

Managing the Digital Thread For Structural Applications with Fit For Purpose Materials

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NASA Glenn Research Center



*Innovative solutions through
foundational research and
cross-cutting tools*

2024 LEAD Symposium
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10/1/2024

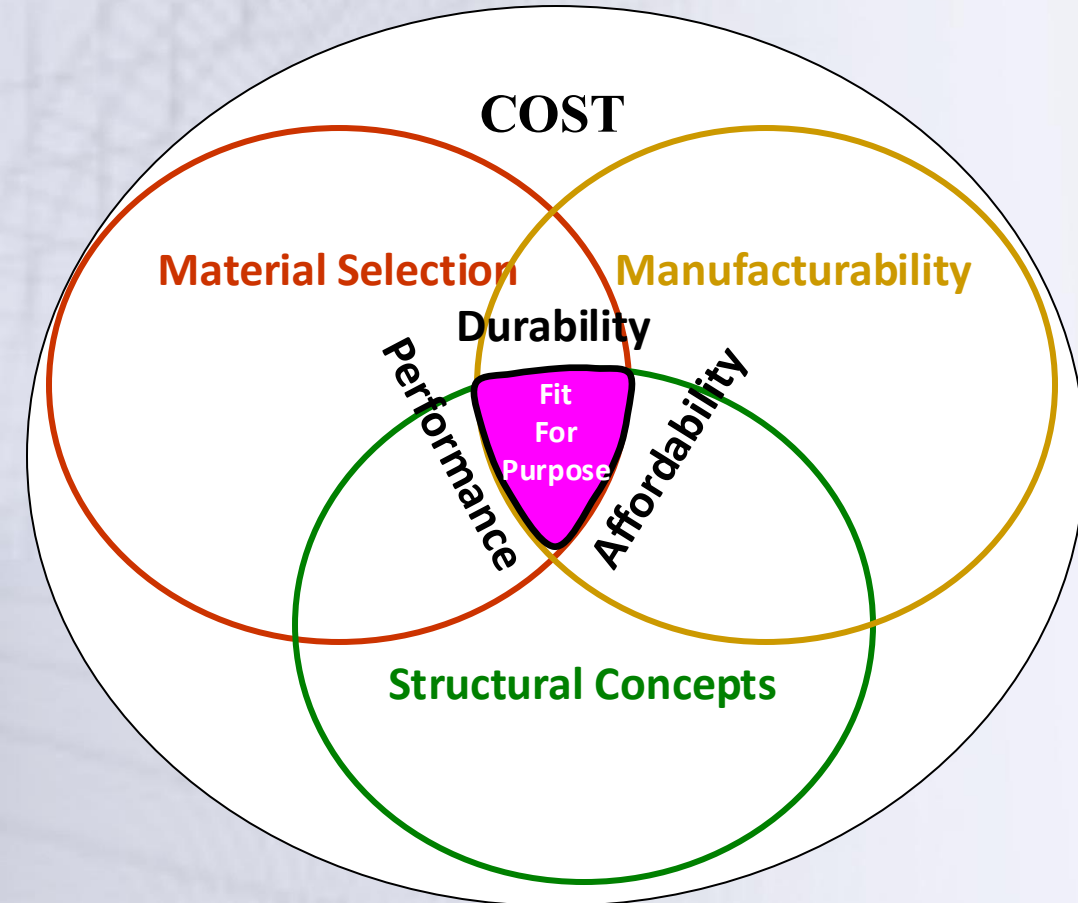
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Performance, Durability, Affordability Is Dependent Upon More Than Just Materials

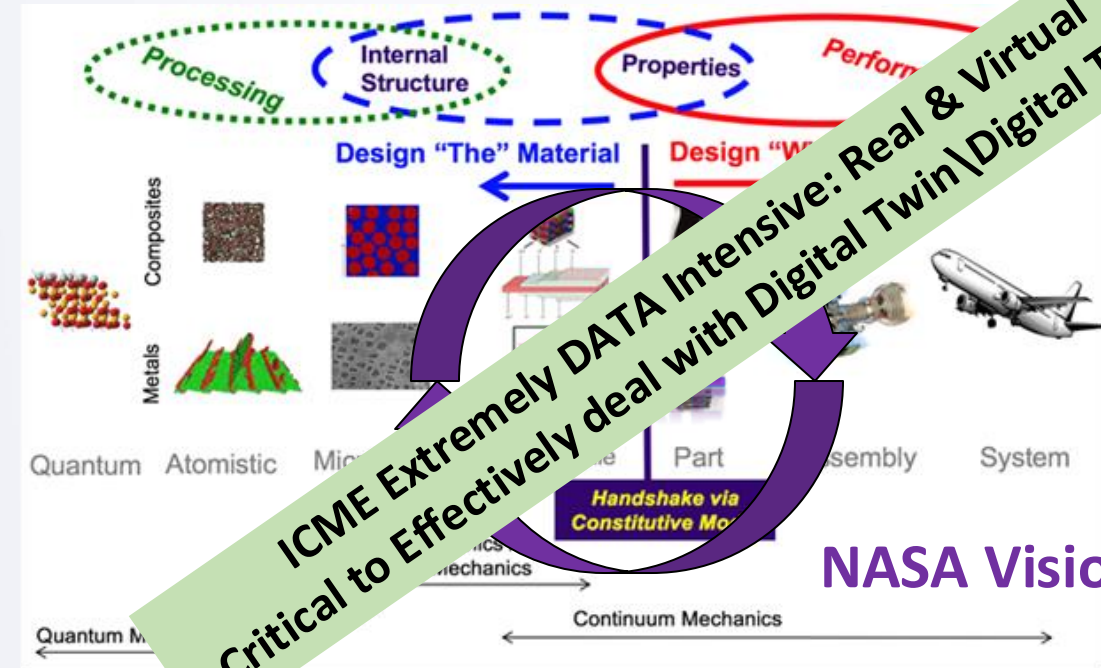


Design Optimization Space Given Application Load History



ICME (Integrated Computation Materials Engineering) & **Vision 2040** looks to bridge the gap between the “Design-the-Material” (Material Science) and “Design-with-the-Material” (Structural) viewpoints

Enables design of ‘fit-for-purpose’ materials



NASA Vision 2040

Requires a robust information management system

Intersection Of Material, Manufacturability And Structural Concept Determines The Engineering Utility Of A Given “System”. Smart materials enlarge this **applicability window** even further

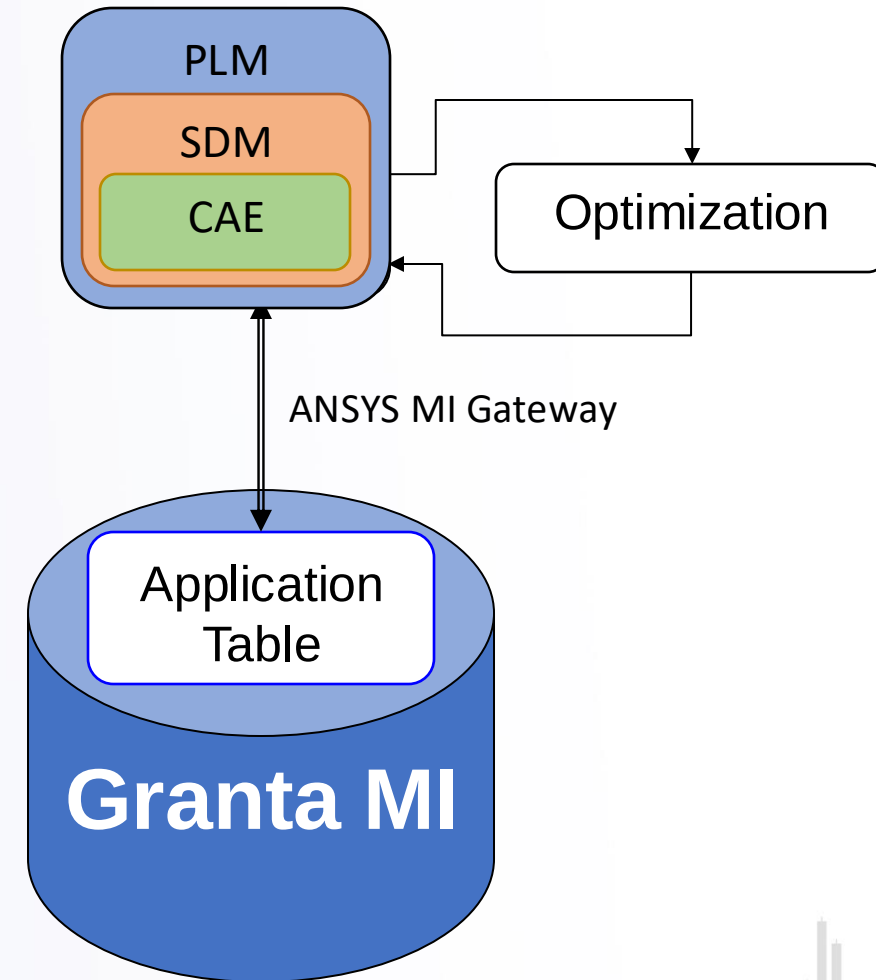
Traditional Database/Simulation Management Only Deals with a Single Scale



Hierarchical Approach

- Select a known material based on application requirements
 - Use macroscale material properties (which incorporate all lower length scales effects)
- Iterate on the structural design until requirements in the PLM/SDM are met
 - If requirements cannot be met, select a new material

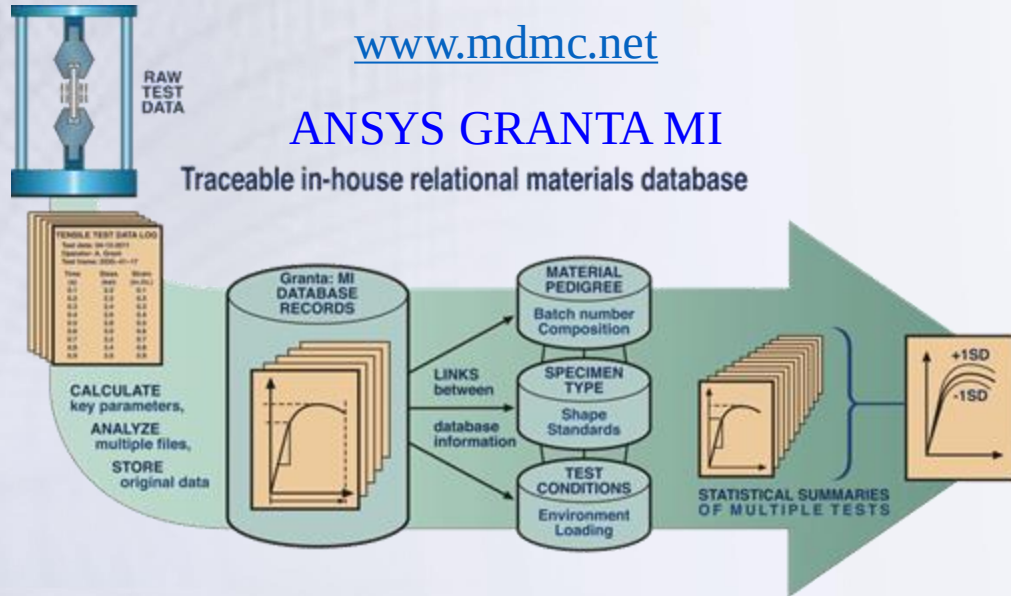
**Material and Structure viewpoints are
non - concurrent/synergistic!**



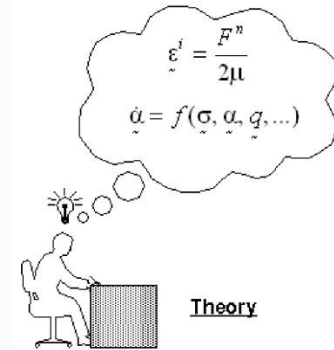
Integrated Workflow for Physics-Based Design and Analysis of a Component at Elevated Temperature



Cradle



Mathematical Characterization Of Material Behavior



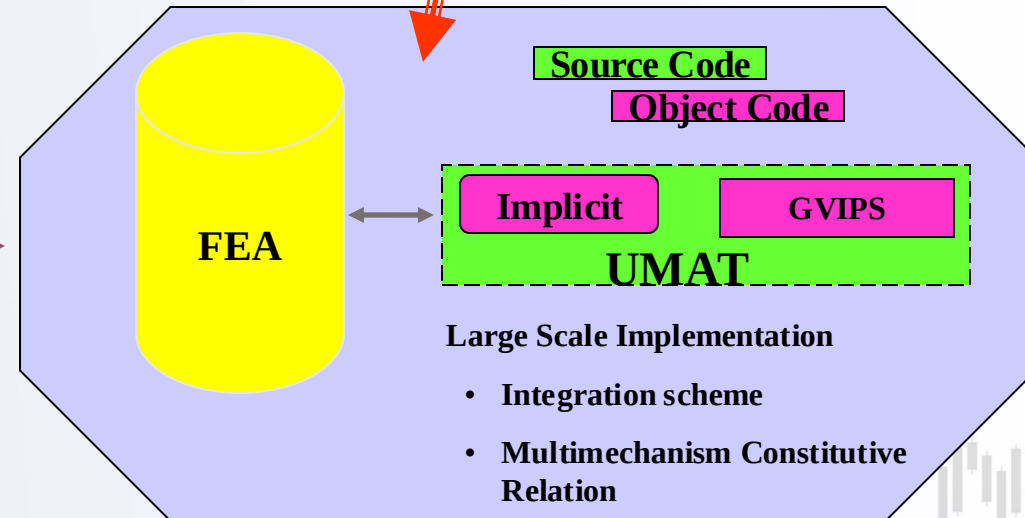
COMPARE

Automatically write required input information

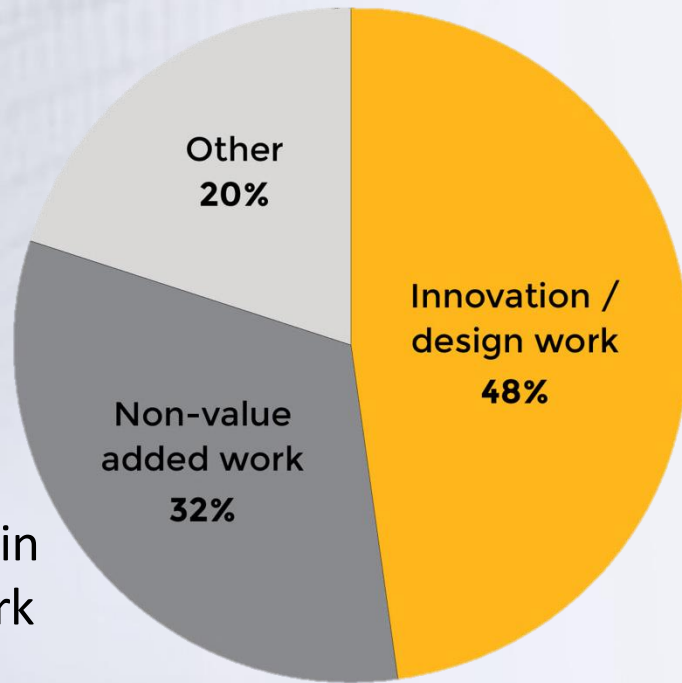
Arm-Chair



FE Analysis of components



Hidden Risks of “The way we’ve always done things”



Engineers spend
1/3rd of their time in
non-value add work

Source - <https://tech-clarity.com/documents/Tech-Clarity-Perspective-DDAa.pdf>

What DT is not is just using digital technology to merely digitize or automate **existing processes and products**.

