Billion-Way Resiliency for Extreme Scale Computing

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Failures on HPC systems

- Exponential growth in computational power
  - Enables finer grained simulations with shorter period time
- Overall failure rate increase accordingly because of the increasing system size
- 191 failures out of 5-million node-hours
  - A production application of Laser-plasma interaction code (`pF3D`)
  - Hera, Atlas and Coastal clusters @LLNL

Estimated MTBF (w/o hardware reliability improvement per component in future)

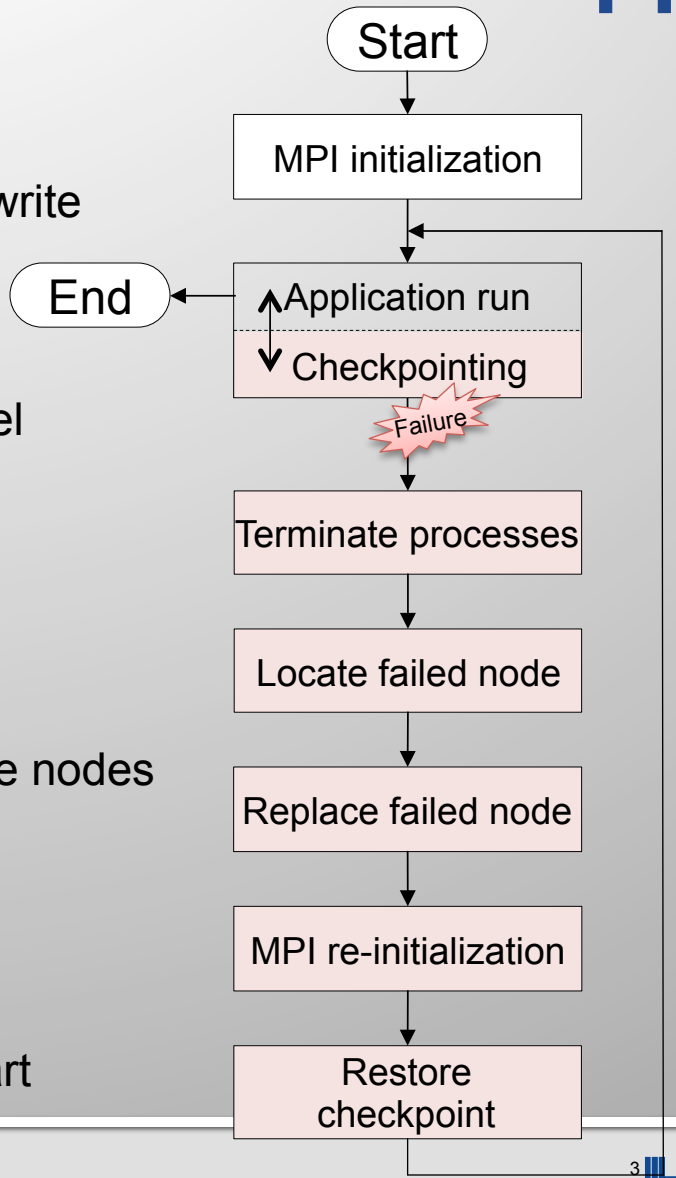
	1,000 nodes	10,000 nodes	100,000 nodes
MTBF	1.2 days (Measured)	2.9 hours (Estimation)	17 minutes (Estimation)

Source: A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System (SC 10)

- Will be difficult for applications to continuously run for a long time without fault tolerance at extreme scale

Conventional fault tolerance in MPI apps

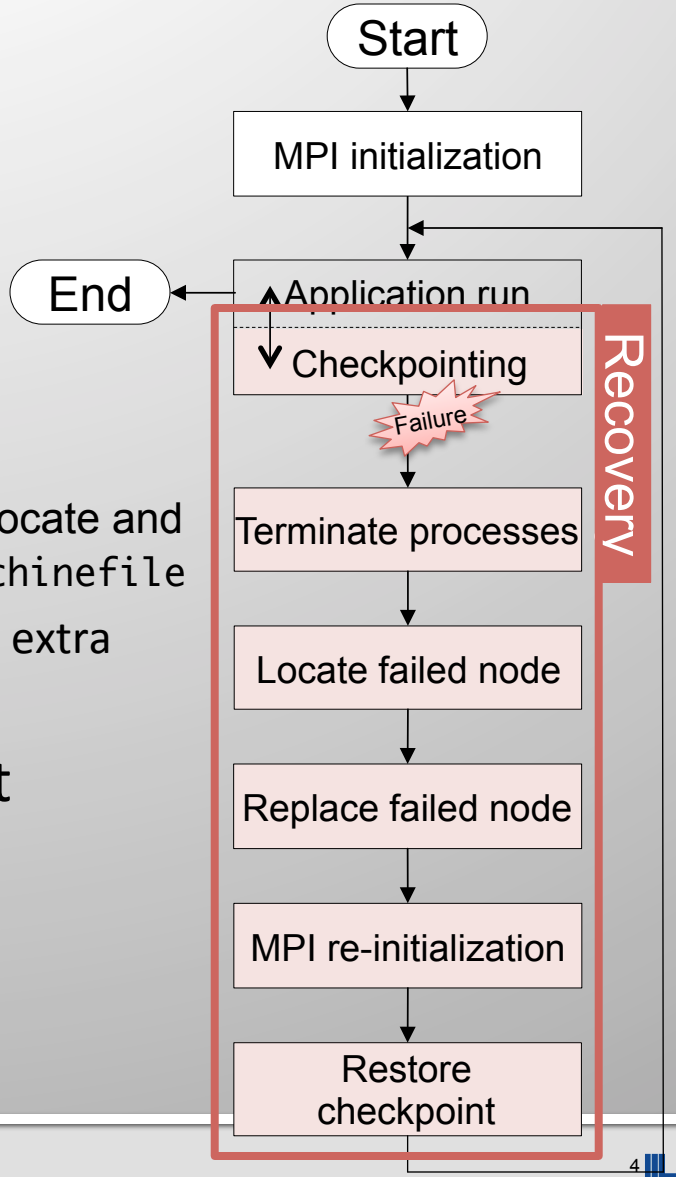
- Checkpoint/Recovery (C/R)
  - Long running MPI applications are required to write checkpoints
- MPI
  - De-facto communication library enabling parallel computing
  - Standard MPI employs a fail-stop model
- When a failure occurs …
  - MPI terminates all processes
  - The user locate, replace failed nodes with spare nodes
  - Re-initialize MPI
  - Restore the last checkpoint
- The fail-stop model of MPI is quite simple
  - All processes synchronize at each step to restart



Requirement of fast and transparent recovery

- Failure rate will increase in future extreme scale systems

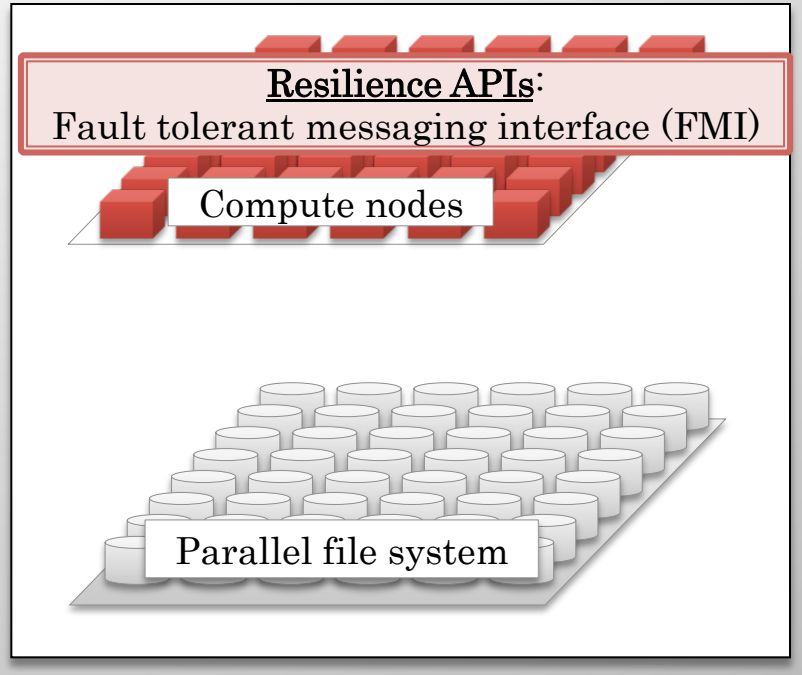
- Applications will use more time for recovery
  - Whenever a failure occurs, users manually locate and replace the failed nodes with spare nodes via `machinefile`
  - The manual recovery operations may introduce extra overhead and human errors
- Resilience APIs for fast and transparent recovery is becoming more critical for extreme scale computing



Resilience APIs, Architecture and the model

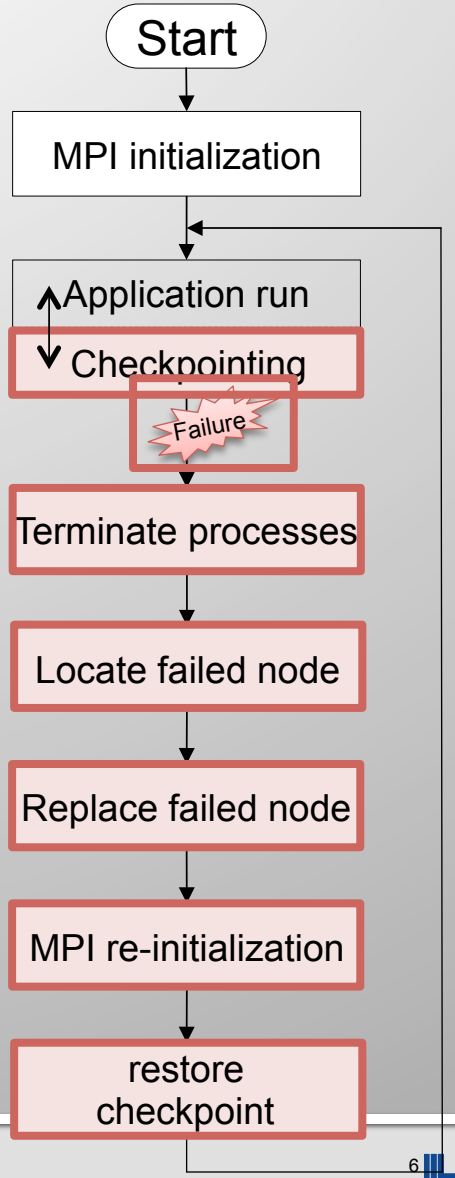
- Resilience APIs

  ⇒ Fault tolerant messaging interface (FMI)

