SAND2018-5282PE

A Perspective on the Future of Engineering Design through Computation

ASC PI Meeting, 16 May 2017

PRESENTED BY

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Motivation

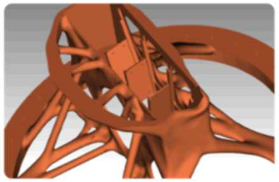
For "Exceptional Service in the National Interest"

- Improve quality (safety, security, and effectiveness)
- Reduce reliance on testing – cannot rely exclusively on testing
  - Some tests cannot be performed
  - Often limited parts are available
  - Tests are expensive (some are very expensive)
  - Note that experiments are necessary for both discovery and validation
- Reduce design and qualification time
- Reduce cost

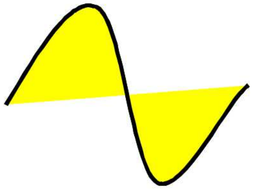
In addition to other strategies:

Leverage computational simulation capabilities in new ways to help make these goals a reality

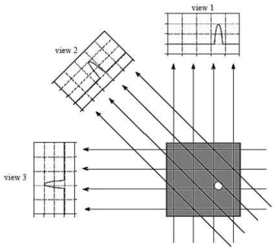
Vision for Future of Engineering Design through Computation (a few selected topics)



- Designs released from artificial constraints
  - *Topology Optimization*
    - Unconstrained by current limits in manufacturing
    - Unconstrained by current limits in materials



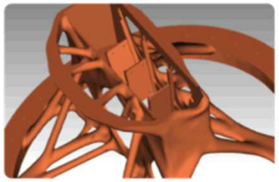
- Computation to ensure quality and reduce cost
  - *Next-Generation Meshing*
  - *Model-Based Design*
  - *Born Qualified*



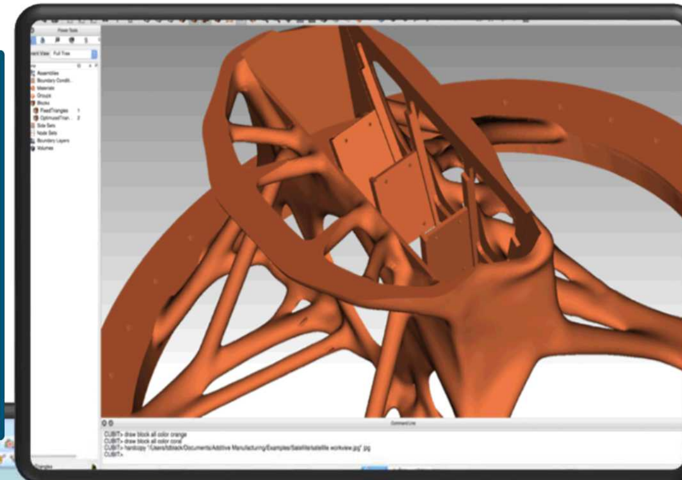
- Improved life-cycle management
  - Understand system risk with *Full System Models*
  - Use *Digital Twins* to
    - Understand impact of manufacturing variations
    - Understand impact of environmental history

Vision for Future of Engineering Design through Computation (a few selected topics)

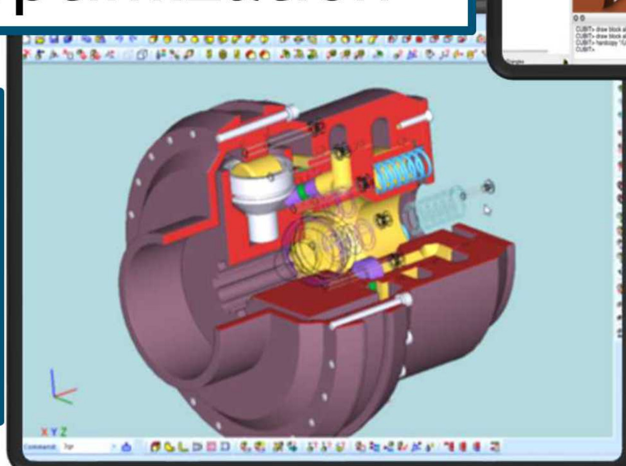
Designs released from artificial constraints



