Resiliency for high-performance computing

Presented by

Christian Engelmann

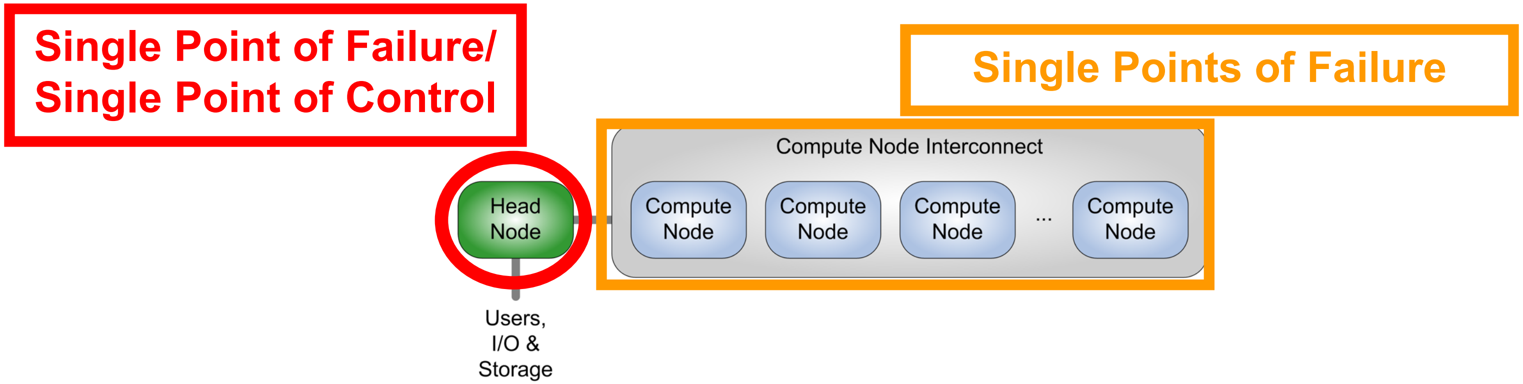
Computer Science and Mathematics Division
Oak Ridge National Laboratory, Oak Ridge, TN, USA

OAK RIDGE National Laboratory

Outline

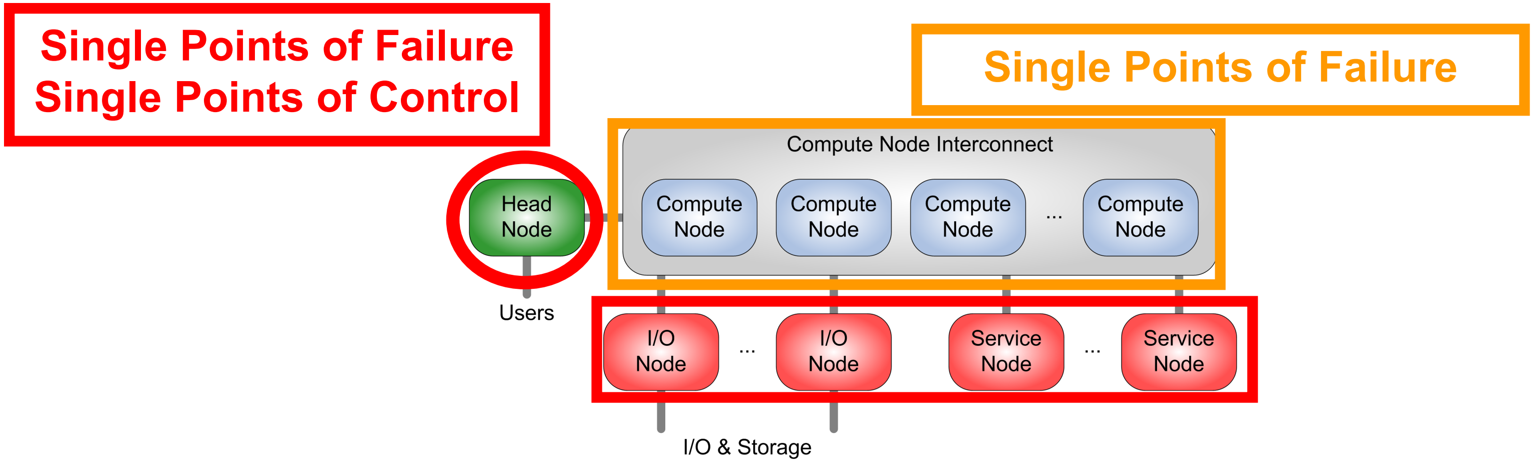
- Resilience deficiencies of high-performance computing architectures
- Research and development goals and projects overview
- Symmetric active/active redundancy for head and service nodes
- Job pause approach for reactive compute node fault tolerance
- Pre-emptive migration for proactive compute node fault tolerance
- Reliability analysis and modeling for fault prediction and anticipation
- Evaluation of compute node fault tolerance policies using simulation
- Vision of a holistic resiliency framework concept
- Conclusion: Achievements, ongoing work and future plans

Traditional Beowulf cluster computing architecture



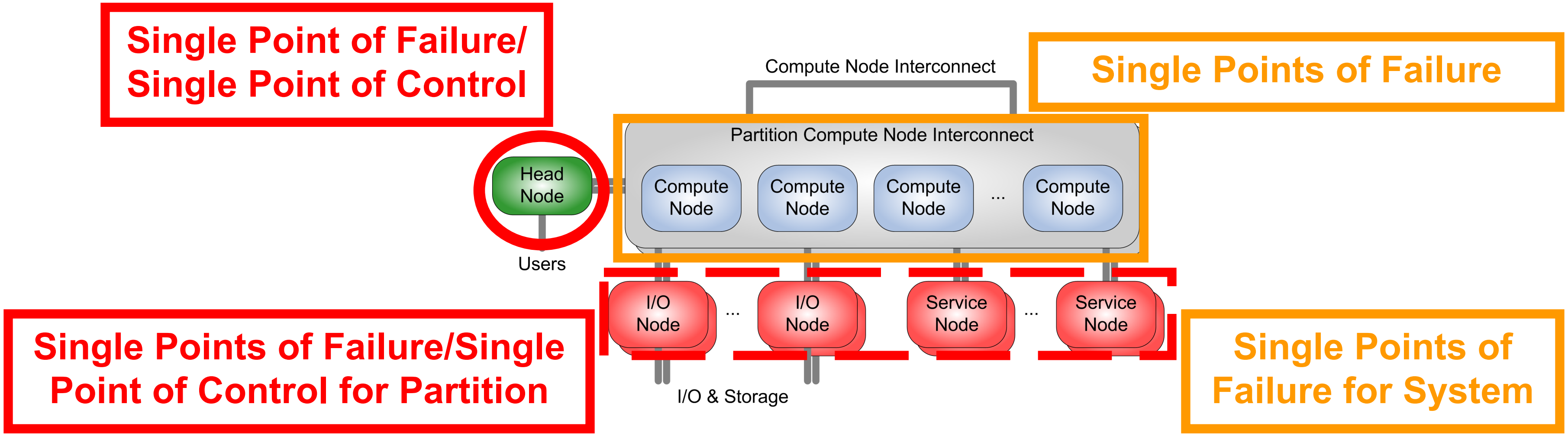
- Single head node manages entire HPC system
- System-wide services are provided by head node:
  - Job & resource management, networked file system, …
- Local services are provided by compute nodes
  - Message passing (MPI, PVM), …

Recent trend toward massively parallel processing (MPP) architectures



- **Single head node and additional service nodes manage the entire HPC system**
- **System-wide services are provided by head node and are offloaded to service nodes, e.g., networked file system**
- **Local services are provided by service nodes and compute nodes, e.g., message passing**

Recent trend toward partitioned MPP architectures



- **Single head node manages entire HPC system**
- **Service nodes manage and support compute nodes belonging to their partitions**

Availability Measured by the Nines

http://info.nccs.gov/resources - HPC system status at Oak Ridge National Laboratory

9's	Availability	Downtime/Year	Examples
1	90.0%	36 days, 12 hours	Personal Computers
2	99.0%	87 hours, 36 min	Entry Level Business
3	99.9%	8 hours, 45.6 min	ISPs, Mainstream Business
4	99.99%	52 min, 33.6 sec	Data Centers
5	99.999%	5 min, 15.4 sec	Banking, Medical
6	99.9999%	31.5 seconds	Military Defense

- Enterprise-class hardware + Stable Linux kernel = 5+
- Substandard hardware + Good high availability package = 2-3
- Today's supercomputers = 1-2
- My desktop = 1-2

Typical Failure Causes in HPC Systems

- **Hardware failures due to wear/age of:**
  - Hard drives, memory modules, network cards, and processors
- **Software failures due to bugs in:**
  - Operating system, middleware, applications
- **Stress-related failures that exceed design specifications in:**
  - Hardware, e.g. due to excessive heat radiation
  - Software, e.g. due to (unintentional) denial of service
- **Radiation-induced soft errors (bit flips due to electromagnetic interference, heat radiation, natural neutron radiation) in:**
  - Memory modules, network cards, and processors

➔ **Different scale requires different solutions:**
  - Compute nodes (up to 150,000)
  - Front-end, service, and I/O nodes (1 to 150)

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Research and development goals

- <u>Efficient redundancy strategies</u> for head and service nodes in HPC systems to provide high availability as well as high performance of critical infrastructure services
- <u>Reactive fault tolerance</u> for HPC compute nodes utilizing the job pause approach as well as checkpoint interval and placement adaptation to actual and predicted system health threats
- <u>Proactive fault tolerance</u> using system-level virtualization in HPC environments for pre-emptive migration of computation away from compute nodes that are about to fail
- <u>Reliability analysis</u> for identifying pre-fault indicators, predicting failures, and modeling and monitoring of individual component and overall HPC system reliability
- <u>Holistic fault tolerance</u> technology through combination of adaptive proactive and reactive fault tolerance mechanisms in conjunction with system health monitoring and reliability analysis

MOLAR: Adaptive runtime support for high-end computing operating and runtime systems

- **Previous effort: 2004-2007**
- **Addresses the challenges for operating and runtime systems to run large applications efficiently on large-scale supercomputers**
- **Part of the Forum to Address Scalable Technology for Runtime and Operating Systems (FAST-OS)**
- **MOLAR is a collaborative research effort (www.fastos.org/molar):**

