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OAK RIDGE NATIONAL LABORATORY
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The University of Reading

Service-Level High Availability in Parallel and Distributed Systems

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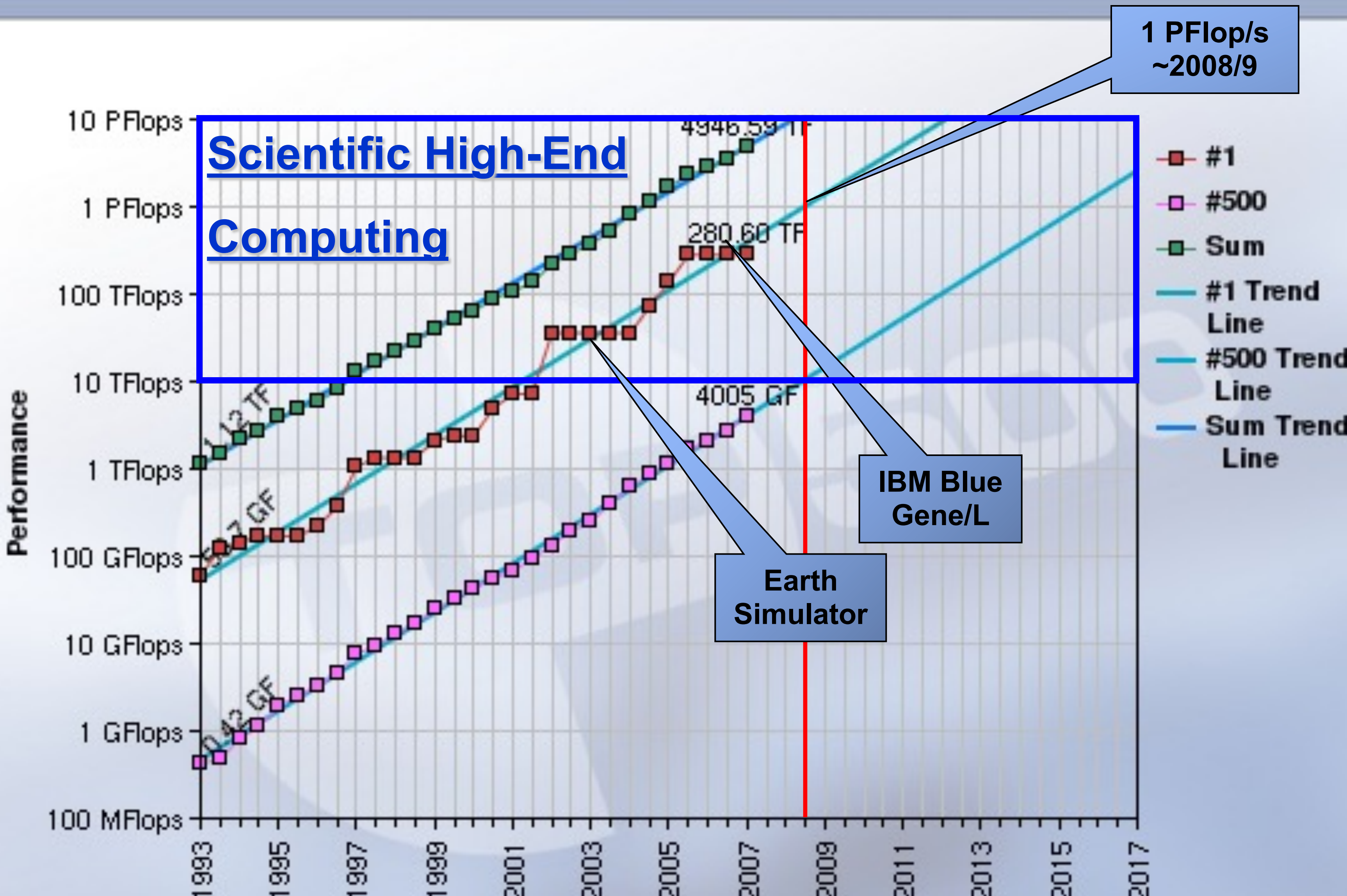
Talk Outline

- 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
- Enhancing the transparency of the HA infrastructure
- 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.
  - 100 TFLOP – 1PFLOP with 100 TB – 10 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

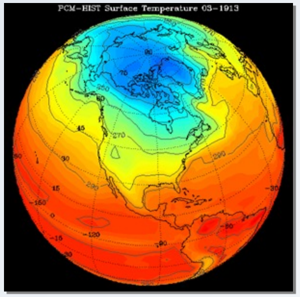


National Center for Computational Sciences

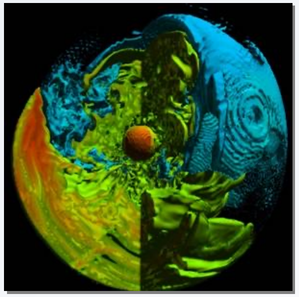
- 40,000 ft^2 (3700 m^2) computer center:
  - 36-in (~1m) raised floor, 18 ft (5.5 m) deck-to-deck
  - 12 MW of power with 4,800 t of redundant cooling
  - High-ceiling area for visualization lab:
    - 35 MPixel PowerWall, Access Grid, etc.

- 2 systems in the Top 500 List of Supercomputer Sites:
  - Jaguar: 2. Cray XT3, MPP with 11508 dual-core Processors ⇨ 119 TFlop.
  - Phoenix: 58. Cray X1E, Vector with 1014 Processors ⇨ 18 TFlop.

