NRIC TECH TALKS

Digital Engineering

February 16, 2021

Ashley Finan, Ph.D.

NRIC Director

Nuclear Reactor Innovation Center

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Christopher Ritter

Digital Engineering Technical Lead

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Digital Engineering Overview

Chris Ritter, NRIC Digital Engineering Technical Lead
Director, Digital Innovation Center (DICE)

February 16, 2021

Digital Engineering

What is Digital Engineering?

Digital Engineering (DE) embodies a deliberate transformational approach to the way systems are designed, engineered, constructed, operated, maintained, and retired

Why?

“Air Force flies 6th-gen stealth fighter – 'super fast' **with digital engineering**” – Air Force has already built and flown a new sixth-generation stealth fighter jet originally scheduled for ~2030 (almost a decade early).

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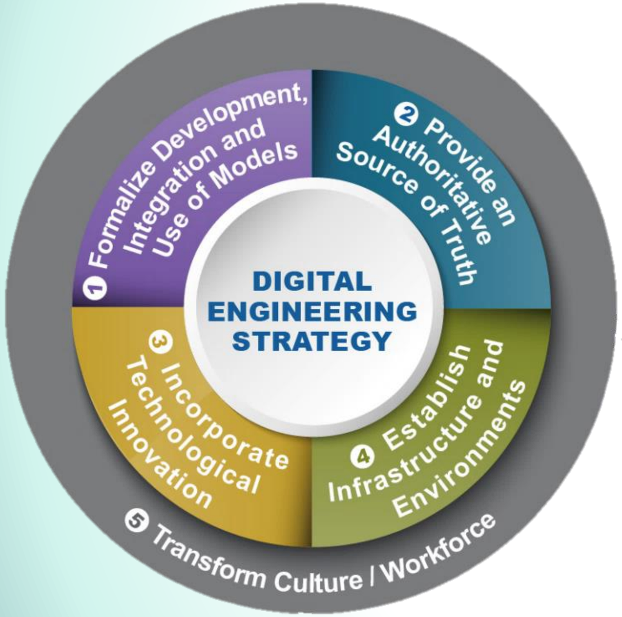
NRIC Strategy



DoD Digital Engineering

MBSE ①

Digital Thread ②

Digital Twin ③

Cloud & HPC ④

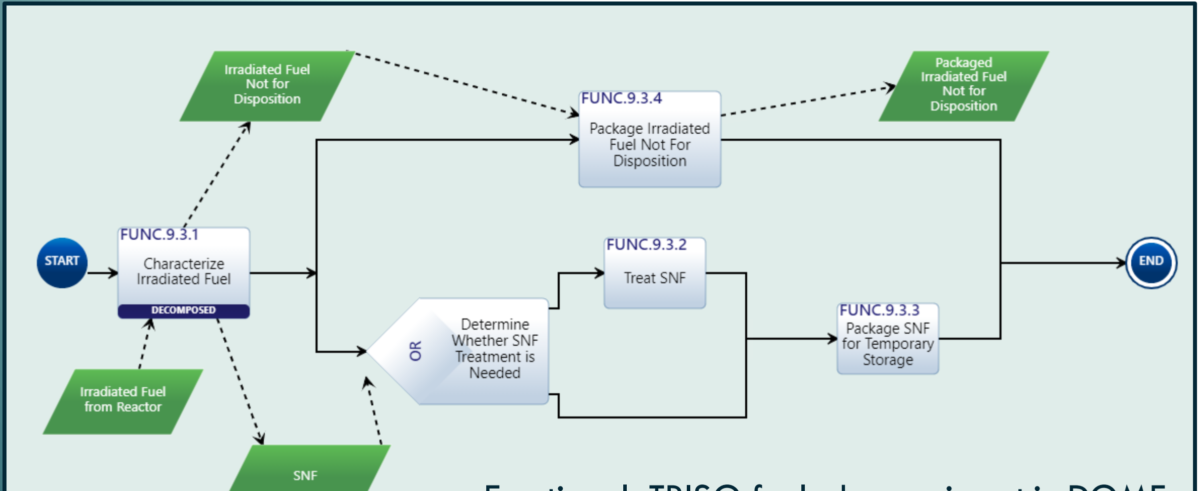
DICE ⑤

Model-Based Systems Engineering (MBSE) Environment for INL Test Beds and Industry Team

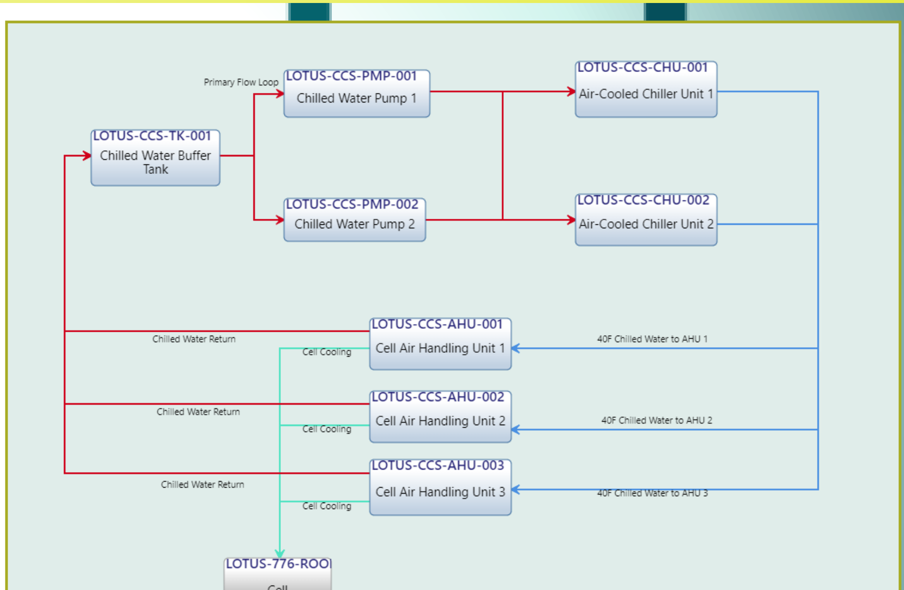
Emphasis on development of functional analysis (activity diagrams) and physical analysis (asset, internal block diagrams) over document creation

System models (SysML/LML) are linked to the requirements document in the same tool environment to provide system-level traceability

Models are integrated across teams (from INL test beds through contractor design teams)



Functional: TRISO fueled experiment in DOME



Physical: Cell Cooling System

4.1.1 Maximum Thermal Load

The thermal energy removal system shall remove a maximum of 500kW thermal energy from the ZPPR Cell.

4.1.2 Minimum Thermal Load

The thermal energy removal system shall remove a minimum of 50kW thermal energy from the ZPPR Cell.

4.1.3 Variable Heat Removal

ZTB shall provide a feature for the thermal energy removal system which can vary the amount of thermal energy removed from the reactor.

Requirements integrated with MBSE model

MBSE

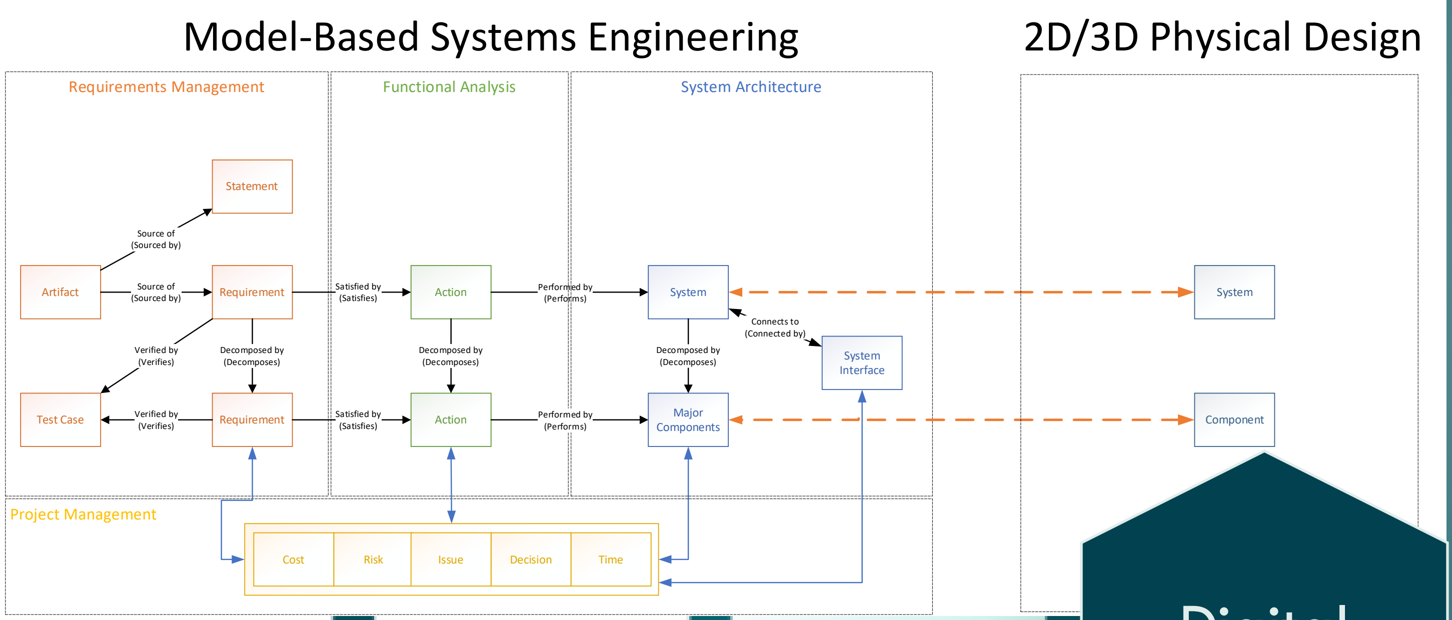
1

Building the Digital Thread with Model-Based Systems Engineering (MBSE) and digital engineering

- Computer Aided Design (CAD) bidirectional integration with MBSE models to reduce error transferring from systems through detailed design (leveraging existing laboratory university research on Deep Lynx)
- Generating reports in INL- and NRIC-compliant formats to automate documentation needs at the system level
- Integration with the overall digital engineering ecosystem which will provide analysis integrations at the system, civil design physics, and nuclear physics codes
- Overall plan to integrate this system (used in design) with operating facilities to enable a full digital twin

Develop fully traced model-based systems engineering model (digital thread)

Demonstrate CAD elements to/from systems design for demonstration test bed



Digital Thread

2

Nuclear Reactor Digital Twins

What is a Digital Twin?

Digital Twins represent the merging of digital thread, controls theory, artificial intelligence, and online monitoring into a single cohesive unit, a virtual model that comprehensively captures all relevant aspects of the underlying system, utilizing bidirectional communication to track and trend both simulated and measured physical responses.

NNSA Safeguards by Design Digital Twin Project

Digital Twin

3

Cloud and High-Performance Computing

- Microsoft Azure for Government Environment
  - Single Sign-On for Industry
  - Secure Environment (OUO/ECI)
  - Hub/Spoke Deployment Model
  - Interconnection to HPC (in process)
- Access to DOE-NE HPC Resources
  - Sawtooth (5.6 Petaflop/s)
  - Lemhi (1.0 Petaflop/s)
  - Falcon (1.1 Petaflop/s)

Cloud
& HPC

Thank You

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Peter Suyderhoud, B.S.

Systems Engineer

Idaho National Laboratory

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Using MBSE in Nuclear Design

Peter Suyderhoud
February 16, 2021

Systems Thinking

- Relationships/Connectedness
- Process vs. Structure
- The Whole
- Patterns and Context

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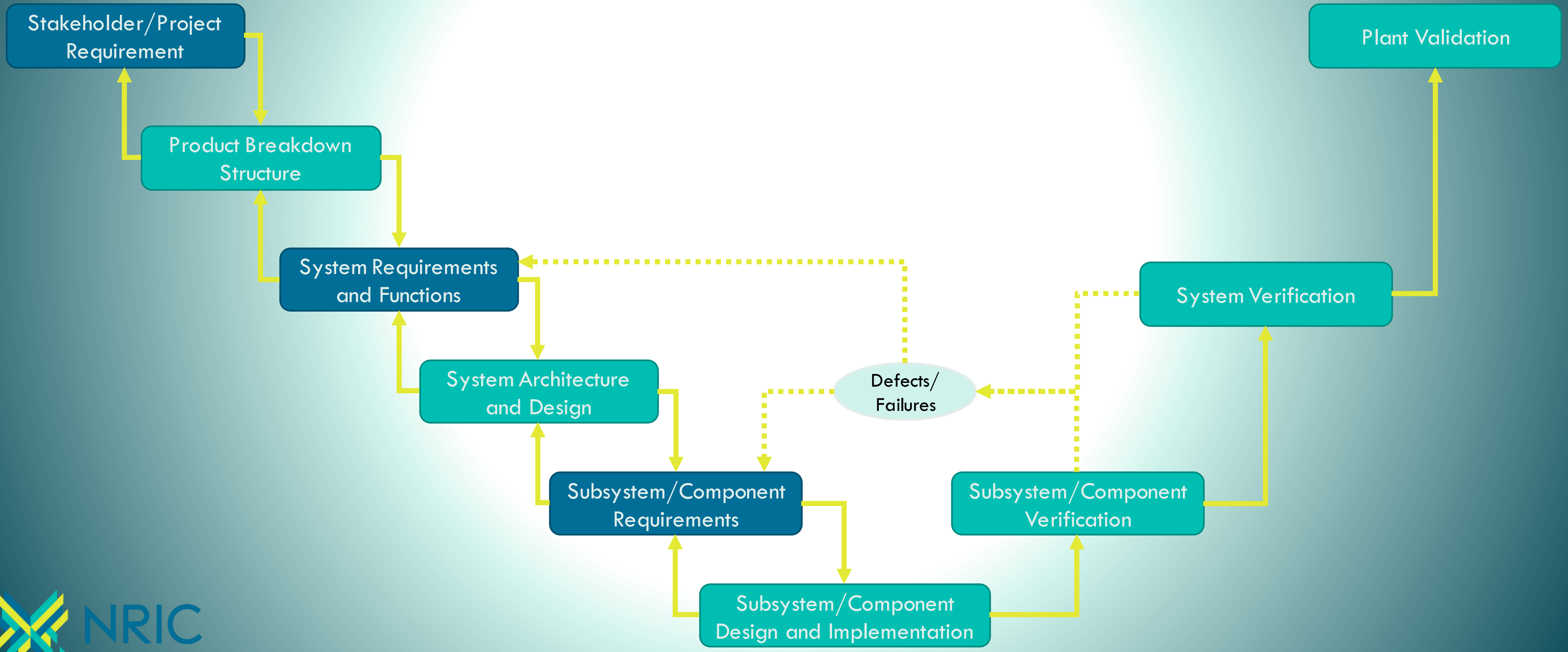
Systems Engineering (SE)

- The application of Systems Thinking principles to complex engineering projects
- System<u>s</u> Engineering is distinctly different from System Engineering
- Interdisciplinary, structured process and means to enable the realization of successful systems or a plant – concentration *on the* “whole” rather than the “parts”

"V" Diagram



Stakeholder/Project Requirement

Product Breakdown Structure

System Requirements and Functions

System Architecture and Design

Subsystem/Component Requirements

Subsystem/Component Design and Implementation

Subsystem/Component Verification

System Verification

Plant Validation

Defects/ Failures

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Current Nuclear Industry Application of SE

- Microsoft Word, PDFs, Spreadsheets, and Paper Documents dominate the design process
- Requirements Management tools used as repositories to stash already-drafted/completed information
- Changes must be manually assessed for downstream design impacts
- Software/design tools are disparate and siloed
- This process isn't wrong, but it is tedious and costly

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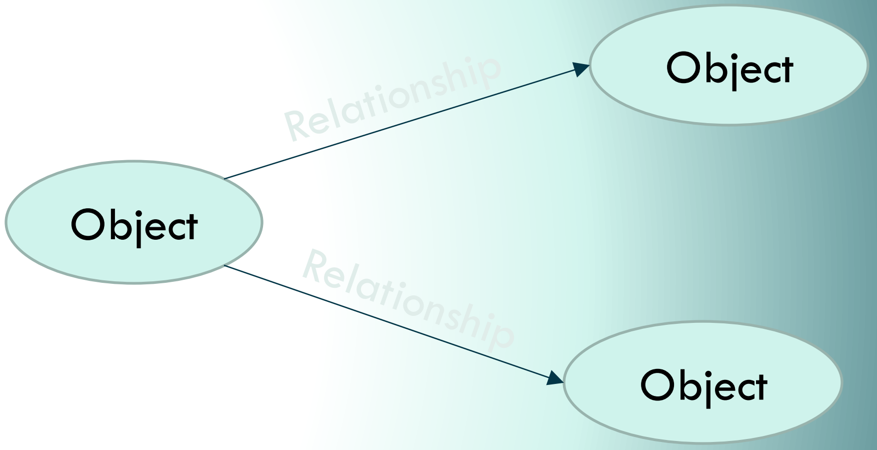
Moving Towards Using Digital Engineering Tools for SE

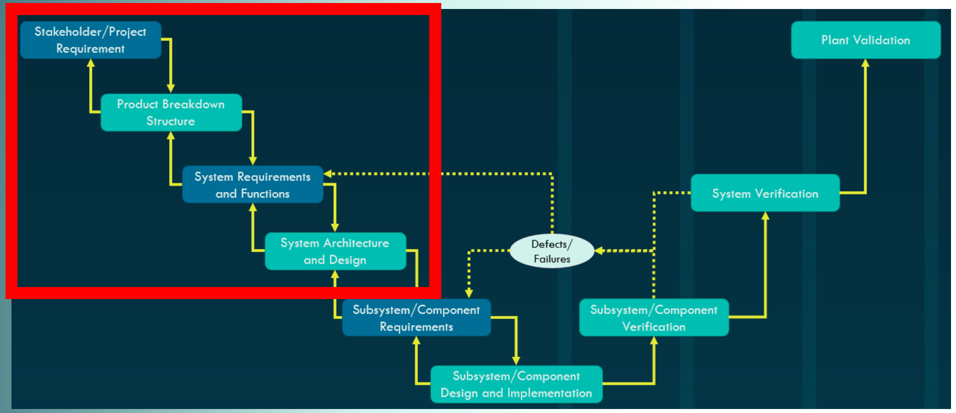
- Model-Based Systems Engineering (MBSE): Shifting from a document-based approach to the use of models and databases as a means of information exchange
- Model: A simplified version of a concept or structure; graphical representation of a process; abstraction of information to facilitate understanding and eliminate unnecessary components
- Models/databases form an integral part of the technical baseline at the beginning of a project – visual learning and understanding tool
- Departure from static, obsolete Word/PDF etc. documentation

Basic Concepts of MBSE

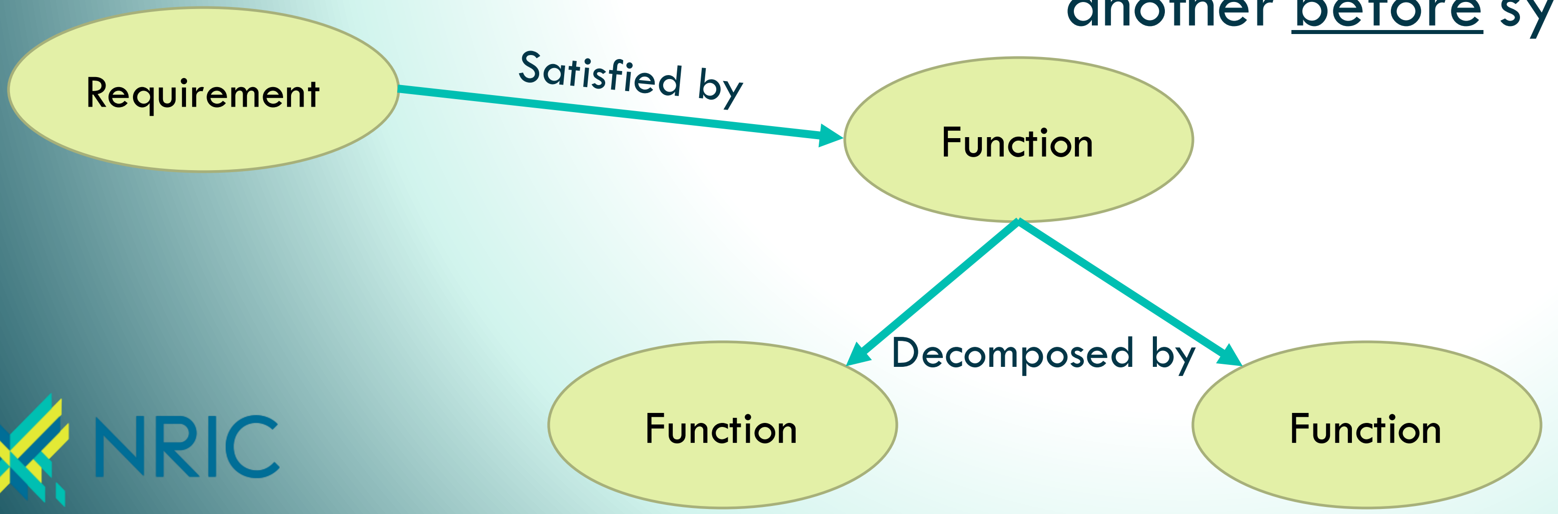
- Nodes and edges
- Objects/Entities
  - Things (nouns) that make up a plant, both physical and conceptual
  - Requirements, components, organizations, risks, interfaces, etc.
  - Identifiable through established numbering and naming conventions
- Attributes
  - Supplemental information used to further describe entities (adjectives)
  - Shape, size, volume, temperature, importance, etc.
- Relationships
  - The associations (verbs) that occur between entities