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Reliability, Availability, and Serviceability (RAS) for Petascale High-End Computing and Beyond

- **Current effort: 2008-2011**
- **Addresses the fault resilience challenges for operating and runtime systems of next-generation large-scale supercomputers**
- **Part of the Forum to Address Scalable Technology for Runtime and Operating Systems (FAST-OS)**
- **RAS HPC is a collaborative research effort (www.fastos.org/ras):**

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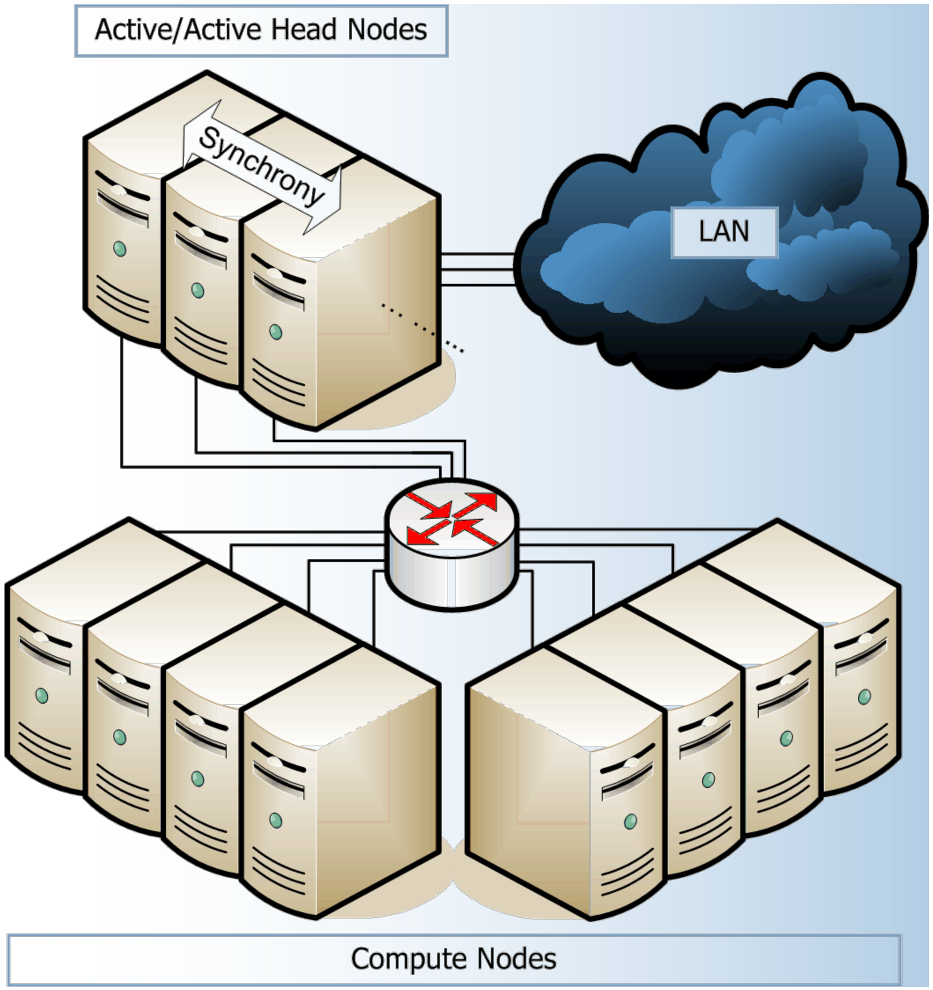
Symmetric active/active redundancy for head and service nodes



- Many active head nodes
- Work load distribution
- Symmetric replication between head nodes
- Continuous service
- Always up to date
- No fail-over necessary
- No restore-over necessary
- Virtual synchrony model
- ↓ Complex algorithms
- → Prototypes for PBS Torque and PVFS metadata server

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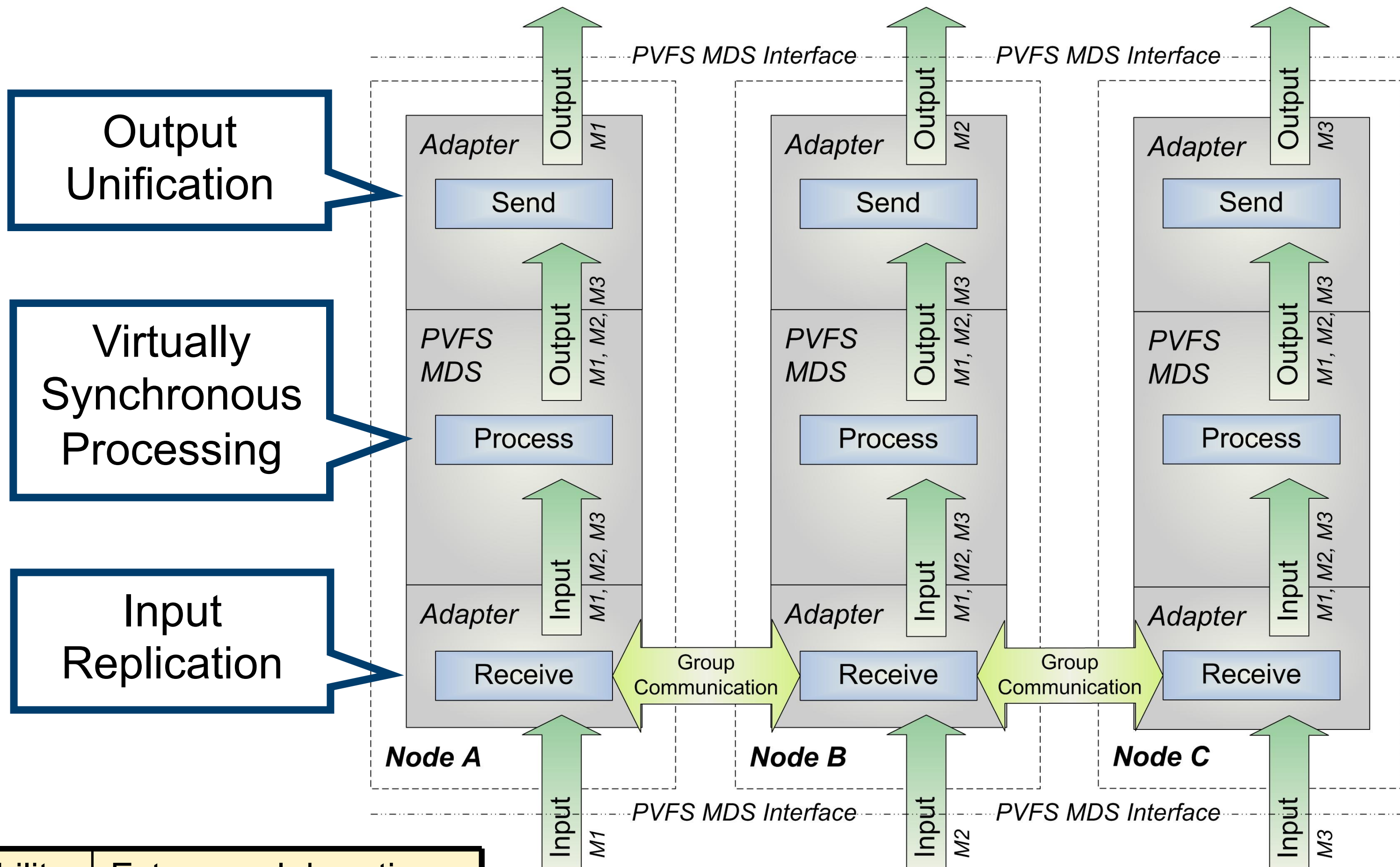
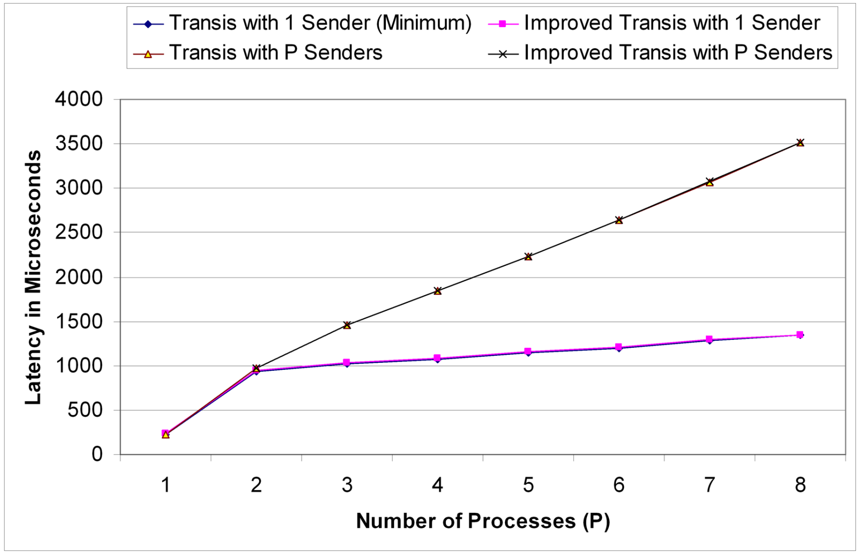
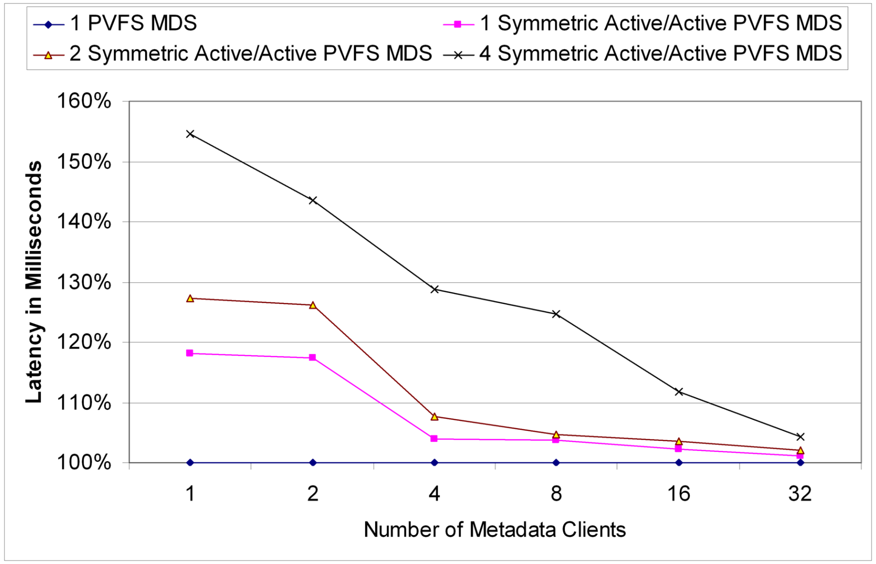
Symmetric active/active replication