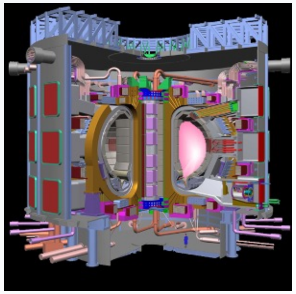
At Forefront in Scientific Computing and Simulation



- **Leading partnership in developing the National Leadership Computing Facility**
  - **Leadership-class scientific computing capability**
  - **119 TFlop/s in 2007 (recently installed)**
  - **250 TFlop/s in 2007/8 (commitment made, after SC07)**
  - **500 TFlop/s in 2008 (commitment made, UT/ORNL)**
  - **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 (10Gbps)**

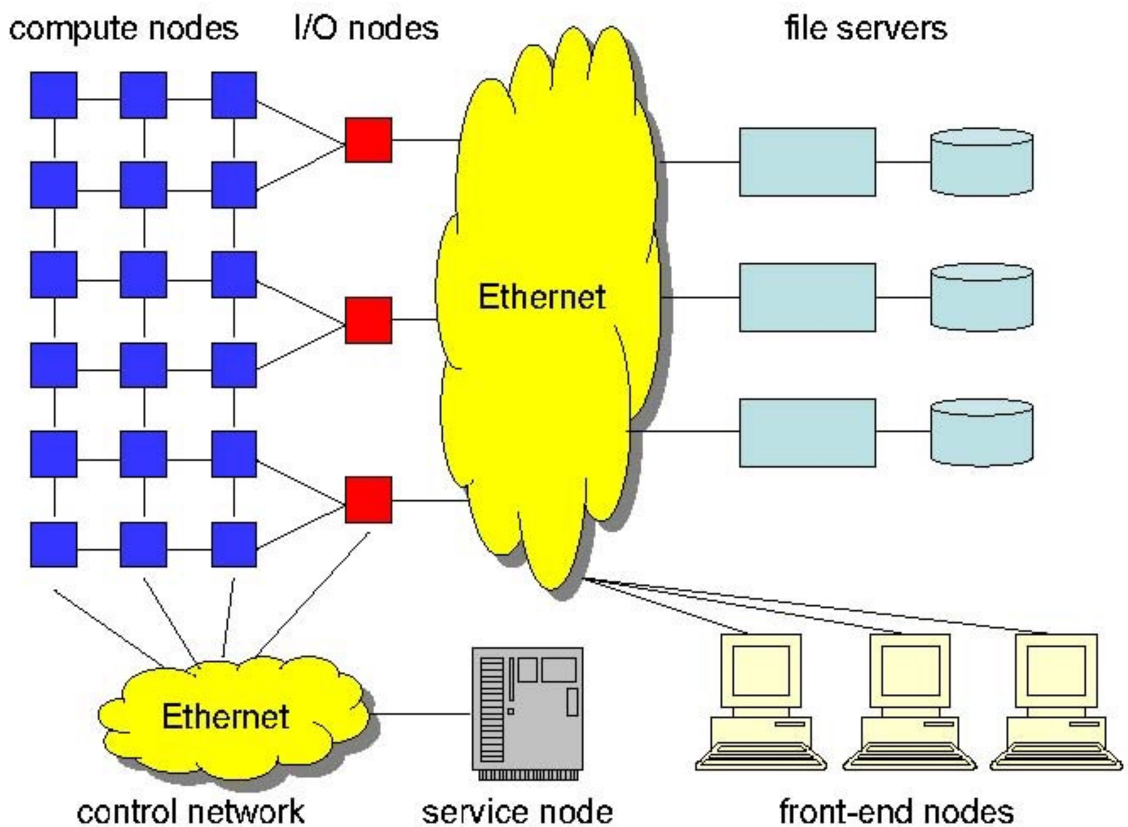
Availability Measured by the Nines

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:

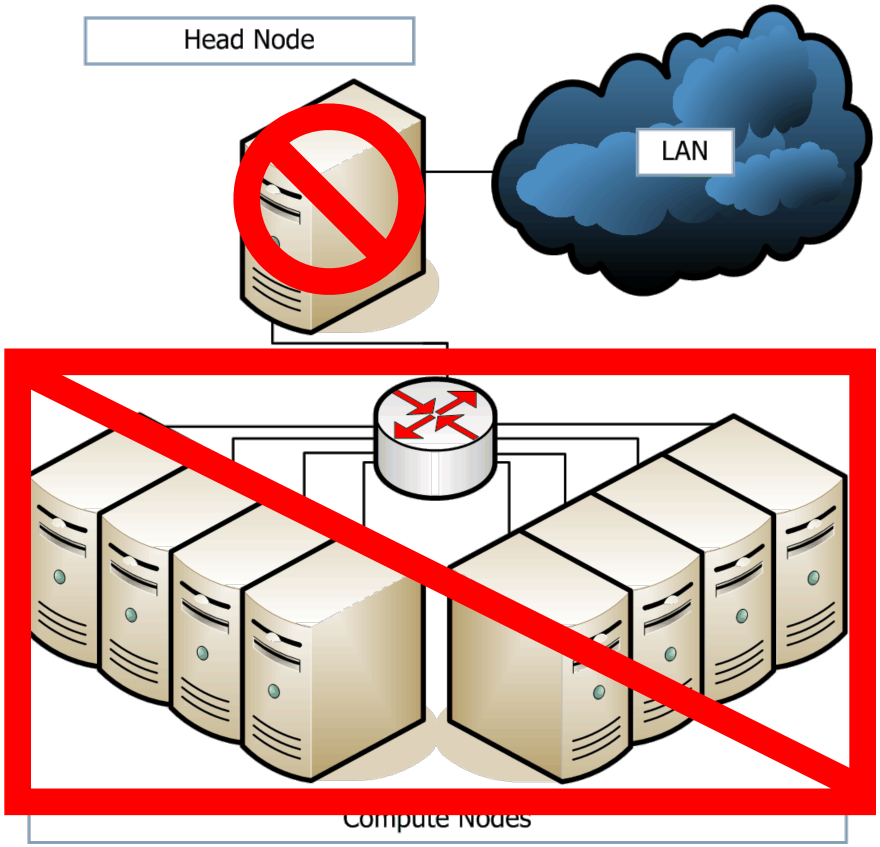
- Overheating !!!
- Memory errors
- Network errors
- Other hardware issues
- Software bugs

