High Availability for Ultra-scale Scientific High-End Computing

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Talk Outline

- Computer science research at Oak Ridge National Laboratory: Who we are and what we do…
- Availability deficiencies of today's scientific high-end computing systems.
- Existing high availability solutions for scientific high-end computing systems.
- Proposed Thesis: High availability framework for scientific high-end computing systems.
- Internship opportunities for current MSc students.

Computer Science Research at Oak Ridge National Laboratory

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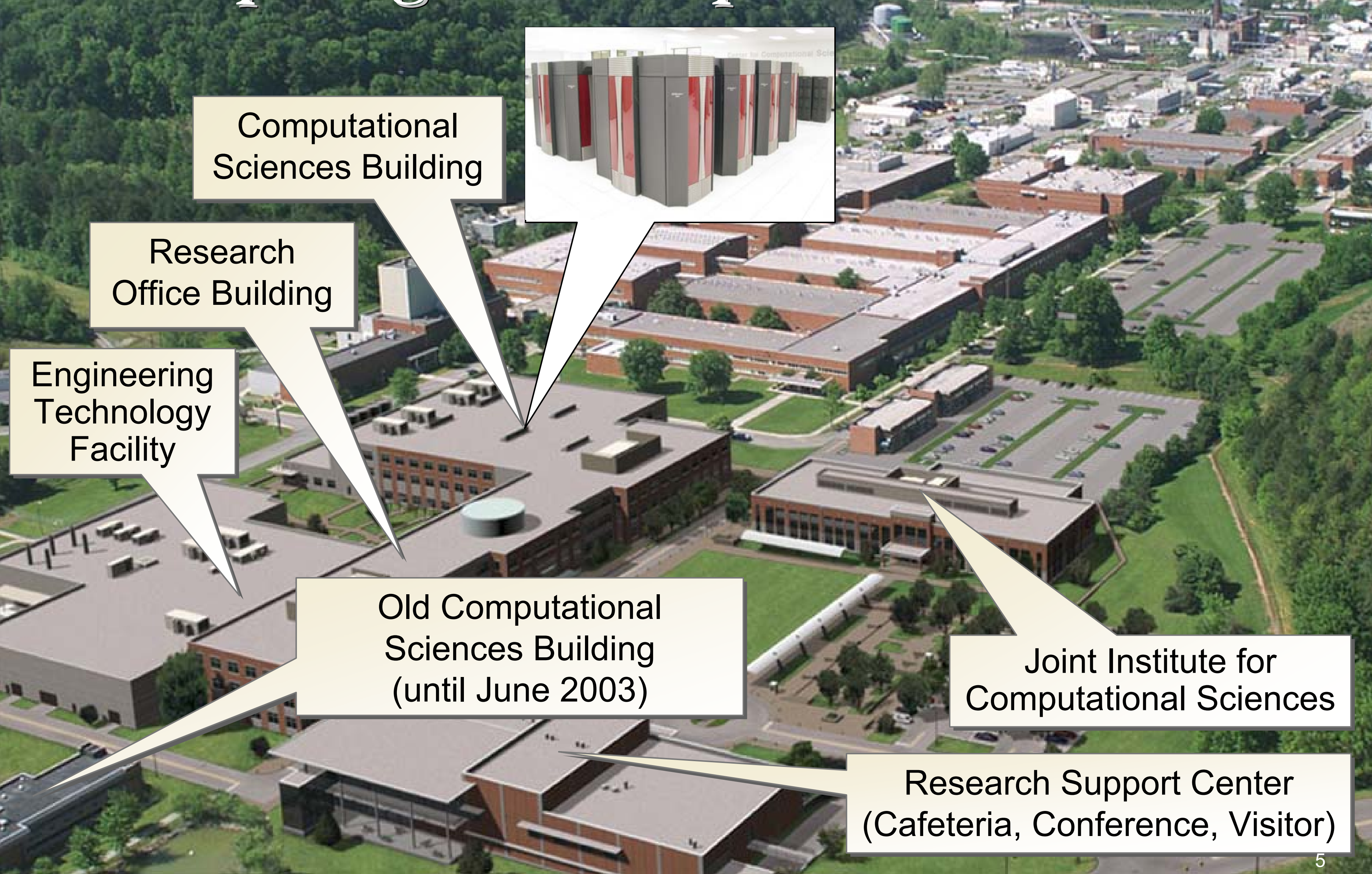
Largest Multipurpose Science Laboratory within the U.S. Department of Energy

- Privately managed for US DOE
- $1.06 billion budget
- 3,900 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
- $300 million modernization in progress

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

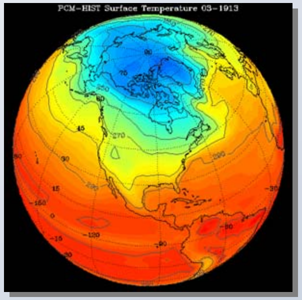


National Center for Computational Sciences

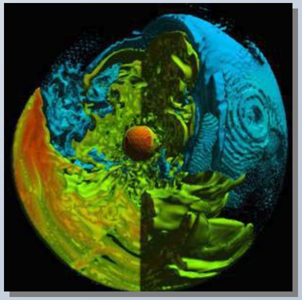
- **40,000 ft^2 (3700 m^2) computer center:**
  - **36-in (~1m) raised floor, 18 ft (5.5 m) deck-to-deck**
  - **12 MW of power with 4,800 t of redundant cooling**
  - **High-ceiling area for visualization lab:**
    - **35 MPixel PowerWall, Access Grid, etc.**

- **3 systems in the Top 500 List of Supercomputer Sites:**
  - **Jaguar: 10. Cray XT3, MPP with 5212 Procs./10 TByte ⇨ 25 TFlop/s.**
  - **Phoenix: 17. Cray X1E, Vector with 1024 Procs./ 4 TByte ⇨ 18 TFlop/s.**
  - **Cheetah: 283. IBM Power 4, Cluster with 864 Procs./ 1 TByte ⇨ 4.5 TFlop/s.**
  - **Ram: SGI Altix, SSI with 256 Procs./ 2 TByte ⇨ 1.4 TFlop/s.**

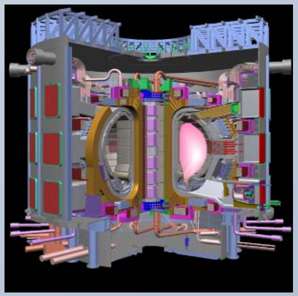
At Forefront in Scientific Computing and Simulation



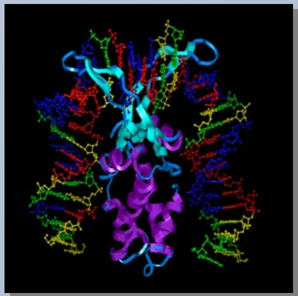
- Leading partnership in developing the National Leadership Computing Facility
  - Leadership-class scientific computing capability
  - 100 TFlop/s in 2006 (commitment made)
  - 250 TFlop/s in 2007 (commitment made)
  - 1 PFlop/s in 2008 (proposed)



- Attacking key computational challenges
  - Climate change
  - Nuclear astrophysics
  - Fusion energy
  - Materials sciences
  - Biology

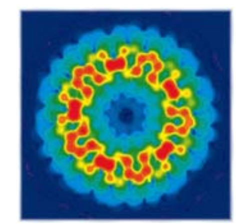


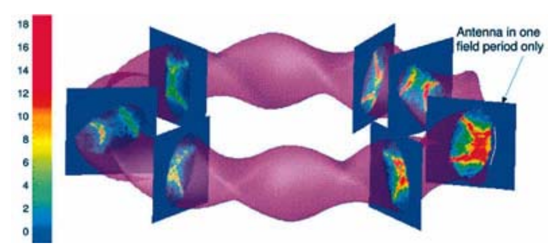
- Providing access to computational resources through high-speed networking (10Gbps)



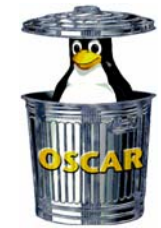
Computer Science Research Groups

- Computer Science and Mathematics (CSM) Division.
  - Applied research focused on computational sciences, intelligent systems, and information technologies.
- CSM Research Groups:
  - Climate Dynamics
  - Complex Systems
  - Computational Chemical Sciences
  - Computational Materials Science
  - Future Technologies
  - Statistics and Data Science
  - Computational Mathematics
  - *Network and Cluster Computing*
    (~20 researchers, 2 postdocs, 5 postmasters, 4 students, ++)



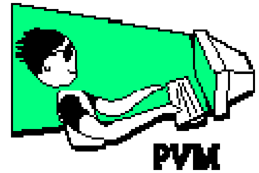


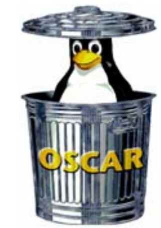
Network & Cluster Computing Projects



- Parallel Virtual Machine (PVM).
- MPI Specification, FT-MPI and Open MPI.
- Common Component Architecture (CCA).
- Open Source Cluster Application Resources (OSCAR).
- Scalable cluster tools (C3).
- Scalable Systems Software (SSS).
- Fault-tolerant metacomputing (HARNESS).
- High availability for high-end computing (RAS/MOLAR).
- Super-scalable algorithms research.
- Parallel storage systems (Freeloader).