Using MBSE for Early Project Development



- Focuses on eliciting initial high-level requirements and capturing them within a database
- Deriving plant functions and creating relationships to originating requirements
- Modeling how these functions relate to one another before synthesizing a plant architecture

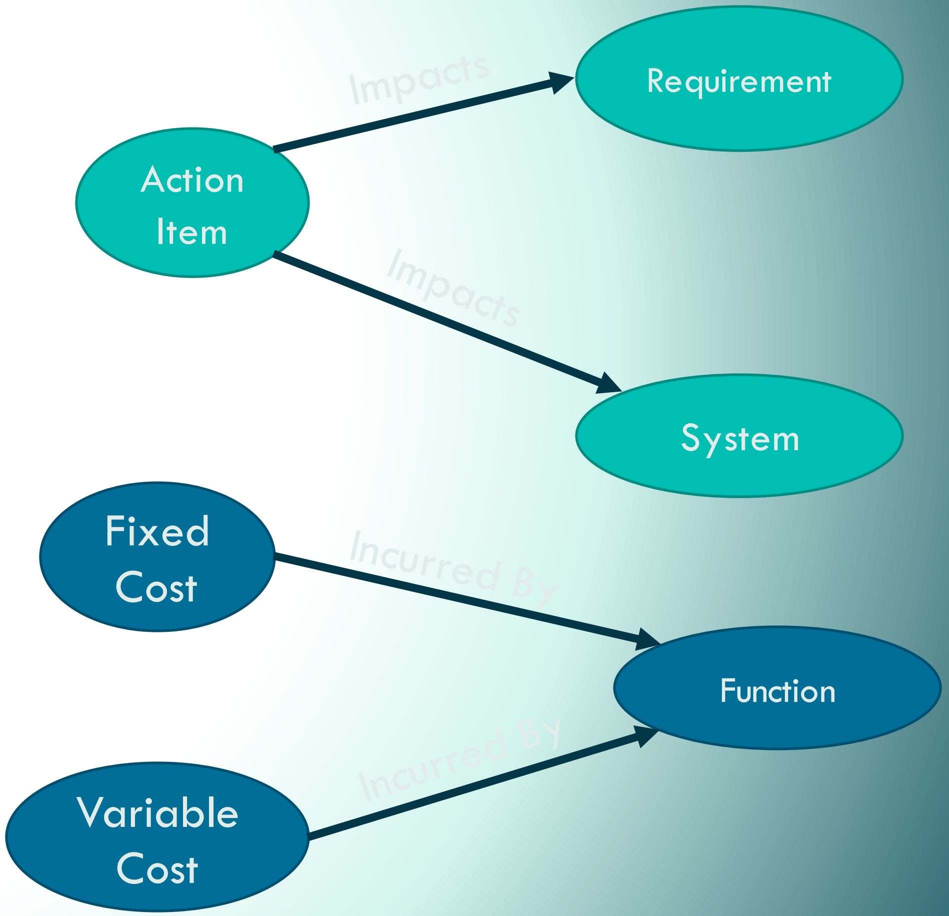


Forming a Complete System Model

- Continuing to develop behavioral/functional models
  - Capturing inputs/outputs
  - Assigning durations to functions
  - Sequencing functions to understand dependencies
- Using behavioral/functional models to formulate a plant structure
  - Identifying systems that exhibit the behavior of the plant concept
  - Establishing a hierarchy between systems, subsystems, and their components
  - Linking structures, systems, and components to the functions they perform
- Defining how systems relate to one another
  - Capturing interfaces

Integrating Aspects of Project Management

- Action Item Tracking
- Schedule Integration
- Cost Estimation
- Technical Decision Tracking/Logging



Additional SE Activities Facilitated by MBSE

System Validation

- Functional models can be used to validate that system concepts perform as expected

Requirement Verification

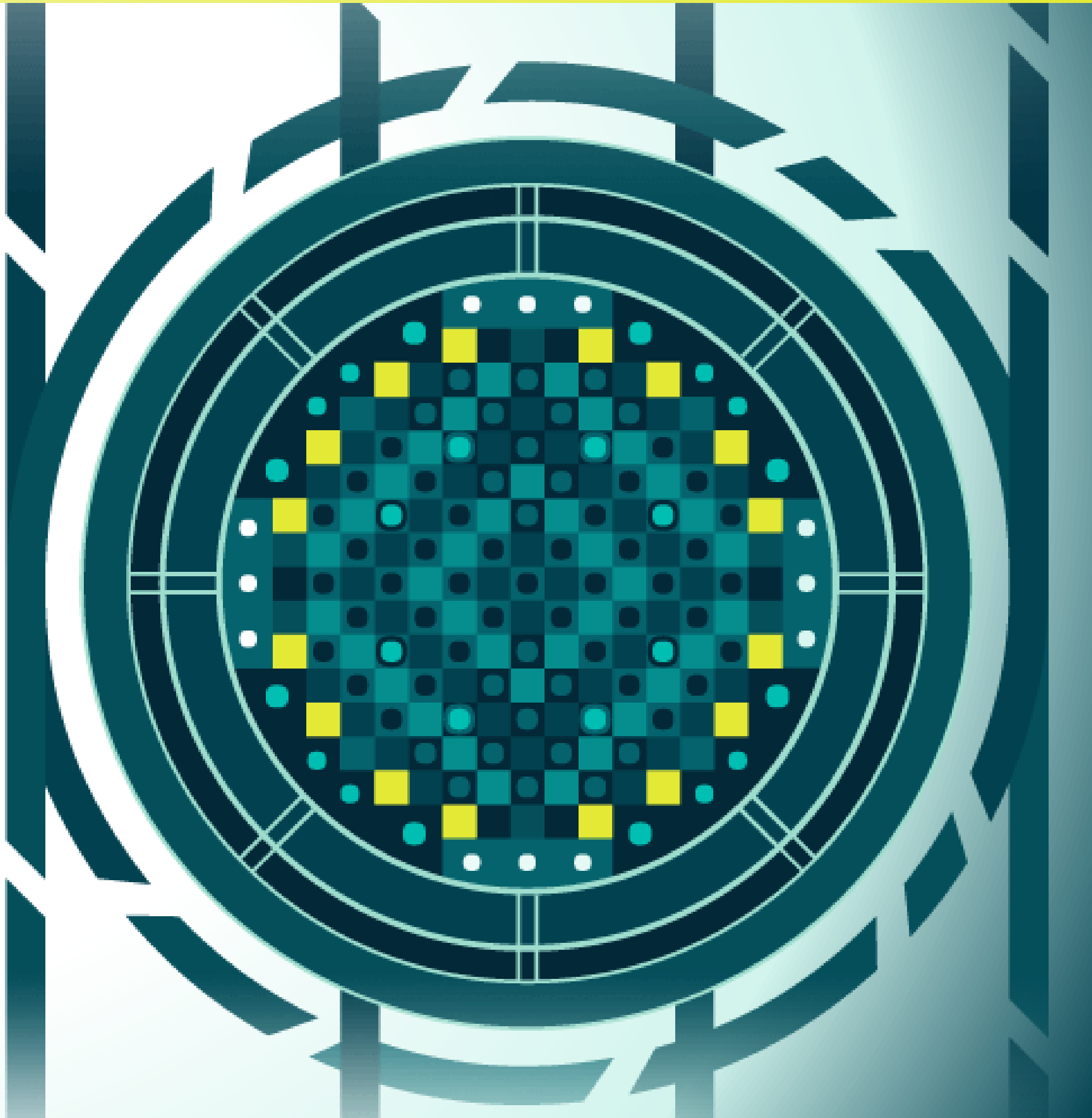
- Automated reports based on established database traceability

Risk Analysis

- Traceability through the database to methods used to mitigate project risks

Challenges of MBSE

- Organizational Resistance – requires a cultural mindset change
- Undue complexity if not managed properly – graded approach
- Reporting/visualizing discrete sets of information
- Regulations and compliance associated with the "source of truth"
- Lack of communication with other engineering activities



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Brennan Harris, B.S.

Full Stack Developer

Idaho National Laboratory

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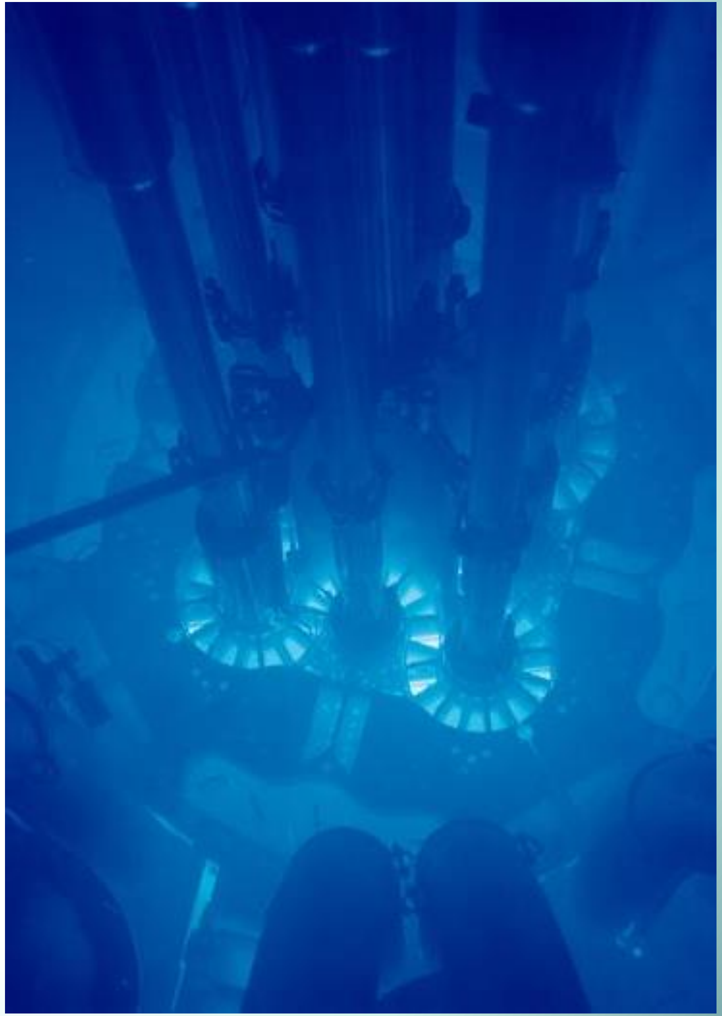
Engineering Collaboration

A vision for advanced collaboration on complex engineering projects

A vision for advanced collaboration on complex engineering projects

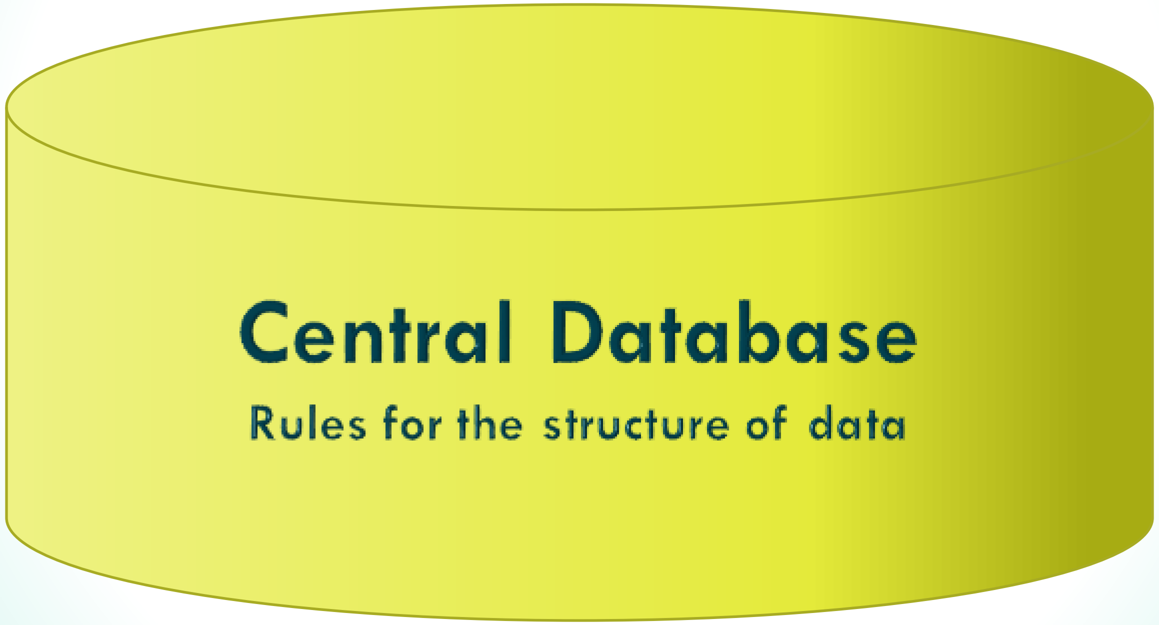
Engineering Megaprojects



Barriers to Engineering Collaboration

- The Legacy Era (mid 1980s to mid 2010s)
  - Software isn't connected to the internet
  - Licenses and files are saved on engineers' machines
  - New features follow an annual release schedule
- The Modern Era (mid 2010s to today)
  - Engineering data is tied to a proprietary ecosystem
  - New features are released on a rolling basis, but limited to the software author's priorities from all clients, and corporate priorities
- Persistent problems
  - Cultural resistance to change
  - Training for new systems and methods is expensive

