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Modeling and Simulation of Extreme-Scale Systems for Resilience by Design

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Motivation

- **The Paradox of Choice:**
  - Many possible solutions for resilience in extreme-scale high-performance computing systems [hardware, system software, algorithm-based, programming model-based, etc.]

× Incomplete understanding of protection coverage against high probability & high impact vs. less likely & less harmful faults

× No good evaluation methods & metrics that consider
  - Fault impact scope, handling coverage and handling efficiency
  - Performance, resilience and power trade-offs

× No mechanisms and interfaces for coordination for avoidance of costly overprotection

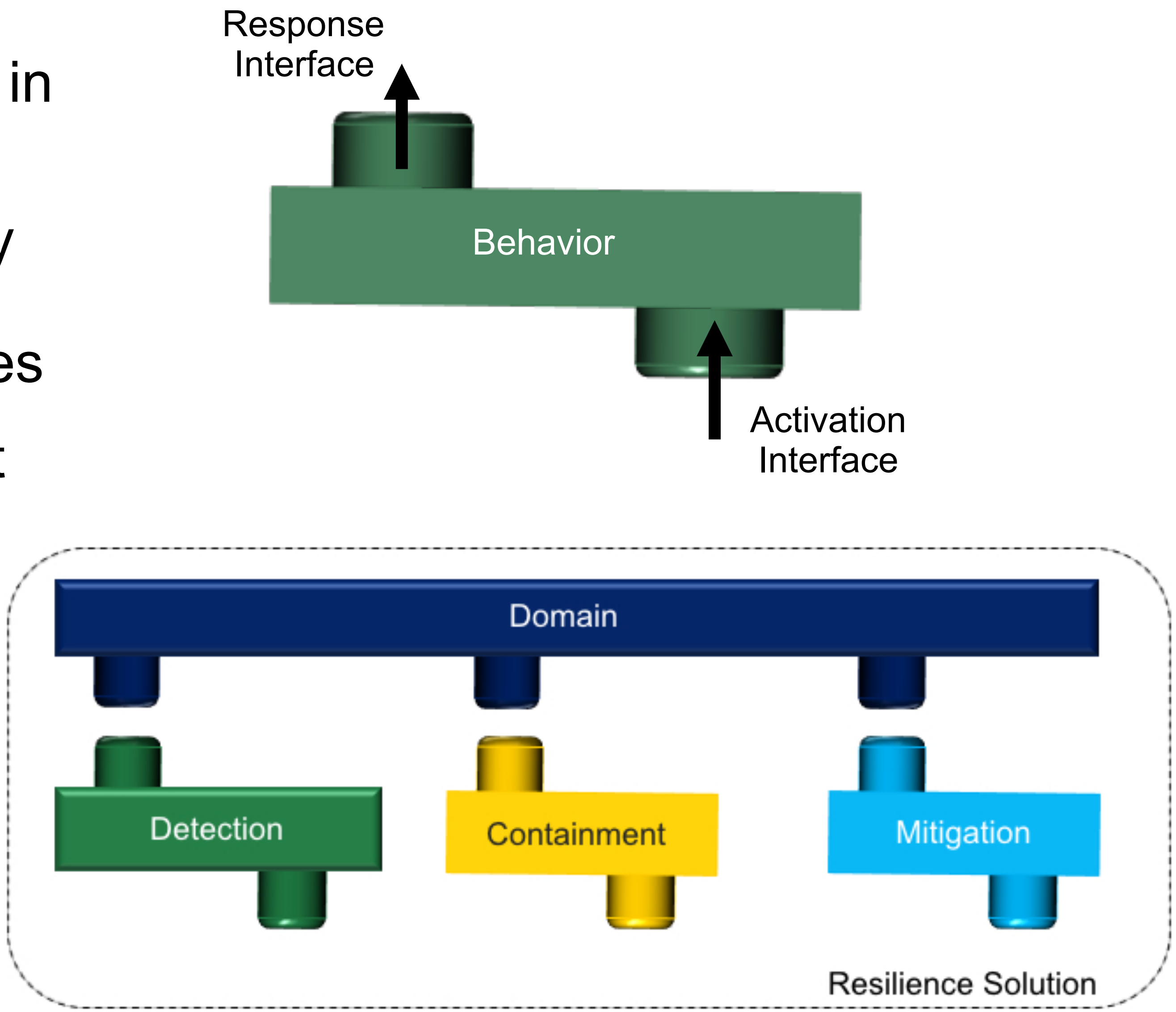
× No resilience portability across architectures and software environments

Design Patterns for Resilience

- A design pattern provides a generalizable solution to a recurring problem
- It formalizes a solution with an interface and a behavior specification
- Design patterns do not provide concrete solutions
- They capture the essential elements of solutions, permitting reuse and different implementations
- *State patterns* provide encapsulation of system state for resilience:
  - *Persistent State*, *Dynamic State*, *Environment State* and *Stateless* patterns
- *Behavioral patterns* provide encapsulation of *detection*, *containment* and *mitigation* techniques for resilience:
  - *Strategy*, *Architecture*, and *Structural* patterns