Network & Cluster Computing Projects





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Availability Deficiencies of Today's Scientific HEC Systems

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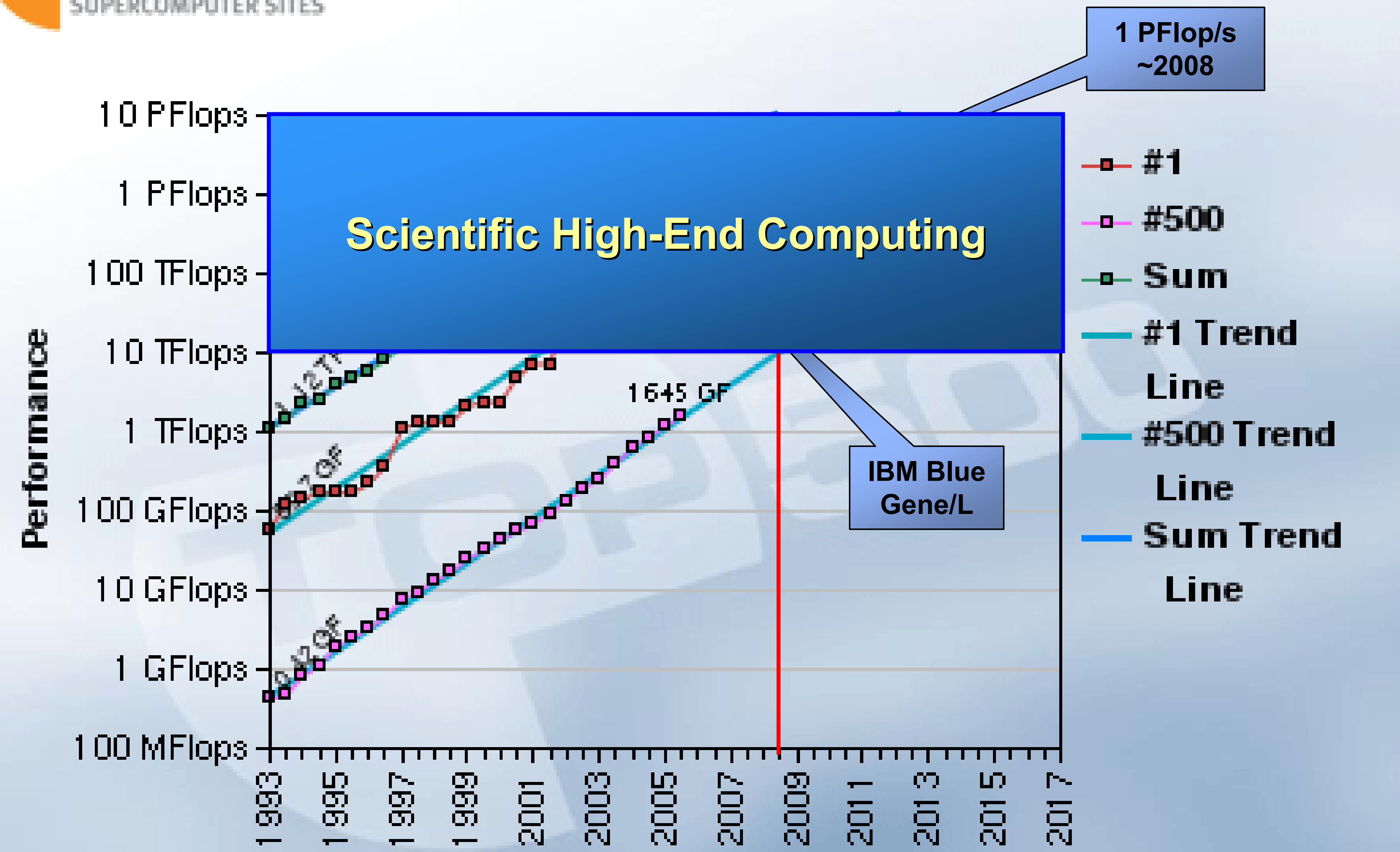
Scientific High-End Computing (HEC)

- Large-scale HPC systems.
  - Tens-to-hundreds of thousands of processors.
  - Current systems: IBM Blue Gene/L and Cray XT3
  - Next-generation systems: IBM Blue Gene/P and Cray XT4
- Computationally and data intensive applications.
  - 10 TFLOP – 1PFLOP with 10 TB – 1 PB of data.
  - Climate change, nuclear astrophysics, fusion energy, materials sciences, biology, nanotechnology, …
- Capability vs. capacity computing
  - Single jobs occupy large-scale high-performance computing systems for weeks and months at a time.