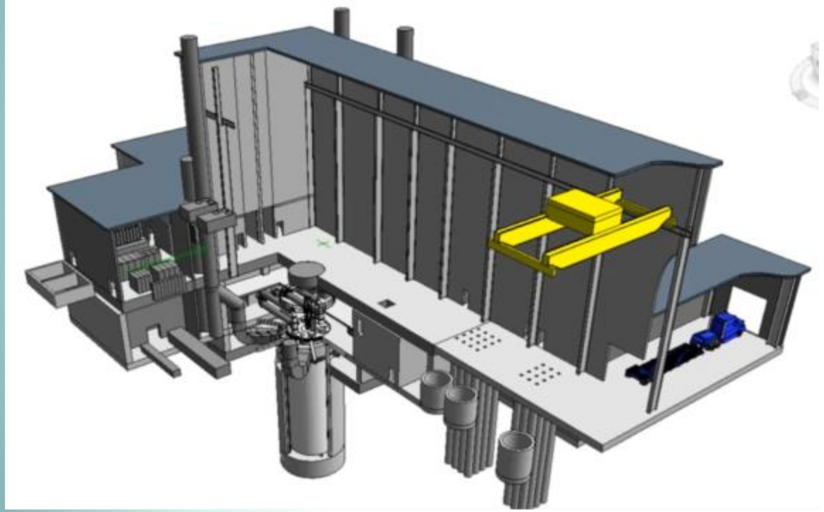
A Solution: Centralized Data



Central Database

Rules for the structure of data

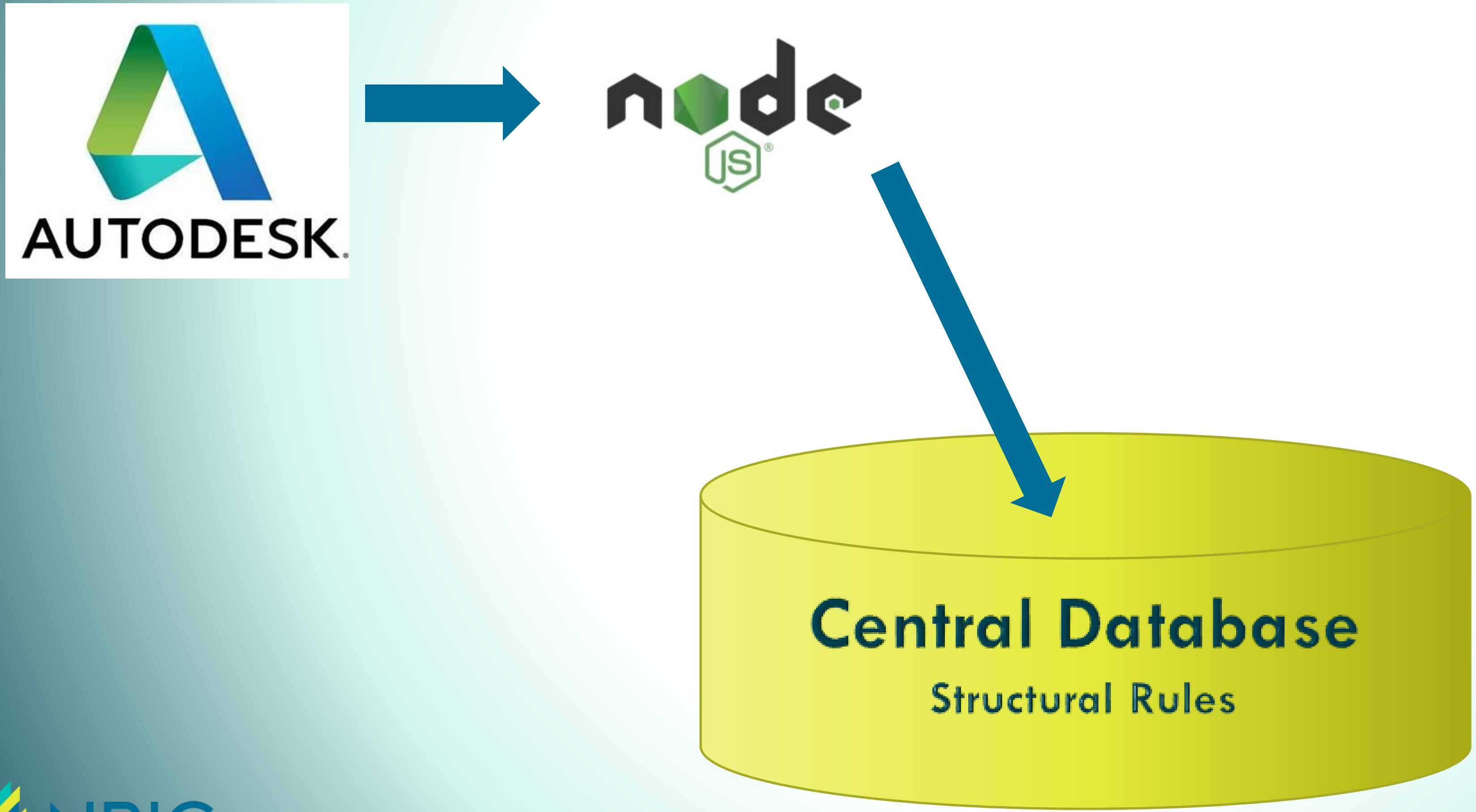
Accessing Engineering Data



AUTODESK

node
JS

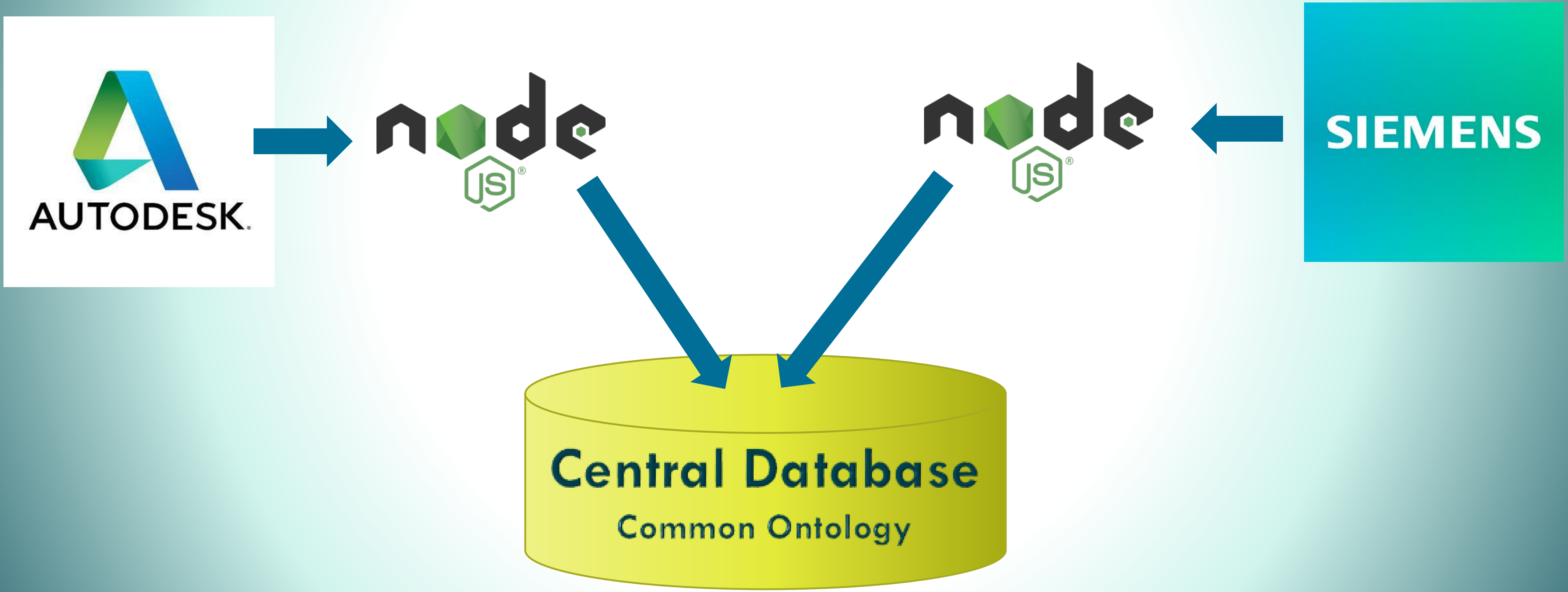
Centralizing Engineering Data



Central Database

Structural Rules

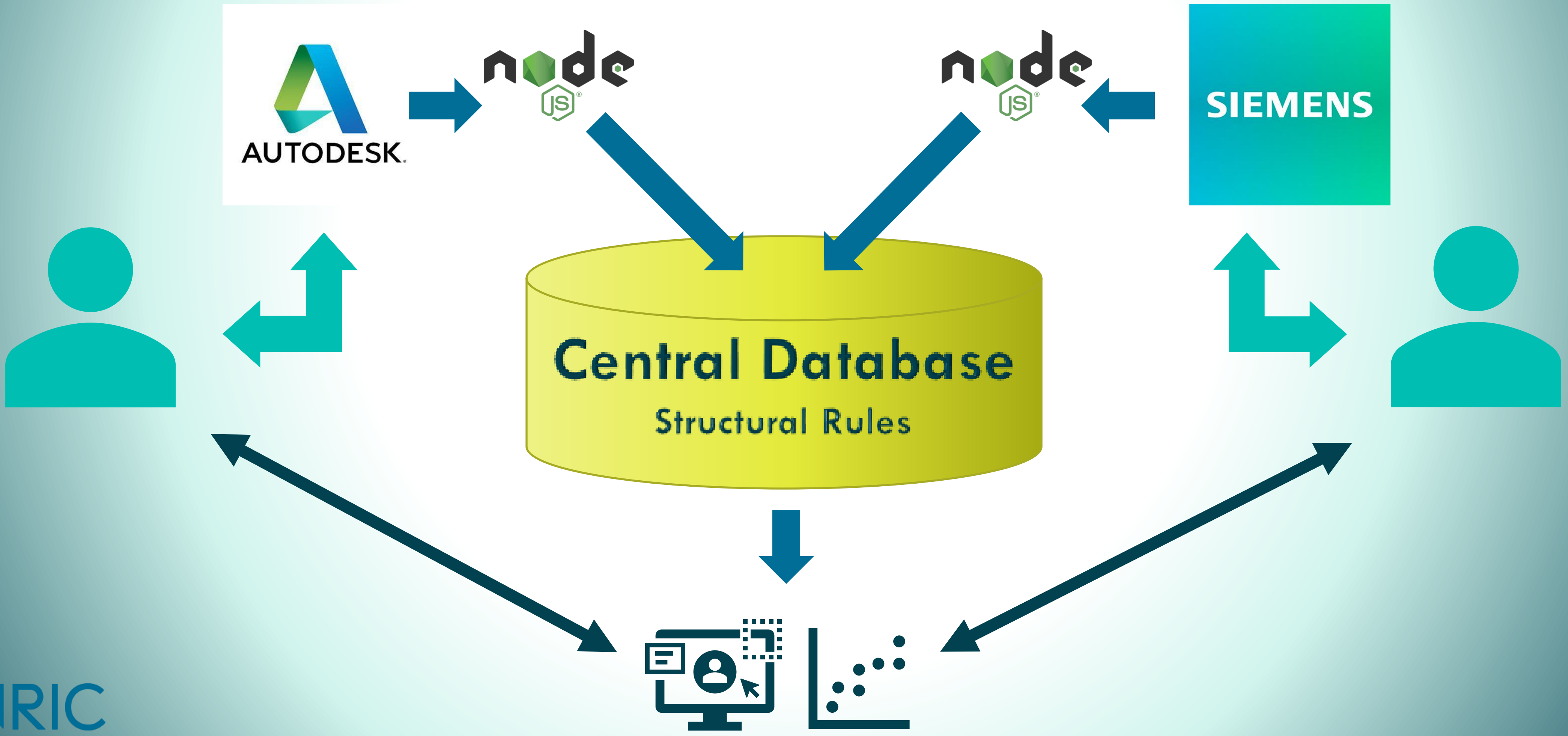
Adding Sources of Engineering Data



Central Database

Common Ontology

Creating Manager-happy Collaboration



Thank You

Breakout 1: Digital Ecosystems

Brennan Harris
Full Stack Developer
Idaho National Laboratory

Taylor Ashbocker
Principal Cloud Architect
Idaho National Laboratory

Realize your digital thread through the cloud computing and data transformation pipelines that help enable systems integration and digital engineering. These connections reduce silent error introduction in design, significantly reducing reactor design and construction risk.

Breakout 2: Digital Twins

Jeren Browning

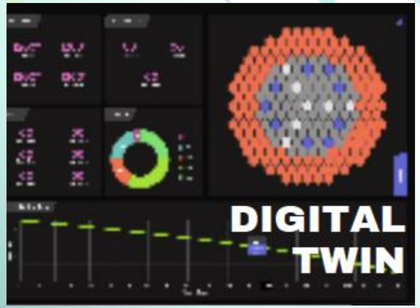
Software Engineer

Idaho National Laboratory

Ross Kunz, Ph.D.

Data Scientist

Idaho National Laboratory



Merge your digital thread, controls theory, artificial intelligence, and online monitoring into a single cohesive unit. A virtual model comprehensively captures all relevant aspects of the underlying system and enable autonomous control, predictive maintenance, and misuse detection technologies.

Breakout 3: NMDQi

Zachary Prince
Research Scientist
Idaho National Laboratory

R. Allen Roach
Digital Engineering Technical Lead
Idaho National Laboratory

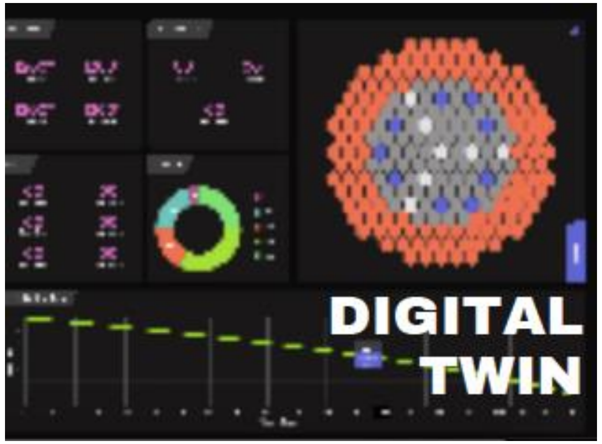
Andrew Slaughter, Ph.D.
Computer Scientist, MOOSE
Idaho National Laboratory

The Nuclear Materials Discovery and Qualification Initiative (NMDQi) is designed to accelerate nuclear materials qualification to fulfill the promises of early and advanced reactor technologies as a safe, clean, and low-cost base-load energy. NMDQi will establish tools and capabilities that will greatly accelerate the nuclear fuels and materials development process.

Choose your experience

Please visit the NRIC website for your breakout link.

Breakout Room 1



Breakout Room 2

Breakout Room 3

Link provided in Q&A Section

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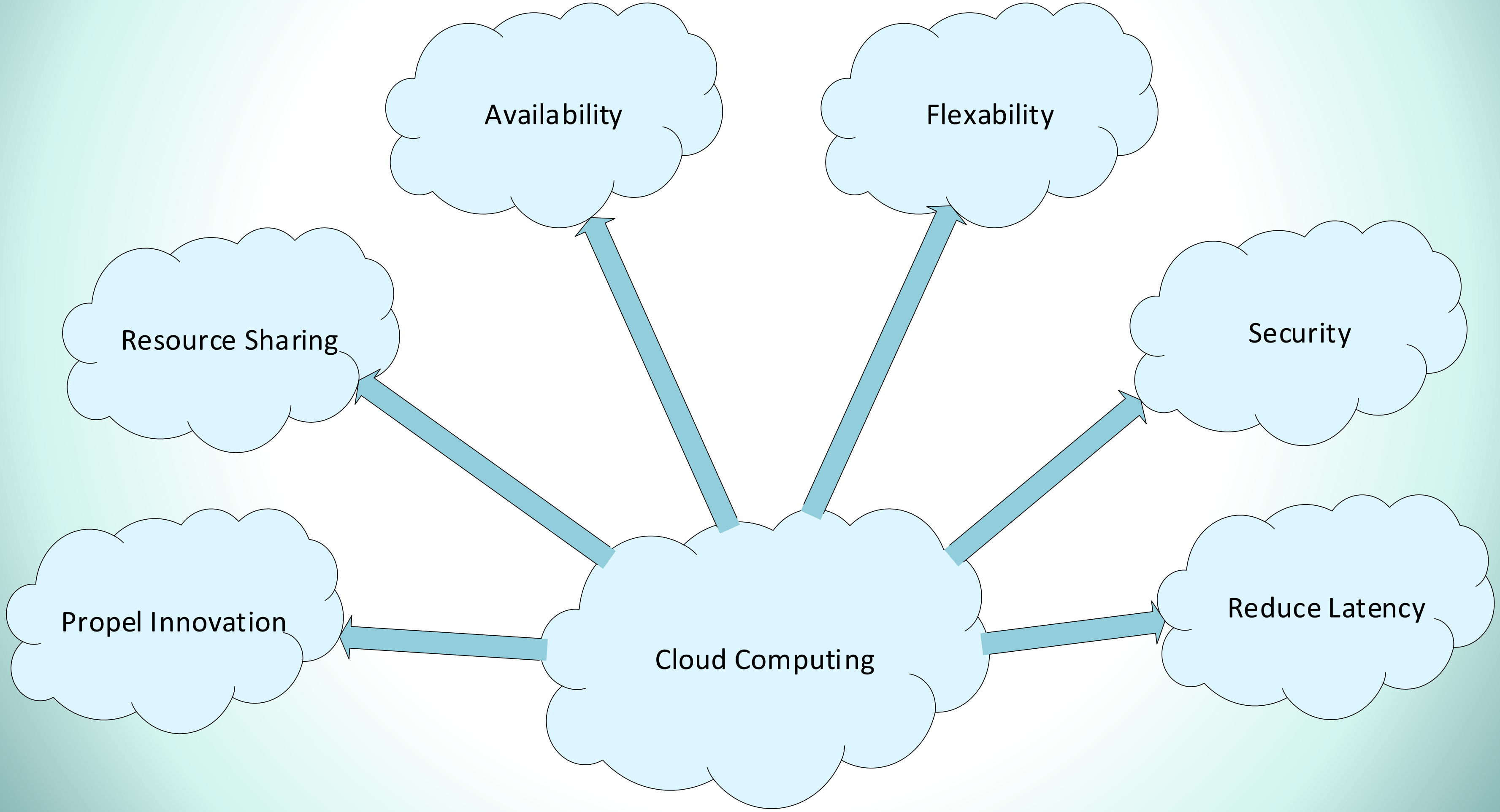
Digital Ecosystems in the Cloud

A cloud first approach to propel digital innovation

Taylor Ashbocker

February 16, 2021

Why the cloud?



Cloud Security

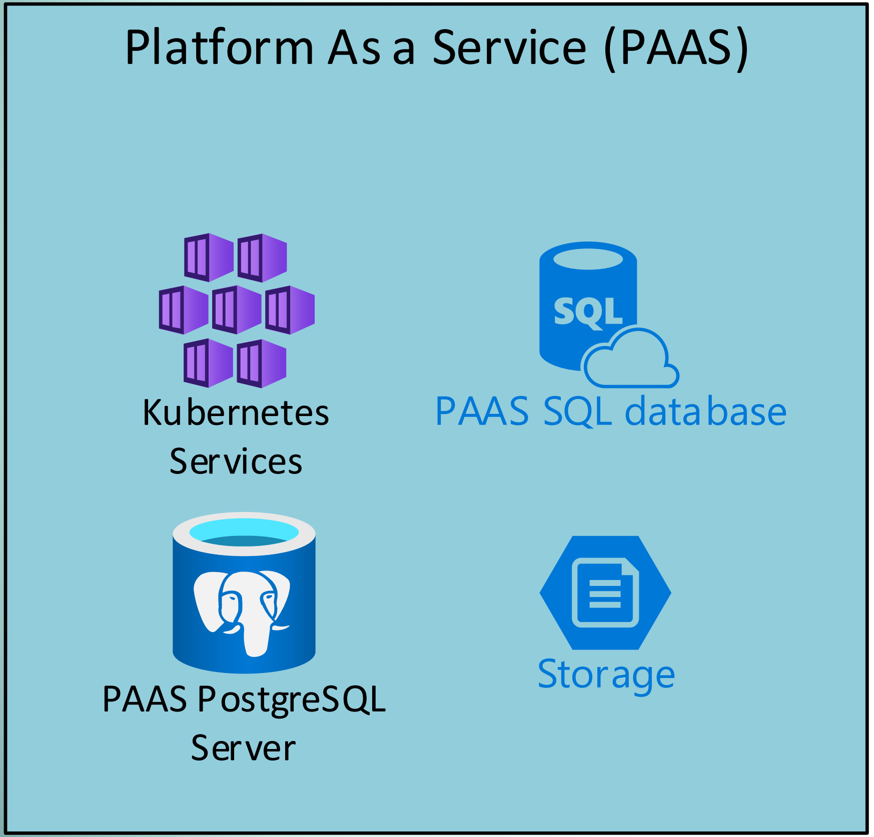
US Federal Government ATO

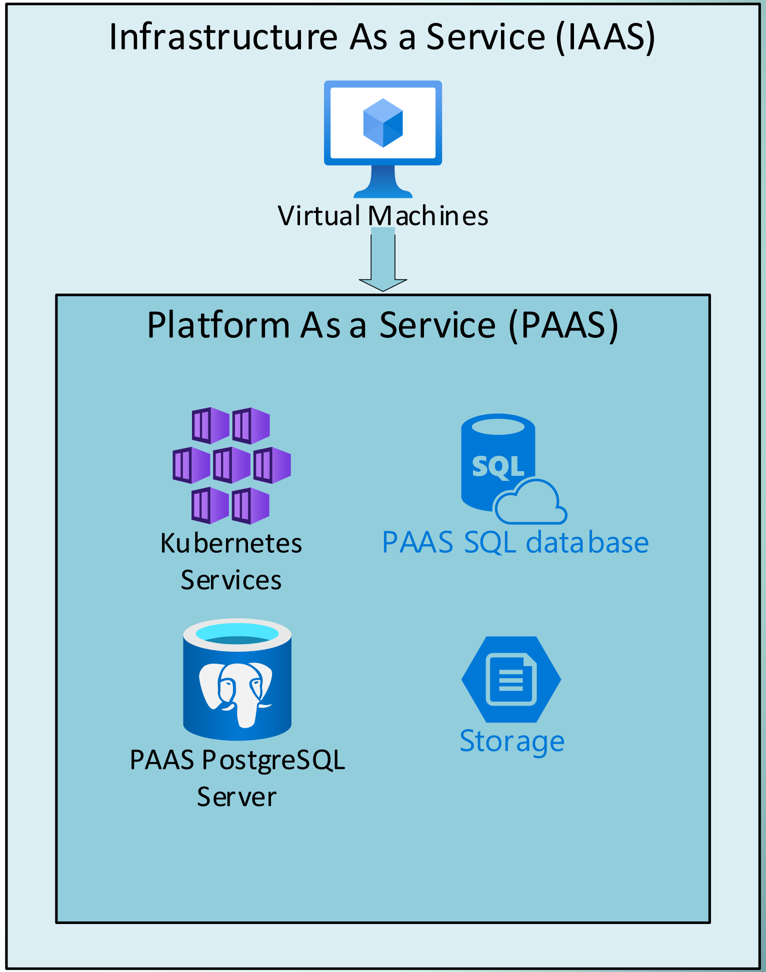
- Why do I need an ATO?
- What are the requirements of an ATO?