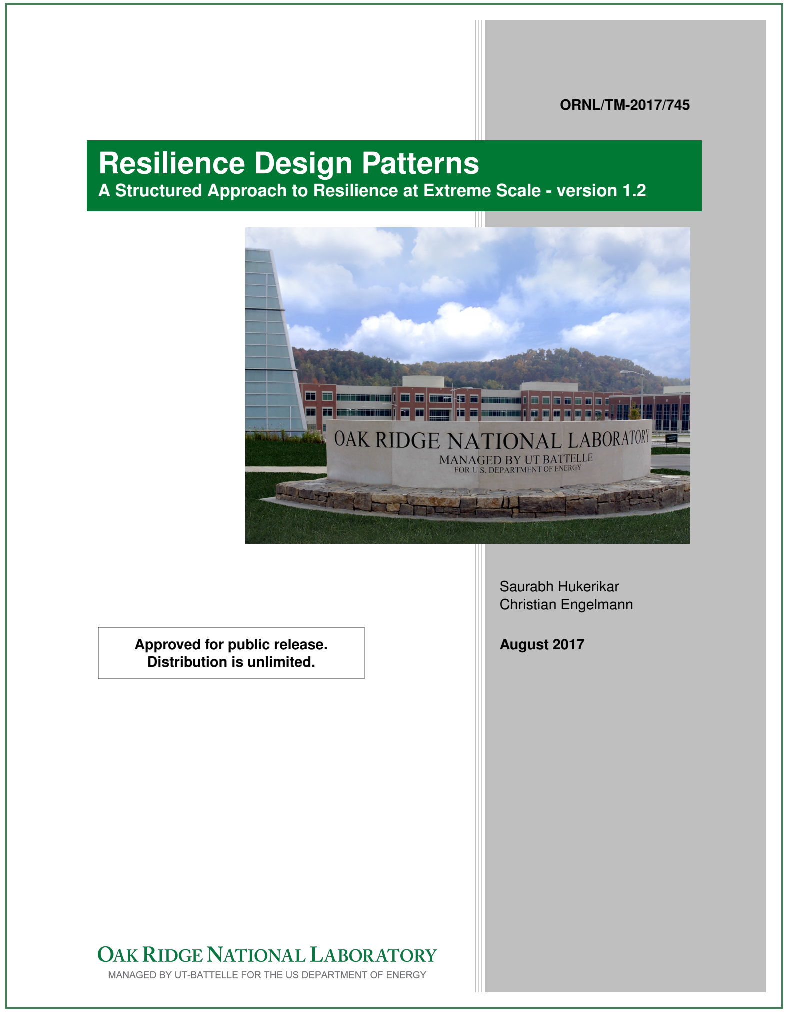
Anatomy of a Resilience Design Pattern

- A resilience design pattern is defined in an event-driven paradigm
- Instantiation of pattern behaviors may cover combinations of *detection*, *containment* and *mitigation* capabilities
- Enables writing patterns in consistent format to allow readers to quickly understand context and solution



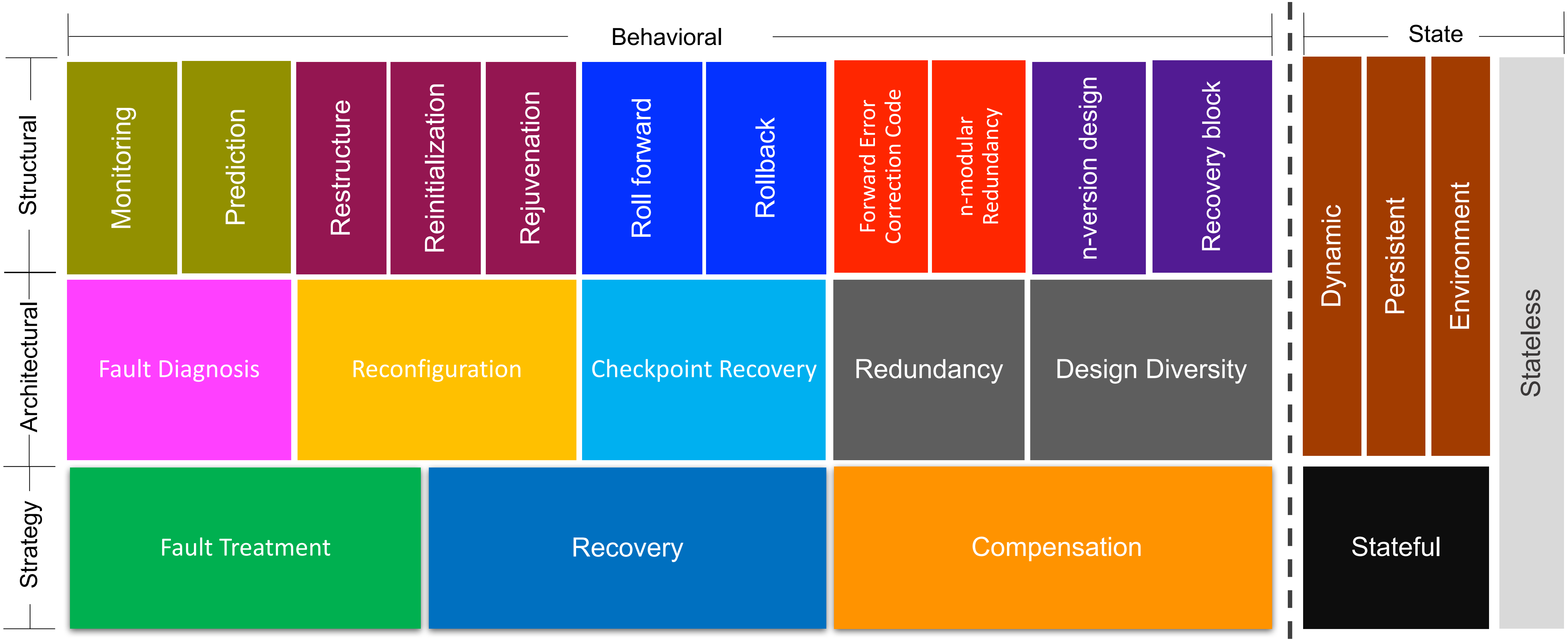
Resilience Design Patterns Specification v1.2

- Taxonomy of resilience terms and metrics
- Survey of resilience techniques
- Classification of resilience design patterns
- Catalog of resilience design patterns
  - Uses a pattern language to describe solutions
  - 3 strategy patterns, 5 architectural patterns, 11 structural patterns, and 5 state patterns
- Case studies using the design patterns
- A resilience design spaces framework