Complex Design Made Simple through HPC and AM

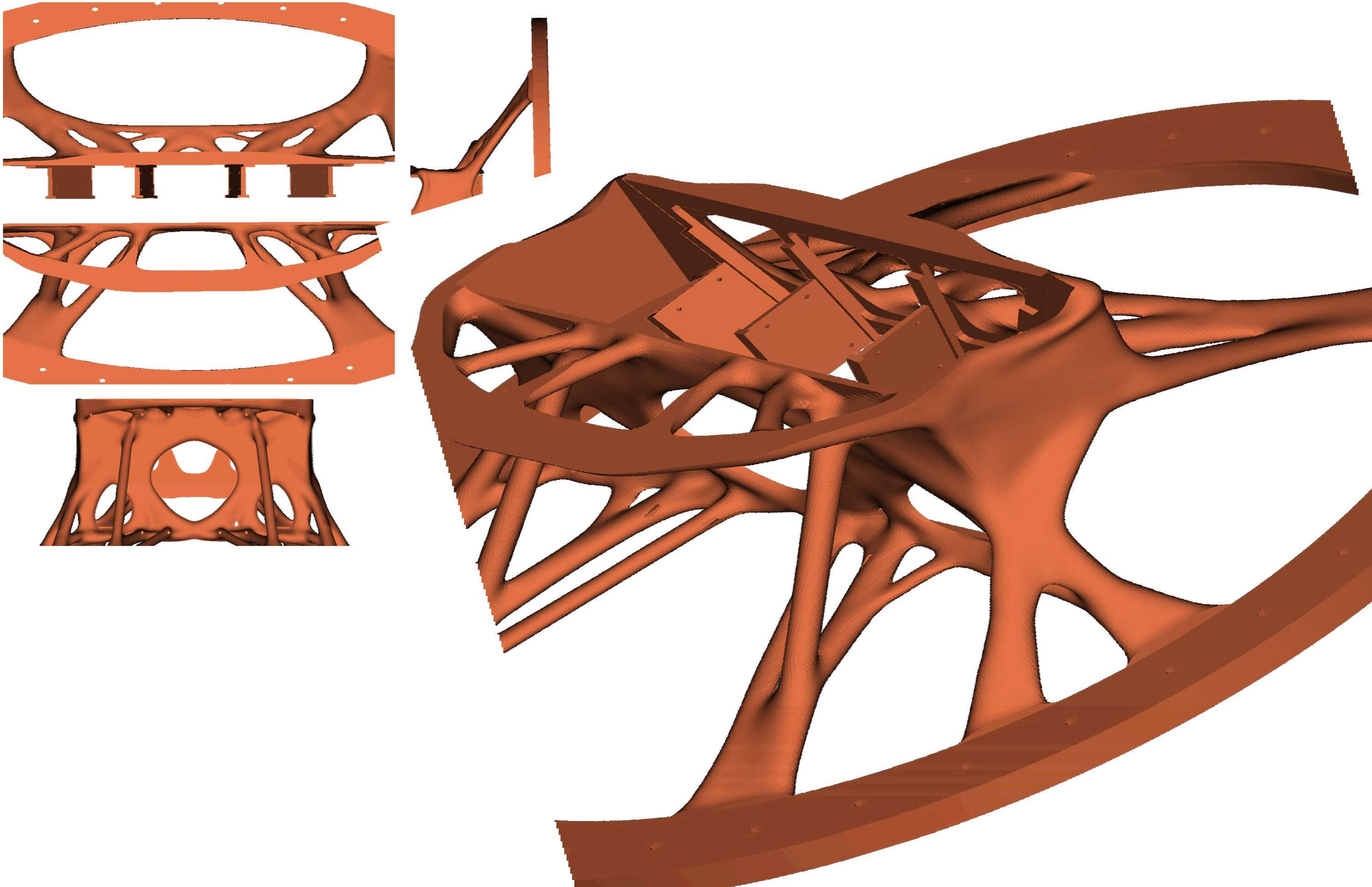


2nd Design
Revolution
CAD to Topology
Optimization

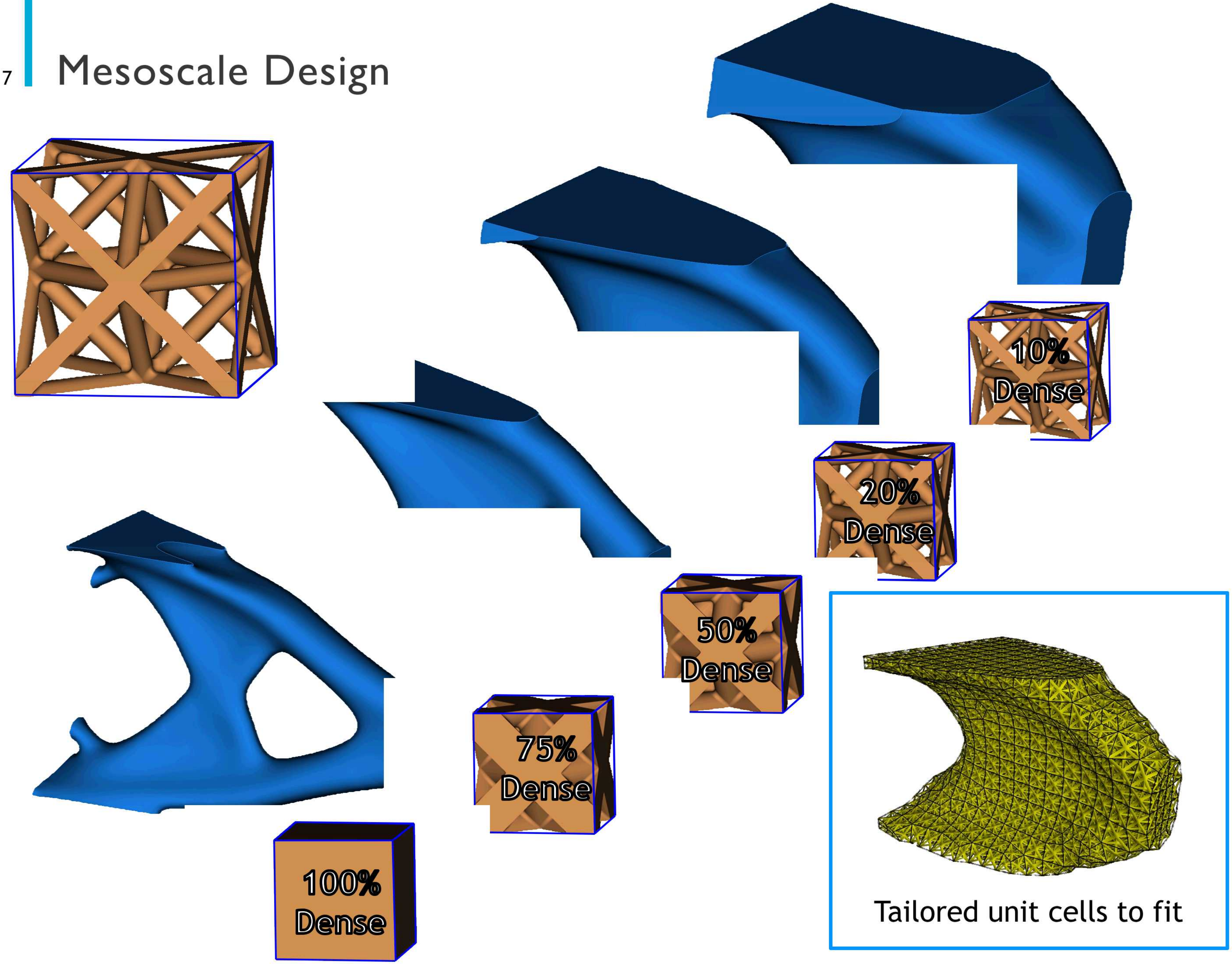


1st Design
Revolution
Drafting to CAD
(Documentation)

Topologically Optimized Designs



Mesoscale Design



Design Space Explosion

Minimize: $(1-\alpha) * \text{compliance} + \alpha$ □ thermal

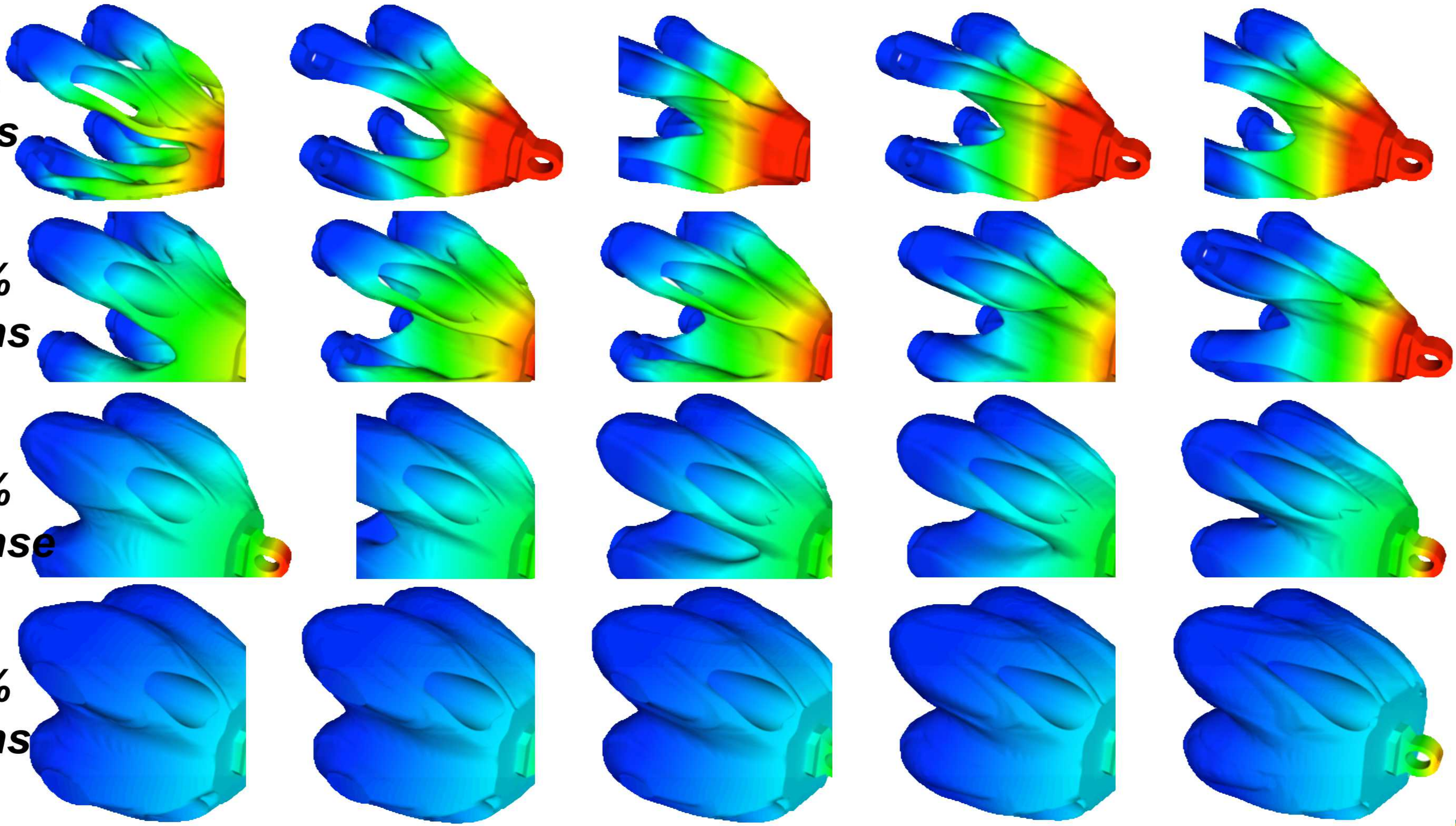
$\alpha = 0.1$ $\alpha = 0.3$ $\alpha = 0.5$ $\alpha = 0.7$ $\alpha = 0.9$