Done right, DT calls companies to focus on the value and products that will be needed/possible in the future as the world changes and then **reinvent their business processes**, **culture**, and **customer experiences** to meet those changing business and marketplace requirements.

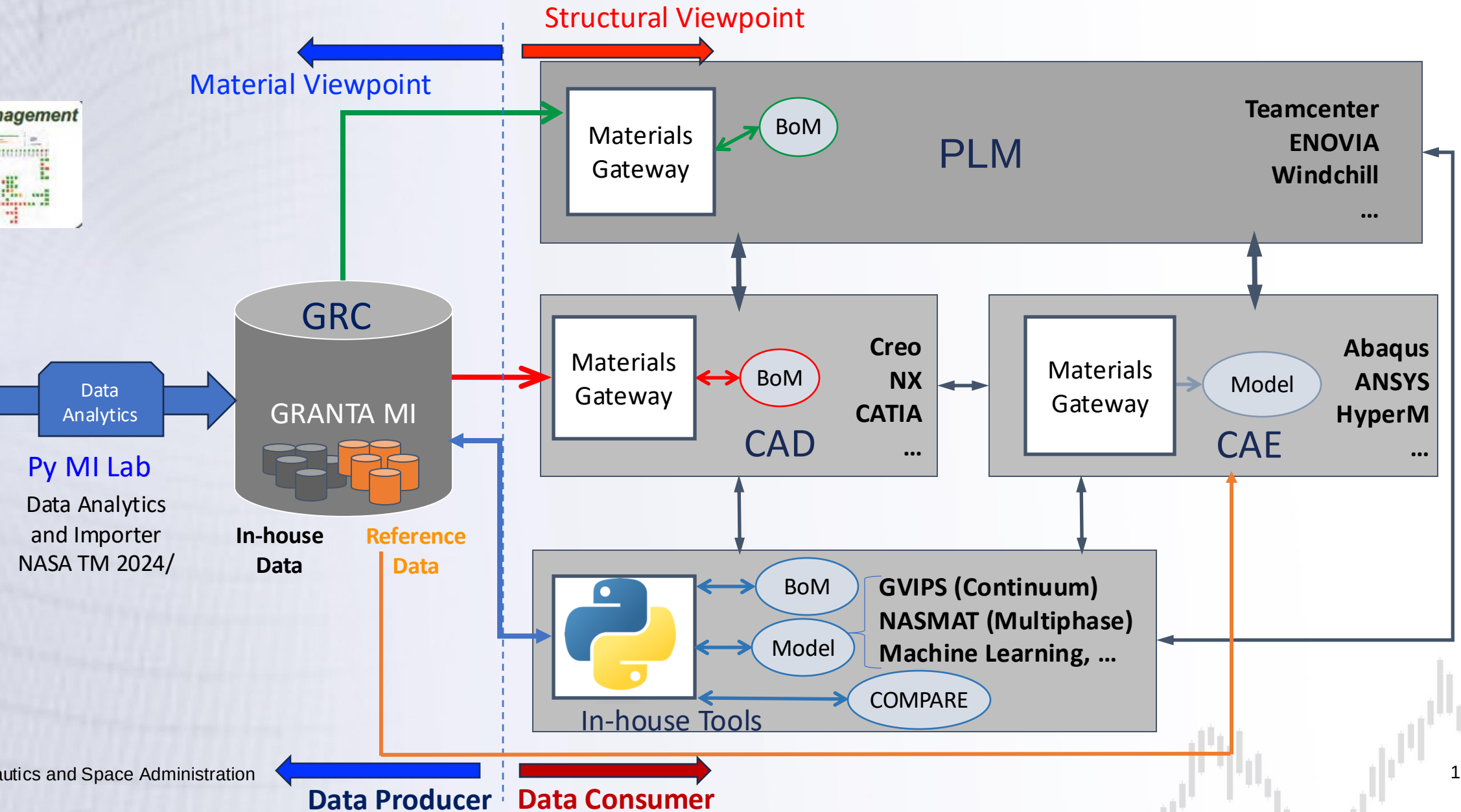
Digital Transformation at NASA and Why It Matters!

By Jill Marlowe, NASA Digital Transformation Officer, NASA Headquarters

Engineering Community is fully behind DT
AIAA Digital Twin: Ref Model, Realization... ;
AIAA Digital Thread: Definition, Value and Ref Model



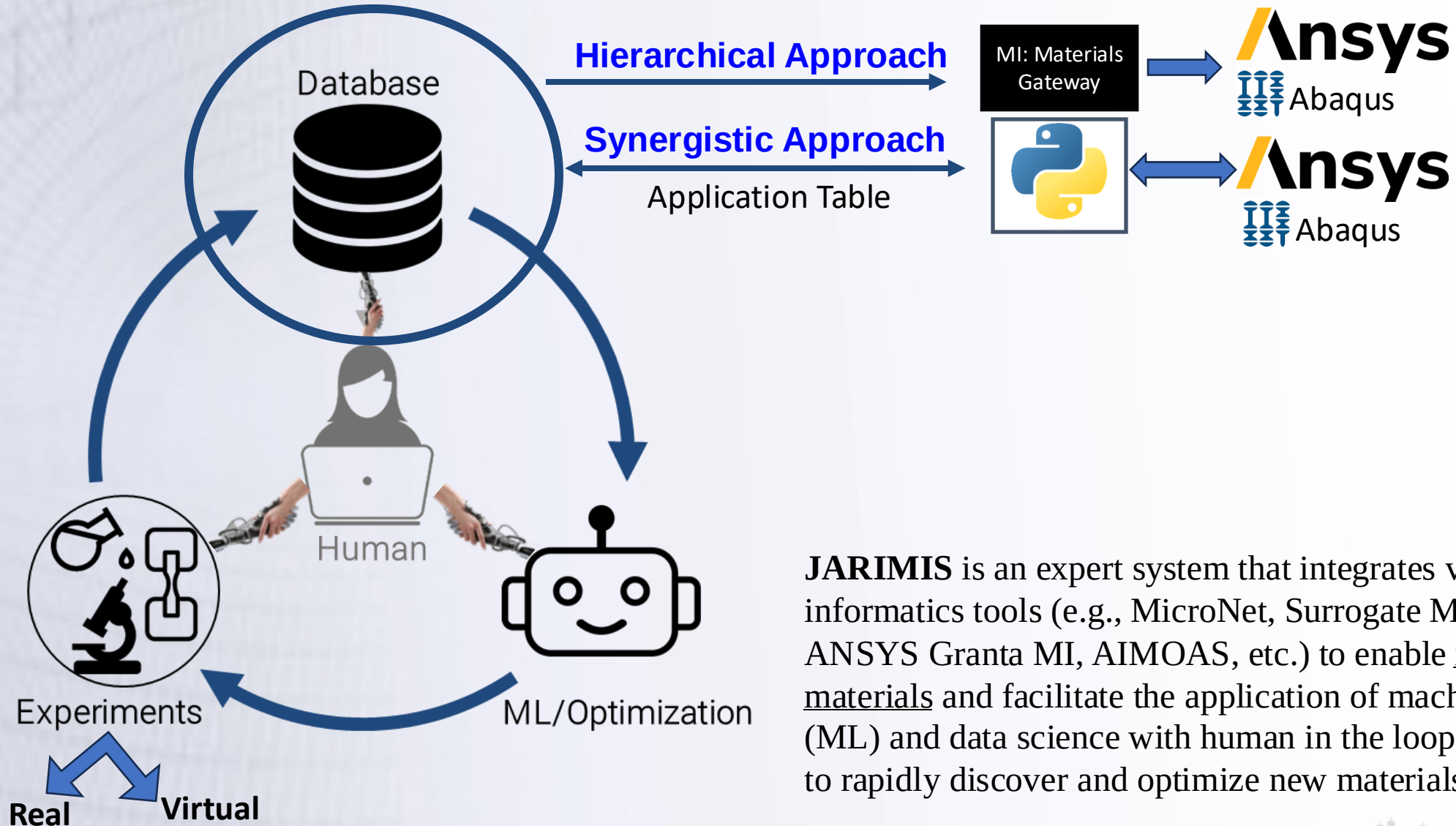
Structural Engineers Benefit From Linkage Between MLM and Engineering Application Software



T³

JARIMIS

Just a Rather Intelligent Materials Interrogation System



JARIMIS is an expert system that integrates various materials informatics tools (e.g., MicroNet, Surrogate ML models, ANSYS Granta MI, AIMOAS, etc.) to enable inverse design of materials and facilitate the application of machine learning (ML) and data science with human in the loop decision making to rapidly discover and optimize new materials

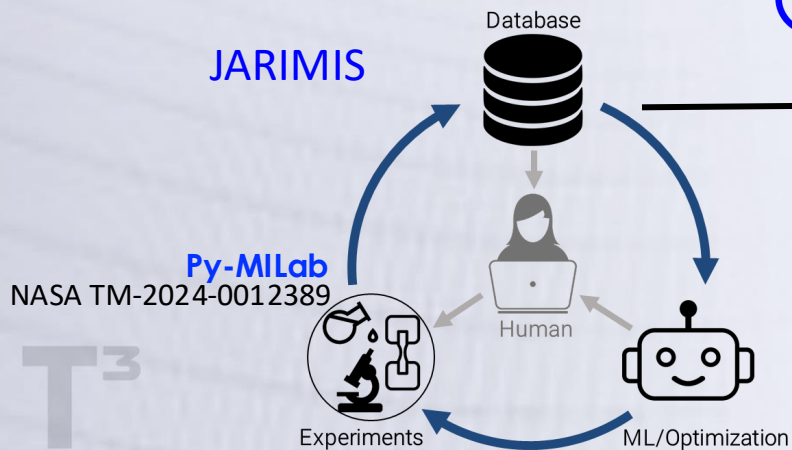
Information Management Essential For Fit-For-Purpose Material Design



Established Data Schema for ICME that Enables Linkage of Test Data with Simulation Data at Different Length Scales:

- Required establishment of Material Pedigree, Manufacturing, Microstructure, Model Pedigree, and Software Tools Tables within Granta MI
- Digital Thread / Digital Twin
- Seven key **accomplishments**