Projected Performance Development



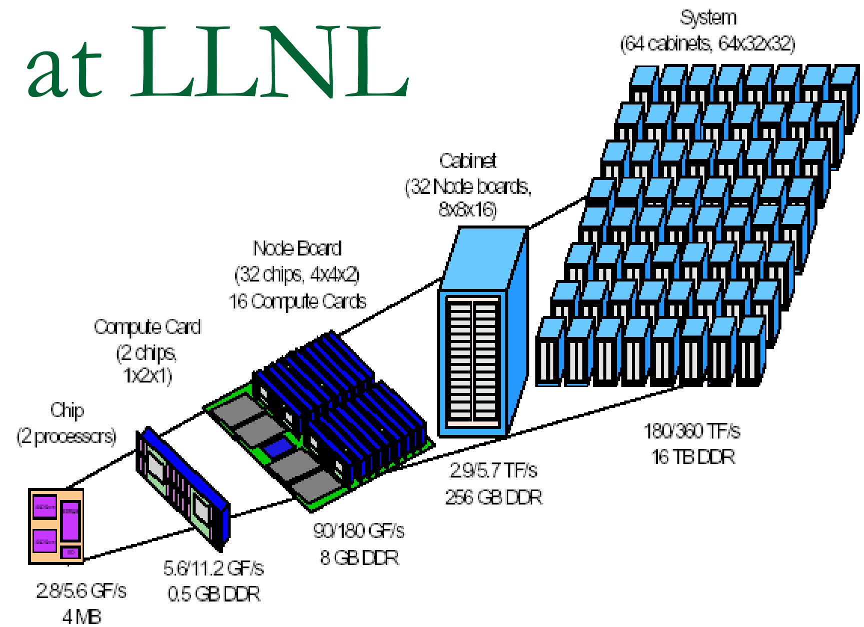
Availability Measured by the Nines

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

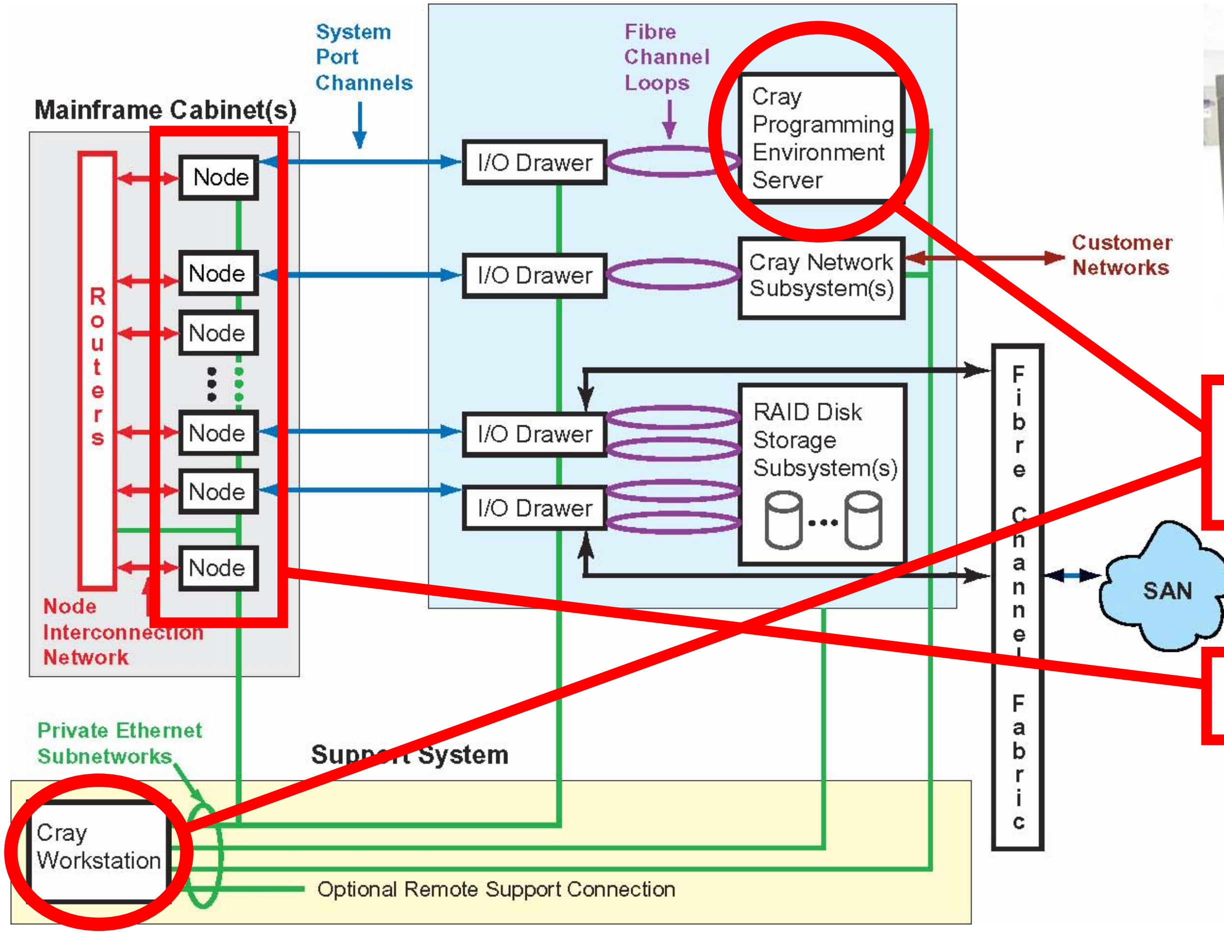
- Enterprise-class hardware + Stable Linux kernel = 5+
- Substandard hardware + Good high availability package = 2-3
- Today's supercomputers = 1-2
- My desktop = 1-2

IBM Blue Gene/L at LLNL

- #1 in Top 500.
- 367 TFLOPS.
- 131072 (700MHz) Power PC processors.
- 32 TB RAM.
- Partition (512 nodes) outage on single failure.
- MTBF = 40-50 hours.
- Weak I/O system prohibits checkpointing.



Vector Machines: Cray X1 (Phoenix)

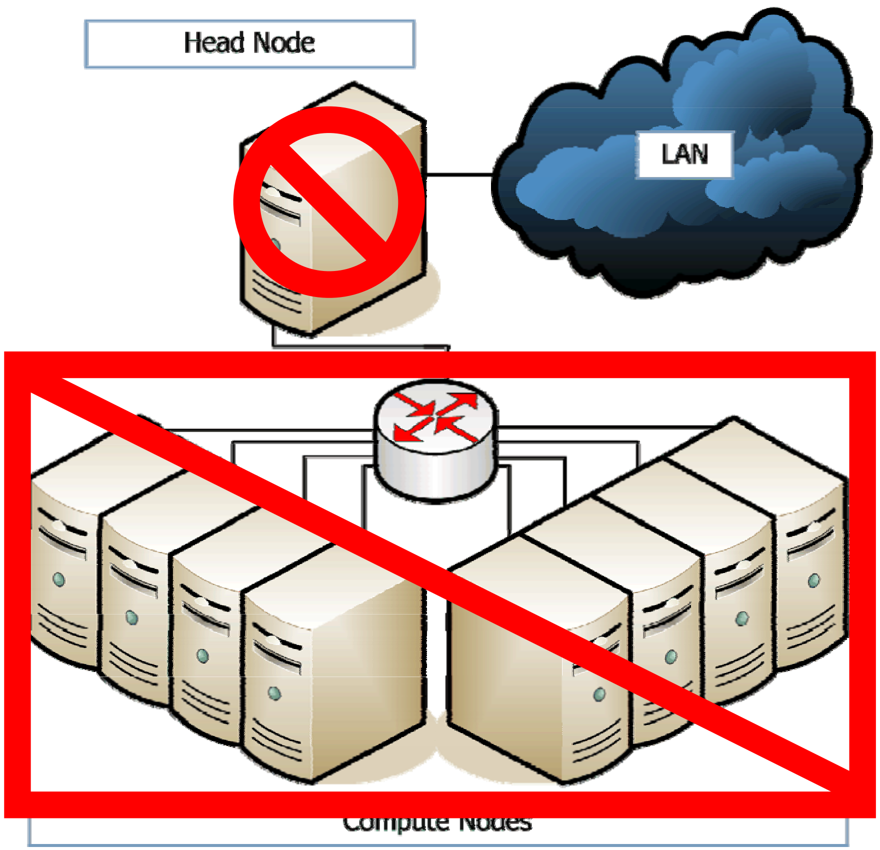


Single Points of Failure, Single Points of Control

Single Points of Failure

- Number 17 in Top 500
- 1024 Vector Processors
- 4TB RAM, 18 TFLOPS

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**.

High Availability Solutions for Scientific HEC Systems

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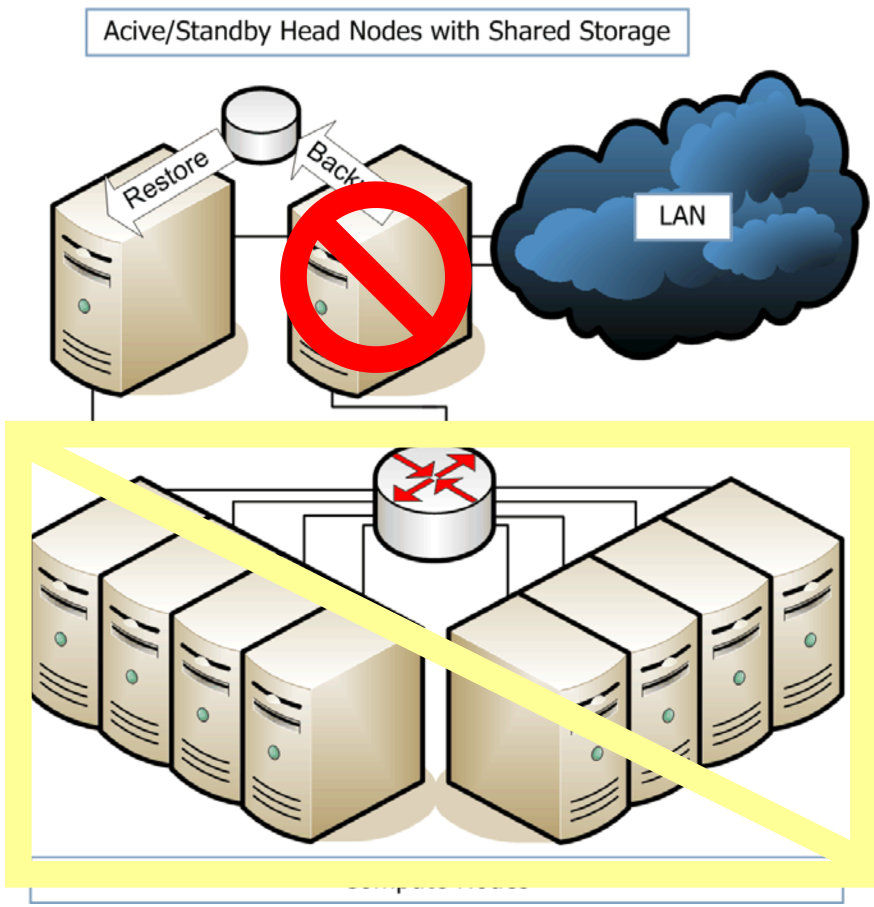
High Availability Models

- Active/Standby (Warm or Hot):
  - For one active component at least one redundant inactive (standby) component.
  - Fail-over model with idle standby component(s).
  - Level of high-availability depends on replication strategy.
- Active/Active (Asymmetric or Symmetric):
  - Multiple redundant active components.
  - No wasted system resources.
  - State change requests can be accepted and may be executed by every member of the component group.

