On Programming Models for Service-Level High Availability

Christian Engelmann[1,2], Stephen L. Scott[1], Chokchai (Box) Leangsuksun[3], Xubin (Ben) He[4]

[1] Oak Ridge National Laboratory, Oak Ridge, USA
[2] The University of Reading, Reading, UK
[3] Louisiana Tech University, Ruston, USA
[4] Tennessee Tech University, Cookeville, USA

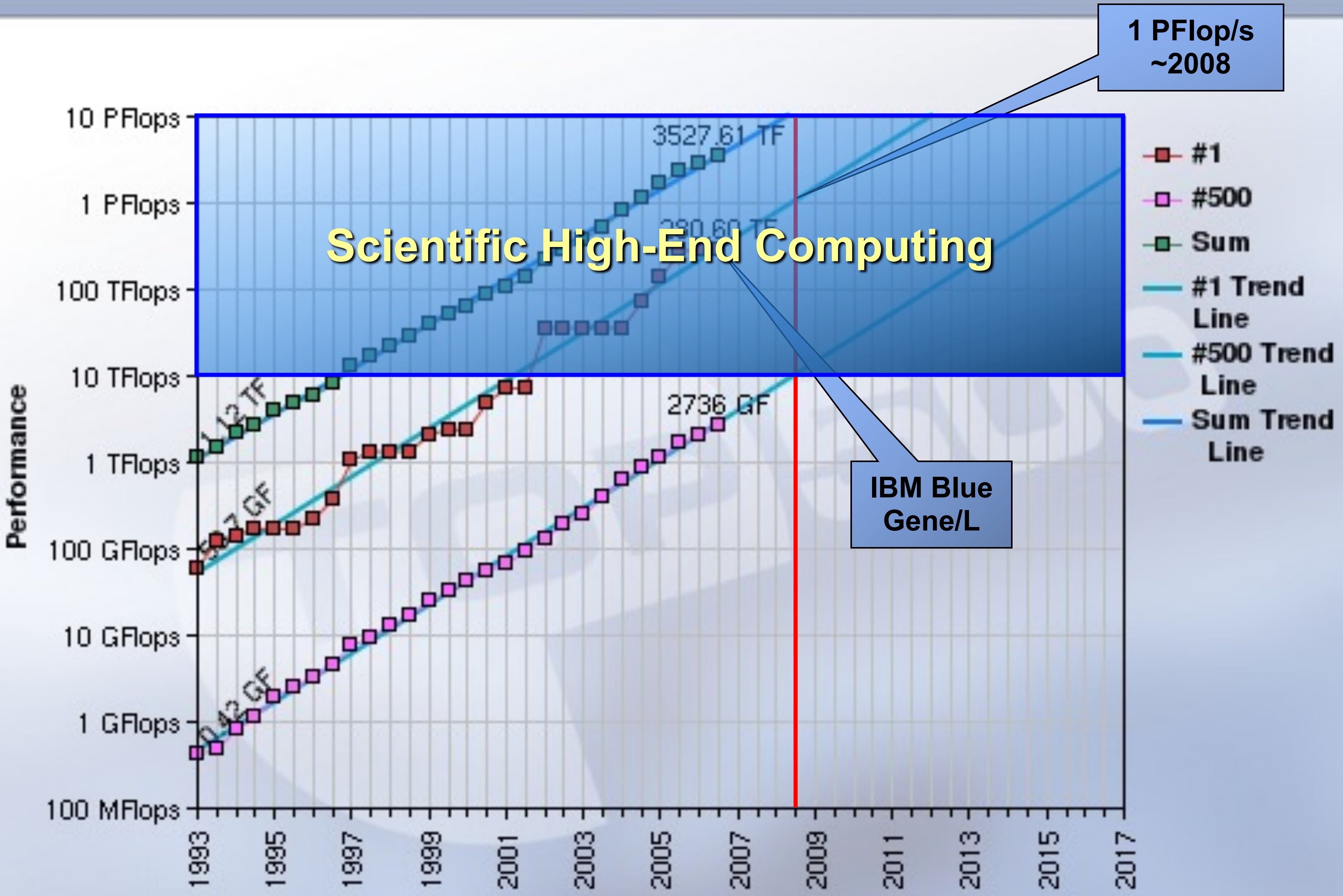
Talk Outline

- Scientific high-end computing (HEC)
- Availability deficiencies of today's HEC systems
- Projects and accomplishments overviews
- High availability (HA) models for services
- Developed prototypes overview
- Existing limitations and most pressing issues
- Generalization of HA programming models
- Generic HA framework infrastructure

Scientific High-End Computing (HEC)

- Large-scale HPC systems.
  - Tens-to-hundreds of thousands of processors.
  - Current systems: IBM Blue Gene/L and Cray XT4
  - Next-generation: petascale IBM Blue Gene and Cray XT
- 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



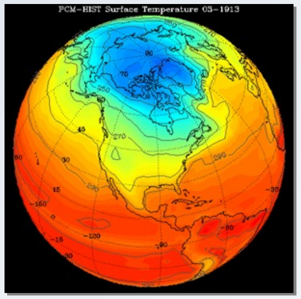
National Center for Computational Sciences

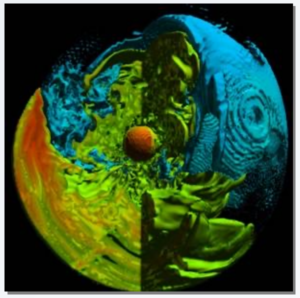
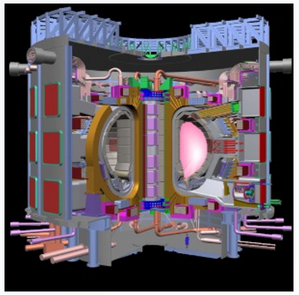
- 40,000 ft^2 (3700 m^2) computer center:
  - 36-in (~1m) raised floor, 18 ft (5.5 m) deck-to-deck
  - 12 MW of power with 4,800 t of redundant cooling
  - High-ceiling area for visualization lab:
    - 35 MPixel PowerWall, Access Grid, etc.