Additive Manufacturing
ICMAMS 2023, Aug 9, 2023

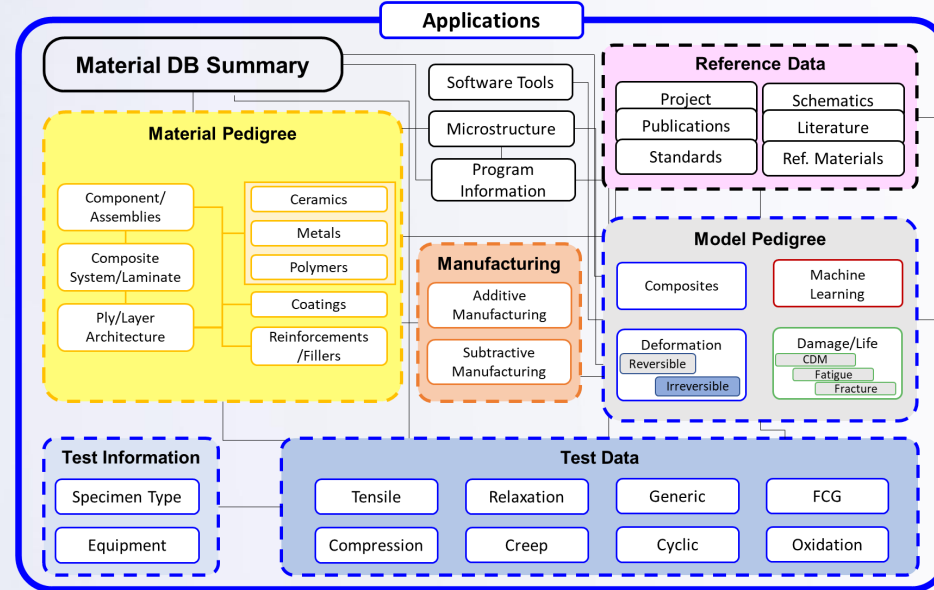


Py-MILab
NASA TM-2024-0012389

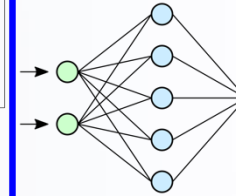


National Aeronautics and Space Administration

Application Table NASA TM-2022-00184033

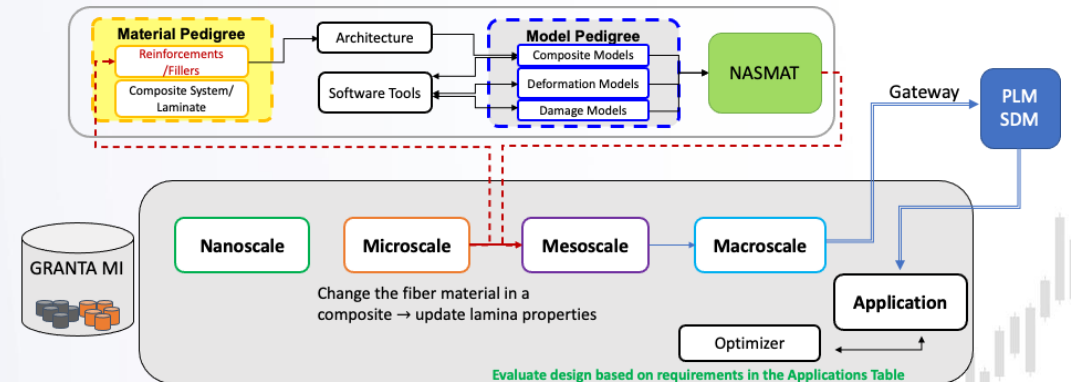


**NASA GRC ICME Schema:
Executive Summary**
NASA TM-2023-0018337



Machine Learning Table
NASA TM-2022-0017137

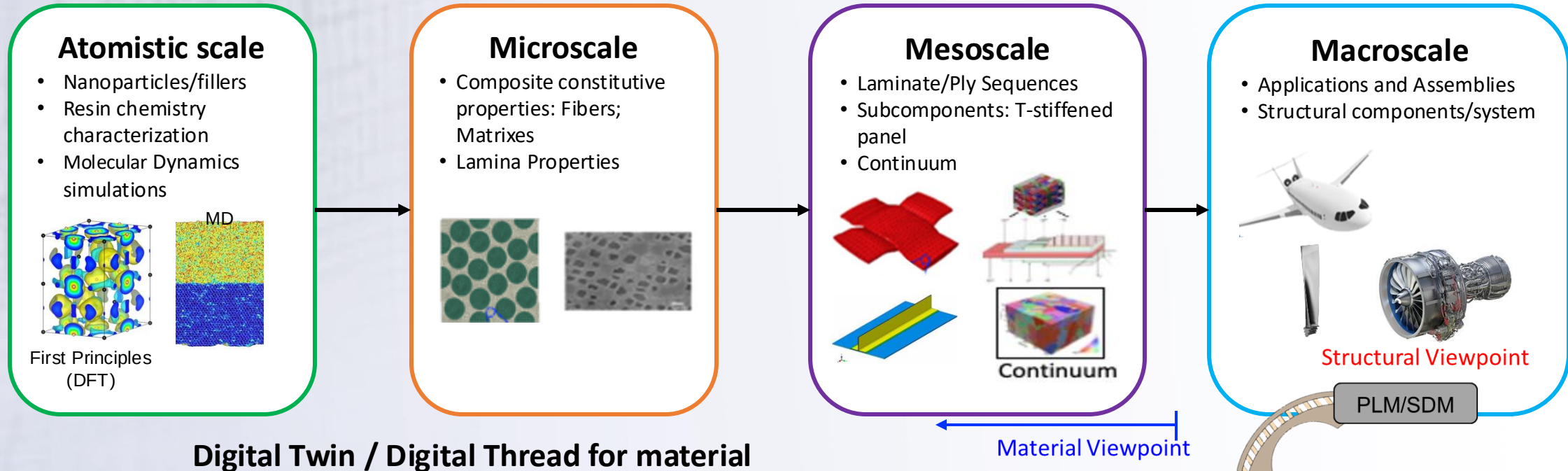
**AIMAOS: Automated Information
Management Across Organizations and Scales**
(Digital Thread Manager)



(TMS ICME, May 21, 2023)

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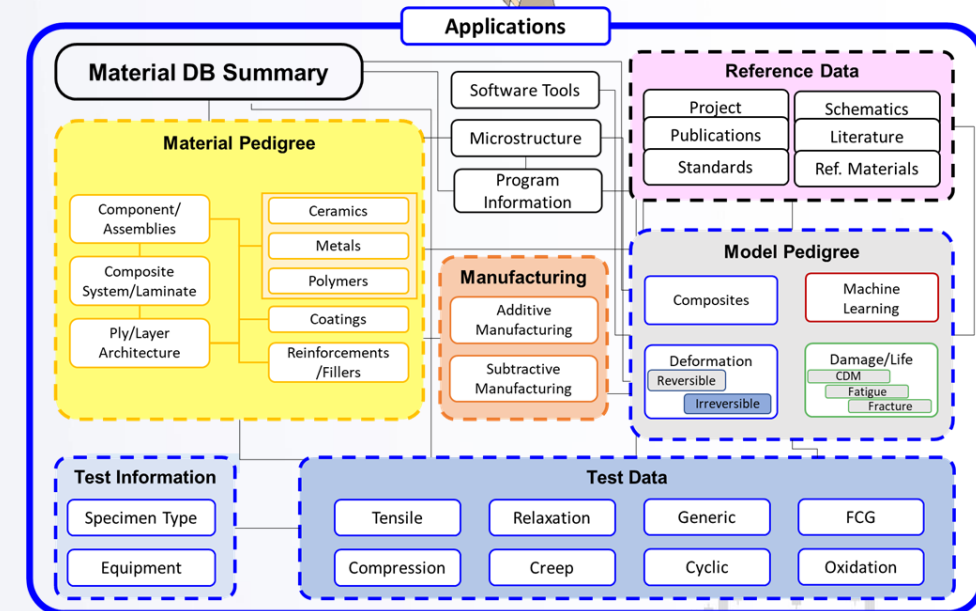
Multiscale Information Management for ICME Focus



Digital Twin / Digital Thread for material

Recently published **NASA GRC ICME Schema: An Executive Summary** (NASA TM-2023-0018337)

- To-date detailed summary on NASA GRC's efforts for effective data management towards Vision 2040
- Offers new users a starting point for effective materials information management
- Summary of database tools developed at GRC

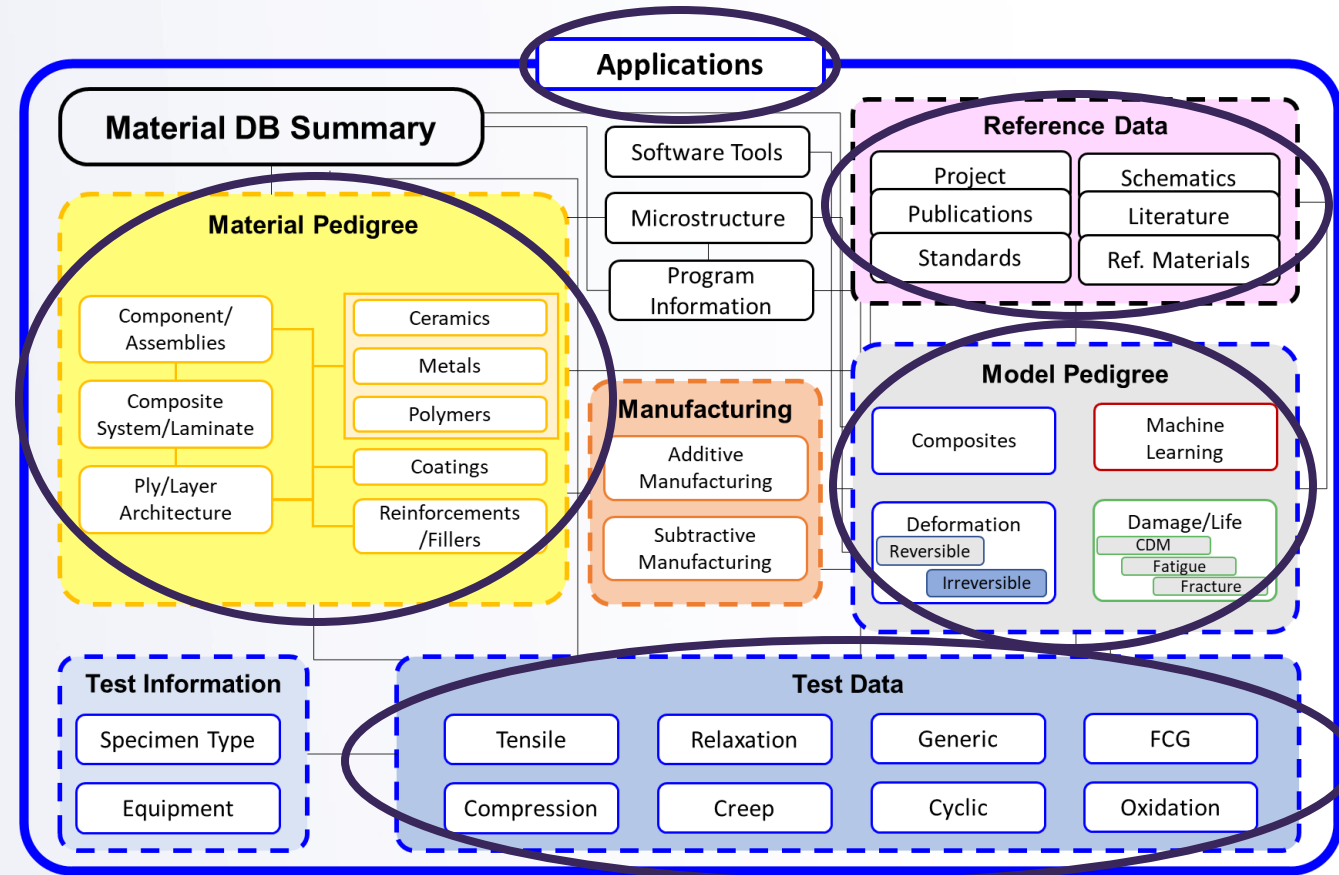


NASA GRC ICME Schema: An Executive Summary



NASA TM-2023-0018337

- Developed the NASA GRC ICME Schema within the Granta MI Material Information Management Platform
 - Material Pedigree:** Store material source information, properties, etc.
 - Test Data/Statistical Data:** Store in-house experimental data and summarize into material properties
 - Model Pedigree:** Store material models developed from experimental and virtual data (machine learning)
 - Reference Data:** Store references, literature data, virtual data, etc.
 - Application Table:** Link material models to parts for digital thread maintenance



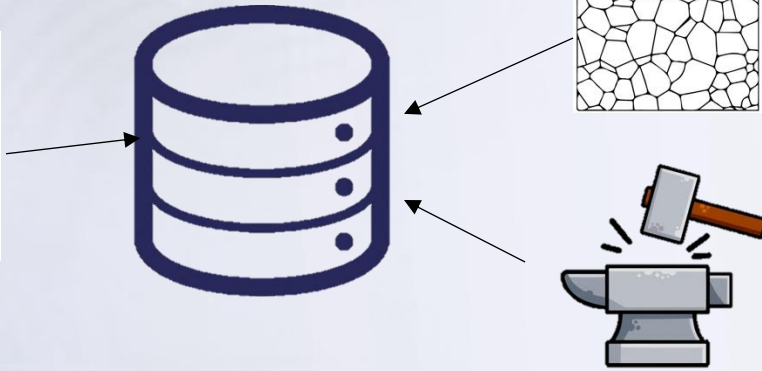
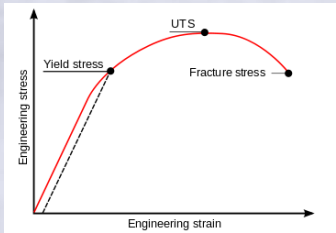
Schema documented in the NASA GRC
ICME Schema: An Executive Summary
NASA TM-2023-0018337

Database Best Practices and Philosophy are Critical to Effective Materials Lifecycle Management



Capture

- Capture data beyond point-wise properties (curves, pedigree information, microstructure, etc.) and from multiple locations



Maintain

- Ensure traceability between material pedigree, test data, developed models, and application
- Cope with changing data, people, and environments
- Avoid duplication of data to reduce the risk that the digital thread is compromised



Analyze

- Ensure quality of data reduction or analysis by maintaining full pedigree information
- Easily enable addition of new data through automatic processing and analysis



Disseminate

- Ensure data is easily findable and reusable to prevent duplication of data creation
- Scalability, robustness, security across enterprises
- Get data to the right people, at the right time, in the right format, at the right scale



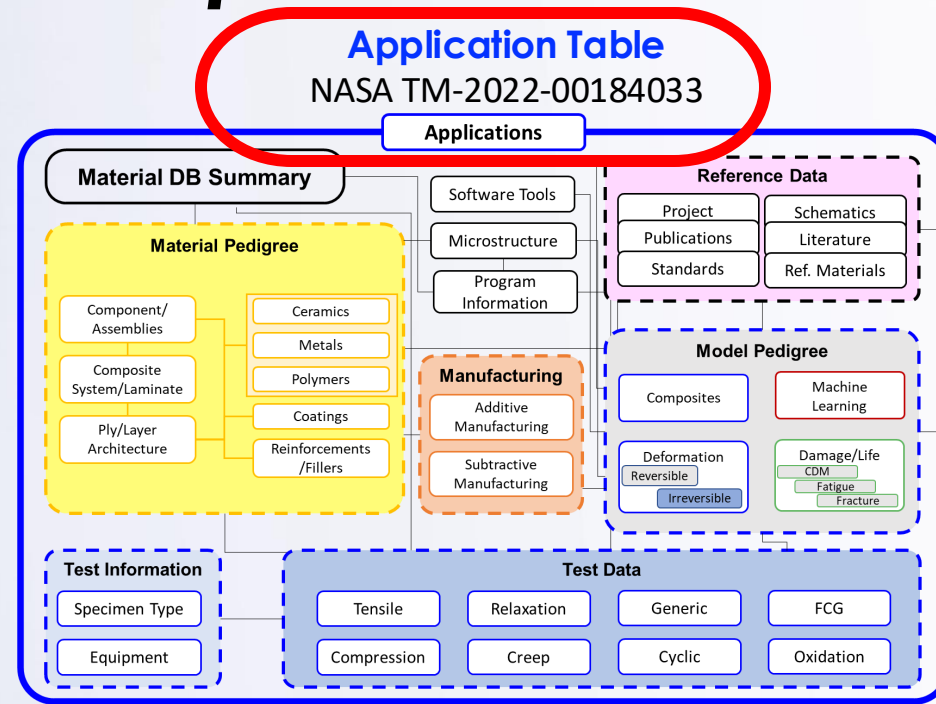
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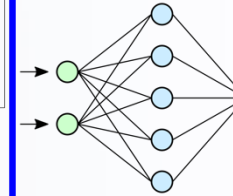
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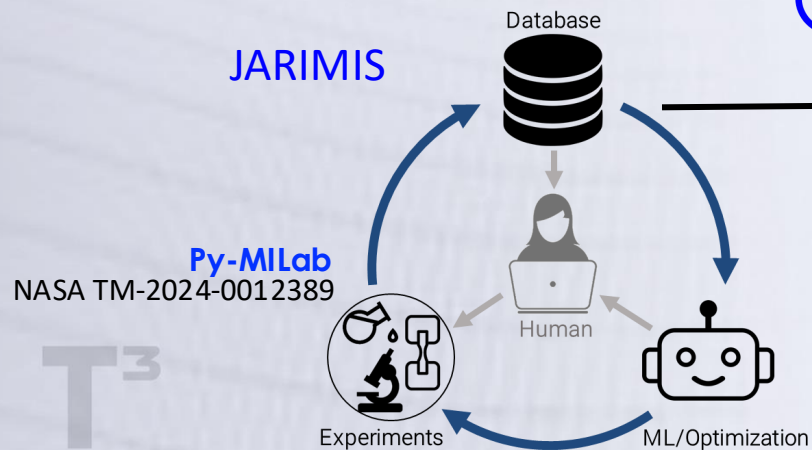
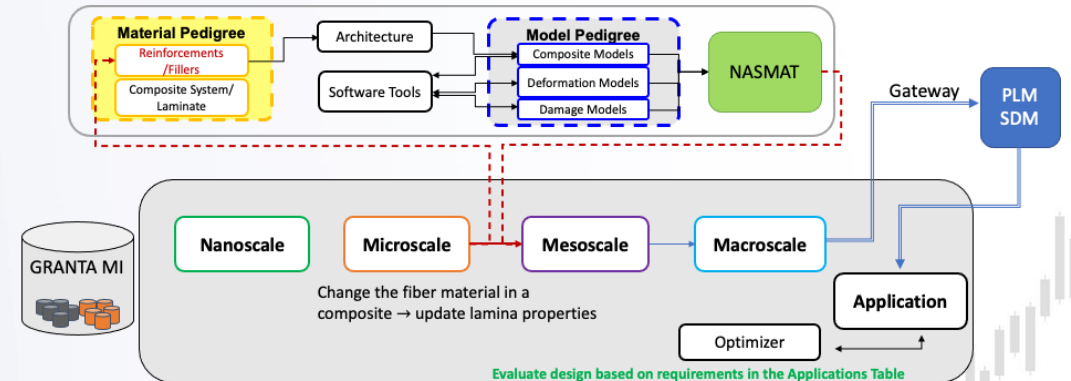


