Co-Design for Heterogeneous Integration: A Failure Analysis Perspective

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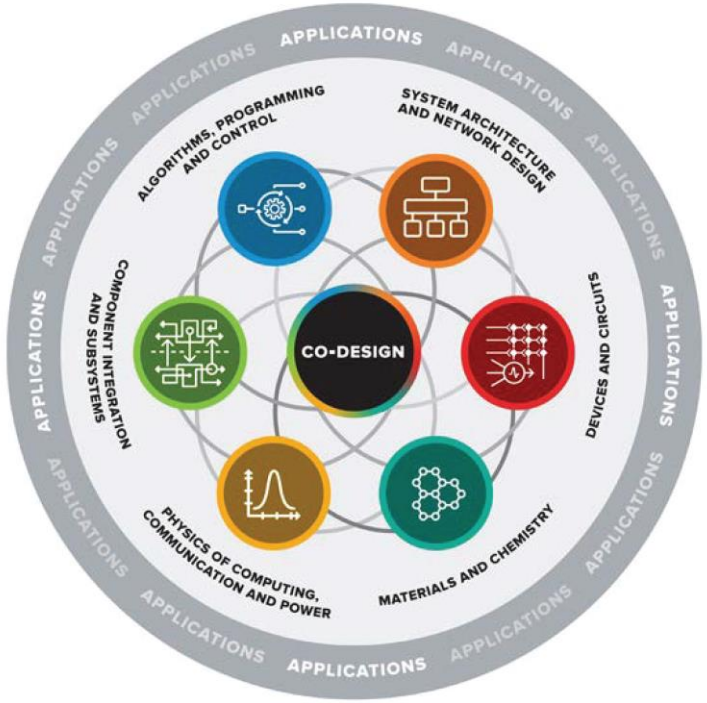
Parallel Paths from Design to Reliable Products

- "…Fundamental rethinking is needed of the science behind the materials, devices, synthesis and fabrication technologies, architectures, and algorithms. …"*
- "…Advances must be conceived and developed collectively, in a spirit of ***co-design***, where each scientific discipline informs and engages the others…"*
- Successful ***co-design*** will result in "…parallel but intimately networked efforts to create radically new capabilities that would not have resulted from the historical linear development process. …"*

"AI won't replace the scientist, but scientists who use AI will replace those who don't"†



* DOE Office of Science *Basic Research Needs for Microelectronics* Report (October 2018)

How do we rapidly design hardware in regimes where learning cycles rely on accurate understanding across length scales (single atoms to mm sized integrated chiplets)?

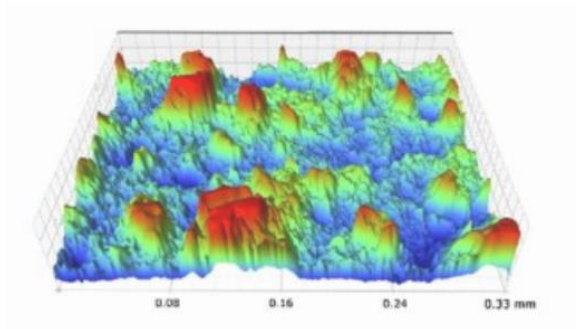
How do we cross the chasm from discovery to reliability?

†ASCAC Subcommittee on AI/ML, Data-Intensive Science and HPC, Sept. 2020

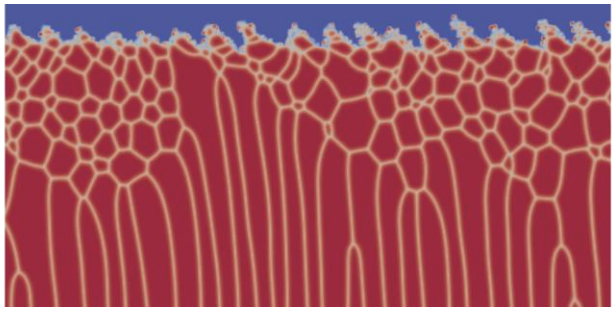
S&T Challenge: Fusing data across modalities

Pre-process

Stage	Composition	Concentration
Electroless nickel plating	$NiSO_4 \cdot 6H_2O$	30 g L^{-1}
	$NaH_2PO_2 \cdot H_2O$	30 g L^{-1}
	$Na_3C_6H_5O_7 \cdot 2H_2O$	20 g L^{-1}
Electroplating	$Ni(SO_3NH_2)_2 \cdot 4H_2O$	300 g L^{-1}
	$NiCl_2 \cdot 6H_2O$	15 g L^{-1}
	H_3BO_3	20 g L^{-1}