- 2 systems in the Top 500 List of Supercomputer Sites:
  - Jaguar: 10? Cray XT3, MPP with 12500 dual-core Processors ⇨ 119 TFlop.
  - Phoenix: 32? 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
  - 100 TFlop/s in 2007 (recently installed)
  - 250 TFlop/s in 2007/8 (commitment made)
  - 1 PFlop/s in 2008/9 (proposed)
- Attacking key computational challenges
  - Climate change
  - Nuclear astrophysics
  - Fusion energy
  - Materials sciences
  - Biology
- Providing access to computational resources through high-speed networking (10Gbps)



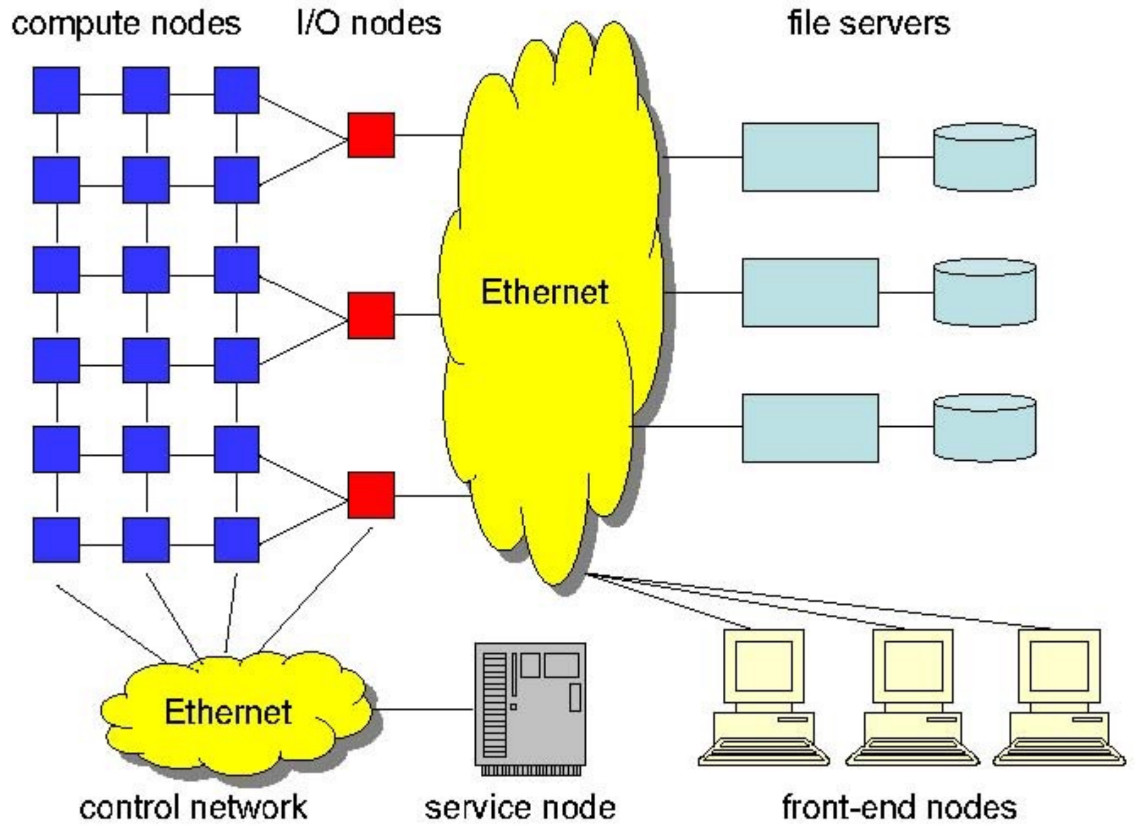
Availability Measured by the Nines

see <http://info.nccs.gov/resources> for current status of HPC systems 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 HEC System Architecture