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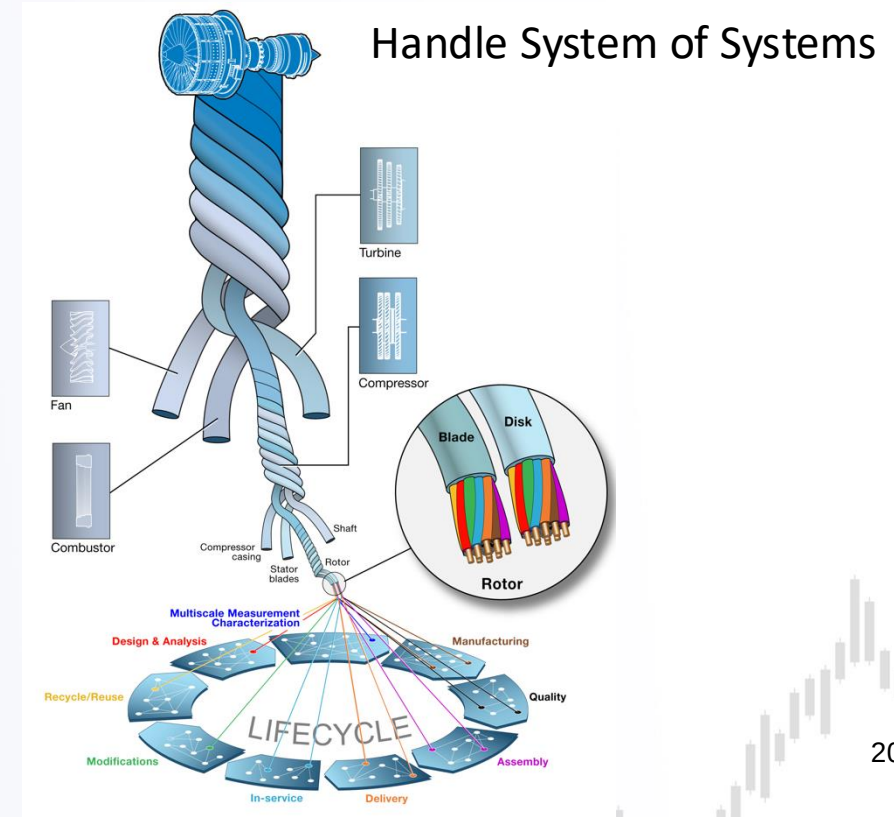
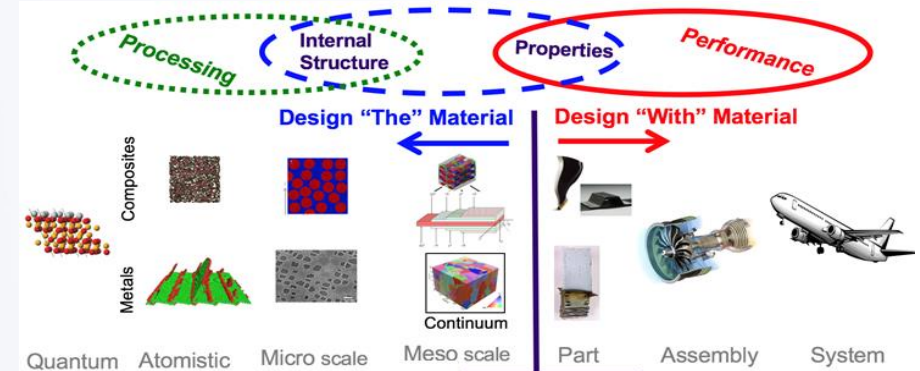
National Aeronautics and Space Administration

(TMS ICME, May 21, 2023)

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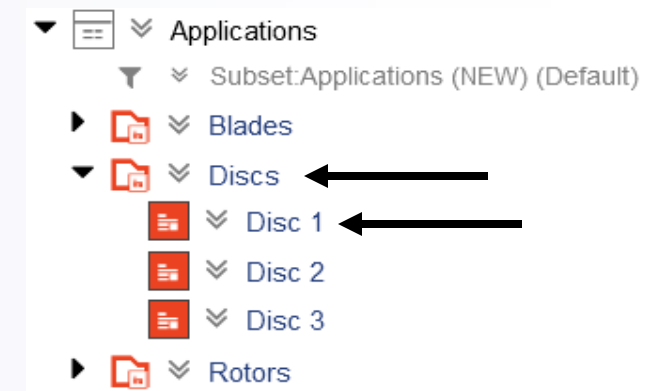
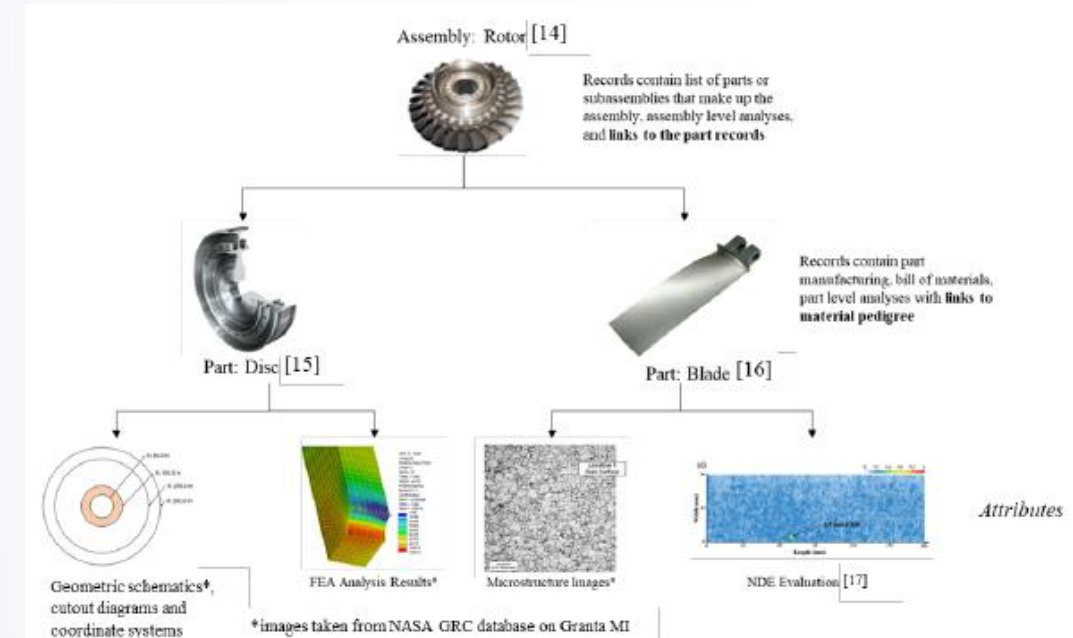
Application Table: Bridging the Gap Between Material Science and Structural Engineering

- The **Application Table** is the intended “bridge” between “**Designing the Material**” and “**Designing with the Material**” and is the “**brains**” for ICME
 - Orchestrates the ICME Process
- Enables unique location to link CAD/PLM/SDM information to materials information as well as **BOM**
- Provide information (application requirements) that can be used to drive the design and manufacture of “fit-for-purpose” materials
- Provides spatial and temporal information on application microstructure, residuals, damage, etc.
 - Maintenance of the **Digital Thread**



Demonstration Through Example: Rotor Assembly

- Rotor Assembly
 - Define *Application Table* records for **parts** (e.g., disc, blade), and **assemblies** (e.g., rotor), where the part records are *linked* to the assembly records
- General Folder Organization
 - Each application has a **generic record** that contains typical requirements, approved materials, etc. for the application *in general*
 - Use this information in the early stages of design
 - **Records within** each generic record relate to specific applications/parts to be produced
 - Use this record as a part of the **digital thread** for the actual part



Application Table Orchestrates ICME By Linking Processing, Microstructure, Properties, and Performance



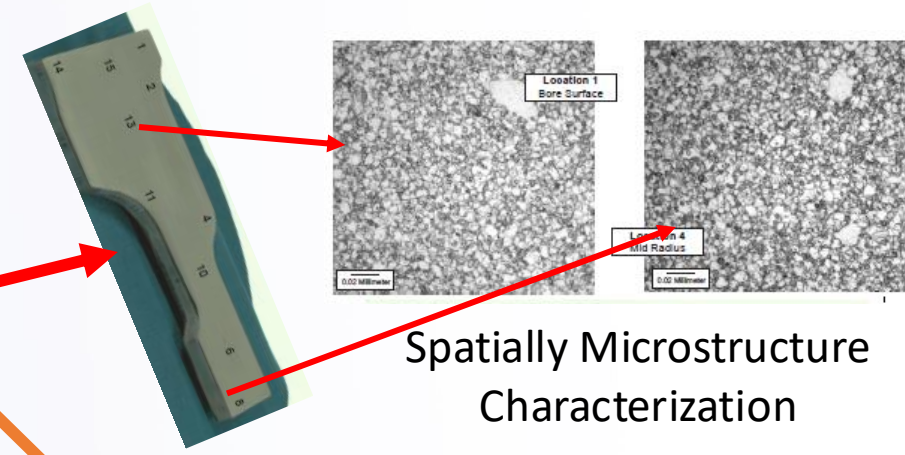
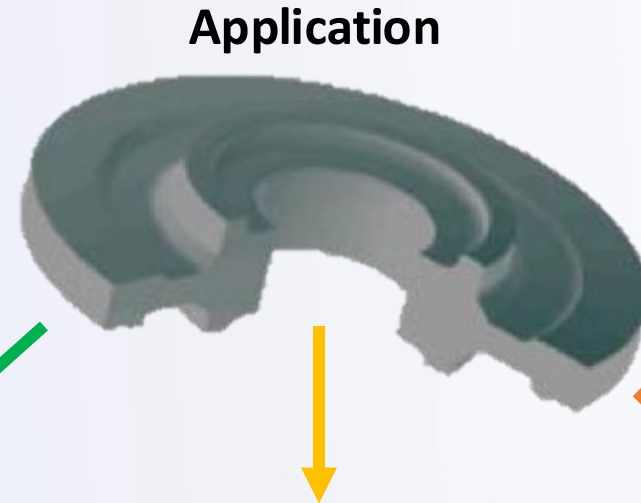
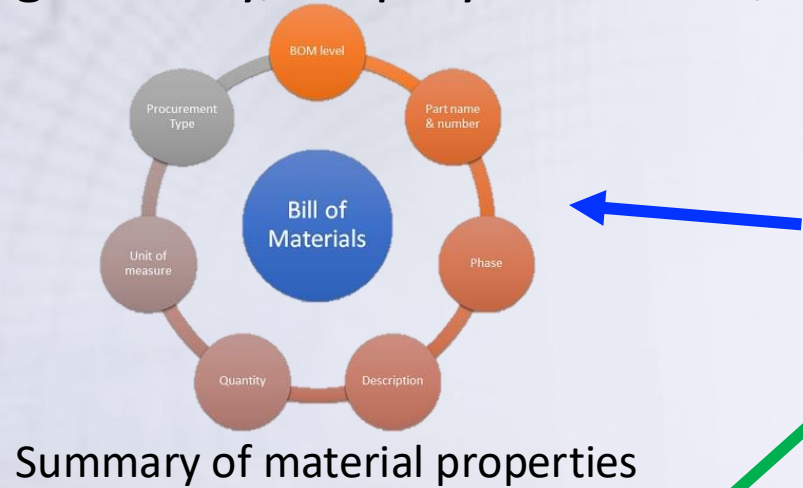
- Attributes and Layout defined to handle any type of application or requirements
 - Nine major categories specified with associated attributes
 - Associated requirements are dispersed throughout three major category (Geometric, Performance, Material)
 - Can be application-based or spatial (allow definition of design points)
 - Contains evaluation criteria (analysis performed and results)
 - Scorecards and Readiness Levels for the requirements
- Granta MI Tabular attribute type used extensively due to its flexibility and generality
 - Significant number of additional attributes associated with each column of a tabular attribute
 - Each row can represent different specifications