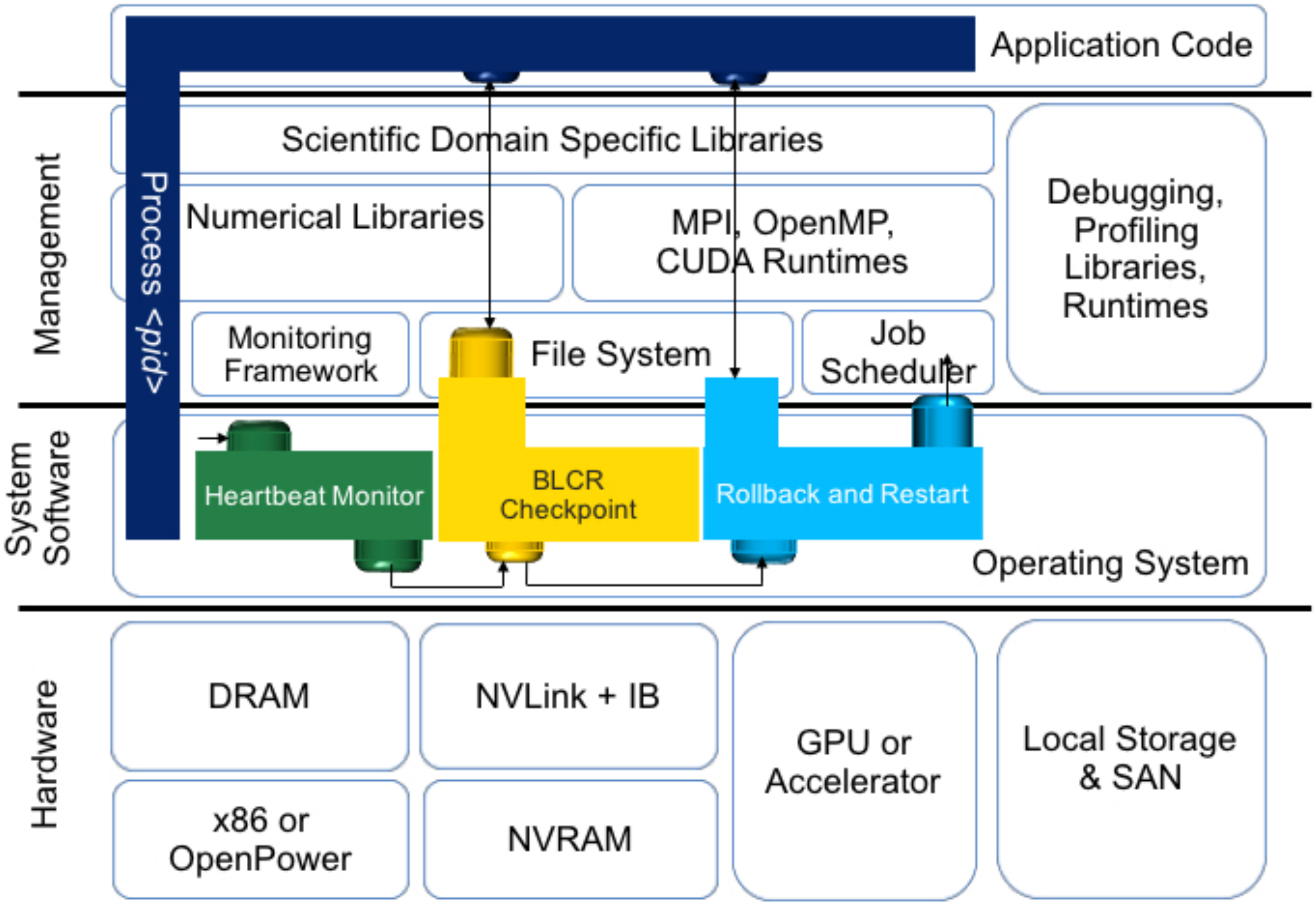


Saurabh Hukerikar and Christian Engelmann. **Resilience Design Patterns: A Structured Approach to Resilience at Extreme Scale (Version 1.2)**. Technical Report, ORNL/TM-2017/745, Oak Ridge National Laboratory, Oak Ridge, TN, USA, August, 2017. DOI: 10.2172/1436045

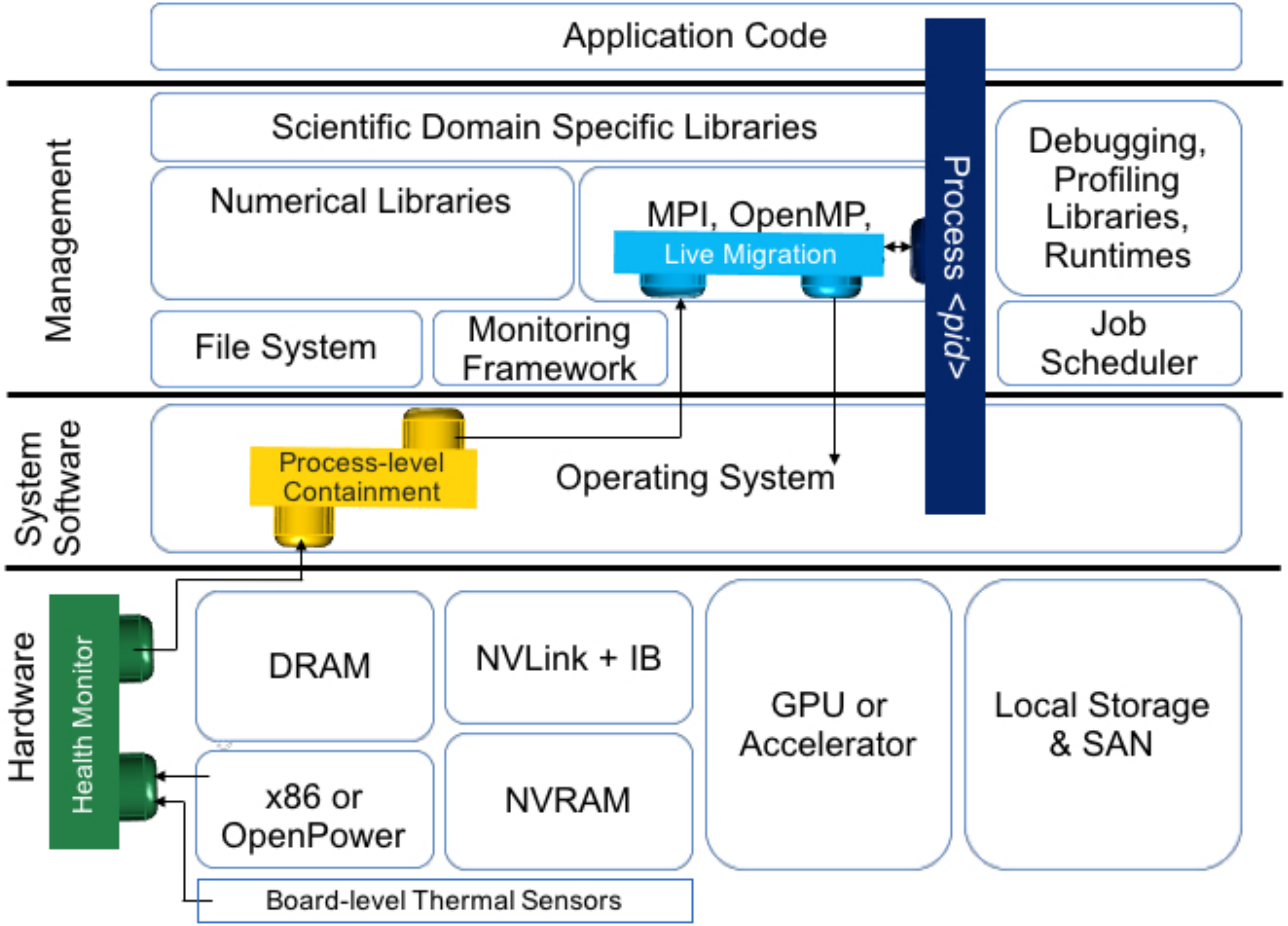
Resilience Design Patterns Classification