75% Dense

50% Dense

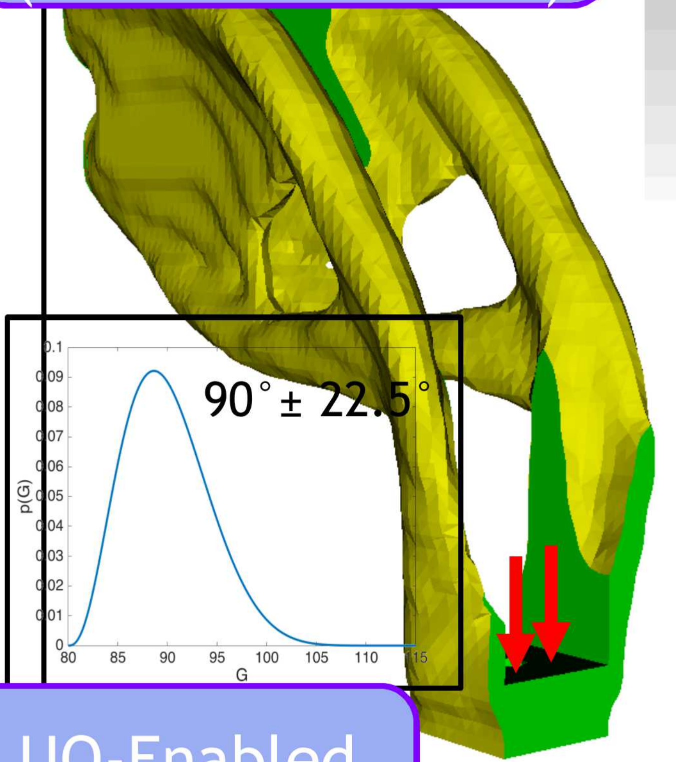
20% Dense

10% Dense

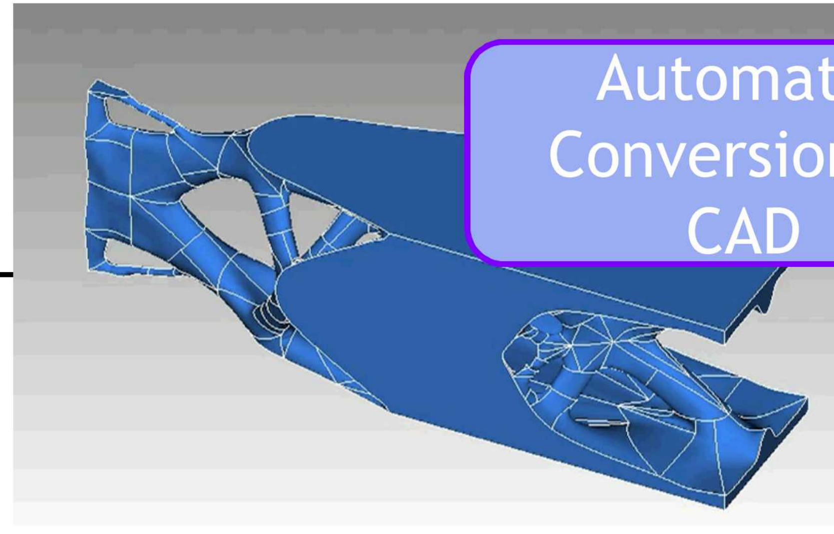


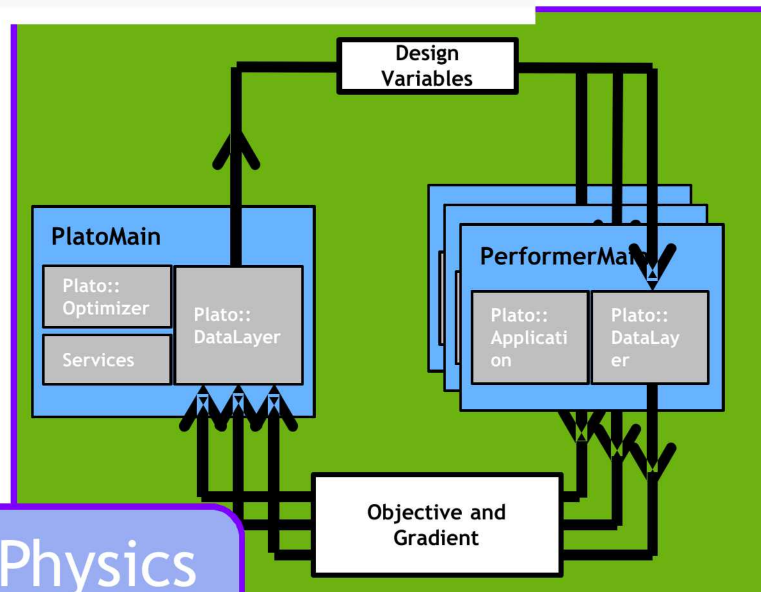
Optimization Coupled with Multiphysics Simulation & UQ Lead to Next-Generation Designs

Adaptive Prune Refine
(Good Results Fast)



Automatic Conversion to CAD



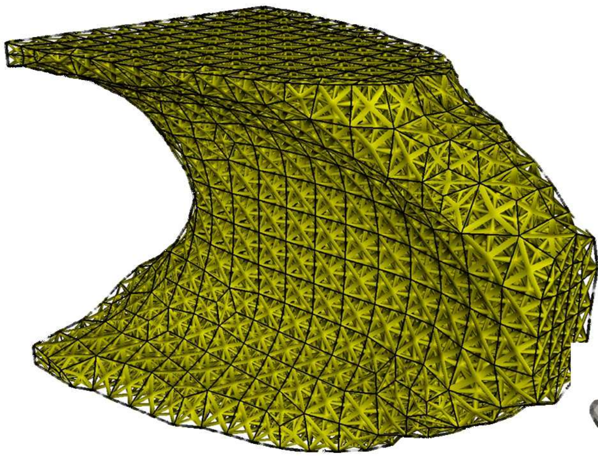


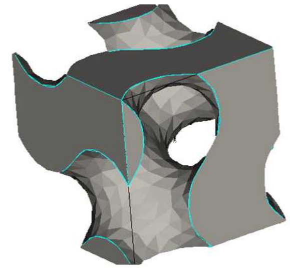
UQ-Enabled Optimization

Multi-Physics Platform

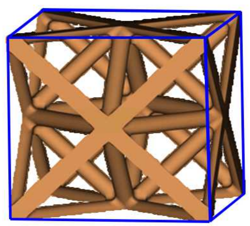
Lattice and Multi-Materials Enable Novel Functionality