Attribute	Type	Attribute	Type
General Information		Analyses Performed	
Application Name	STXT	Analyses Performed	TABL
Application Description	LTXT	Analyses Performed (Subcomponents)	TABL
Data Ownership	DCT	Analyses Profiles	TABL
Data Ownership (Other)	STXT	Load Profiles	TABL
Distribution Category	DCT	Analyses Range Definitions	TABL
Funding Organization	STXT	Failure Mechanism/Modes	
Performing Organization	STXT	Failure Mode and Effect Analysis	TABL
Project Name	STXT	Material Selection	
Project Code	STXT	Material Requirements*	TABL
Project Notes	LTXT	Part List	TABL
Point of Contact	TABL	Bill of Materials*	TABL
Geometric/Manufacturing Requirements		Software Tools Used**	TABL
Owner Information	TABL	Selection Criteria	FILE
Surface Area	RNG	Property File	FILE
Volume	RNG	Material Selection Assumptions	LTXT
Bounding Box Dimensions	LTXT	Inspection	
CAD/CAE Link	HYP	Inspectability Notes	LTXT
Manufacturing Process	DCT	Evaluator	TABL
Manufacturing Process (Other)	STXT	NDE Method	DCT
Geometric Schematic Time History	TABL	NDE Geometry	TABL
Geometric Description	TABL	Equipment	TABL
Coordinate System Definitions	TABL	Examination	TABL
Design Points / Points of Interest*	TABL	Calibration	TABL
Geometric Notes	LTXT	Testing Parameters	TABL
Manufacturing Requirements*	TABL	NDE Images	TABL
Part Yield	RNG	NDE Comments	LTXT
Surface Treatment	DCT	NDE Information	FILE
Manufacturing Notes	LTXT	Scorecards	
Microstructure Profile	TABL	Requirements Scorecard*	TABL
Performance Requirements		Risk Scorecard*	TABL
Weight	RNG	Readiness Levels	
Life	RNG	Technology Readiness Level (TRL)	DCT
Cost	RNG	Manufacturing Readiness Level (MRL)	DCT
Risk	DCT	Integration Readiness Level (IRL)	DCT
Storage Energy	RNG	System Readiness Level (SRL)	DCT
Ultimate Strength	RNG	* Changed with feature request ** Removed with feature request	
Performance Standards*	TABL	DCT	Discrete Text (specified choices)
Mechanical Requirements*	TABL	FILE	Allows the association of any file type to a given record
Thermal Requirements*	TABL	HYP	Hyperlink to a web address
Environmental Requirements*	TABL	IMG	Allows the association of any image format to a given record
Other Performance Requirements*	TABL	LTXT	Long Text Field
Performance Notes	LTXT	PNT	Point Value
Form/Fit/Function Notes	LTXT	RNG	Range Variable
		STXT	Short Text Field
		TABL	Tabular Attribute



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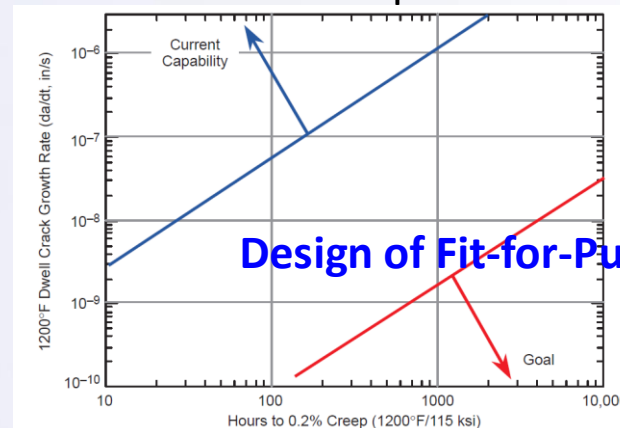
- Application Table links part requirements, microstructure information, material properties, geometry, employed models, relevant analysis, and performance



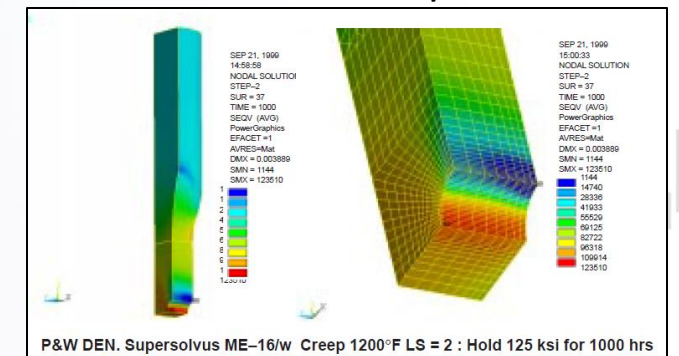
Part Geometry

Assembly	Designed Schematic	Designed Measurements/Tolerances
D1		Inner Radius = 86.0 in +/- 0.005 in Outer Radius = 101.5 in +/- 0.05 in
D1		Inner Radius = 290.0 in +/- 0.05 in Outer Radius = 302.0 in +/- 0.01 in

Performance Requirements



Summary of Relevant Analyses with Links to PLM/SDM



Scorecards/Readiness Levels



- The Scorecards header give a summary of the status of every requirement for the given application

Requirement Type	Requirement Name	Component / Zone	Design Point 1	Design Point 2	Design Point 3	Design Point 4	Design Point 5	Design Point 6	Design Point 7
Mechanical	Creep vs Crack Growth	Met	Could apply to the whole part or individual design points						
Mechanical	Safety Factor		5.0	3.5	1.9	1.8	1.7	1.6	1.5
Thermal	Stress vs Temperature	Met	Could be logical (Met/Not Met) or a margin						
Material	Maximum Temperature		Not Met	Not Met	Met	Met	Met	Met	Met

- Final section further summarizes the application through the various readiness levels

- Provide traceability as to why we're at a certain readiness levels from scorecards
- Assess what level we're at

Technology Readiness Level (TRL)	TRL 4
Manufacturing Readiness Level (MRL)	MRL 3
Integration Readiness Level (IRL)	IRL 5
System Readiness Level (SRL)	SRL 3

Integration Readiness Levels

Level	IRL Description
1	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship.
2	There is some level of specificity to characterize the interaction between technologies through their interface.
3	There is compatibility between technologies to orderly and efficiently integrate and interact.
4	There is sufficient detail in the quality and assurance of the integration between technologies.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
6	The integrating technologies can accept, translate, and structure information for its intended application.
7	The integration of technologies has been verified and validated with sufficient detail to be actionable.



Information Management Essential For Fit-For-Purpose Material Design

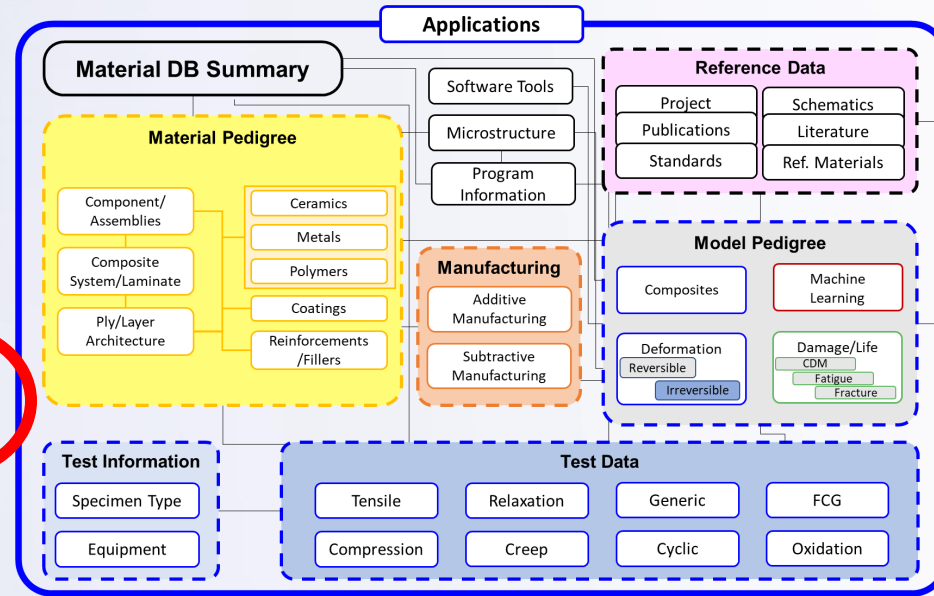


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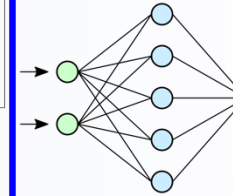
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ICMAMS 2023, Aug 9, 2023

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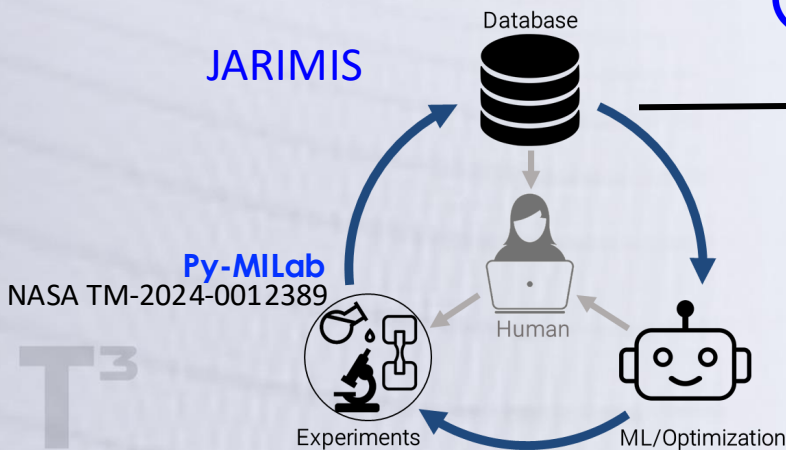
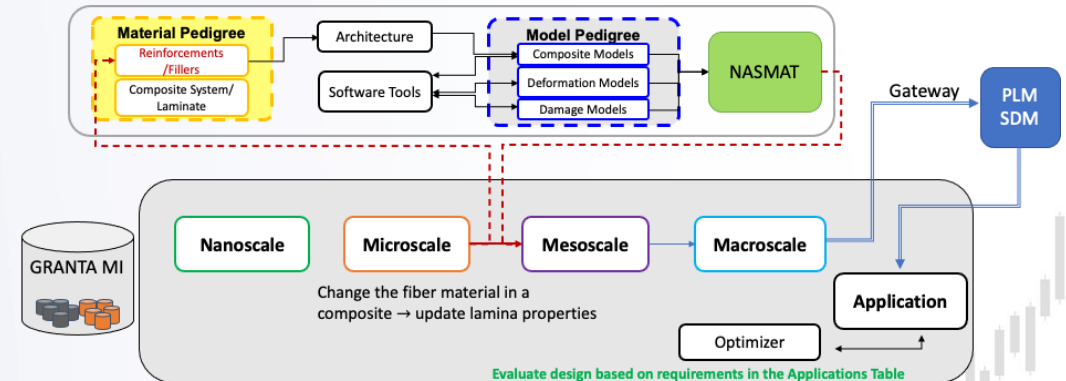


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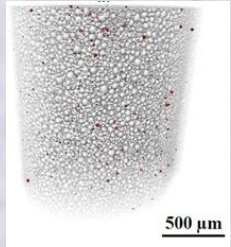
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Extending Pedigree and Application Table to Additive Manufacturing



Example Workflow for Additive Manufacturing

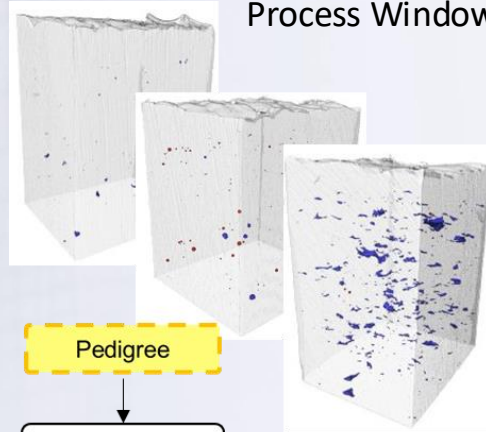
Powder Microstructure Characterization



Pedigree

Microstructure

Perform Multiple Builds to determine Process Window



Pedigree

Microstructure

Define Build Parameters

Manufacturing Process

[Hide table](#)

Method Name	Method Type	Feedstock Type	Parameter	Range	Units	Parameters Used
Laser Powder Bed Fusion	Melt-Based	Powder	Deposition Rate	$12.5 < x < 33.3$	mm ³ /s	15
			Power	$150 < x < 400$	W	280
			Laser Speed	$200 < x < 2000$	mm/s	1200
			Layer Thickness	$25 < x < 65$	μm	30
			Hatch Spacing	$20 < x < 250$	μm	140

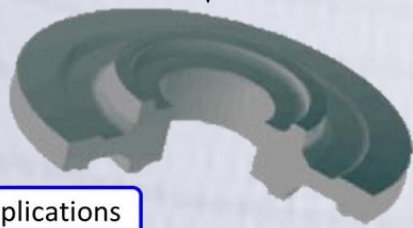
Viewed from Manufacturing Table
Defined for each build record