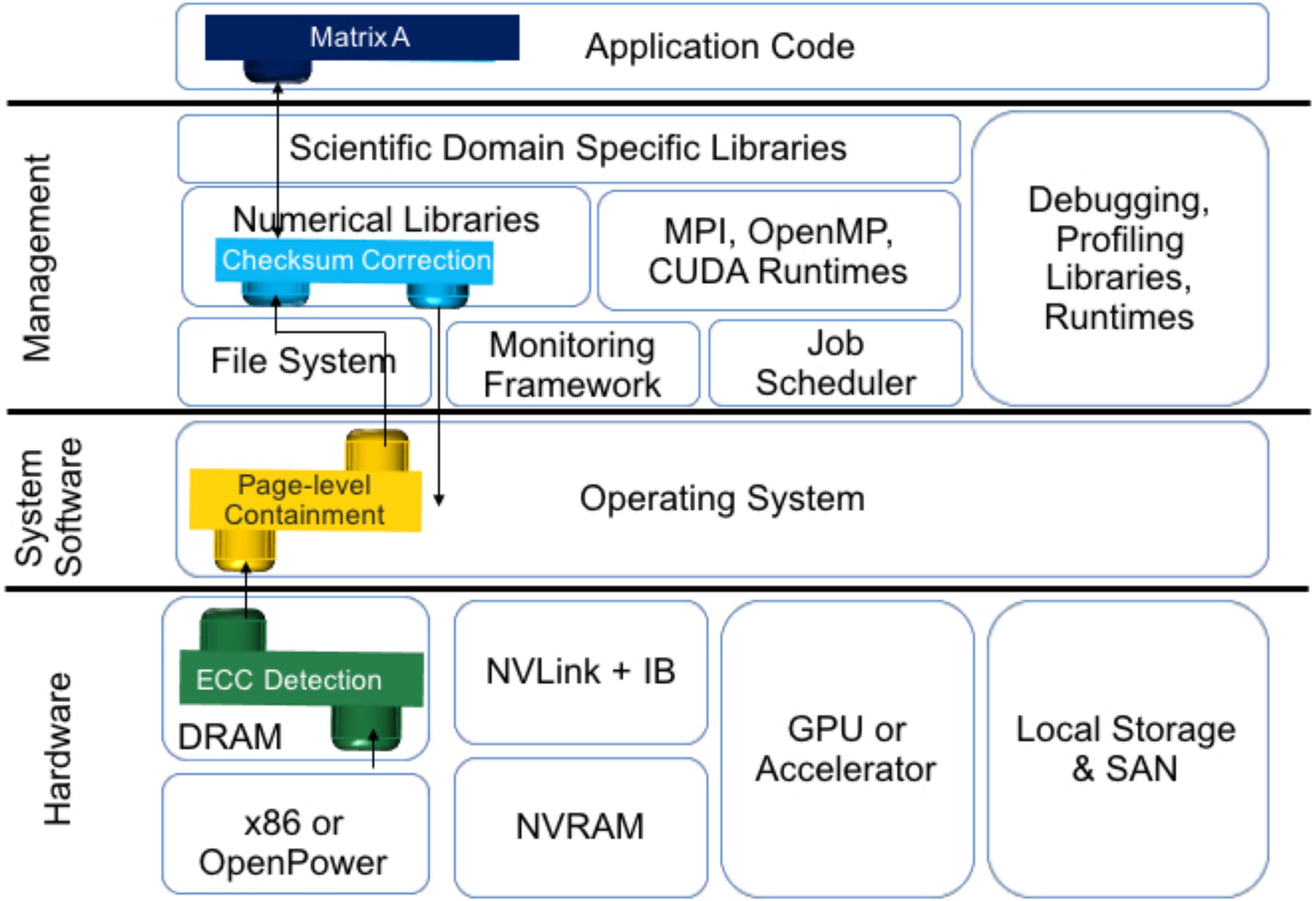
Case Study: Checkpoint Recovery with Rollback