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

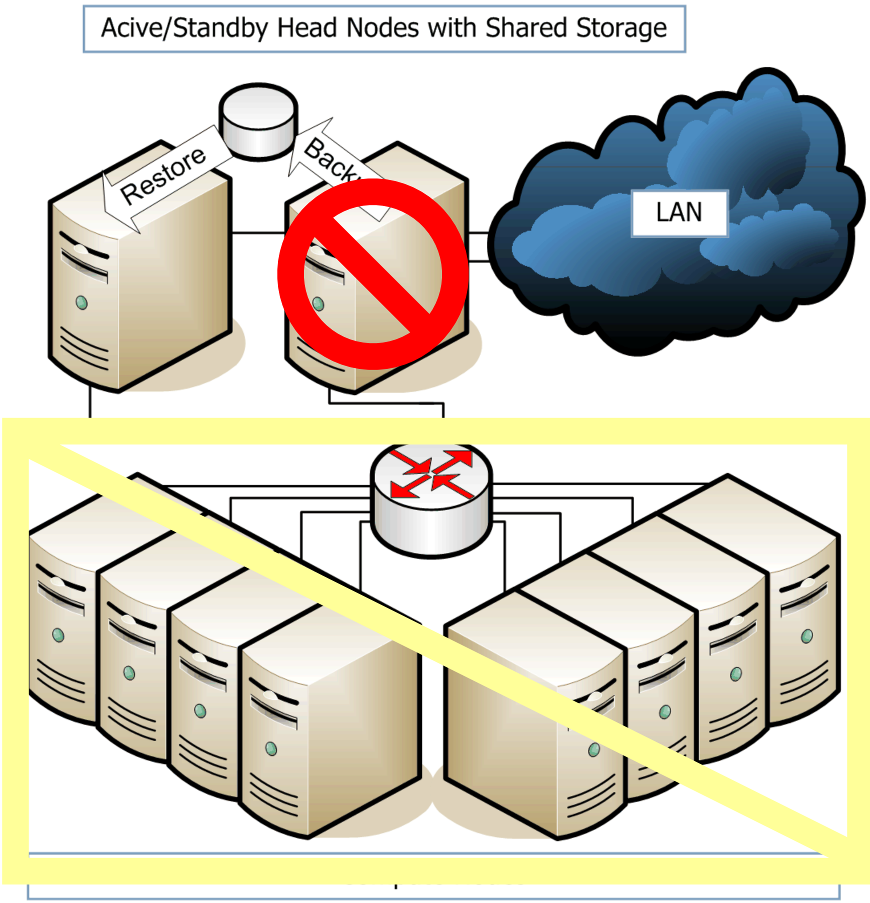
- Initial **HA-OSCAR** research in active/standby technology for the batch job management system
- Recent **MOLAR/FAST-OS** research in compute/ service node fault tolerance & high availability
- Recent **RAS LDRD** research in service node fault tolerance & high availability
- Ongoing **RAS/FAST-OS** research in compute node fault tolerance & high availability

→ 4-5 years of research and development in fault tolerance & high availability for HPC

