Advanced Fault Tolerance Solutions for High Performance Computing

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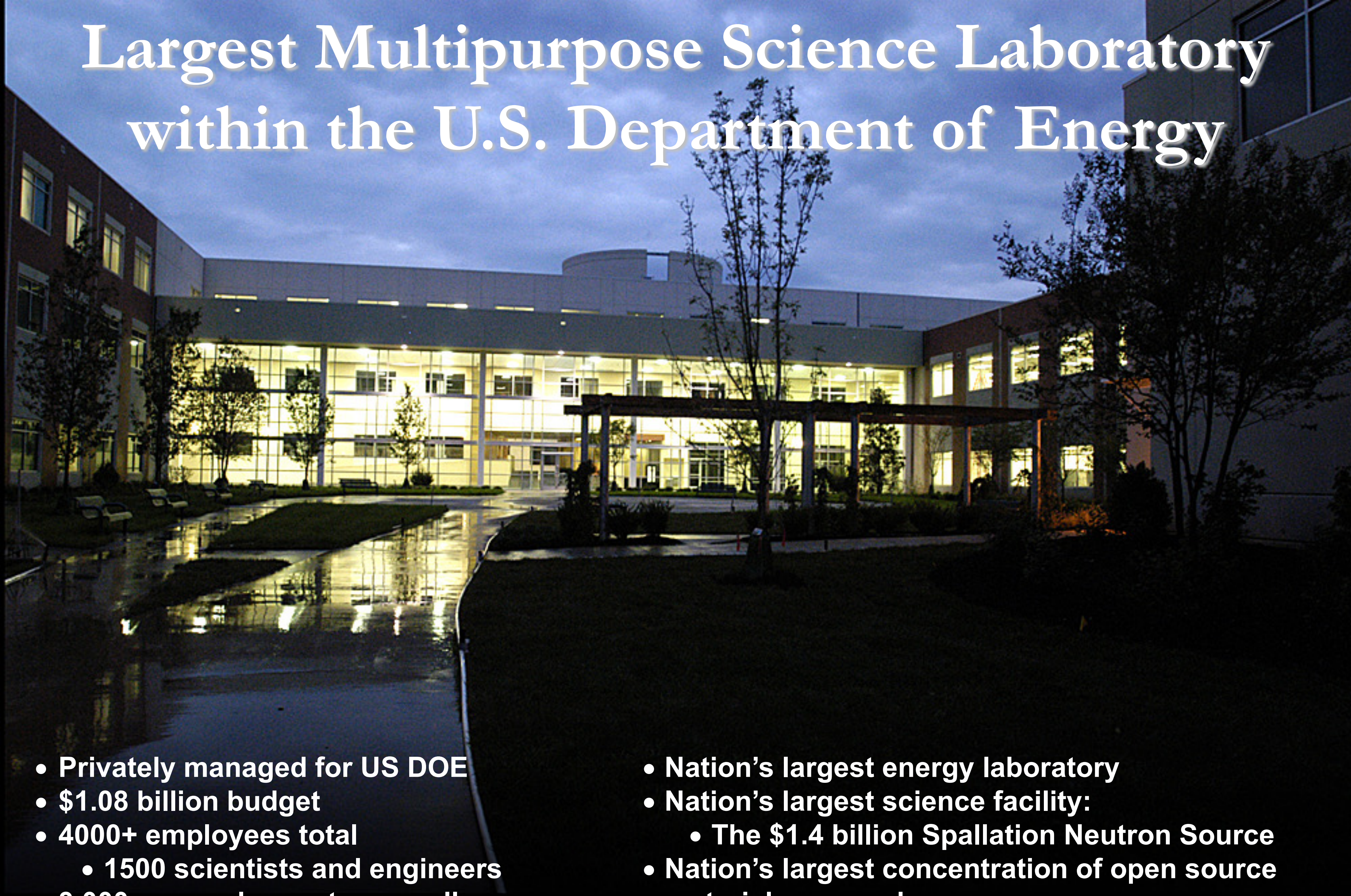
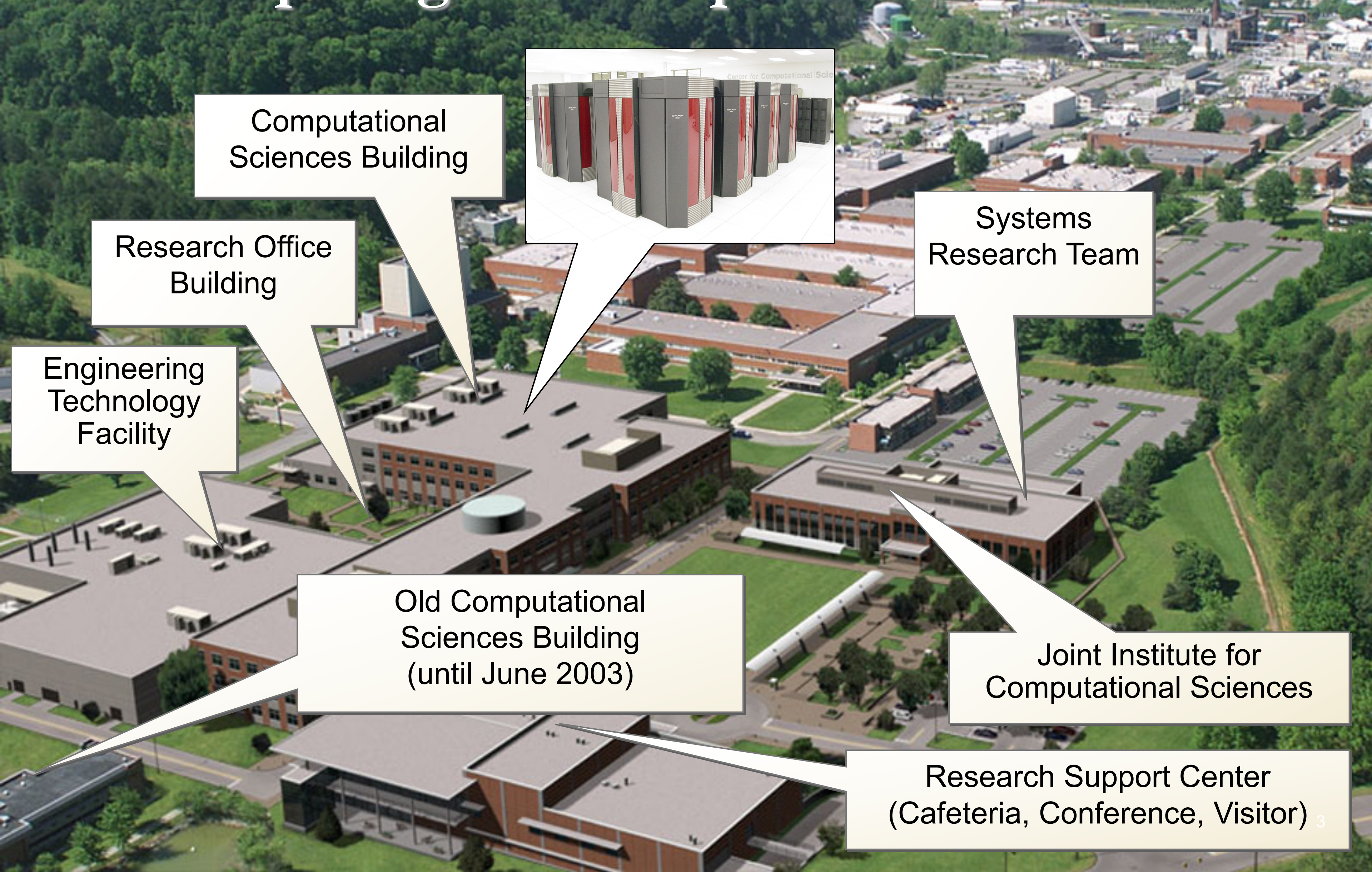
Largest Multipurpose Science Laboratory within the U.S. Department of Energy



- Privately managed for US DOE
- $1.08 billion budget
- 4000+ employees total
  - 1500 scientists and engineers
- 3,000 research guests annually
- 30,000 visitors each year
- Total land area 58mi^2 (150km^2)
- Nation’s largest energy laboratory
- Nation’s largest science facility:
  - The $1.4 billion Spallation Neutron Source
- Nation’s largest concentration of open source materials research
- Nation’s largest open scientific computing facility

ORNL East Campus: Site of World Leading Computing and Computational Sciences



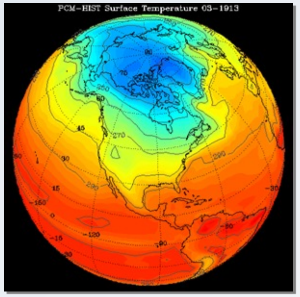
National Center for Computational Sciences

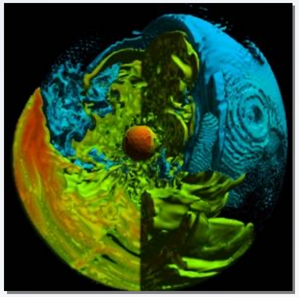
- **40,000 ft² (3700 m²) computer center:**
  - **36-in (~1m) raised floor, 18 ft (5.5 m) deck-to-deck**
  - **12 MW of power with 4,800 t of redundant cooling**
  - **High-ceiling area for visualization lab:**
    - **35 MPixel PowerWall, Access Grid, etc.**

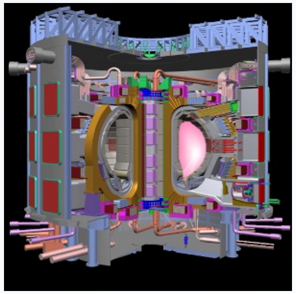
- **3 systems in the Top 500 List of Supercomputer Sites:**
  - **Jaguar: 7. Cray XT3, MPP with 11508 dual-core Processors ⇨ 119 TFlop**
  - **Jaguar: 41. IBM Blue Gene/P, MPP with 2048 quad-core Processors ⇨ 27 TFlop**
  - **Phoenix: 80. Cray X1E, Vector with 1014 Processors ⇨ 18 TFlop**

At Forefront in Scientific Computing and Simulation

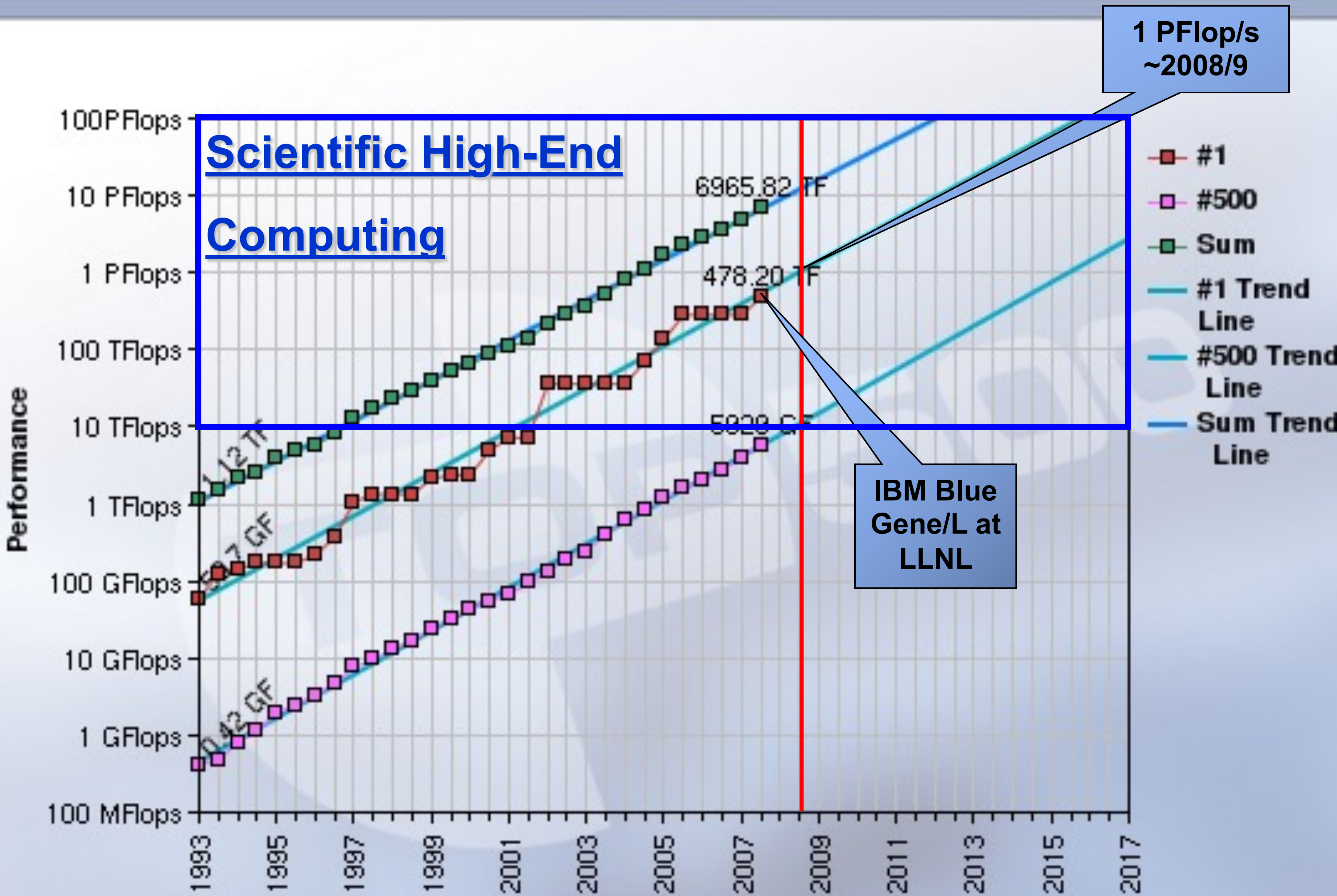
- Leading partnership in developing the National Leadership Computing Facility
  - Leadership-class scientific computing capability
  - 250 TFlop/s in 2008 (upgrade in progress)
  - 500 TFlop/s in 2008 (commitment made)
  - 1 PFlop/s in 2008/9 (commitment made)
- Attacking key computational challenges
  - Climate change
  - Nuclear astrophysics
  - Fusion energy
  - Materials sciences
  - Biology
- Providing access to computational resources through high-speed networking