Case Study: Proactive Process Migration



Case Study: Cross-Layer Hardware/Software Hybrid Solution



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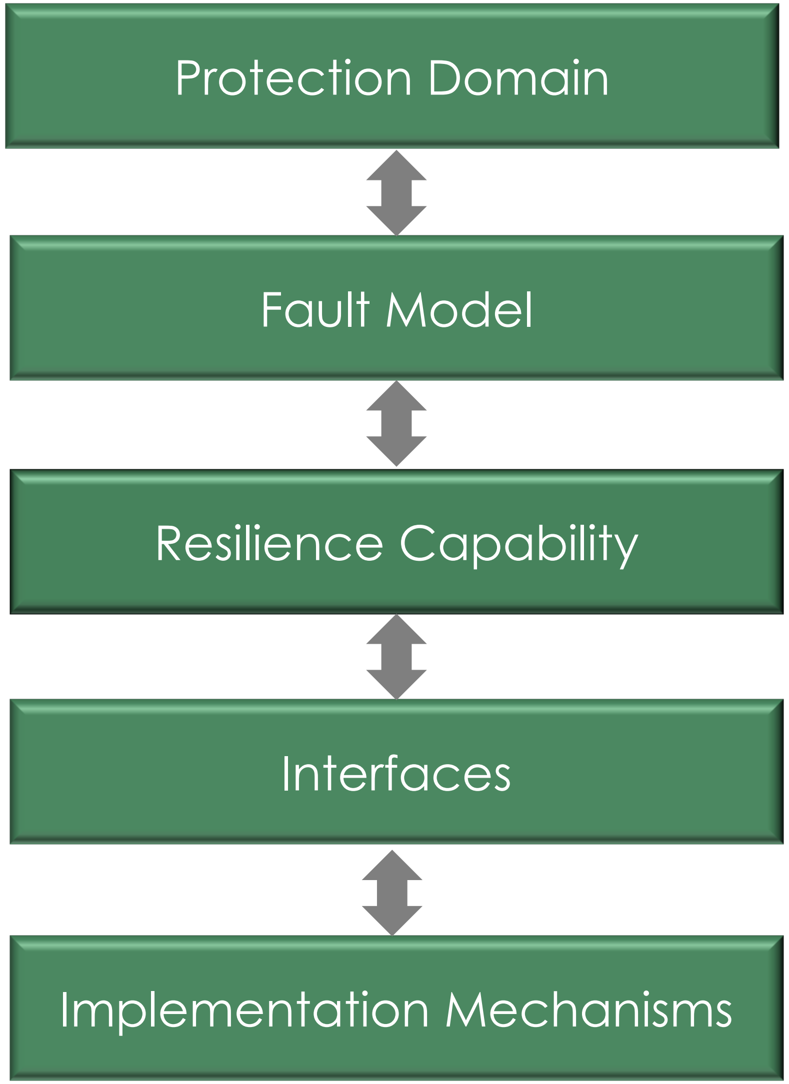
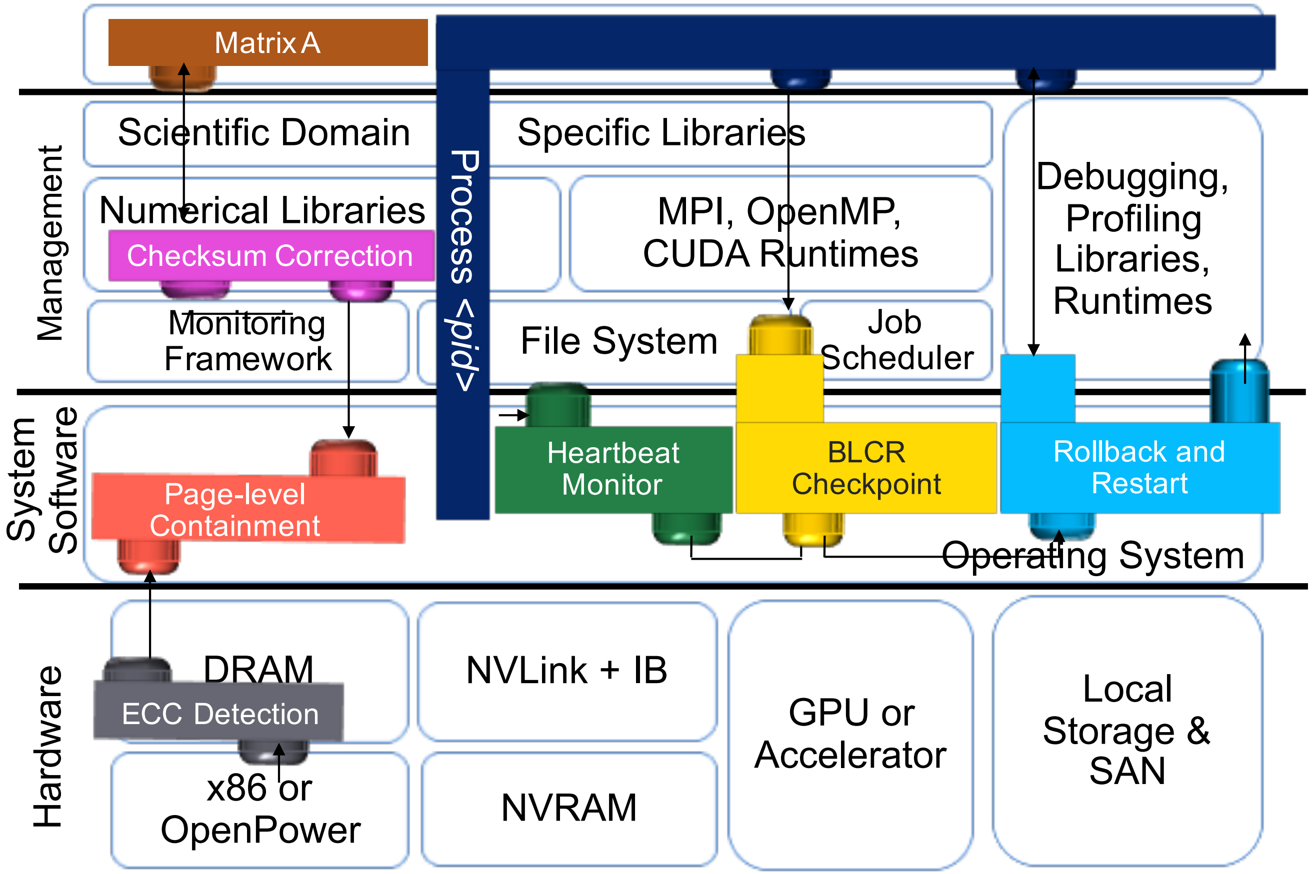
Resilience Design Spaces Framework

