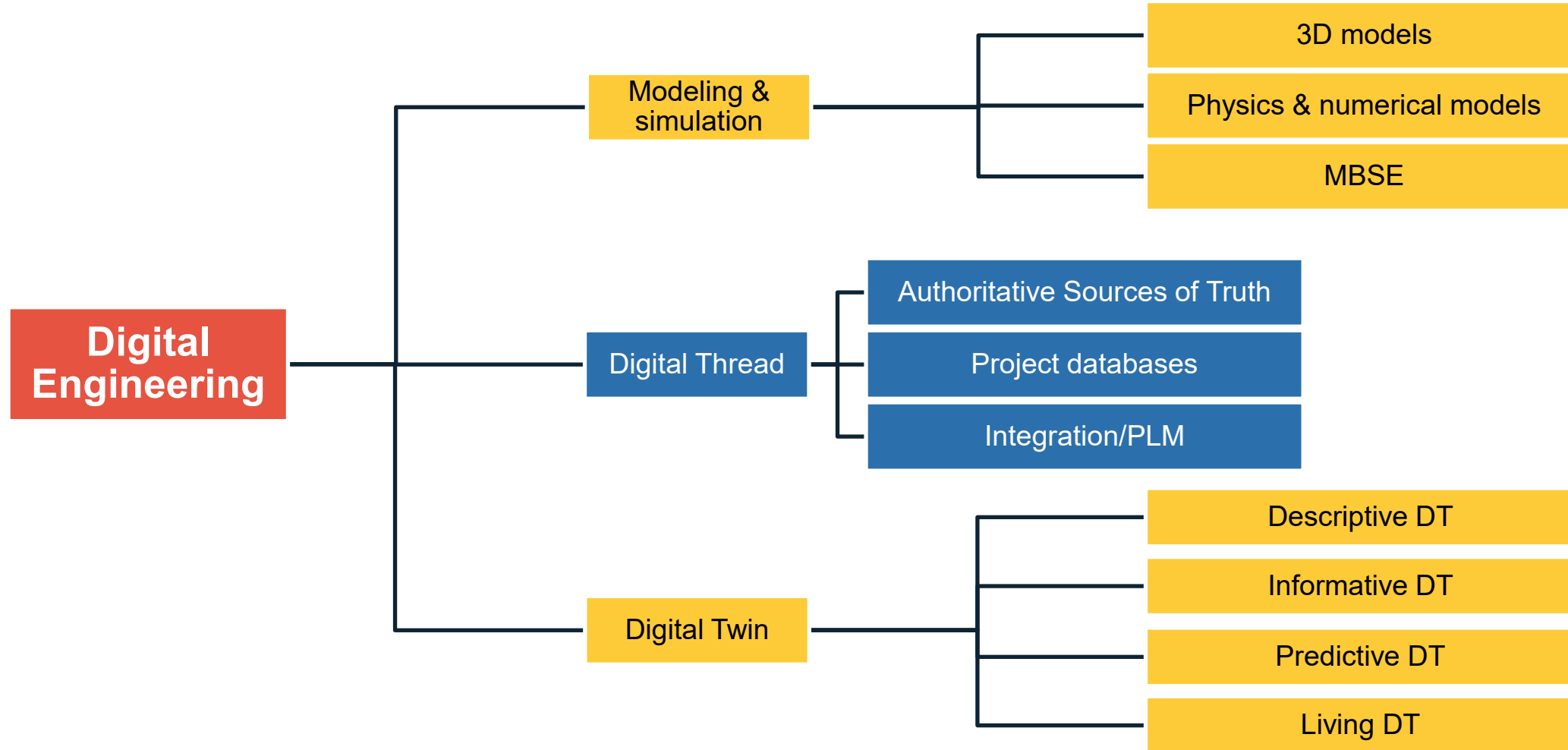
Artificial Intelligence

Computers emulating complex human behaviors (e.g., learning, processing human languages)