Microsoft Azure for Government Environment

- Centralized MFA for all applications
- End to End Encryption
- WAF technology in combination with IDS/IPS
- Network Micro segmentation
- Cloud native security and network tools

How we built the platform





Planning for the future

- Continue leveraging PAAS technology and utilizing the flexibility of the cloud
- Build applications in a secure manner
- Continue to support and build new tools to support collaboration
- Finally, evaluating what has worked well and what has not to drive a better experience

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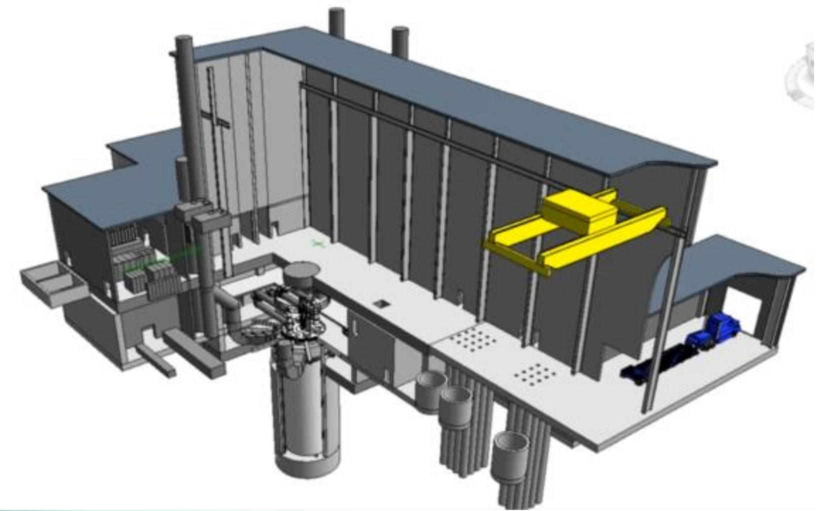
Digital Ecosystem

Brennan Harris

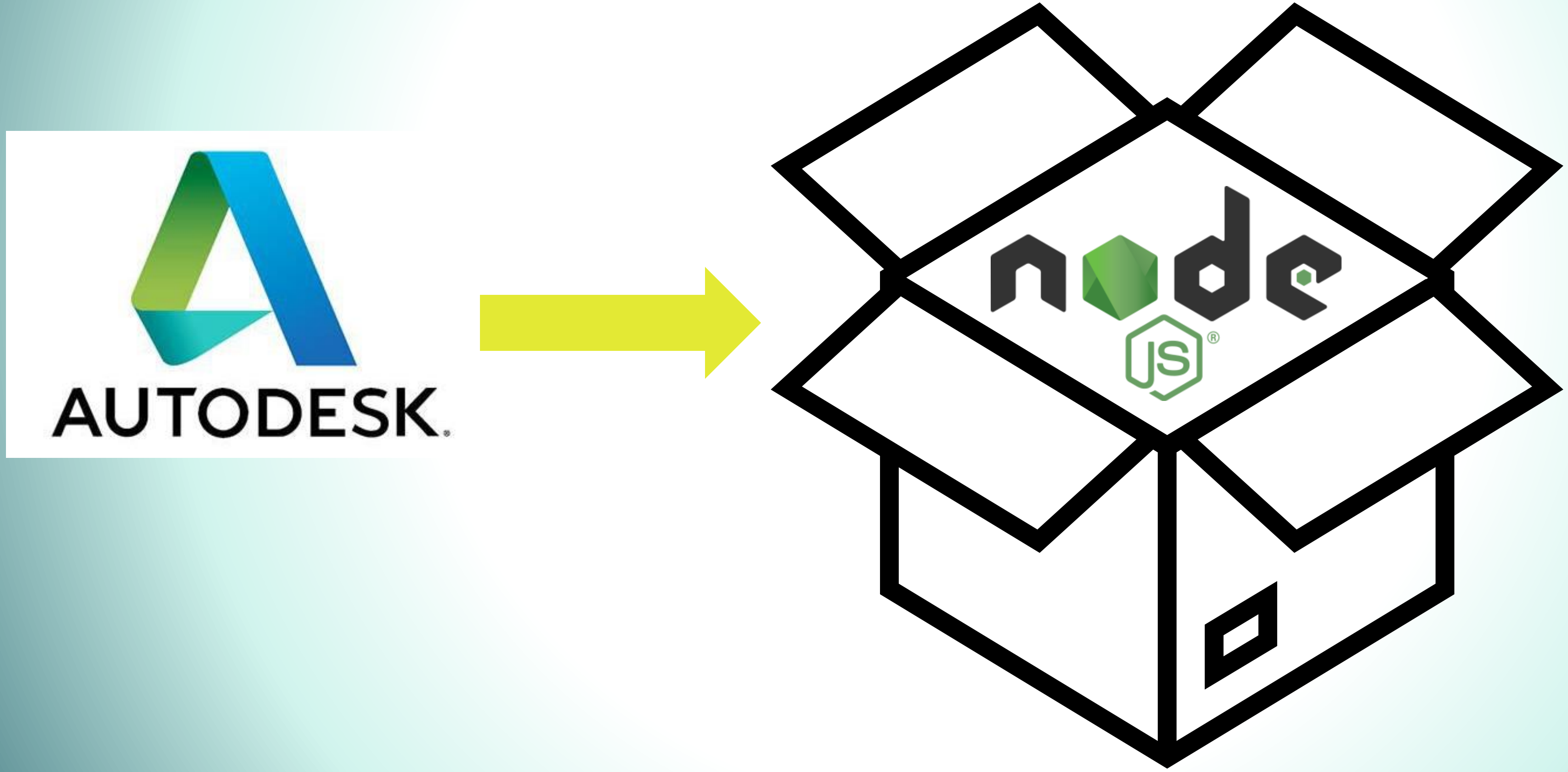
February 16, 2021

Developing Engineering Software

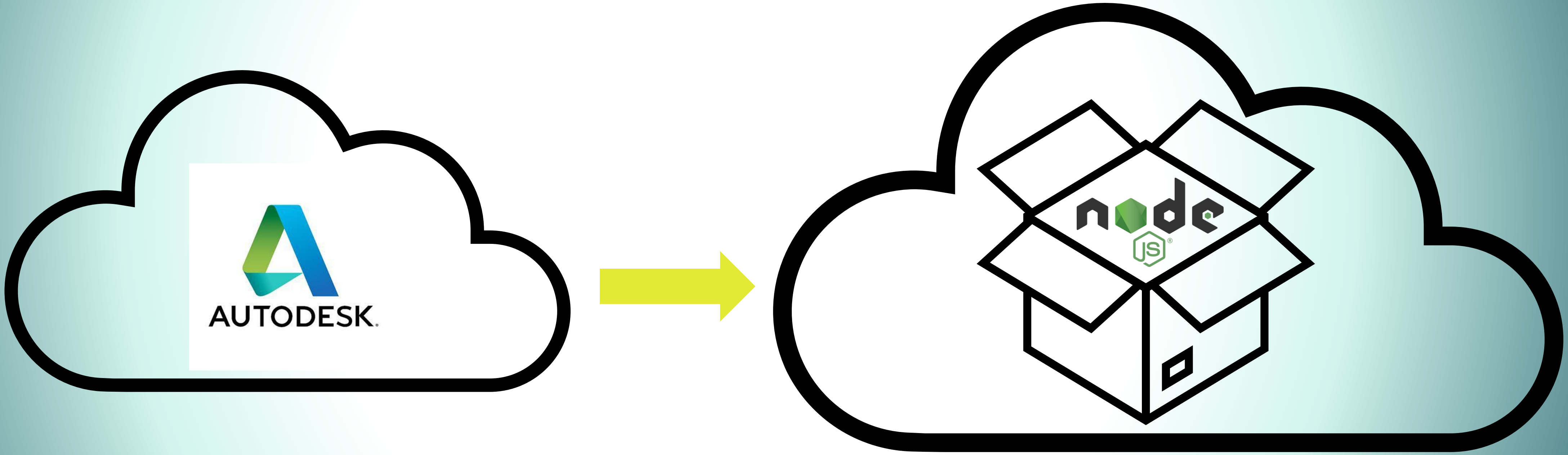


AUTODESK → node JS

Containerization



Strategies



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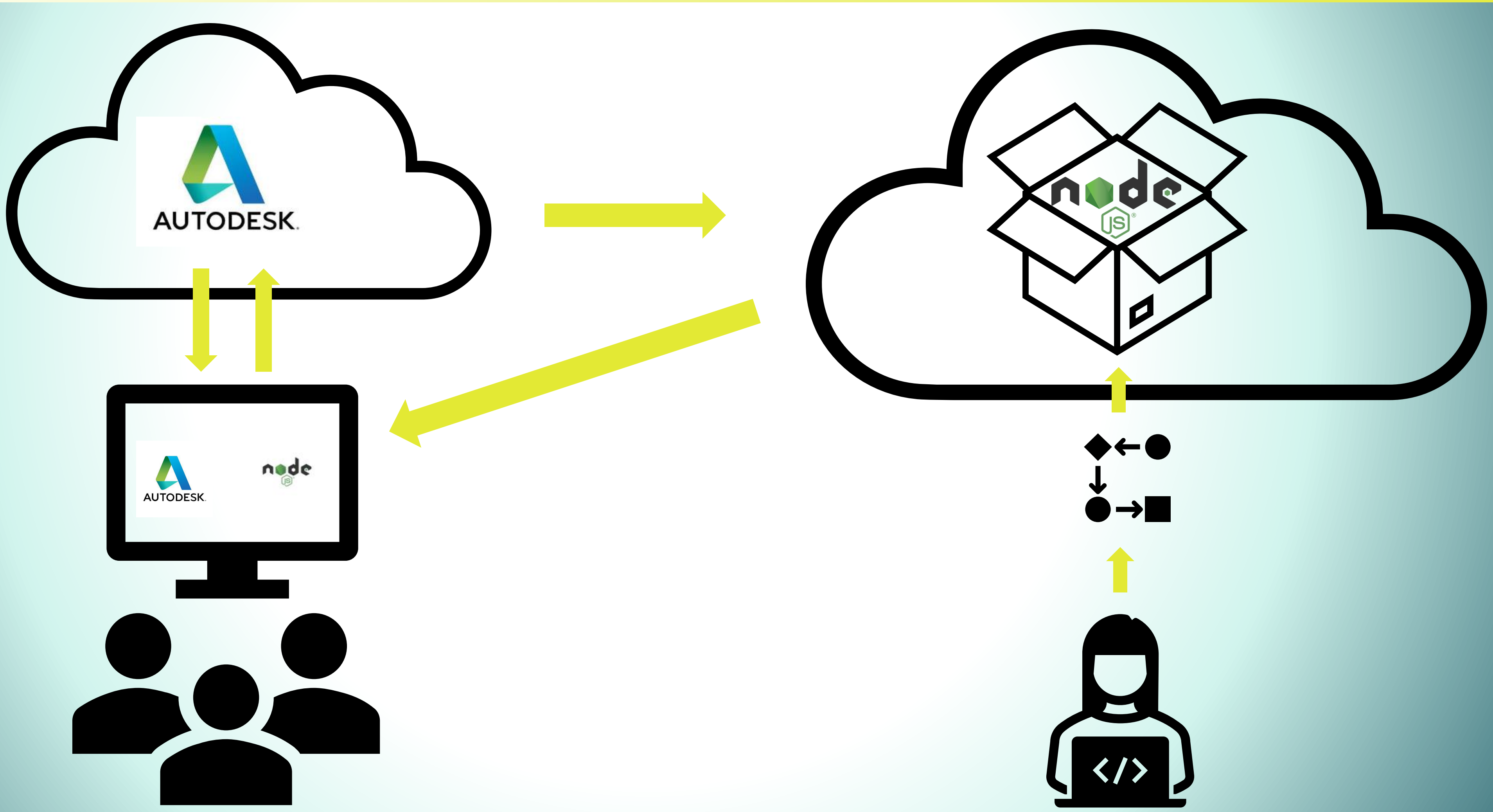

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Running Engineering Software in a Digital Environment

- Connection between apps are tightly controlled.
- Minimum disruption to existing engineering workflows
- Updates to software happen instantly

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Thank You

Please “leave” your breakout session and “rejoin” the main event.

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Digital Twins

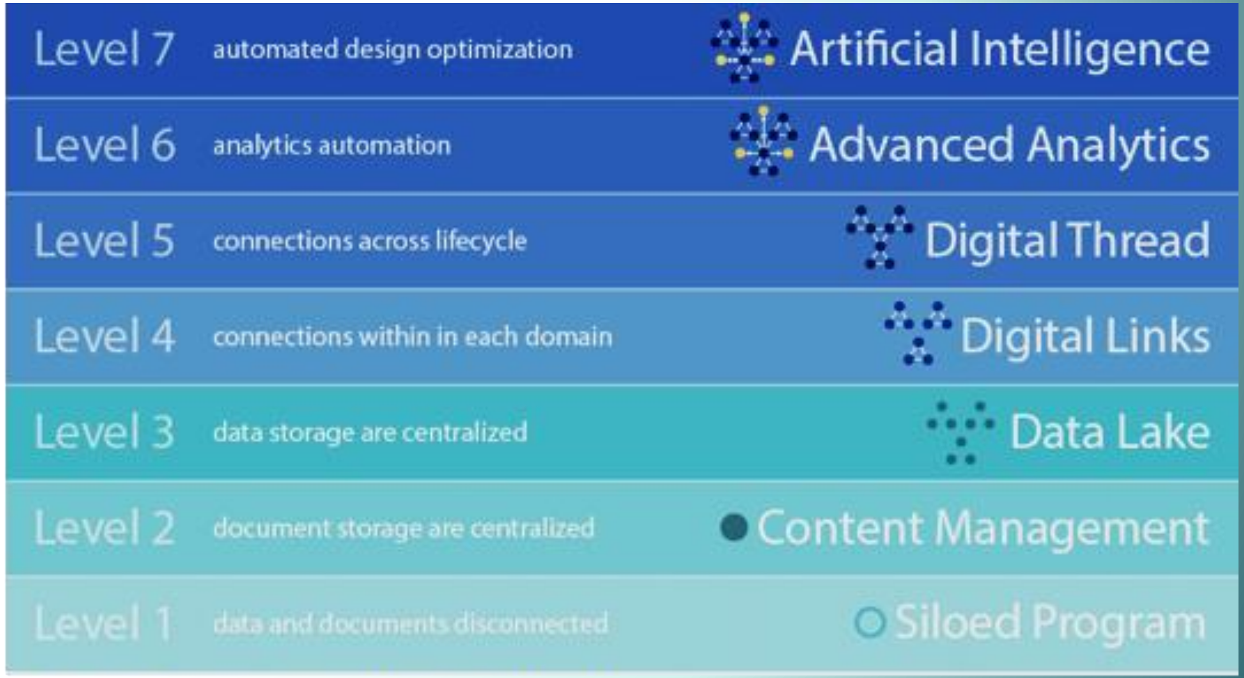
Basics and Examples

Jeren Browning & Ross Kunz

February 16, 2021

Definition

- Digital Twin: *the computational simulation of a physical process or system that has a live link to the physical system, enabling enhanced verification of the simulation, control of the physical system, and analysis of trends via artificial intelligence and machine learning.*
- Digital Twin Requirements
  - Digital Thread
  - Enables advanced analytics and artificial intelligence (AI)
- Pinnacle of digital engineering model



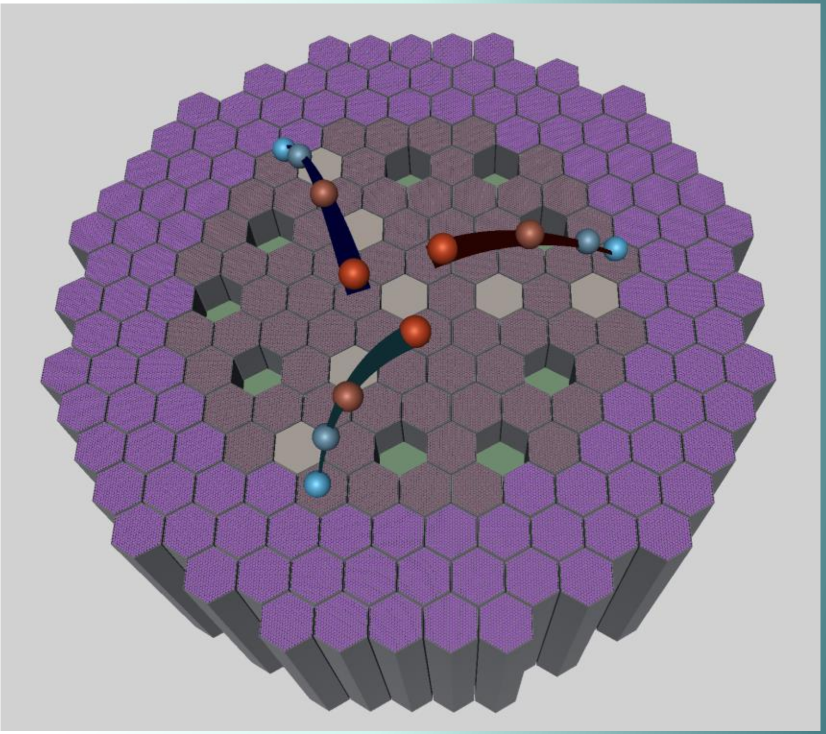
Level 7	automated design optimization	Artificial Intelligence
Level 6	analytics automation	Advanced Analytics
Level 5	connections across lifecycle	Digital Thread
Level 4	connections within in each domain	Digital Links
Level 3	data storage are centralized	Data Lake
Level 2	document storage are centralized	● Content Management
Level 1	data and documents disconnected	○ Siloed Program

Digital Engineering Maturity Model

Ritter. "Digital Innovation Center of Excellence (DICE)" 2020.

Benefits

- Holistic view of the physical process or system
- Intelligent and automated use of system data
- Traceability of the data (source of truth)
- Cloud benefits
  - Scaling
  - On-demand deployment
- Creation of a digital twin requires an integrated team across domains
  - Software, modeling and data, physics, AI, hardware, visualization



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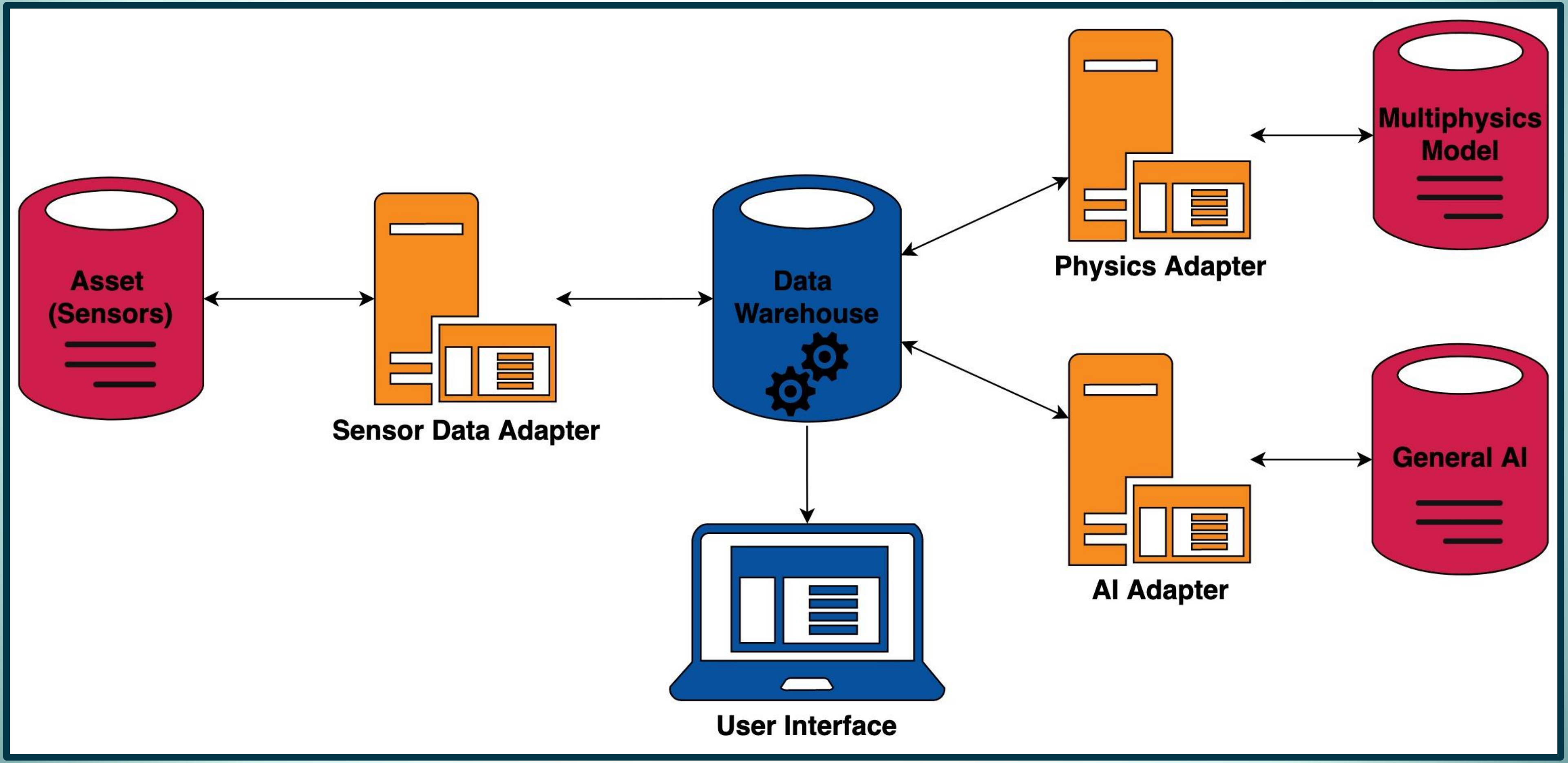
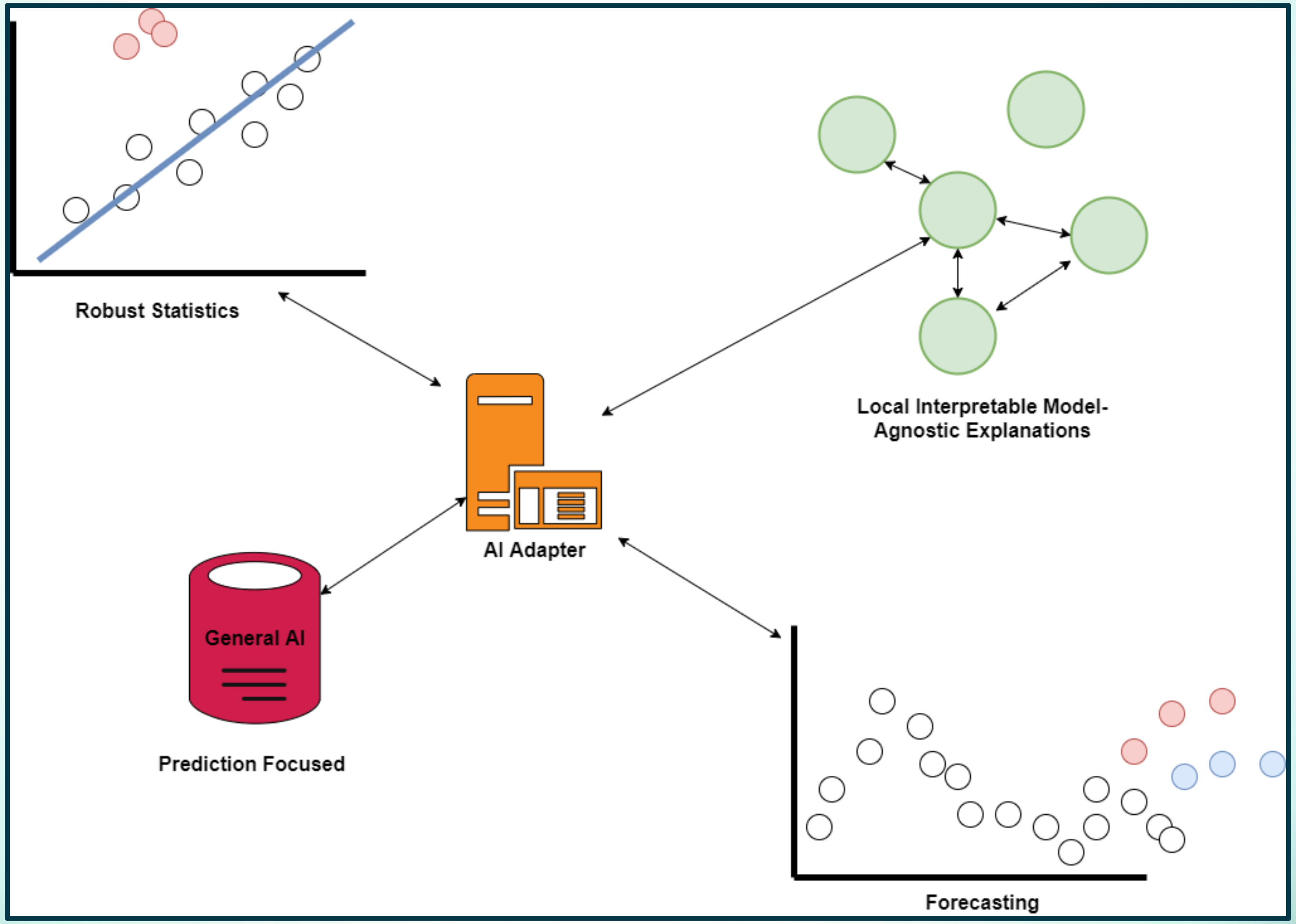
Example Architecture