Active/Standby Head/Service Nodes with Heartbeat Package and Shared Storage



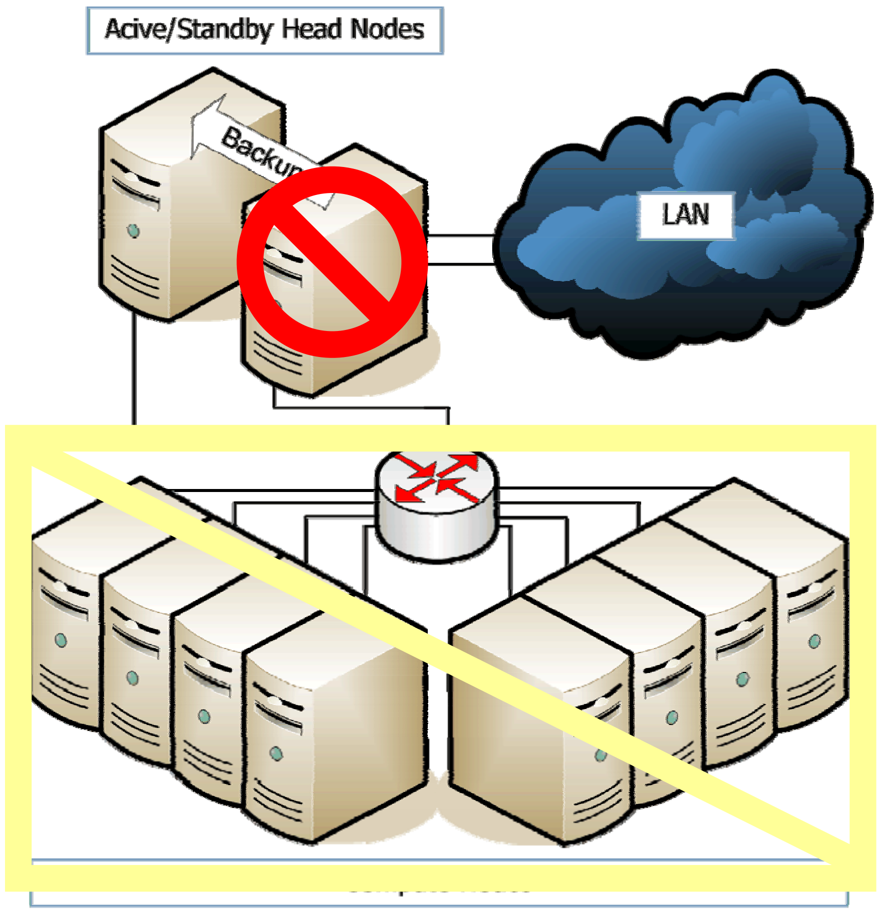
- Single active head node.
- Backup to shared storage.
- Simple checkpoint/restart.
- Fail-over to standby node.
- Corruption of backup state when failing during backup.
- Introduction of a new single point of failure.

➔ Correctness and availability are NOT guaranteed.

➔ Folks, don't do this!!!

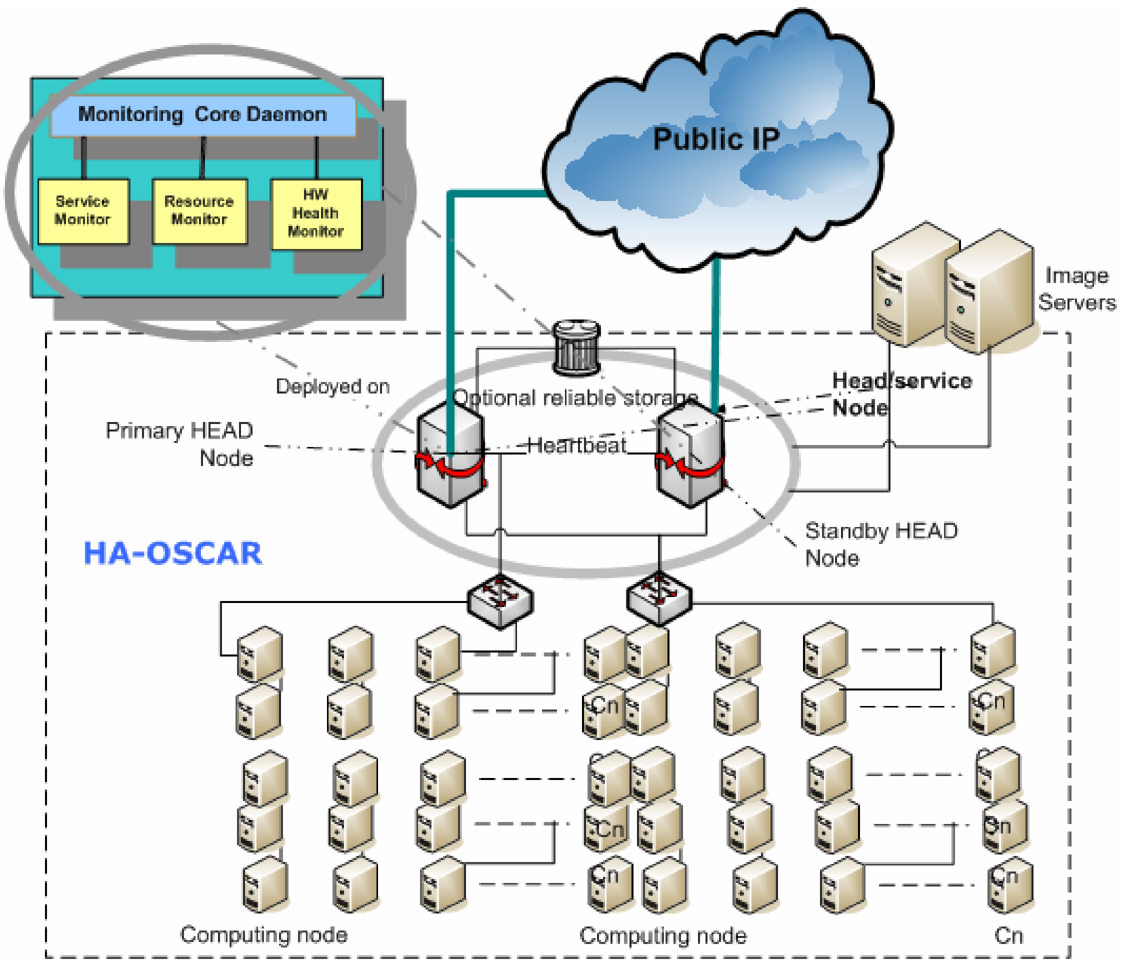
➔ Bad examples: SLURM, PVFS2, and Luste.

Active/Standby Head/Service Nodes



- 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.
- Examples: HA-OSCAR, Torque on Cray XT3