Projected Performance Development



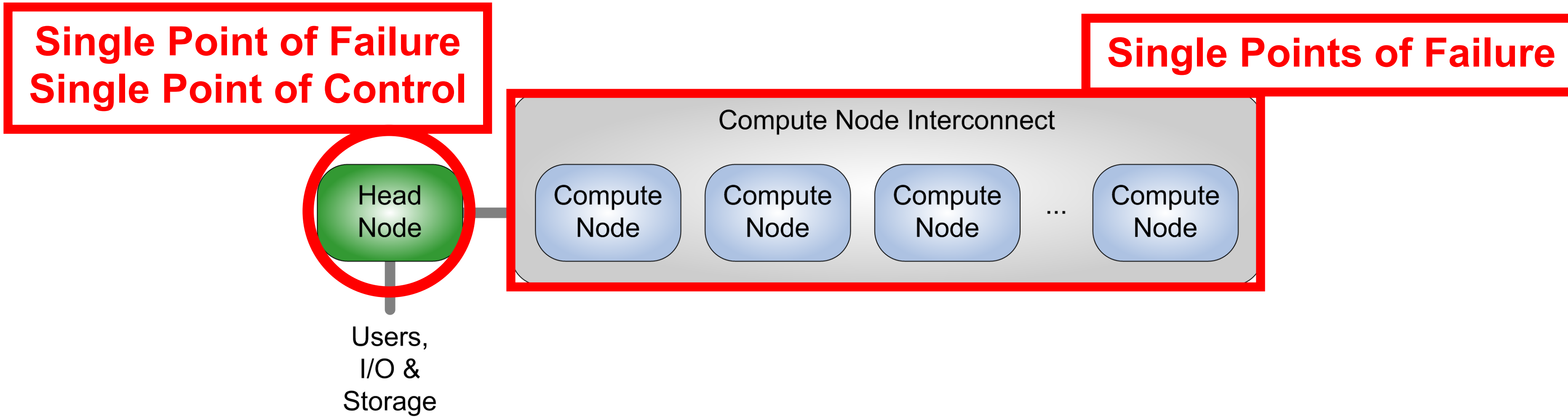
Talk Outline

- High performance computing system architectures
- Fault tolerance solutions for head & service nodes:
  - Active/standby with shared storage
  - Active/standby replication
  - Asymmetric active/active replication
  - Symmetric active/active replication
- Fault tolerance solutions for compute nodes:
  - Reactive: Checkpoint/restart and message logging
  - Proactive: Preemptive migration
  - Algorithmic approaches

Advanced Fault Tolerance Solutions for High Performance Computing

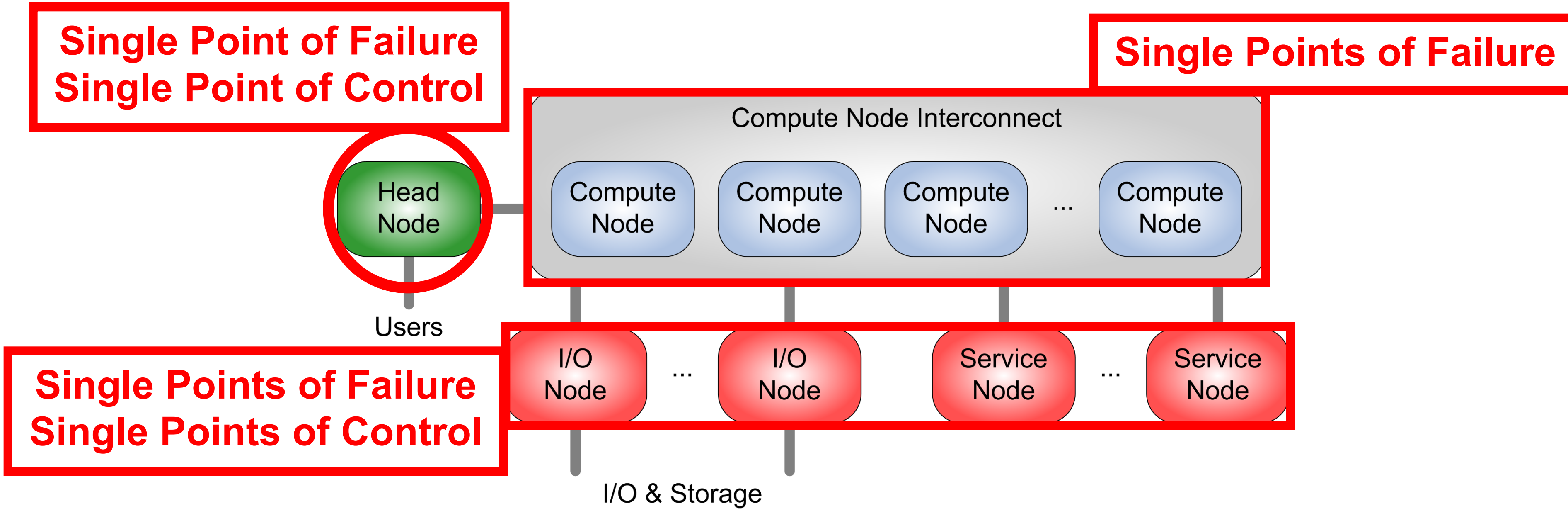
HPC System Architectures

Beowulf Cluster Computing Architecture



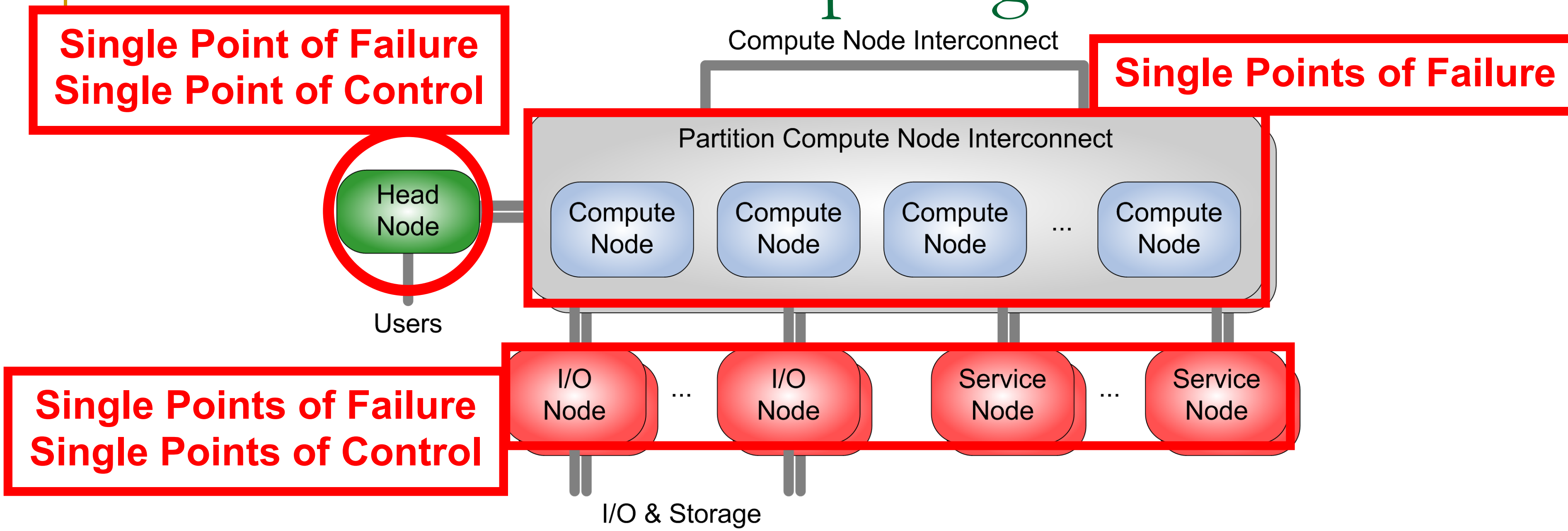
- Single head node manages entire HPC system
- System-wide services are provided by head node:
  - Job & resource management, networked file system, …
- Local services are provided by compute nodes
  - Message passing (MPI, PVM), …

Massively Parallel Computing Architecture



- 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

Partitioned MPP Computing Architecture



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

Typical Failure Causes in HPC Systems

- Overheating!!!
- Memory and network errors (bit flips)
- Hardware failures due to wear/age of:
  - Hard drives, memory modules, network cards, processors
- Software failures due to bugs in:
  - Operating system, middleware, applications

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

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

Fault Tolerance & High Availability Goals

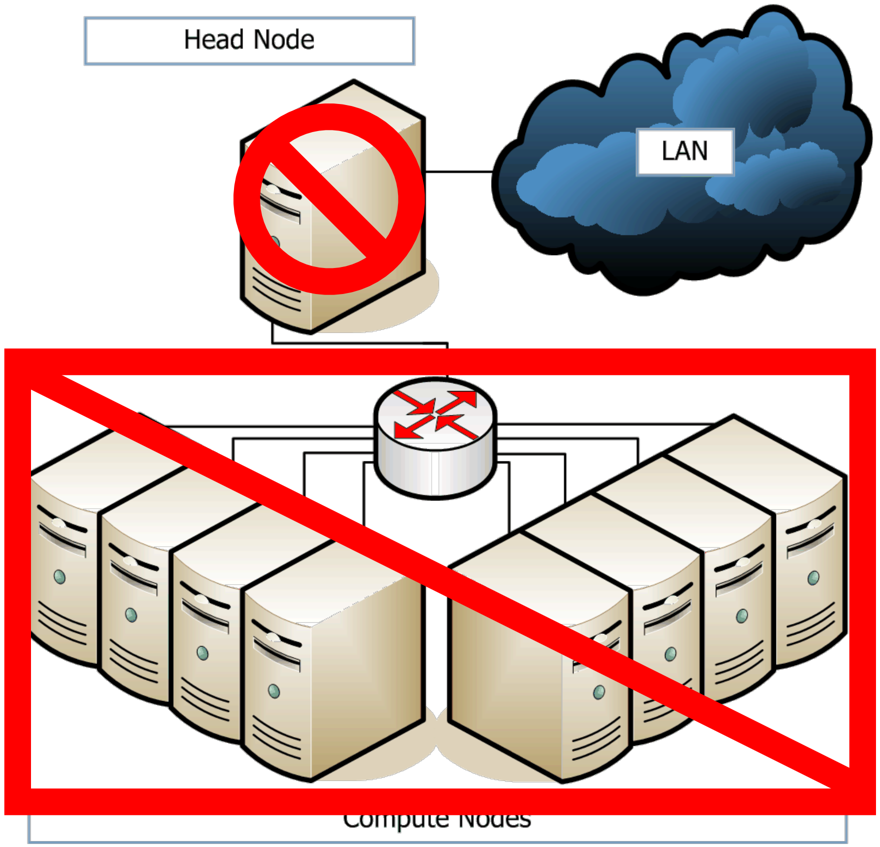
- Provide high-level Reliability, Availability, and Serviceability (RAS) capabilities
- Eliminate many of the numerous single-points of failure and control in HPC systems