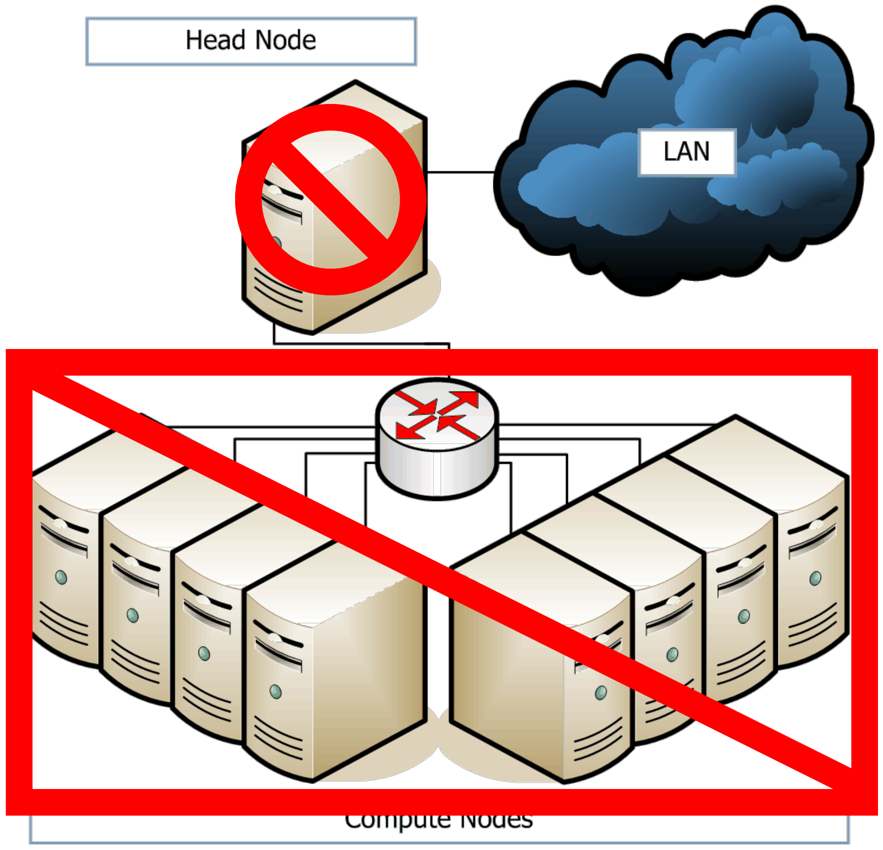


Typical failure causes:
- Overheating !!!
- Memory errors
- Network errors
- Other hardware issues
- Software bugs

Different scale requires different solutions:
- Compute nodes (10,000+)
- Front-end, service, and I/O nodes (50+)

Image source: Moreira et al., "Designing a Highly-Scalable Operating System: The Blue Gene/L Story" *Proceedings of the 2006 ACM/IEEE Conference on Supercomputing, Nov. 11-17, Tampa, FL, USA.*

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**.

Projects Overview

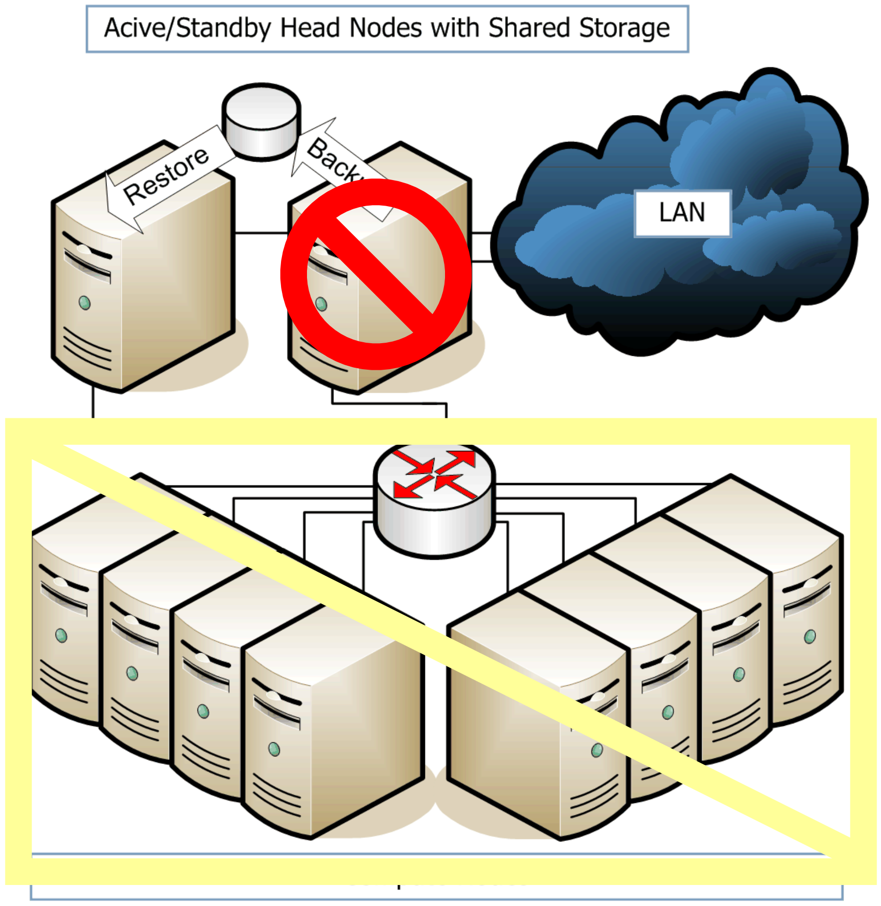
- Initial **HA-OSCAR** research in active/standby technology for the batch job management system
- Ongoing **MOLAR** research in active/standby, asymmetric and symmetric active/active technology
- Recent **RAS LDRD** research in symmetric active/active technology

→ 3-4 years of research and development in high availability for high-performance computing system services

Accomplishments Overview

- Investigated the overall background of HA technologies in the context of HPC
  - Detailed problem description
  - Conceptual models
  - Review of existing solutions
- Developed different replication strategies for providing high availability for HPC system services
  - Active/standby
  - Asymmetric active/active
  - Symmetric active/active
- Implemented several proof-of-concept prototypes