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

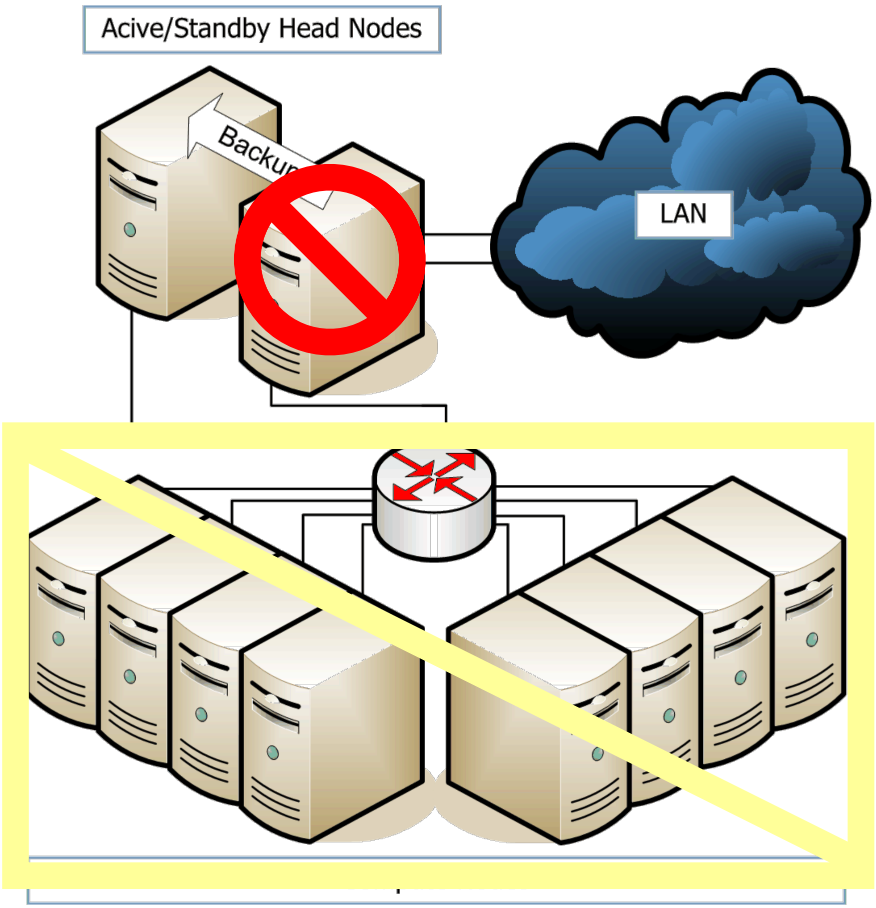
Active/Standby with Shared Storage



- 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

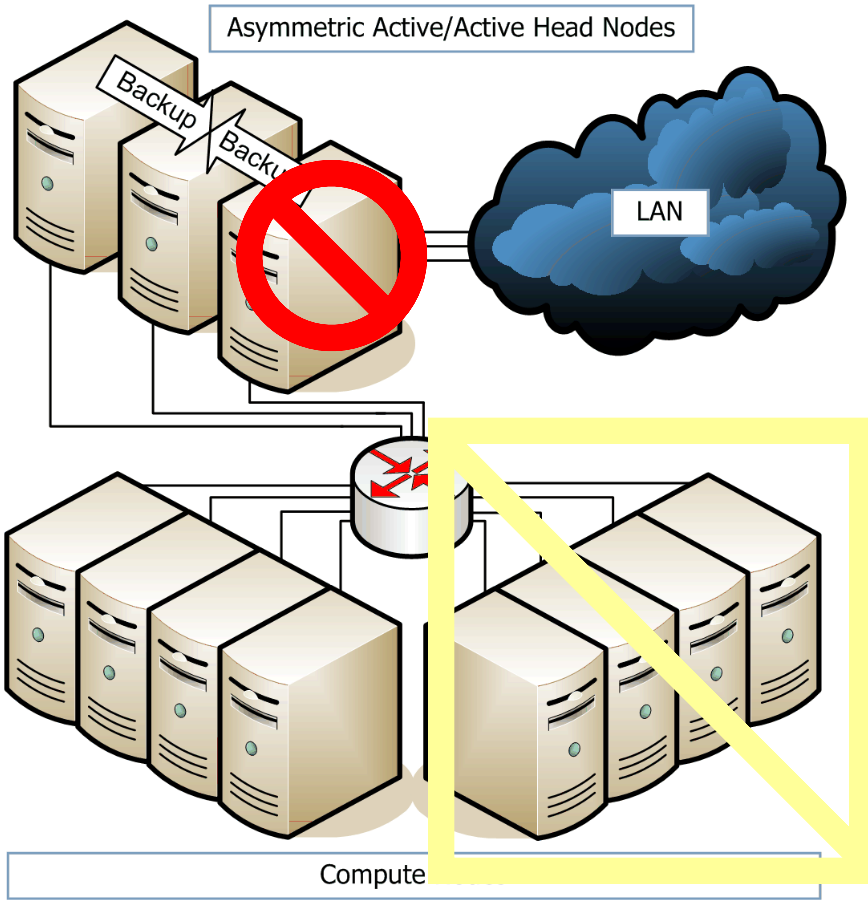


- Single active head node
- Backup to standby node
- Simple checkpoint/restart
- Fail-over to standby node
- Idle standby head node
- Rollback to backup
- Service interruption for fail-over and restore-over

➔ Torque on Cray XT

➔ HA-OSCAR prototype

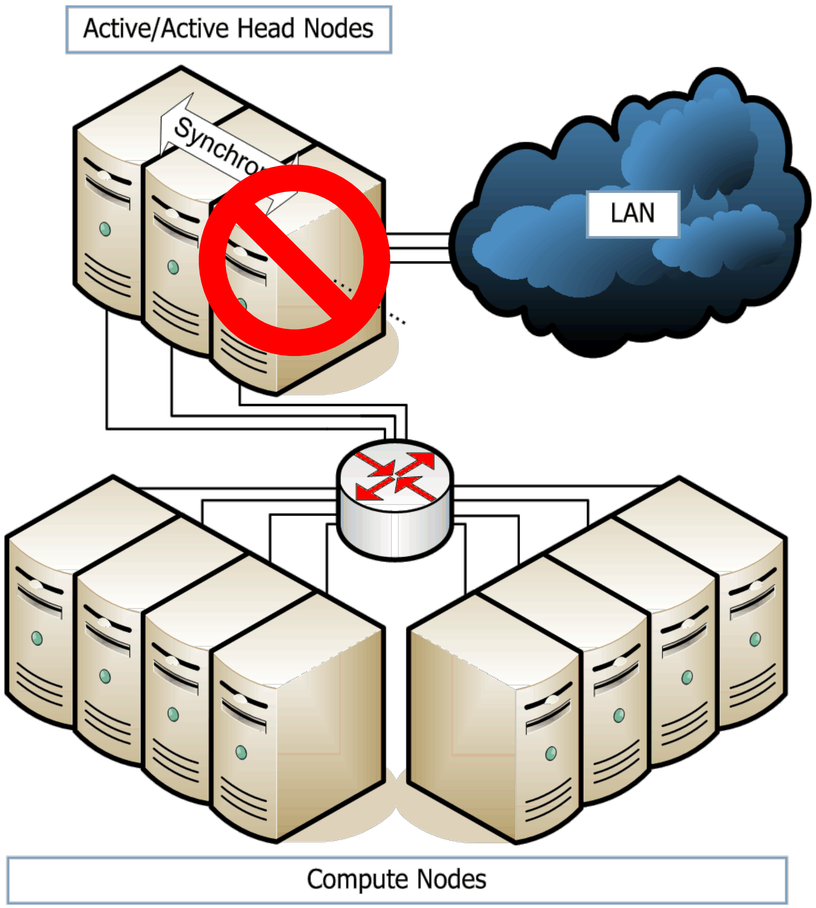
Asymmetric Active/Active Redundancy



- 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
- Prototype for Torque & PVFS

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 and for PVFS metadata server