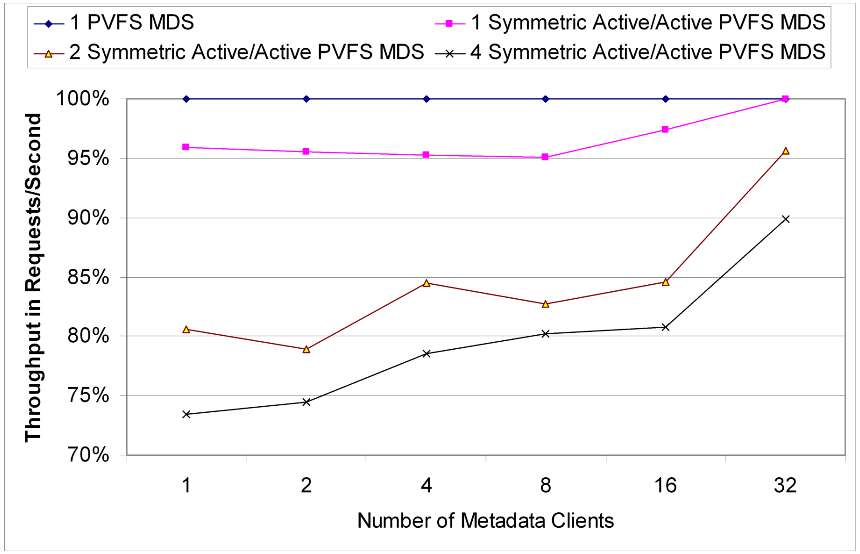


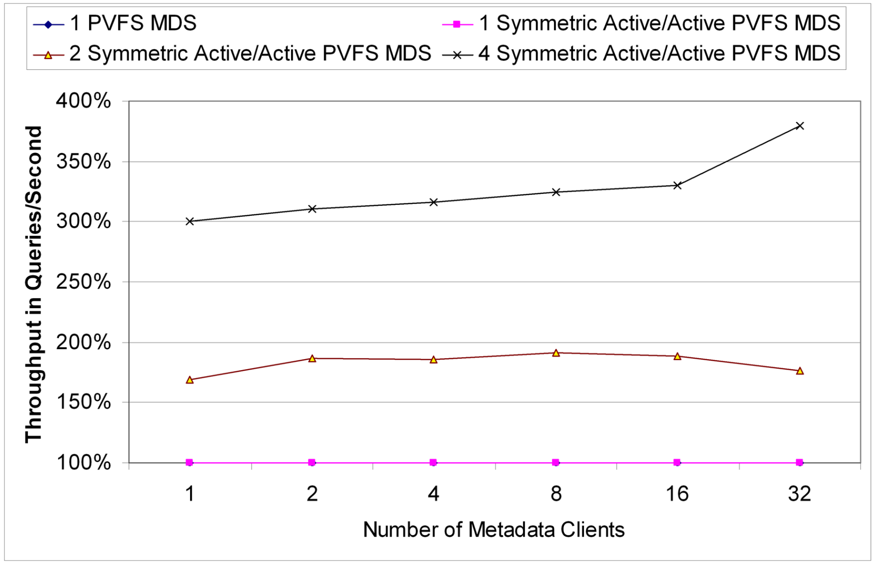
Nodes	Availability	Est. annual downtime
1	98.58%	5d 4h 21m
2	99.97%	1h 45m
3	99.9997%	1m 30s

Symmetric active/active Parallel Virtual File System metadata service









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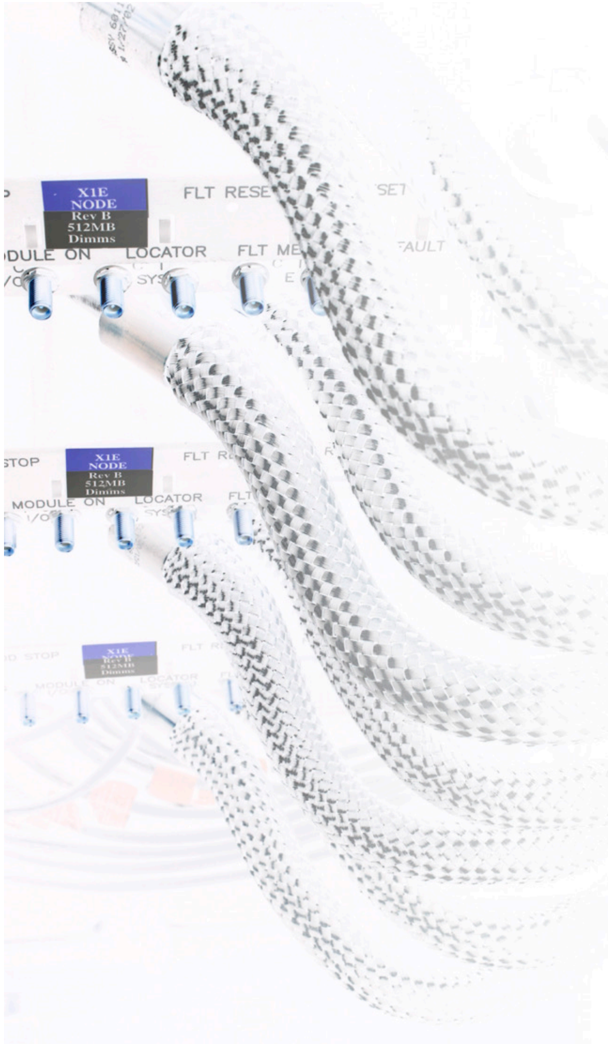
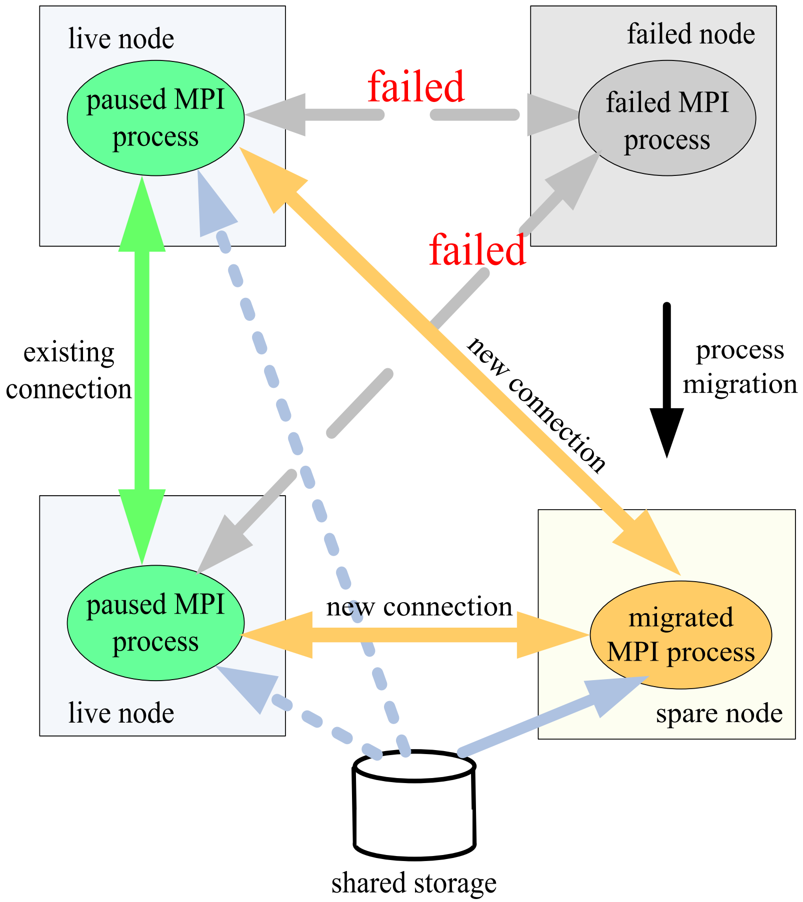
Reactive vs. proactive fault tolerance for compute nodes



- **Reactive fault tolerance:**
  - State saving during failure-free operation
  - State recovery after failure
  - Assured quality of service, but limited scalability
- **Proactive fault tolerance:**
  - System health monitoring and online reliability modeling
  - Failure anticipation and prevention through prediction and reconfiguration before failure
  - Highly scalable, but not all failures can be anticipated

➔ **Ideal solution: Matching combination of both**

Enhanced reactive fault tolerance with LAM/MPI+BLCR job pause mechanism



- Operational nodes: Pause
  - BLCR reuses existing processes
  - LAM/MPI reuses existing connections
  - Restore partial process state from checkpoint
- Failed nodes: Migrate
  - Restart process on new node from checkpoint
  - Reconnect with paused processes