Applications of AI/ML to Data Sources



Robust Statistics

Local Interpretable Model-Agnostic Explanations

AI Adapter

General AI

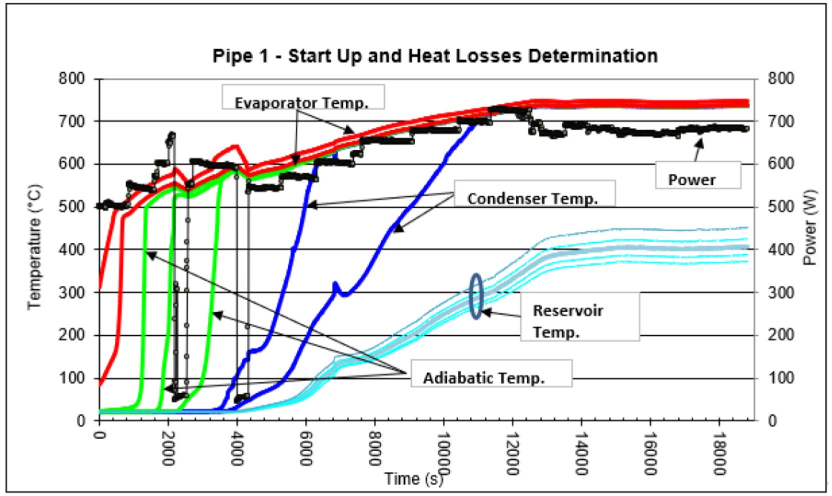
Prediction Focused

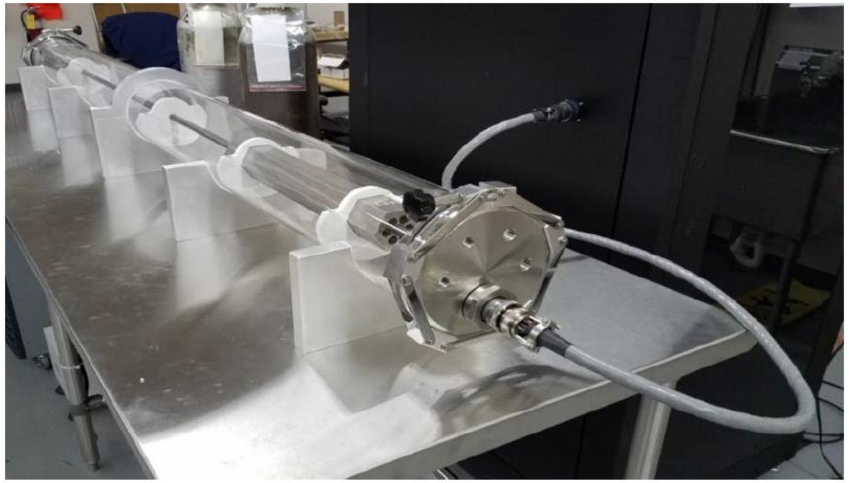
Forecasting

Ribeiro et al. "" Why should I trust you?" Explaining the predictions of any classifier." 2016.

Example 1: Forecasting and Robust Statistics for Simulation

- Machine Learning Goal: Optimize Operation Conditions
  - Robust initial estimates for Mod / Sim
  - Forecasting when the heat pipe is out of tolerance
  - Consensus between Mod / Sim and data stream
  - Infer relationships between system measurements

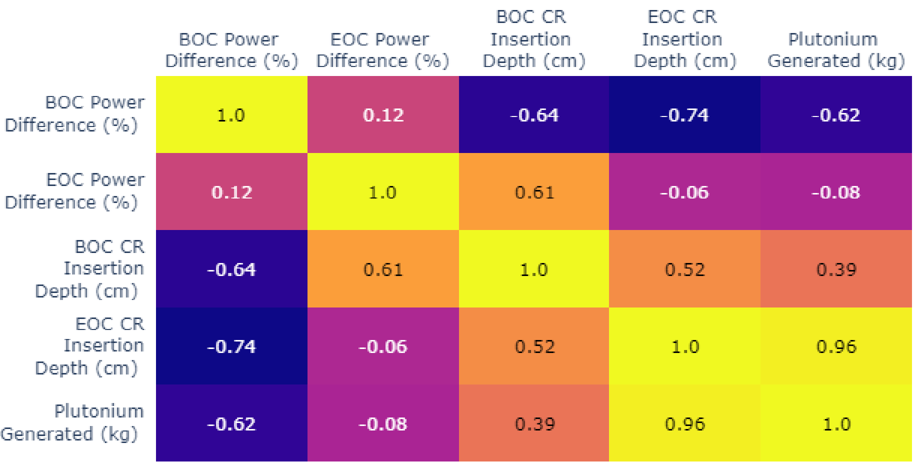




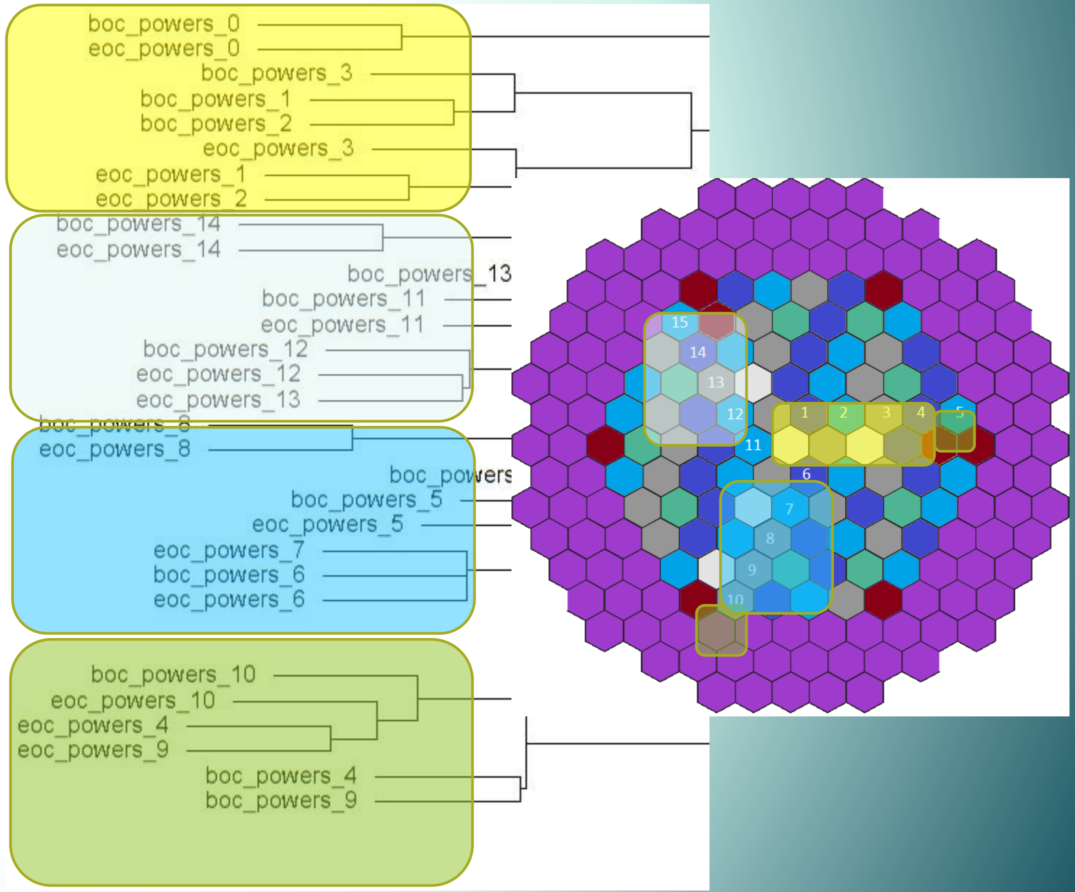
Sabharwall et al. "SPHERE Assembly and Operation Demonstration". 2020.

Example 2: Prediction simplification via LIME approach

- Machine Learning Goal: Detection of reactor misuse
  - Prediction of plutonium and classification
  - Robust Analysis on data injection / scrubbing
  - Spatial correlation between assemblies
  - Temporal projections of plutonium amount
  - Classification of different sources within reactor



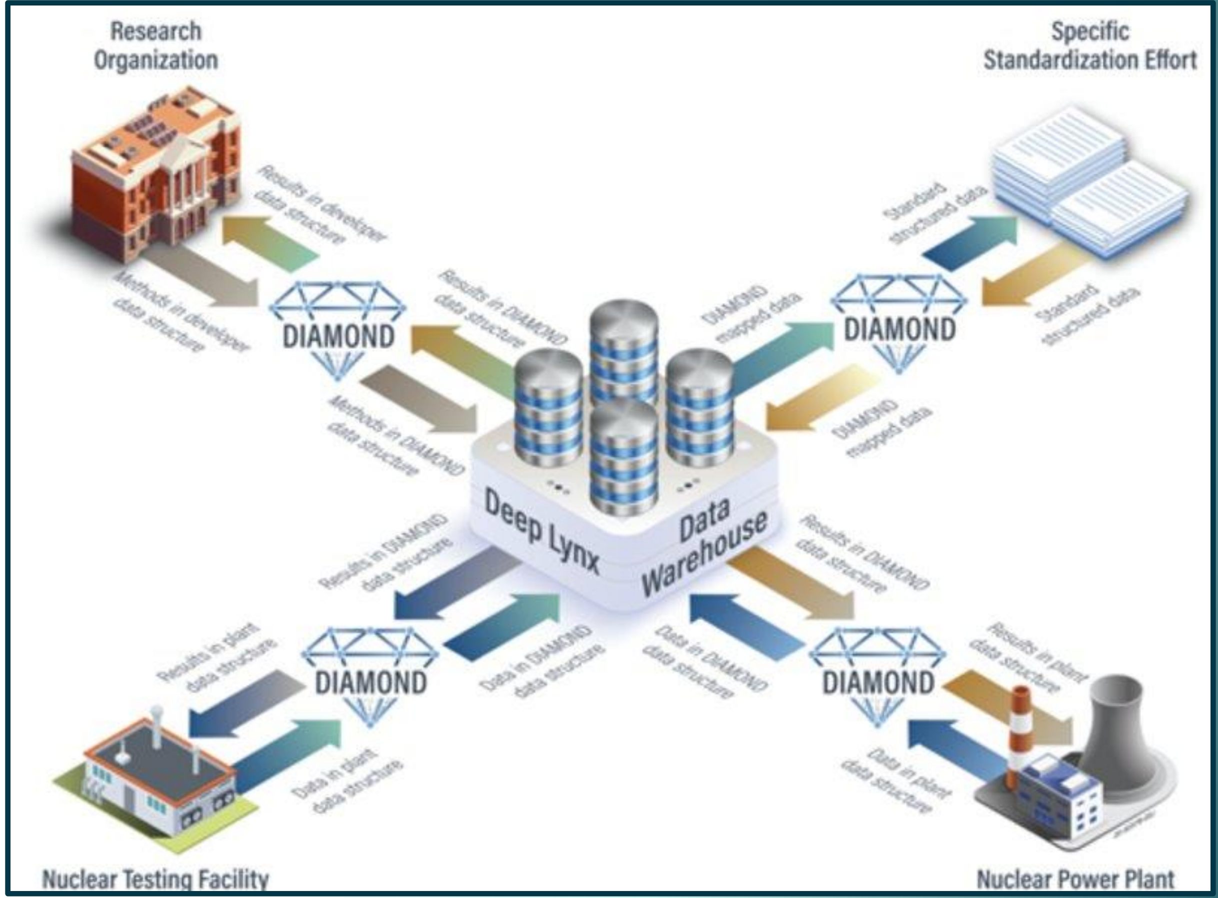
	BOC Power Difference (%)	EOC Power Difference (%)	BOC CR Insertion Depth (cm)	EOC CR Insertion Depth (cm)	Plutonium Generated (kg)
BOC Power Difference (%)	1.0	0.12	-0.64	-0.74	-0.62
EOC Power Difference (%)	0.12	1.0	0.61	-0.06	-0.08
BOC CR Insertion Depth (cm)	-0.64	0.61	1.0	0.52	0.39
EOC CR Insertion Depth (cm)	-0.74	-0.06	0.52	1.0	0.96
Plutonium Generated (kg)	-0.62	-0.08	0.39	0.96	1.0



Stewart et al. “Examination of Diversion and Misuse Detection for a Generalized Sodium-cooled Fast Test Reactor”, submitted 2021.

Current Challenges & Future Work

- Security concerns
- Sending control requests to an asset
- Creating a reusable framework
- AI goal of data fusion
  - Different incoming data sources
  - Physics models
  - Integration of digital twins
    - Modular vs expanding



Thank You

Please “leave” your breakout session and “rejoin” the main event.

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NMDQi

Overview of Nuclear Materials Discovery & Qualification initiative (NMDQi)

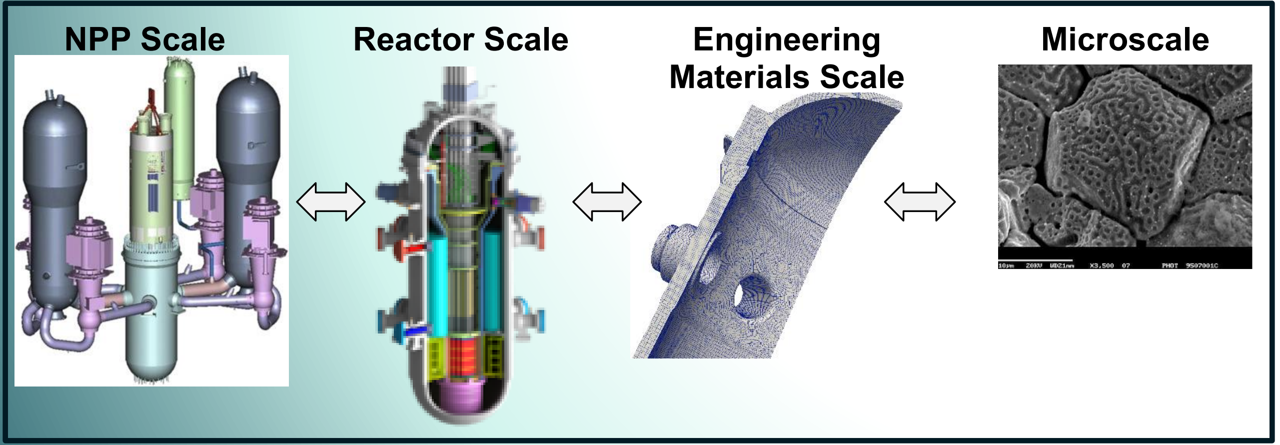
R. Allen Roach

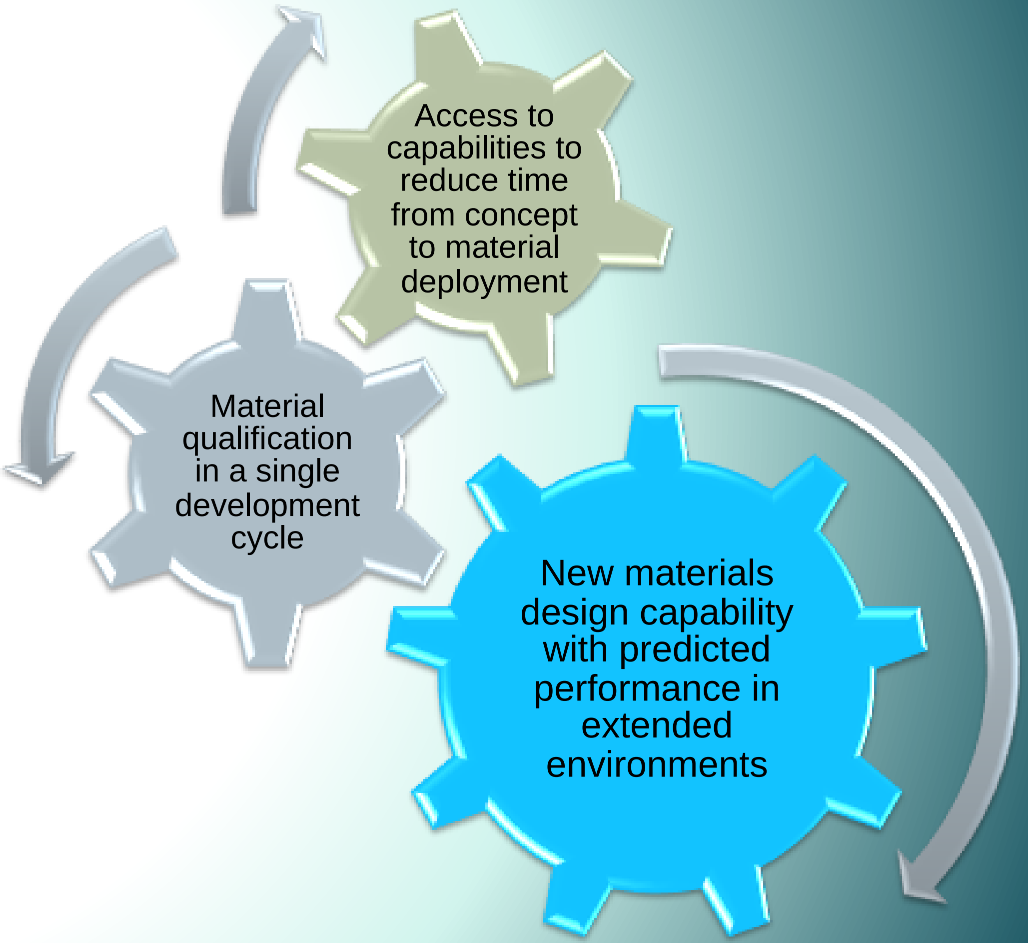
February 16, 2021

NMDQi Nuclear Materials Discovery and Qualification Initiative

NMDQi takes a Grand Challenge R&D approach to establish the prediction of material performance in their service environment before creation.