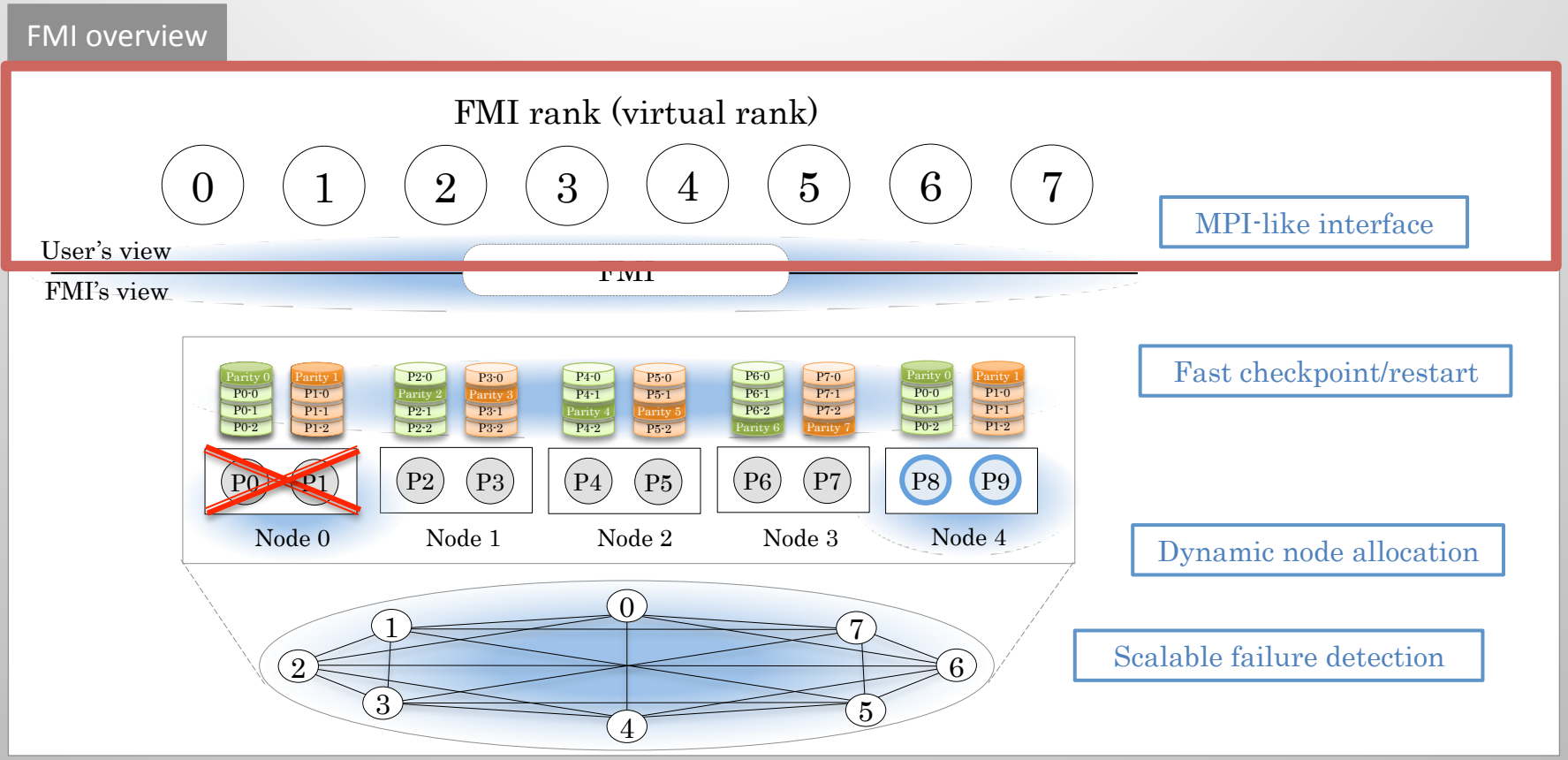


Challenges for fast and transparent recovery

- Scalable failure detection
  - When recovering from a failure, all processes need to be notified
- Survivable messaging interface
  - At extreme scale, even termination and Initialization of processes will be expensive
  - Not terminating non-failed processes is important
- Transparent and dynamic node allocation
  - Manually locating, and replacing failed nodes will introduce extra overhead and human errors
- Fast checkpoint/restart



FMI: Fault Tolerant Messaging Interface [IPDPS2014]



- FMI is a survivable messaging interface providing MPI-like interface
  - Scalable failure detection => Overlay network
  - Dynamic node allocation => FMI ranks are virtualized
  - Fast checkpoint/restart => Diskless checkpoint/restart

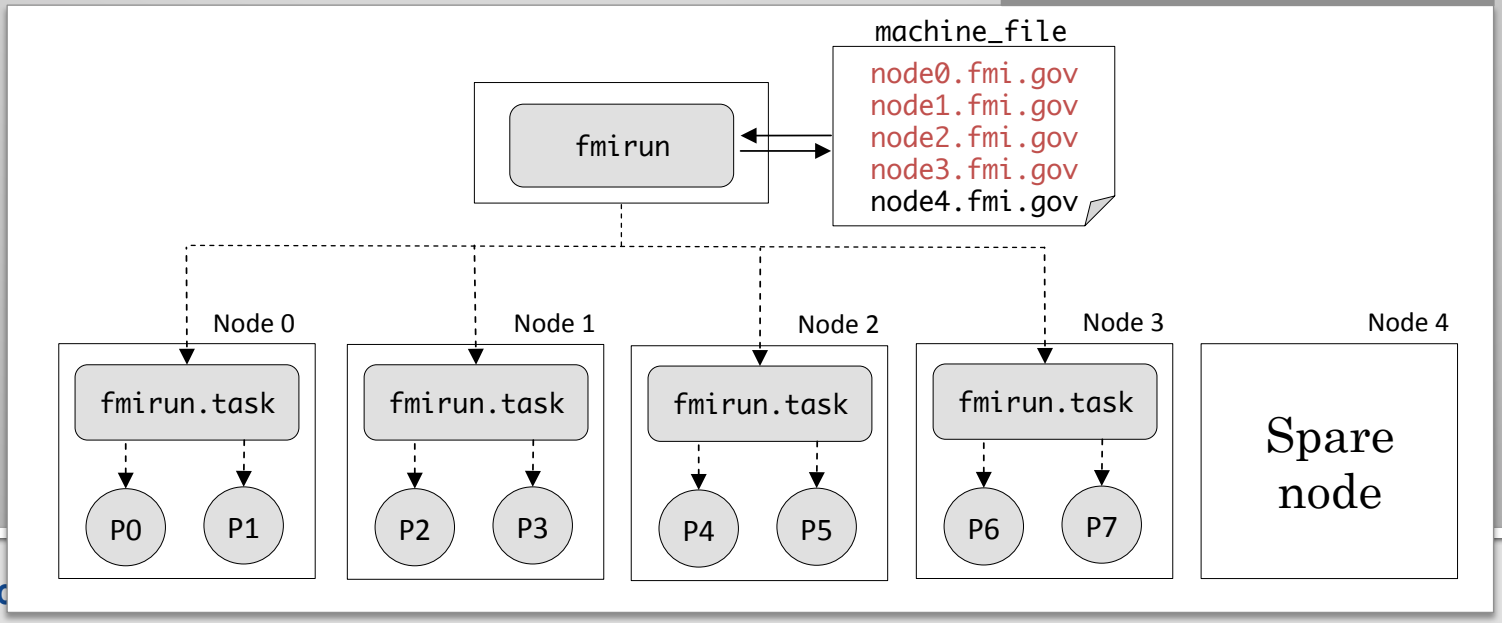
How FMI applications work ?

FMI example code

```
int main (int *argc, char *argv[]) {
  FMI_Init(&argc, &argv);
  FMI_Comm_rank(FMI_COMM_WORLD, &rank);
  /* Application's initialization */
  while ((n = FMI_Loop(…)) < numloop) {
    /* Application's program */
  }
  /* Application's finalization */
  FMI_Finalize();
}
```

- FMI_Loop enables transparent recovery and roll-back on a failure
  - Periodically write a checkpoint
  - Restore the last checkpoint on a failure
- Processes are launched via `fmirun`
  - `fmirun` spawns `fmirun.task` on each node
  - `fmirun.task` calls fork/exec a user program
  - `fmirun` broadcasts connection information (endpoints) for FMI_init(…)

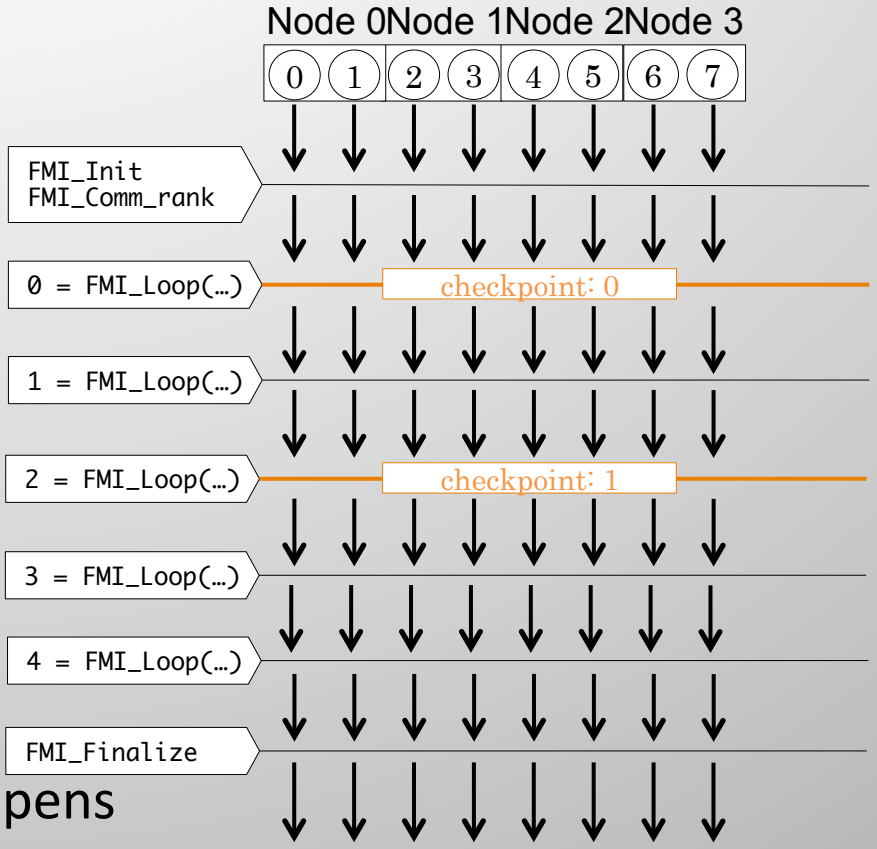
Launch FMI processes



User perspective: No failures

FMI example code

```
int main (int *argc, char *argv[]) {
  FMI_Init(&argc, &argv);
  FMI_Comm_rank(FMI_COMM_WORLD, &rank);
  /* Application's initialization */
  while ((n = FMI_Loop(…)) < 4) {
    /* Application's program */
  }
  /* Application's finalization */
  FMI_Finalize();
}
```



- User perspective when no failures happens
- Iterations: 4
- Checkpoint frequency: Every 2 iterations
- FMI_Loop returns incremented iteration id