➔ Scalable MPI membership management for low overhead

➔ Efficient, transparent, and automatic failure recovery

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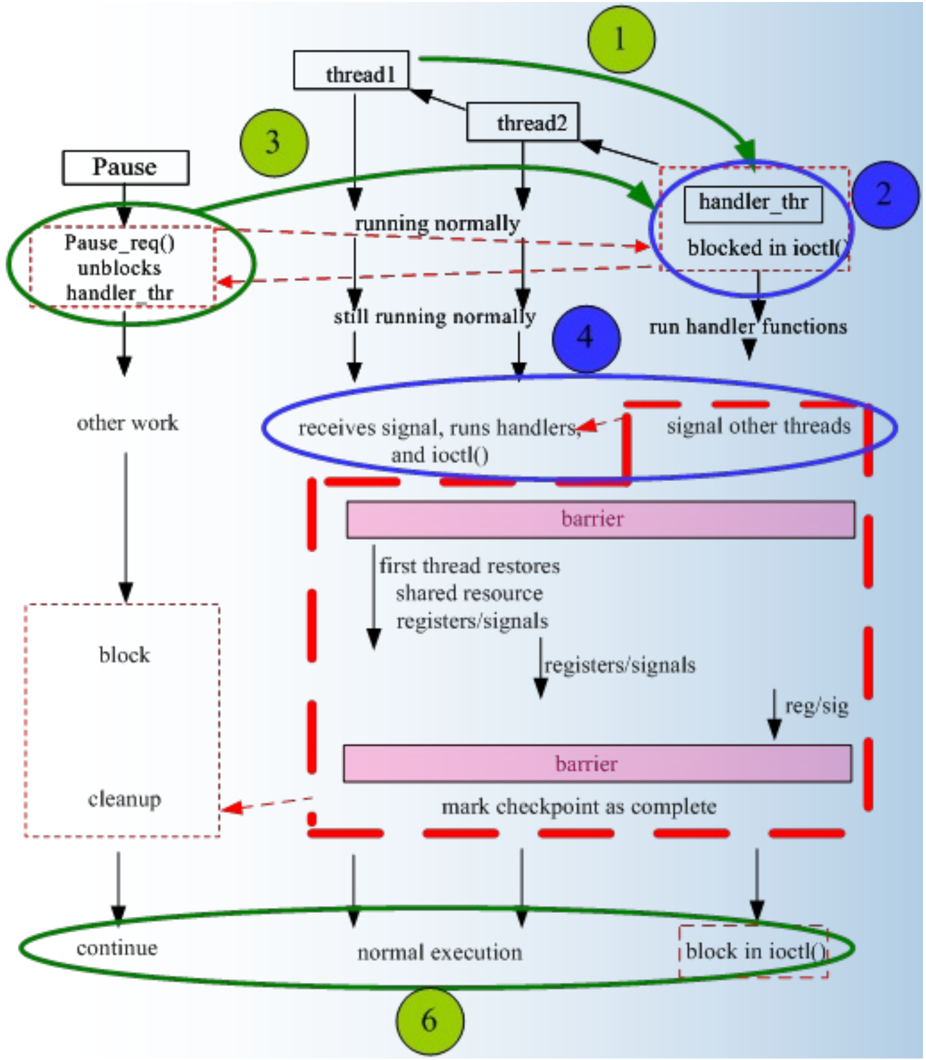
New job pause mechanism in BLCR

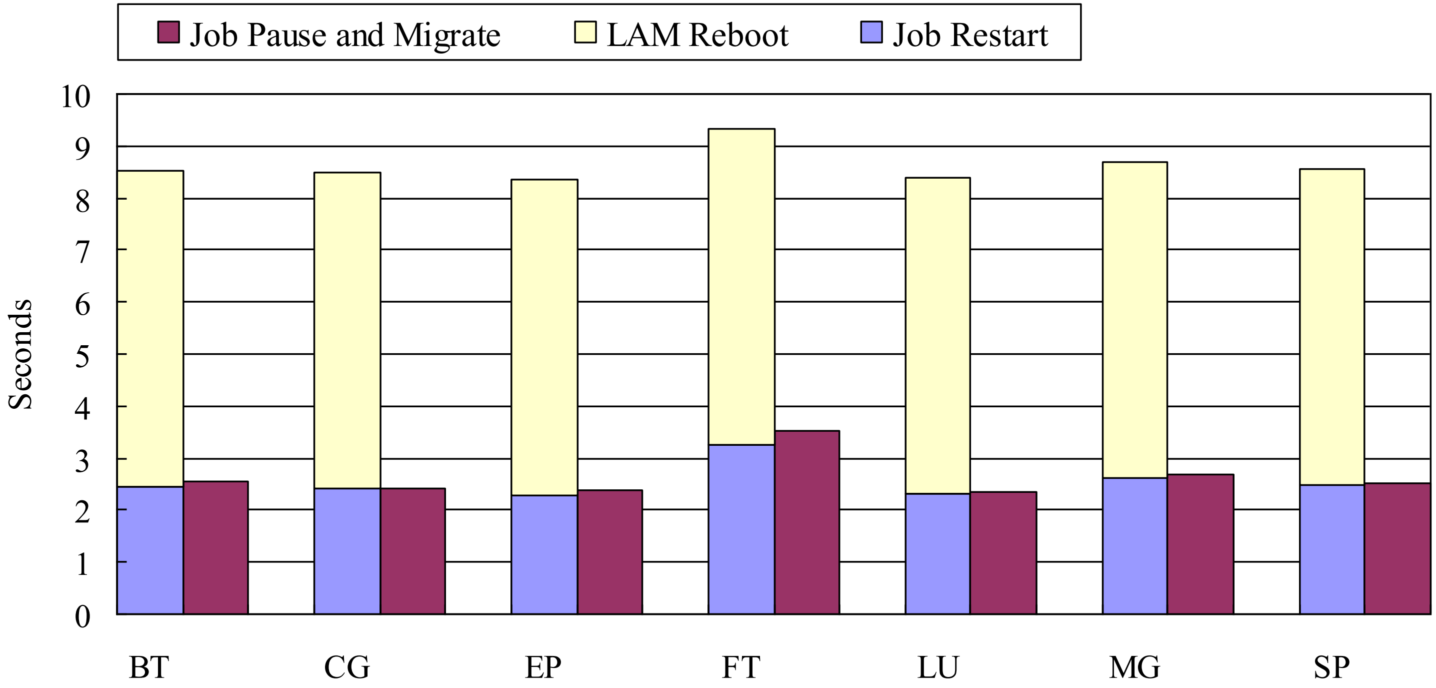
- **Application registers threaded callback ➔ spawns callback thread**
- **Thread blocks in kernel**
- **Pause utility calls ioctl(), unblocks callback thread**
- **All threads complete callbacks and enter kernel**

➔ **New: All threads restore part of their states**

- **Run regular application code from restored state**



LAM/MPI+BLCR job pause performance



- **3.4% overhead over job restart, but**
  - **No LAM reboot overhead**
  - **Transparent continuation of execution**
- **No re-queue penalty**
- **Less staging overhead**

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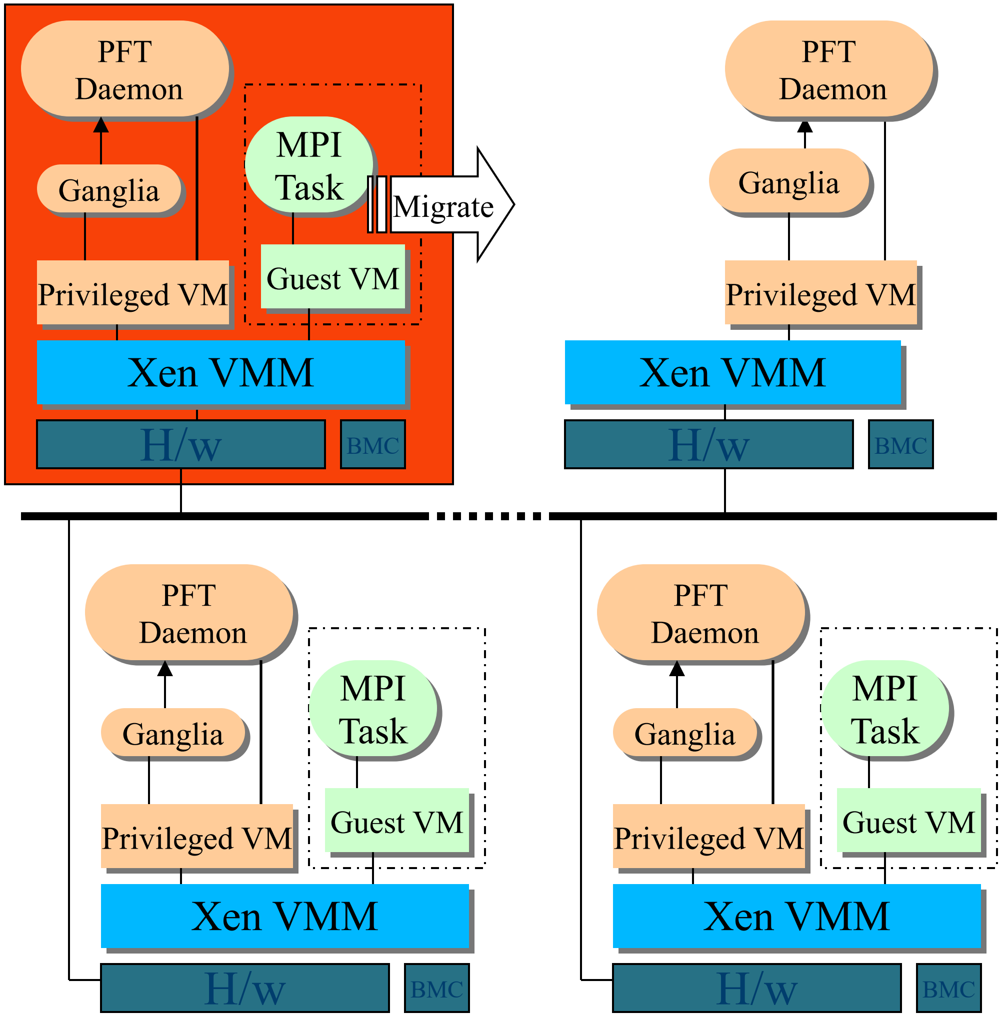
Proactive fault tolerance using Xen virtualization



- **Stand-by Xen host (spare node without guest VM)**
- **Deteriorating health:**
  - **Migrate guest VM to spare node**
- **New host generates unsolicited ARP reply**
  - **Indicates that guest VM has moved**
  - **ARP tells peers to resend to new host**