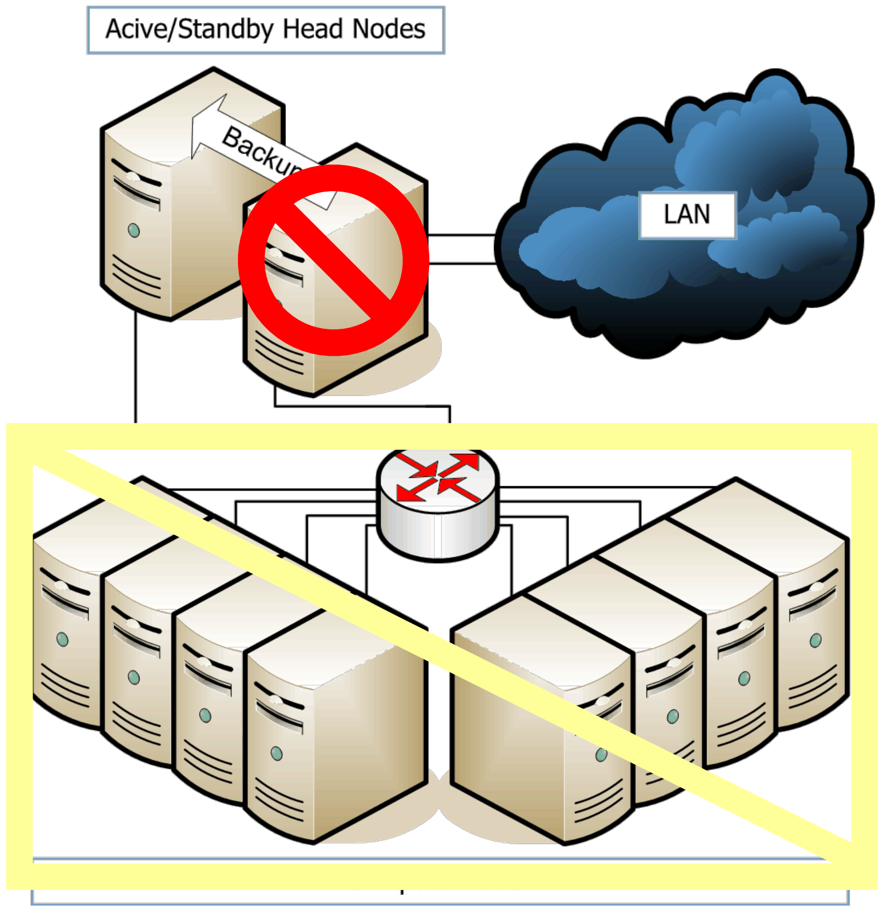
Active/Standby with Shared Storage



- 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, meta data servers of PVFS and Lustre

Active/Standby Redundancy

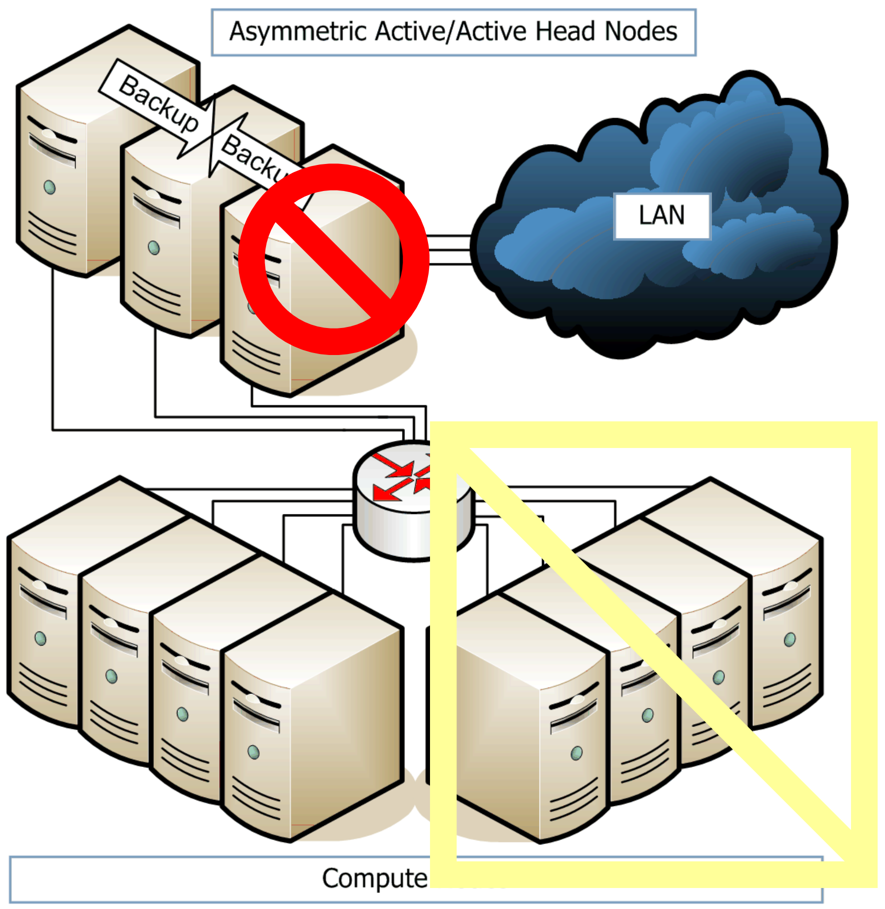


- Single active head node
- Backup to standby node
- Simple checkpoint/restart
- Fail-over to standby node
- Idle standby head node
- Rollback to backup
- Service interruption for fail-over and restore-over