- *Development of techniques to enable HPC systems to run computational jobs 24x7 without interruption*
- *Development of proof-of-concept implementations as blueprint for production-type RAS solutions*

Advanced Fault Tolerance Solutions for High Performance Computing

Head and Service Nodes

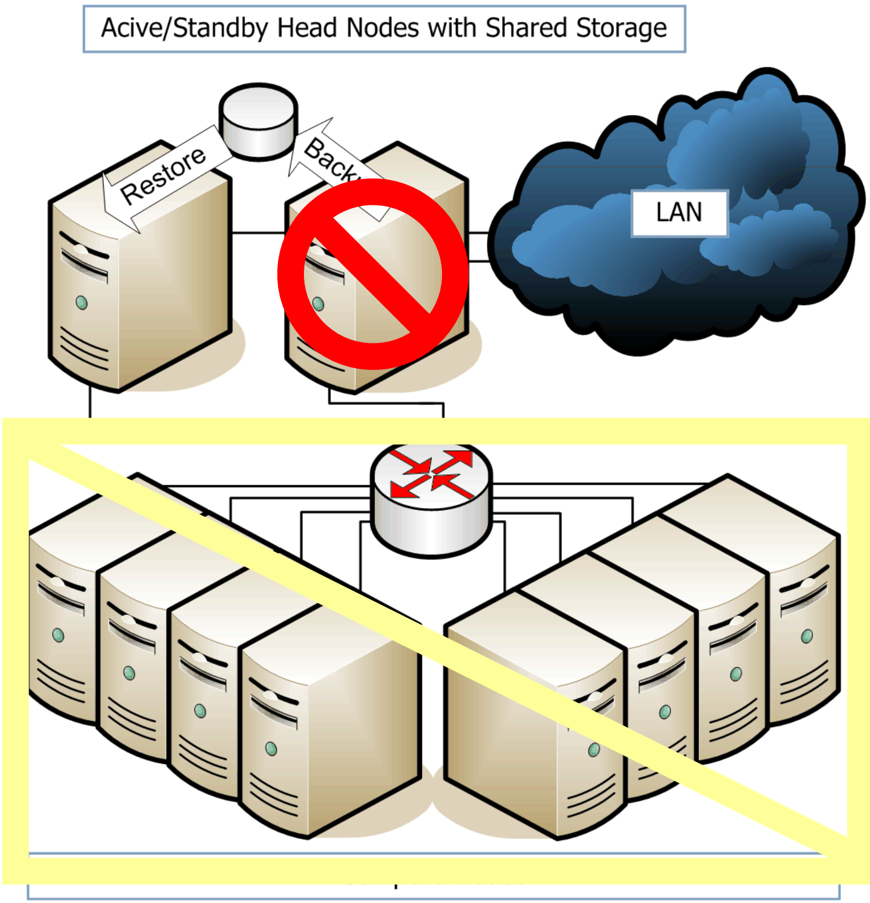
Single Head/Service Node Problem



- Single point of failure
- Compute nodes sit idle while head node is down
- A = MTTF / (MTTF + MTTR)
- MTTF depends on head node hardware/software quality
- MTTR depends on the time it takes to repair/replace node

➢ MTTR = 0 ➔ A = 1.00 (100%) **continuous availability**

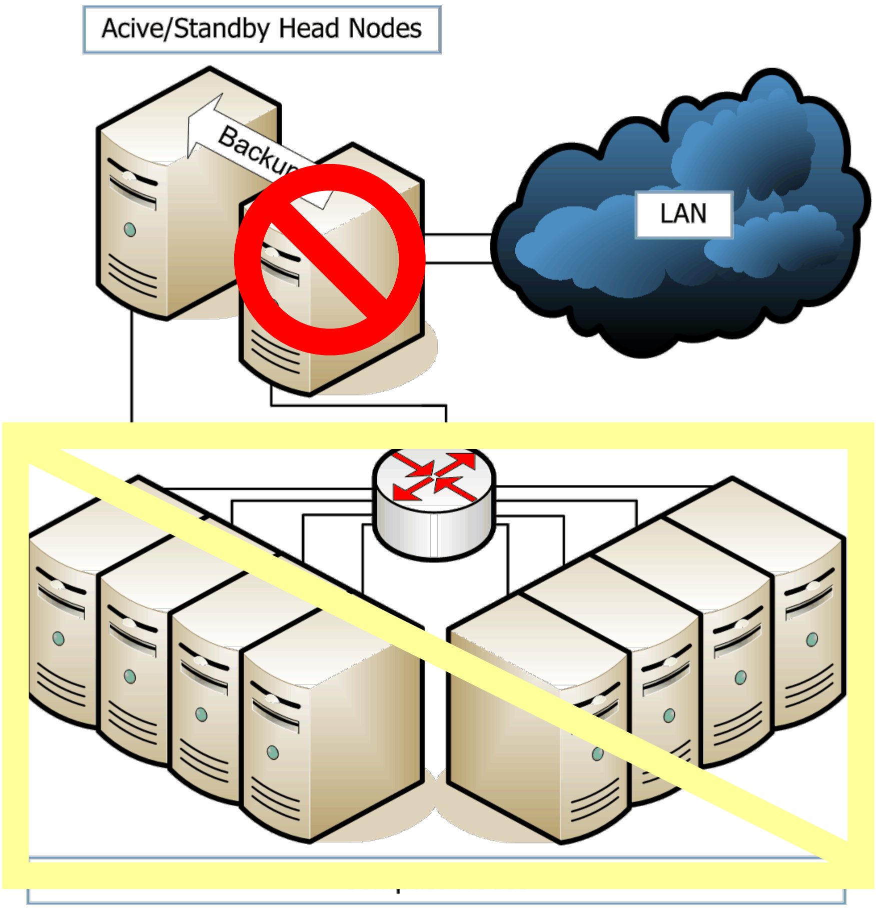
Active/Standby with Shared Storage



- Single active head node
- Backup to shared storage
- Simple checkpoint/restart
- Fail-over to standby node
- Possible corruption of backup state when failing during backup
- Introduction of a new single point of failure
- Correctness and availability are NOT ALWAYS guaranteed

➔ SLURM, metadata servers of PVFS and Lustre

Active/Standby Redundancy

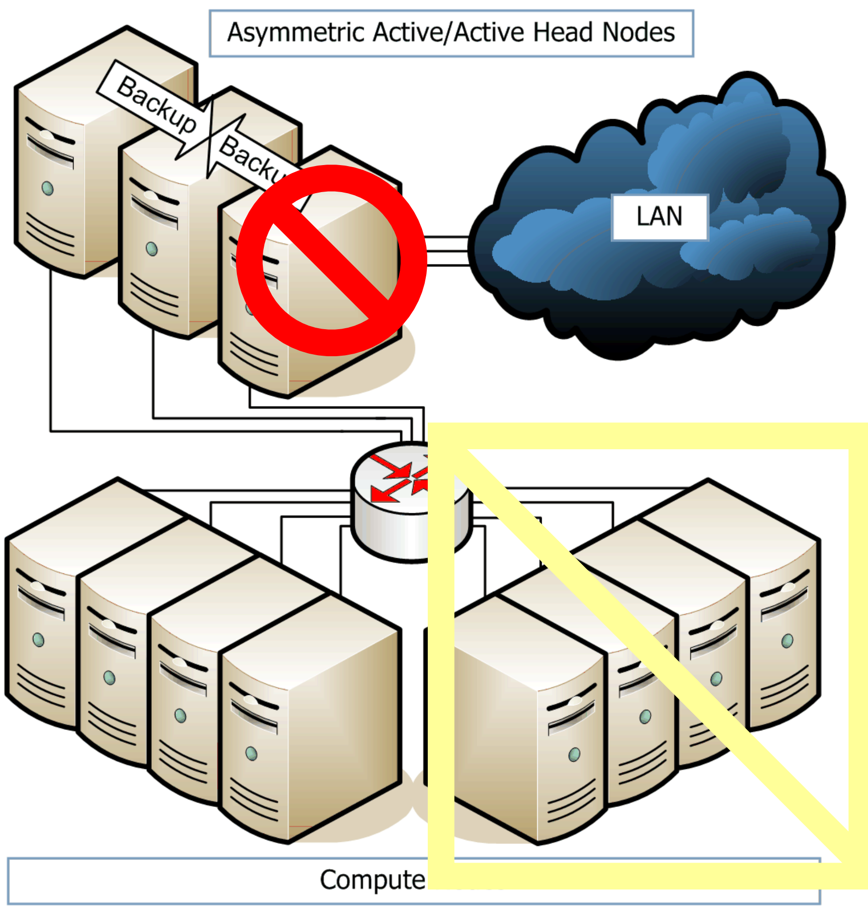


- Single active head node
- Backup to standby node
- Simple checkpoint/restart
- Fail-over to standby node
- Idle standby head node
- Rollback to backup
- Service interruption for fail-over and restore-over

➔ Torque on Cray XT

➔ HA-OSCAR prototype

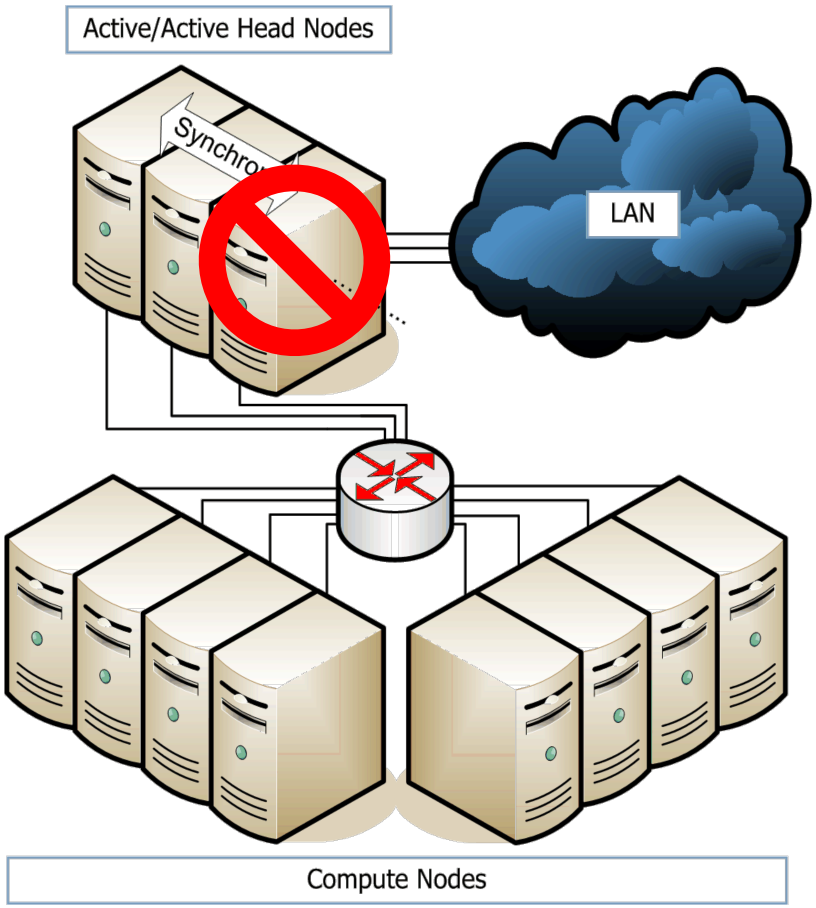
Asymmetric Active/Active Redundancy



- Many active head nodes
- Work load distribution
- Optional fail-over to standby head node(s) (*n+1* or *n+m*)
- No coordination between active head nodes
- Service interruption for fail-over and restore-over
- Loss of state w/o standby
- Limited use cases, such as high-throughput computing