➔ **Novel fault tolerance scheme that acts before a failure impacts a system**

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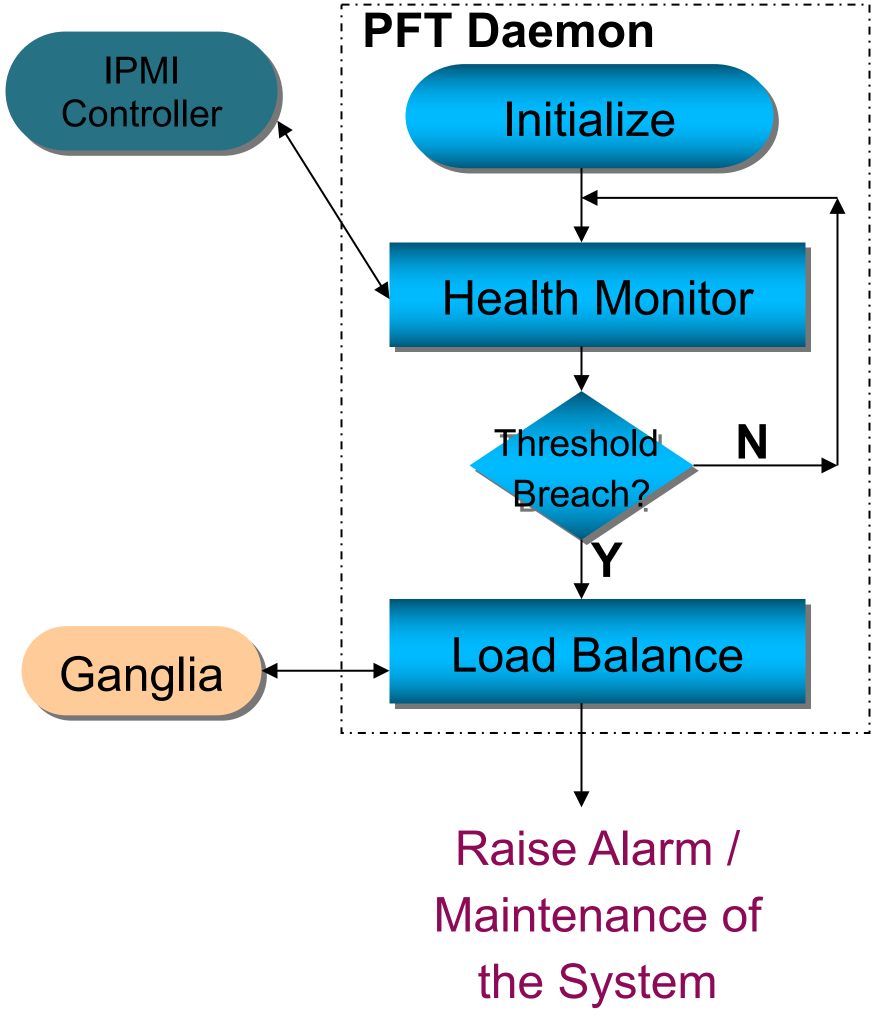
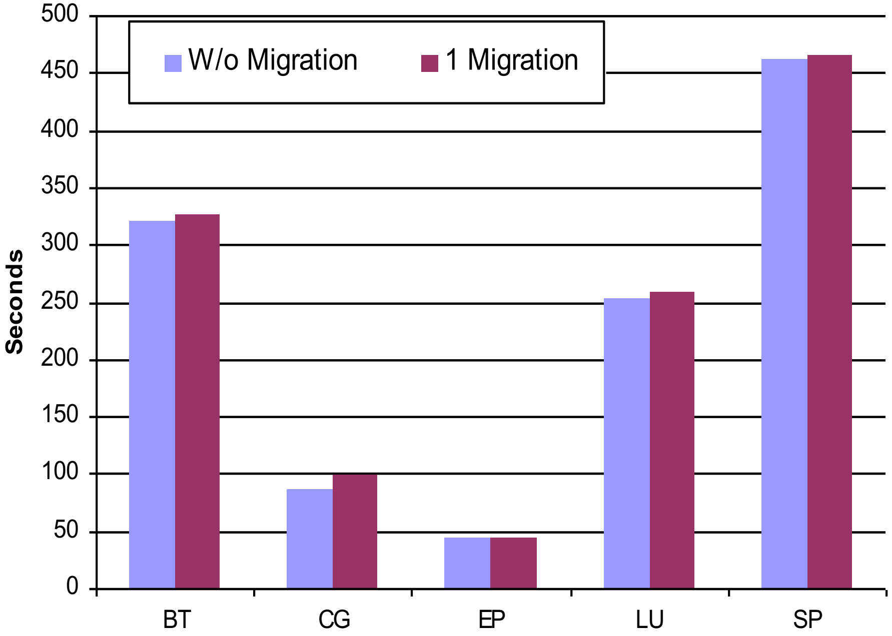
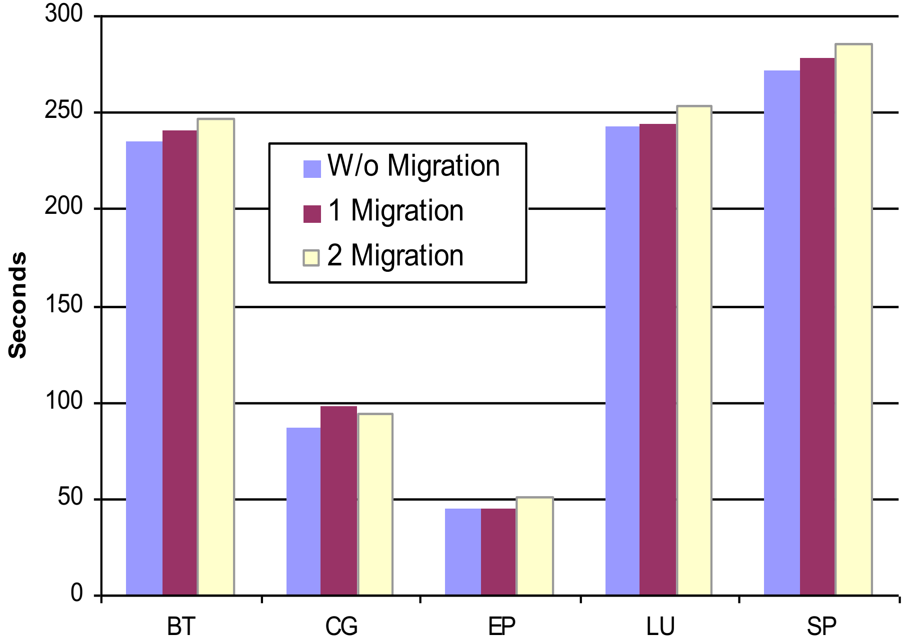
Proactive fault tolerance (PFT) daemon

- **Runs in privileged domain (host)**
- **Initialization**
  - **Read safe threshold from config file**
  - **Init connection with IPMI controller**
  - **Obtain/filter set of available sensors**
- **Health monitoring**
  - **Read sensors from IPMI controller**
  - **Periodically sample data**
  - **Trigger load balancing if exceeding sensor threshold**
- **VM migration**
  - **Select target based on load**
  - **Invoke Xen live migration for VM**



VM migration performance impact





- **Single node failure: 0.5-5% additional cost over total wall clock time**
- **Double node failure: 2-8% additional cost over total wall clock time**

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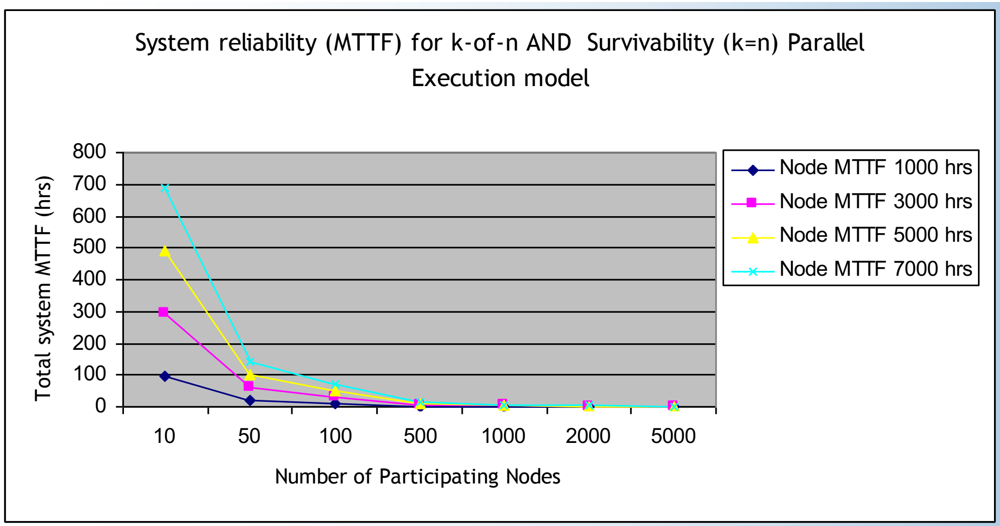
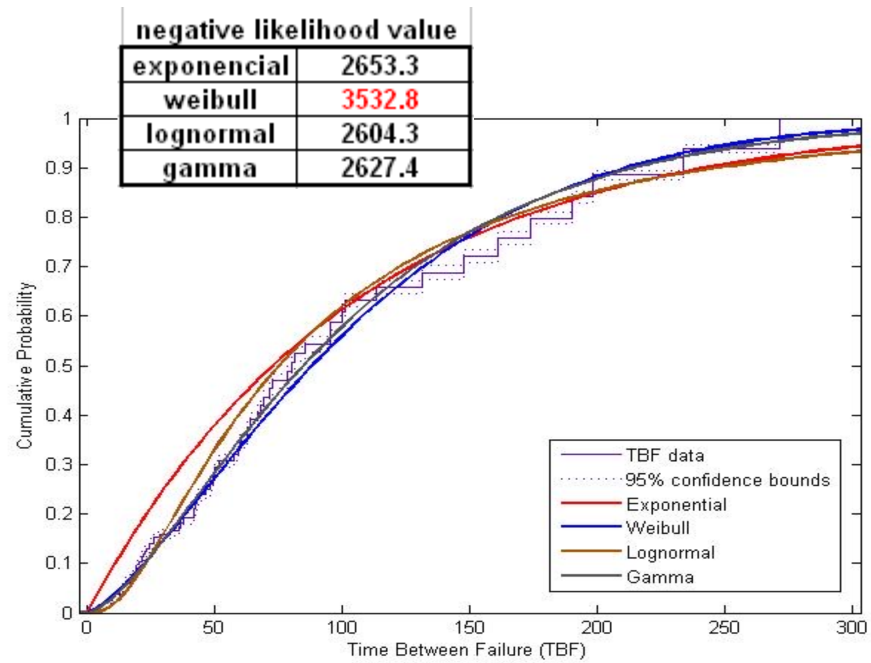
HPC reliability analysis and modeling for prediction and anticipation