Allows materials discovery and qualification to become conjoined, accelerating development and qualification of new nuclear materials for future reactor technologies.





Access to capabilities to reduce time from concept to material deployment

Material qualification in a single development cycle

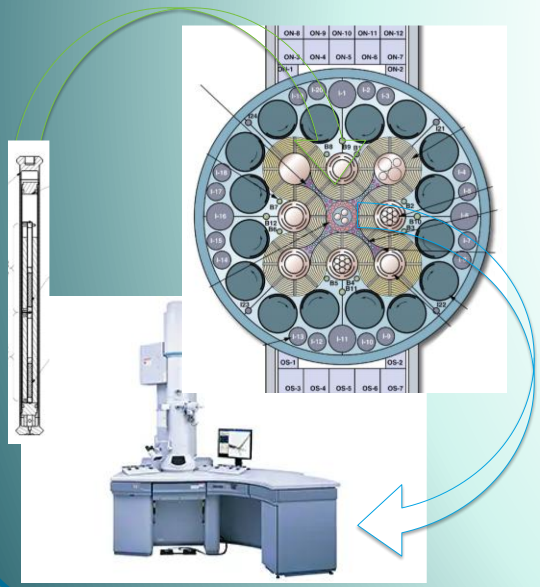
New materials design capability with predicted performance in extended environments

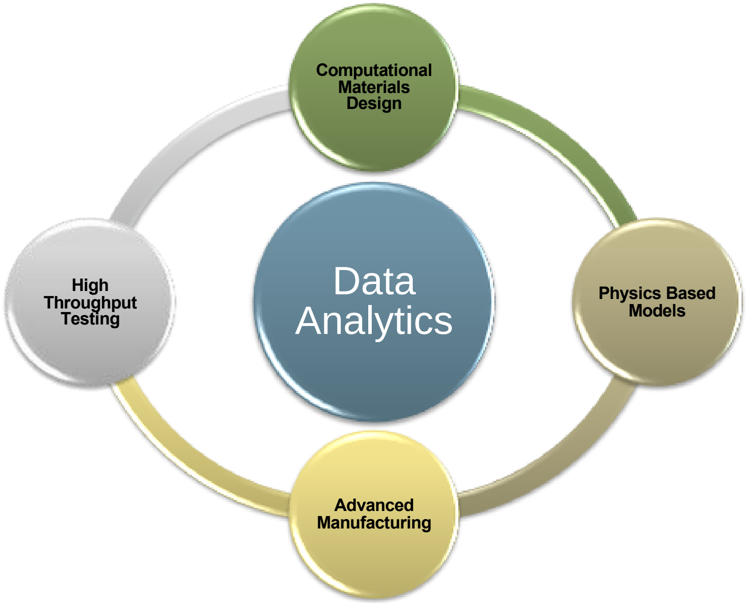
Ultimate R&D objective is materials-structure-based qualification of new, designed materials

NMDQi Nuclear Materials Discovery and Qualification Initiative

For nuclear energy applications, the environmental and irradiation conditions must be correlated to materials' evolution and degradation in service

<u>Physics-based modeling and rapid testing & characterization</u> links microstructures & service conditions to properties




Computational Materials Design

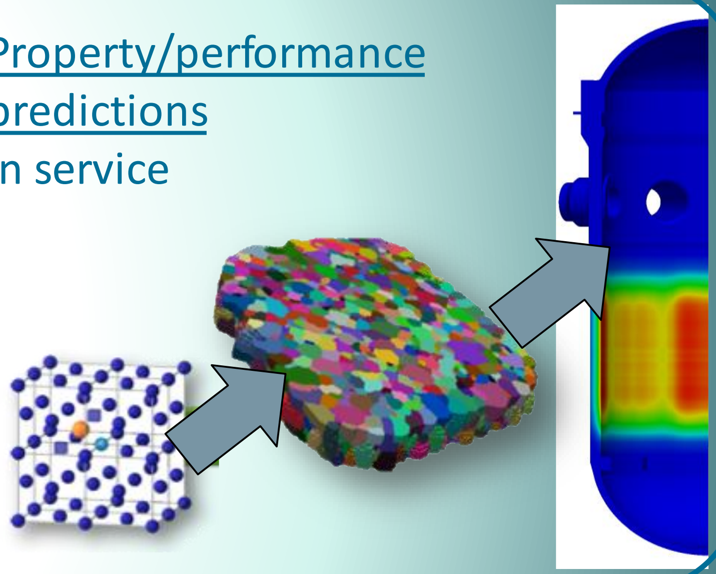
High Throughput Testing

Data Analytics

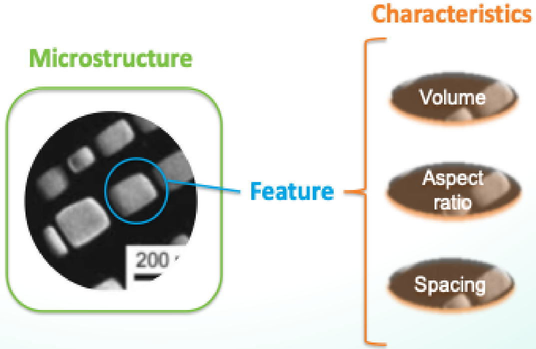
Physics Based Models

Advanced Manufacturing

<u>Property/performance predictions</u> in service

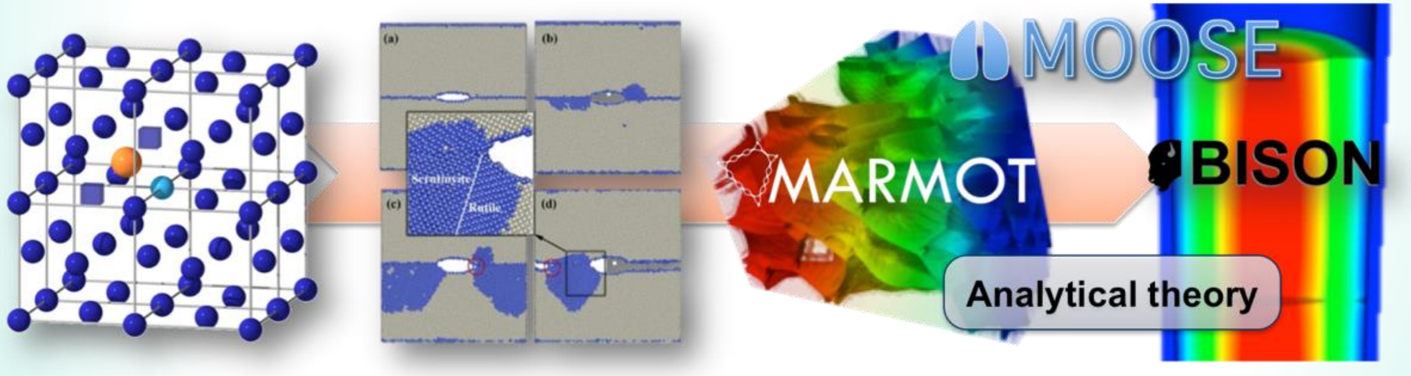


<u>Machine learning</u> to harness data in new ways for improved physics-based predictions



NRIC

- Focus: Incorporate physics-based models and machine learning capability for a new paradigm of PSPP predictions to predict material performance in advanced reactors
- Demonstrate stochastic tool module within MOOSE supporting integration of high-throughput data from experiments to reliably represent important material features



Tonks, *INL/EXT-15-351-8,* 2015

nanometers
First Principles
- Identify critical bulk mechanisms
- Determine bulk properties

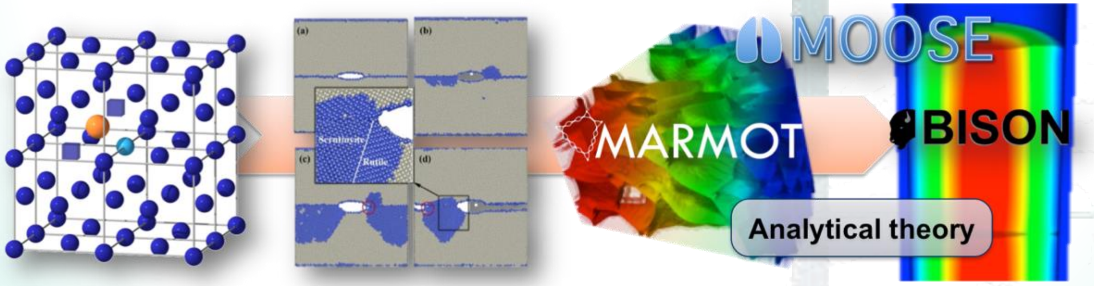
100's of nanometers
Molecular Dynamics
- Identify interfacial mechanisms
- Determine interfacial properties

microns
Mesoscale
- Predict microstructure evolution
- Determine impact on properties

millimeters and up
Engineering scale
- Use analytical theory
- Predict fuel performance

FY21 Plans for Physics Models and Data Analytics

- Develop capability to solve "inverse problem": optimizing properties in computational domain to obtain given boundary conditions - for example, back-calculate thermal properties from temperature data
- Enhance MOOSE crystal plasticity capability to support high fidelity models of dislocation-driven and creep-driven deformation
- Develop modern machine-learning tool for use with database of high-throughput DFT simulations to target energetics of different defect structures for property prediction of irradiated materials
- Demonstrate Magpie + phase field for a real materials system with focus on recombination from the initial radiation damage event



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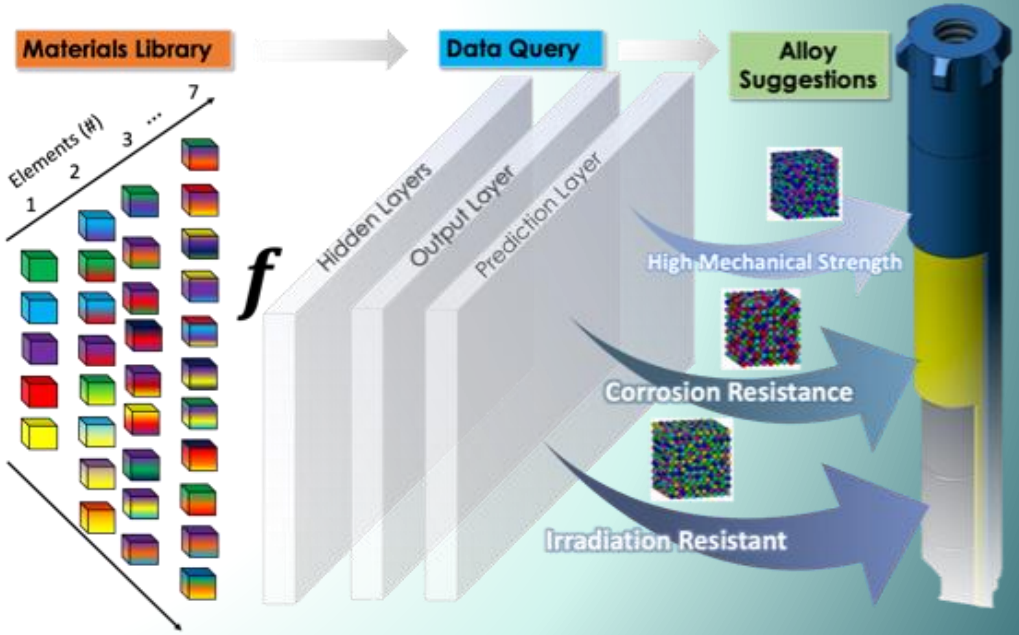
Engineering scale
- Use analytical theory
- Predict fuel performance

Future Outcomes

- Development and demonstration of new methods, approaches, techniques, & tools for accelerating development and qualification of new materials
- Establishing rapid qualification capability that is materials-structure-based and grounded in science
- High throughput irradiation and characterization capabilities - refitting new capabilities into existing facilities and obtaining multimodal data from individual samples
- Establishing combinatorial approach to shorten the nuclear materials development and research cycle by integrating physics-based modeling, data analytics, and rapid experimental frameworks



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Thank You

Please “leave” your breakout session and “rejoin” the main event.

NRIC TECH TALKS

Panel Discussion

February 16, 2021

Panel Discussion Lead By

Michael deLamare

Systems Engineering

Bechtel

Jared Harper

Systems Engineering

TerraPower

NRIC

NRIC TECH TALKS

Digital Engineering at Bechtel

February 16, 2021

Panel Discussion

Michael deLamare

Bechtel Corporation

Family-owned since 1898, Bechtel's four global business units are trusted engineering, construction, and project management partners to industry and government. We align our capabilities to our customers' missions with safety, quality, ethics, and integrity.

Nuclear, Security & Environmental

- 80% of nuclear plants in the U.S., and 150 worldwide designed, serviced, or delivered by Bechtel
- Construction and operation of national security facilities
- Building the world's largest and most complex radioactive waste treatment plant

Oil, Gas & Chemicals

- 1/3 of global LNG capacity currently under construction
- 275+ refinery expansions and modernizations
- 50,000 miles (80,500 km) of pipeline systems
- 380+ major chemical and petrochemical projects

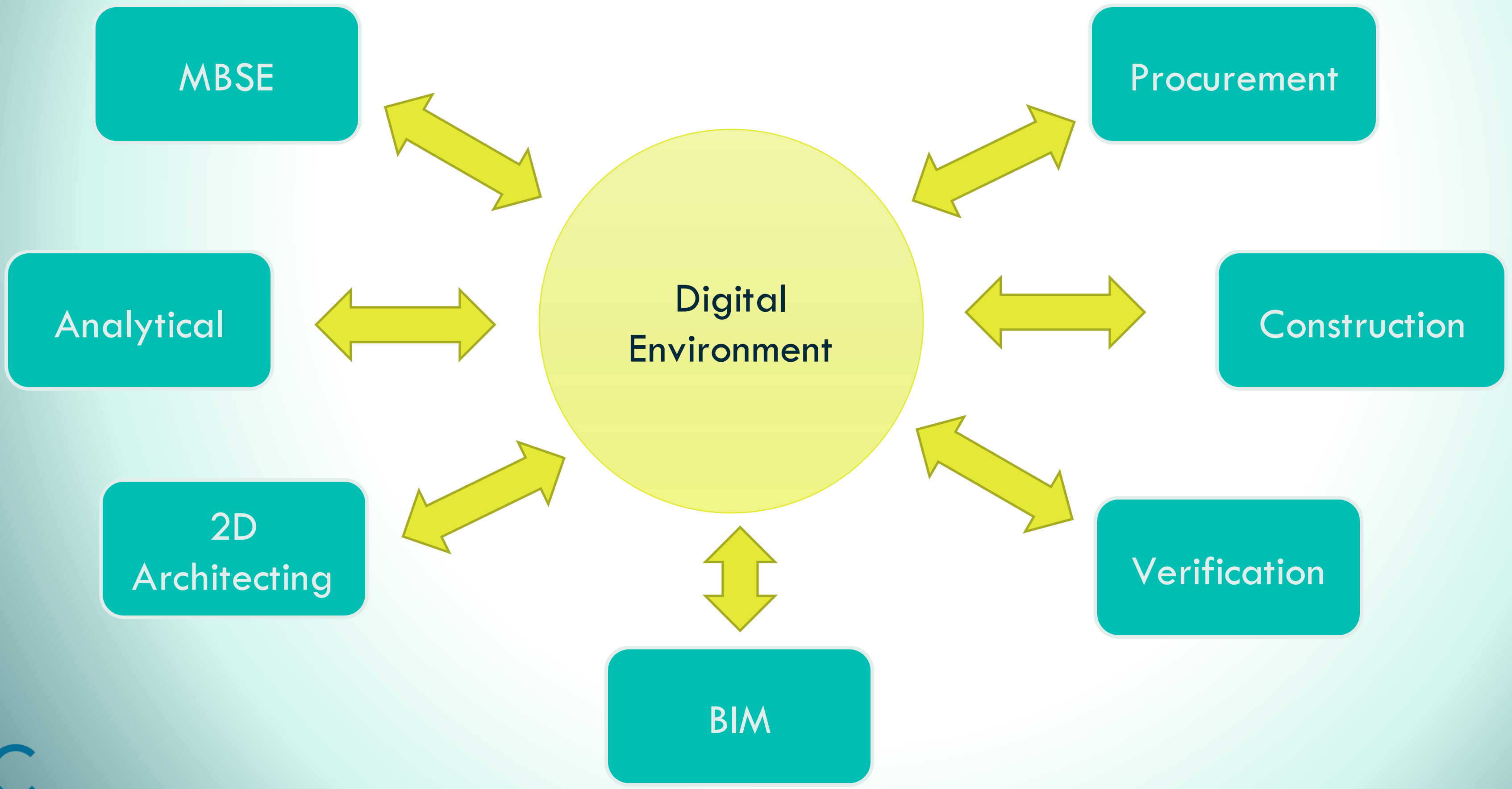
Mining & Metals

- 200 million metric tons per annum of installed iron ore productions
- 42 major copper projects
- 30 aluminum smelter projects
- 8 alumina refinery projects

Infrastructure

- 300 subway and rail projects
- 17,200+ miles (27,700 km) of highways and roads
- 6,200+ miles (10,000 km) of railroads
- 390 individual power plants

Digital Environment



Digital Environment

MBSE

Analytical

2D Architecting

BIM

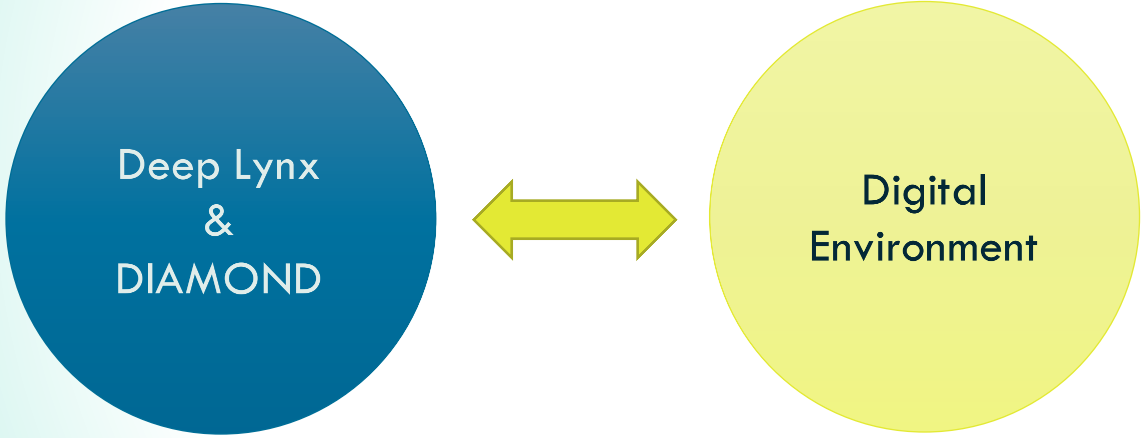
Procurement

Construction

Verification

NRIC

External Integration



Deep Lynx
&
DIAMOND

Digital
Environment

Digital Engineering

Jared Harper
Senior System Design Engineer

DIGITAL ENGINEERING

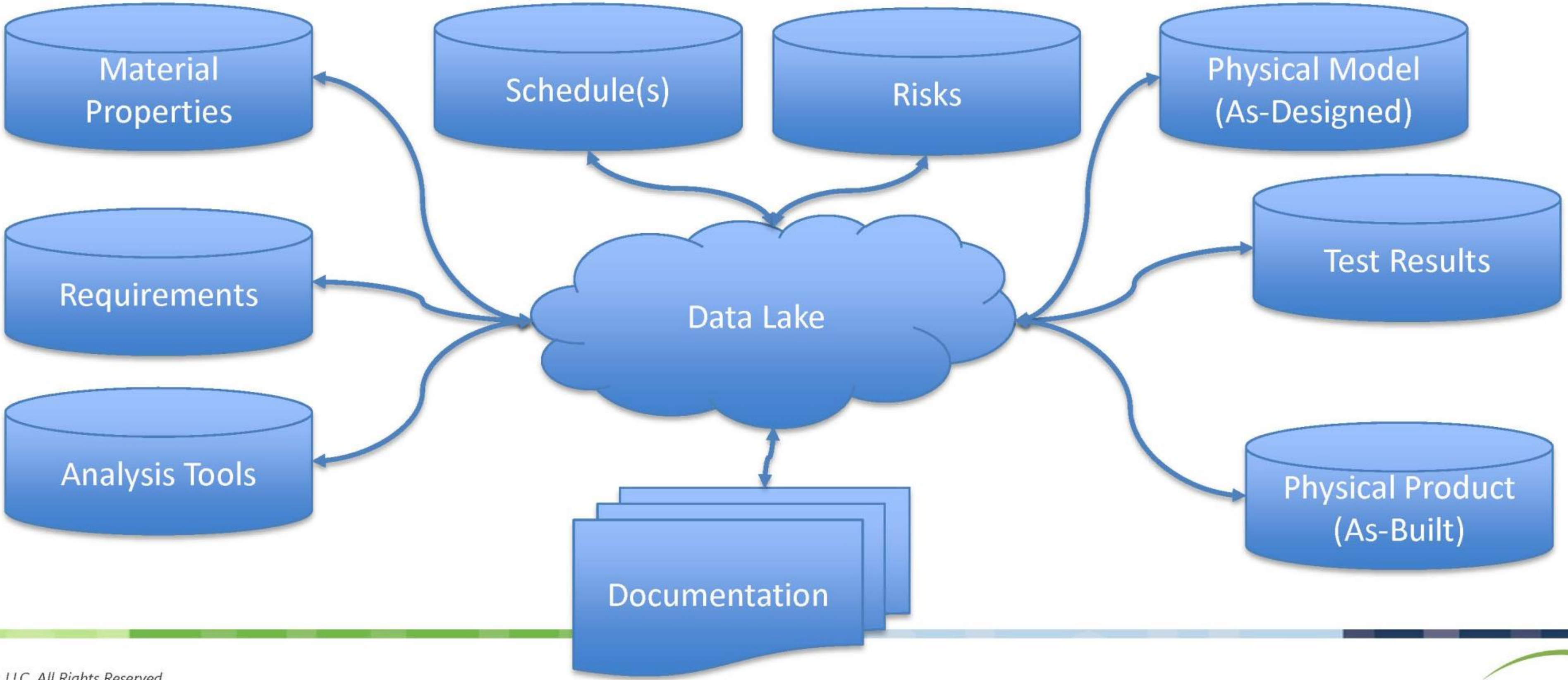
What is "digital engineering" at the 10,000 ft. level?
Why should I care?