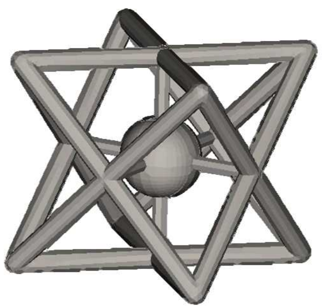
Organic Shape Lattice Insertion

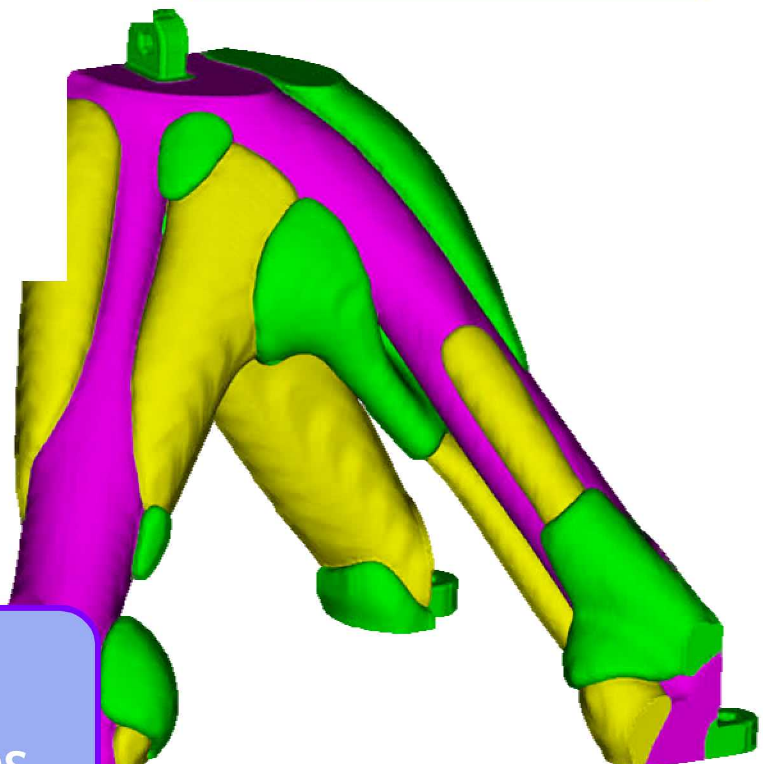




Multi-Material Optimization



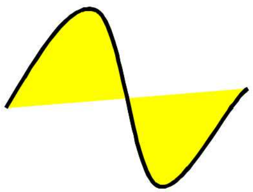




Families of Lattice Types

Vision for Future of Engineering Design through Computation (a few selected topics)

Computation to ensure quality and reduce cost



Next-Generation Meshing

Turn around analyses in minutes not months

Today: traditional hex meshing

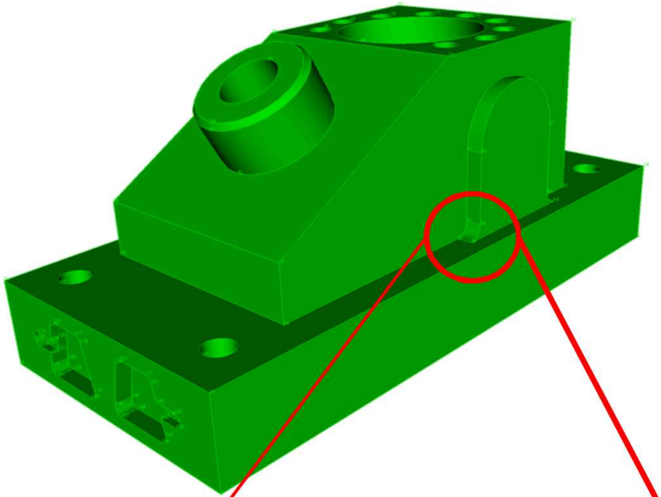
CAD cleanup → CAD de-feature → CAD decomposition

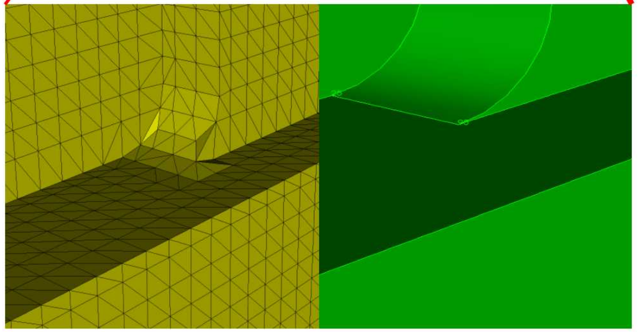
months

minutes

ProE CAD → Future: background grid meshing straight from CAD →

Next-generation meshing:
No geometry clean-up
Fitting to CAD geometry
Parallel
Runnable (requiring new discretizations)

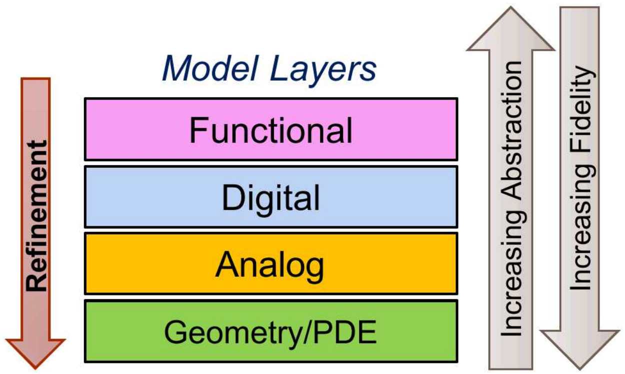


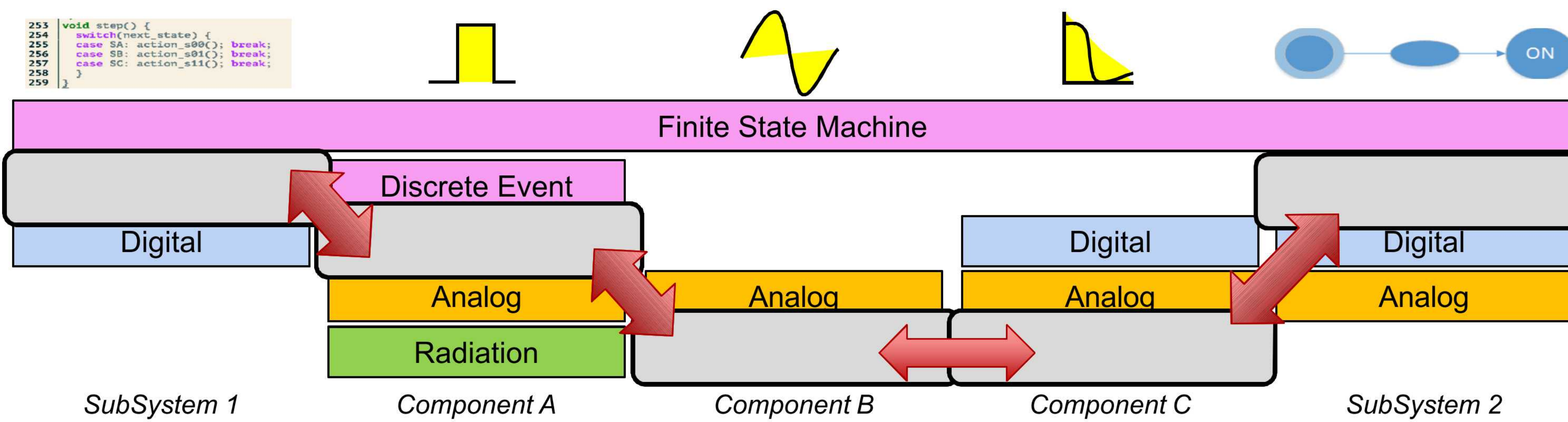


Model-Based Design: Integrated Multi-Scale Electrical Simulation

Key Challenges

- Interfaces between distinct models and tools
- UQ and V&V for multi-scale, e.g., mixed analog-digital
- Model consistency, selection, and abstraction
- Leverage and integrate with design activities





Model-Based Design: Key Elements

Application of formal analysis

- Proven (formally verified) design
- Correct by construction

Comprehensive integrated approach to analysis and design verification

- Physical test – Sample
- Formal analysis (proofs) – Proofs for limited number of key properties
- Computational simulation (virtual test) – Sample

Integration with Systems and Design Engineering process

- MBSE (representations)
- Verifiable requirements

Born Qualified

Combine promise of additive manufacturing with deep materials & process understanding to revolutionize design, manufacturing, & qualification paradigms.