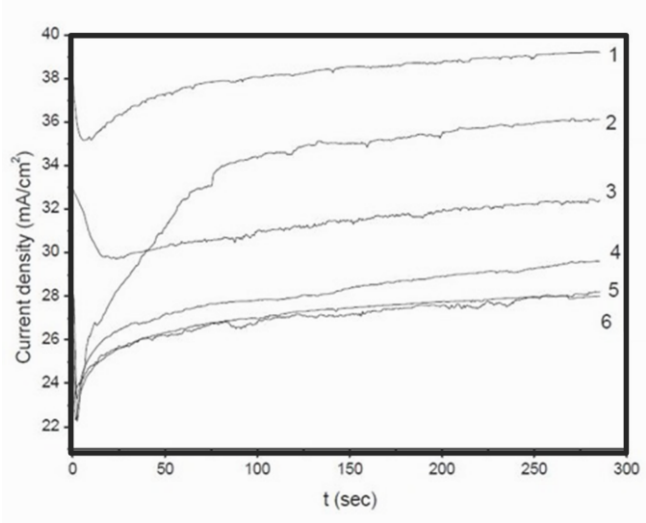


Precursor characterization

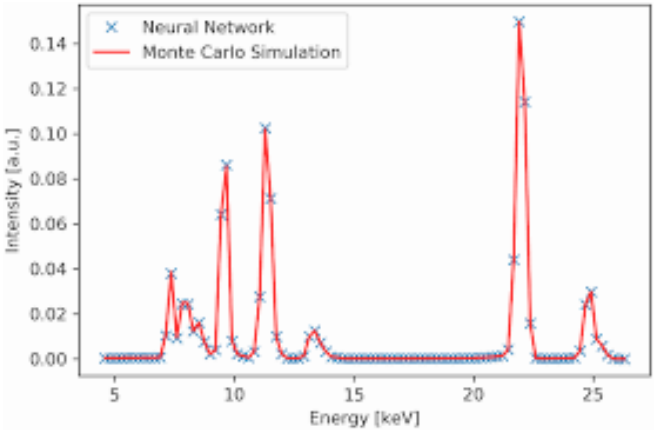


High-fidelity mod/sim

In-process

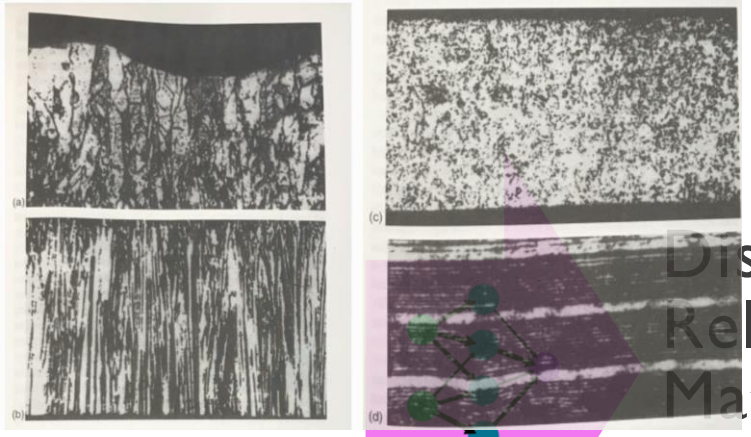


Time-series data

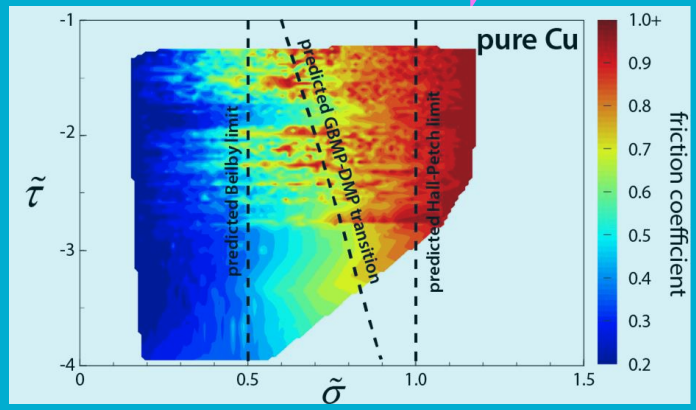


In-situ characterization

Post-process



Microscopy & Characterization



Property/Performance/Aging Measurements

Discover Reliable Materials/ Processes

Governing equations can be integrated with data

Pre-process

In-process

Post-process

Stage	Composition	Concentration
Electroless nickel plating	$NiSO_4 \cdot 6H_2O$	30 g L^{-1}
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Time-series data