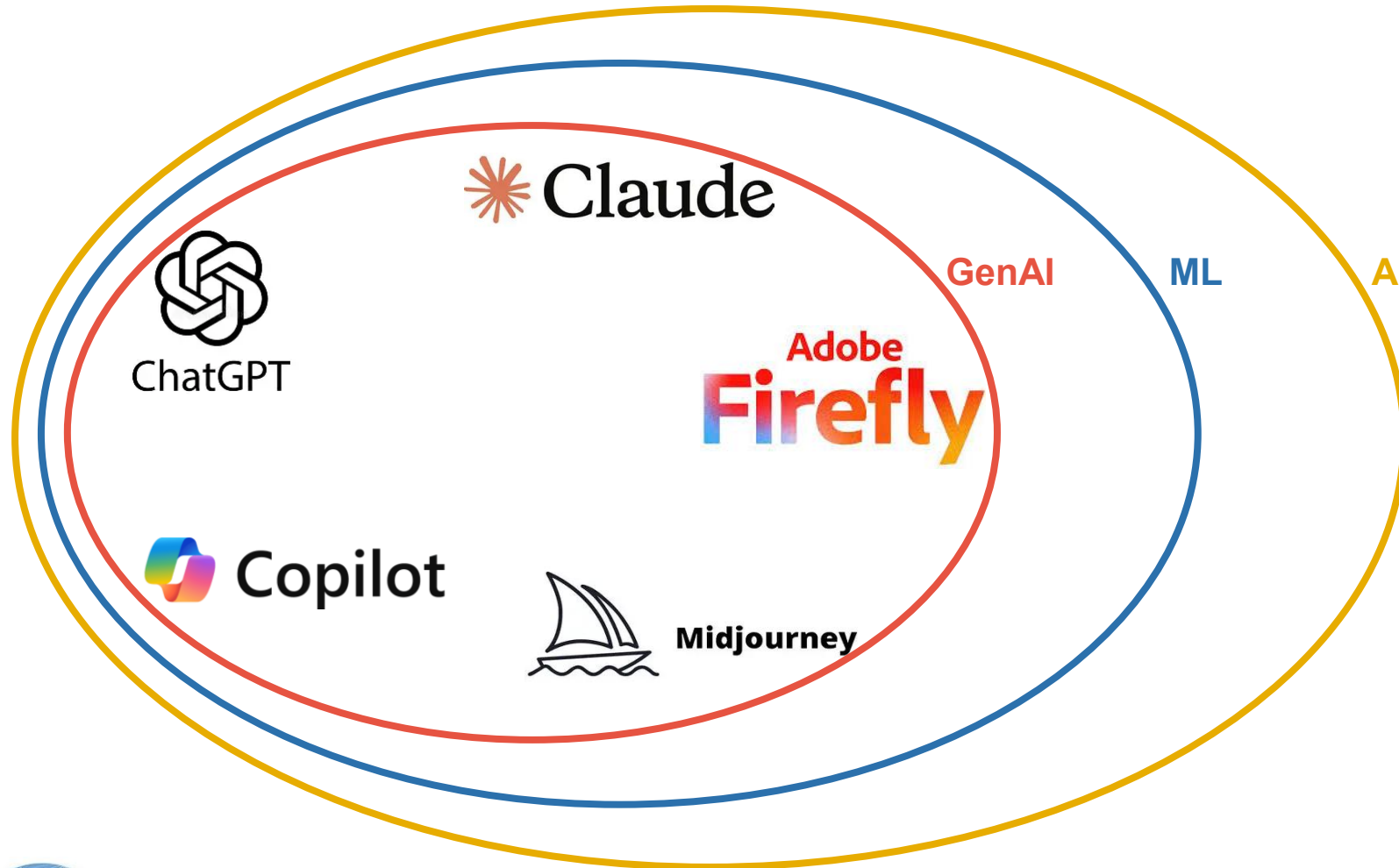
Automation/autonomy, data interpretation & analytics