Key Elements

- Advanced in-situ measurements (thermal, defects)
- Feedback control, process optimization
- Uncertainty quantification, high-throughput material testing
- Integrated Computational Materials Engineering (ICME)

Enables informed design optimization.

Enhanced by future exascale computing.

Born Qualified – Why Now?

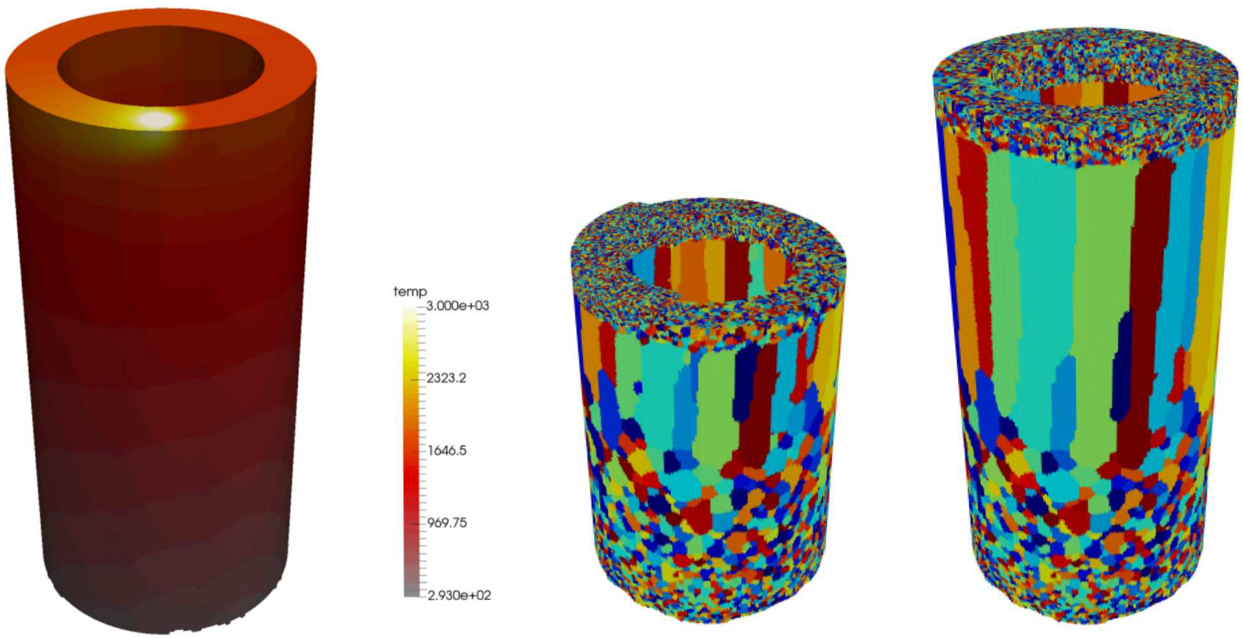
Major recent advances in

- Additive manufacturing
- Measurement techniques
- Process understanding and control
- Machine Learning
- Exascale Computing

Feedback control, process optimization – Microstructure prediction

Thermal History Prediction

Microstructure Prediction



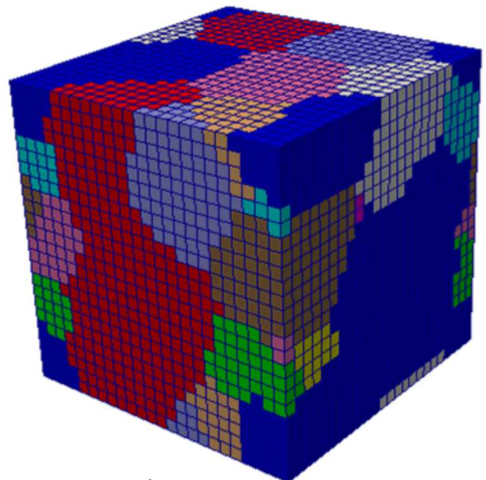
T=410 s

T=273 s

T=410 s

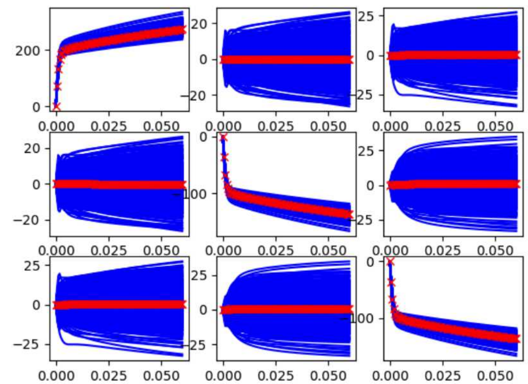
Machine Learning can Represent Complicated Material Properties based on Process Modeling Realizations