Manufacturing

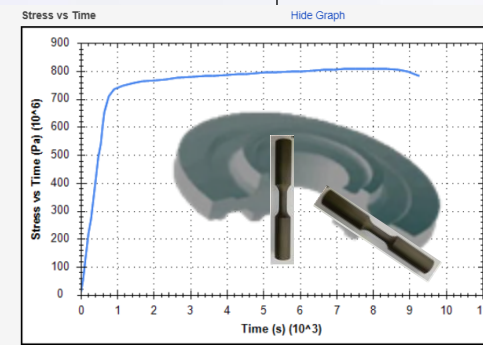
Pedigree

Model Pedigree

Applications



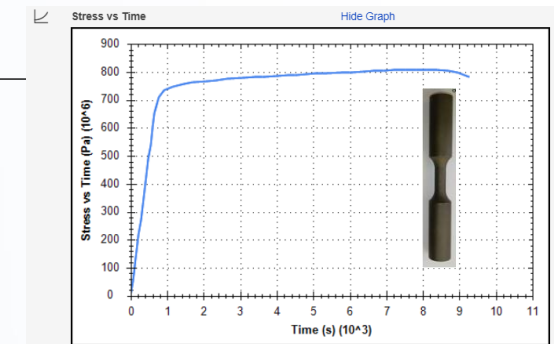
Design Final Part



Design, Build, and Test Witness Articles

Applications

Test Data



Perform Characterization Tests

Test Data

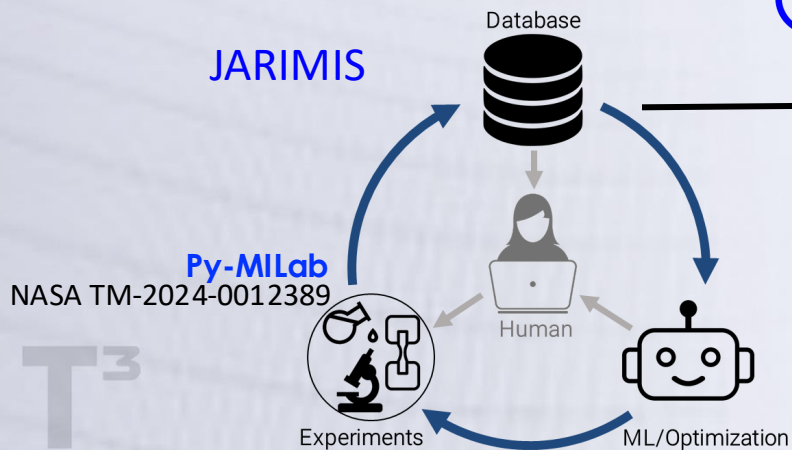
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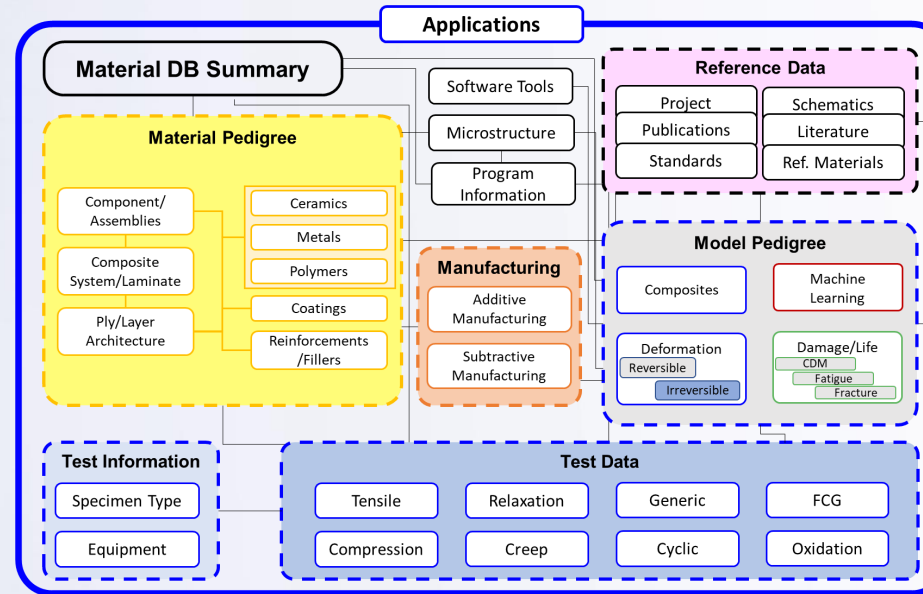


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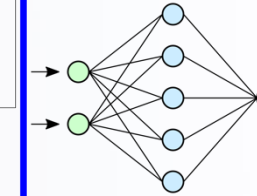


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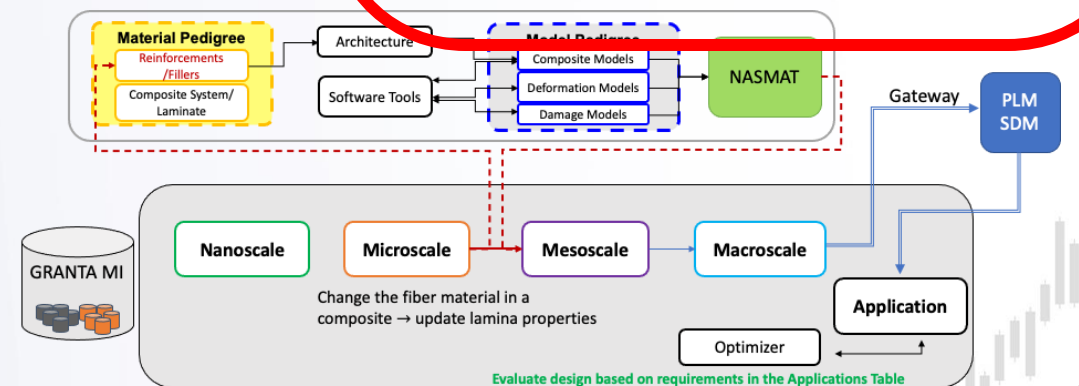


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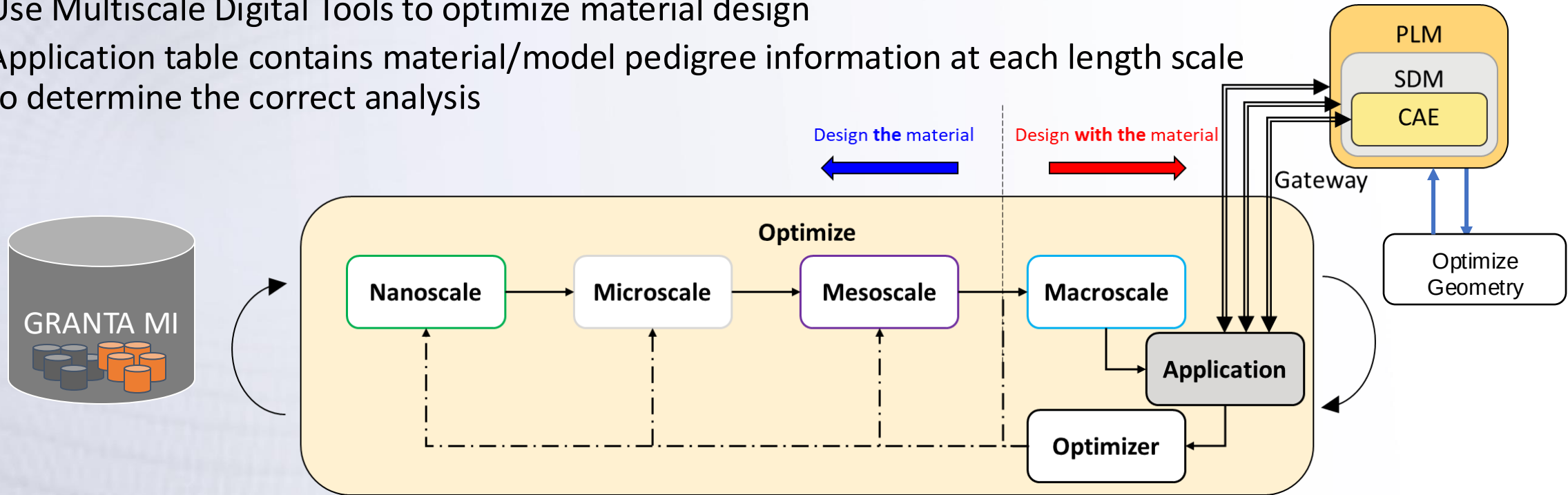
JARIMIS/ Application Table/ AIMAOS Orchestrates ICME Process



- **ICME** Design

Fit-for-Purpose Material Design

- Design the material for a specific application from processing through performance (fit-for-purpose)
- Use Multiscale Digital Tools to optimize material design
- Application table contains material/model pedigree information at each length scale to determine the correct analysis



- Re-evaluate the requirements locally with periodic global (structural – PLM/SDM) updates

Remember the two important key words in ICME being

- 1) **Integrated** wherein processing histories, influence internal structure, which in turn drive properties, which then drive performance and
- 2) **Engineering** which signifies industrial utility!

AIMAOS: Digital Thread Maintenance Tool



- **AIMAOS** – **A**utomatic **I**nformation **M**anagement **A**cross **O**rganizations and **S**cales

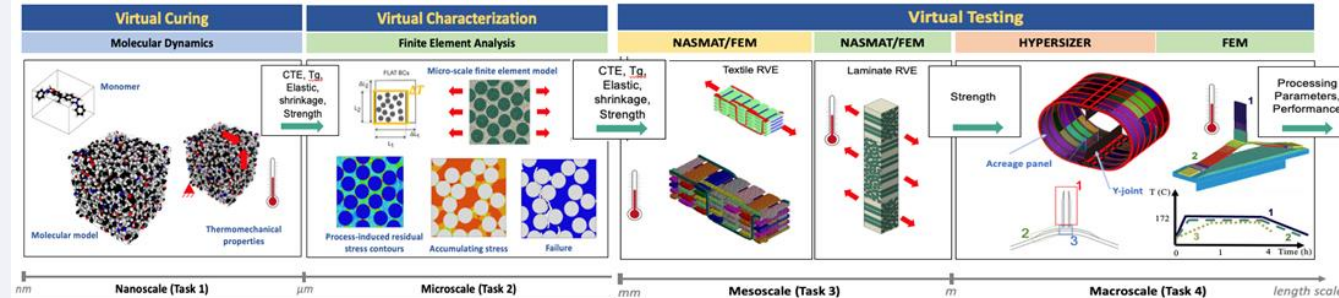
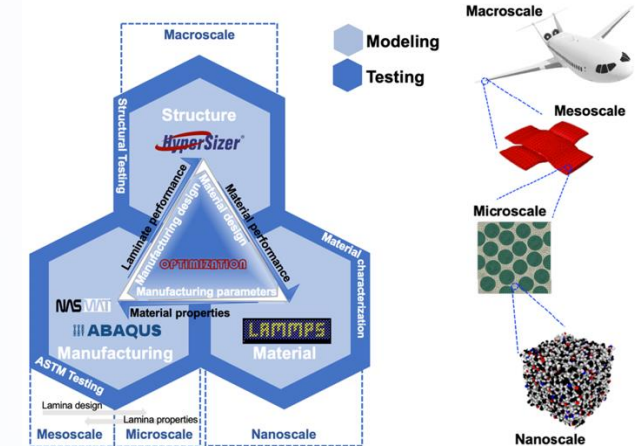
- Digital thread maintenance tool which orchestrates the ICME process through *judicious automation* across organizations and scales

- Motivation

- Benchmark problem will serve to demonstrate the benefits of the ICME)
 - **Digital Twins** at each scale
 - Input/output from each scale will constitute the **digital thread**

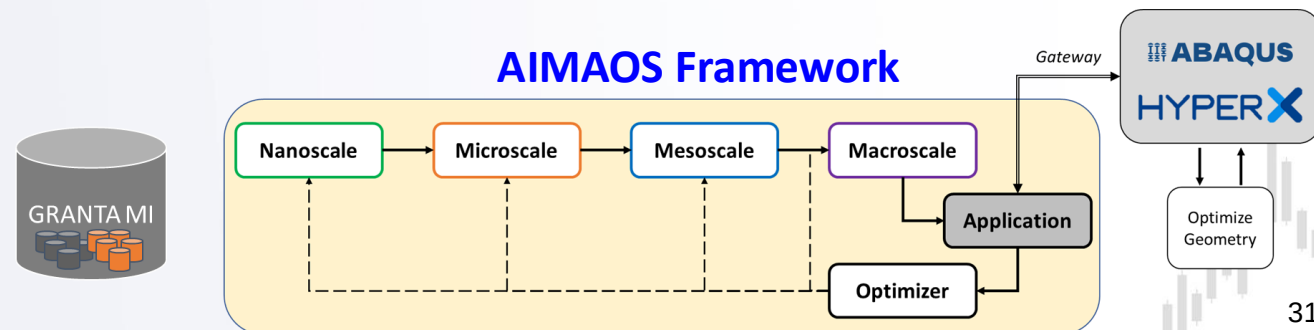
- Won the 2022 AIAA ICME Prize

- 17% manufacturing cost savings for the Y-joint
- 30% weight reduction for the part
- Fuel cost savings of \$1204 per aircraft per year
- Manufacturing cost savings to investment of additional material cost (GNP reinforcement) can produce a ROI 200:1



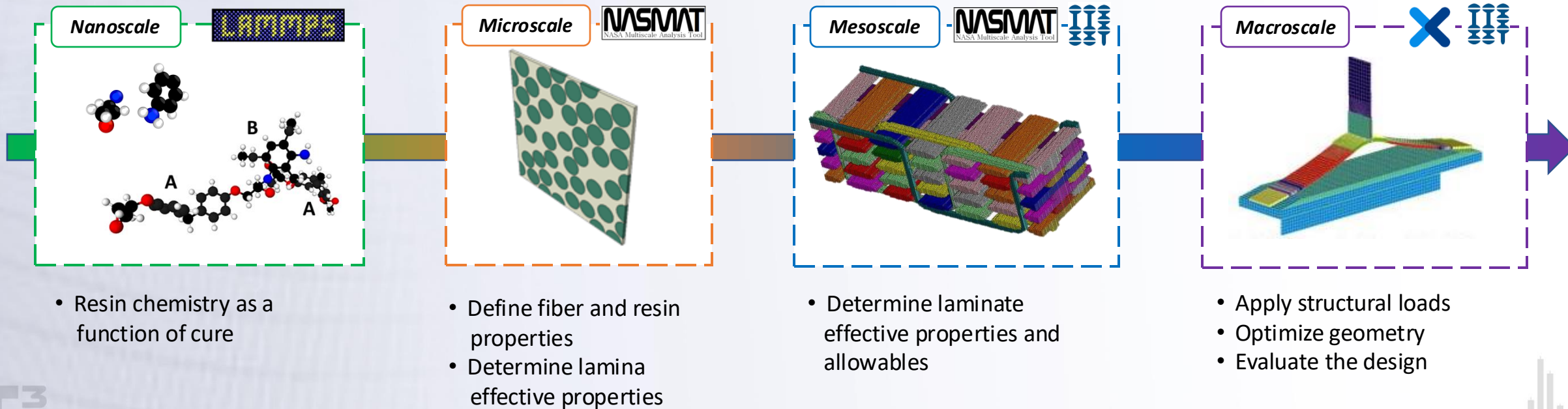
Challenge:

Required **extensive coordination** between team members to pass information across scales and relied on users to **manually track changes** that occurred in the design