Systems Engineering

Digital Engineering



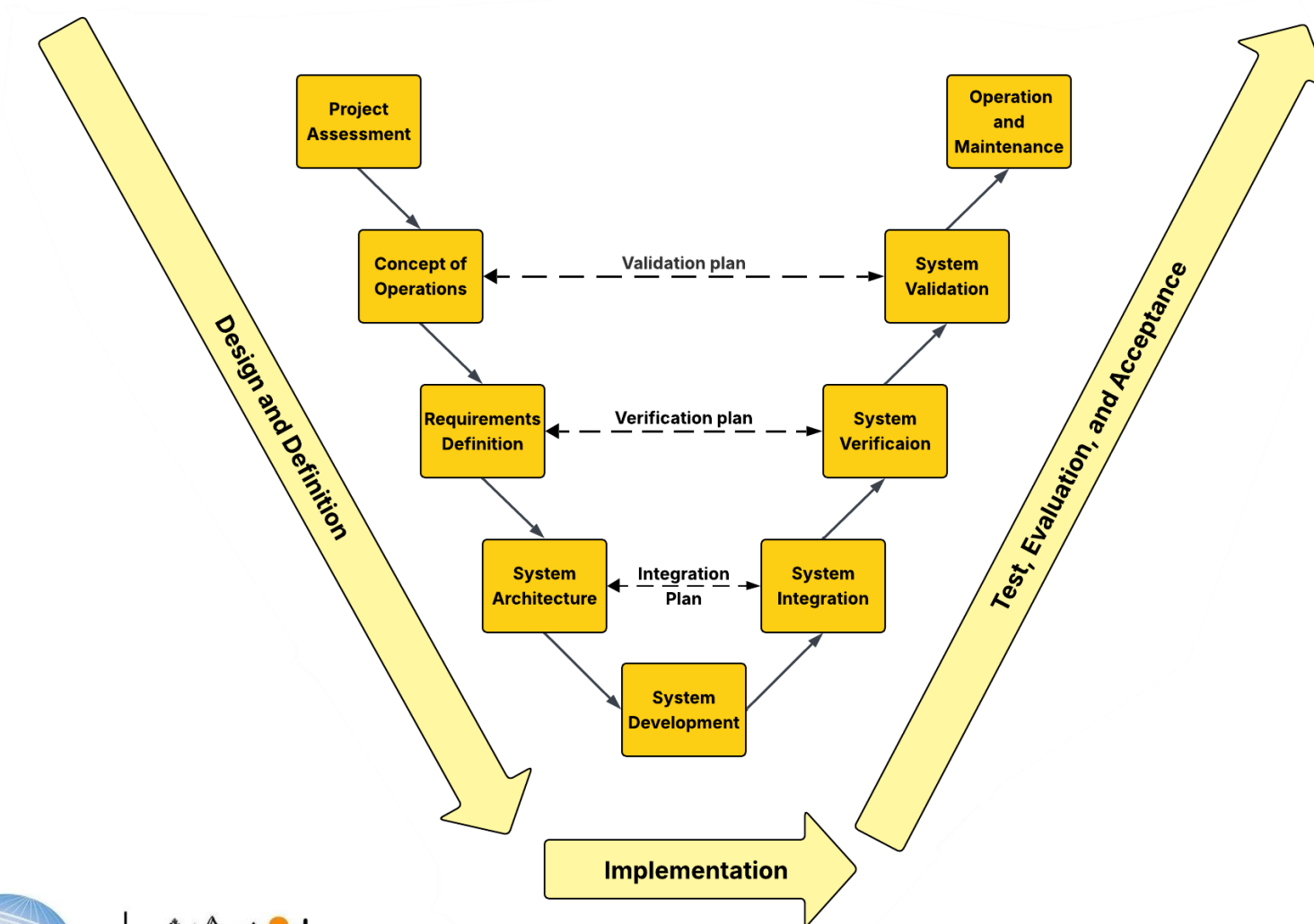
Artificial Intelligence



Key AI concepts for energy applications:

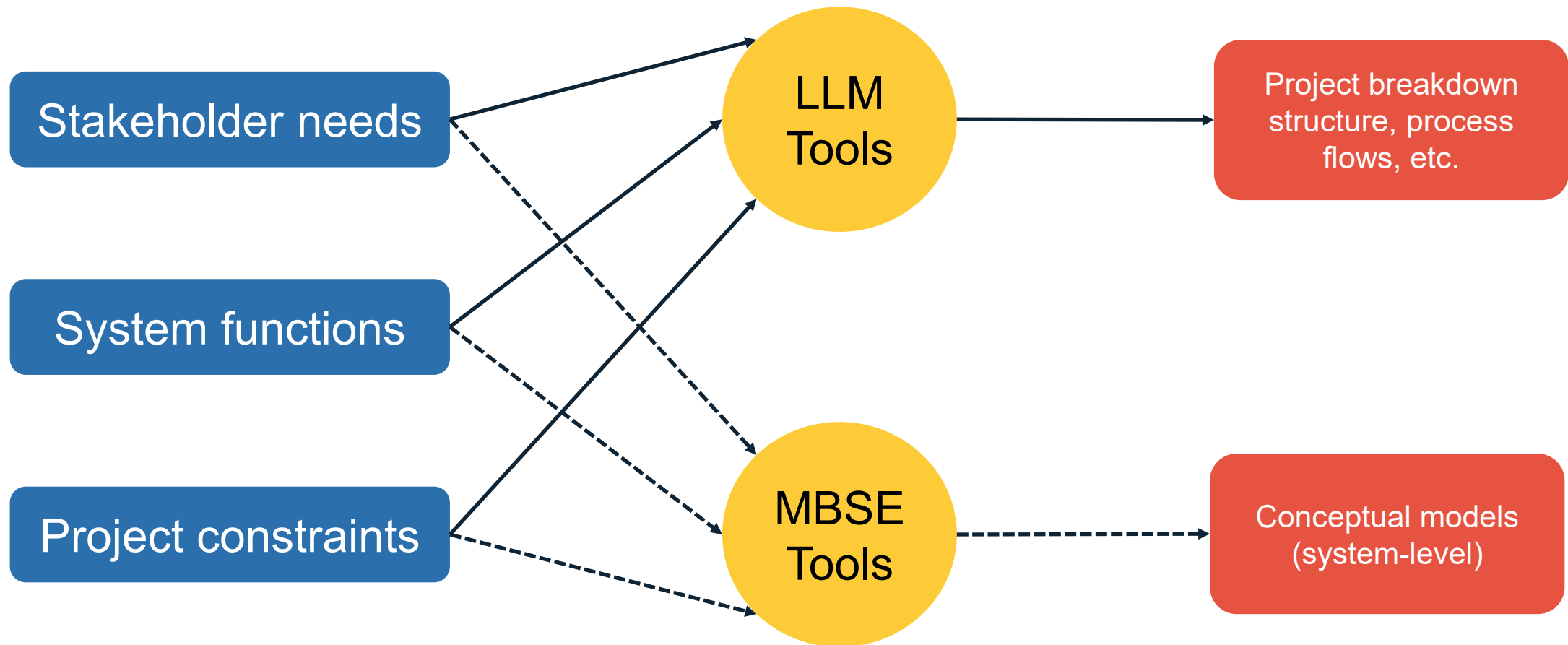
- Supervised, unsupervised, and reinforcement learning
- Physics-informed neural networks (PINN)
- Natural Language Processing (NLP)
- Large Language Models (LLMs)
- Engineering-oriented GenAI (e.g., text-to-CAD)