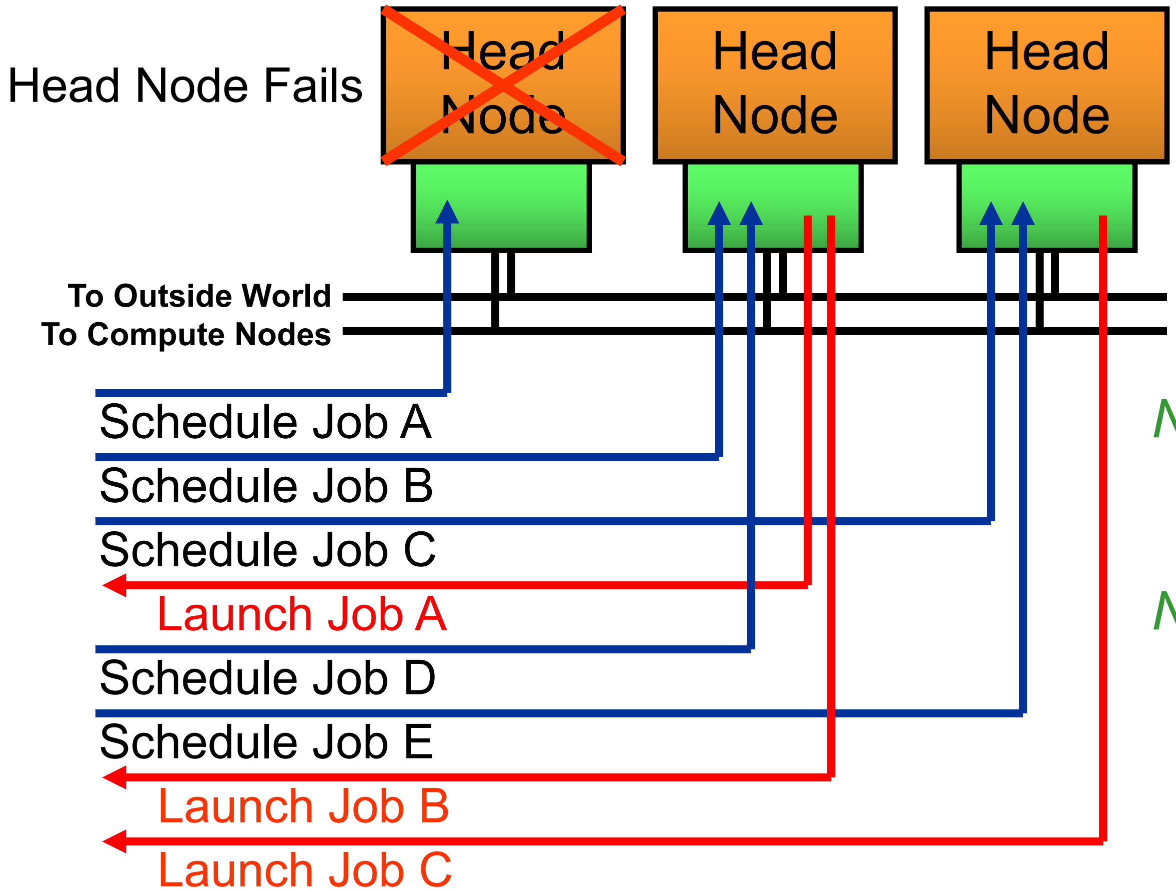
➔ Prototype based on HA-OSCAR

Symmetric Active/Active Redundancy



- Many active head nodes
- Work load distribution
- Symmetric replication between head nodes
- Continuous service
- Always up-to-date
- No fail-over, no restore-over
- Virtual synchrony model
- Complex algorithms
- <u>JOSHUA prototype for Torque</u>
- <u>PVFS metadata server</u>

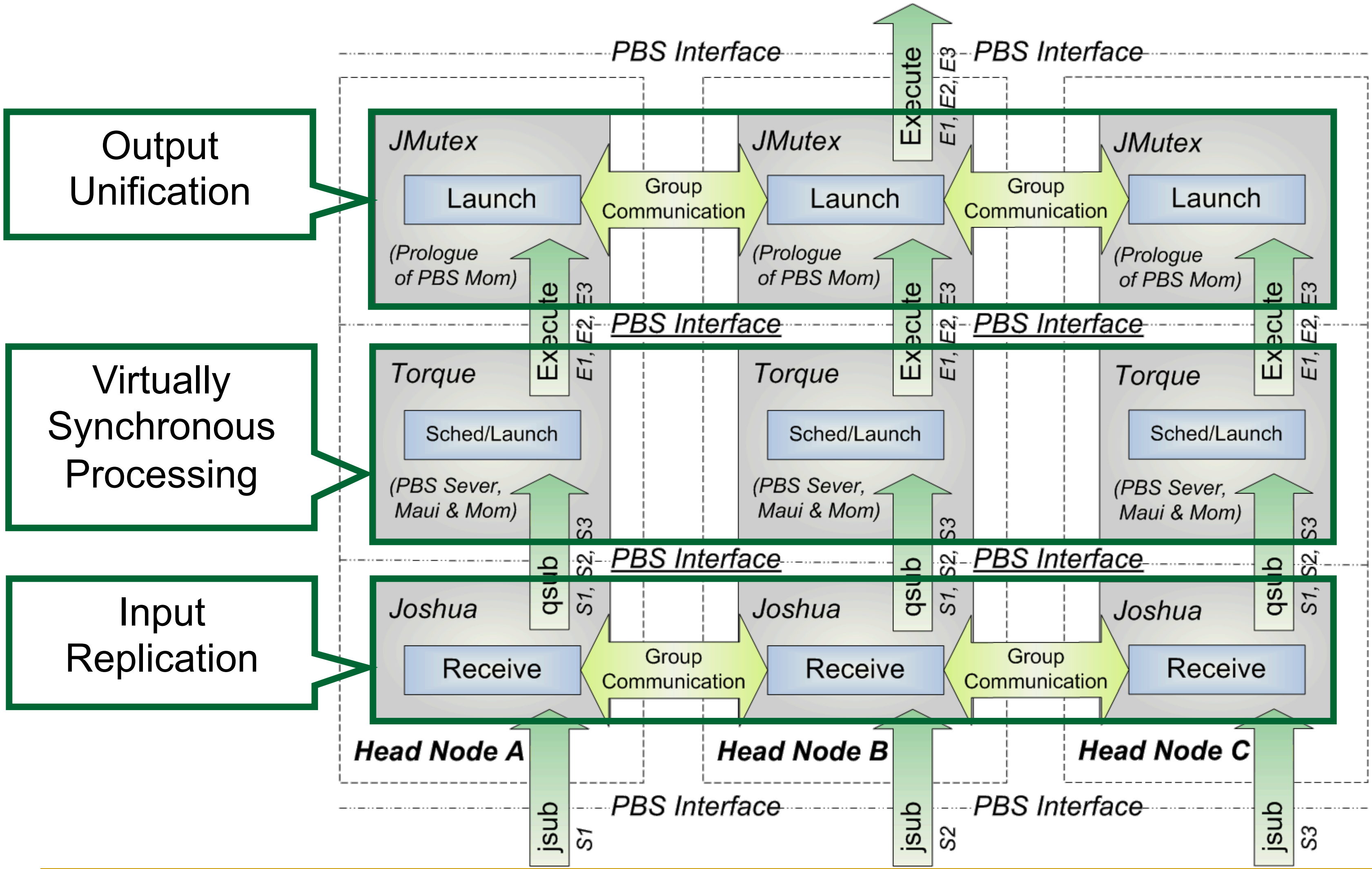
JOSHUA: Symmetric Active/Active Replication for PBS Torque