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

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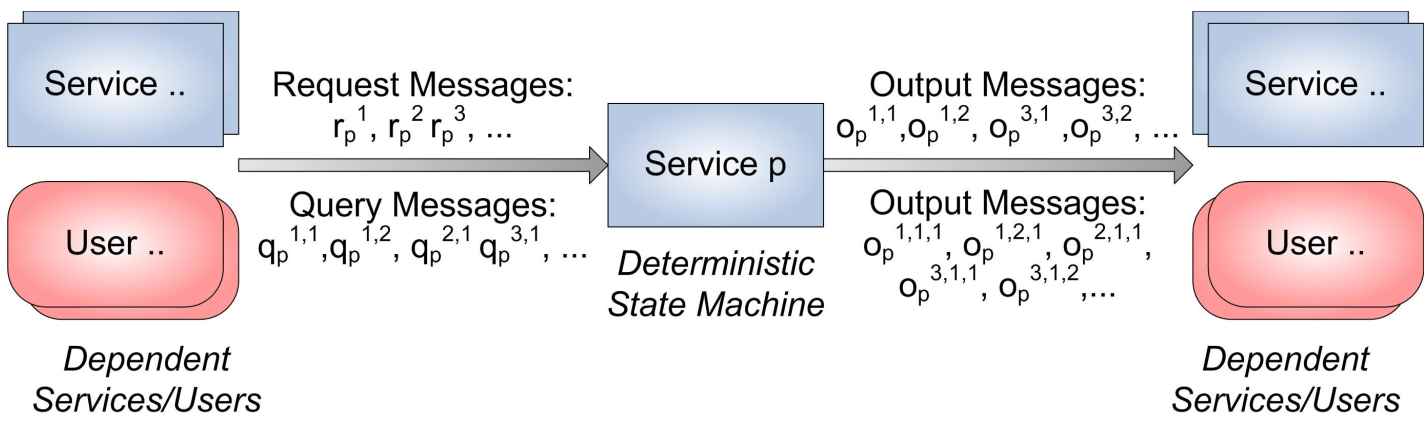
➔ Portability

➔ Ease-of-use

Failure Model

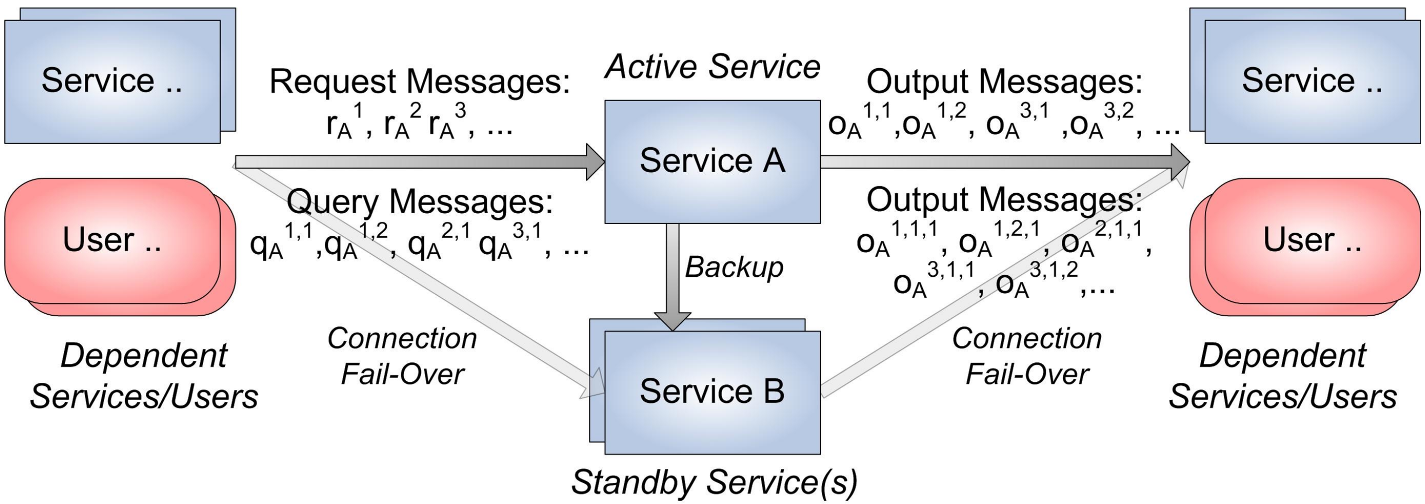
- Fail-stop
  - The service, its node, or its communication links, fail by simply stopping.
  - Failure detection mechanisms may be deployed to assure fail-stop behavior in certain cases, such as for incomplete or garbled messages.
- Permanent failures
  - Non-transient behavior assured by detection 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