The Systems Engineering V-model

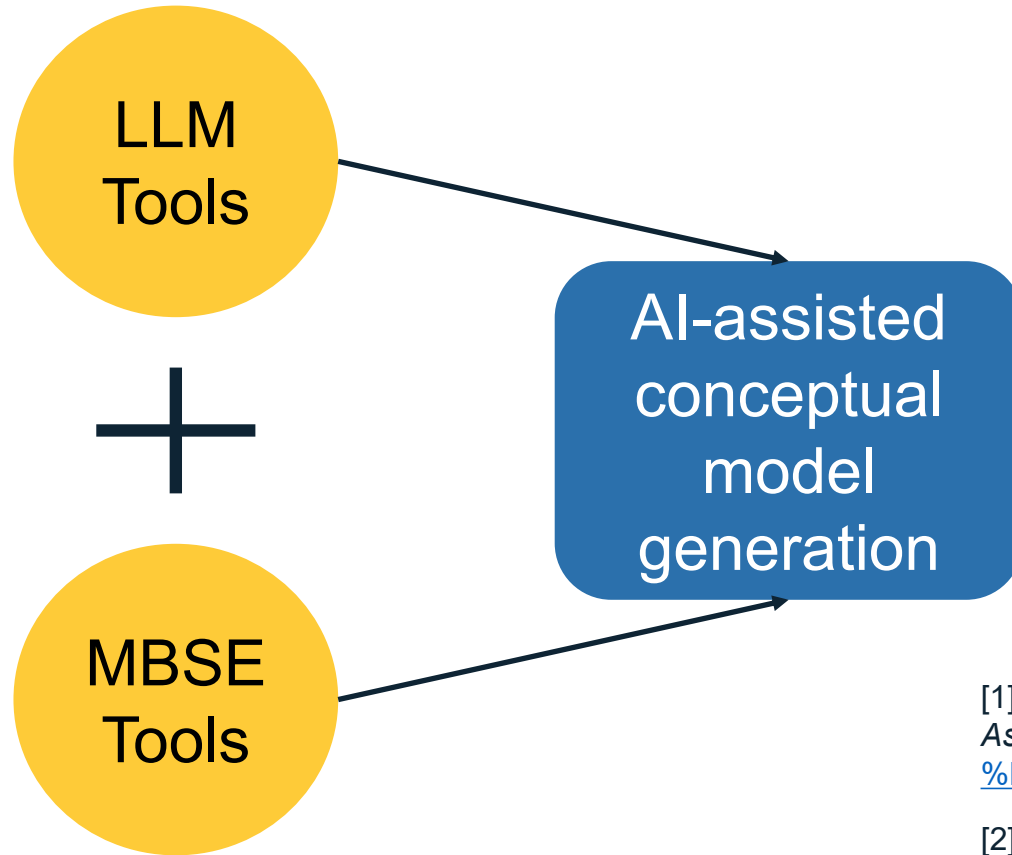


How can DE and AI augment/accelerate each step of the SE V-model, especially for the energy sector?

Project Assessment and ConOps



LLM + MBSE for Conceptual Modeling



Examples:

- MITRE's Systems Engineering Language Modeling Assistant (SELMA) [1]
- NASA' multi-step LLM-based conceptual modeling tool [2]

[1] Gadewadikar, J., Esho, T., & Marshall, J. (2024). *Systems Engineering Language Modeling Assistant (SELMA)*. <https://sercuarc.org/wp-content/uploads/2024/09/Slides-%E2%80%8BSystems-Engineering-Language-Modeling-Assistant.pdf>

[2] VanGundy, B., Schneide, M., Phojanamongkolkij, N., Levitt, I., & Brown, B. (2024). *Developing Concepts of Operations Using Multi-Step Tool Techniques With Large Language Models*. <https://ntrs.nasa.gov/citations/20240011037>

Requirements Definition

Requirements Management Tools:



IBM Rational
DOORS Next Generation



AI for automated requirements elicitation, document analysis, traceability, impact analysis, etc.

Requirements in MBSE Software:



VR Verification Requirements	Quality Score	Labels	Identifier
VR.1 Space Vehicle First-mode Natural Frequency The space vehicle first-mode natural frequency shall be verified by analysis and test.	89%	Analysis X Demonstration X Safety Requirement X Verification Requirement X	1175
VR.1.1 Natural Frequency Analysis The analysis shall develop a multi-node finite element model to estimate natural modes.	89%	Analysis X Modeling & Simulation X Information Requirement X Verification Requirement X	1126
VR.1.2 Natural Frequency Test The test shall conduct a modal survey (sine sweep) of the vehicle using a vibration table.	89%	Test X Verification Requirement X	589
VR.2 Appropriate Markings The appropriate markings on all system structural components shall be verified by inspection. The inspection shall determine if axes and identifications are properly indicated.	67%	Default X Inspection X Verification Requirement X	871
VR.3 Altitude Accuracy The accuracy of the altitude determination system estimates shall be verified by analysis. The analysis shall use Monte Carlo simulations of expected sensor accuracy, plus noise, to determine statistical distribution error.	78%	Analysis X Verification Requirement X	867