User perspective : Failure

FMI example code

```
int main (int *argc, char *argv[]) {
  FMI_Init(&argc, &argv);
  FMI_Comm_rank(FMI_COMM_WORLD, &rank);
  /* Application's initialization */
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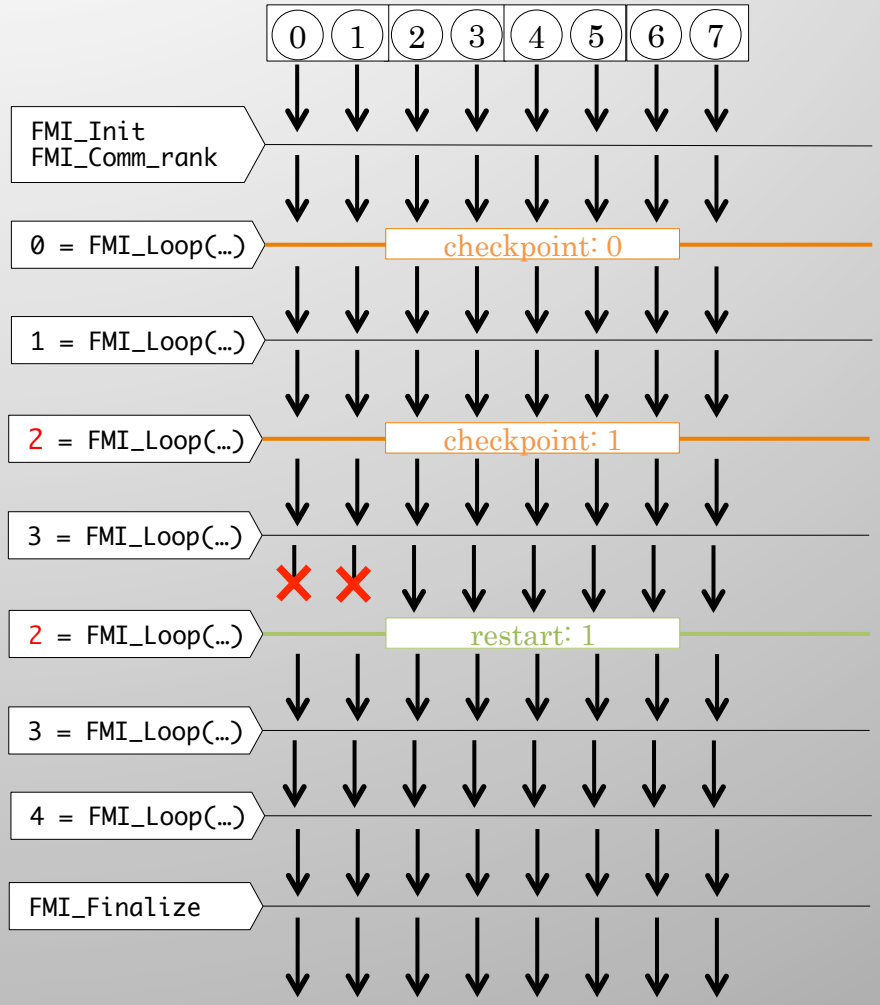


- Transparently migrate FMI rank 0 & 1 to a spare node
- Restart form the last checkpoint
  - 2th checkpoint at iteration 2
- With FMI, applications still use the same series of ranks even after failures

FMI_Loop

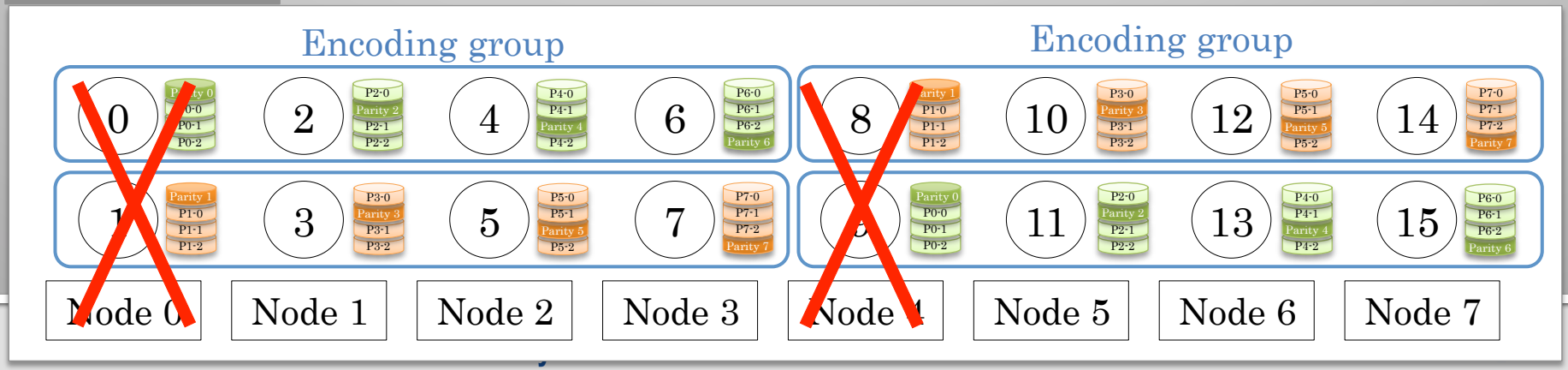
```
int FMI_Loop(void **ckpt, size_t *sizes, int len)
```

- `ckpt` : Array of pointers to variables containing data that needs to be checkpointed
- `sizes` : Array of sizes of each checkpointed variables
- `len` : Length of arrays, `ckpt` and `sizes`

returns iteration id

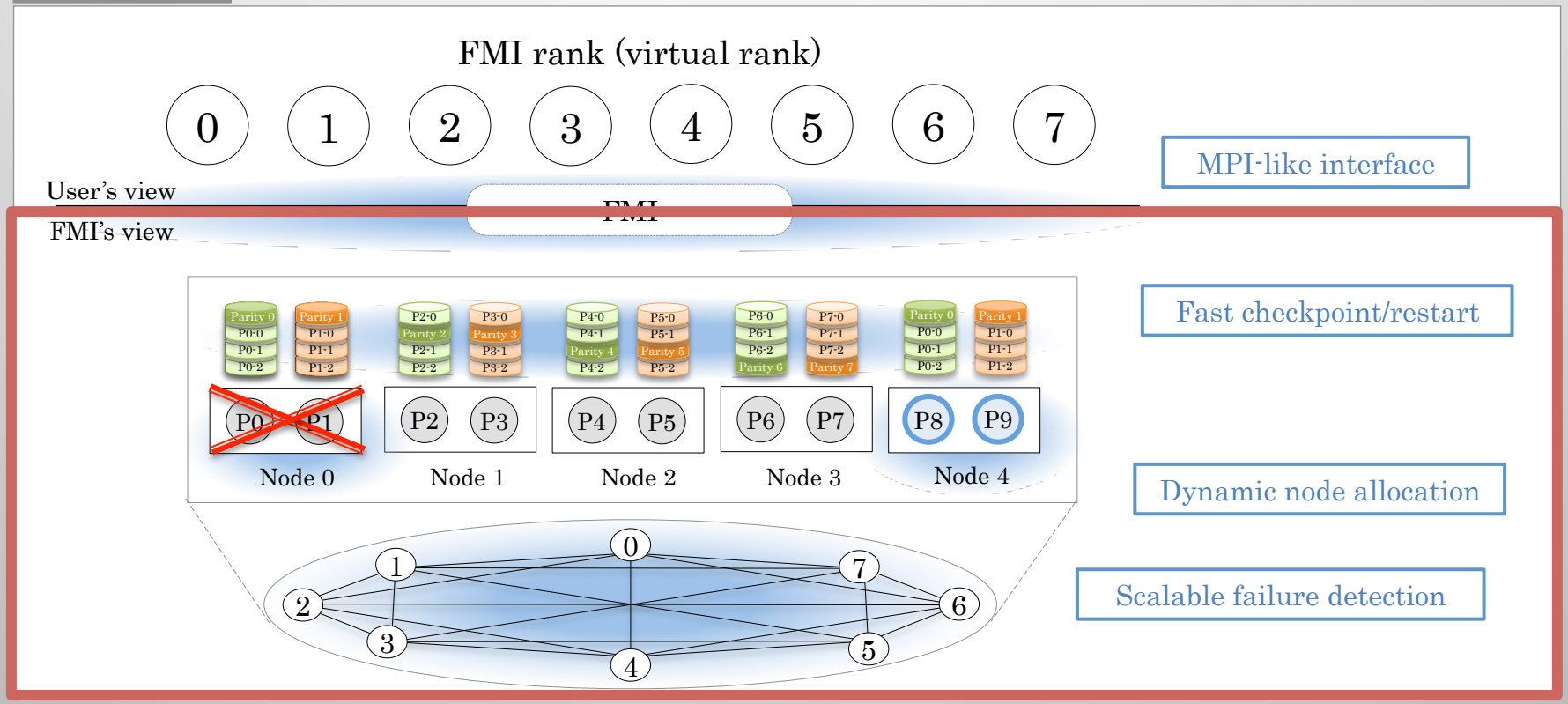
- FMI constructs in-memory RAID-5 across compute nodes
- Checkpoint group size
  - e.g.) group_size = 4

FMI checkpointing



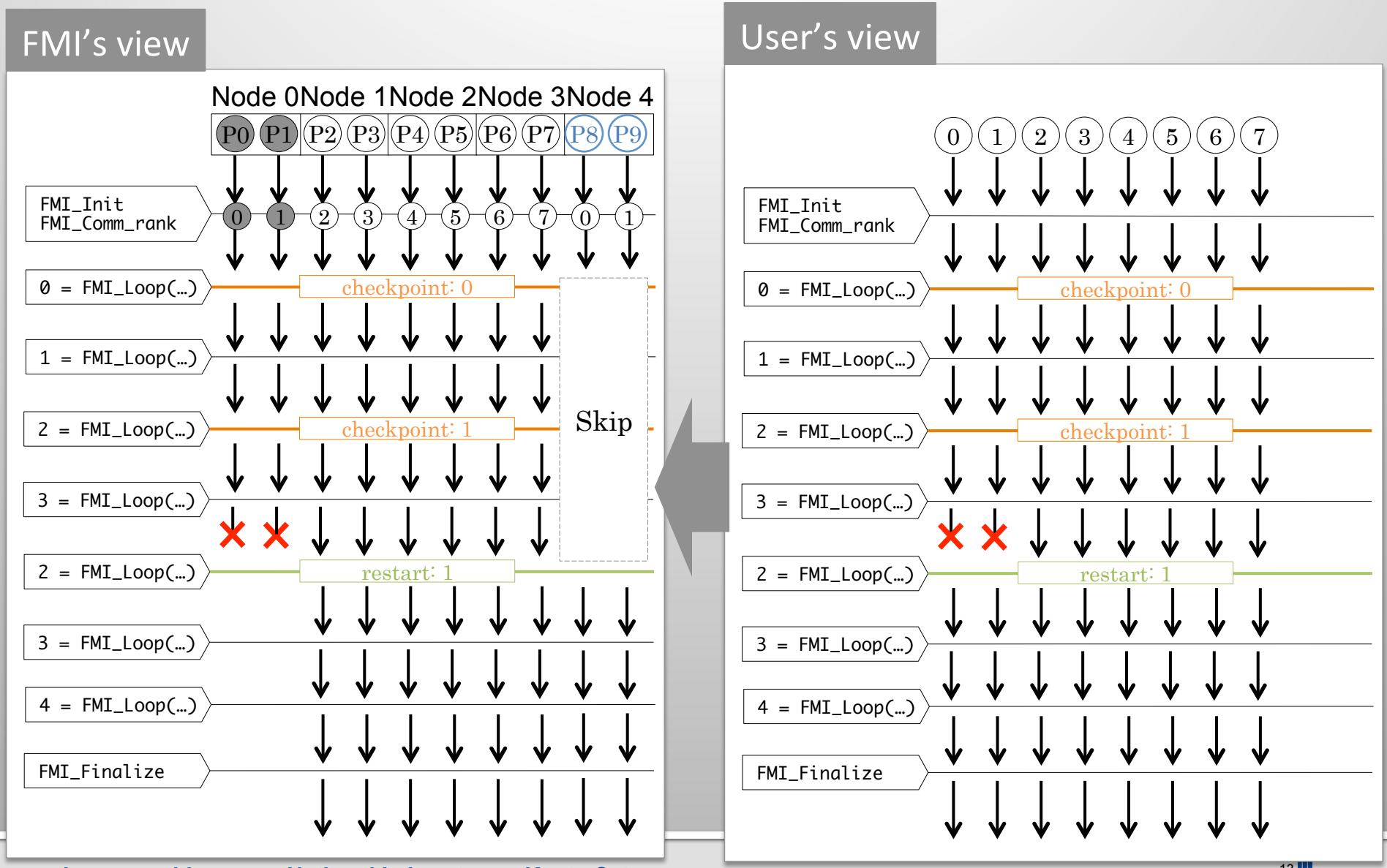
FMI: Fault Tolerant Messaging Interface

FMI overview

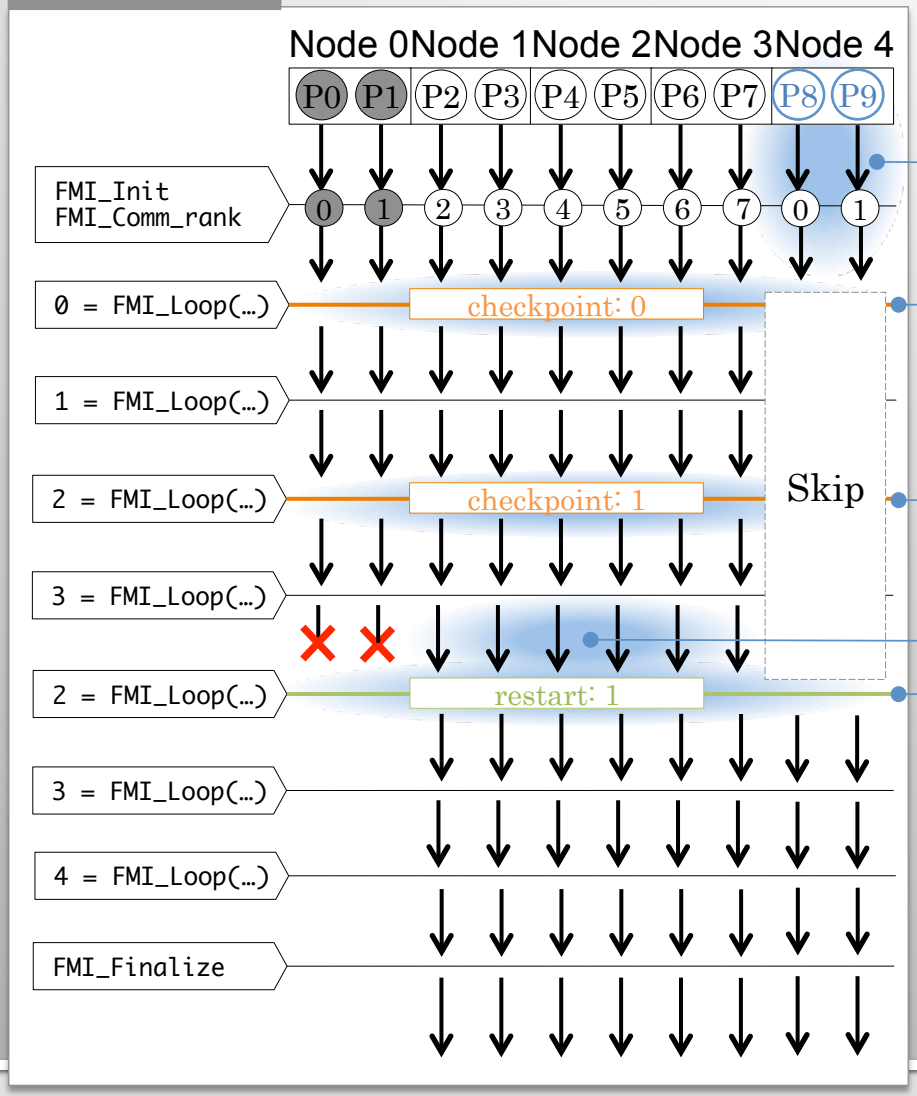


- FMI is an MPI-like survivable messaging interface
  - Scalable failure detection => Overlay network for failure detection
  - Dynamic node allocation => FMI ranks are virtualized
  - Fast checkpoint/restart => Diskless checkpoint/restart

FMI's view & User's view



FMI's view

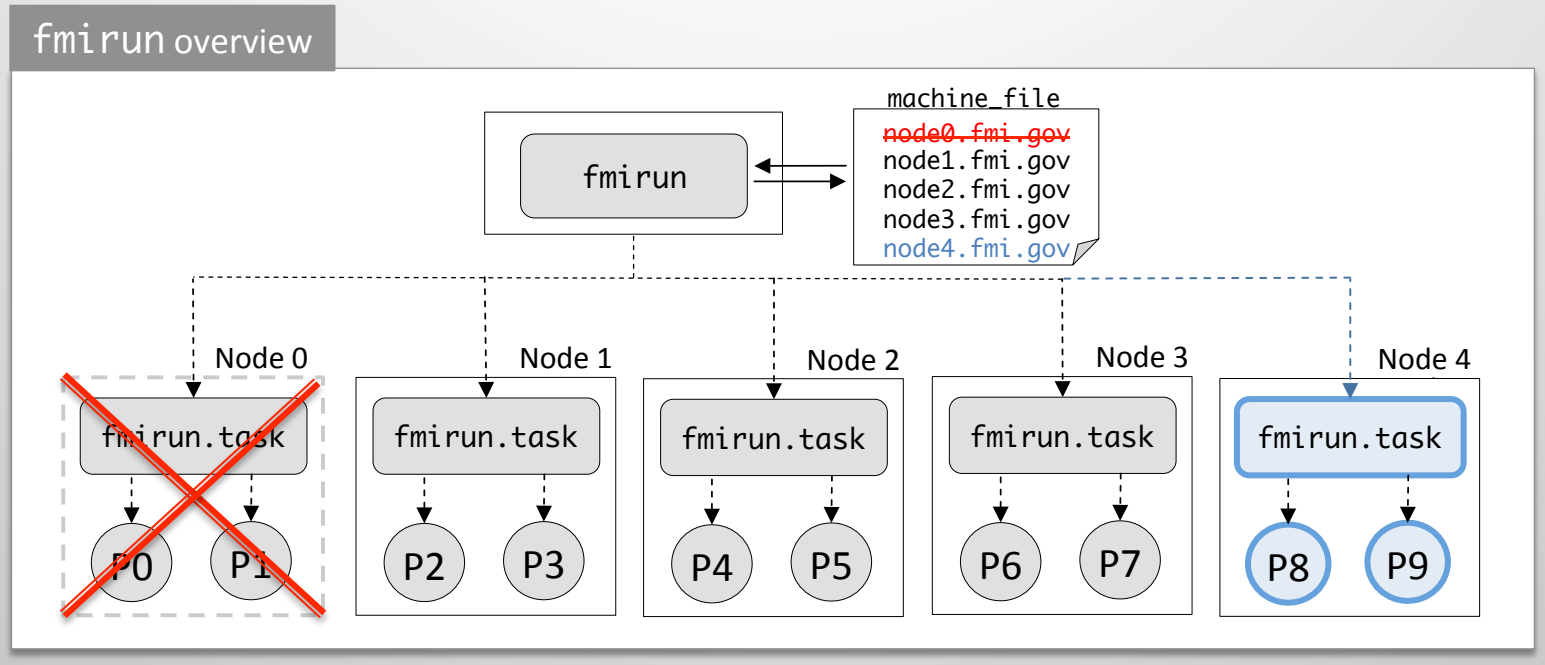


Transparent & Dynamic node allocation

Scalable failure detection & notification

Fast checkpoint/restart

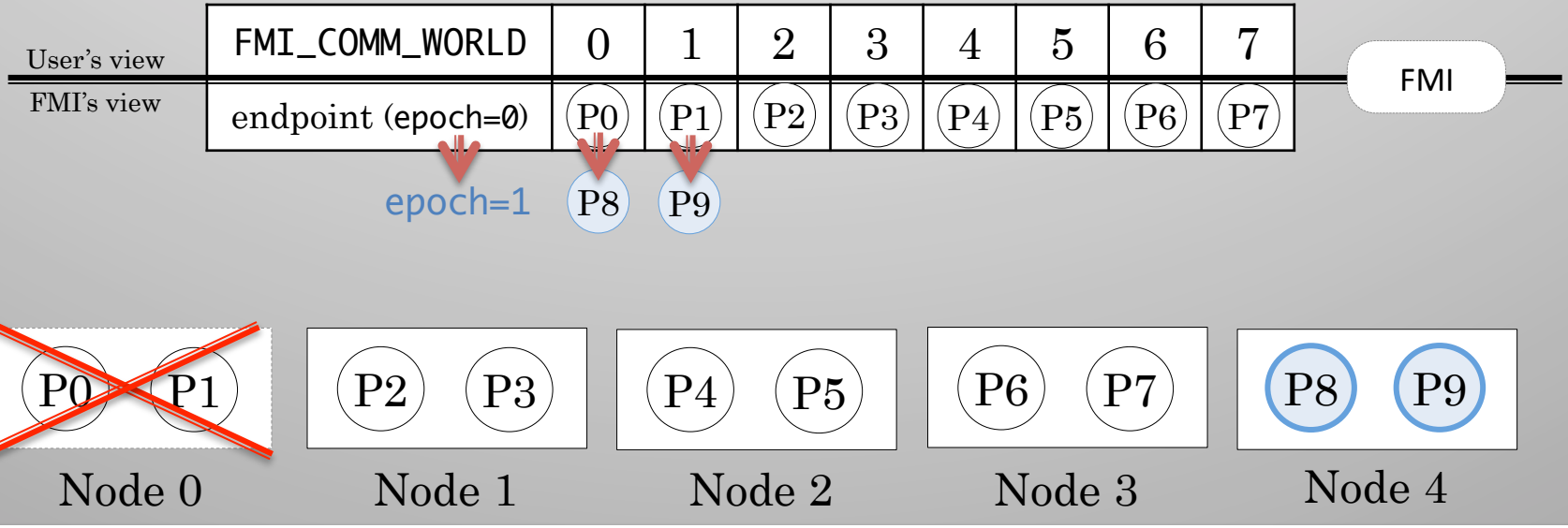
Transparent and dynamic node allocation



- If fmirun.task receives an unsuccessful exit signal from a child process
  - `fmirun.task` kills any other running child processes in the node, and exits with `EXIT_FAILURE`
- When fmirun receives the EXIT_FAILURE from the fmirun.task,