Texture ensemble of grains & orientations

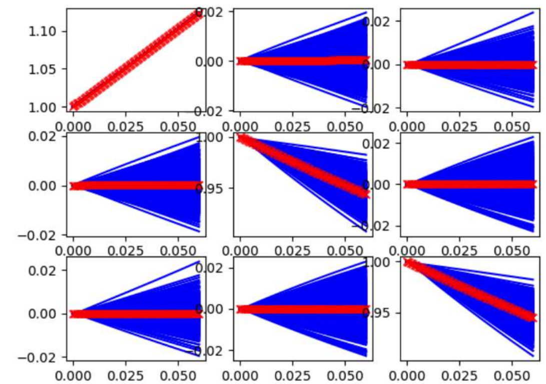


Inputs

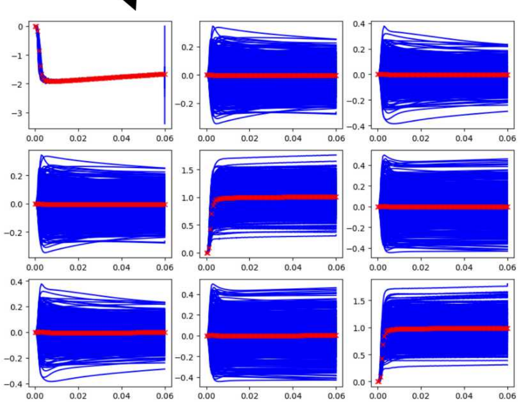
Stress



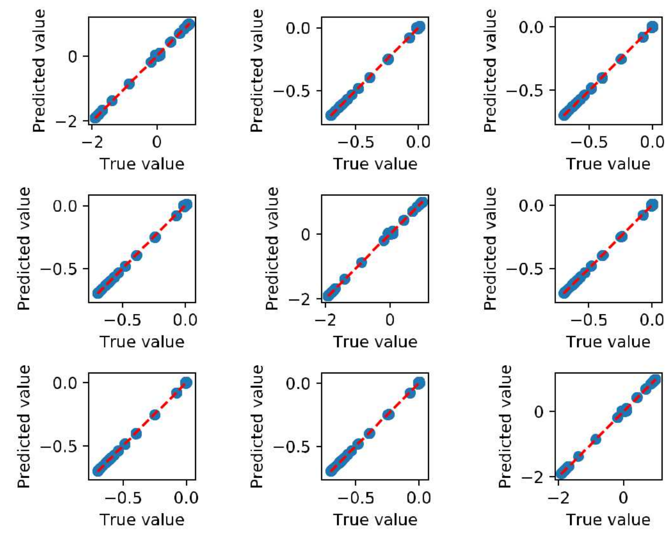
Strain



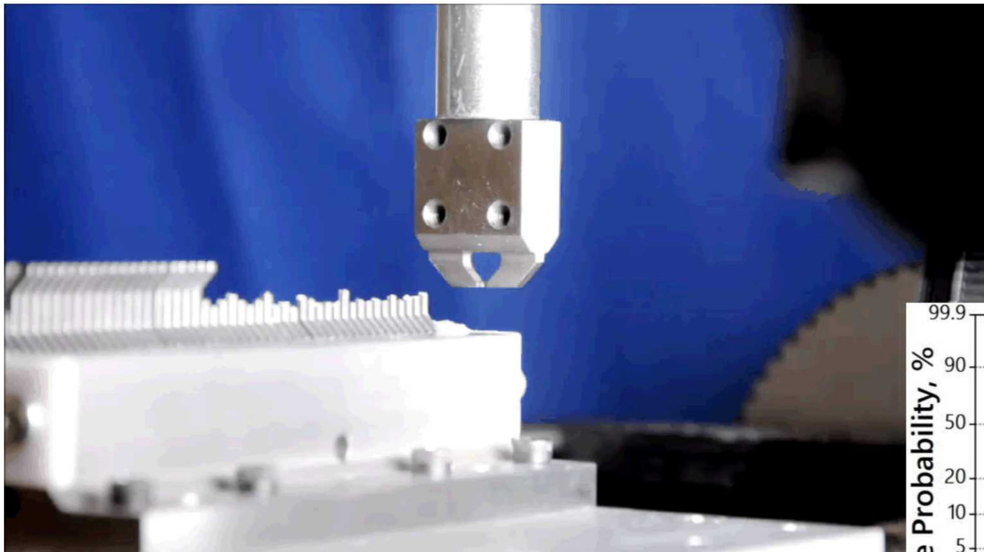
Outputs
Plastic Evolution

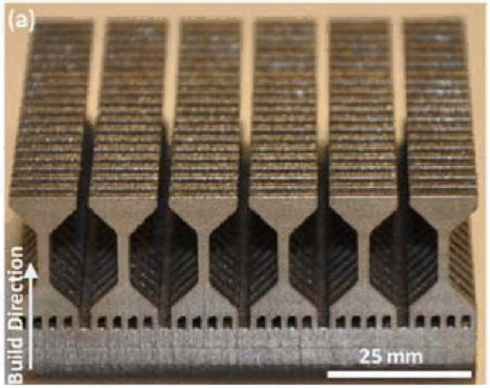


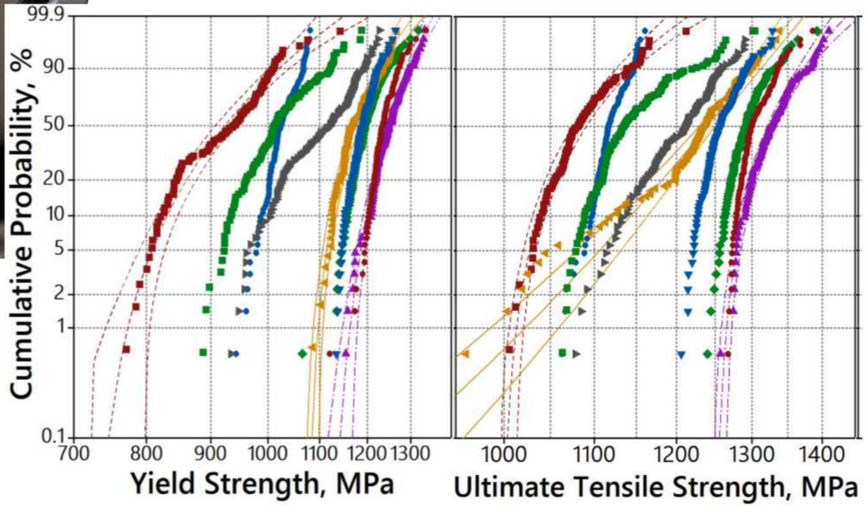
Trained Tensor Basis Neural Network



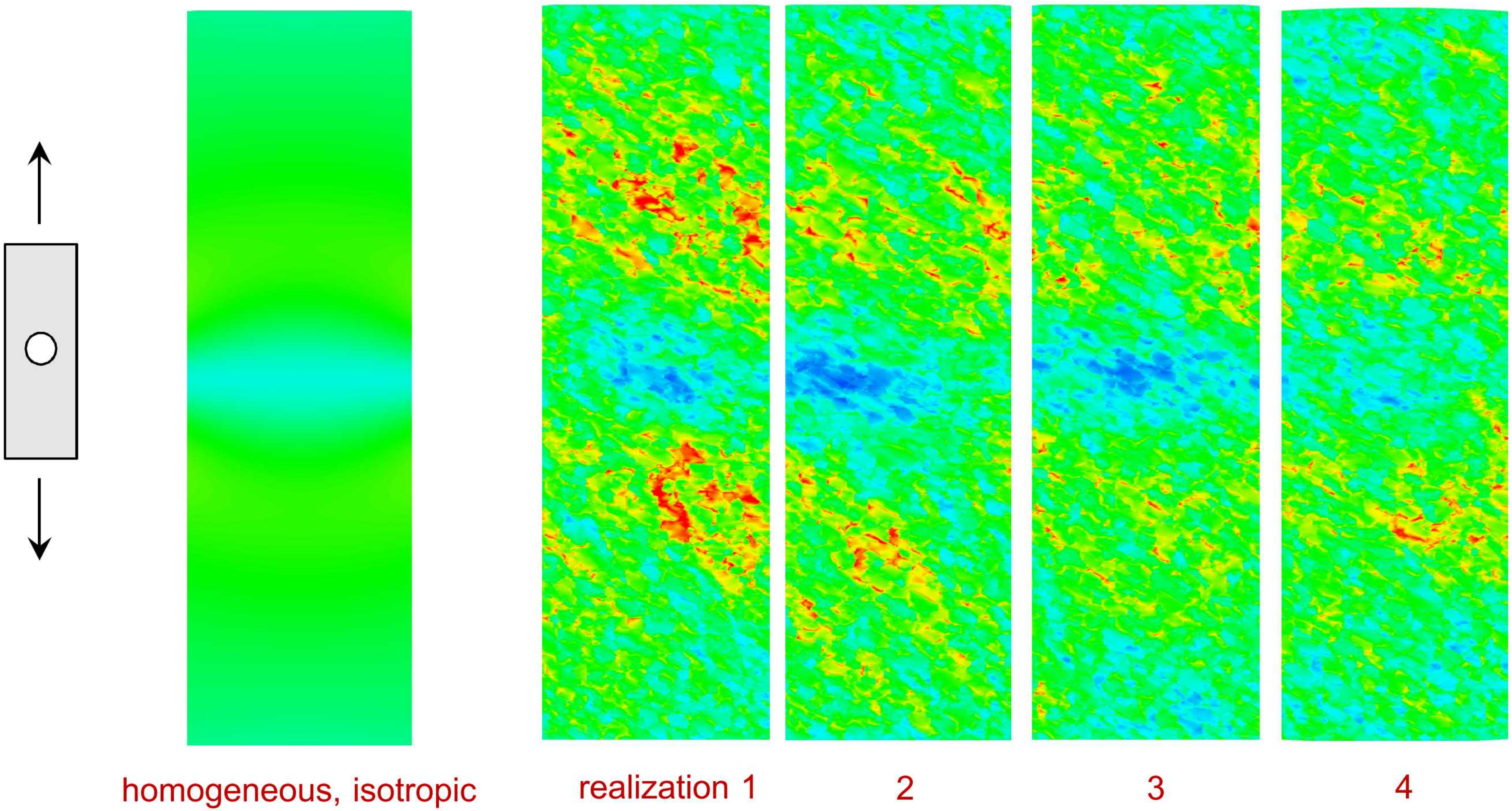
Uncertainty quantification, high-throughput material testing







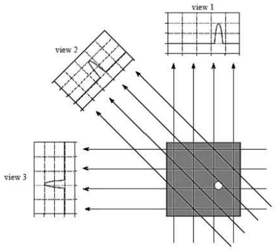
Multiscale stress analysis (see digital twins later)