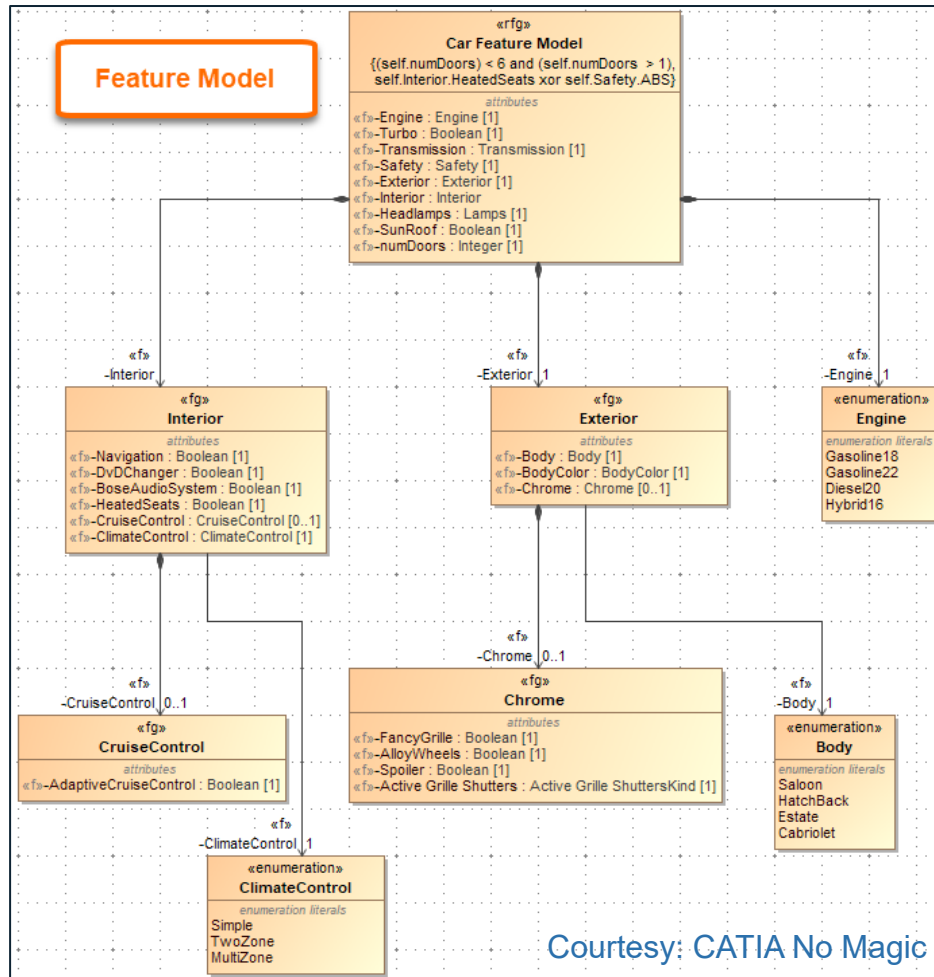
Courtesy: SPEC Innovations



Index	ID	Summary	Implemented	Verified
Import1	000005e0	References to DOORS_req_func_spec		
1	CC-REQ-1	Driver Switch Request Handling		
1.1	CC-REQ-2	Switch precedence		
1.2	CC-REQ-3	Avoid repeating commands		
1.3	CC-REQ-4	Long Switch recognition		
1.4	CC-REQ-5	Waiting state for Long Increment switch det.		
1.5	CC-REQ-6	Waiting state for Long Decrement switch de.		
1.6	CC-REQ-7	Cancel Switch Detection		
1.7	CC-REQ-8	Set Switch Detection		
1.8	CC-REQ-9	Enable Switch Detection		
1.9	CC-REQ-10	Resume Switch Detection		
2	CC-REQ-11	Increment Switch Detection		
2.1	CC-REQ-12	Increment Short Switch Detection		
2.2	CC-REQ-13	Increment Long Switch Detection		
2.3	CC-REQ-14	Intermediate state		
2.4	CC-REQ-15	Decrement Switch Detection		
2.5	CC-REQ-16	Decrement Short Switch Detection		
2.6	CC-REQ-17	Decrement Long Switch Detection		
2.7	CC-REQ-18	Intermediate state		
3	CC-REQ-19	Cruise Control Mode		
3.1	CC-REQ-20	Calculate Target Speed and Throttle Value		