- Design for resilience can be viewed as a series of refinements
- The design process is defined by 5 design spaces
- Navigating each design space progressively adds more detail to the overall design of the resilience solution
- A single solution may solve more than one resilience problem
- Multiple solutions often solve different resilience problems more efficiently



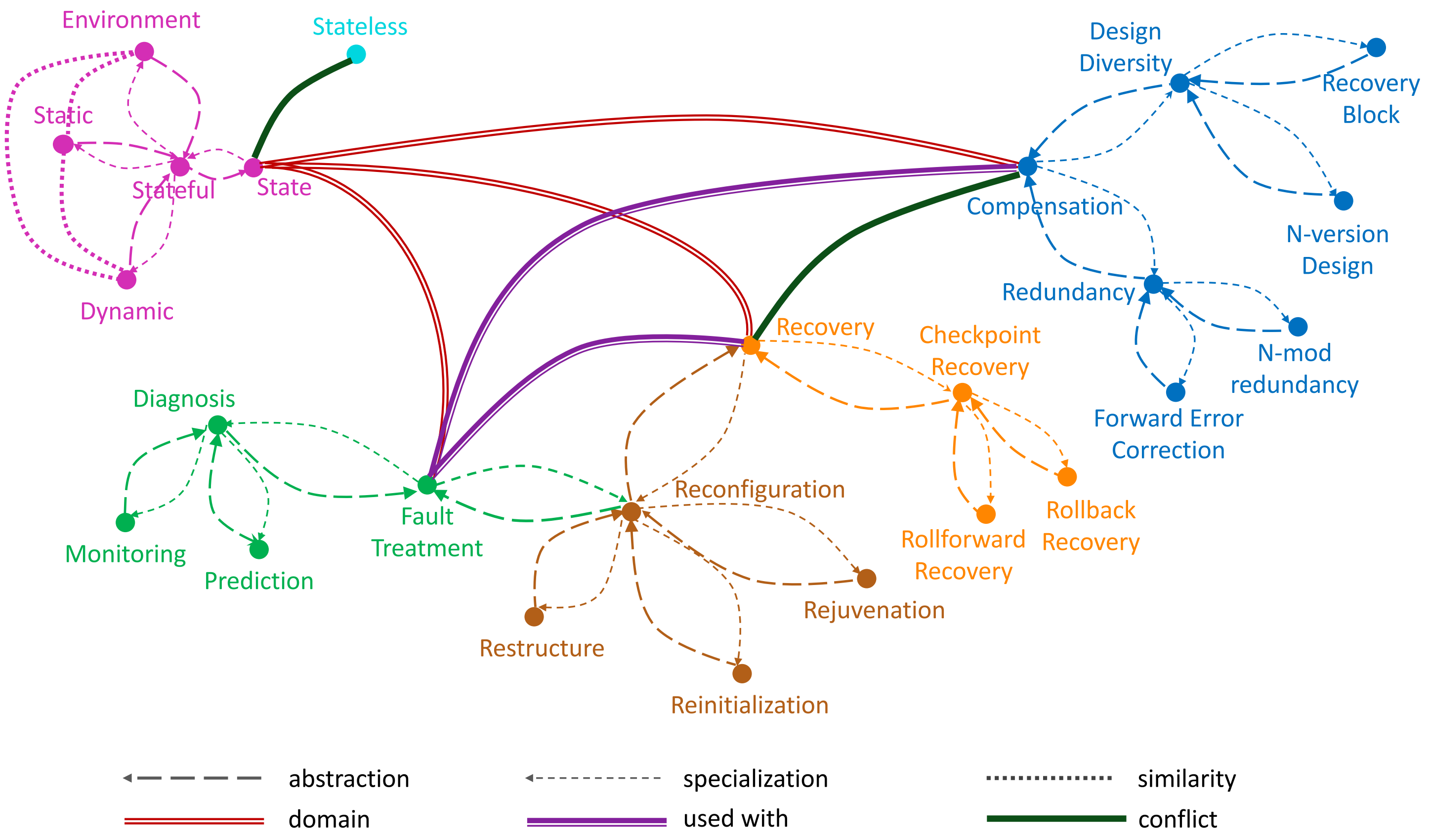
Design Space Exploration for Resilience

- Vertical and horizontal pattern compositions describe the resilience capabilities of a system
- Pattern coordination leverages beneficial and avoids counterproductive interactions
- Pattern composition optimizes the performance, resilience and power consumption trade-off