AIMAOS Methodology

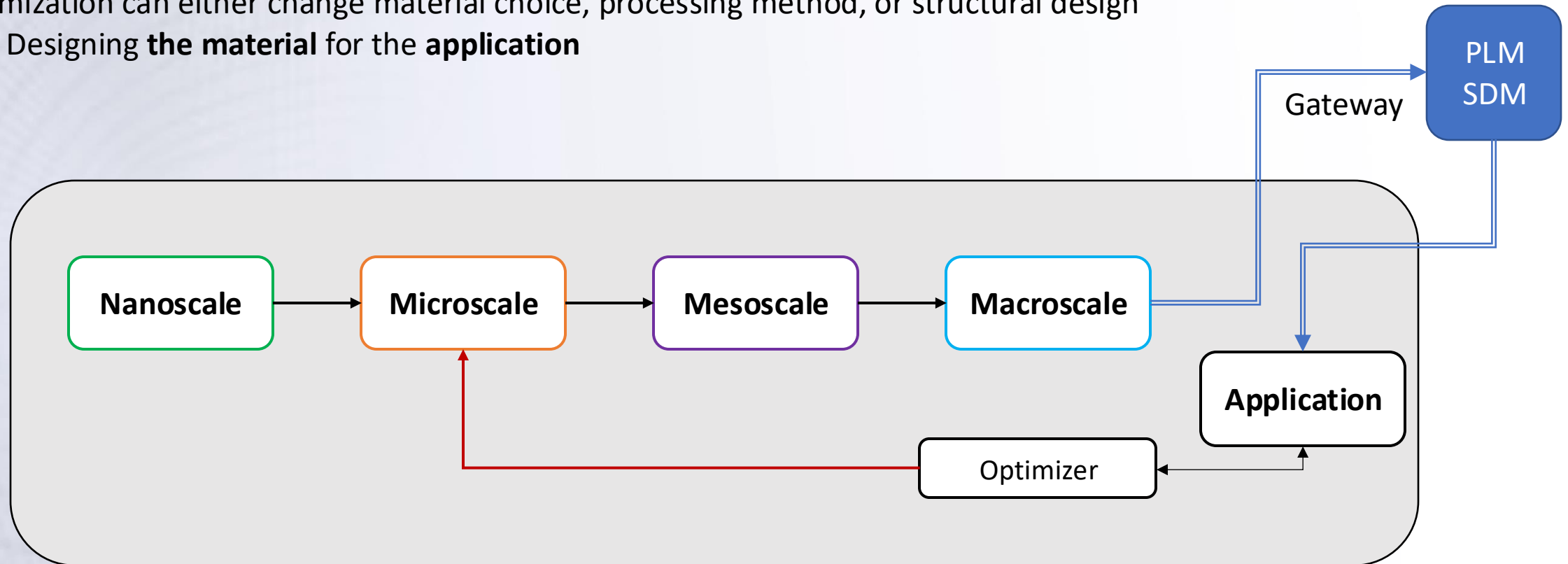
- Create a Python-based tool that can store information, write input decks, and read output decks across the various scales
- Develop a GUI so users can easily navigate through the different scales as changes occur and
- Store **digital twins** at each scale as input/output decks between tool sets
- Establish minimum metadata to describe a **digital twin** and distinguish from a **digital representation** as time evolves



ALMAOS assists Digital Thread Management in ICME



- Consider changing the material characteristics at lower scales
- Optimization can either change material choice, processing method, or structural design
 - Designing **the material** for the **application**

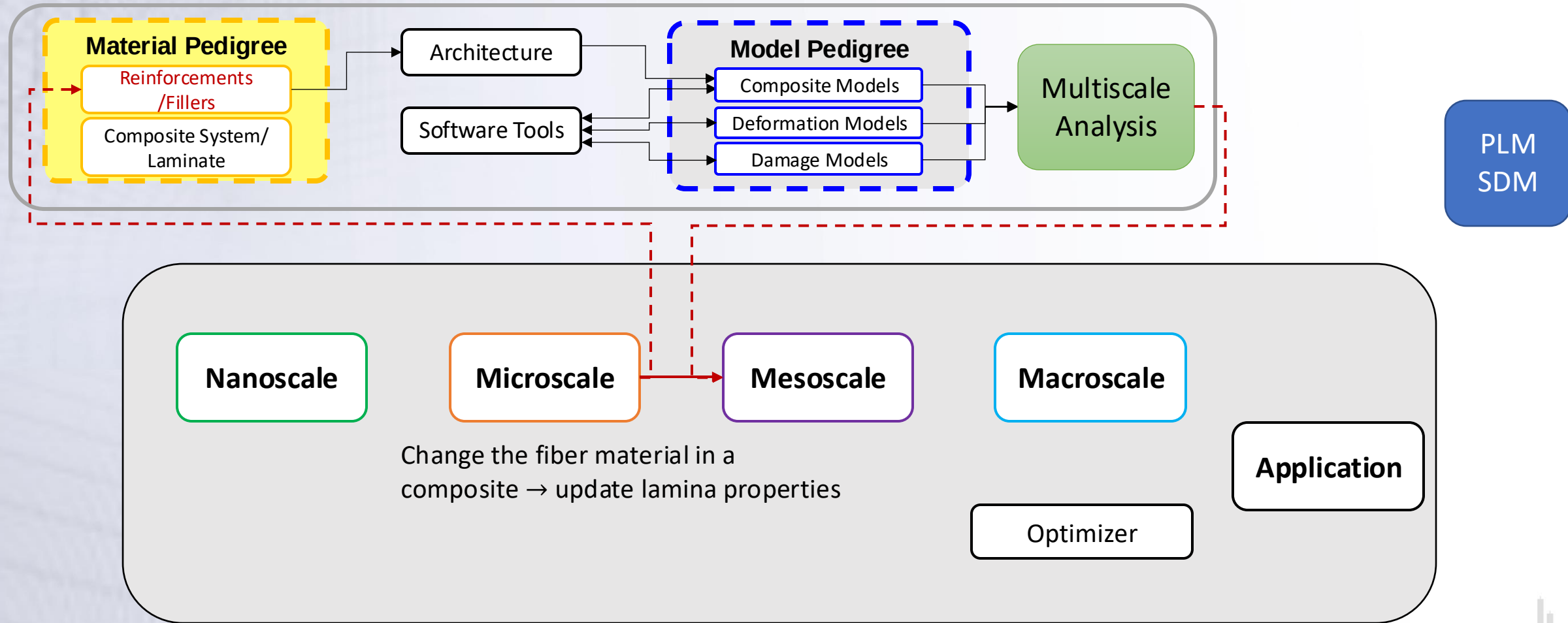


Illustrate with Example in which the **fiber reinforcement of a composite material** used for a structural component is varied

ALMAOS assists Digital Thread Management in ICME



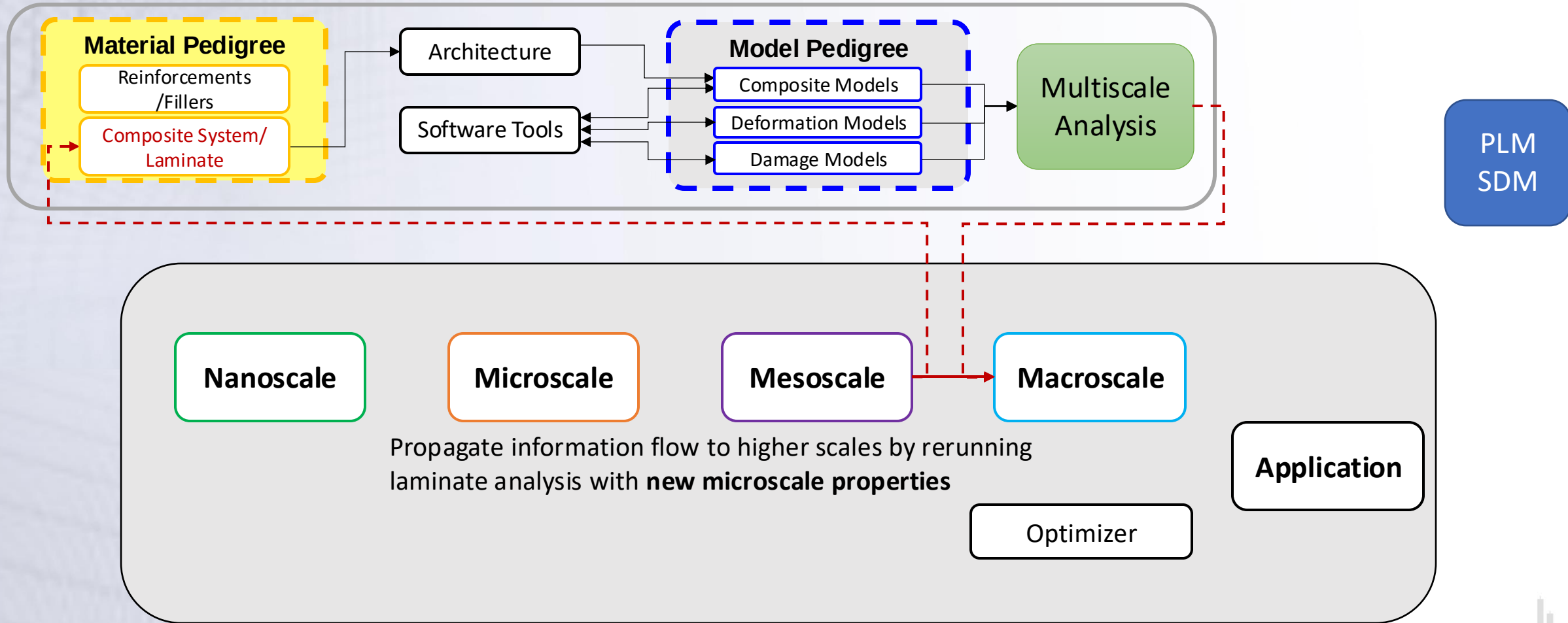
Automation of read/write and tool execution in background



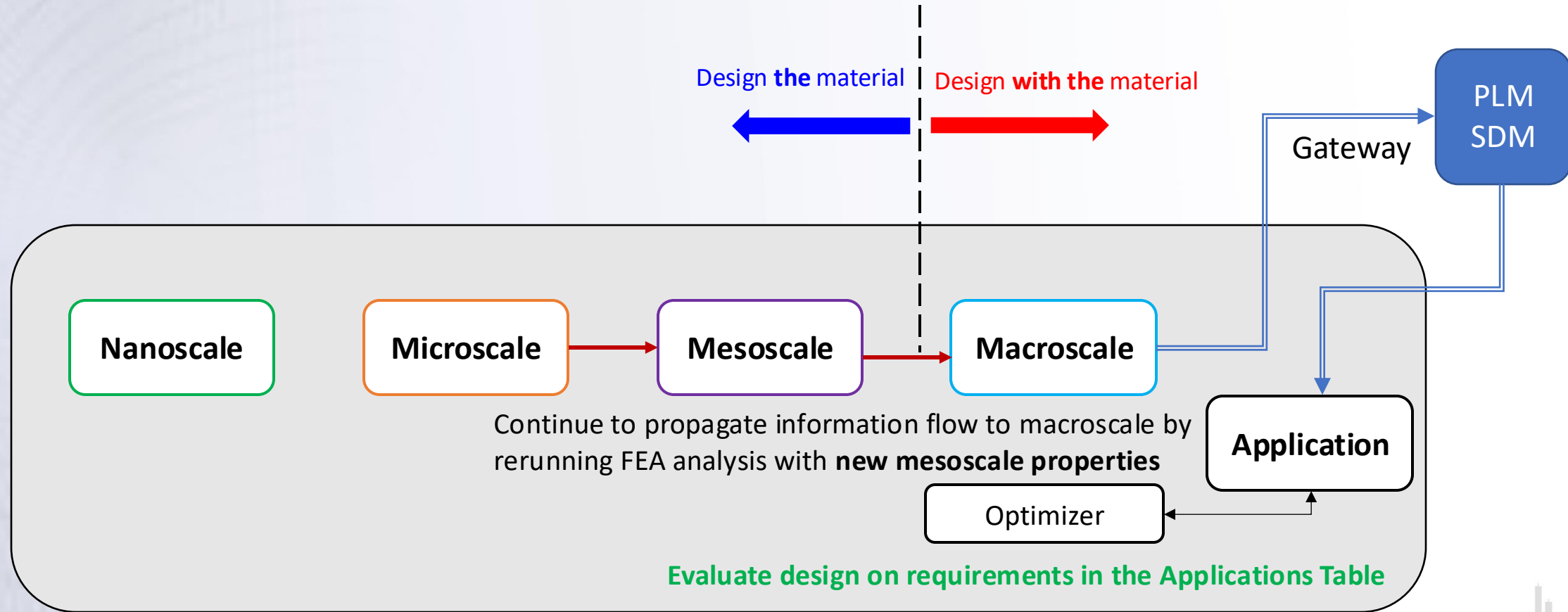
AIMAOS assists Digital Thread Management in ICME



Automation of read/write and tool execution in background



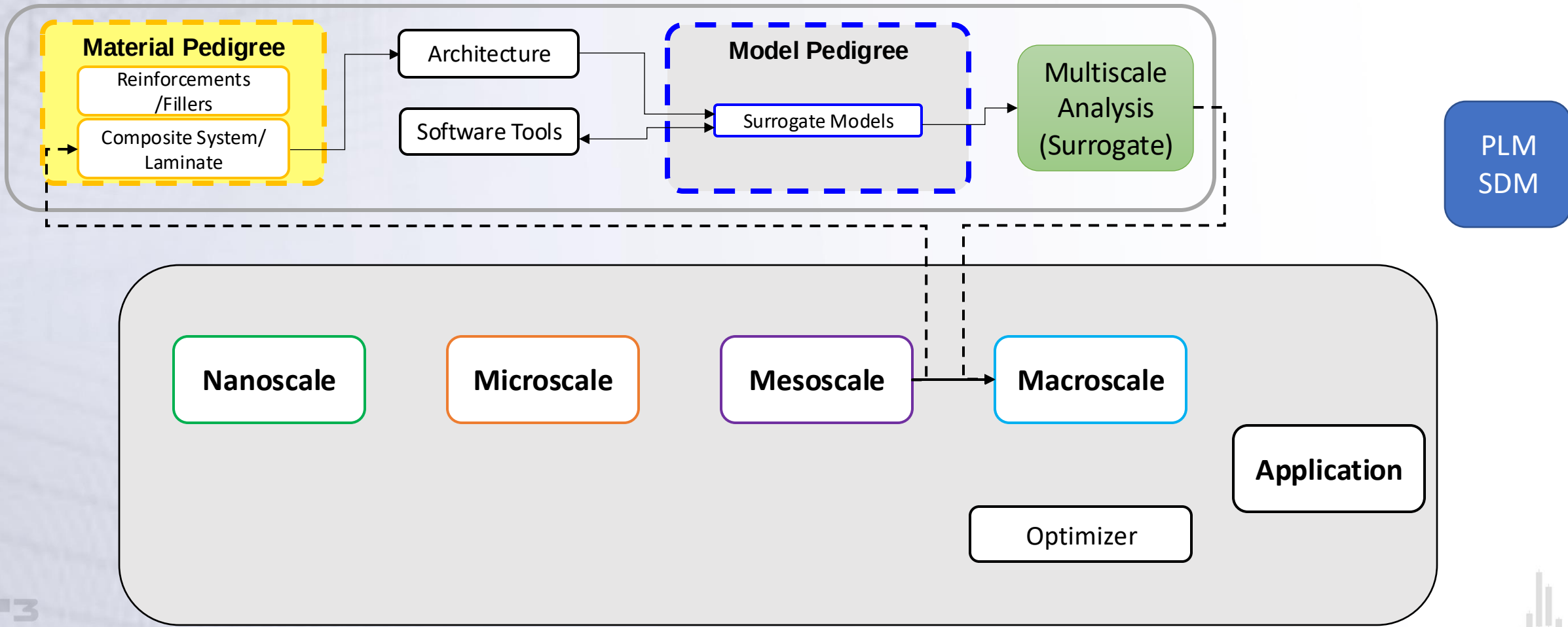
ALMAOS assists Digital Thread Management in ICME