Courtesy: MathWorks

System Architecture



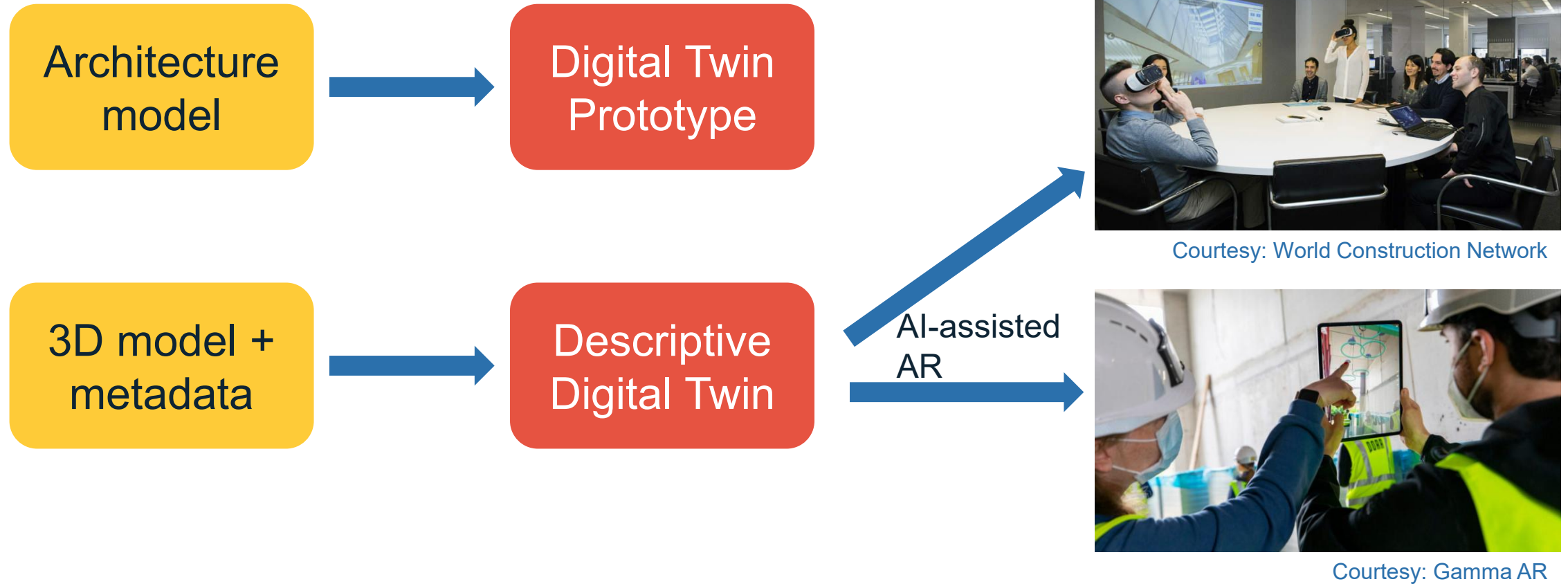
Digital thread

- 3D models
- Physics-based simulations
- PLM tools or databases
- Other project artifacts

AI-assisted system architecture?

- Identify candidate architectures based on requirements and constraints,
- Iteratively optimize the architecture based on metrics like cost and performance,
- Automate the connections across the digital thread,
- Conduct system-level risk assessments, etc.

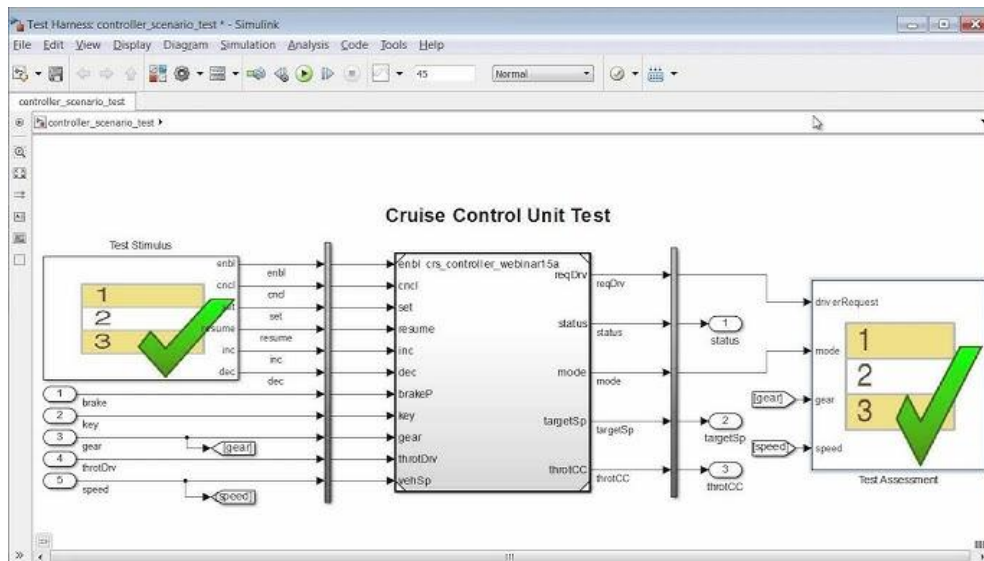
System Development and Integration



Verification and Validation

V&V within MBSE Tools

Example: Simulink Test



Courtesy: MathWorks

Potential for AI:

- Parsing text-based requirements and identifying the systems they apply to.
- Autonomous generation of test cases for V&V.
- Automated sequencing and execution of simulation-based tests under various operating conditions.
- Early detection of errors and conflicts.