- **Programming paradigm and system scale impact reliability**
- **Reliability analysis:**
  - **Estimate mean time to failure (MTTF)**
  - **Obtain failure distribution: Exponential, Weibull, Gamma, ...**
- **Feedback into fault tolerance schemes for adaptation**





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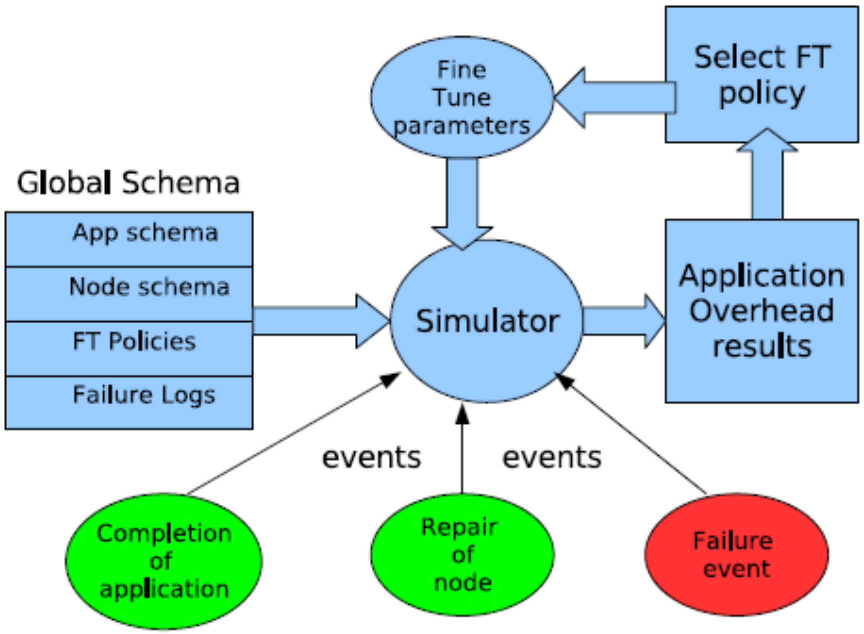
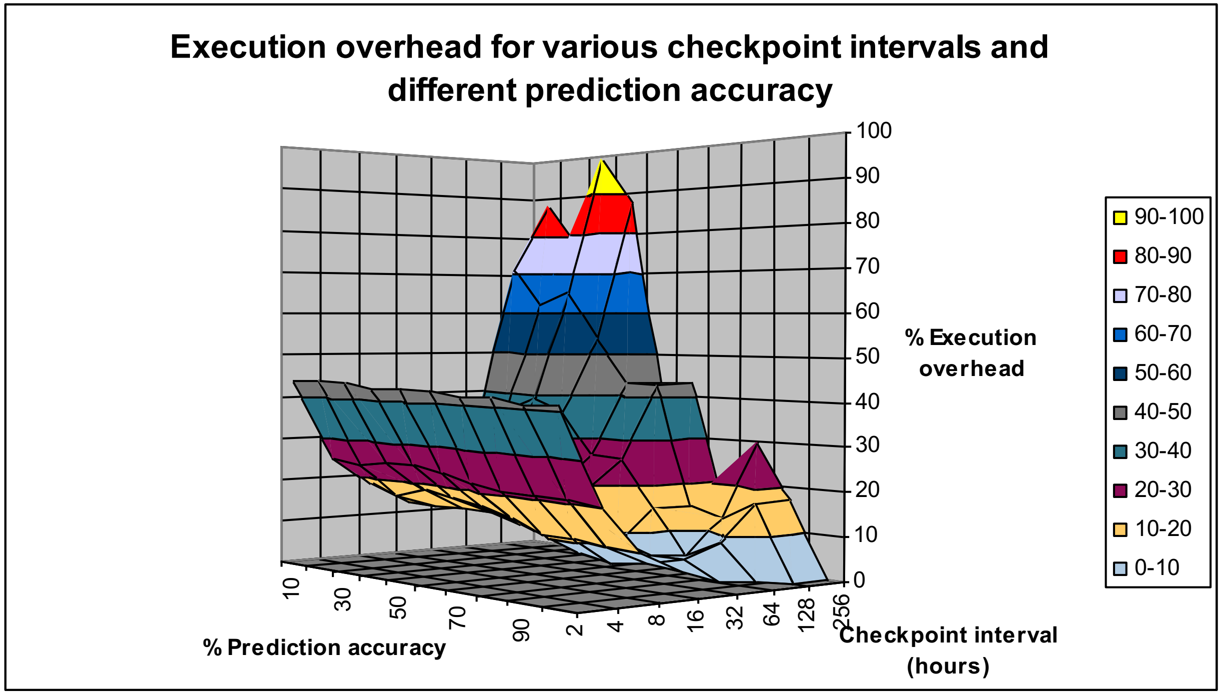
Simulation framework for HPC fault tolerance policies

- Evaluation of fault tolerance policies
  - Reactive only
  - Proactive only
  - Reactive/proactive combination
- Evaluation of fault tolerance parameters
  - Checkpoint interval
  - Prediction accuracy
- Event-based simulation framework using actual HPC system logs
- Customizable simulated environment
  - Number of active and spare nodes
  - Checkpoint and migration overheads



Combination of proactive and reactive fault tolerance: Simulation example 1

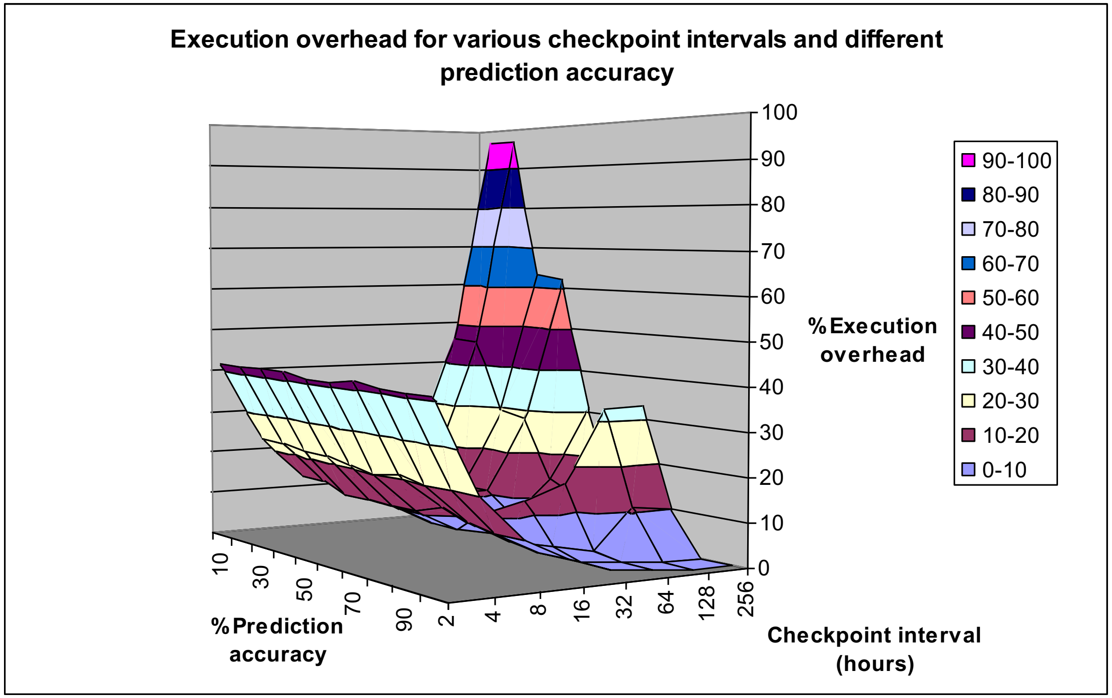


- Best: Prediction accuracy >60% and checkpoint interval 16-32 hours
- Better than only proactive or only reactive
- Results for higher prediction accuracies and very low checkpoint intervals are worse than only proactive or only reactive

Number of processes	125
Active nodes / Spare nodes	125 / 12
Checkpoint overhead	50 min/Checkpoint
Migration overhead	1 min/Migration

Simulation based on ASCI White system logs (nodes 1 – 125 and 500-512)

Combination of proactive and reactive fault tolerance: Simulation example 2



- **Best: Accuracy >60%, interval 16-64h**
- **70% and 32 hours:**
  - **8% gain over reactive only**
  - **24% gain in over proactive only**
- **80% and 32 hours:**
  - **10% gain over reactive only**
  - **3% loss over proactive only**

Number of processes	**125**
Active nodes / Spare nodes	**125 / 12**
Checkpoint overhead	**50 min/Checkpoint**
Migration overhead	**1 min/Migration**

Simulation based on ASCI White system logs (nodes 126 – 250 and 500-512)