Microscopy & Characterization

$$j = i_0 F\left[\exp\left(\frac{\alpha_a F\eta}{RT}\right) - \exp\left(\frac{-\alpha_c F\eta}{RT}\right)\right]$$

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D\left(\frac{z\,c\,F}{R\,T}\frac{\partial V}{\partial x} + \frac{\partial c}{\partial x}\right)$$

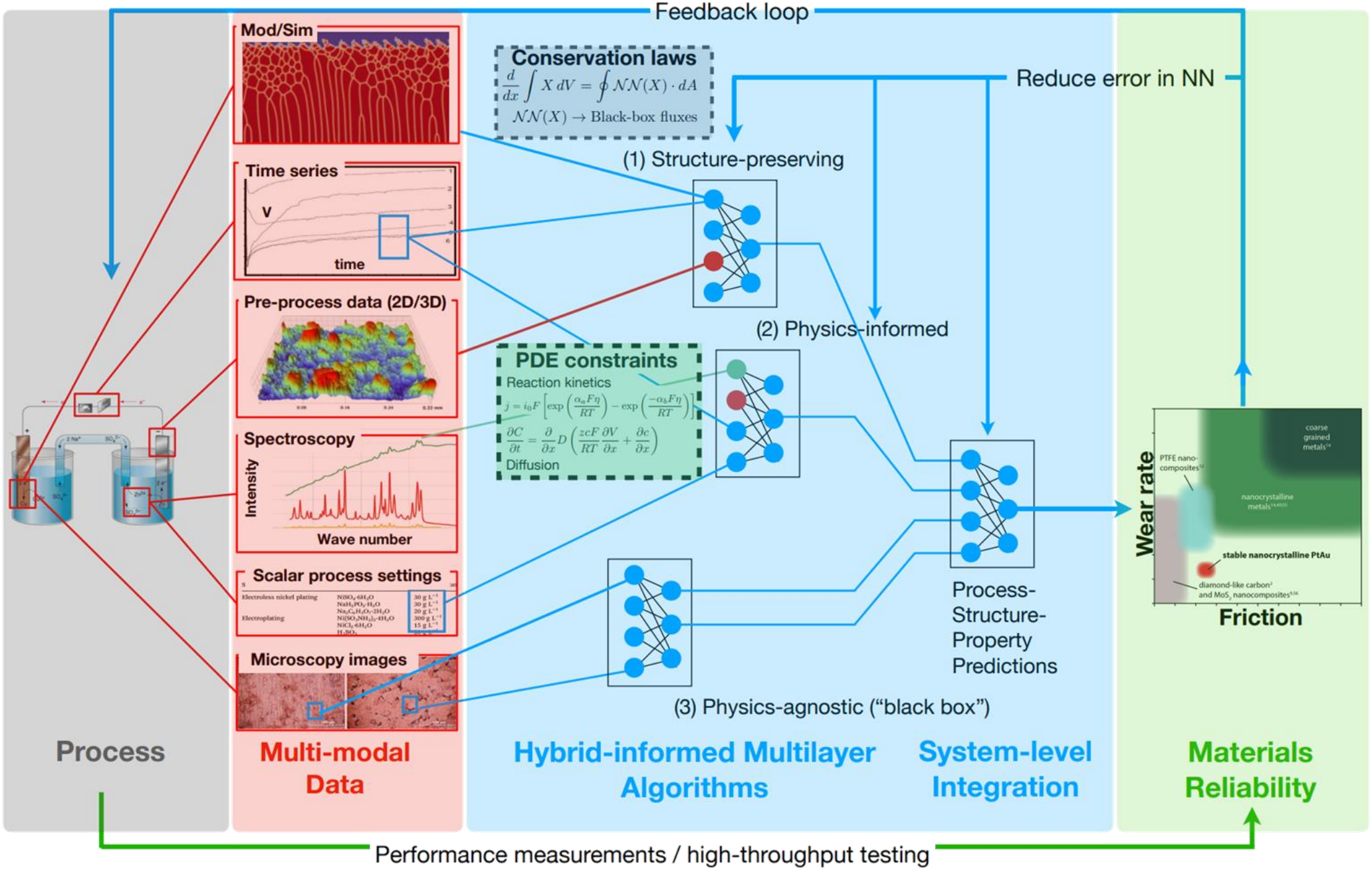
Discover Reliable Materials/ Processes

High-fidelity mod/sim predictions

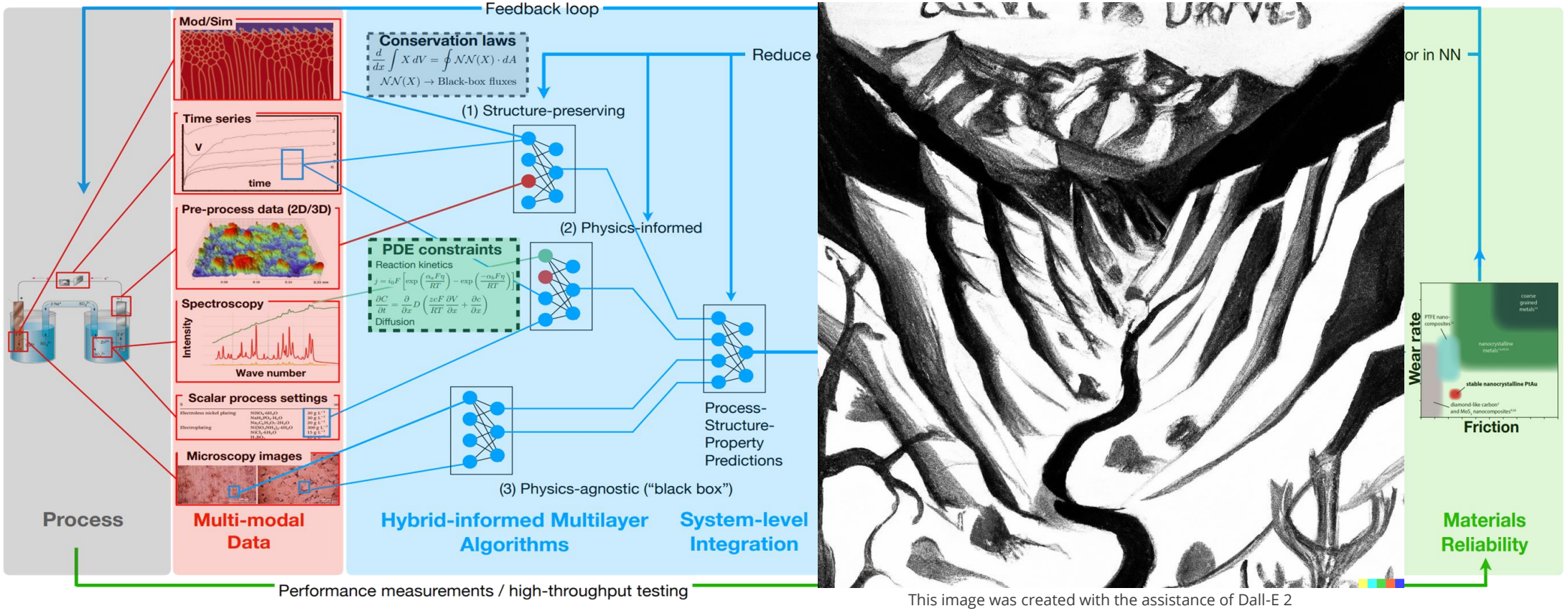
In-situ characterization

Property/Performance/Aging Measurements

HIMULAYA: BeyondFingerprinting's Process Optimization Vision