Active/Standby PBS with HA-OSCAR



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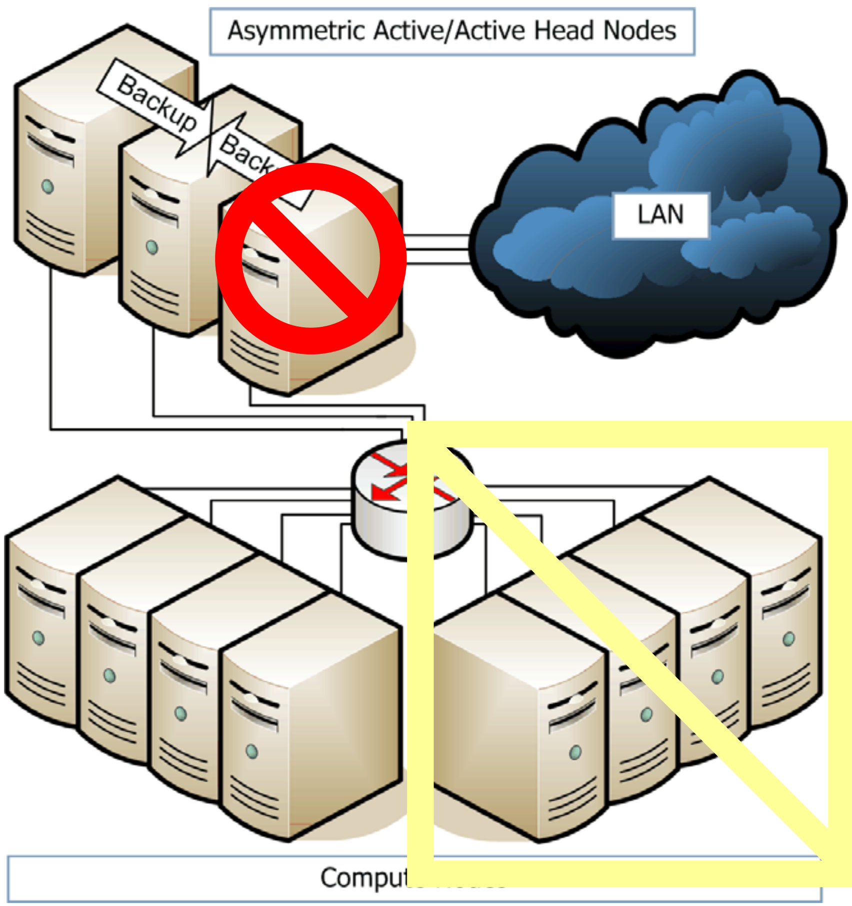
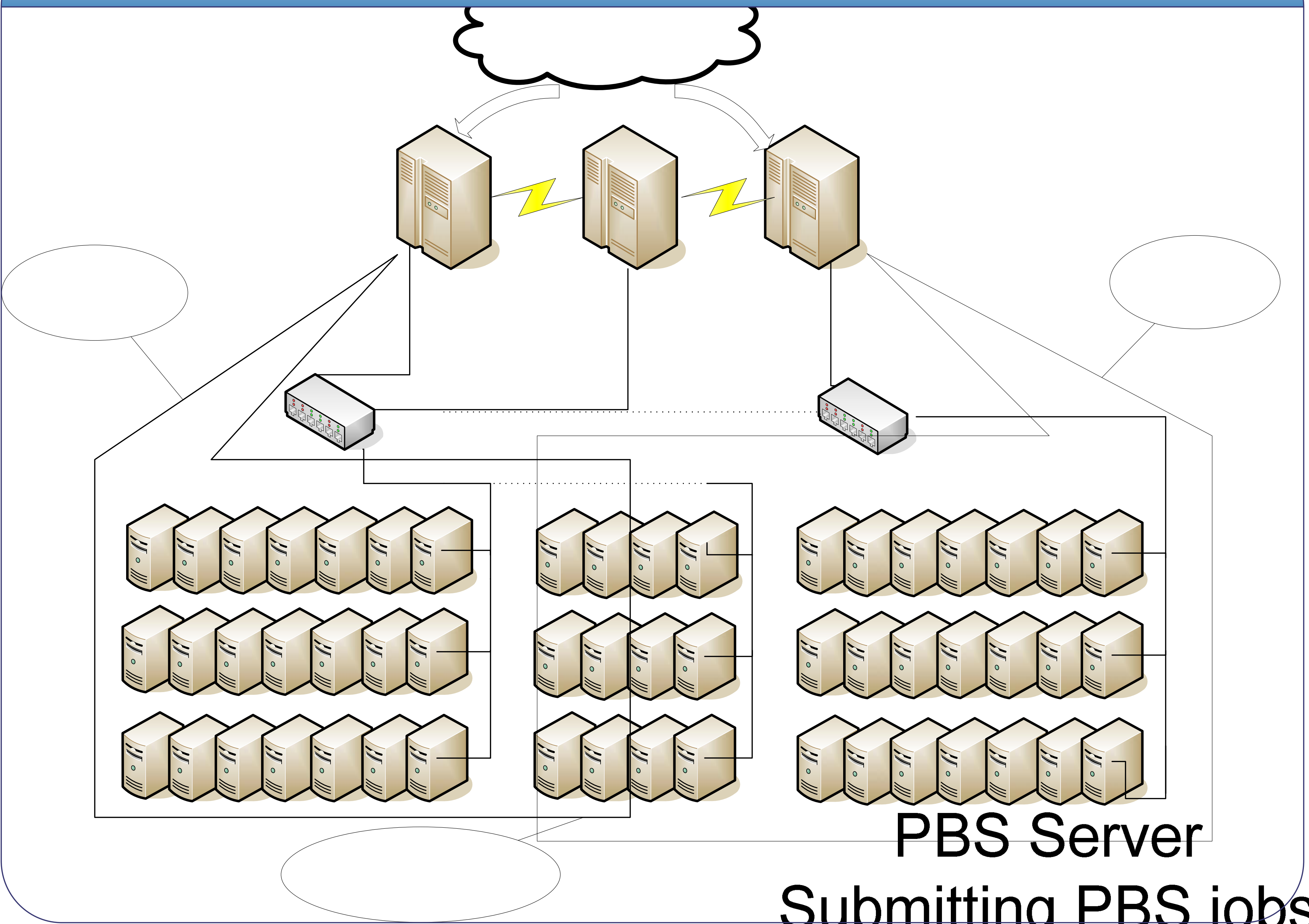
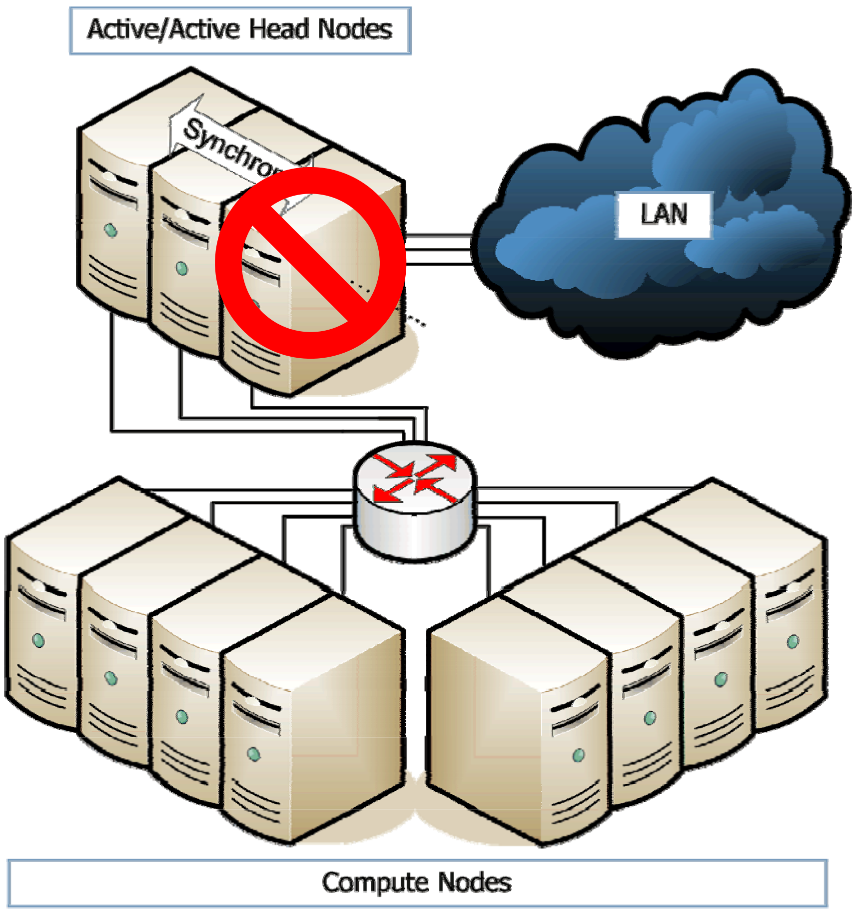
A-Active/Active Head/Service Nodes



- 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.
- Only solution: A-Active/Active HA-OSCAR.