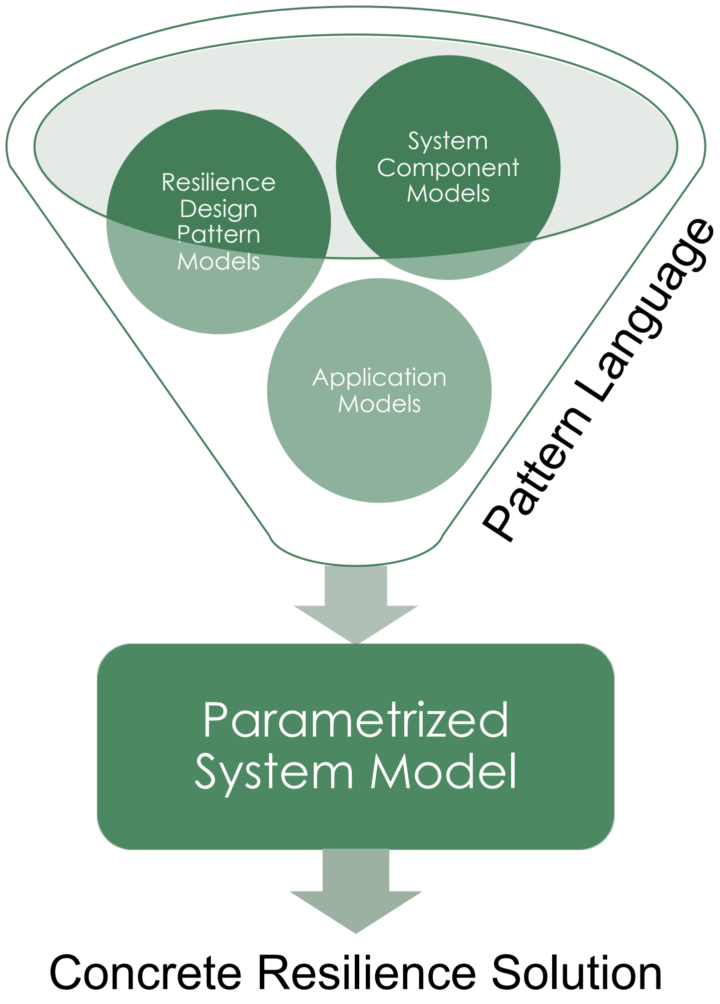
Resilience Design Pattern Language

- Identifies relationships between patterns
  - Abstraction vs. specialization
  - Used with vs. conflict
  - Similarity
  - Domain
- Uses graph representation
- Enables structured analysis



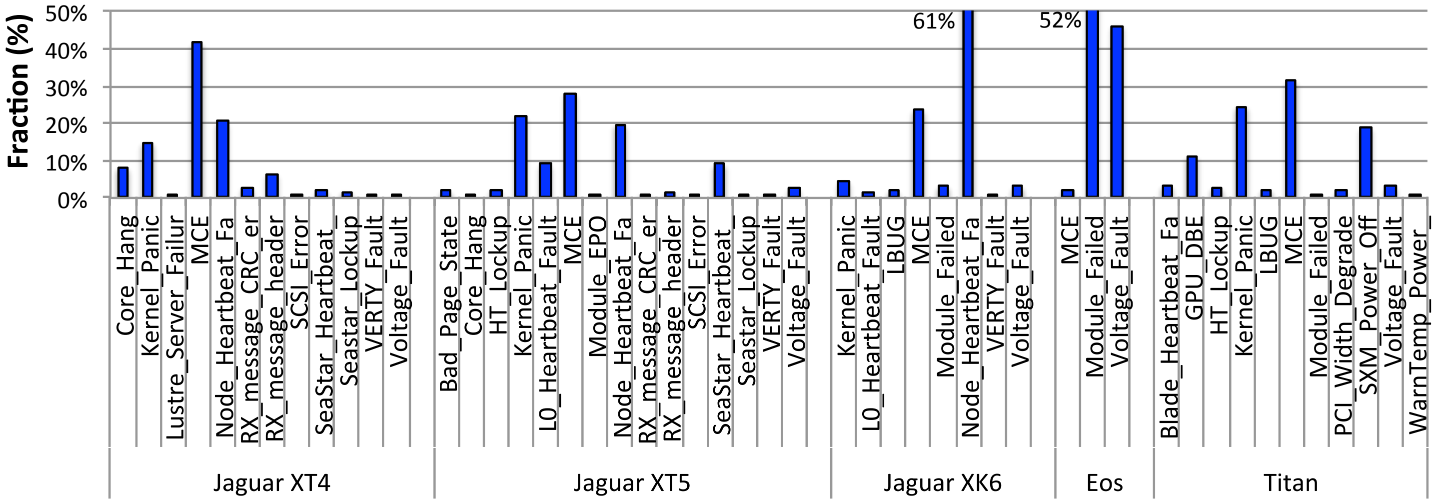
Systematic Modeling & Design of Resilience Solutions

- Abstract the system with models:
  - System component models (performance, resilience and power consumption models)
  - Resilience design pattern models (performance, resilience and power consumption models)
  - Application models (performance, resilience and power consumption models)
- Evaluate solutions using modeling and simulation
- Discover suitability of pattern combinations for system-specific resilience problems
- Predict behavior on different hardware architectures and in different software environments

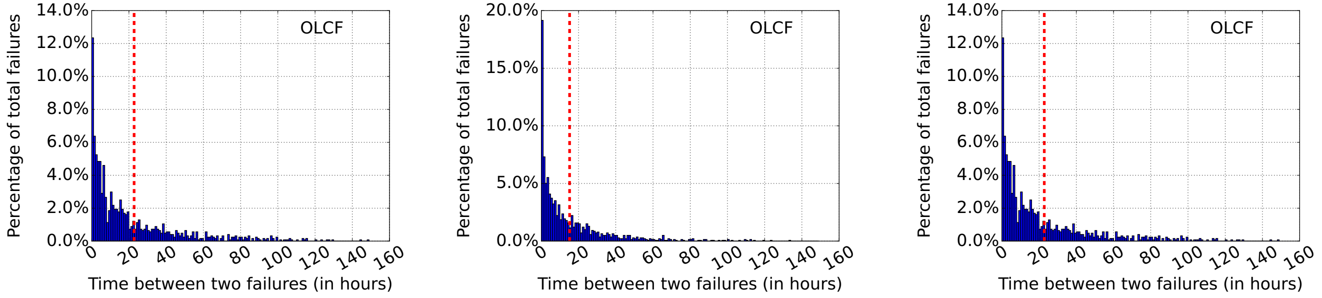


System Component Models

- Already extensive work by ORNL, ANL and LLNL in analyzing DOE systems
- The *Catalog* project identifies, categorizes and models the fault, error and failure properties of DOE systems
  - Fault, error and failure types
  - Probability distributions
  - Temporal and spatial locality and correlation
  - Propagation paths and detection latency



Fraction of each failure type on 5 ORNL systems



Failure inter-arrival time for 3 ORNL systems (MTBF as red vertical line)