➔ Torque on Cray XT

➔ HA-OSCAR prototype

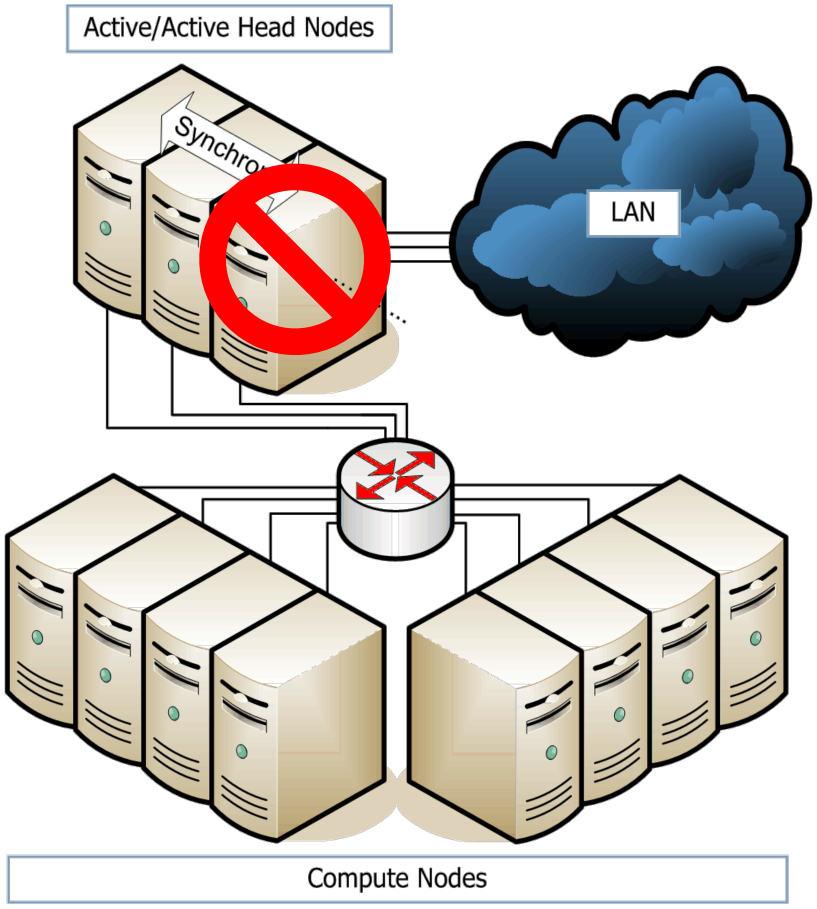
Asymmetric Active/Active Redundancy



- 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 necessary
- No restore-over necessary
- Virtual synchrony model
- Complex algorithms
- JOSHUA prototype for Torque

Developed Prototypes Overview (1/2)

- Active/Standby HA-OSCAR
  - High availability for Open PBS/TORQUE
  - Integration with compute node checkpoint/restart
- Asymmetric active/active HA-OSCAR
  - High availability for Open PBS & SGE
  - High throughput computing solution
- Symmetric active/active JOSHUA
  - High availability for PBS TORQUE
  - Fully transparent replication

Existing Limitations

- The active/standby and asymmetric active/active technology interrupts the service during fail-over
- Generic *n+1* or *n+m* asymmetric active/active configurations have not been developed yet
- The 2+1 asymmetric active/active configuration uses two different service implementations
- The developed symmetric active/active technology has certain stability and performance issues
- All developed prototypes use a customized high availability environment
- Missing interaction with compute node fault tolerance mechanisms (except for HA-OSCAR for head node fail-over)

Most Pressing Issues

- For production-type deployment
  - Stability – guaranteed quality of service
  - Performance – low replication overhead
  - Interaction with compute node fault tolerance mechanisms – e.g. procedure for failing PBS mom
  - ➔ Testing, enhancements, and staged deployment
- For extending the developed technologies
  - Portability – ability to apply technology to different services
  - Ease-of-use – simplified service HA management (RAS)
  - ➔ Generic HA framework needed

Next Step: Generic HA Framework

- Generalization of HA programming models
  - Active/Standby
  - Asymmetric active/active
  - Symmetric active/active
- Enhancing the transparency of the HA infrastructure
  - Minimum adaptation to the actual service protocol
  - Virtualized communication layer for abstraction

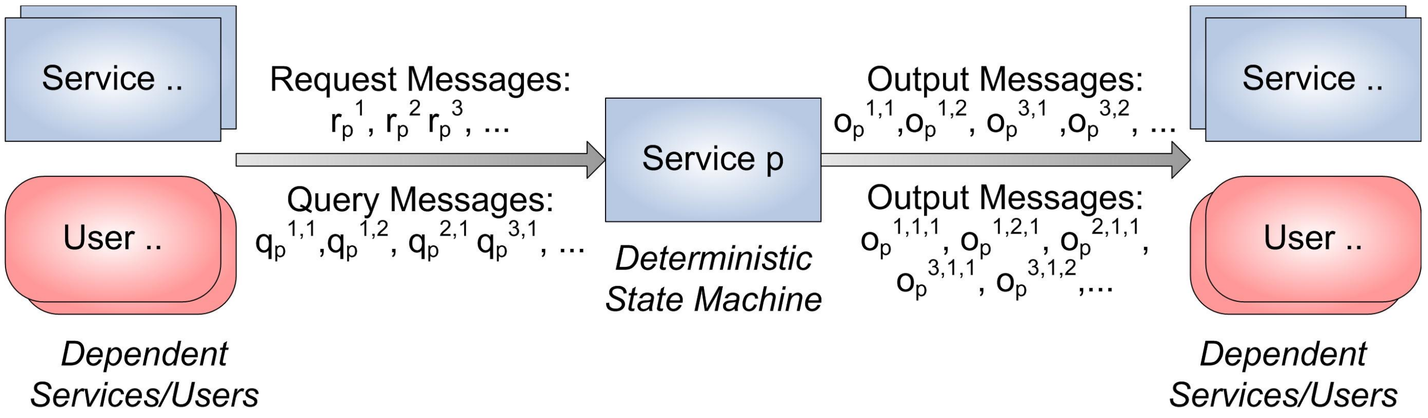
→ Portability

→ Ease-of-use

Failure Model

- Fail-stop
  - The service, its node, or its communication links, fail by simply stopping.
  - Failure detection mechanisms may be deployed to assure fail-stop behavior in certain cases, such as for incomplete or garbled messages.
- Permanent failures
  - Non-transient behavior assured by detection mechanisms via node fencing.
  - Recovery requires external intervention, such as repair or replacement of the failed component.
- Both assumptions match real-world properties.