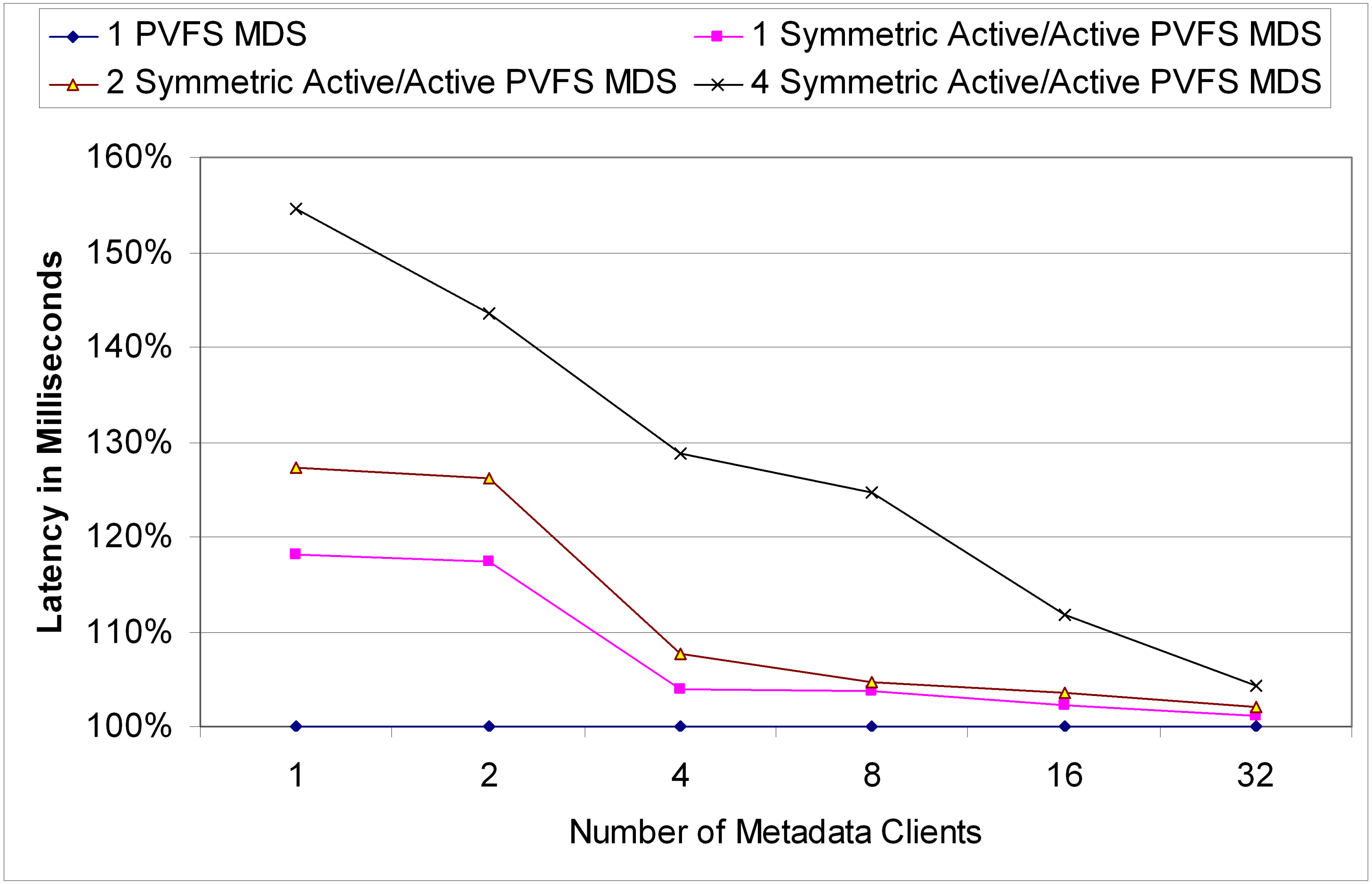
No Single Point of Failure

No Single Point of Control

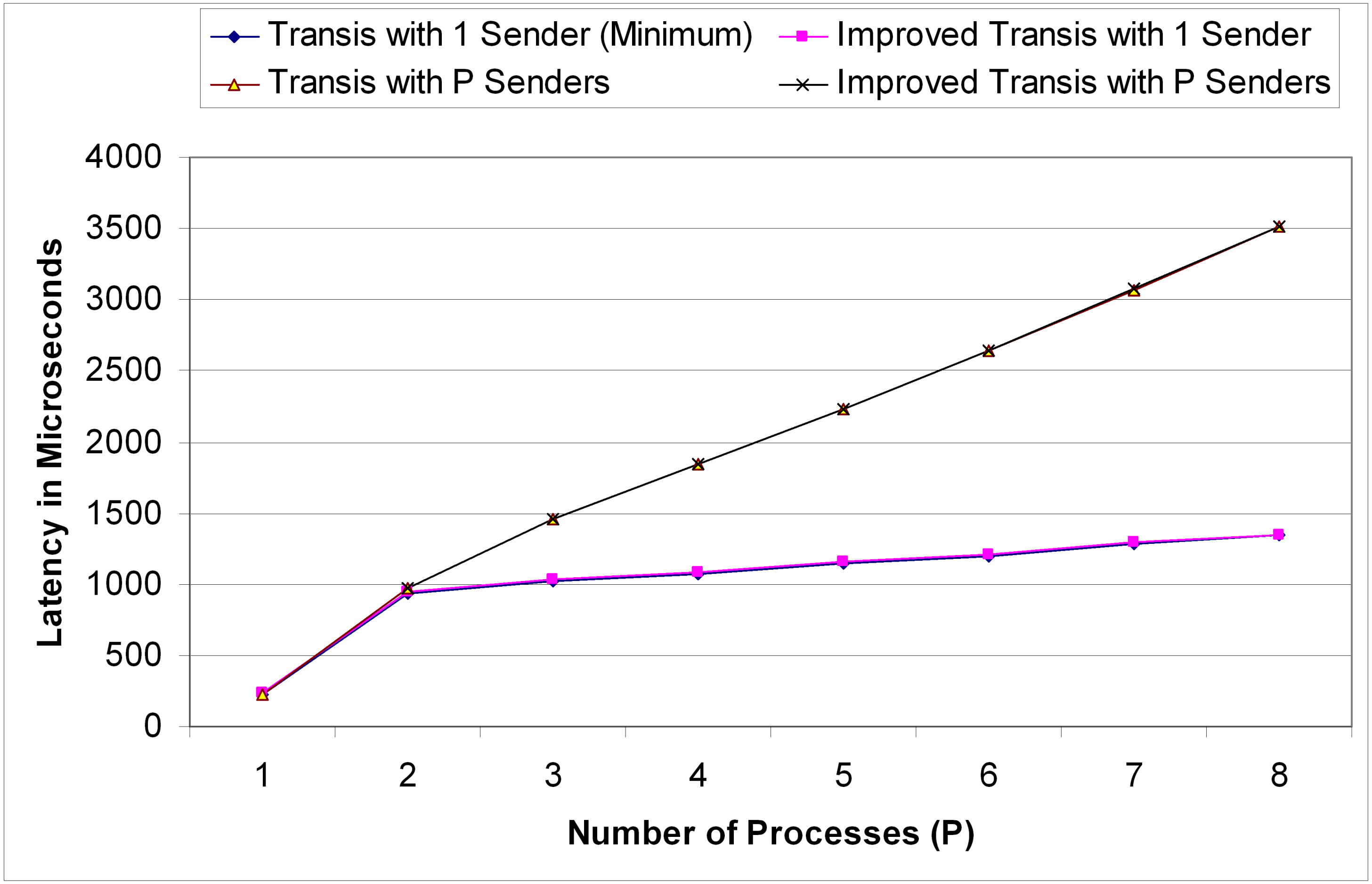
Symmetric Active/Active Replication



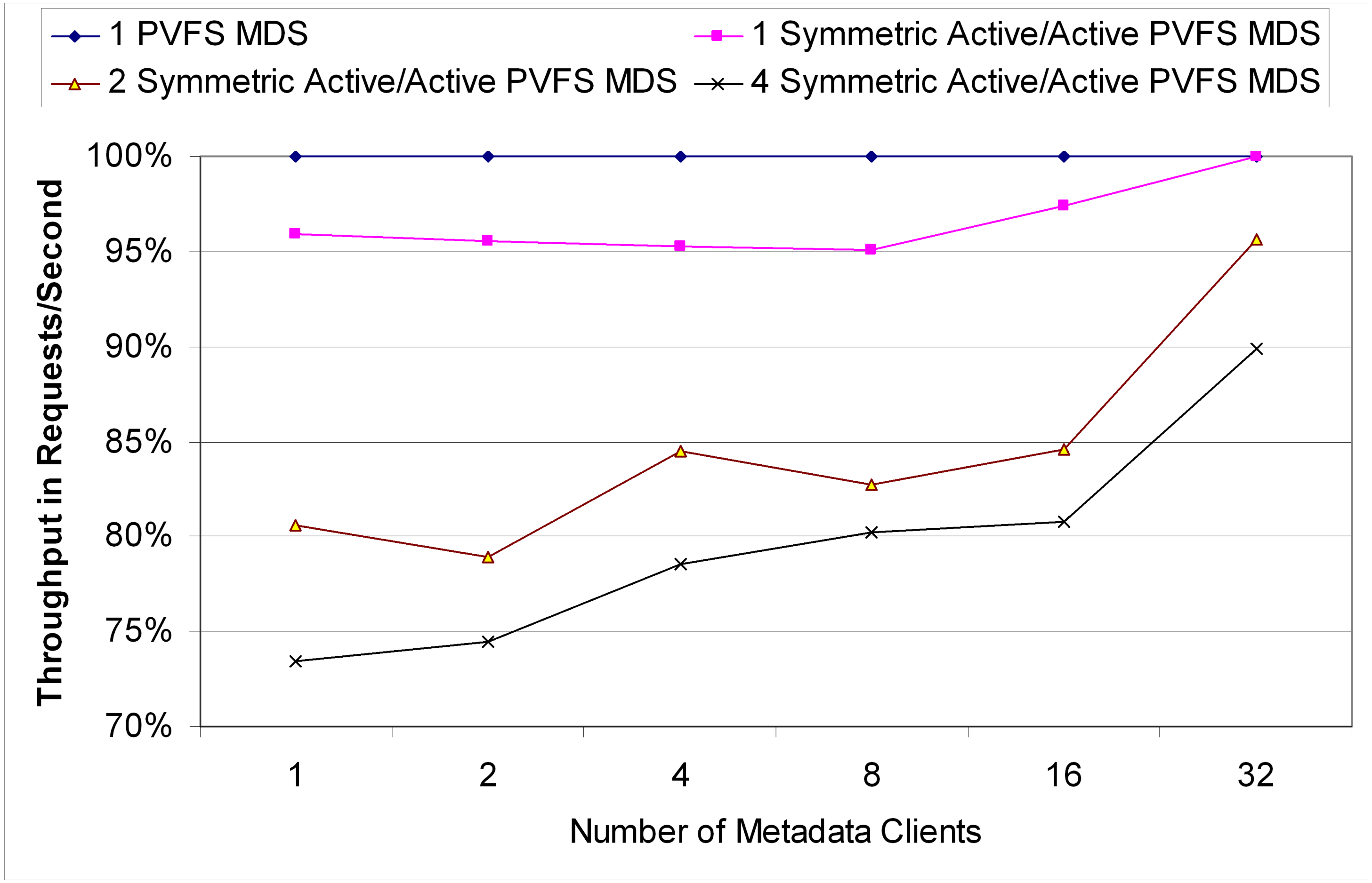
Symmetric Active/Active PVFS Metadata Service Latency



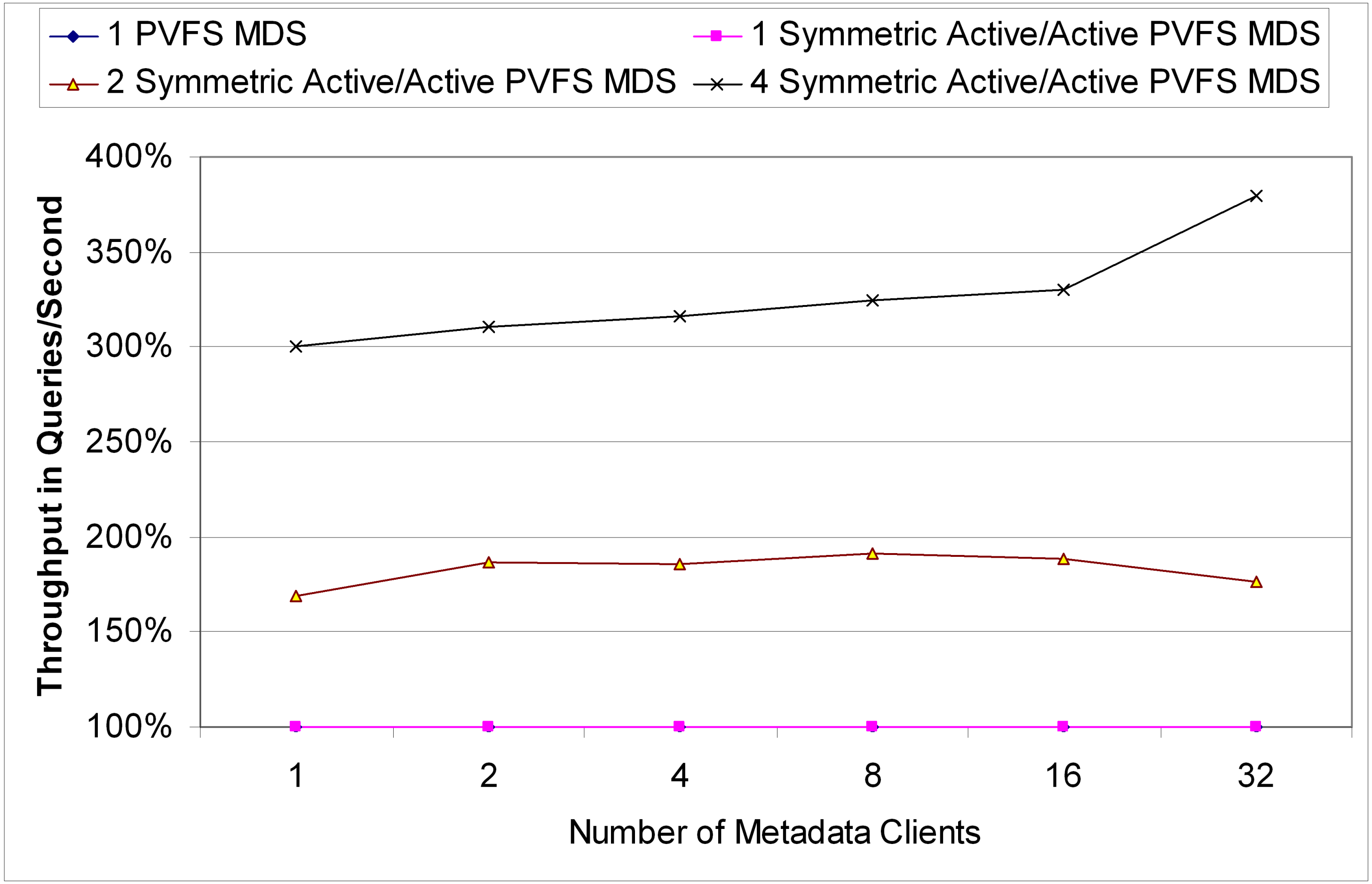
Total Message Order Latency



Symmetric Active/Active PVFS Metadata Service Write/Request Throughput



Symmetric Active/Active PVFS Metadata Service Read/Query Throughput



Symmetric Active/Active Availability

- $A_{component}$ = MTTF / (MTTF + MTTR)
- A_{system} = 1 - (1 - $A_{component}$) n
- T_{down} = 8760 hours * (1 – A)
- Single node MTTF: 5000 hours
- Single node MTTR: 72 hours

Nodes	Availability	Est. Annual Downtime
1	98.58%	5d 4h 21m
2	99.97%	1h 45m
3	99.9997%	1m 30s
4	99.999995%	1s

Single-site redundancy for 7 nines does not mask catastrophic events.

Advanced Fault Tolerance Solutions for High Performance Computing

Compute Nodes

Reactive vs. Proactive Fault Tolerance

- 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

Reactive Fault Tolerance Techniques (1/2)

- Checkpoint/restart:
  - Application state from all processors is saved regularly on stable storage, such as local disk or networked file system
  - On failure, application is restarted using saved state
  - Checkpoint always involves data movement (local/network)
  - Restart always involves a rollback, i.e., lost computation
  - Example: Berkeley Lab Checkpoint/Restart (Linux mod.)
  - May be used in combination with message logging to avoid rollback (see next slide)