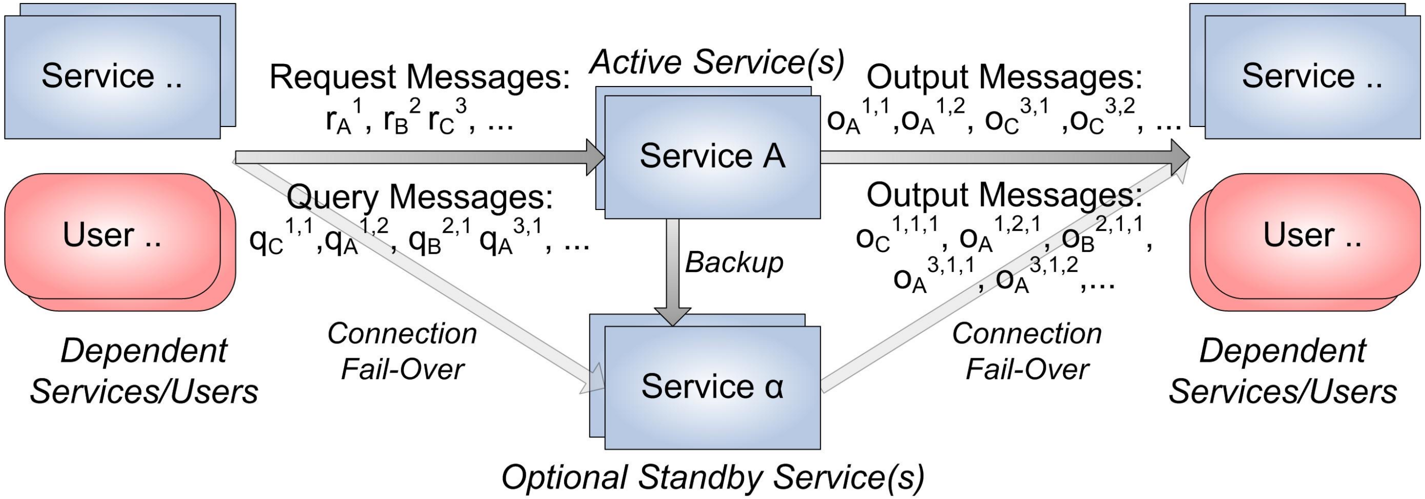
- Most, if not all, HPC system services are deterministic
- Non-determinism introduced by random number generators or unsynchronized timers:
  - Removal of the use of random number generators in HPC system services
  - Synchronization of timers (clocks) between replicas is trivial:
    - Closely coupled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

Active/Standby Generalization



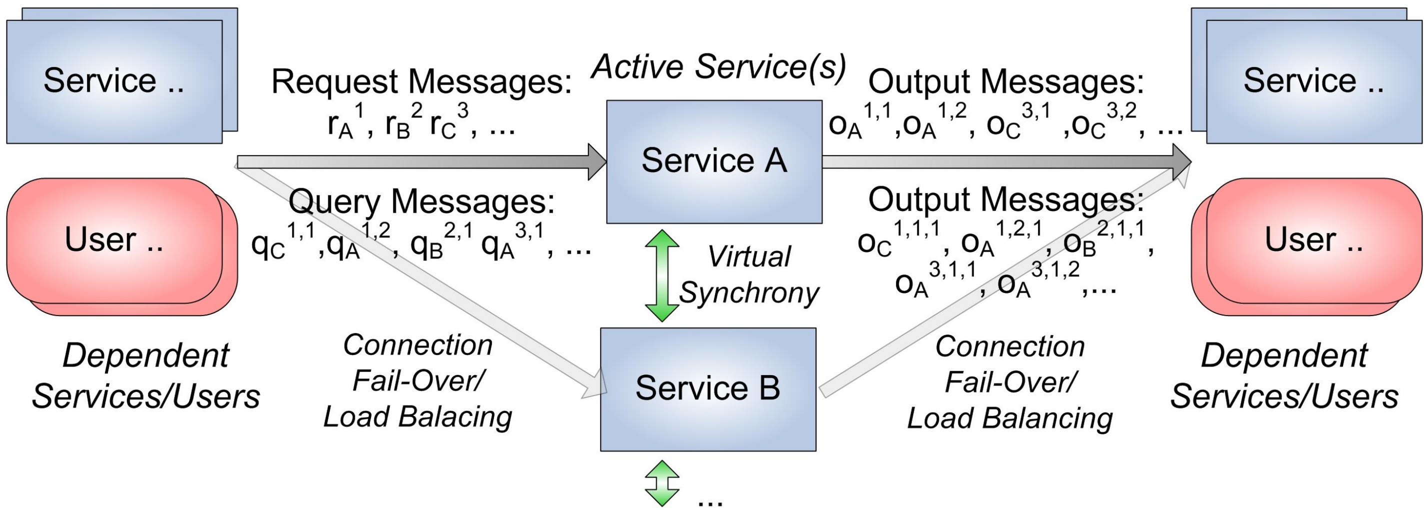
- Warm-Standby:
  - Regular state updates from Active Service to Standby Service (push or pull)
- Hot-Standby
  - On-change state updates from Active Service to Standby Service (push)
- Group communication style consistency required for state updates to multiple Standby Services

Asymmetric Active/Active Generalization



- 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



- <u>Replication of service capability</u> via multiple Active Services
- <u>Replication of state</u> 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 (Heartbeat)

T_f = time between failure detection and fail-over (STONITH)