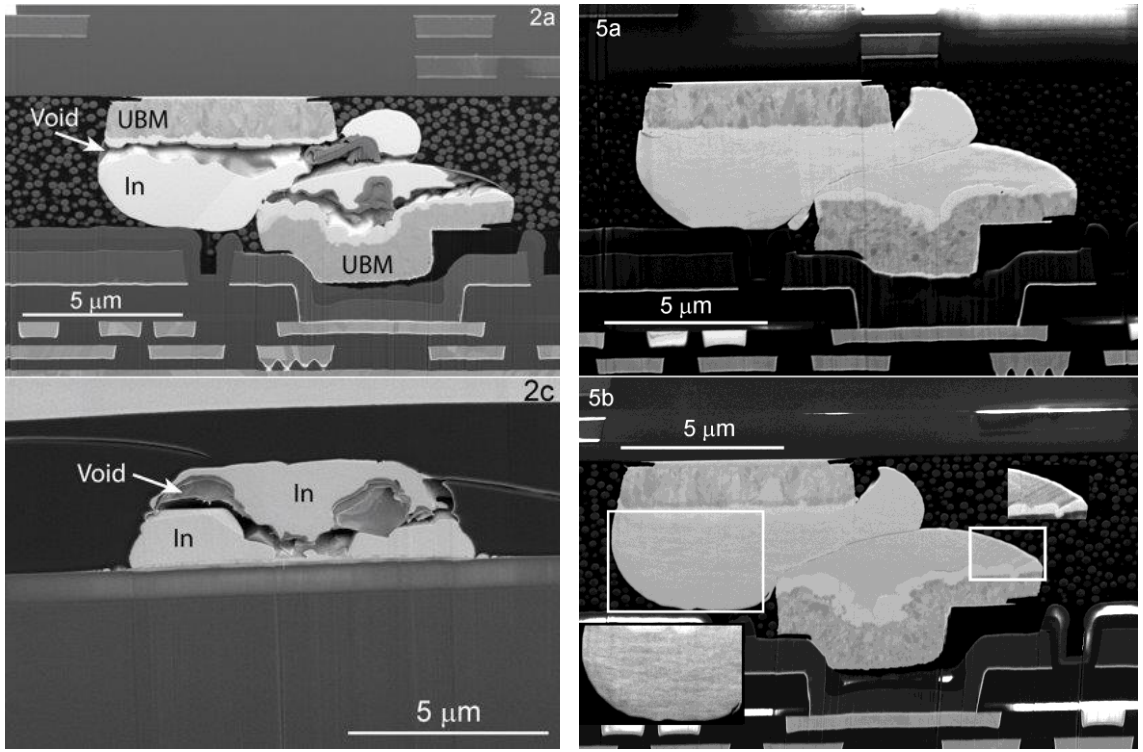
Complexity of Heterogenous Integration



This image was created with the assistance of Dall-E 2

A chasm opens between single material reliability & lifetime estimation and failure of complex parts with mixed materials, interfaces, and numerous failure mechanisms

Failure Analysis & the Observer's Paradox



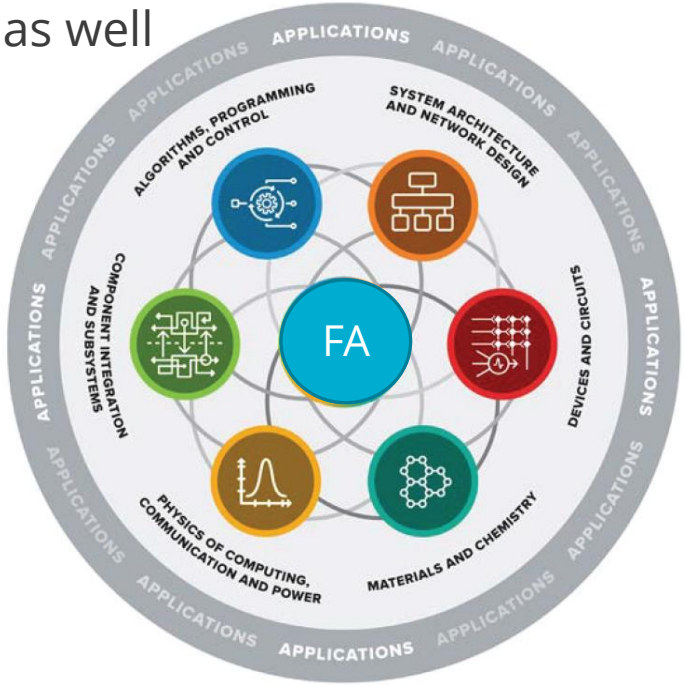
J. Michael, et al., *Microscopy and Microanalysis, 28*(3), 603-610 (2022)

Indium bump cross sections by Xe+ plasma FIB at room temperature (left) and at cryo (-150 C) (right)

Physical limitations drive design limitations
How do we observe without inducing effects?

Failure analysis techniques to new integration methods could induce observations of false failure modes

Co-design of new structures requires not only development and optimization spanning materials to algorithms, but necessary to involve FA/materials characterization techniques as well



End-state performance & reliability of next generation HI products rely not only on optimal designs of hardware and software, but investments in FA techniques