Database/Simulation Management in ICME



Enhancing optimization and design speed by replacing physics-based models with **surrogate models** developed using **machine learning** at **any scale**



Information Management Essential For Fit-For-Purpose Material Design



Established Data Schema for ICME that Enables Linkage of Test Data with Simulation Data at Different Length Scales:

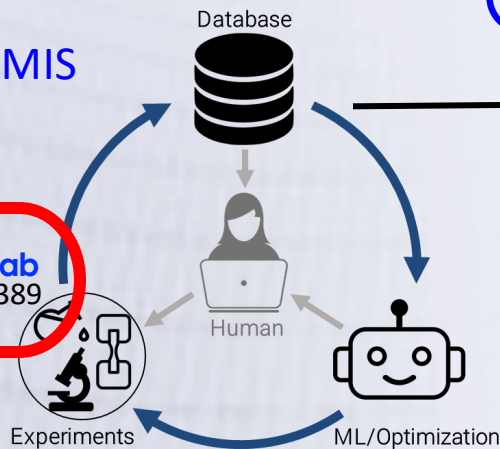
- Required establishment of Material Pedigree, Manufacturing, Microstructure, Model Pedigree, and Software Tools Tables within Granta MI
- Digital Thread / Digital Twin
- Seven key **accomplishments**

Additive Manufacturing
ICMAMS 2023, Aug 9, 2023

JARIMIS

Py-MILab

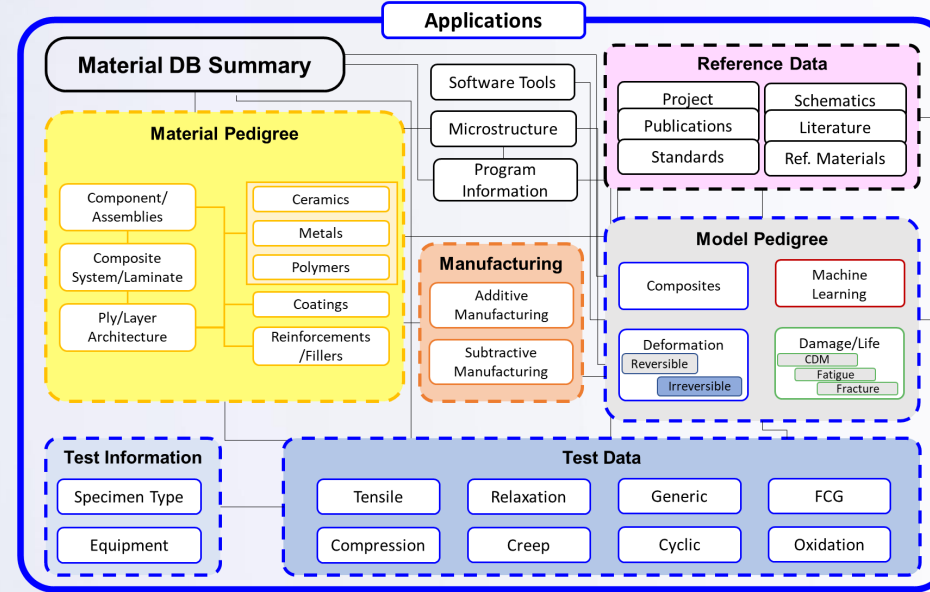
NASA TM-2024-0012389



National Aeronautics and Space Administration

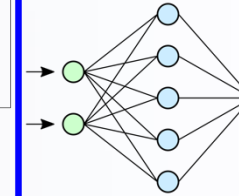
Application Table

NASA TM-2022-00184033



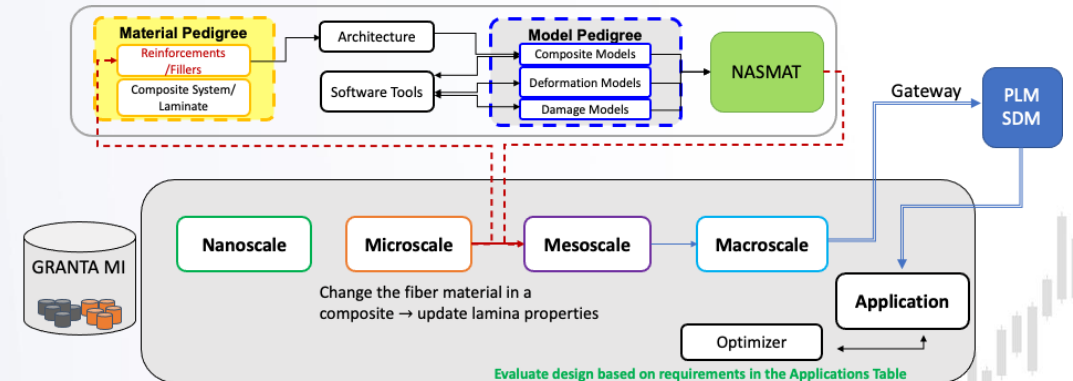
NASA GRC ICME Schema: Executive Summary

NASA TM-2023-0018337



Machine Learning Table
NASA TM-2022-0017137

AIMAOS: Automated Information Management Across Organizations and Scales
(Digital Thread Manager)

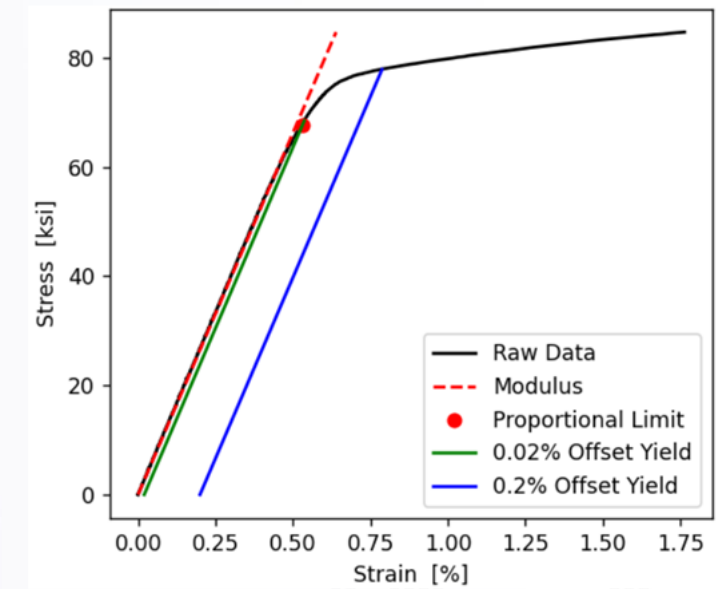
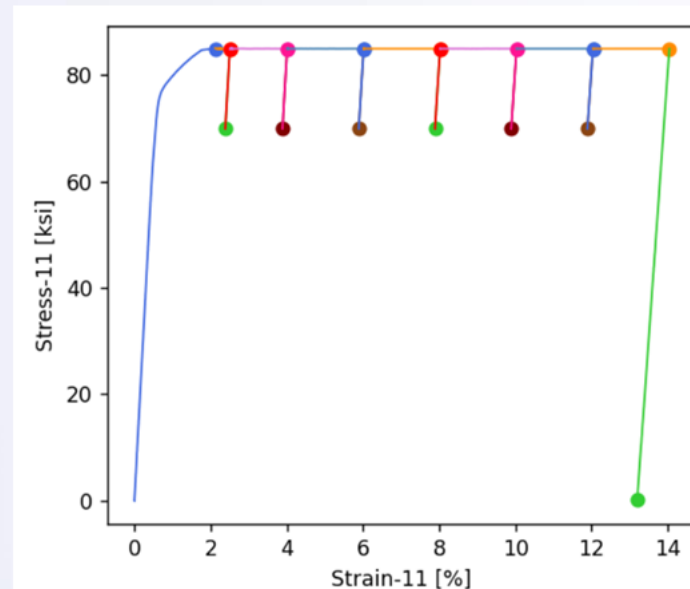
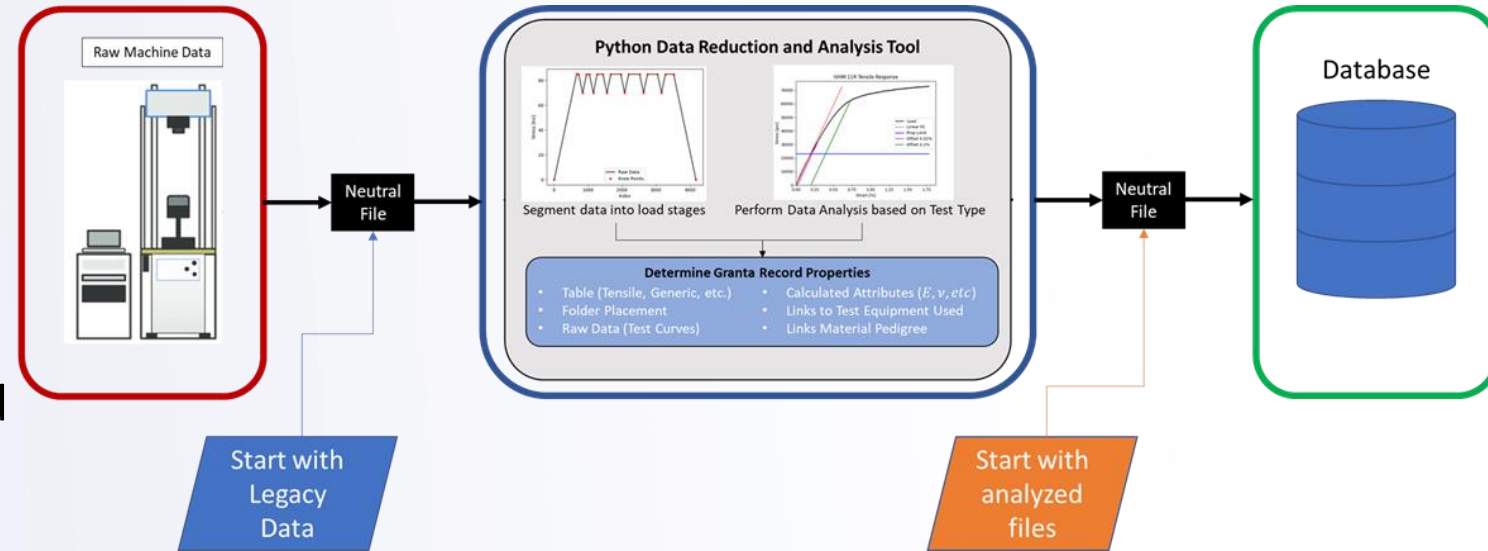


(TMS ICME, May 21, 2023)

- Re-evaluate the requirements locally with periodic global (structural – PLM/SDM) updates

Py MILAB: Analyzing and Storing Test Data

- Developed Py MILAB:
 - Python-based GUI Tool
 - Reads raw test data and user input
 - Performs data analysis
 - Stores the data automatically
- Automatic segmentation for complex load histories
 - User has ability to edit within the GUI
- Performs automatic analysis of test data
 - Tension, Compression, Shear, Creep, Relaxation, and Generic
- Automatic placement in the database
 - Users can configure schema to the tool for automation
- Modular design for flexibility
 - Start from legacy data or new data
 - Swap in different analysis codes





Closing Comments

- Effective Material ***Information Management*** is essential for efficient and cost-effective design of new materials
 - Data management is a critical element of the NASA Vision 2040
- Granta MI offers a platform for importing, storing, and disseminating data to the right people, in the right format, at the right scale, and at the right time
 - Commercial database platforms remove the burden from end users of maintaining a database system and allow focus to be placed on schema design and development of auxiliary tools
- NASA GRC has developed a robust schema to handle both real (test) and virtual (simulation) data, physics-based and data driven models, and applications to facilitate capturing and *maintaining institutional knowledge*
- The toolsets developed at NASA GRC interact with the database to enable automatic capture, analysis, maintenance, and dissemination of data to realize 'fit-for-purpose' materials

Comments/Issues

- **Informatics is a foundational technology - can't be minimized**
 - Technology (“software”) is often seen as the (easy) choice
 - Process (“language”) is more important, and should be a focus
- People and organization (“culture”) constitute the biggest challenge – **MUST DEVELOP DIGITAL CULTURE**
- Data sharing requires that **data can be parsed, understood, and reused by people and applications** other than those that created the data
- Security throughout system is paramount!!
- ***2040 VISION will require the merging of application focused technologies and material focused technology into a seamless toolset.***
- Must realize, solution will most likely ***not*** be a single toolset/environment or “database” therefore essential to identify/specify requirements for communication.

Available Publications

- [NASA TM-20230018337](#) : NASA GRC ICME Schema for Materials Information Management: An Executive Summary
- [NASA TM-20220018403](#) : Application Table: A Bridge Connecting the Designing “With-The-Material” and “The-Material” Paradigms
- [NASA TM-20220017137](#) : A Robust Machine Learning Schema for Developing, Maintaining, and Disseminating Machine Learning Models
- [NASA TM-20240012389](#): TMAAnalysis: Automatic Segmentation and Analysis of Uniaxial Test Data
- [NASA TM-20240010796](#): Automation of the ICME Workflow Incorporating Material Digital Twins at Different Length Scales Within a Robust Information Management System

Thank You for Your Attention



Integrate Don't Duplicate

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