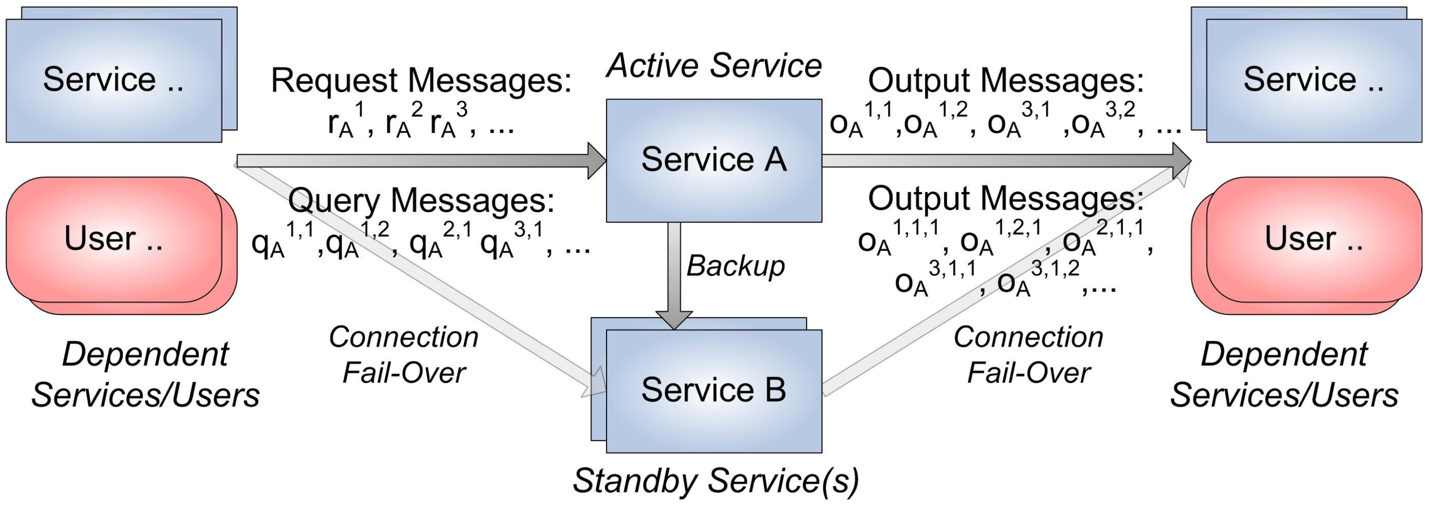
Communicating Process Generalization



Service ..
User ..
Dependent Services/Users
Request Messages:
$r_p^1, r_p^2\ r_p^3, \ldots$
Query Messages:
$q_p^{1,1}, q_p^{1,2}, q_p^{2,1}\ q_p^{3,1}, \ldots$
Service p
Deterministic State Machine
Output Messages:
$o_p^{1,1}, o_p^{1,2}, o_p^{3,1}, o_p^{3,2}, \ldots$
Output Messages:
$o_p^{1,1,1}, o_p^{1,2,1}, o_p^{2,1,1}, o_p^{3,1,1}, o_p^{3,1,2}, \ldots$
Service ..
User ..
Dependent Services/Users

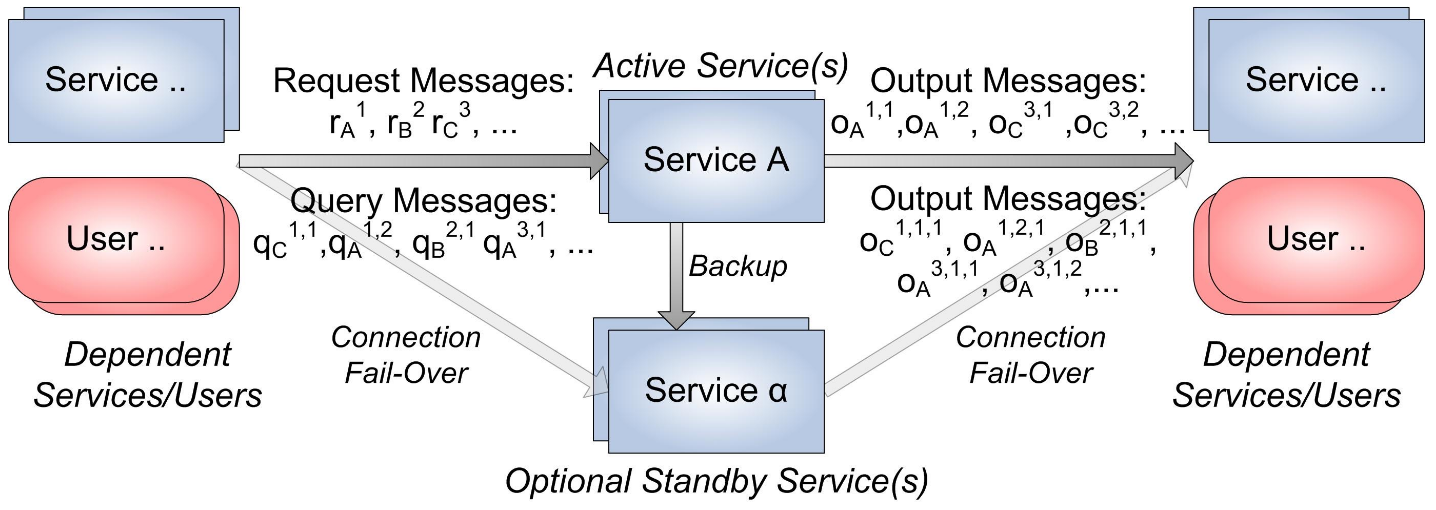
- Most, if not all, HPC system services are deterministic
- Non-determinism introduced by random number generators or unsynchronized timers:
  - Removal of the use of random number generators in HPC system services
  - Synchronization of timers (clocks) between replicas is trivial:
    - Closely coupled local area networks with low and constant latency
    - Clock skew tolerable within certain boundaries (not real-time, not fully synchronous)