Resilience Design Pattern Models

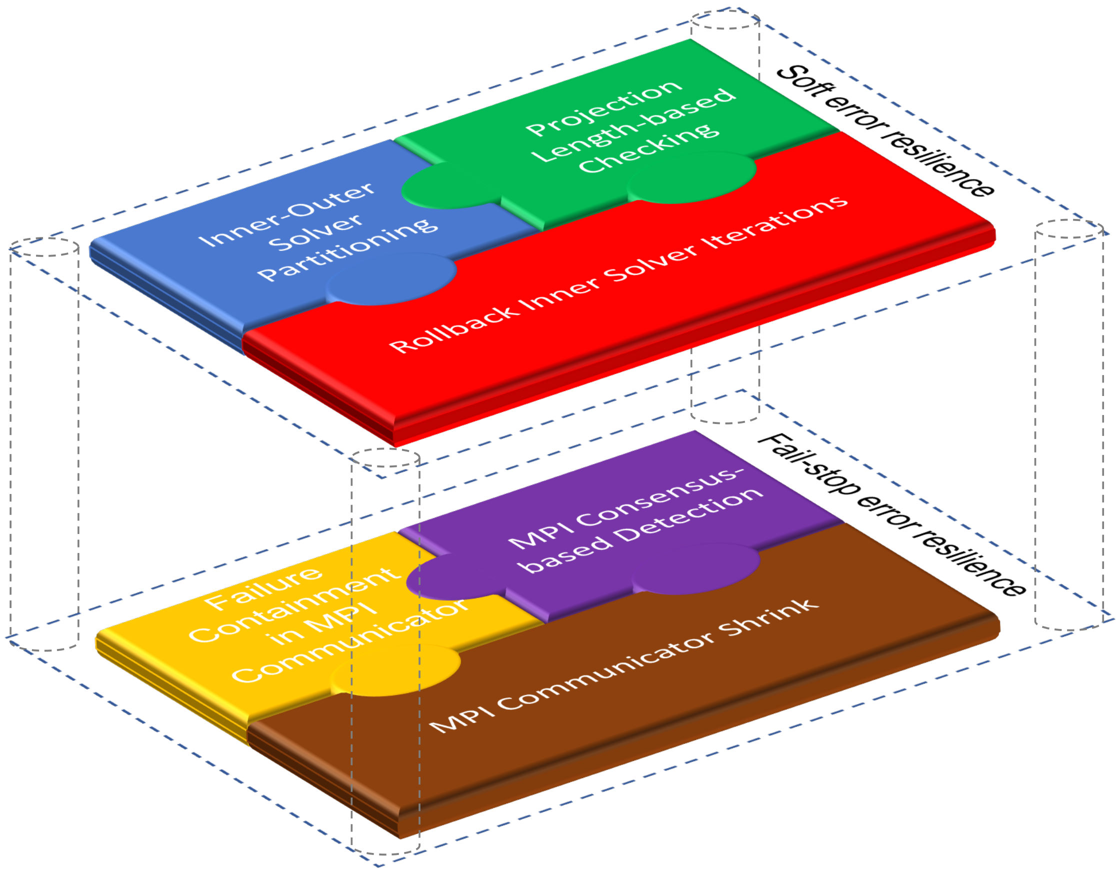
- Preliminary mathematical reliability and performance models for each pattern
  - Take into account detection latency and performance loss due to repair and/or system degradation
- Ongoing work in outcome-based metrics considers value and performance efficiency
  - Correctness and time to solution
- Preliminary power consumption models are still work in progress

Pattern	Performance Model
Fault Diagnosis	$T_{system} = T_0 + \sum_{k=1}^{n} t_{inference}/\eta$
Reconfiguration	$T_{system} = T_{FF} + (1 - T_{FF}).\frac{n-1}{n} + T_R$
Rollback	$T_{system} = (T_{FF} + \gamma)/\eta$ where $\mathrm{T}_{FF} = \mathrm{o} + \delta/\mathrm{r}$.
Roll forward	$T_{system} = o + \delta/r$
Redundancy	$T_{system} = T_{SER}.((1 - \mathcal{A}) + \beta.\mathcal{A})) + T_{MV}$

Application Models

- Significant amount of existing work in application performance models
- Some amount of existing work in application reliability models
  - Application vulnerability studies
  - Error propagation patterns
  - Resilient solvers
  - *More work is needed*
- Some amount of existing work in application power consumption models
  - *More work is needed*

FT-GMRES Solver



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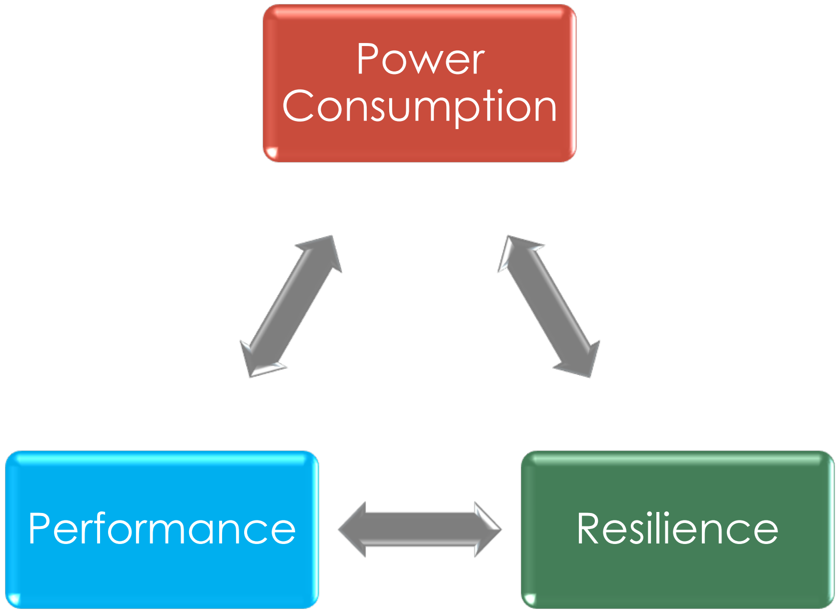
Modeling and Simulation for Design Space Exploration (Future Work)

- Model the performance, resilience, and power consumption of an entire system
- Start at compute-node granularity with
  - System component models
  - Resilience design pattern models
  - Application models
- Simulate dynamic interactions between the system, resilience solutions and applications
- Move to finer-grain resolution to include on-node communication, computation and storage
- Build upon prior work with the Extreme-scale Simulator (xSim)



Contact & Acknowledgements

- Web site: https://ornlwiki.atlassian.net/wiki/spaces/RDP
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