Why Digital Engineering?

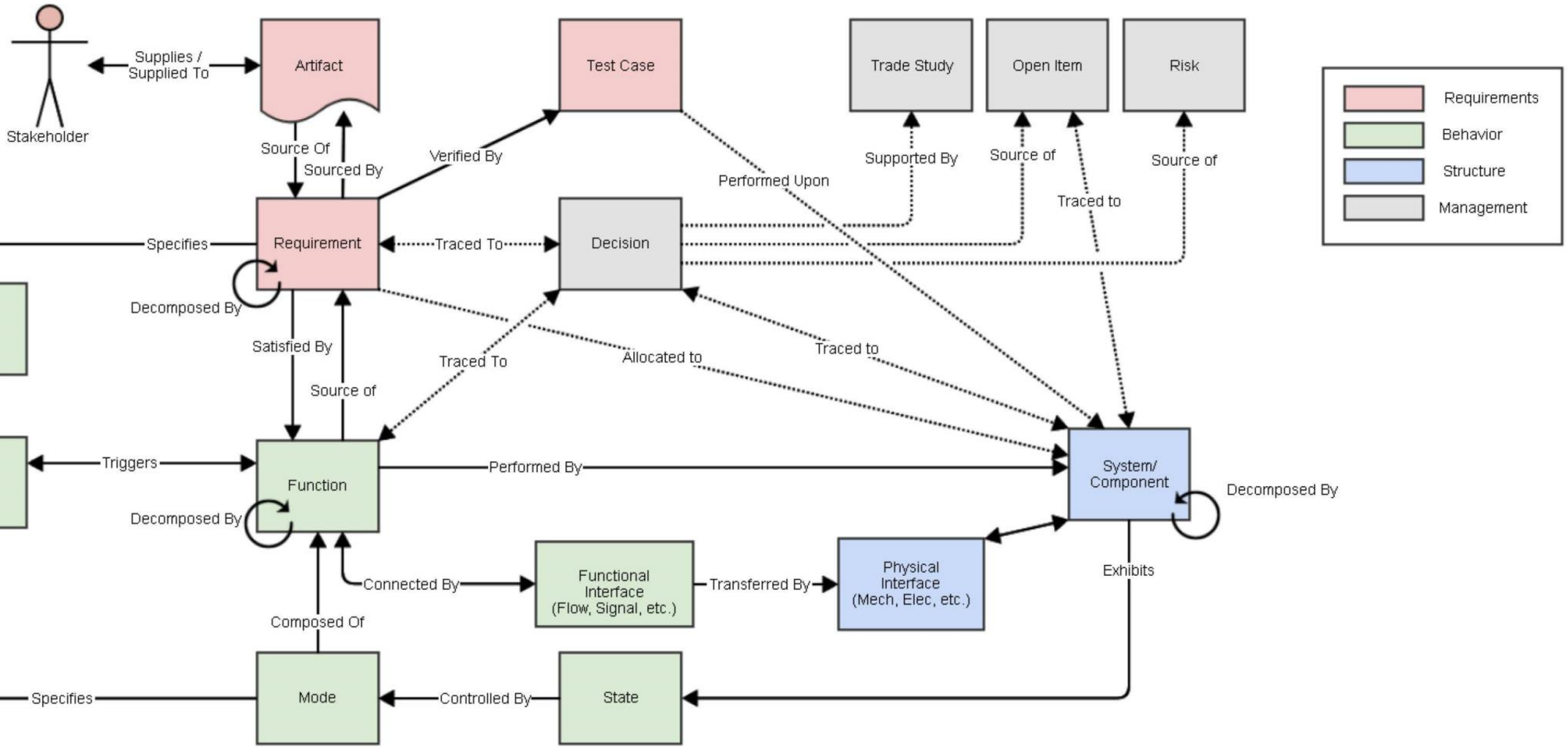
- Nuclear engineering projects are complex. Really complex.
- We control this complexity through modern project management and systems engineering practices.
- We make this process both easier and more efficient through digital tools (i.e. MBSE, Digital Twin, etc.)
- On the flip side, you can make this process onerous and expensive through traditional documentation methods.

What does Digital Engineering look like?

- Digital Engineering is essentially a group of connected and interactive databases that share information



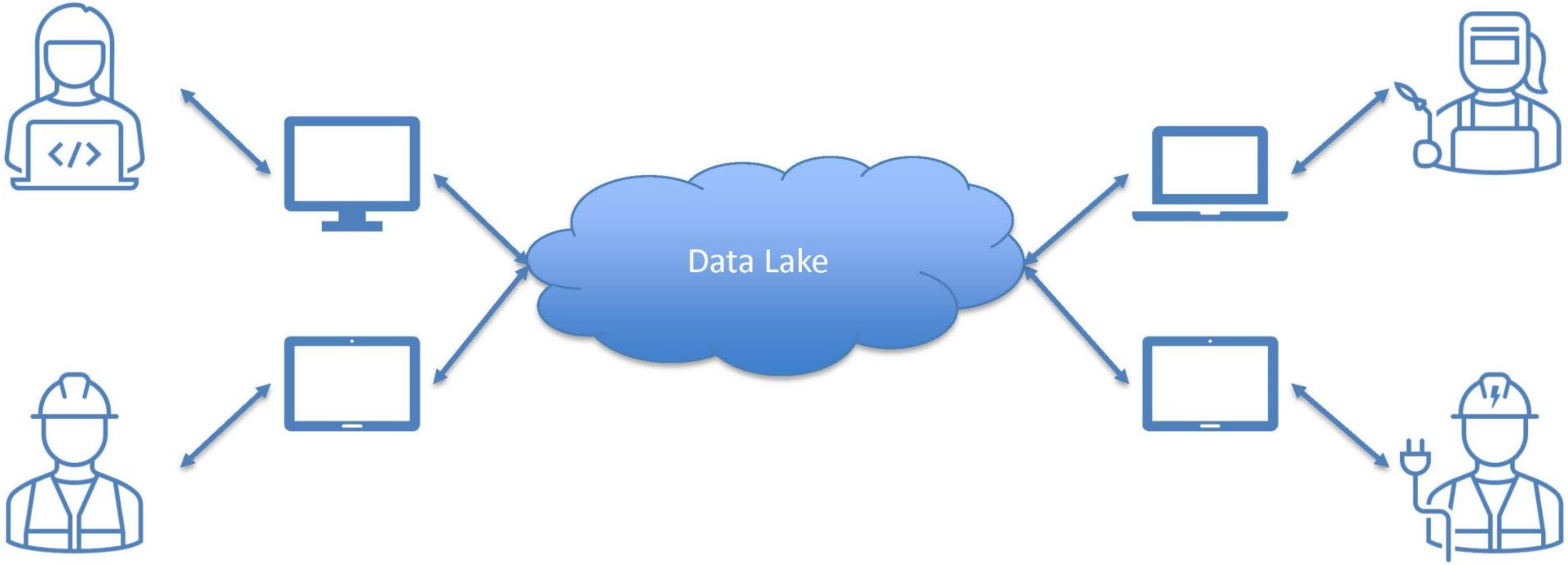
These databases house information that is relevant to reactor design



TerraPower

Any user can query any information that they need

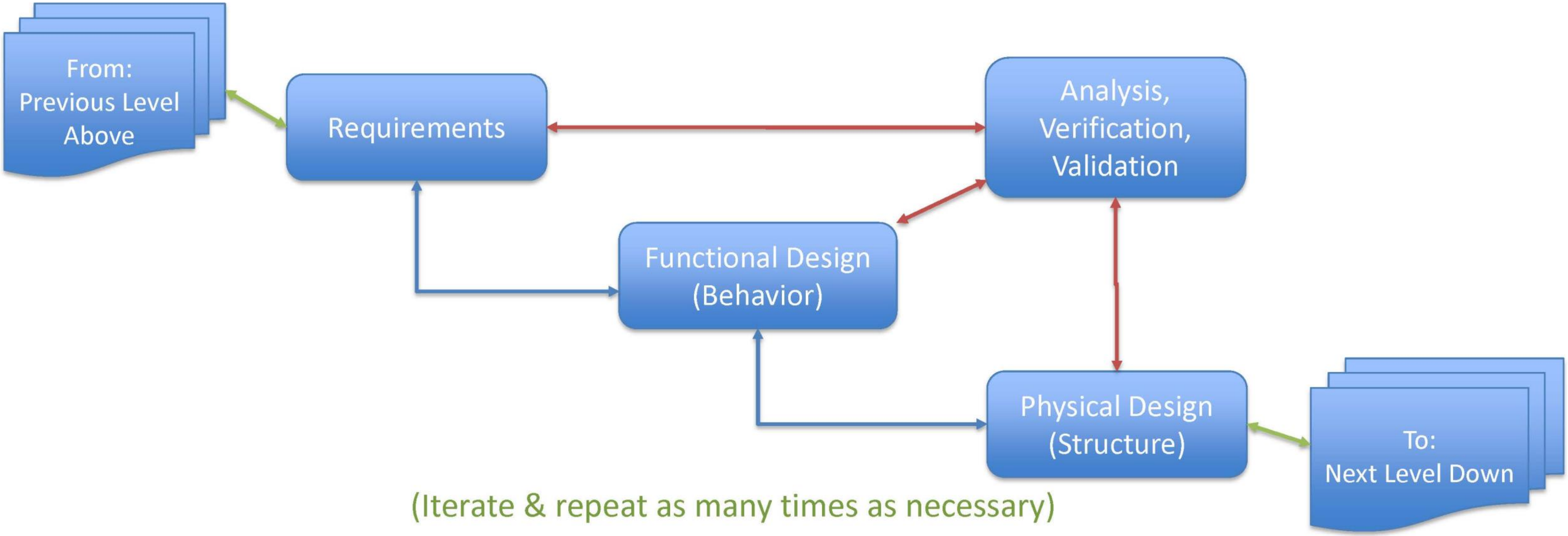
- The entire model / database is in sync across the board



MODEL BASED SYSTEMS ENGINEERING

One aspect of the digital engineering ecosystem

A Digital Workflow is Different from a Document Workflow



From:
Previous Level
Above

Requirements

Analysis,
Verification,
Validation

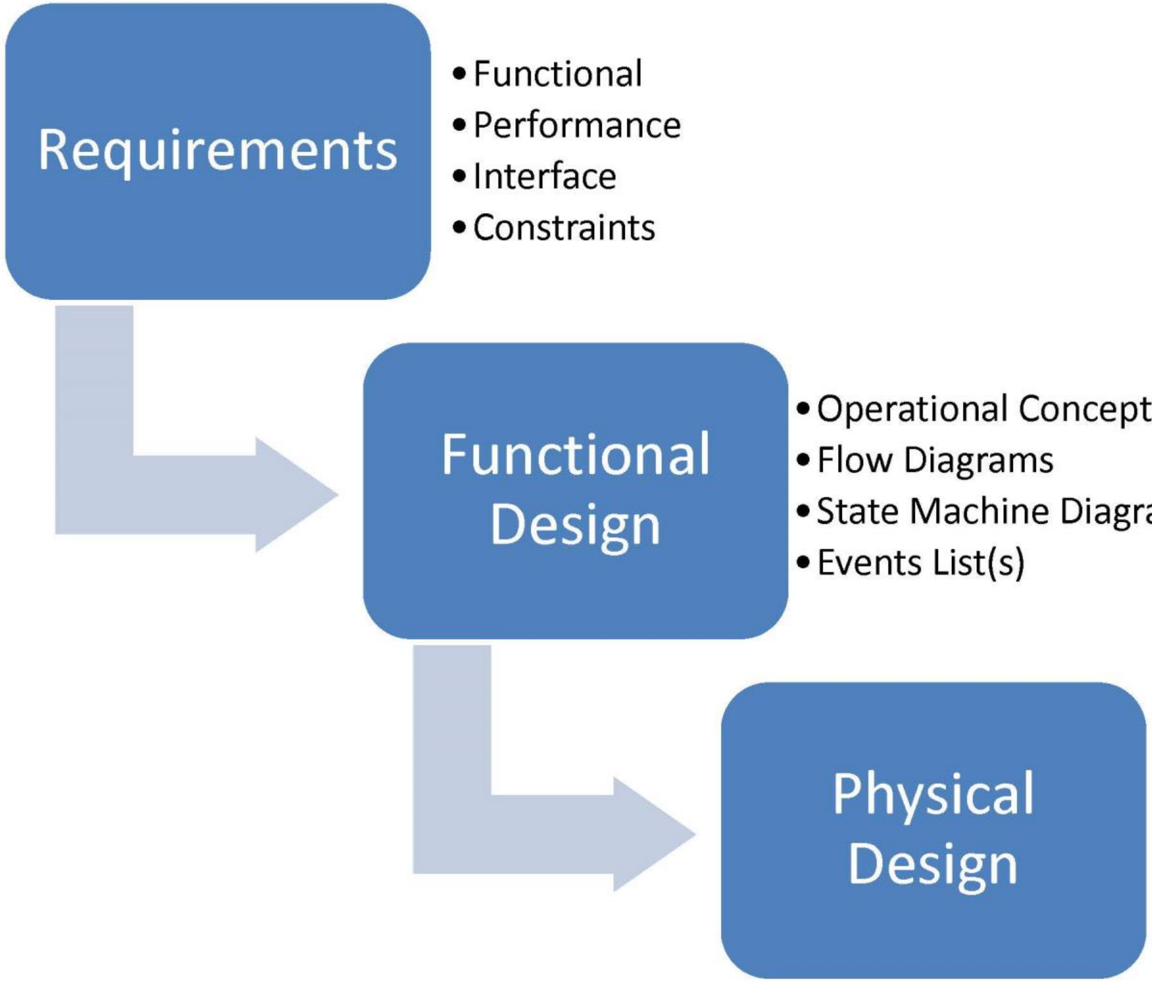
Functional Design
(Behavior)

Physical Design
(Structure)

To:
Next Level Down

(Iterate & repeat as many times as necessary)

A Digital Workflow is Different from a Document Workflow



Requirements

- Functional
- Performance
- Interface
- Constraints

Functional Design

- Operational Concept(s) & Scenarios
- Flow Diagrams
- State Machine Diagrams
- Events List(s)

Physical Design

- 3D CAD
- P&IDs
- Wiring Diagrams
- Assembly/Part Drawings

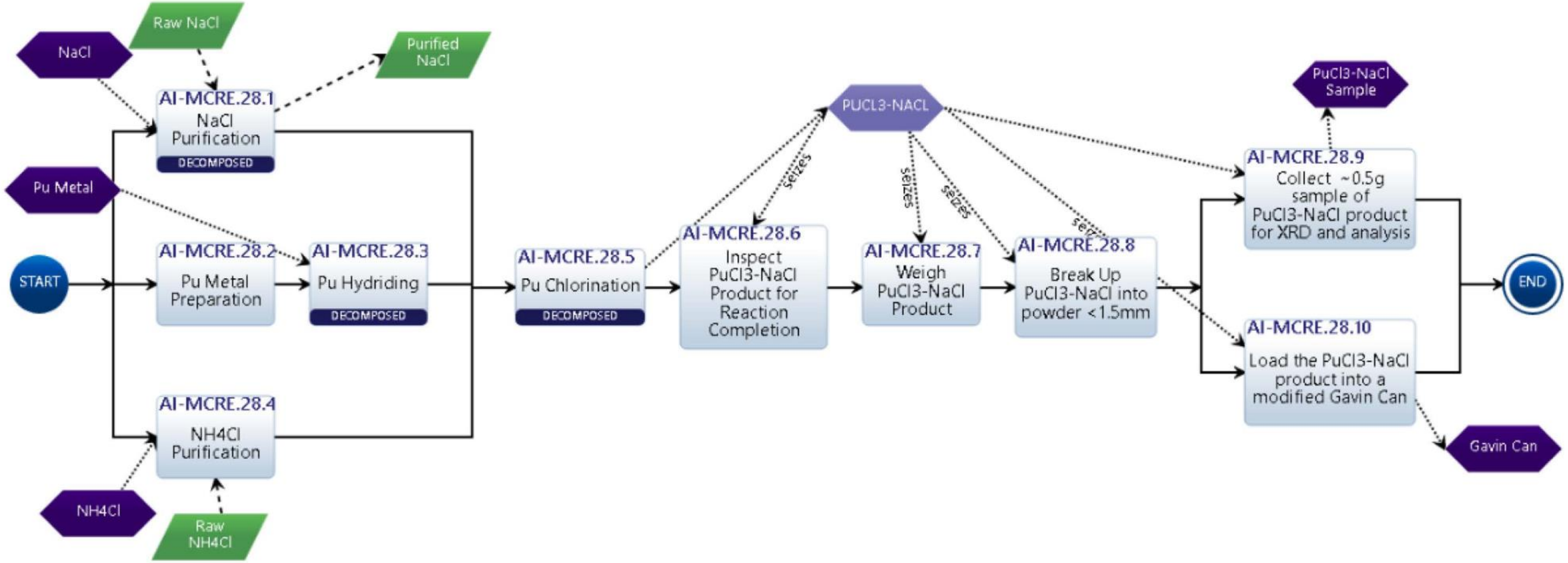
What does a "Model-Based Solution" Look Like

- In all honesty, a "model" looks like a bunch of boxes, lines, and text.

- You enter data into the visual *model*.
- That data from the visual model is stored in the central database.
- You can query the database for literally anything within it.
- The end goal is to have a centralized mega-database that reduces the amount of data re-entry and finger fudging across the program.