Will require massive (Exascale) resources to capture material structure of components

Vision for Future of Engineering Design through Computation (a few selected topics)

Improved life-cycle management



Full Engineering Models to Expedite Qualification and Guide Surveillance

Single Physics | Code Linking | Tight Coupling | Full Physics

Single Physics

- Enhanced physics models with improved understanding and reduced uncertainty
- Workflow to automate model building and shorten time to solution
- Embedded UQ to identify critical sensitivities
- Conversion of CT Images to models to enable serial number based models (digital twins)

Code Linking

- Aging mechanisms into lifetime prediction
- Bridging length scales to embed local effects into global modeling
- Evolution of performance and safety assessments based on in-service conditions

Tight Coupling

- Combined environments drivers pushing to Exascale
- Multiphysics within components

Full Physics

- Data fusion techniques for integration of experimental and computational data
- Capabilities to assess large ensemble data sets to challenge our intuition
- Institutional efforts to create accessible cloud based data lakes

Digital Twins Enable a Data-Driven Approach to Life-Cycle Management

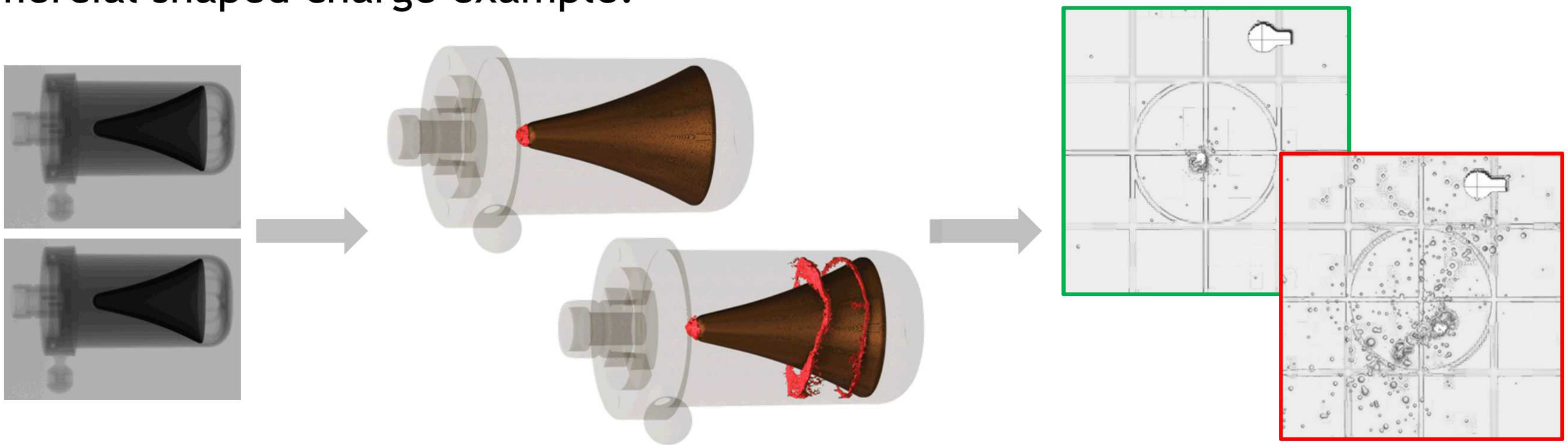
Generate models from CT data for direct numerical simulation

- Greatly simplifies analysis workflow
- Permits analysis of as-built systems
- Aging of each serialized unit can be studied
- Statistical lot acceptance can be replaced with individual performance acceptance

Commercial shaped charge example:

Unit #44

Unit #50



CT Scanning Process

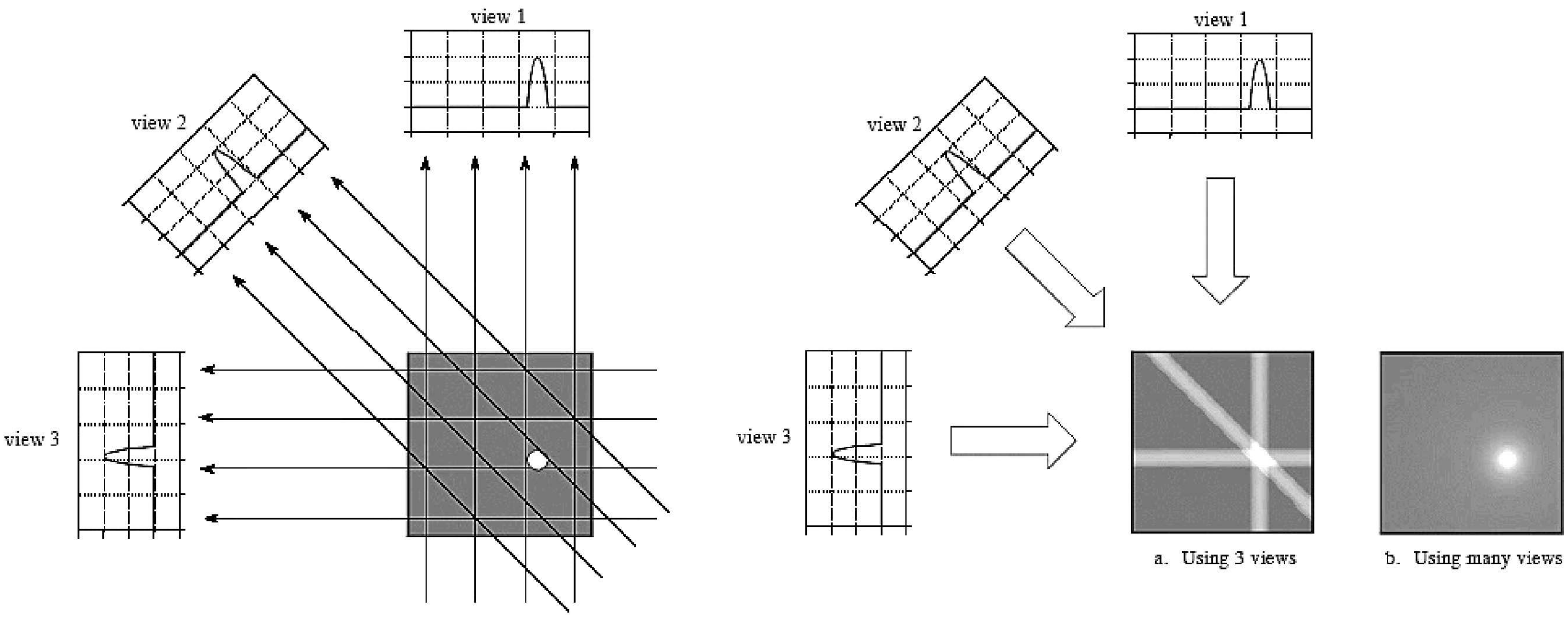
Segmentation and Defect Identification

Simulation of Individual Performance

CT* Imaging will Lead to Models of As-Built Hardware

A classic inverse problem → What cast this shadow?