  - `fmirun` attempts to find spare nodes to replace the failed nodes in the `machine_file`
  - `fmirun` spawns new processes on the spare nodes
- `fmirun` boradcasts connection information (endpoint) of new processes, P8 and P9

Transparent and dynamic node allocation (cont'd)

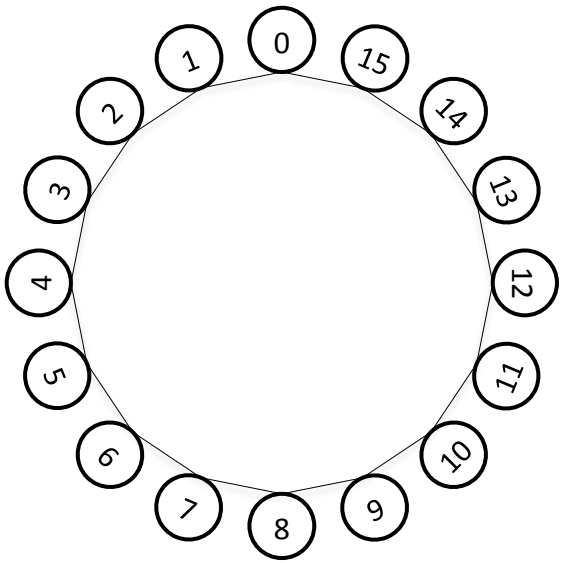
- In FMI, FMI_COMM_WORLD manages process mapping between FMI ranks and processes
  - Once receiving endpoints, the mapping table is updated (=> bootstrapping)
    - Applications can still use the same ranks
  - Then, increment a "**epoch**" number to be able to discard staled messages
    - After recovery, processes may receive old data which is sent before a failure happens



Scalable failure detection

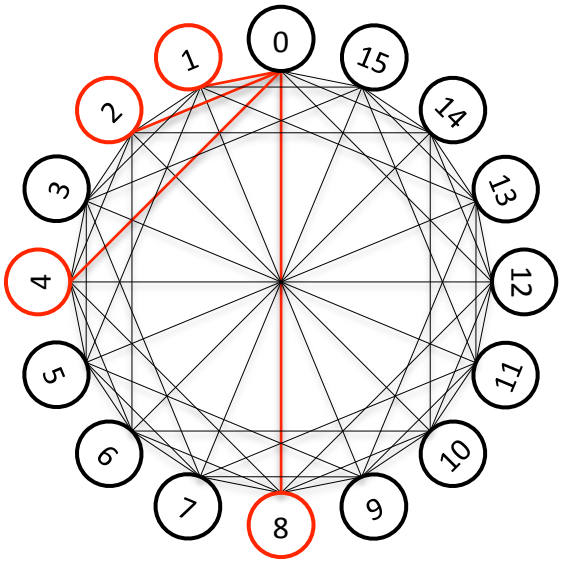
- FMI processes check if other processes are alive or not each other using overlay network
- Log-ring overlay network
  - Each FMI rank connects to 2^k-hop neighbors ($k = 0, 1 \ldots$)
  - e.g.) FMI rank 0 connects to FMI rank $1, 2, 4$ and 8
- Log-ring overlay is scalable for both construction and detection

Ring overlay



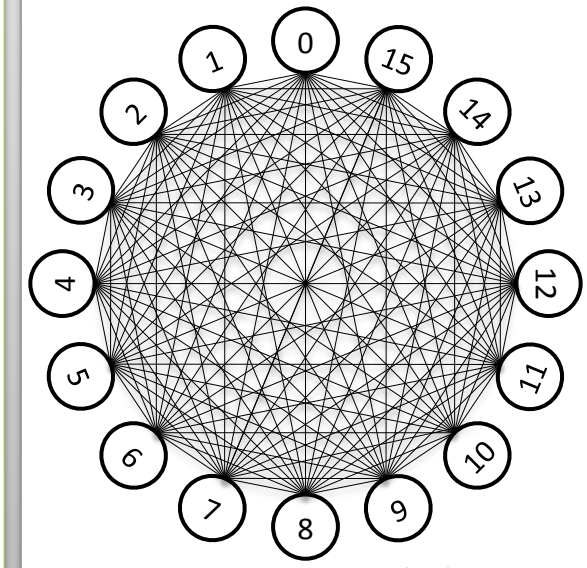
Construction: $O(1)$
Global detection: $O(N)$

Log-ring overlay



Construction: $O(\log N)$
Global detection: $O(\log N)$

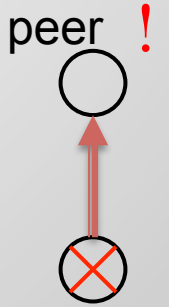
Complete overlay



Construction: $O(N)$
Global detection: $O(1)$

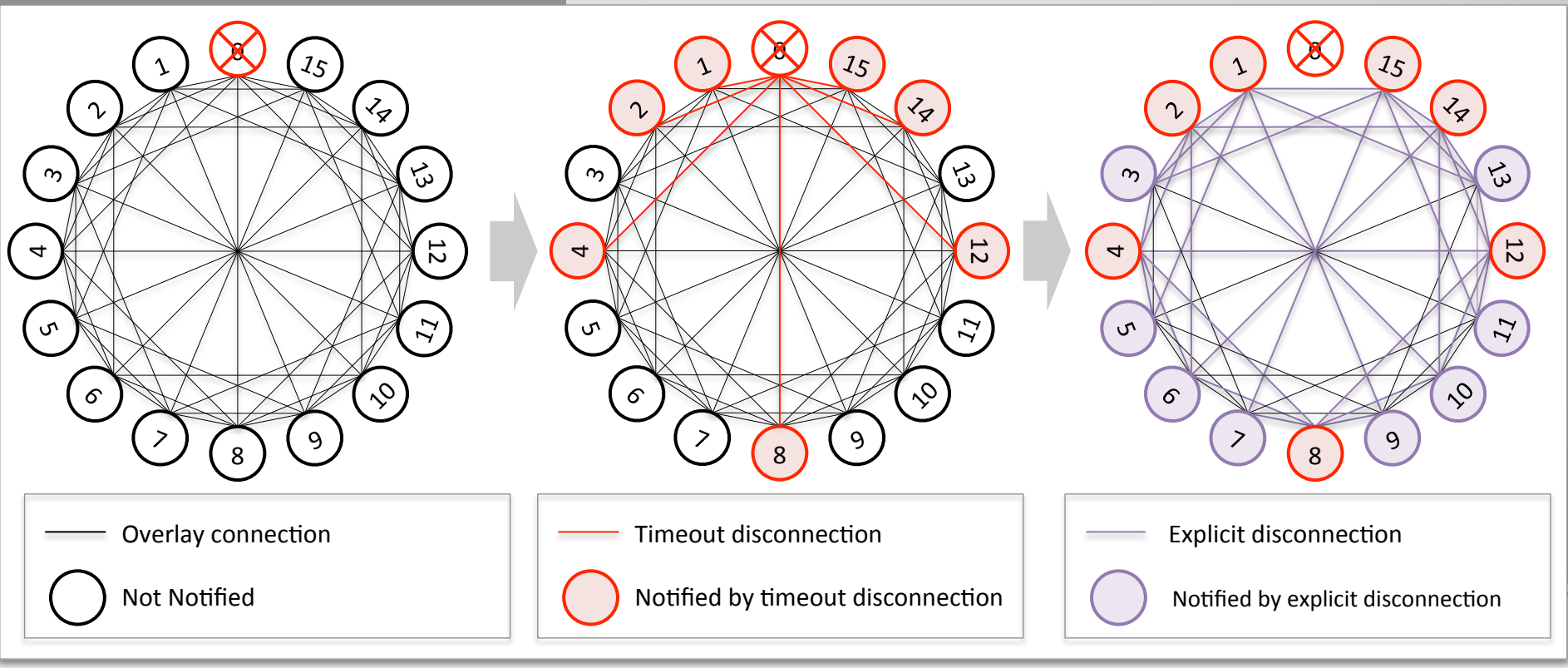
Scalable failure detection (cont'd)

- Log-ring overlay network using ibverbs (constructed in FMI_init(…))
  - Connection-based communication: if a process is terminated, the peer processes receive the disconnection event



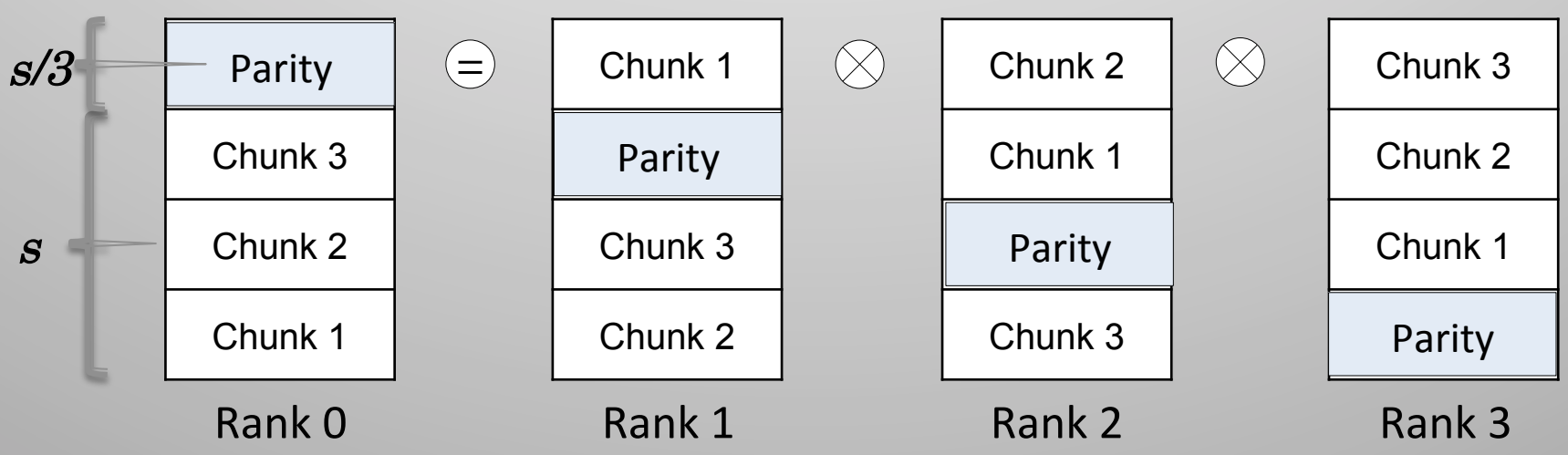
- FMI global failure notification
  - When FMI processes receive disconnection events, the processes explicitly disconnect all of ibverbs connections

Example of global failure notification



In-memory XOR checkpoint/restart algorithm