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

Next Step: Generic HA Framework

- Generalization of HA programming models
  - Active/Standby
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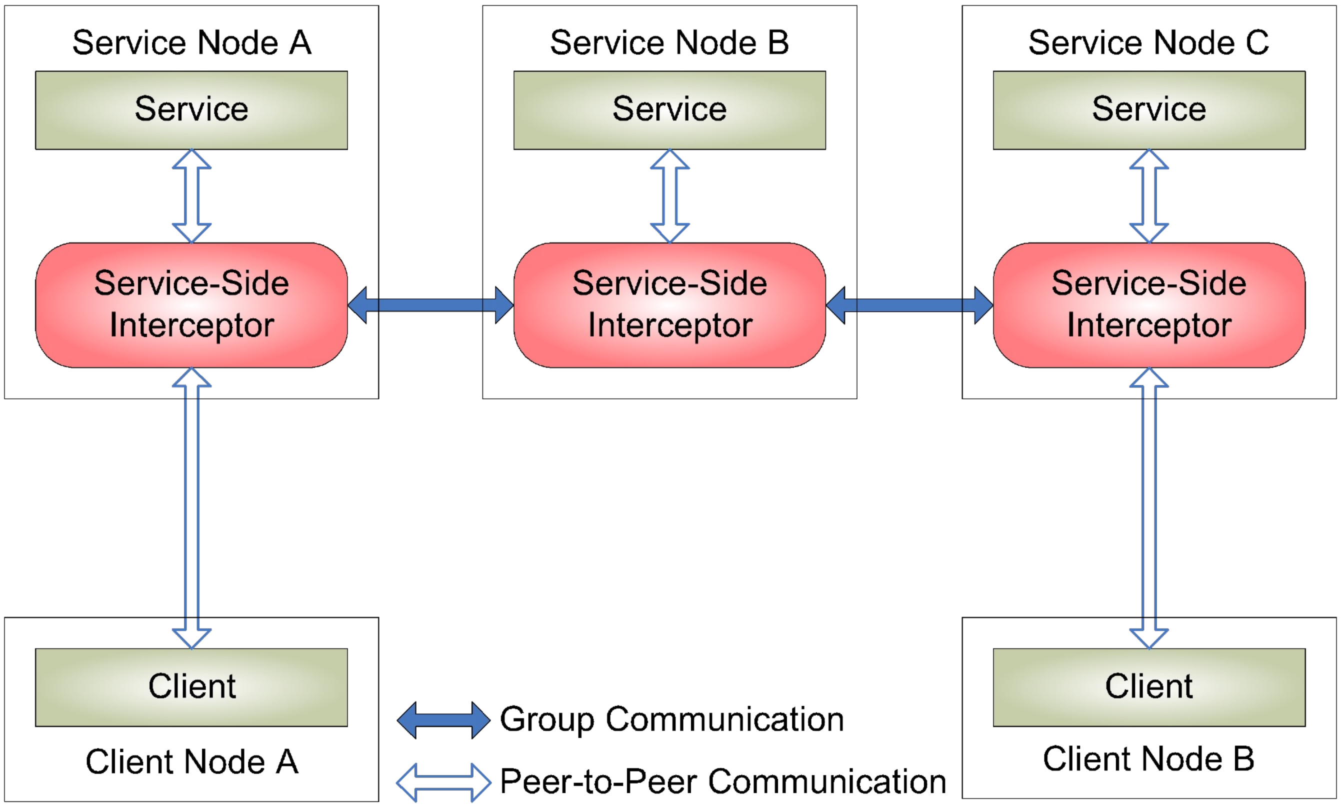
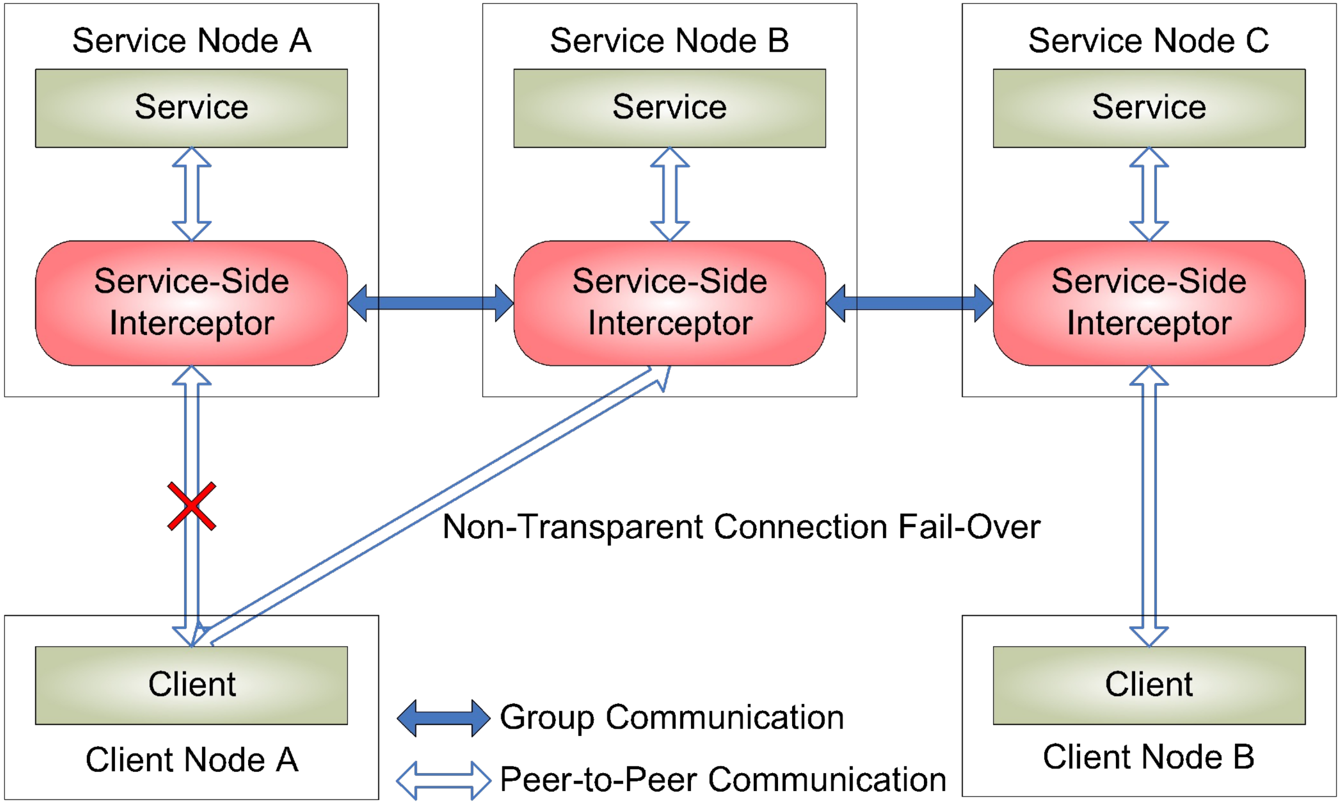
➔ Portability