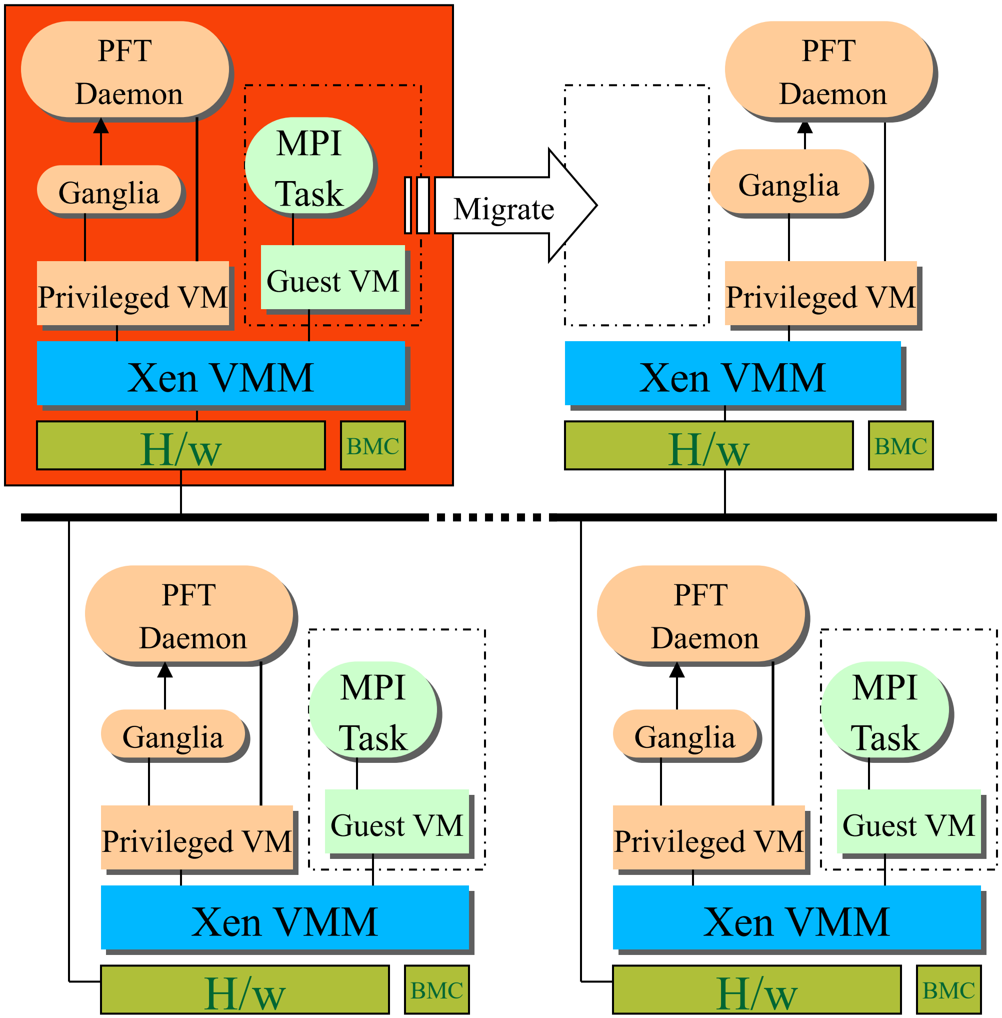
Reactive Fault Tolerance Techniques (2/2)

- Message logging:
  - All messages sent between application processes are logged to a central server
  - On failure, only the failed application part is restarted and replayed with saved messages
  - Doubles the number of messages
  - Message replay involves no rollback
  - Example: MPICH-VCL (MPI-based Chandy/Lamport alg.)
  - Combination with checkpoint/restart:
    - No rollback / shorter replay time, even higher overhead

Proactive Fault Tolerance Techniques

- Preemptive migration:
  - System health status is constantly monitored and evaluated
  - Monitoring data is processed by a filtering mechanism and/or an online reliability analysis
  - Pre-failure indicators are used to predict failures based on current system health status and historic information
  - Application parts (processes or virtual machines) are migrated away from compute nodes that are about to fail
  - Migration may be performed by stopping the application or live, while keeping the application running

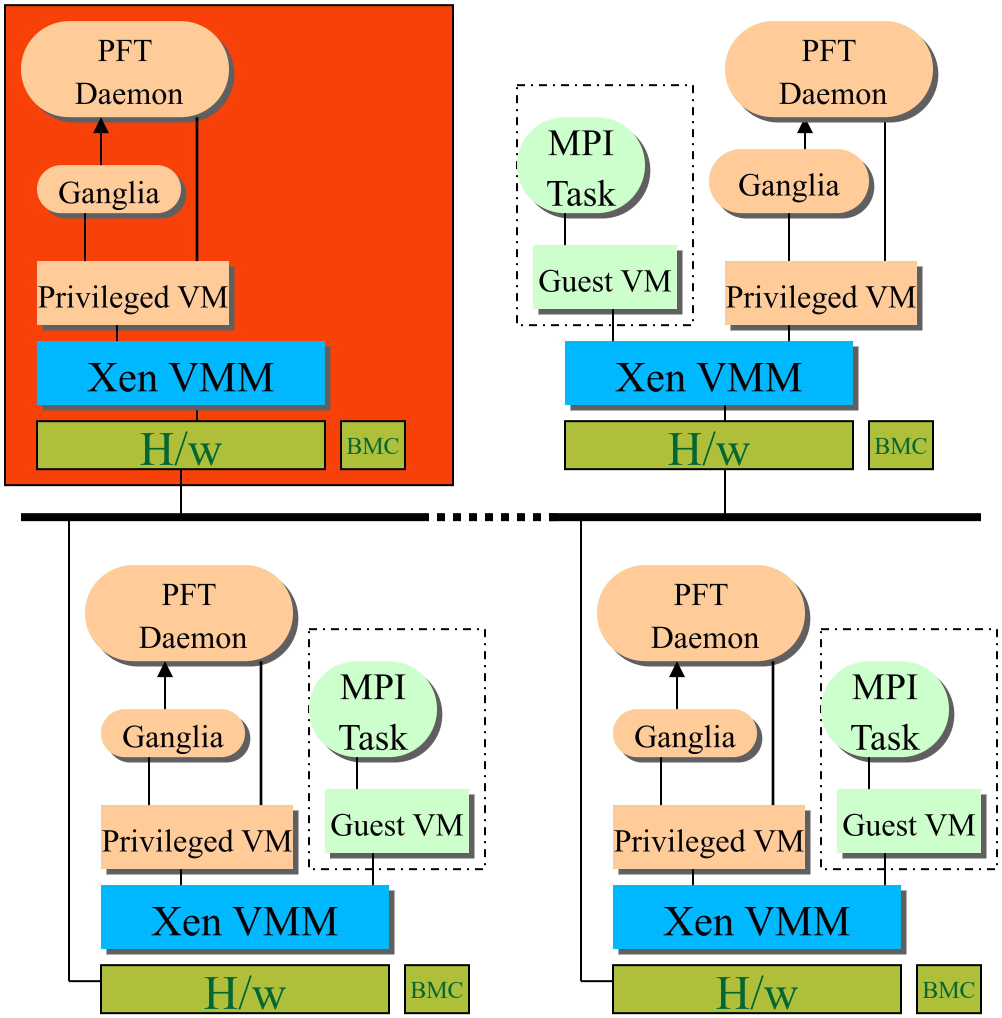
Preemptive Migration with Xen



BMC Baseboard Management Contoller

- Stand-by Xen host, no guest (spare node)
- Deteriorating health → migrate guest (w/ MPI app) to spare node

Preemptive Migration with Xen

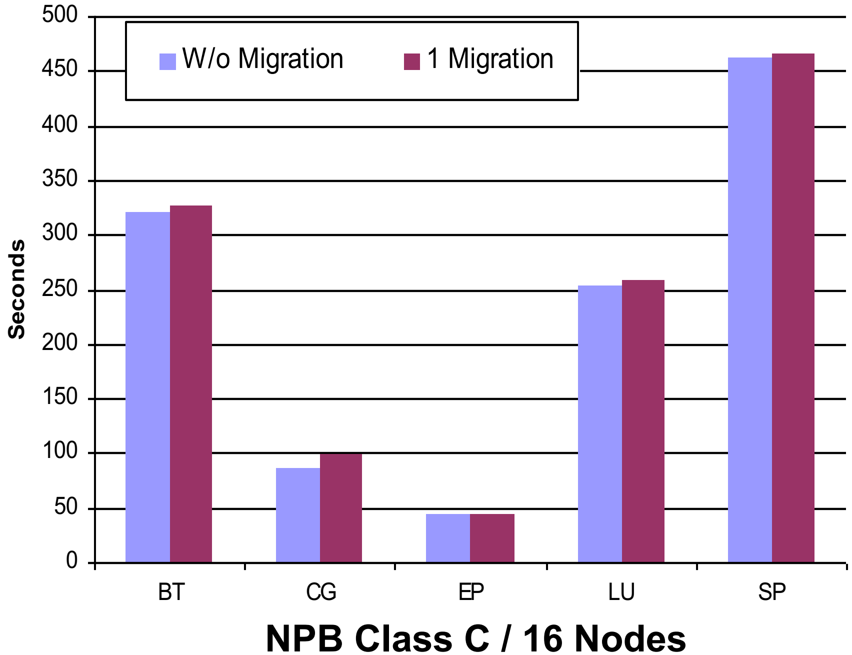


BMC Baseboard Management Contoller

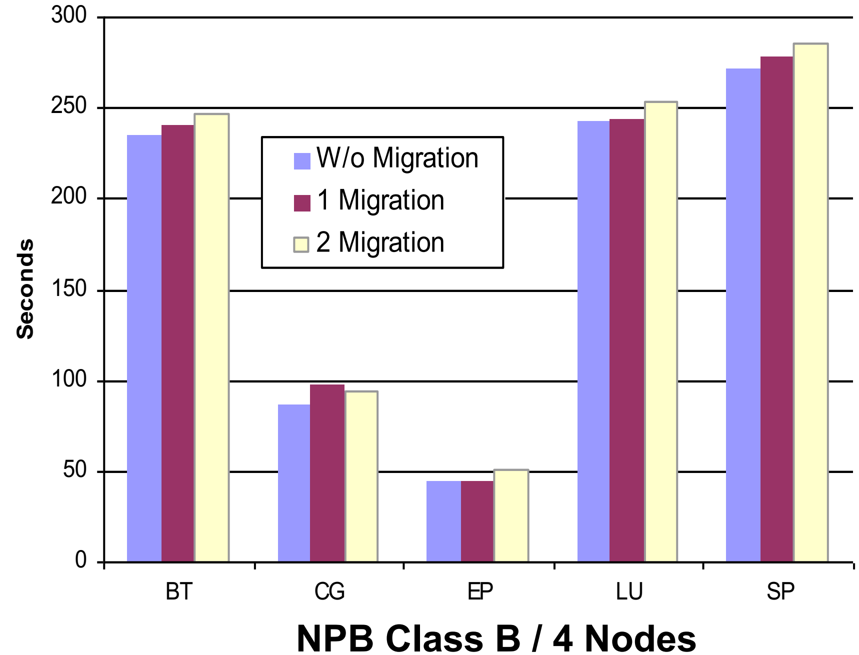
- Stand-by Xen host, no guest (spare node)
- Deteriorating health → migrate guest (w/ MPI app) to spare node
- Destination host generates unsolicited ARP reply
  - indicates Guest VM IP has moved to new location
  - ARP tells peers to resend packets to new host

Preemptive Migration Overhead

1. Single node failure



2. Double node failure

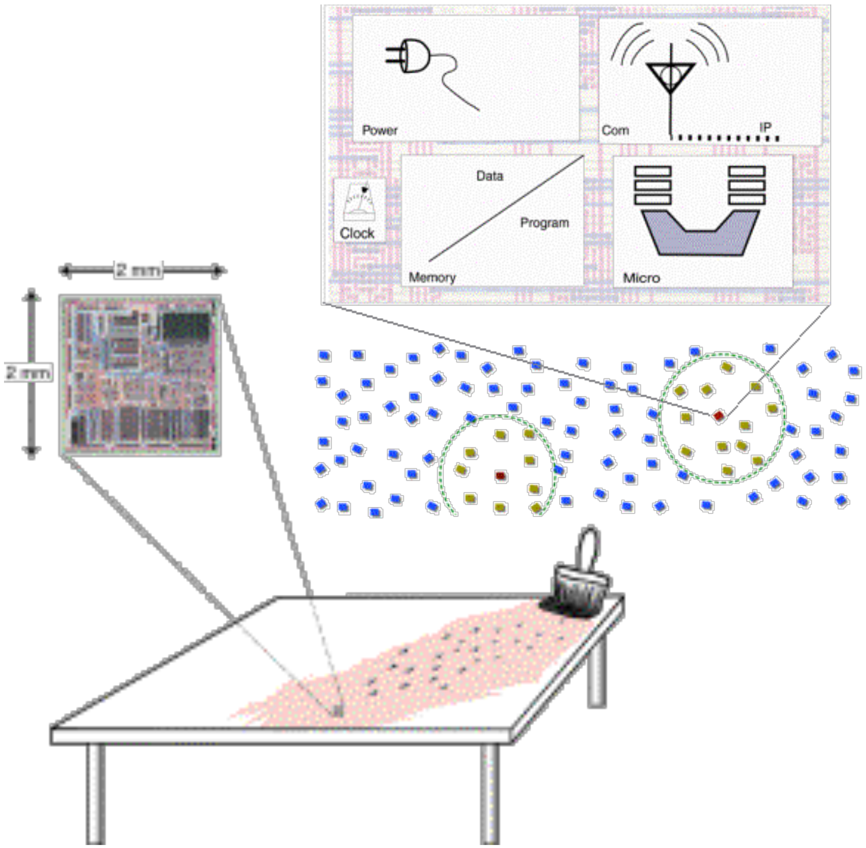


- Single node failure: 0.5-5% add'l cost over total wall clock time
- Double node failure: 2-8% add'l cost over total wall clock time