- XOR checkpoint/restart algorithm
  1. Write checkpoint using `memcpy`
  2. Divides into chunks, and allocate memory for party data
  3. Send parity data to one neighbor, receive parity data from the other neighbor, and compute XOR
  4. Continue 3. until first parity come back
  5. (For restart) gather all restored data



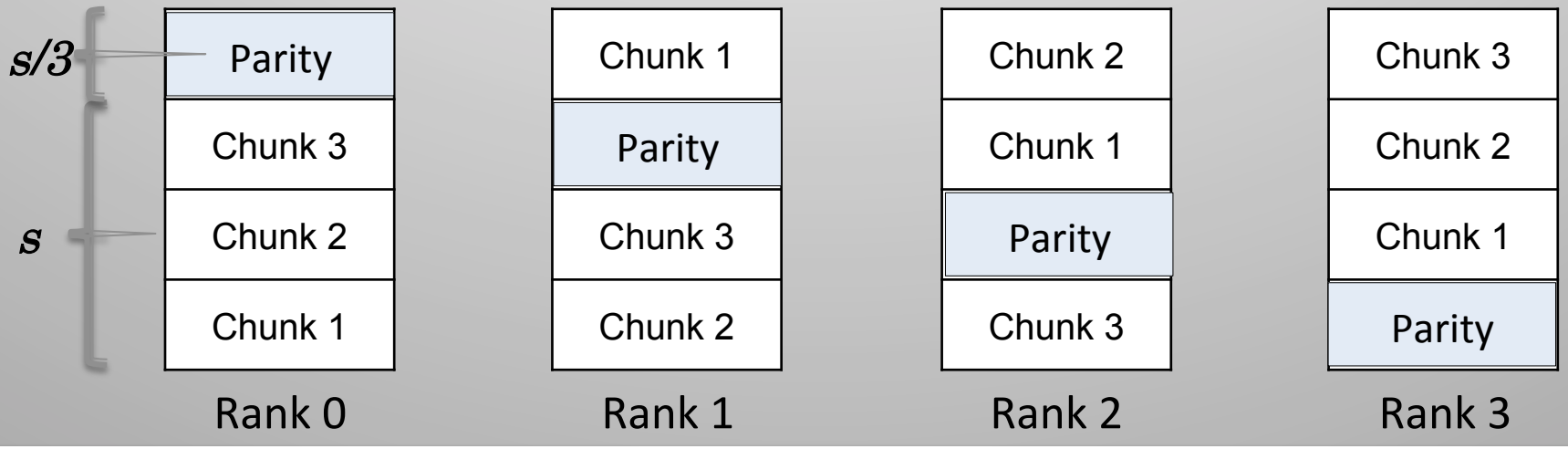
Source: A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System," in Proceedings of the 2010 ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC 10).

In-memory XOR checkpoint/restart model

- In-memory XOR checkpoint/restart time depends on only XOR group size

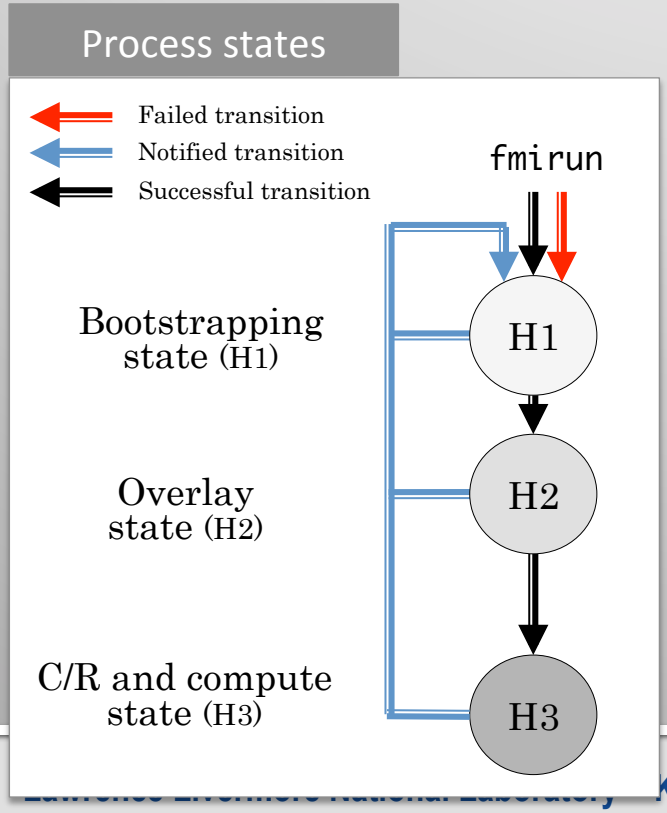
s : ckpt size, n : group size, ***mem_bw*** : memory bandwidth, ***net_bw*** : network bandwidth

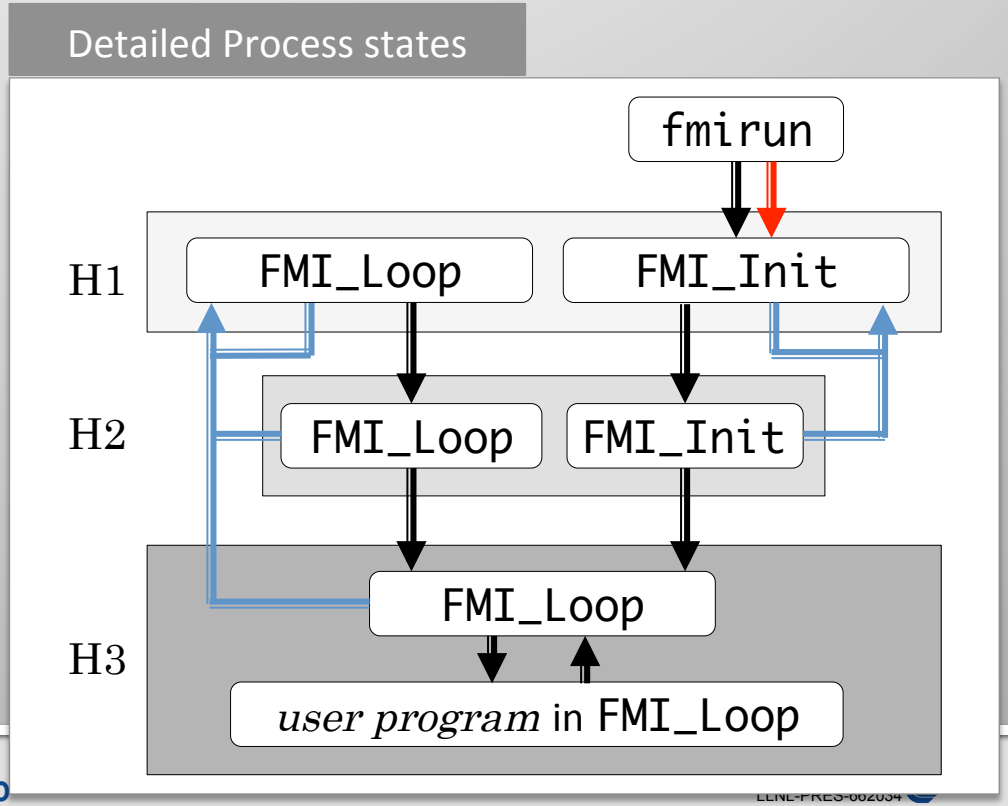
	memcpy	parity transfer	encoding	gathering
Checkpoint	$= \frac{s}{mem\_bw} \oplus$	$\frac{s + s/(n-1)}{net\_bw} \oplus$	$\frac{s}{mem\_bw}$	
Restart	$= \frac{s}{mem\_bw} \oplus$	$\frac{s + s/(n-1)}{net\_bw} \oplus$	$\frac{s}{mem\_bw} \oplus$	$\frac{s}{net\_bw}$



Process state manage

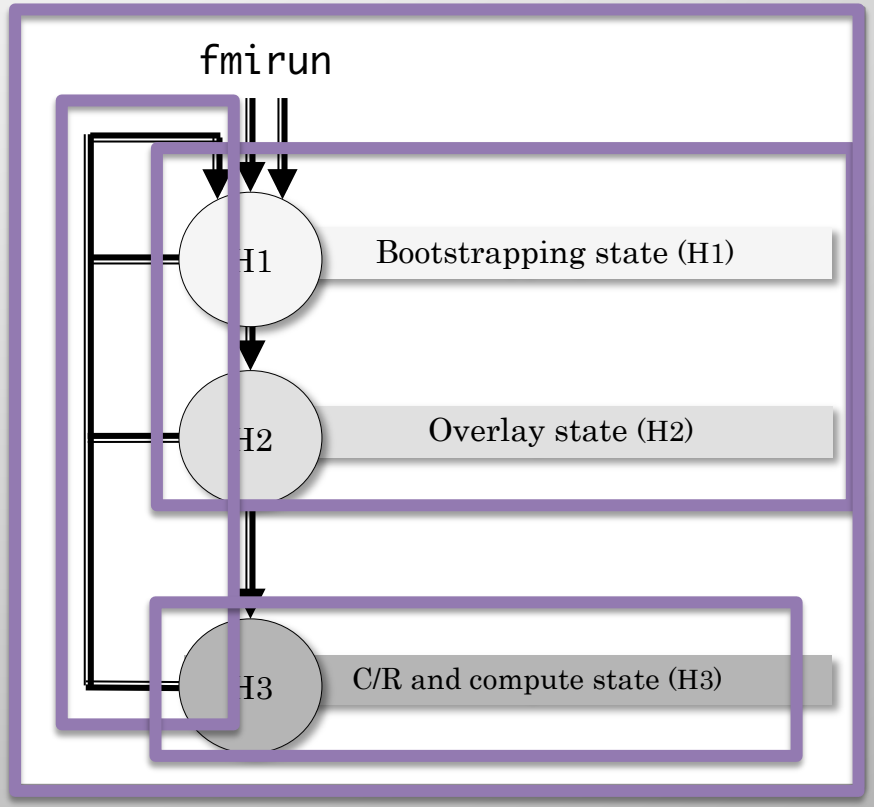
- FMI manages three states to make sure all processes to synchronously
  - H1: Bootstrap for endpoint, process mapping update, and epoch
  - H2: Construct overlay for scalable failure detection
  - H3: Do computation and checkpoint
- Whenever failures happens, all processes transitions to H1 to restart





Evaluations

- Initialization
  - FMI_Init time
- Detection
- Checkpoint/restart
- Benchmark run
- Simulations for extreme scale



Experimental environment

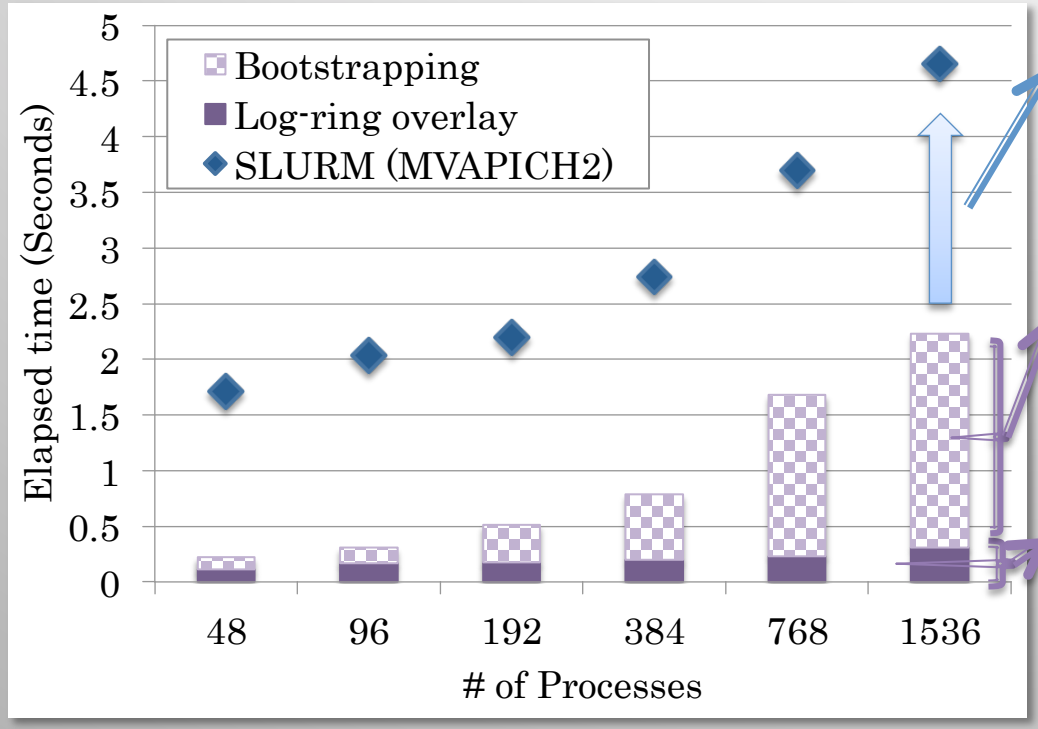
- Sierra cluster @LLNL

TABLE 4.1: Sierra Cluster Specification

Nodes	1,856 compute nodes (1,944 nodes in total)
CPU	2.8 GHz Intel Xeon EP X5660 × 2 (12 cores in total)
Memory	24GB (Peak CPU memory bandwidth: 32 GB/s)