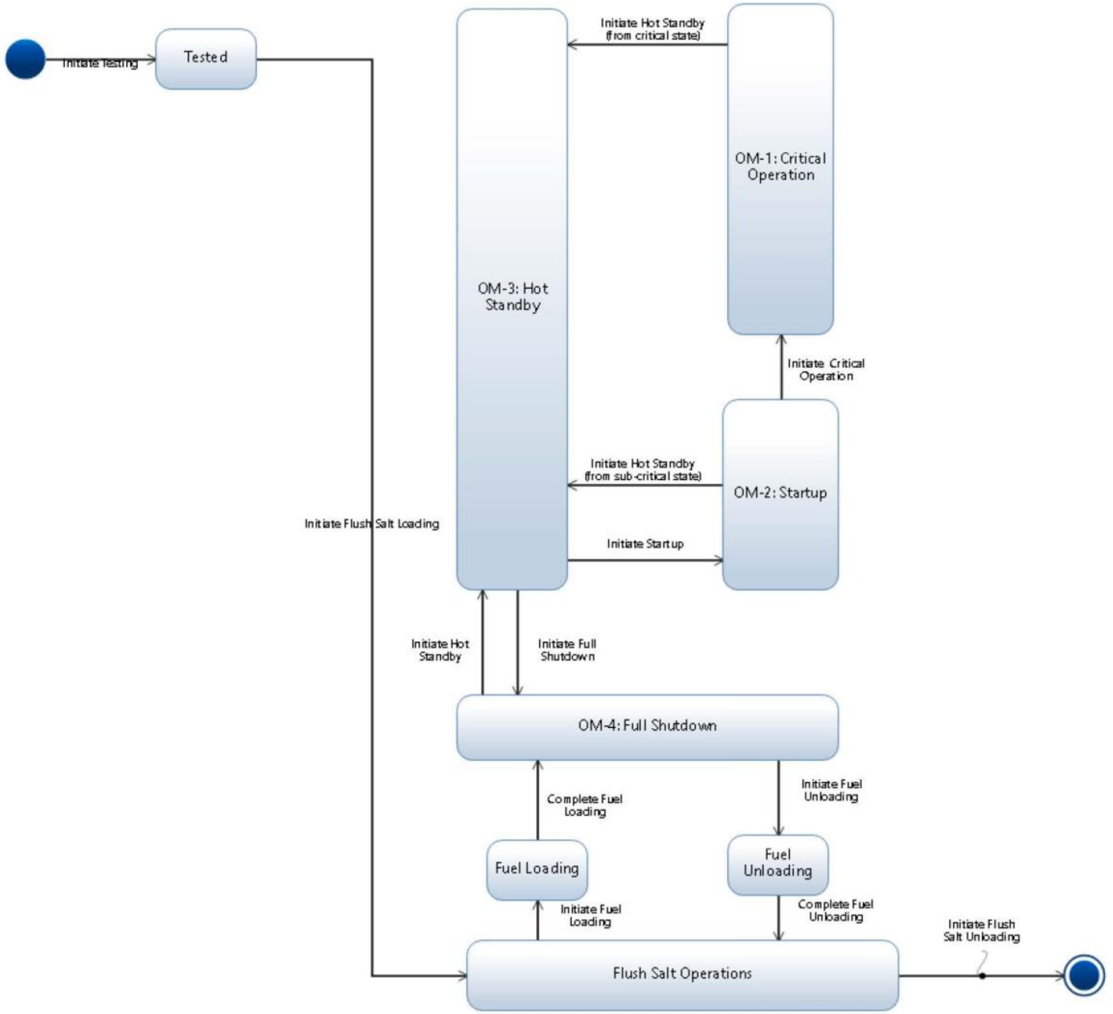
Functional Diagram (1/2)

- The example below is a functional diagram for fuel salt synthesis



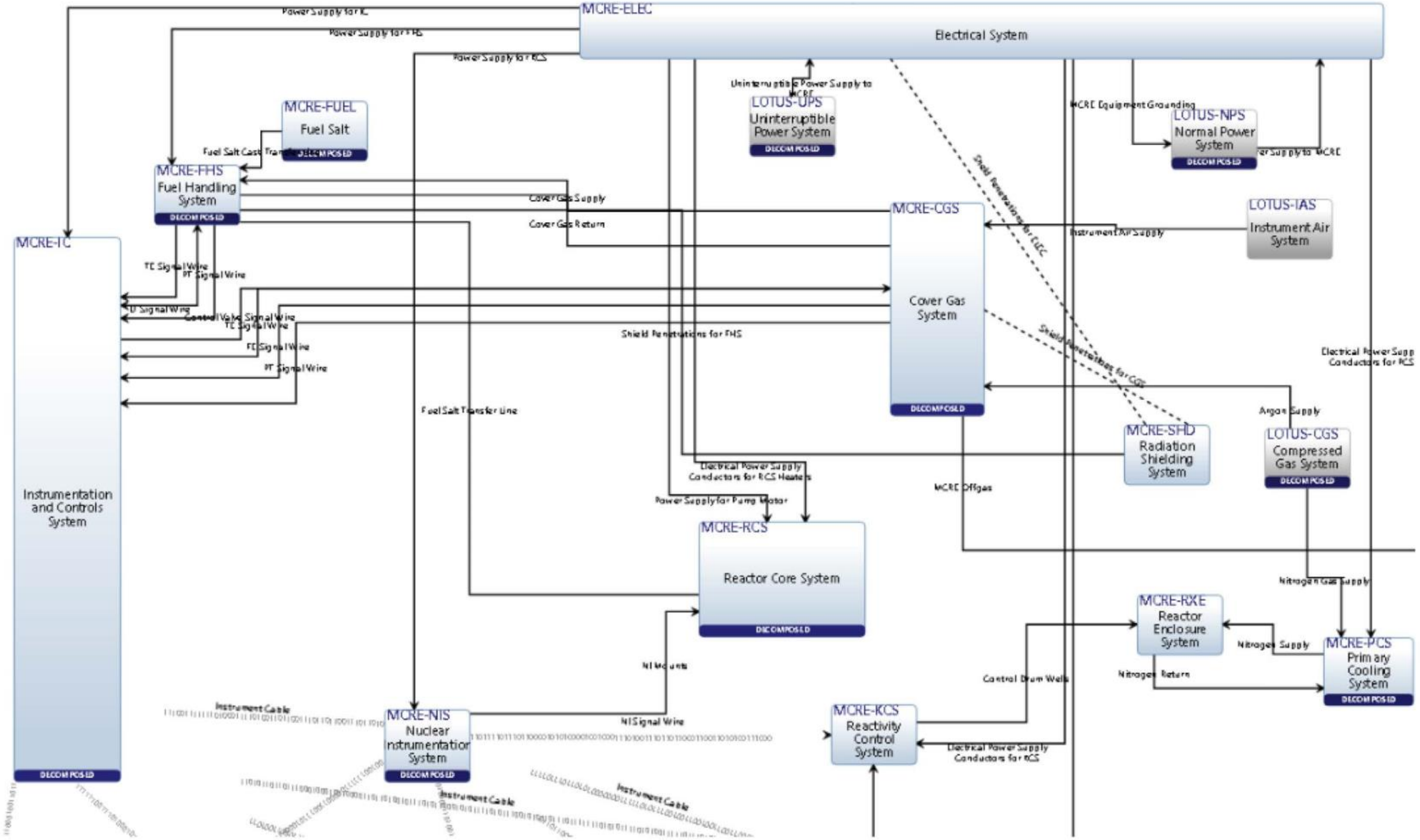
Functional Diagram (2/2)

- The example shown here is a State Machine Diagram (i.e. States and Modes) for a reactor experiment
- You can add as much detail as you desire.

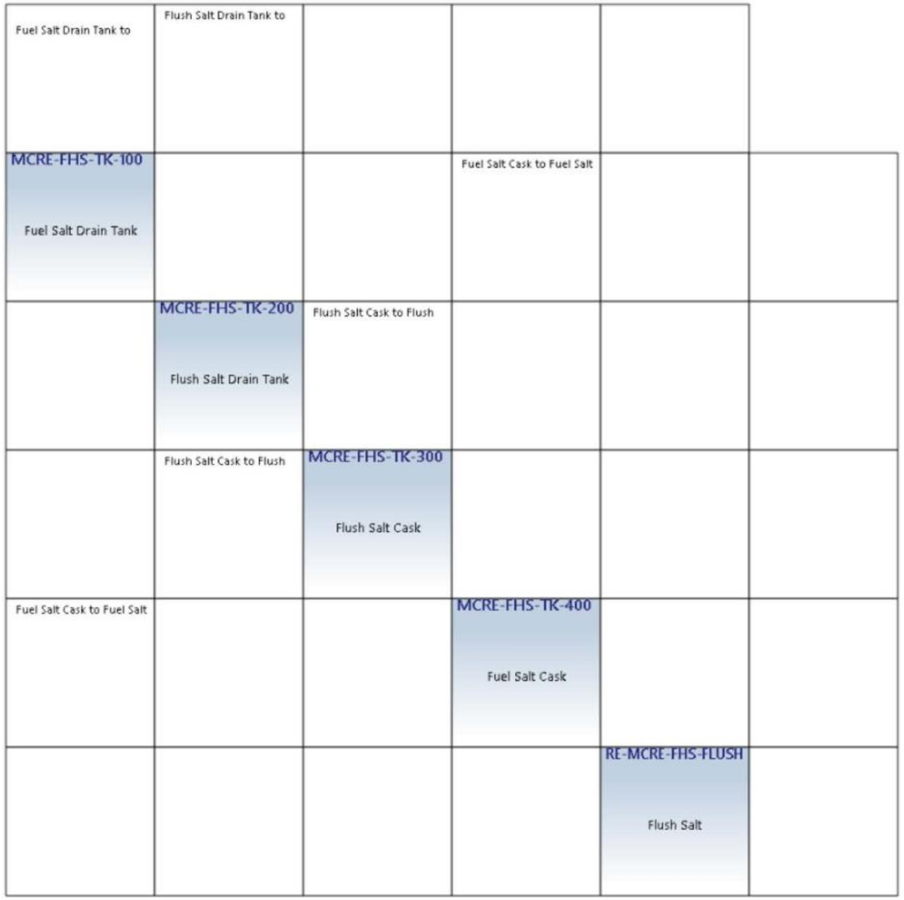


Physical Diagrams

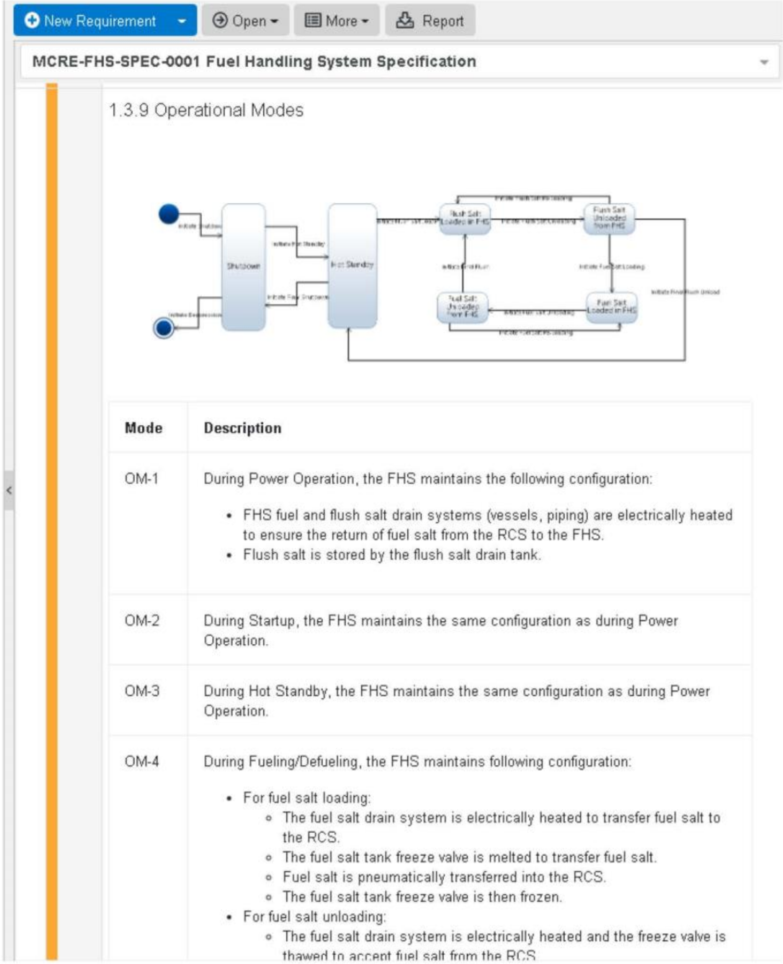
- The example shown here is a physical diagram connecting the reactor experiment systems



Once the model is built, you can produce Reports and Documentation from it



Fuel Salt Drain Tank to	Flush Salt Drain Tank to				
MCRE-FHS-TK-100 Fuel Salt Drain Tank			Fuel Salt Cask to Fuel Salt		
	MCRE-FHS-TK-200 Flush Salt Drain Tank	Flush Salt Cask to Flush			
	Flush Salt Cask to Flush	MCRE-FHS-TK-300 Flush Salt Cask			
Fuel Salt Cask to Fuel Salt			MCRE-FHS-TK-400 Fuel Salt Cask		
				RE-MCRE-FHS-FLUSH Flush Salt	



MCRE-FHS-SPEC-0001 Fuel Handling System Specification

1.3.9 Operational Modes

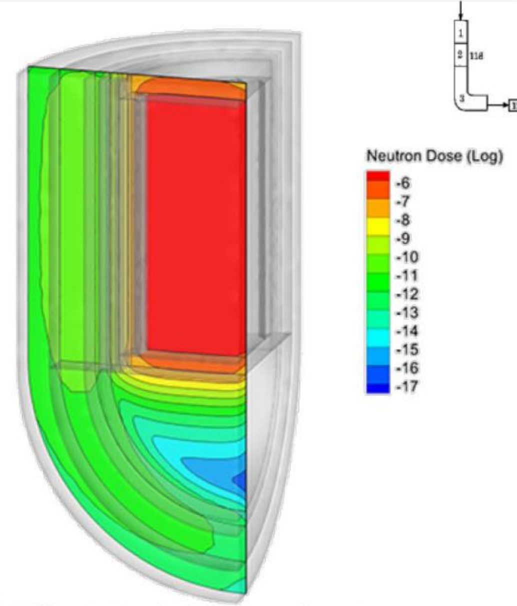
Mode	Description
OM-1	During Power Operation, the FHS maintains the following configuration: • FHS fuel and flush salt drain systems (vessels, piping) are electrically heated to ensure the return of fuel salt from the RCS to the FHS. • Flush salt is stored by the flush salt drain tank.
OM-2	During Startup, the FHS maintains the same configuration as during Power Operation.
OM-3	During Hot Standby, the FHS maintains the same configuration as during Power Operation.
OM-4	During Fueling/Defueling, the FHS maintains following configuration: • For fuel salt loading: ◦ The fuel salt drain system is electrically heated to transfer fuel salt to the RCS. ◦ The fuel salt tank freeze valve is melted to transfer fuel salt. ◦ Fuel salt is pneumatically transferred into the RCS. ◦ The fuel salt tank freeze valve is then frozen. • For fuel salt unloading: ◦ The fuel salt drain system is electrically heated and the freeze valve is thawed to accept fuel salt from the RCS

MODEL BASED ANALYSIS

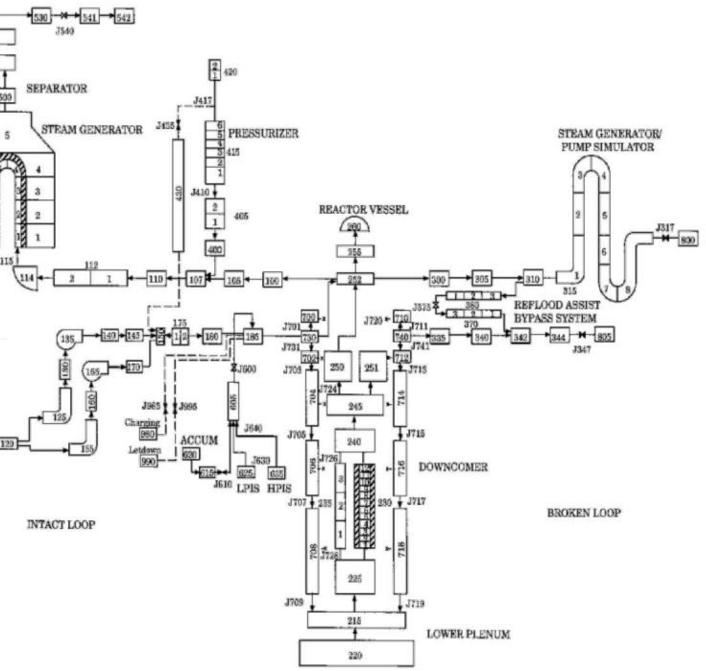
Unique add-ons that could accelerate reactor development

TerraPower does have unique capabilities, but they aren’t fully integrated with MBSE tools

- We utilize a plethora of modeling tools:
  - ARMI®
  - DIF3D - diffusion and transport theory codes
  - MC^2-3 - multigroup cross-sections for fast reactors
  - SAS4A/SASSYS – plant & transients
  - MCNP – neutron transport phenomena
  - RELAP5-3D – coolant modeling
  - Attila – neutron transport phenomena
  - SolidWorks – 3D modeling and simulation
  - AVEVA – 3D modeling and plant modeling
  - AutoCAD – 2D modeling
  - ABAQUS – stress analysis and modeling
  - ANSYS – structural analysis and modeling
  - GOTHIC – pool dynamics
  - SAPHIRE – Probablistic Risk Assessment



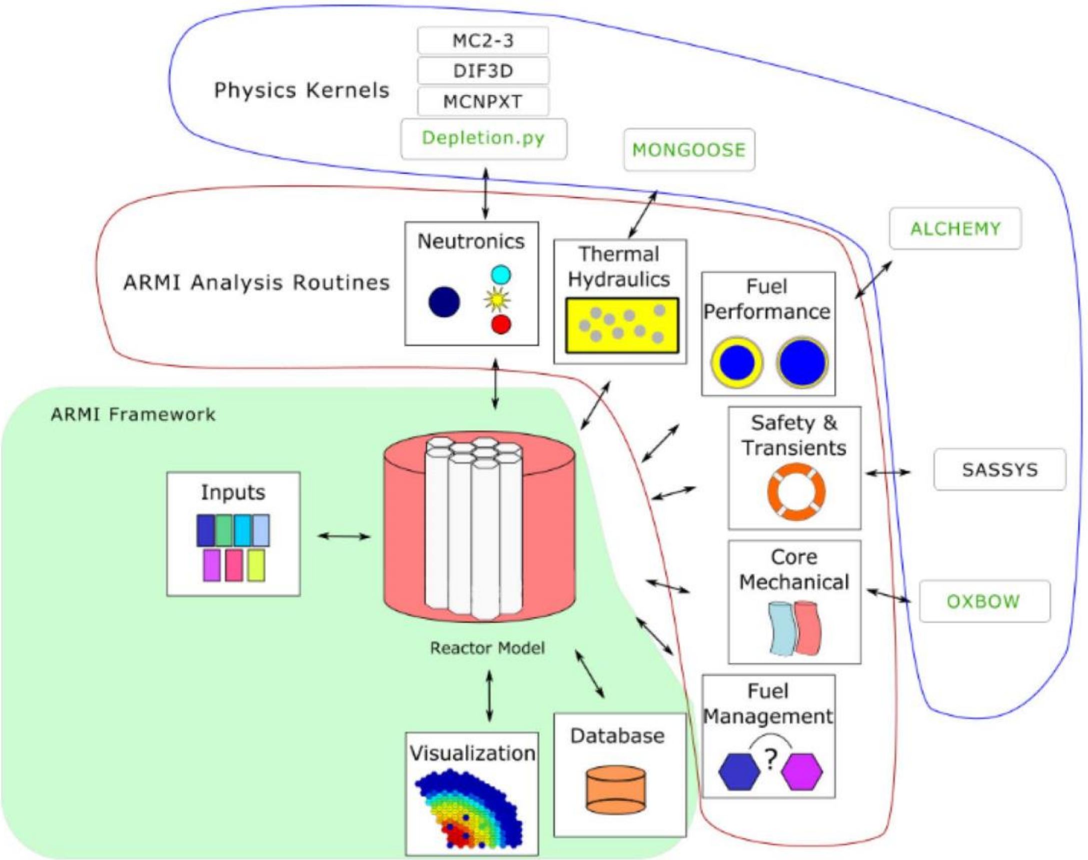
Atilla Model Visualization



RELAP5 Visualization

ARMI® integrates many of these tools for fast-iteration design/analysis work

- See github.com/terrapower/armi
- Tools like ARMI® might be the missing link to a fully executable digital model
- (…. to be continued…)



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End

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