Algorithmic Fault Tolerance Approaches

- Naturally fault tolerant algorithms
  - Processes have only limited knowledge mostly about other processes in their neighborhood
  - Application is composed of local algorithms, where a failure has only a minor local impact
  - Examples: Chaotic relaxation, peer-to-peer communication
- Recovery & erasure codes
  - Reconstruction of lost information through algorithmic redundancy within the application
  - Rollback to consistent state through reverse computation

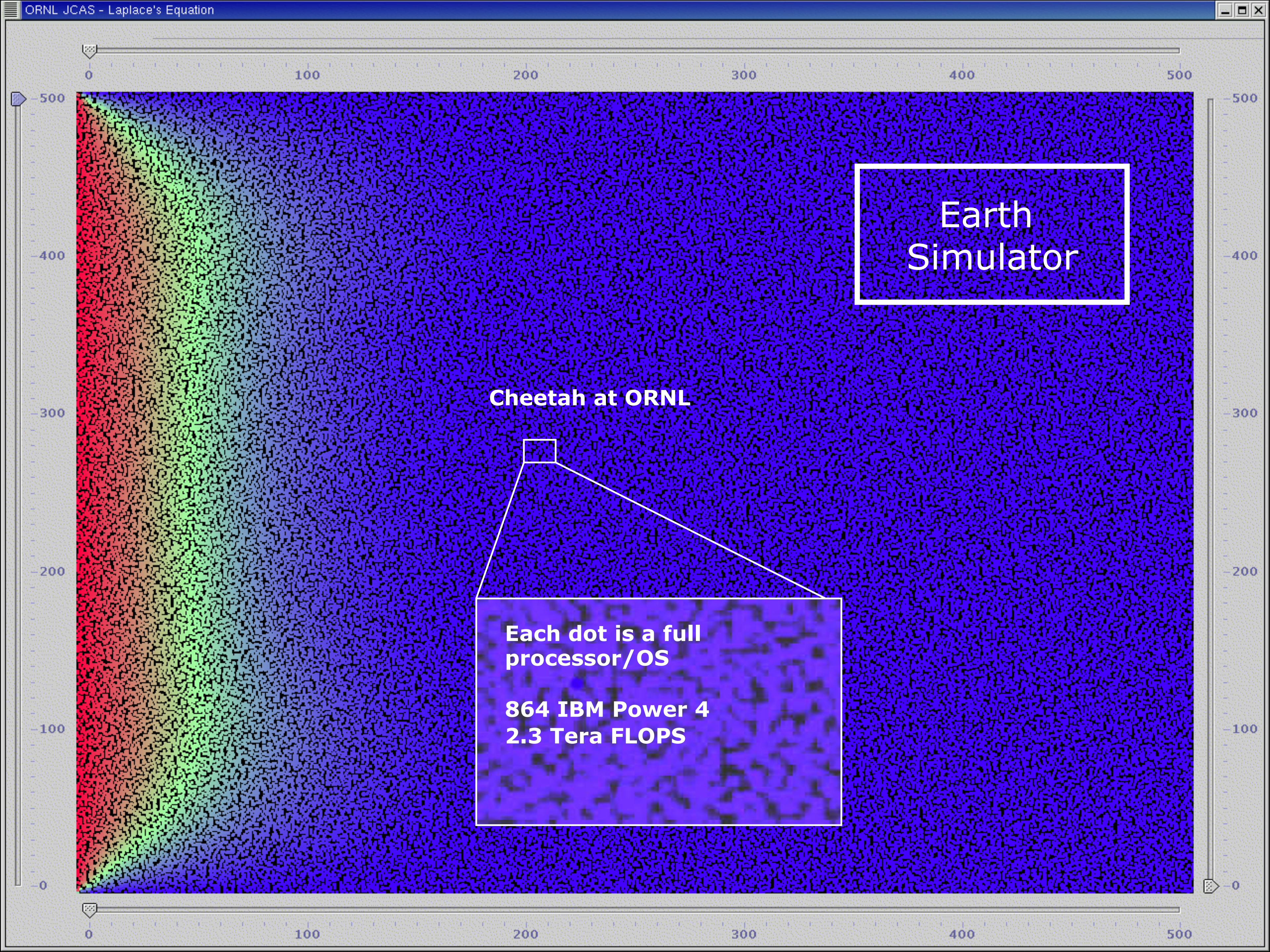
MIT Research: Paintable Computing



- In the future, embedded computers with a radio device will get as small as a paint pigment
- Supercomputers can be easily assembled by just painting a wall of embedded computers
- Applications are driven by cellular algorithms

Cellular Architecture (Smart Dust) Simulator

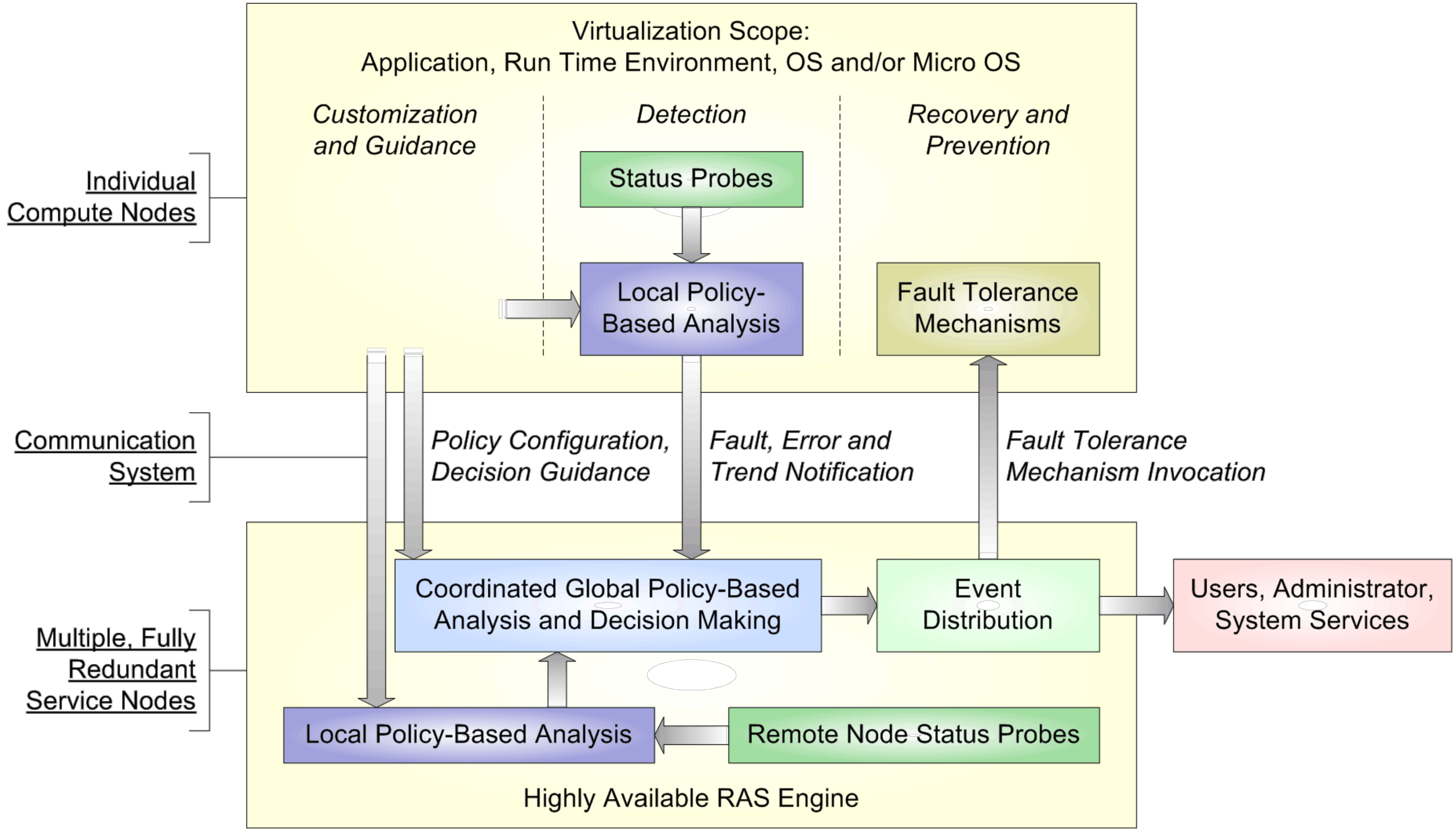
- Developed at ORNL in Java with native C and Fortran application support using JNI
- Runs as standalone or distributed application
- Lightweight framework simulates up to 1,000,000 lightweight processes on 9 real processors
- Standard and experimental networks:
  - Multi-dimensional mesh/torus
  - Nearest/Random neighbors
- Message driven simulation is not in real-time
- Primitive fault-tolerant MPI support


ORNL JCAS - Laplace's Equation
Earth Simulator
Cheetah at ORNL
Each dot is a full processor/OS
864 IBM Power 4
2.3 Tera FLOPS
0
100
200
300
400
500

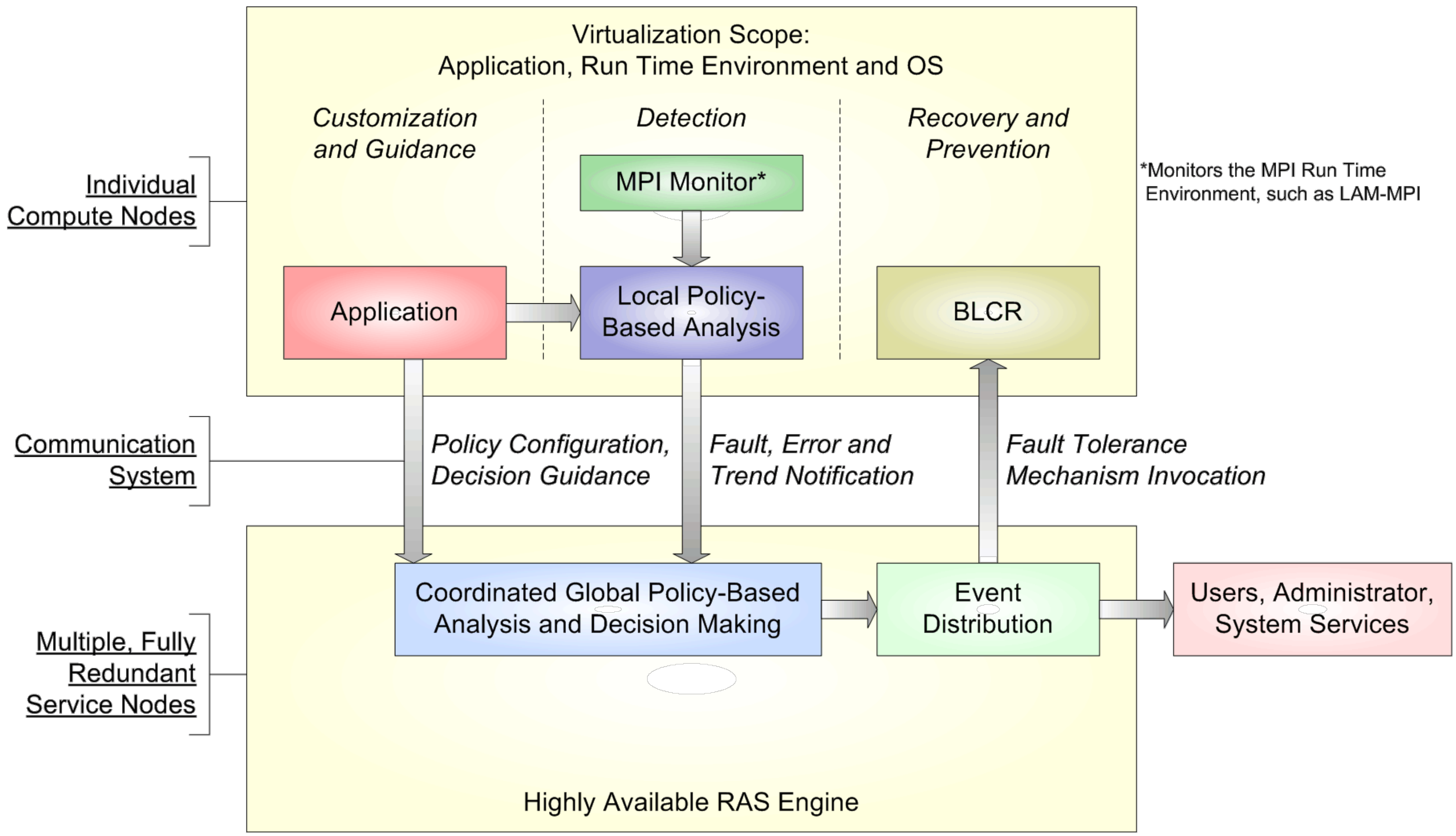
What's Next

- **Reliability analysis** for identifying pre-fault indicators, predicting failures, and modeling and monitoring individual system component reliability as well as overall system reliability
- **Proactive fault tolerance** technology based on preemptive migration of computation away from components that are about to fail using system-level virtualization in HPC environments
- **Reactive fault tolerance enhancements**, such as checkpoint interval and placement adaptation to actual and predicted system health threats, using system- and process-level virtualization
- **Holistic fault tolerance** through combination of adaptive proactive and reactive fault tolerance in conjunction with system health monitoring and reliability analysis