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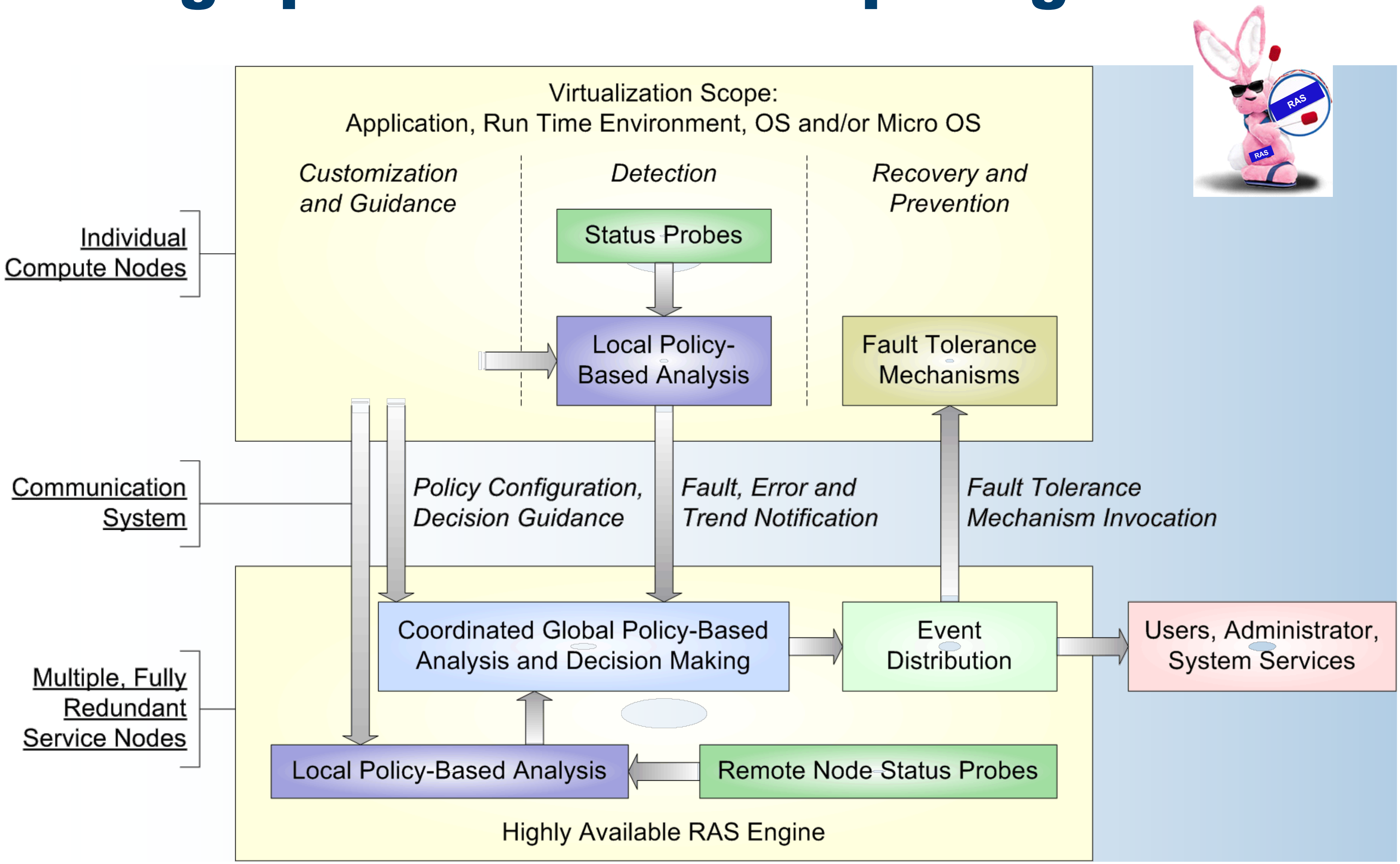
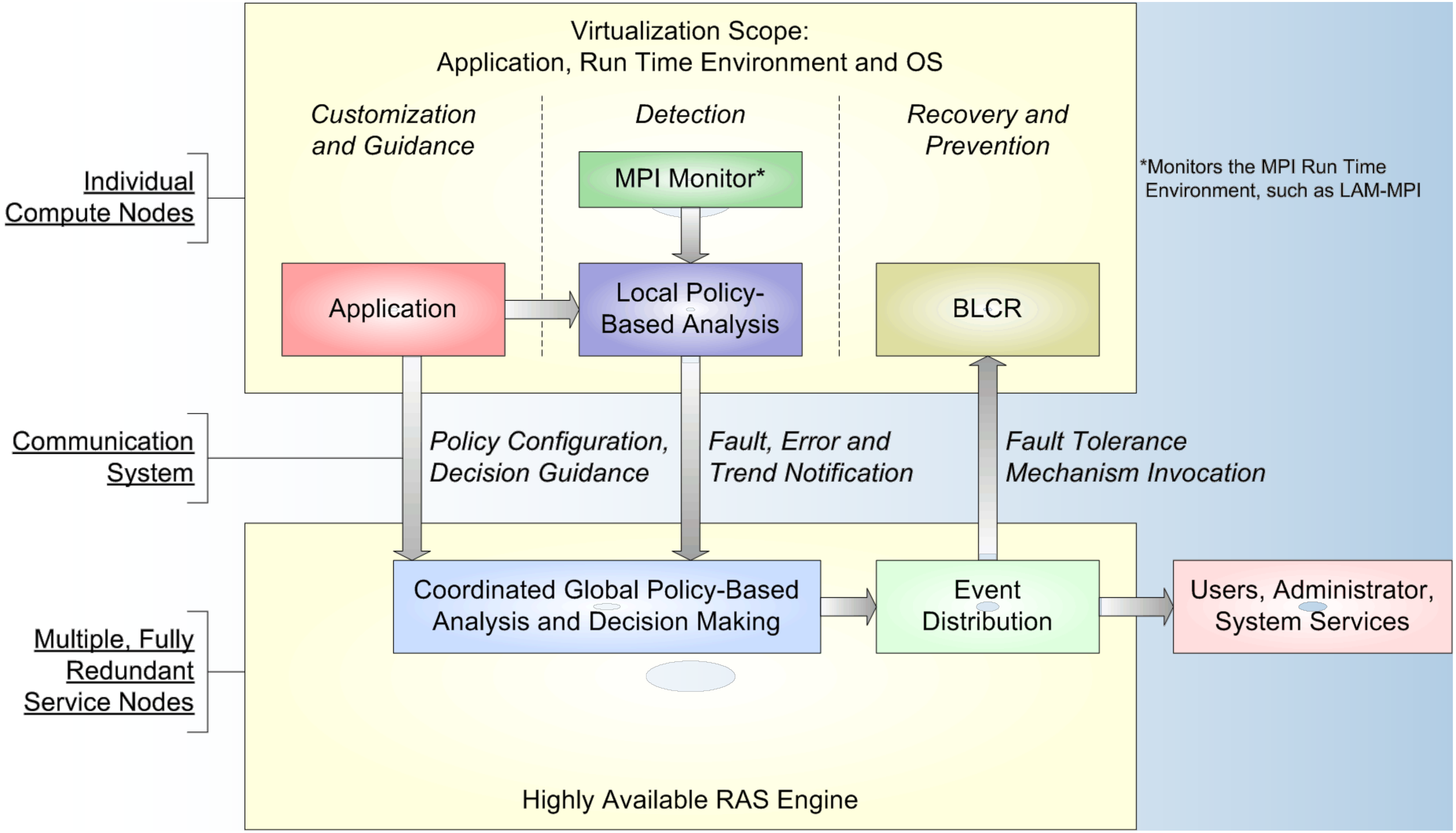
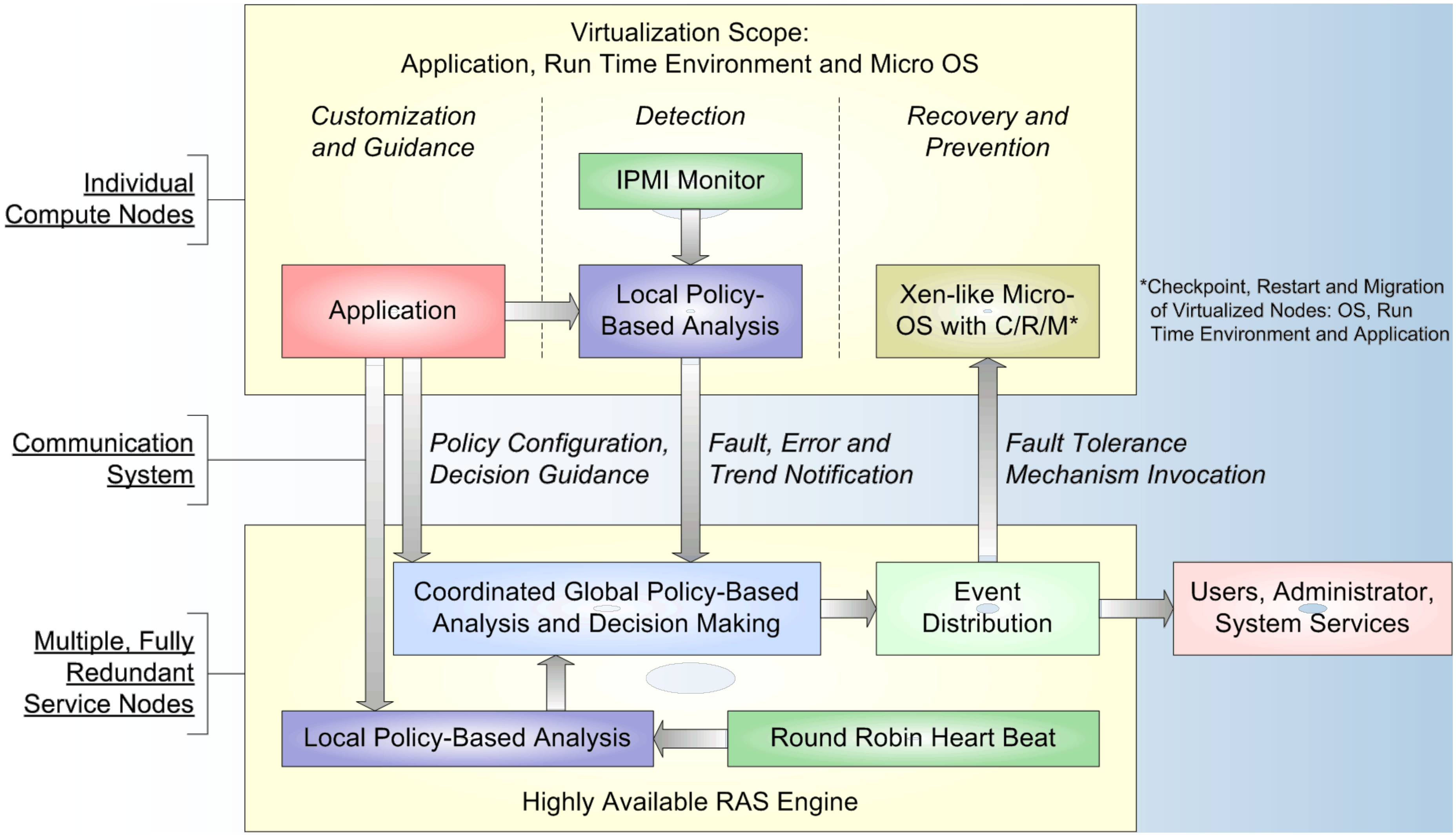
A holistic resiliency framework concept for high-performance computing