Interconnect	QLogic InfiniBand QDR

- MPI: MVAPICH2 (1.2)
  - Runs on top of SLURM
  - `srun` instead of `mpirun` for launching MPI processes

MPI_Init vs. FMI_Init time



Future FMI may reach the same initialization time as MPI one

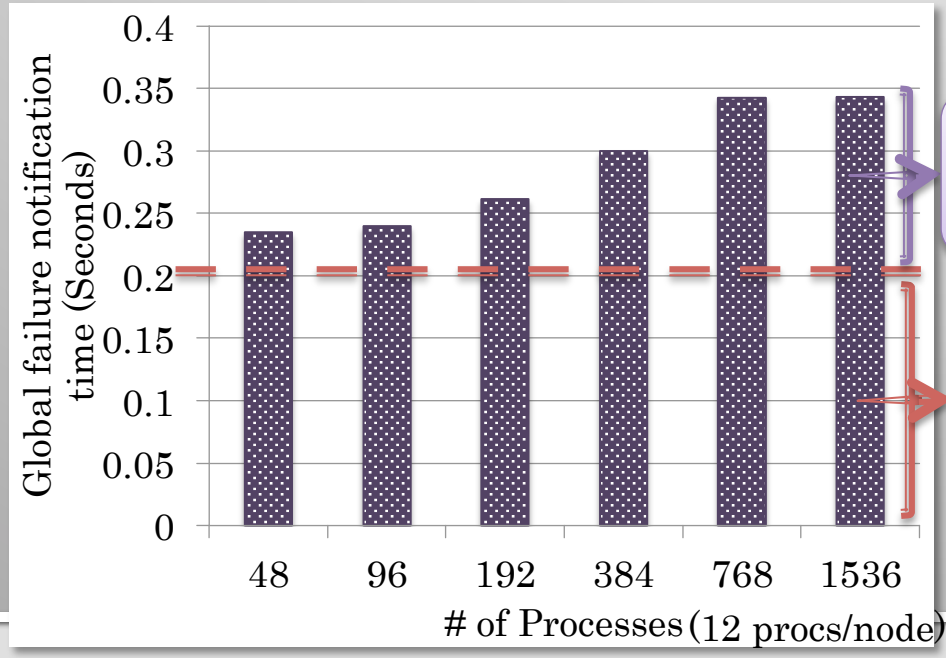
Bootstrapping time is also short
Current FMI do only minimal initialization to start an application

Log-ring construction time is small
the overlay construction time is *O(log(n))*

MPI Initialization: MVAPICH2 MPI_Init(…) launched by `srun`

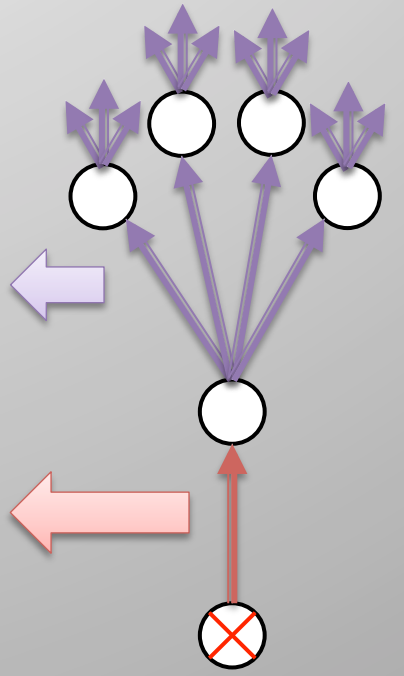
FMI failure detection time

- We measured the time for all processes to be notified of a failure
  - Injected a failure by killing a process
- Once a process receive a disconnection event, the notification exponentially propagate
  - Time complexity: $O(log(N))$ to propagate



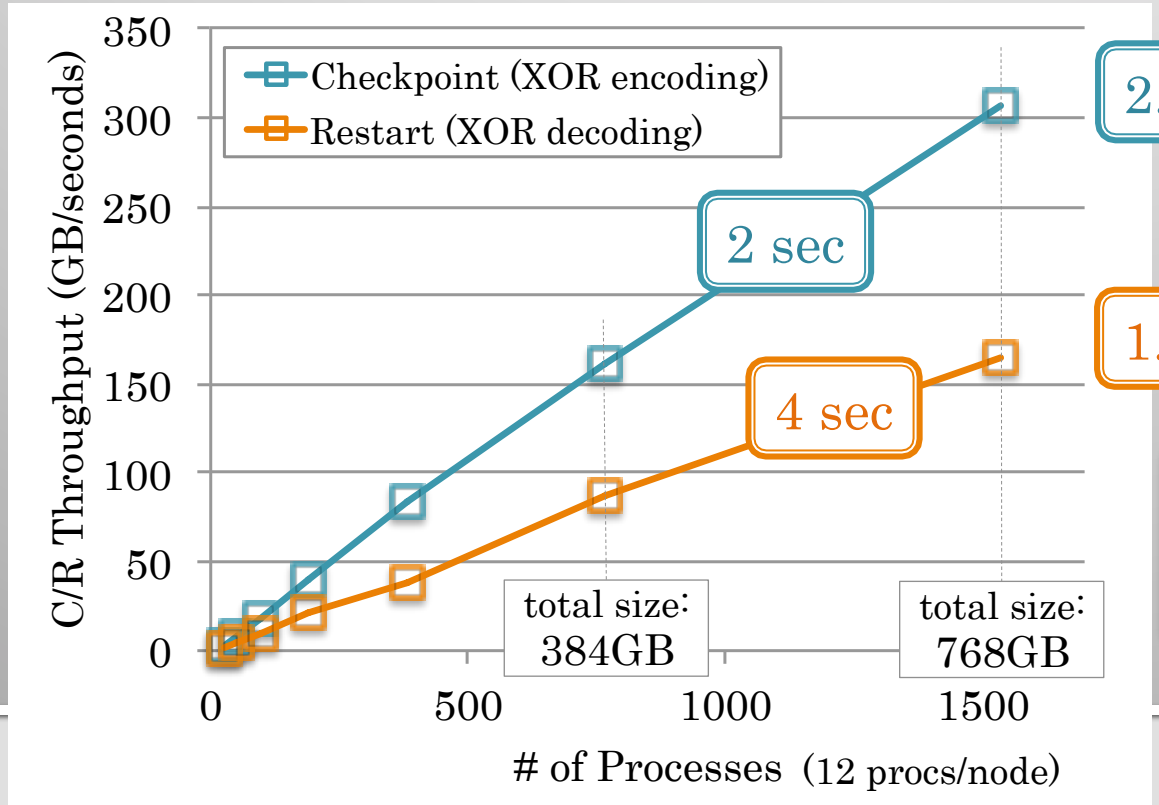
Explicit disconnection
Exponentially propagate notification

Timeout disconnection
about 200 ms



FMI Checkpoint/Restart throughput

- Checkpoint size: 6GB/node
- The checkpoint/restart time of FMI is scalable
  - FMI directly write checkpoint to memory via memcpy
  - As in the model, the checkpointing and restart times are constant regardless of the total number of processes



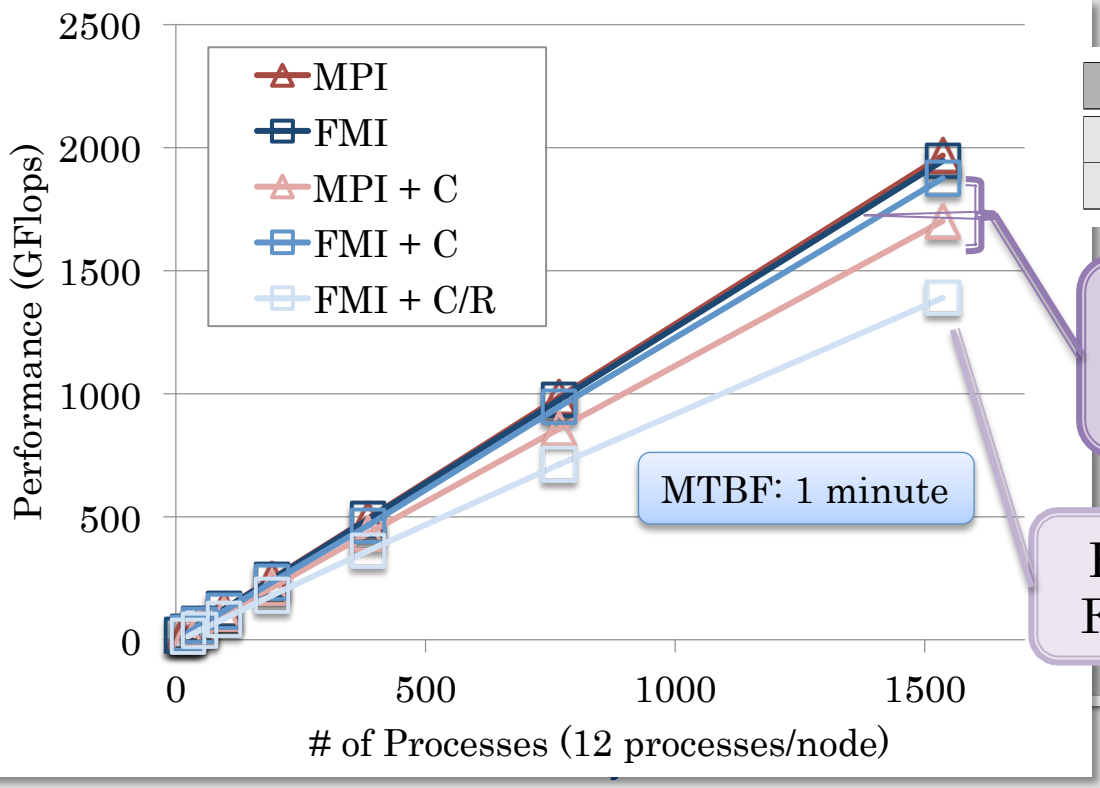
2.4 GB/sec per node

1.3 GB/sec per node

Fast checkpoint/restart
FMI writes and reads checkpoints to/from memory via memcpy

Application runtime with failures

- Benchmark: Poisson's equation solver using Jacobi iteration method
  - Stencil application benchmark
  - MPI_Isend, MPI_Irecv, MPI_Wait and MPI_Allreduce within a single iteration
- For MPI, we use the SCR library for checkpointing
  - Since MPI is not survivable messaging interface, we write checkpoint memory on tmpfs
- Checkpoint interval is optimized by Vaidya's model for FMI and MPI



P2P communication performance