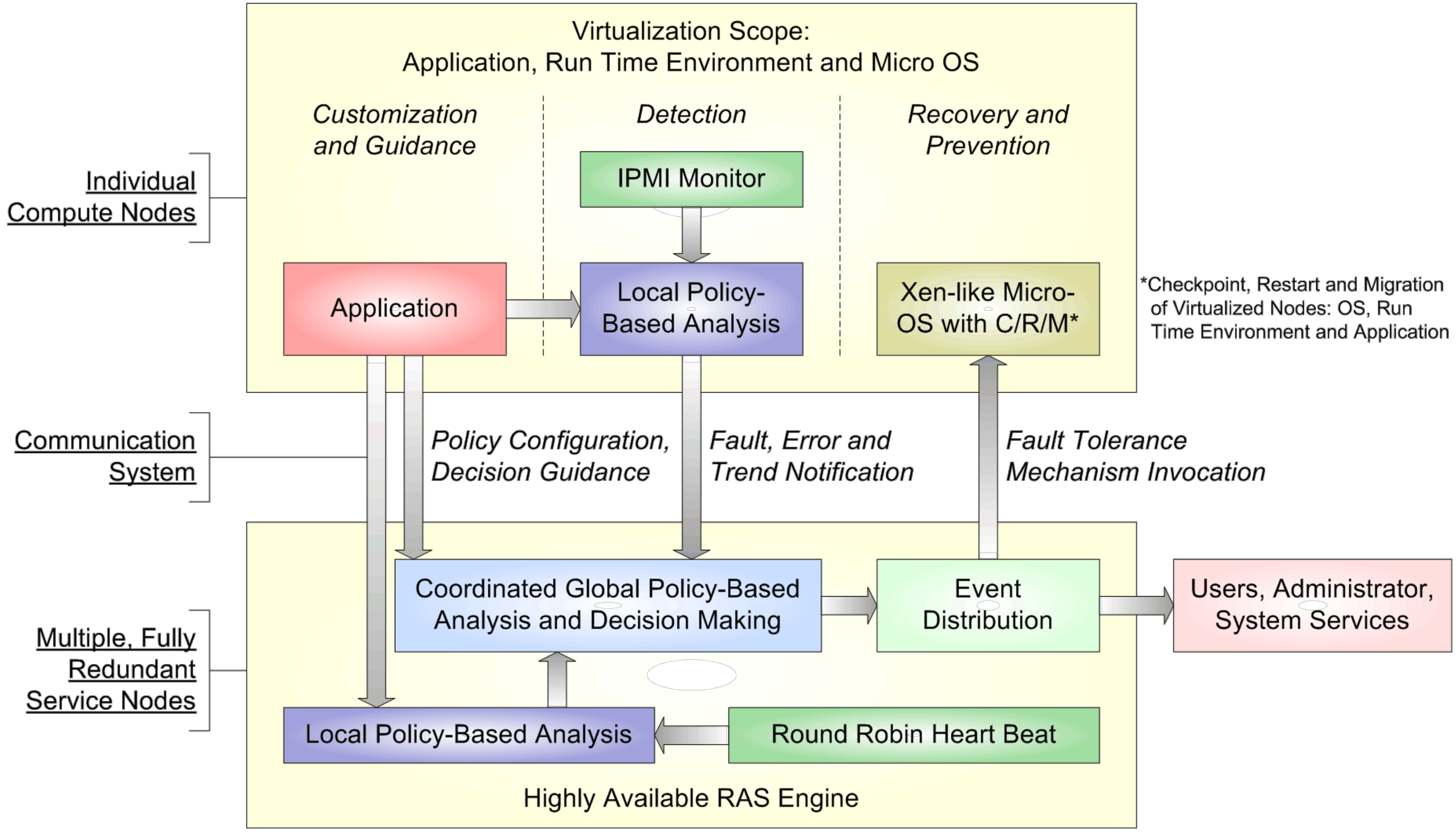
RAS Framework for Petascale HEC



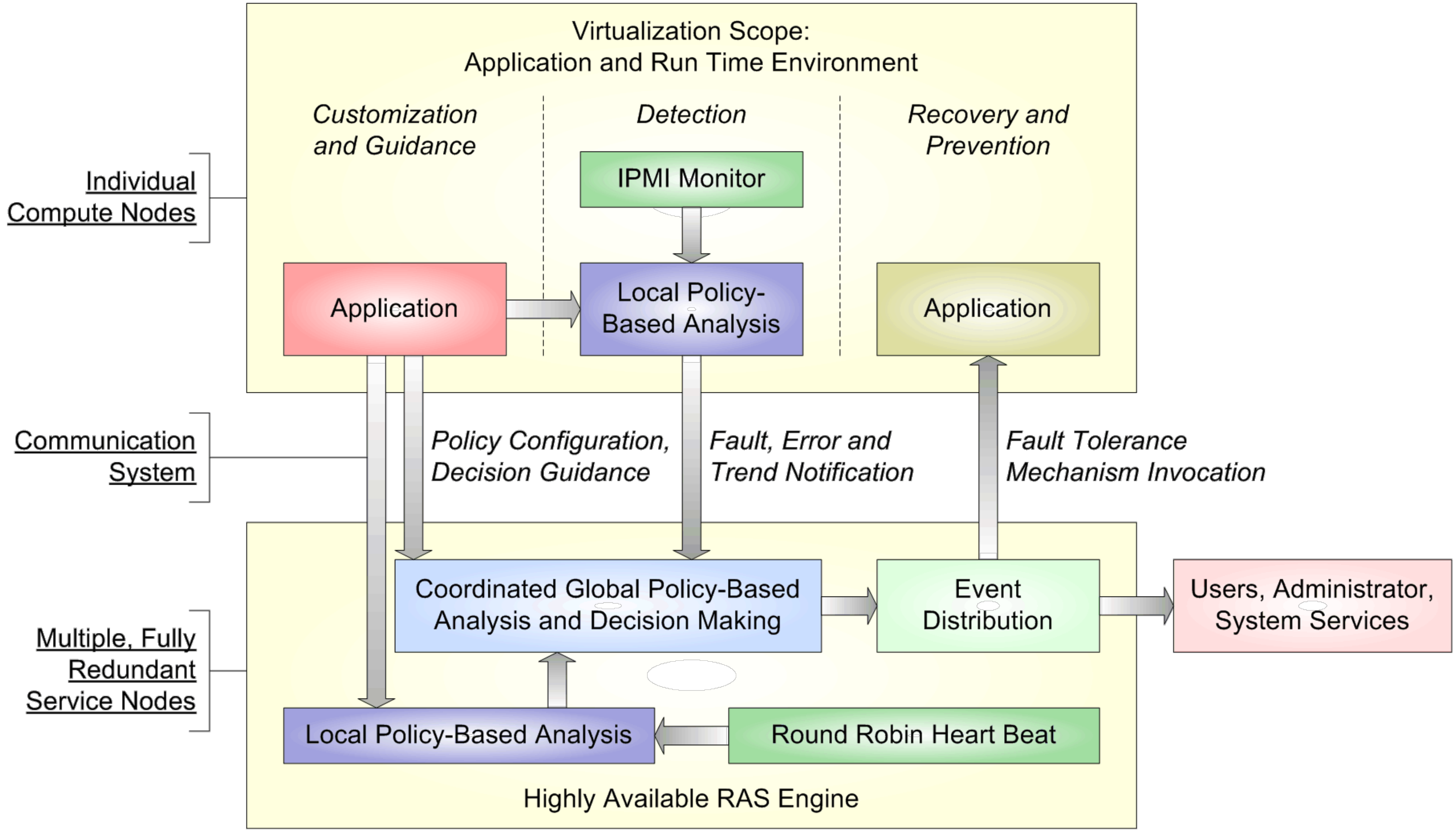
Example 1: Automatic Checkpoint/Restart



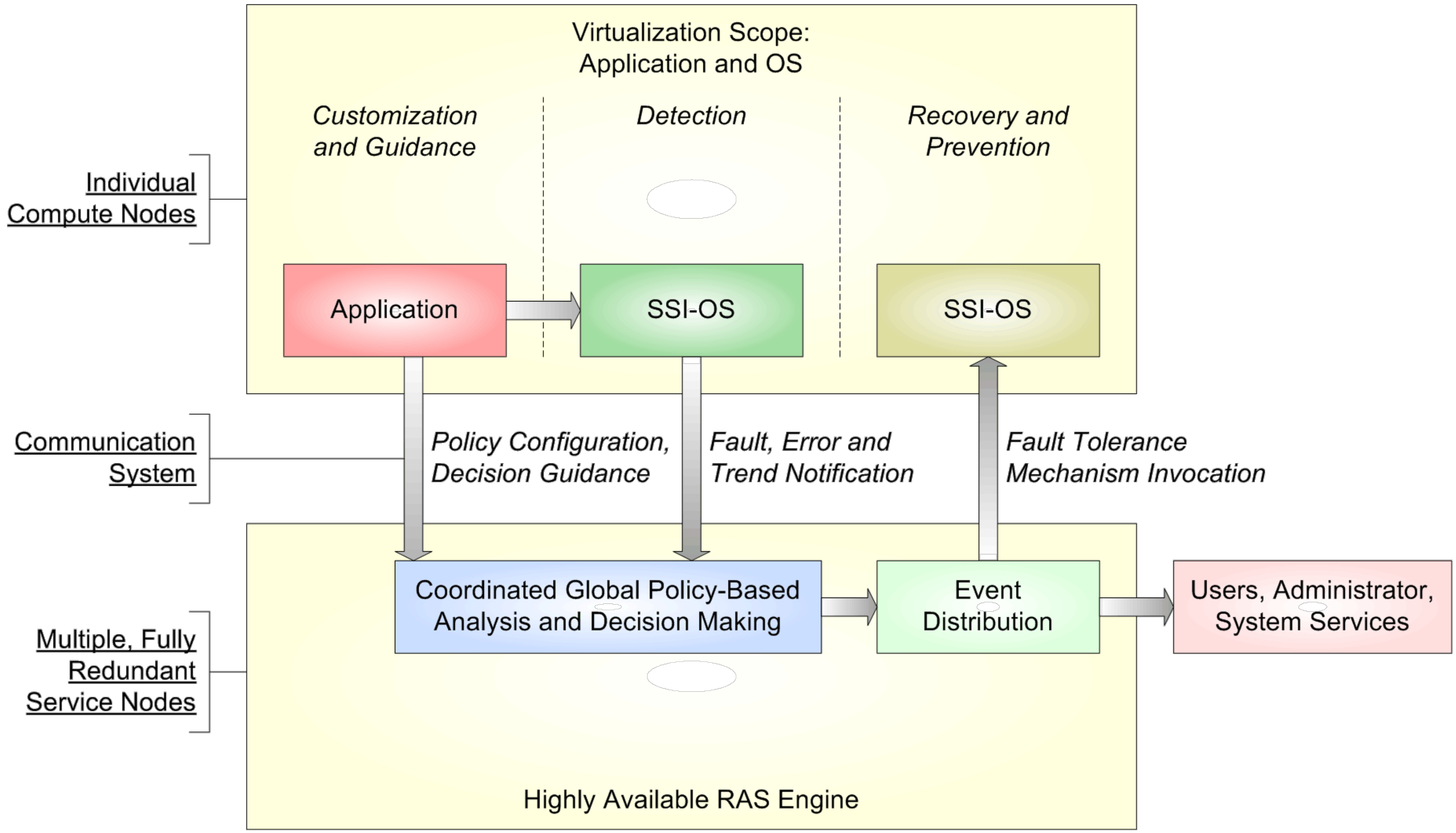
Example 2: Automatic Checkpoint/Restart/Migration



Example 3: Automatic Application-level Checkpoint/Restart



Example 4: OS-Supported Checkpoint/Restart/Migration



Summary and Conclusion

- Presented several traditional and advanced fault tolerance technologies for HPC
- Different scale requires different solutions:
  - Compute nodes
  - Front-end, service, and I/O nodes
- Scalable fault tolerance technologies are paramount to the success of large-scale HPC systems

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