Active/Standby Generalization


Service ..
User ..
Dependent Services/Users
Request Messages: r_A^1, r_A^2 r_A^3, ...
Query Messages: $q_A^{1,1}$,$q_A^{1,2}$, $q_A^{2,1}$ $q_A^{3,1}$, ...
Connection Fail-Over
Active Service
Service A
Backup
Service B
Standby Service(s)
Output Messages: $o_A^{1,1}$,$o_A^{1,2}$, $o_A^{3,1}$,$o_A^{3,2}$, ...
Output Messages: $o_A^{1,1,1}$, $o_A^{1,2,1}$, $o_A^{2,1,1}$, $o_A^{3,1,1}$, $o_A^{3,1,2}$,...
Connection Fail-Over
Service ..
User ..
Dependent Services/Users

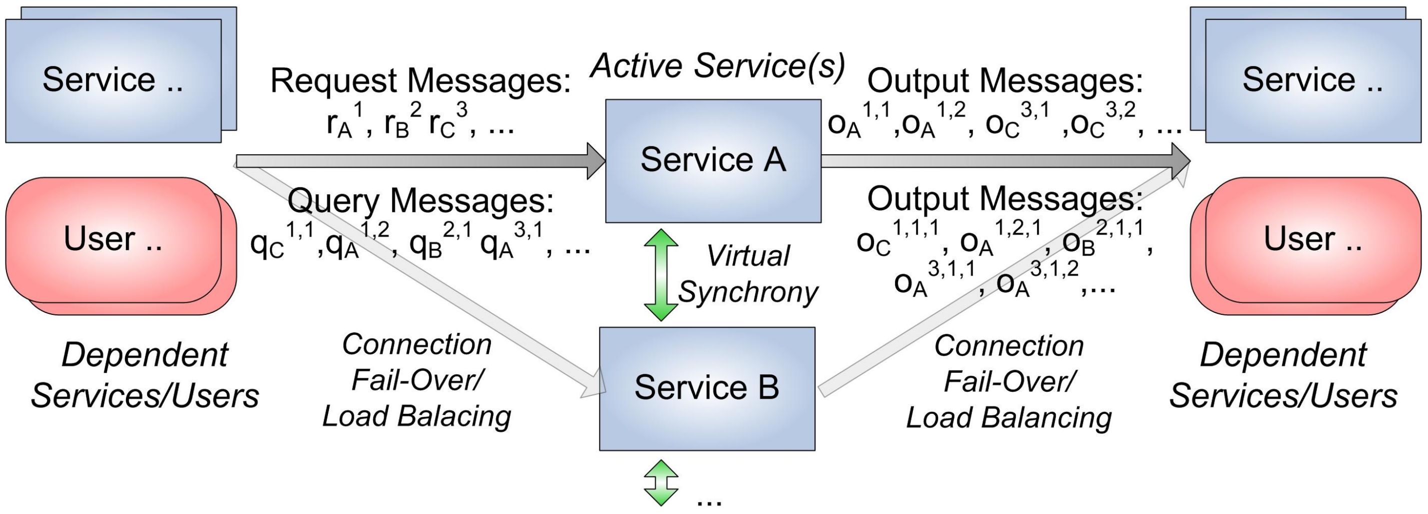
- Warm-Standby:
  - Regular state updates from Active Service to Standby Service (push or pull)
- Hot-Standby
  - On-change state updates from Active Service to Standby Service (push)
- Group communication style consistency required for state updates to multiple Standby Services
- Note: ARES Paper on extended Hot/Passive Replication semantics

Asymmetric Active/Active Generalization


Service ..
User ..
Dependent Services/Users
Request Messages: r_A^1, r_B^2 r_C^3, ...
Query Messages: $q_C^{1,1}$,$q_A^{1,2}$, $q_B^{2,1}$ $q_A^{3,1}$, ...
Connection Fail-Over
Active Service(s)
Service A
Backup
Service α
Optional Standby Service(s)
Output Messages: $o_A^{1,1}$,$o_A^{1,2}$, $o_C^{3,1}$,$o_C^{3,2}$, ...
Output Messages: $o_C^{1,1,1}$, $o_A^{1,2,1}$, $o_B^{2,1,1}$, $o_A^{3,1,1}$, $o_A^{3,1,2}$,...
Connection Fail-Over
Service ..
User ..
Dependent Services/Users

- Replication of service capability via multiple Active Services
- No replication of state among Active Services
- Mechanisms and semantics for optional Standby Services are the same as for Active/Standby