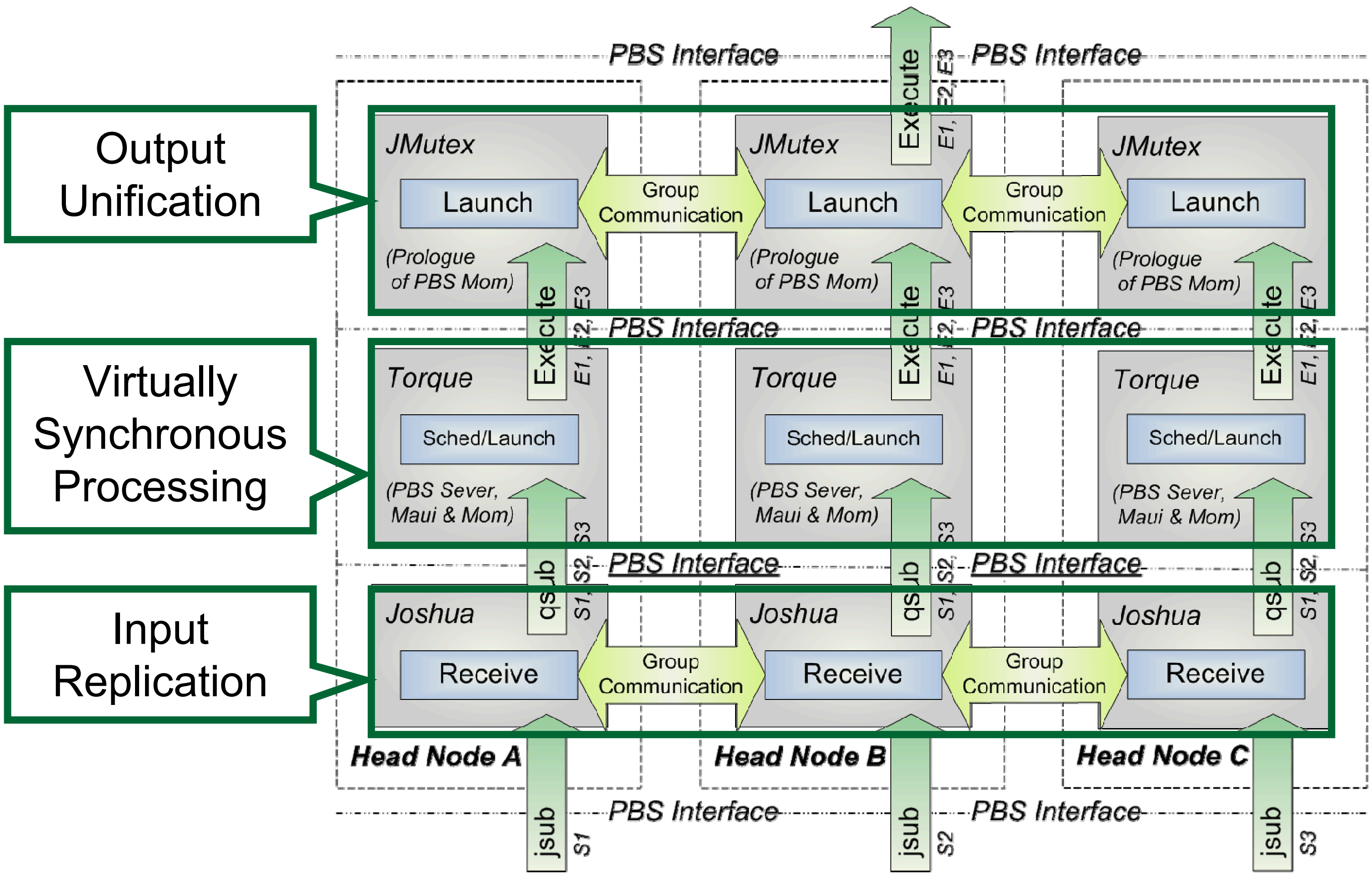

PBS Server
Submitting PBS jobs

S-Active/Active Head/Service Nodes

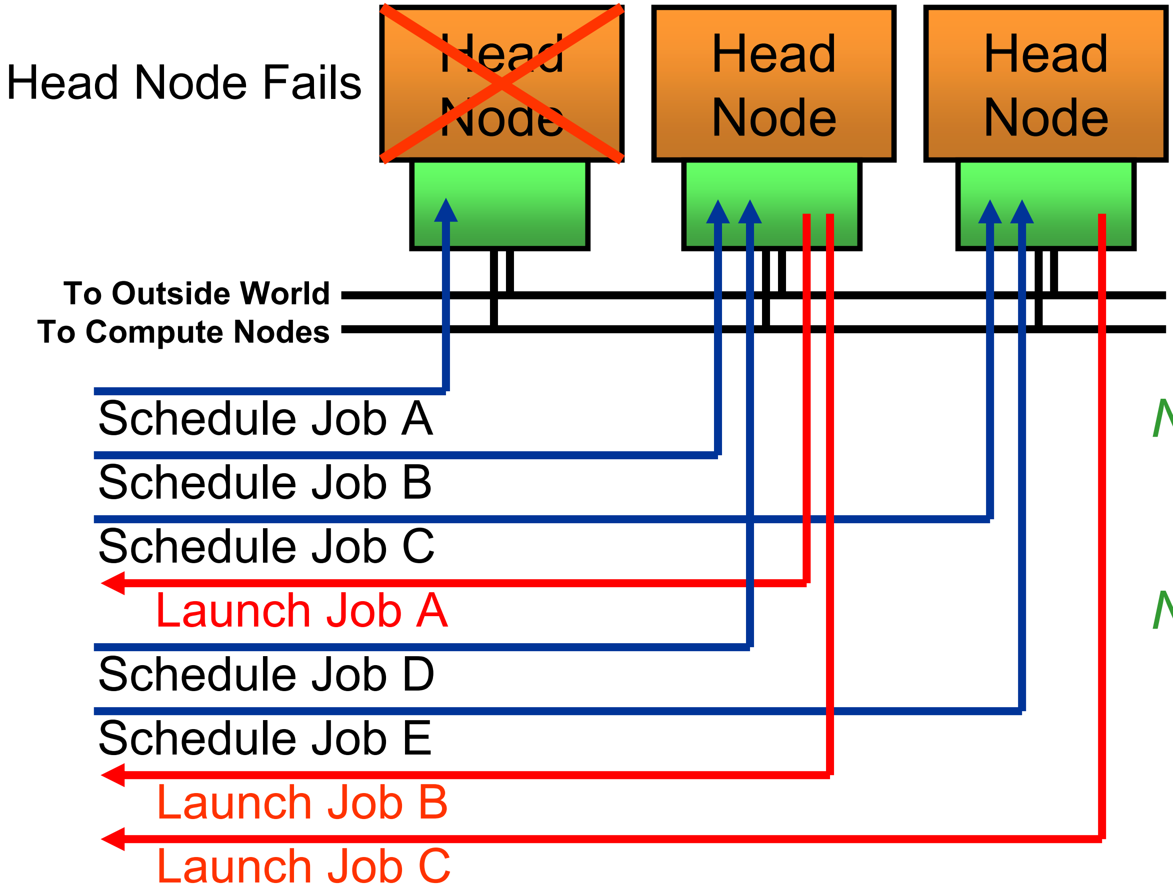


- Many active head nodes.
- Work load distribution.
- Symmetric replication between head nodes.
- Continuous service.
- Always up-to-date.
- No fail-over necessary.
- No restore-over necessary.
- Virtual synchrony model.
- Complex algorithms.
- Only solution: JOSHUA.

S-Active/Active Torque with JOSHUA



S-Active/Active Torque with JOSHUA



No Single Point of Failure

No Single Point of Control

Active/Active Redundancy for Nines

$$A_{component} = MTTF / (MTTF + MTTR)$$

$$A_{system} = 1 - (1 - A_{component})^n$$

$$T_{down} = 8760 \text{ hours} * (1 – A)$$

Signle node MTTF of 5000-hours and MTTR 72 of hours:

Nodes	Availability	Est. Annual Downtime
1	98.58%	5d 4h 21m

Active/Active Redundancy for Nines

$A_{component}$ = MTTF / (MTTF + MTTR)

A_{system} = 1 - (1 - $A_{component}$)^{n}

T_{down} = 8760 hours * (1 – A)

Signle node MTTF of 5000-hours and MTTR 72 of hours:

Nodes	Availability	Est. Annual Downtime
1	98.58%	5d 4h 21m
2	99.97%	1h 45m

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1	98.58%	5d 4h 21m
2	99.97%	1h 45m
3	99.9997%	1m 30s

Active/Active Redundancy for Nines

$A_{component}$ = MTTF / (MTTF + MTTR)

A_{system} = $1 - (1 - A_{component})^n$

T_{down} = 8760 hours * (1 – A)

Signle node MTTF of 5000-hours and MTTR 72 of 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 make sense as it does not mask catastrophic events, such as flood, hurricane, tornado, earthquake, and terrorist attack.

High Availability Framework for Scientific HEC Systems

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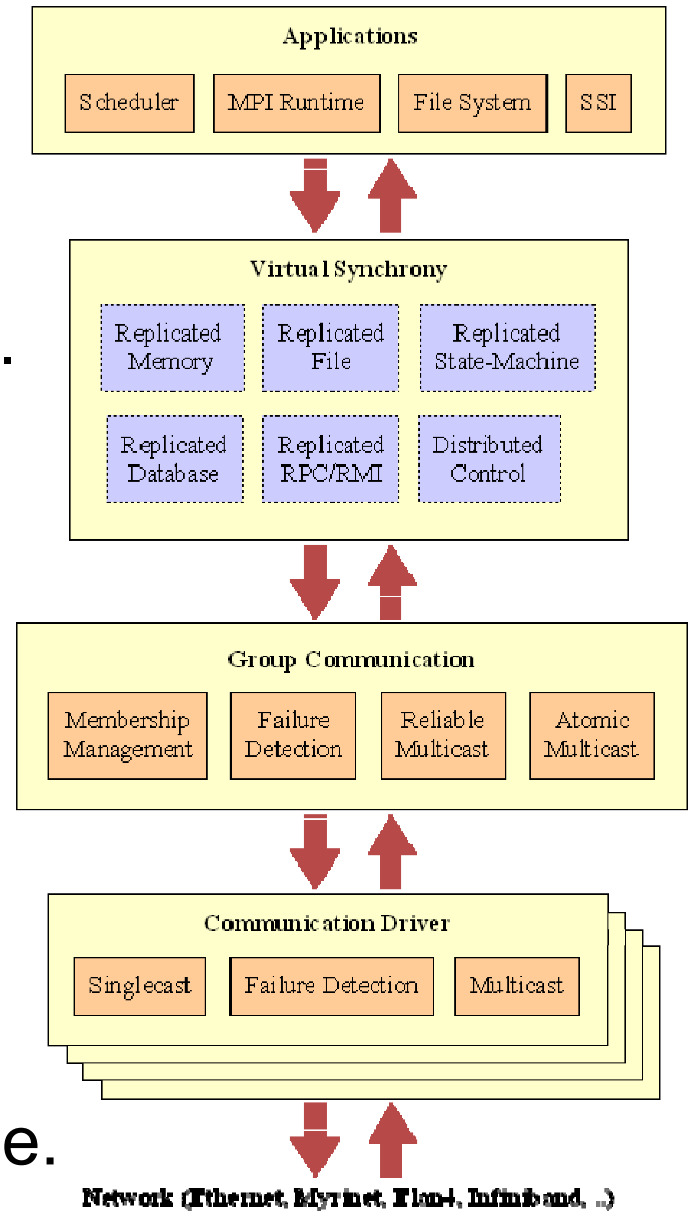
Generic High Availability Framework