	1-byte Latency	Bandwidth (8MB)
MPI	3.555 usec	3.227 GB/s
FMI	3.573 usec	3.211 GB/s

FMI directly writes checkpoints via memcpy, and can exploit the bandwidth

Even with the high failure rate, FMI incurs only a 28% overhead

Simulations for extreme scale

- FMI applications can continue to run as long as all failures are recoverable. To investigate how long an application can
- run continuously with or without FMI, we simulated an application running at extreme scale.
- Types of failures
  - L1 failure: Recoverable by FMI
  - L2 failure: Unrecoverable by FMI
- We scale out failure rates, evaluate
  1. How long applications can continuously run;
  2. efficiency at extreme scale

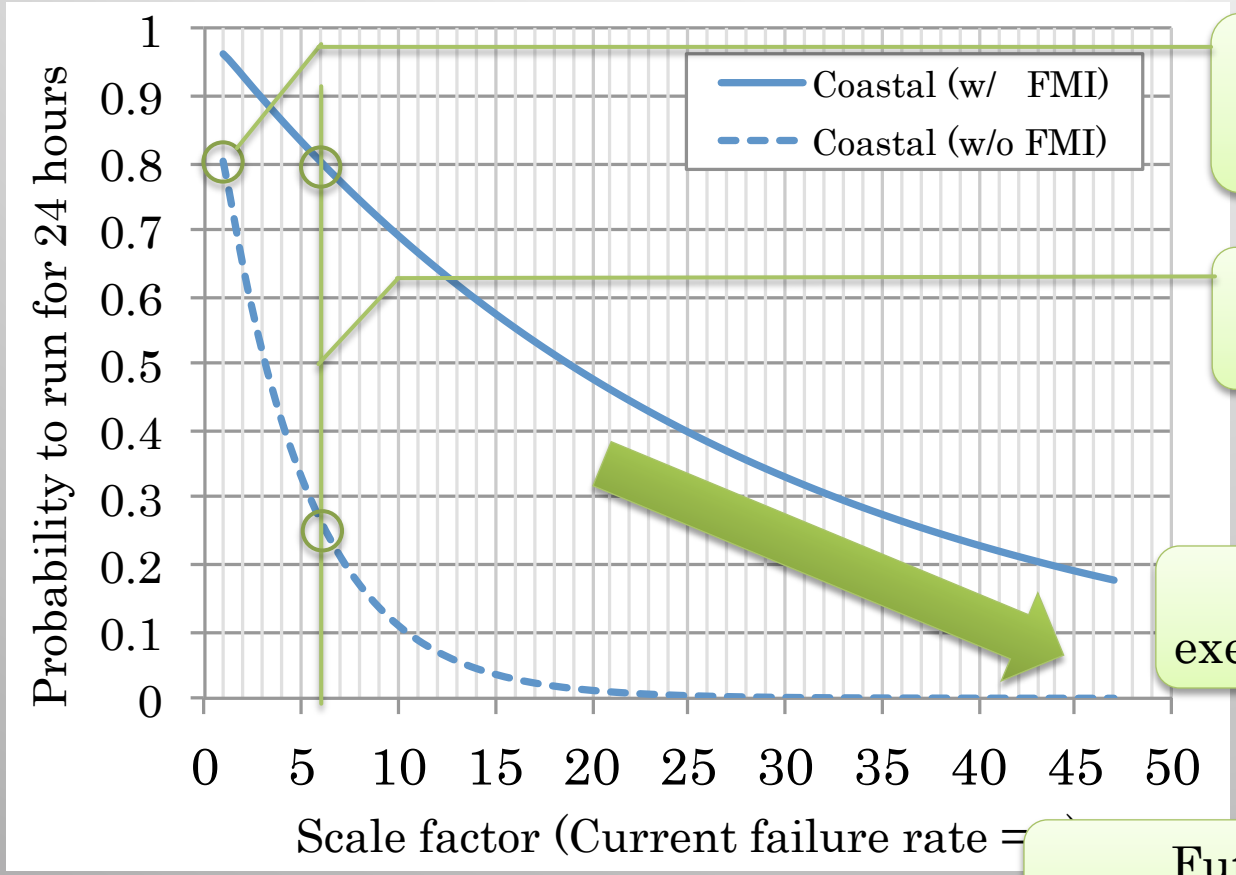
Failure analysis on Coastal cluster

	MTBF	Failure rate
L1 failure	130 hours	2.13^{-6}
L2 failure	650 hours	4.27^{-7}

Source: A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System," in Proceedings of the 2010 ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC 10).

Probability to run for 24 hours

- With FMI, application continuously run for longer time



80% of probability to run for 24 hours on environment with current failure rate

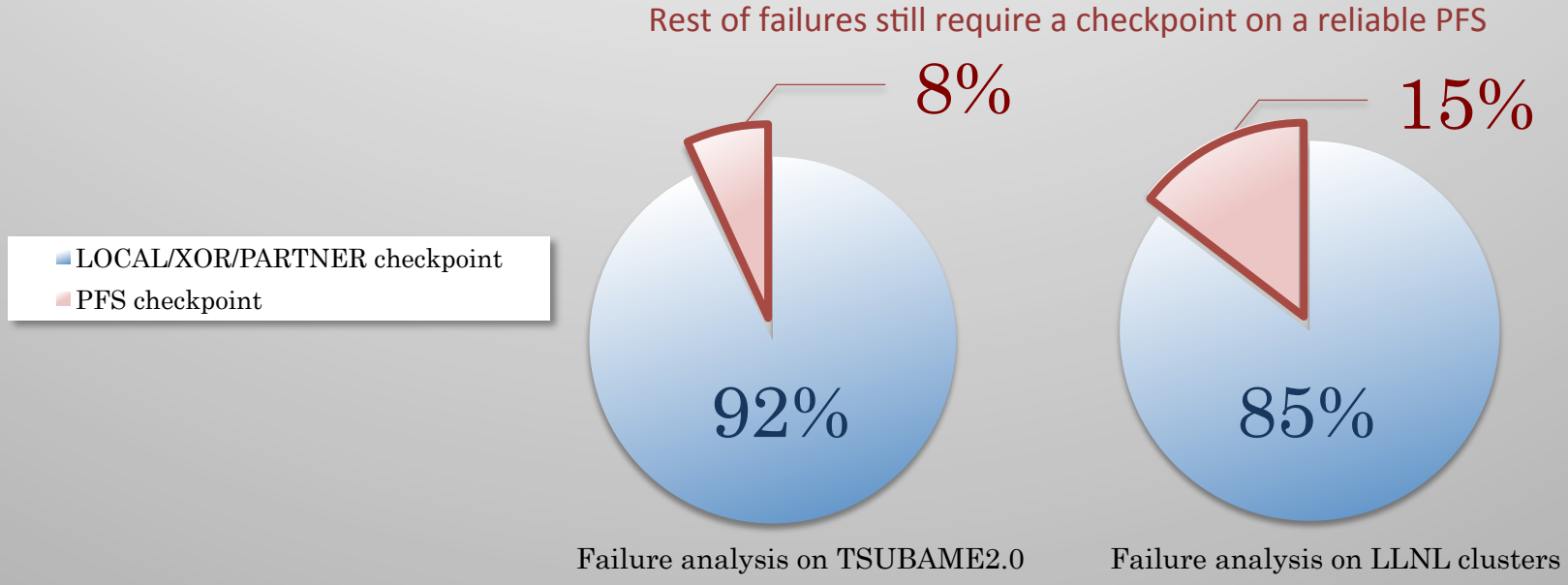
FMI execution: 80%
non-FMI execution: 25%

Even with FMI, most of executions cannot run for 24H

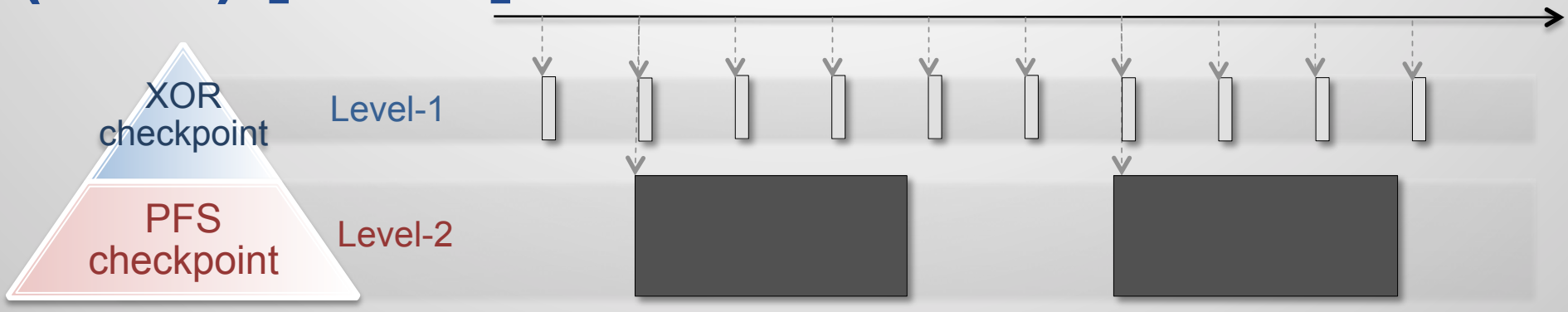
Future FMI will support async. multi-level checkpoint/restart

Single node failure is common

- Most of failures comes from one node, or can recover from XOR checkpoint
  - e.g. 1) TSUBAME2.0: 92% failures
  - e.g. 2) LLNL clusters: 85% failures



Asynchronous multi-level checkpointing (MLC) [SC12]



Source: K. Sato, N. Maruyama, K. Mohror, A. Moody, T. Gamblin, B. R. de Supinski, and S. Matsuoka, "Design and Modeling of a Non-Blocking Checkpointing System," in Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis, ser. SC '12. Salt Lake City, Utah: IEEE Computer Society Press, 2012