➔ Ease-of-use

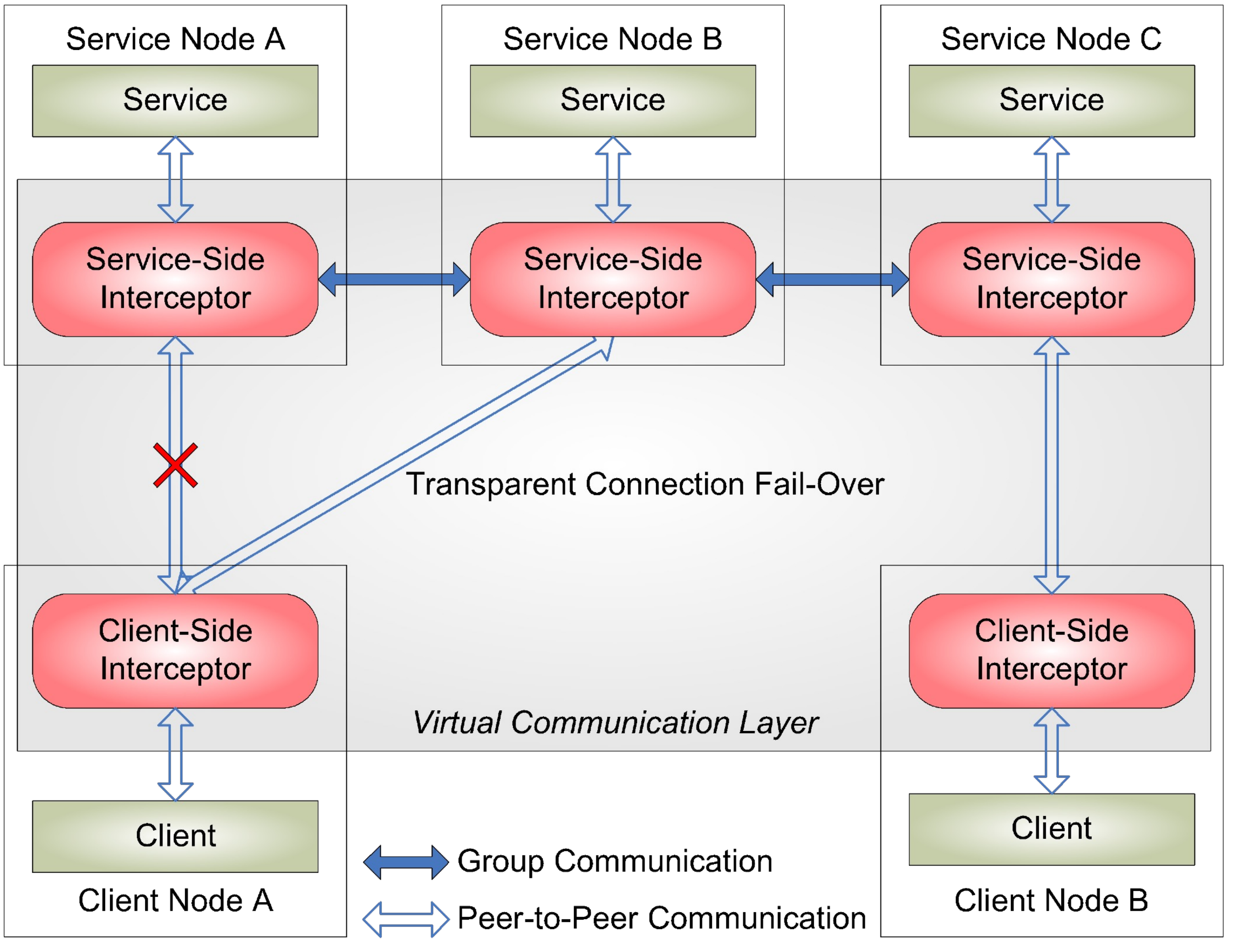
Symmetric Active/Active Replication



Non-Transparent Connection Fail-Over



Transparent Connection Fail-Over



Interceptors in the Communication Path: What about Performance?

Payload	Without Interceptors	With Service Interceptor	With Both Interceptors
$100B$	$149.9\mu s$	$150.6\mu s$/ $+0.5\%$	$178.4\mu s$/$+19.0\%$
$1KB$	$284.3\mu s$	$314.6\mu s$/$+10.7\%$	$346.7\mu s$/$+21.9\%$
$10KB$	$1.9ms$	$1.9ms$/ $\pm 0.0\%$	$2.0ms$/ $+5.3\%$
$100KB$	$22.3ms$	$22.5ms$/ $+0.8\%$	$22.7ms$/ $+1.8\%$

Table 1. Ping-Pong Latency Comparison

Payload	Without Interceptors	With Service Interceptor	With Both Interceptors
$100B$	$667KBps$	$664KBps$/-0.4%	$561KBps$/-15.9%
$1KB$	$3.5MBps$	$3.2MBps$/-8.6%	$2.9MBps$/-17.1%
$10KB$	$5.3MBps$	$5.2MBps$/-1.9%	$5.0MBps$/ -5.7%
$100KB$	$4.5MBps$	$4.4MBps$/-2.2%	$4.4MBps$/ -2.2%

Table 2. Ping-Pong Bandwidth Comparison

Test Results from a 100 Mbit/s LAN Environment

Future Work

- Availability and reliability modeling
- Testing and benchmarking
- What about communication security/integrity?
  - For client-server connections across administrative domains
  - For distributed computing scenarios
- What about interdependent services?

How does this relate to P2P and the Grid

- All presented concepts and prototypes are applicable to any service-oriented architectures (SOAs).
- All prototypes are designed for local area replication, but can be easily used for wide area replication.
- Introduced latency overhead for local area replication protocols are negligible in the wide area context.
- Stateful Grid service replication:
  - Replication of Grid services to meet QoS/SLA guarantees.
- Stateful P2P service replication:
  - Replication of P2P support services for high availability, e.g., for directory servers and brokers.

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*):

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