- HA-OSCAR:
  - Heartbeat for monitoring and IP-failover.
  - PBS specific scripts for replication to standby.
- JOSHUA:
  - Transis for group communication.
  - TORQUE specific commands for input replication.
  - TORQUE specific scripts for output unification.

➢ *How can we provide active/stand-by and active/active high availability solutions for services in a **generic**, **modular** and **configurable** fashion?*

HA Framework



- Pluggable component framework.
  - Communication drivers.
  - Group communication.
  - Virtual synchrony.
  - *Applications.*
- Interchangeable components.
- Adaptation to application needs, such as level of consistency.
- Adaptation to system properties, such as network and system scale.

Initial Prototype

- Flexible, modular, pluggable component framework to provide RAS capabilities for services.
- C++ prototype developed as part of the RAS LDRD:
  - Object-oriented communication stack.
  - Dynamic loading of protocol components (Harness-based).
  - TCP and UDP communication drivers.
- Problems with the use of C++ and dynamic loading.
- Performance overhead due to C++ runtime.
- ➢ Ongoing work focuses on pure C implementation.

Follow-on Prototype

- Unique, flexible, dynamic, C-based component framework: Adaptive Runtime Environment (ARTE).
- Dynamic component loading/unloading on demand.
- XML as interface description language (IDL).
- "Everything" is a component:
  - Communication driver modules.
  - Group communication layer modules.
  - Virtual synchrony layer modules.

Other Major Accomplishments

- Development of a high availability taxonomy for HEC system architectures.
  - Definition of high availability terms and metrics for HEC.
  - Identification of single points of failure and control.
  - Evaluation and classification of existing solutions.
- Development of a high availability programming model for symmetric active/active replication.
  - Virtually synchronous environment model for easily making existing single services highly available.
  - JOSHUA prototype as proof-of-concept developed by Kai Uhlemann (2005/6 Reading MSc student internship).

Future Work

- Implementation of individual framework components.
  - Communication drivers and group communication.
- Design of high availability programming models.
  - Implementation of respective components.
- Integration with the JOSHUA solution.
  - Replacing Transis with the framework.
- Development of highly available system services.
  - Metadata server of a parallel file system, etc.
- Investigation and design of further use cases.
  - MPI, software management, etc.

Publications

- C. Engelmann, S. L. Scott, D. E. Bernholdt, N. R. Gottumukkala, C. Leangsuksun, J. Varma, C. Wang, F. Mueller, A. G. Shet, and P. Sadayappan. **MOLAR: Adaptive runtime support for high-end computing operating and runtime systems**. *ACM SIGOPS Operating Systems Review (OSR)*, 40(2), pages 63-72, 2006.
- C. Engelmann, S. L. Scott, C. Leangsuksun, and X. He. **Active/active replication for highly available HPC system services**. In *Proceedings of The First International Conference on Availability, Reliability, and Security (ARES) 2006*, pages 639–645, Vienna, Austria, April 20-22, 2006.
- C. Engelmann and S. L. Scott. **Concepts for high availability in scientific high-end computing**. In *Proceedings of High Availability and Performance Workshop (HAPCW) 2005*, Santa Fe, NM, USA, October 11, 2005.
- C. Engelmann and S. L. Scott. **High availability for ultra-scale high-end scientific computing**. In *Proceedings of 2nd International Workshop on Operating Systems, Programming Environments and Management Tools for High-Performance Computing on Clusters (COSET-2) 2005*, Cambridge, MA, USA, June 19, 2005.
- C. Engelmann, S. L. Scott, and G. A. Geist. **High availability through distributed control**. In *Proceedings of High Availability and Performance Workshop (HAPCW) 2004*, Santa Fe, NM, USA, October 12, 2004.

Internship Opportunities for Current MSc students

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MSc Internship Basics

- 1-2 students for 6 months at Oak Ridge National Laboratory in Oak Ridge, Tennessee, USA.
- Full-time (40 hours per week) internship supervised by a research staff member.
- Individual leading-edge projects that include background investigation, design, and development.
- Includes MSc thesis and draft research paper writeup as part of the final MSc project.
- $1300-1500 per month stipend plus travel costs depending on student qualifications.

MSc Internship Timeline

- Early June: Application process (now)
  - Specify area of interest/project
  - Submit resume/CV to Vassil
- Late June: Acceptance notification
  Background Check/Subcontracts
  J-1 (Student) Visa application
- August: Visa issued through U.S. Embassy
- September 1: Start of internship
- February 28: End of internship
- March: Defense at the University of Reading

Further Practical Information

- Driver license is a must: No public transport to work.
- $3500 (2700€) in initial minimum funds needed for:
  - First rent and various deposits.
  - One-week car rental (reimbursed afterwards).
    - Is anyone under 25? Car rental/insurance is more expensive.
  - Used car, car sales tax, registration, and insurance.
- Break-even point:
  - 1 student after 4-5 months, 2 students after 2-3 months.
  - Most students leave with a net plus despite extra expenses for: high-speed Internet, cable TV, and weekend trips.

Possible Projects (see Handout)

- Harness
  - Design/Prototyping of Harness workbench architecture
  - Analysis of HPC development and deployment tools
  - Experiments with generalizing selected tools and subsystems
  - Development of prototype plug-in components
- FreeLoader
  - Diskless (in-memory) FreeLoader prototype
  - Data replication techniques
  - Integration of FreeLoader into Harness.

HARNESS: Pluggable Heterogeneous Distributed Virtual Machine

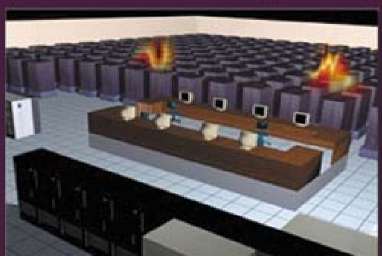
Exploring New Capabilities in Heterogeneous Distributed Computing

A Collaborative Research Effort Between Oak Ridge National Laboratory, University of Tennessee and Emory University

Fault Tolerance

Petascale Approaches Beyond Standard Checkpoint/Restart

- Checksum Based (a la RAID)
- Localized State Neighborhoods
- Incremental Checkpointing