AI-augmented V&V is gaining traction in software engineering; this could be expanded to broader systems engineering applications.

Operations and Maintenance

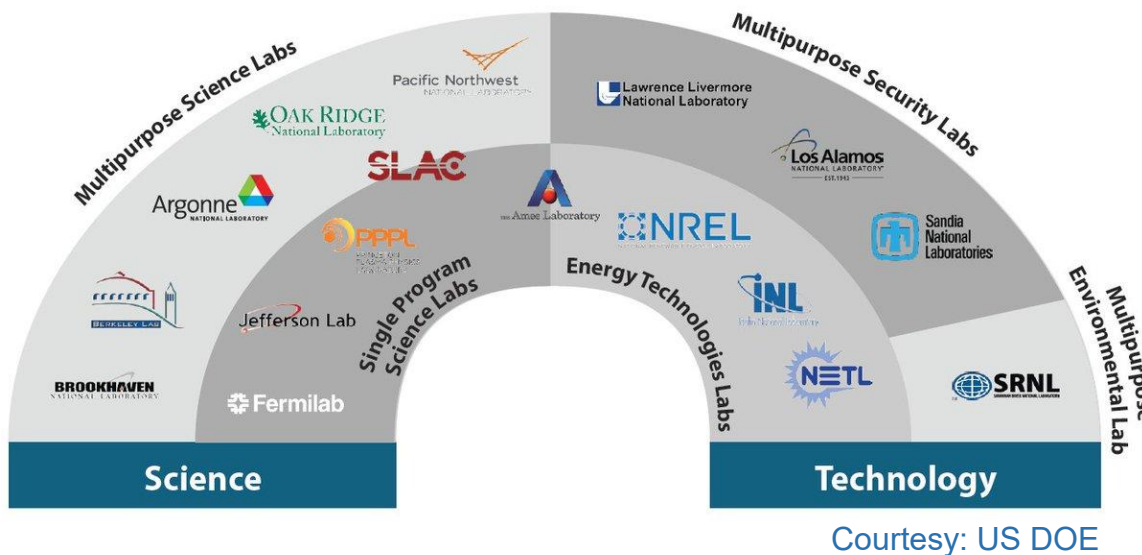


Courtesy: AWS

AI-augmented digital twins can enable:

- Multi-domain coordination
- Live monitoring
- Predictive and preventative maintenance
- Prognostics/diagnostics, anomaly detection, risk assessment
- Performance optimization
- Identification of future design improvements

DE and AI in the DOE National Labs



The DOE National Laboratory complex consists of 17 R&D institutions that tackle challenges related to energy, science, national security, critical materials, etc.

Digital engineering is helping accelerate and optimize projects related to nuclear and alternative energy, defense systems, manufacturing, and fundamental science across the complex.

Artificial Intelligence has been applied to:

- Spectroscopy data analysis and parameter extraction,
- Design optimization for fusion reactions,
- Unsupervised analysis of X-ray experiments,
- Material property prediction,
- Resilient control of microgrids, etc.

DE and AI at Idaho National Laboratory



DIGITAL INNOVATION
CENTER OF EXCELLENCE

Demonstrated first nuclear reactor digital twin, used ML for anomaly detection.

Applied DE and AR technologies to microreactor & nuclear materials testbeds.

DeepLynx: DE integration framework, uses knowledge graphs to store data.

MIRACLE: ML-based application for screening nuclear power plant conditions.

Creating AI-powered digital twin of a test facility for commercial microreactors.

Initiated projects on autonomous design and operation of nuclear reactors.

Challenges and Path Forward

DE/AI Challenges:

- Data security and IP protection
- Quality and reliability of results
- Software integration and interoperability
- Computational cost
- Cultural transformation
- Knowledge transfer

DE/AI Value
Addition



DE/AI
Challenges

- DE + AI → Engineering rigor while accelerating execution/deployment of complex projects.
- This can lead to the **deployment** of new power generation capabilities **at scale, on time, and within budget**.
- Important to mitigate the risks, demonstrate trustworthiness for widespread acceptance, and expand application to prove value addition.



www.incose.org/WSRC