- Hundreds to Thousands of X-ray Images
- Post-processed to produce structured volume data (voxels)



X-ray Imaging

Volume Reconstruction

*As in "CT Scan" – computerized axial tomography

Generating As-Built Digital Twins will Challenge HPC

Continued growth of CT capabilities

- New machines are appearing every few months
- Machines range in cost from $500K to $10M
- These tools mostly assist manual inspection
- This is not your standard medical CT (*Lethal dosage in 5s*)

Small – Cabinet Machines

Medium – Room Size Machines

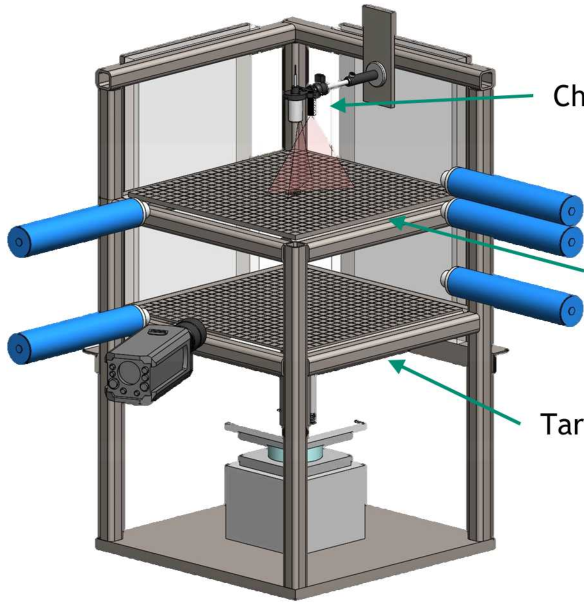
Large – Full Building

Each machine can create 2 terabytes of data per week

This is a Data Science gold mine

Digital Twins have Demonstrated Value in Understanding Shape Charge Variability…

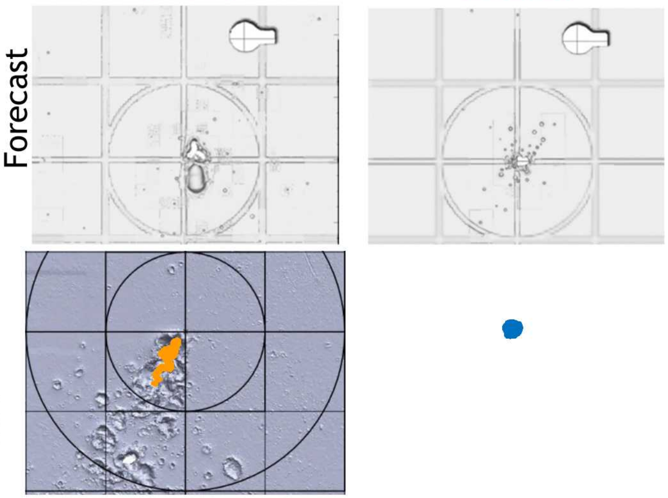
Experimental Setup

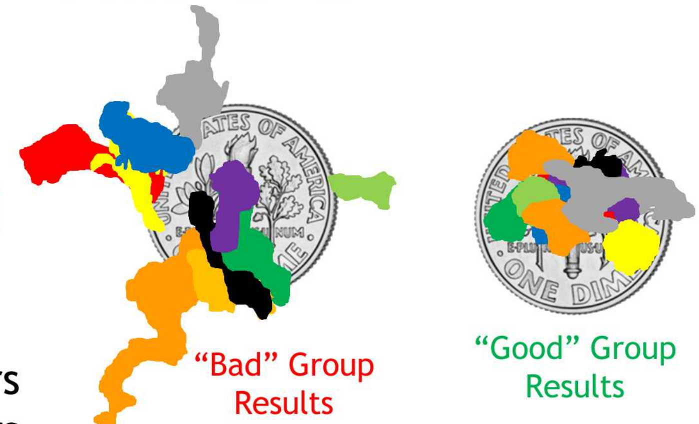


Charge Accuracy at Target Panel

Unit #6

Unit #60

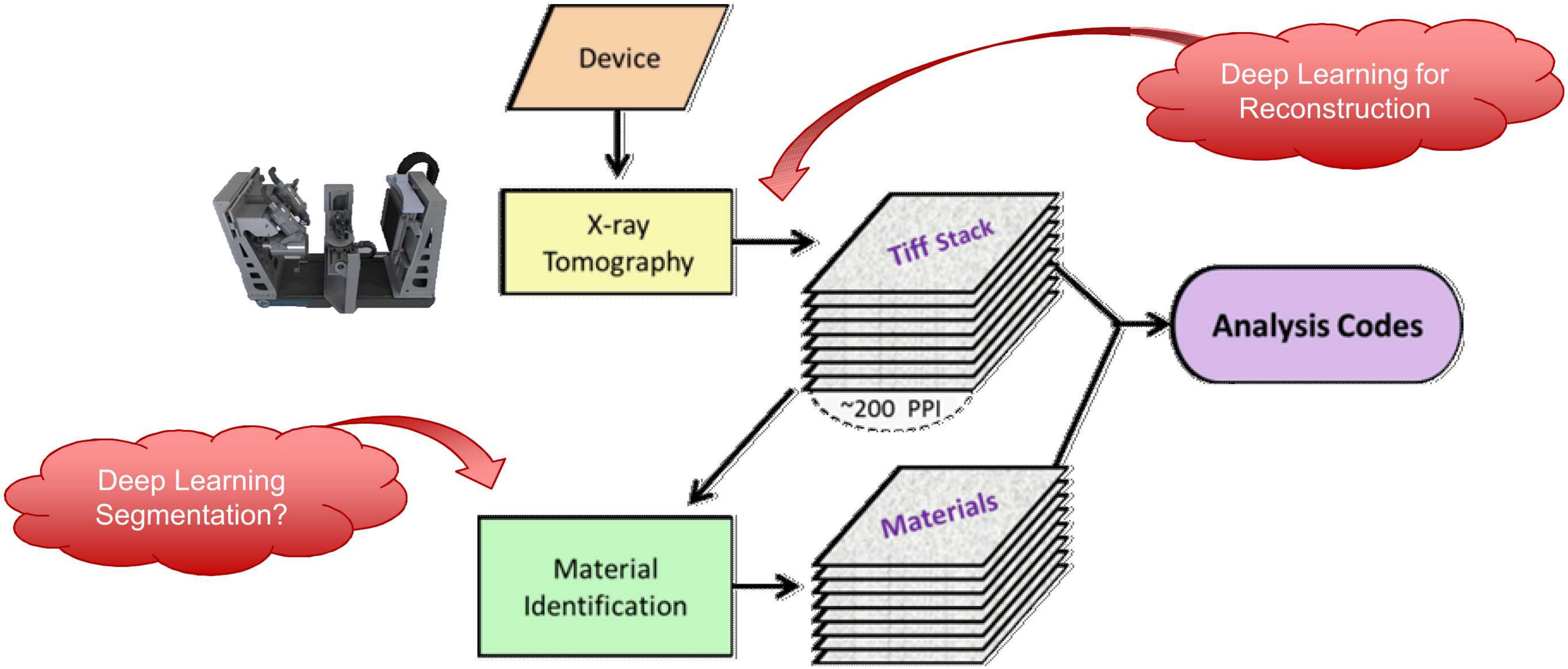




Simulations of digital twins identified bad and good charges

Cost per simulation: 129,600 cpu hours
Total Simulation Set: ~12,000 cpu years

(Future) Workflow for Digital Twins



This process is not a solved problem

- Segmentation is an art form emerging as a science
- Reconstruction of volumes from images is still an immature field

Applications of the Digital Twins

- Use of exact parts and lot numbers showed that part-to-part variation of electrical components tend to dominate the variation seen in flight test measurements
- One of the key concepts behind *Born Qualified* (mentioned earlier)
- One of the key concepts in *Full System Models*

Summary

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- Reduce reliance on testing
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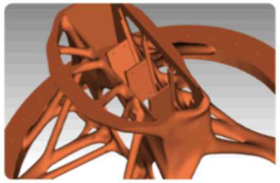
- Reduce cost



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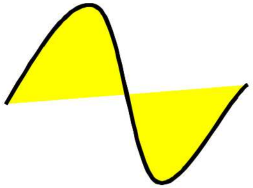

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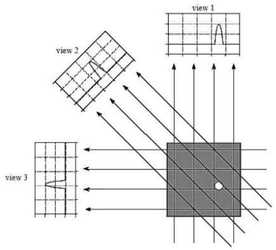

- Improved life-cycle management
  - *Full System Models*
  - *Digital Twins*