Symmetric Active/Active Generalization


Service ..
User ..
Dependent Services/Users
Request Messages: r_A^1, r_B^2 r_C^3, ...
Query Messages: $q_C^{1,1}$,$q_A^{1,2}$, $q_B^{2,1}$ $q_A^{3,1}$, ...
Connection Fail-Over/ Load Balacing
Active Service(s)
Service A
Virtual Synchrony
Service B
...
Output Messages: $o_A^{1,1}$,$o_A^{1,2}$, $o_C^{3,1}$,$o_C^{3,2}$, ...
Output Messages: $o_C^{1,1,1}$, $o_A^{1,2,1}$, $o_B^{2,1,1}$, $o_A^{3,1,1}$, $o_A^{3,1,2}$,...
Connection Fail-Over/ Load Balancing
Service ..
User ..
Dependent Services/Users

- Replication of service capability via multiple Active Services
- Replication of state among Active Services
- Virtual synchrony (active replication) model

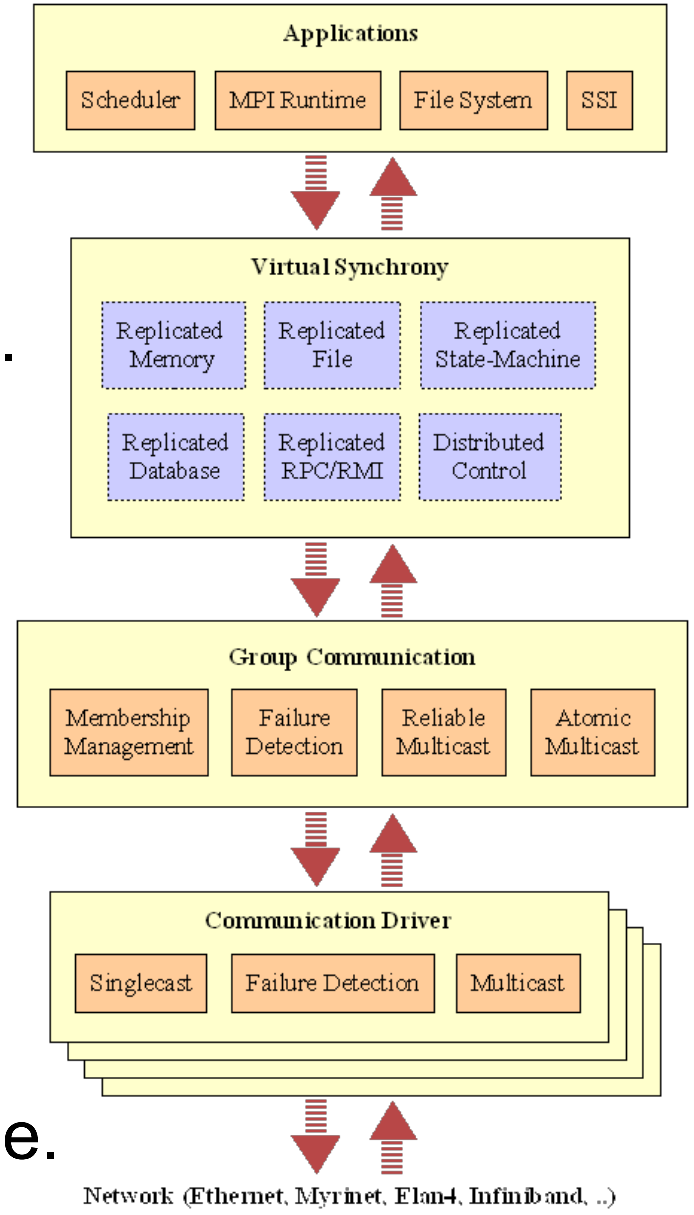
Comparison of Replication Methods

Model	MTTR	Latency Overhead
Warm-Standby	$T_d + T_f + T_c + T_r$	0
Hot-Standby	$T_d + T_f + T_r$	$2l_{A,B}$
Asymmetric	$T_d + T_f + T_c + T_r$ or	0 or
	$T_d + T_f + T_r$	$2l_{A,\alpha}$
Symmetric	T_r	$O(n)$

T_d = time between failure occurrence and detection
T_f = time between failure detection and fail-over
T_c = time to recover from checkpoint to previous state
T_r = time to reconfigure client/user connection
$l_{A,B}$ = communication latency between A and B

Modular 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.



Current 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

Future Work

- Continued implementation of framework components
  - Implementation of HA programming model components
- Integration with existing prototypes
  - For example, replacing Transis with the framework
- Availability and reliability modeling
- Testing and benchmarking
- What about communication security/integrity?
  - For client-server connections across administrative domains
  - For distributed computing scenarios

MOLAR: Adaptive Runtime Support for High-end Computing Operating and Runtime Systems

- Addresses the challenges for operating and runtime systems to run large applications efficiently on future ultra-scale high-end computers.
- 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*):

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Office of Science
U.S. DEPARTMENT OF ENERGY

NC STATE UNIVERSITY

OHIO STATE

LOUISIANA TECH UNIVERSITY

The University of Reading

CRAY THE SUPERCOMPUTER COMPANY

On Programming Models for Service-Level High Availability

Christian Engelmann[1,2], Stephen L. Scott[1],
Chokchai (Box) Leangsuksun[3], Xubin (Ben) He[4]

[1] Oak Ridge National Laboratory, Oak Ridge, USA
[2] The University of Reading, Reading, UK
[3] Louisiana Tech University, Ruston, USA
[4] Tennessee Tech University, Cookeville, USA