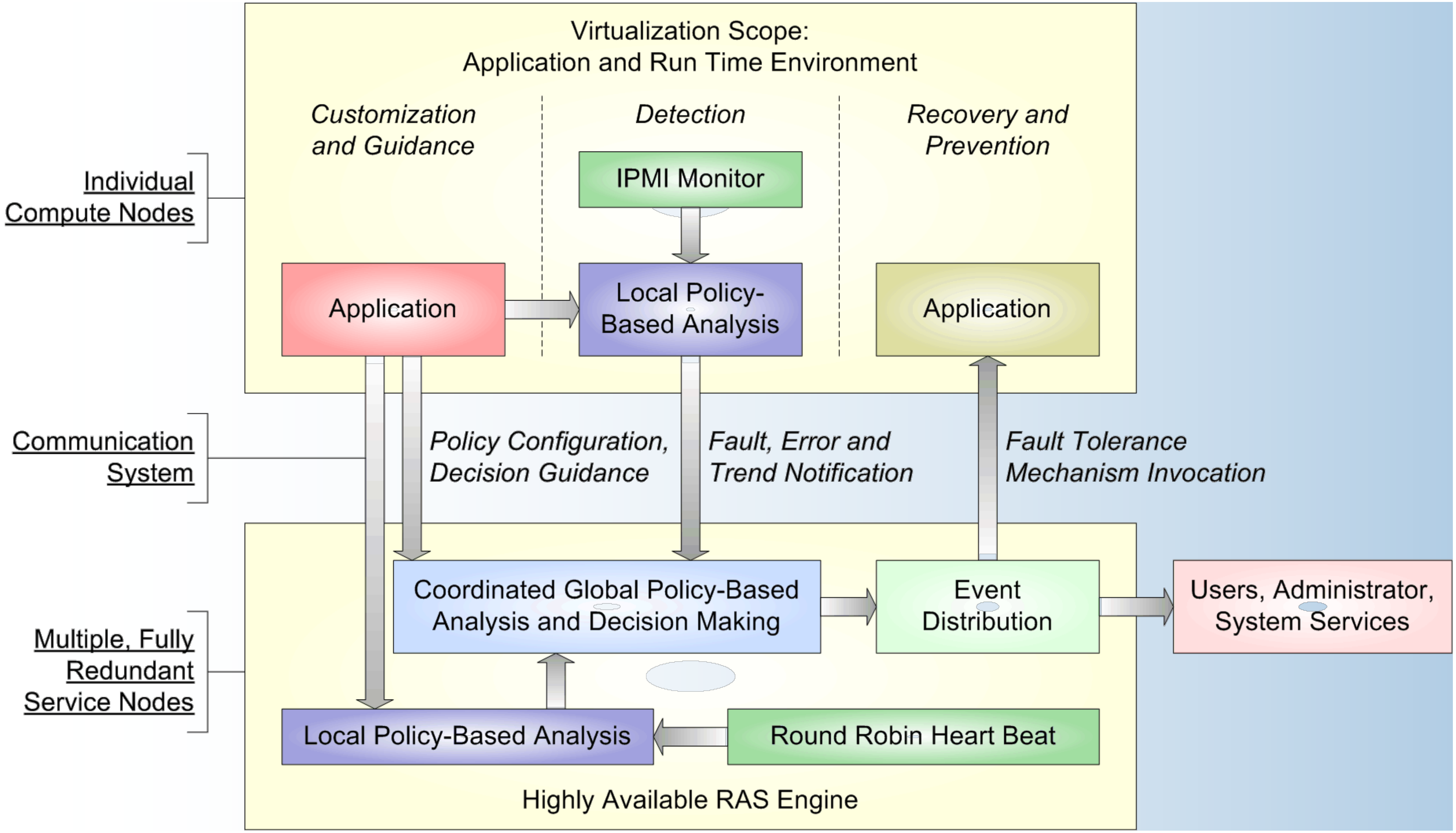
Example 1: Automatic Runtime Environment Checkpoint/Restart



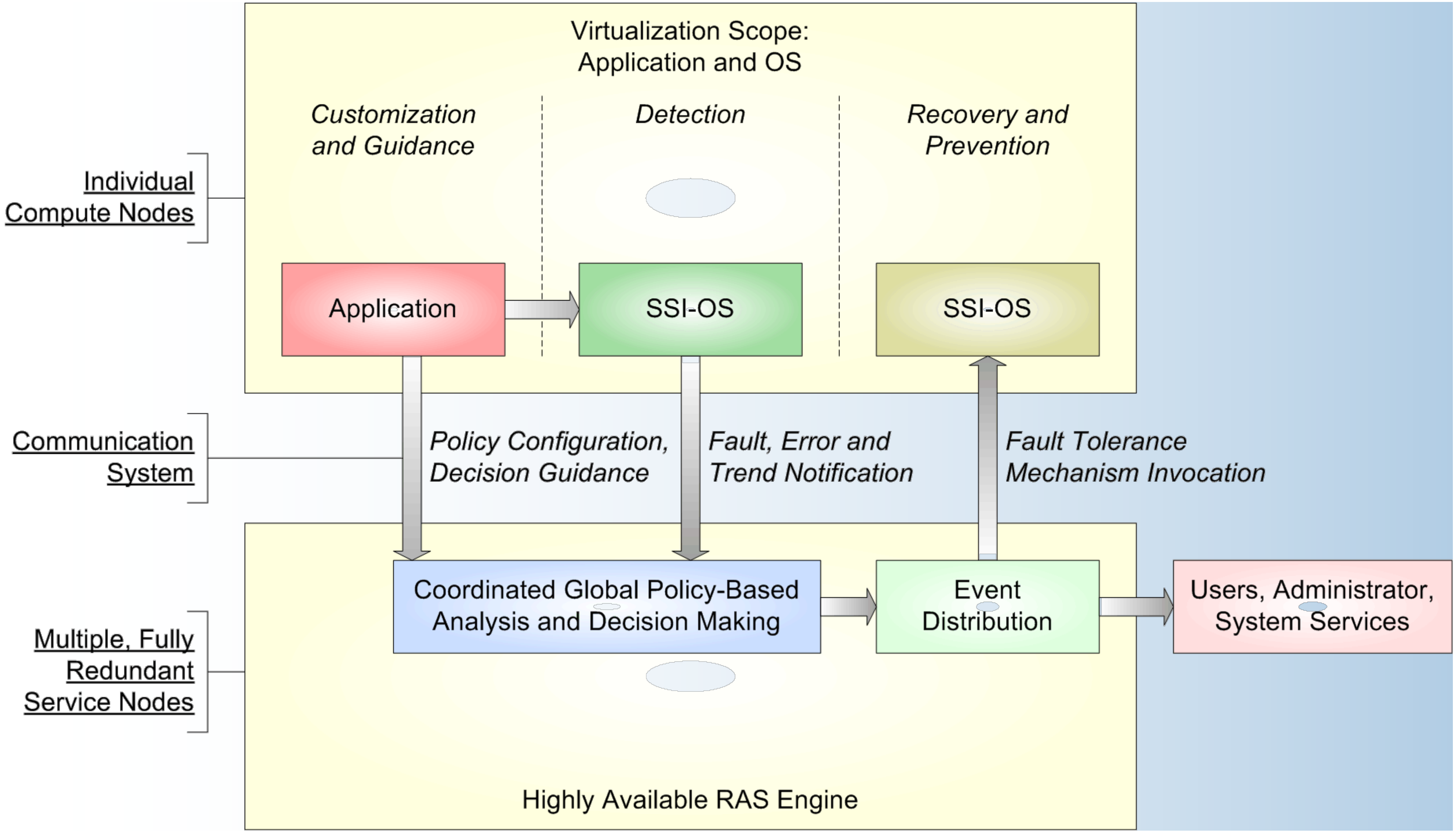
Example 2: Automatic Virtual Machine Checkpoint/Restart/Migration



Example 3: Automatic Application-Level Checkpoint/Restart



Example 4: Automatic OS-Level Checkpoint/Restart/Migration



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Achievements

- Developed efficient redundancy strategies for critical infrastructure services in HPC systems
- Added the job pause approach for HPC compute nodes to enhance reactive fault tolerance
- Implemented threshold-based preemptive migration using system-level virtualization for proactive fault tolerance
- Investigated mean-time to failure characteristics of HPC systems using reliability analysis
- Simulated and evaluated various fault tolerance strategies using actual failure data from HPC system logs
  - Reactive fault tolerance only
  - Proactive fault tolerance only
  - Holistic fault tolerance through reactive/proactive combination

Ongoing work and future plans

- **Finishing development on threshold-based process-level preemptive migration for <u>proactive fault tolerance</u>**
- **Engaging in prediction-based preemptive migration using for <u>proactive fault tolerance</u>**
- **Investigating failure mode, failure detection, and failure distribution characteristics of HPC systems using <u>reliability analysis</u>**
- **Plan to further enhance <u>reactive fault tolerance</u> with checkpoint placement adaptation to actual and predicted system health threats**
- **Plan to develop a <u>holistic fault tolerance</u> framework that offers the mix-and-match approach for various <u>*fault resilience*</u> strategies**

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Contacts

- **Christian Engelmann**

  System Research Team
  Computer Science Research Group
  Computer Science and Mathematics Division
  Oak Ridge National Laboratory

  engelmannc@ornl.gov

- **Stephen L. Scott**

  System Research Team
  Computer Science Research Group
  Computer Science and Mathematics Division
  Oak Ridge National Laboratory

  scottsl@ornl.gov

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