FT-MPI Application Templates

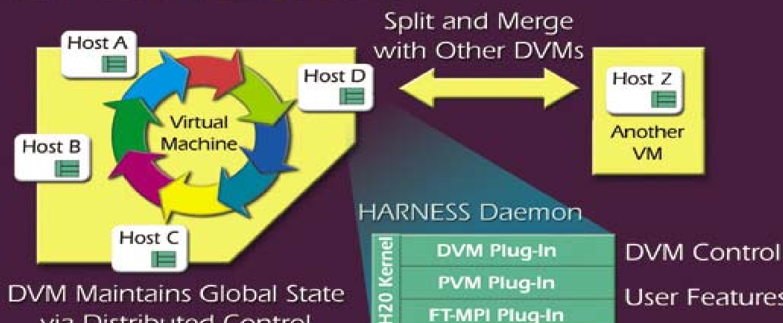
Adaptability

New Dynamic Environments
Collaborating and Personal VMs
Pervasive Computing

Multiple Plug-Ins and Parallel Paradigms

PVM Plug-In
Application Monitoring
Fault-Tolerant MPI Plug-In

Harness Architecture



DVM Maintains Global State via Distributed Control

Dynamically Customize and Extend via Plug-ins

GRID Lite

Personally Controlled (VM) Resource Sharing

Minimum Modular Infrastructure

Complements Existing DOE Data and Science Grids

Near Stateless Computing

Task Communication
Minimized Global State

Self-Assembling Virtual Machine

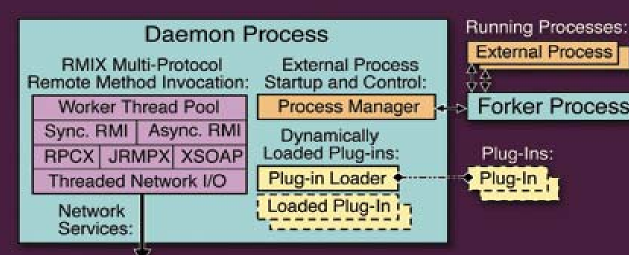
Parallel Plug-Ins Provide Capabilities

Parallel Software Modules (Plug-Ins) for Flexibility and Dynamic Customization

H2O Kernel

Implementations in C and Java

Portable Multi-Threaded C Implementation



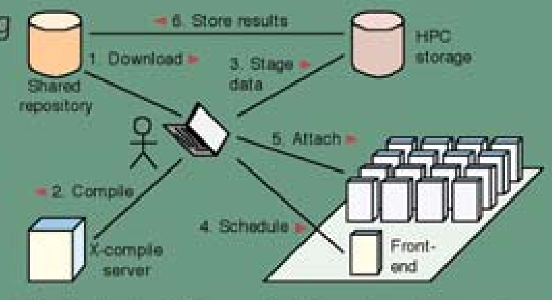
Office of Science
U.S. Department of Energy

http://www.csm.ornl.gov/harness

The Harness Workbench

Unified and adaptive access to diverse HPC platforms

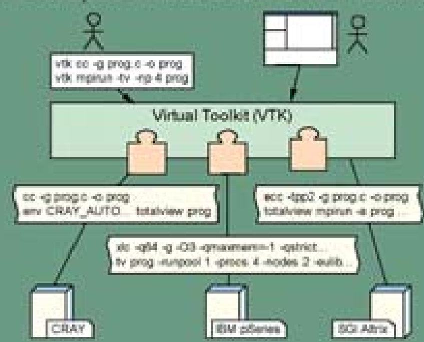
- Increasing the overall productivity of developing and executing computational codes.
- Optimizing the development and deployment processes of scientific applications.
- Simplifying application scientist activities using uniform and adaptive solutions.
- "Automagically" supporting the diversity of existing and emerging HPC architectures.



Typical scientific application development, deployment and execution activities

Virtualized command toolkit (VCT)

- Unified development, deployment and execution
- Common view across diverse HPC platforms
- User-space installation and virtual environments

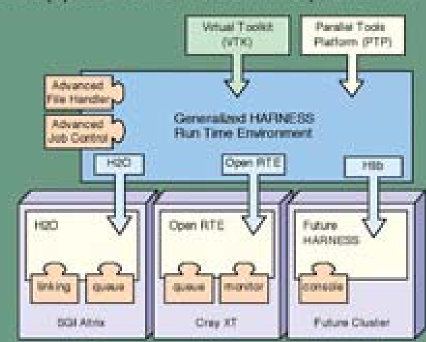


Automatic adaptation using pluggable modules

- Virtualized command toolkit plug-ins
- Runtime environment plug-ins

Next generation runtime environment (RTE)

- Flexible, adaptive, lightweight framework
- Management of runtime tasks
- Support for diverse HPC platforms



Development environment and toolkit interfaces

- Easy-to-use interfaces for scientific application development, deployment and execution

http://icl.cs.utk.edu/harness
http://www.csm.ornl.gov/harness
http://www.mathcs.emory.edu/dcl/harness

INNOVATIVE COMPUTING LABORATORY

EMORY UNIVERSITY

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ORNL

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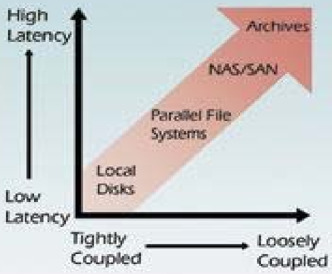
FreeLoader Distributed Storage Infrastructure Using Scavenging

http://www.csm.ornl.gov/~vazhkuda/Morsels

Today's Hierarchical Storage Map



Pros:
- Excellent price/performance ratio
- Optimized for wide-area, bulk transfers and reliability

Cons:
- High deployment/maintenance/ administrative costs
- Specialized software and central points of failure
- Low availability

Motivation

Idea: Aggregate idle desktop storage to use for caching remote datasets

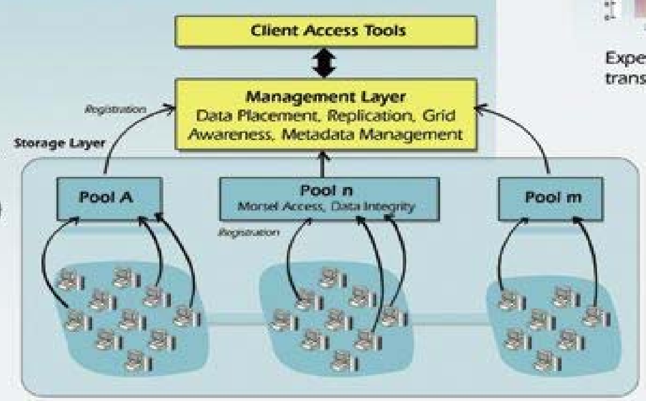
Benefits:
- Low cost (~$1 / GB)
- Low utilization means high availability for aggregation
  - Creates GBs of nearby storage
  - Decreases latency & increases bandwidth to remote datasets
- Low impact on individual desktops (load is shared by many)

Concerns:
- Volatility, trust, performance, user impact (disk, CPU, network)

Scalable, Decentralized Architecture

Storage Layer:
- Benefactor Nodes:
  - Unit of contribution (Morsels)
  - Basic morsel operations
  - Space reclaim
  - Data Integrity through checksums
- Pools:
  - Benefactor registrations (soft state)
  - Dataset distributions, striping
  - Metadata
  - Selection heuristics

Management Layer:
- Pool registrations
- Replication and selection
- Grid awareness



Project Members:
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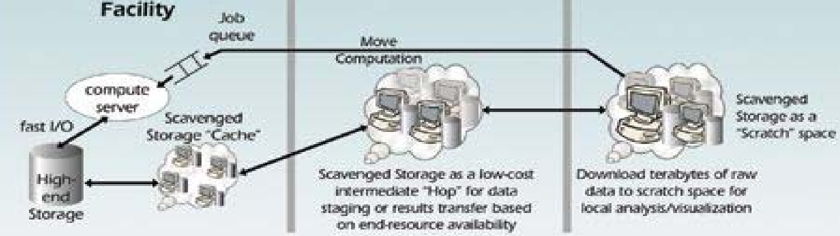
[1] Computer Science and Mathematics Division, Oak Ridge National Laboratory • [2] Computer Science Department, North Carolina State University

Design Objectives and Assumptions

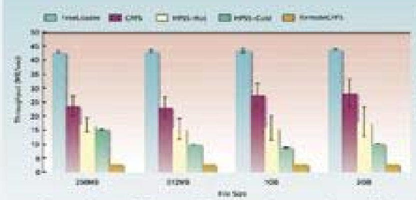
Design Goals:
- Scalable: O(100) or O(1000)
- Utilizing commodity components
- Preserving user autonomy
- Heterogeneity tolerant

Assumptions:
- Well-connected & secure corporate setting
- Large, immutable datasets (WORM)
- Use by wide-area and Grid clients

Use Cases



Status and Preliminary Results



- Client, Manager, Benefactor APIs
- Manager has greedy striping of datasets
- Client morsel-fetch flow control
- User impact analysis and benchmarking
- Testbed: ***A dozen Linux machines; aggregate storage of 120GB; GridFTP access to local and remote GPFS; HSI access to local HPSS archives***

Experiment Setup: FreeLoader results with an 8-node stripe width and 1MB stripe size; GridFTP transfers with 4 parallel streams and 1MB TCP buffers

Conclusions

- **What the scavenged storage "is not":**
  - *Is not* a replacement to high-end storage
  - *Is not* a file system
  - *Is not* intended to integrate storage resources at a wide-area scale
- **What it "is":**
  - *Is* a Low-cost, best-effort alternative
  - *Is* intended to facilitate:
    - Transient access to large, read-only datasets
    - Data sharing within an administrative domain
  - *Is* to be used with high-end and archival storage

Questions and Comments

More information: www.csm.ornl.gov/~engelman

FIFA World Cup Opening Match at 5PM: Germany - Costa Rica