- Asynchronous MLC is a technique for achieving high reliability while reducing checkpointing overhead
- Asynchronous MLC Use storage levels hierarchically
  - XOR checkpoint: Frequent for one node for a few node failure
  - PFS checkpoint: Less frequent and asynchronous for multi-node failure
- Our previous work model the asynchronous MLC

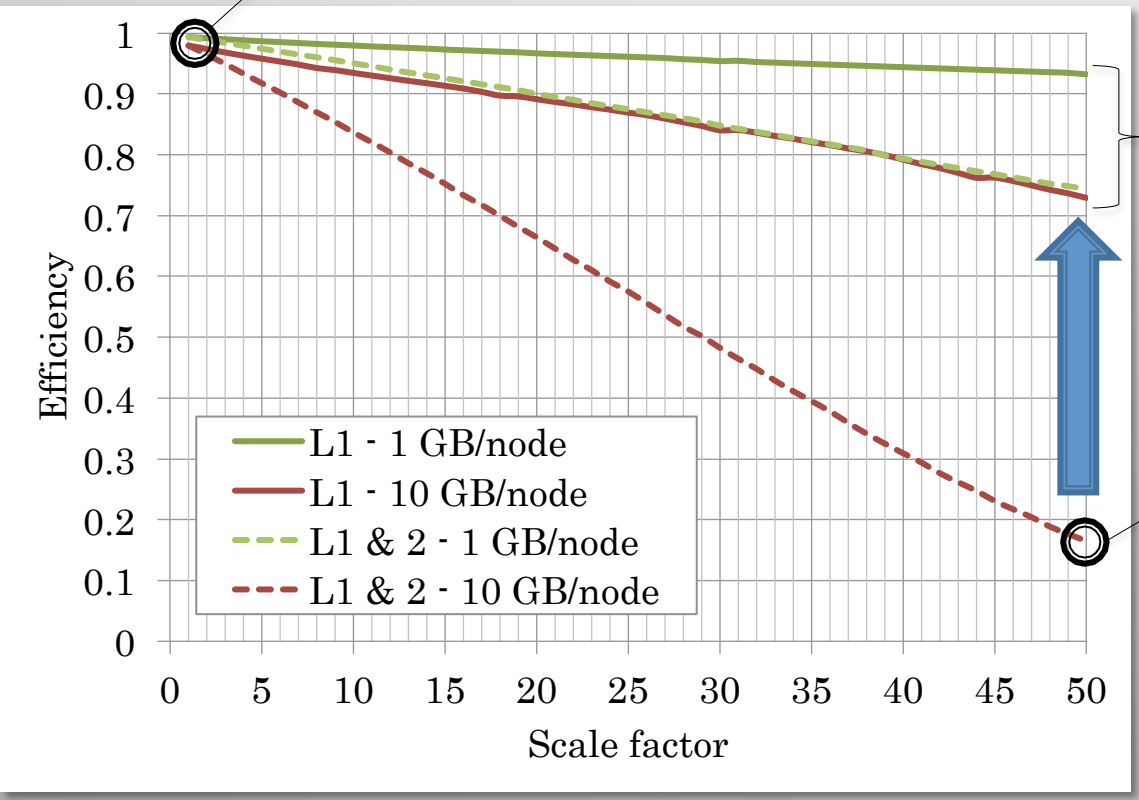
Failure analysis on Coastal cluster

	MTBF	Failure rate
L1 failure	130 hours	2.13^{-6}
L2 failure	650 hours	4.27^{-7}

Source: A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System," in Proceedings of the 2010 ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC 10).

Efficiency with FMI + Asynchronous MLC

- Checkpoint size: 1 and 10 GB/node
- We increase L1 and L1 & L2 failure rates

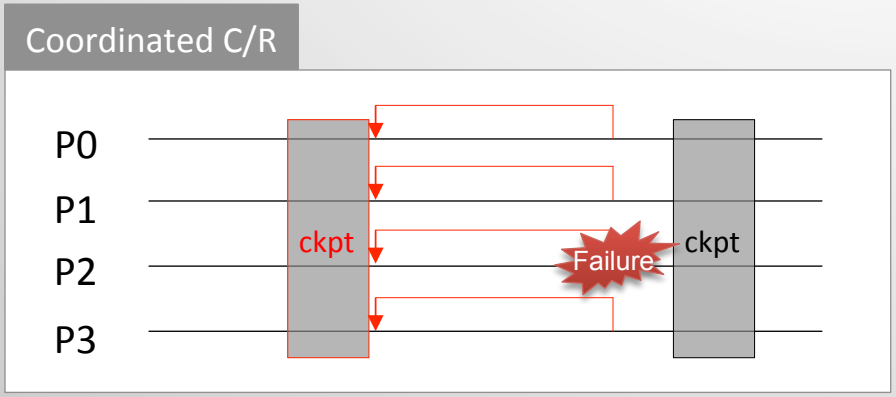


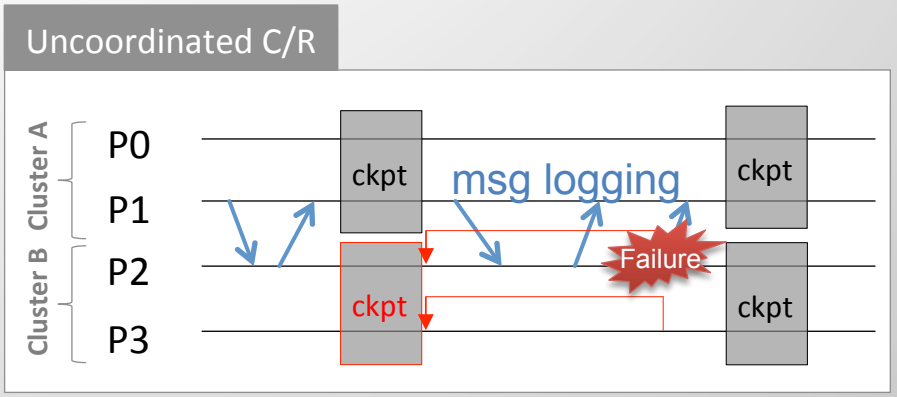
High efficiency with current failure rate

FMI + Asynchronous MLC achieve high efficiency even with much higher failure rate

If both L1 & L2 failure rate increase, and checkpoint size is large, efficiency drops rapidly

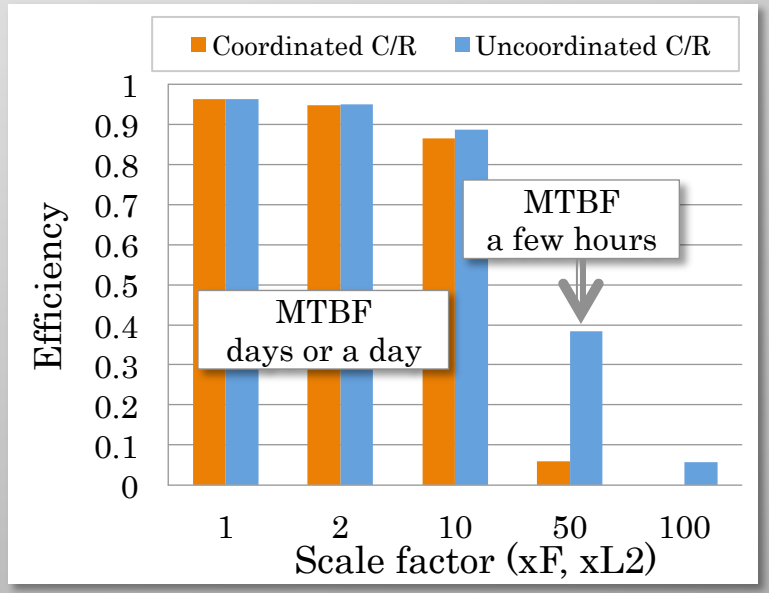
Uncoordinated C/R + MLC





- Coordinated C/R
  - All processes globally synchronize before taking checkpoints and restart on a failure
  - Restart overhead
- Uncoordinated C/R
  - Create clusters, and log messages exchanged between clusters
  - Message logging overhead is incurred, but rolling-back only a cluster can restart the execution on a failure

⇒ MLC + Uncoordinated C/R (Software-level) approaches may be limited at extreme scale



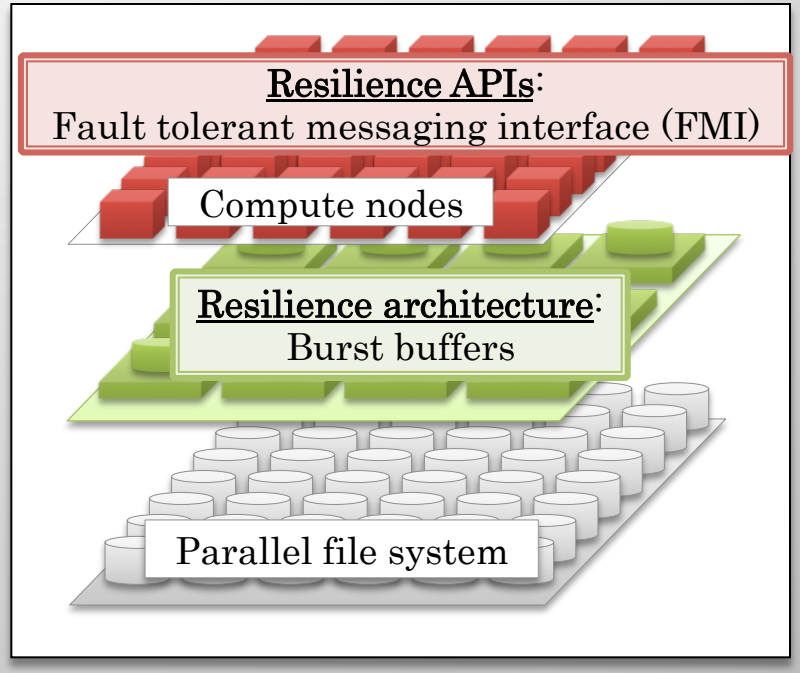
Resilience APIs, Architecture and the model

- Resilience APIs
  - In near future, applications must have capabilities of handling failures as usual events

  ⇒ Fault tolerant messaging interface (FMI) [IPDPS2014]

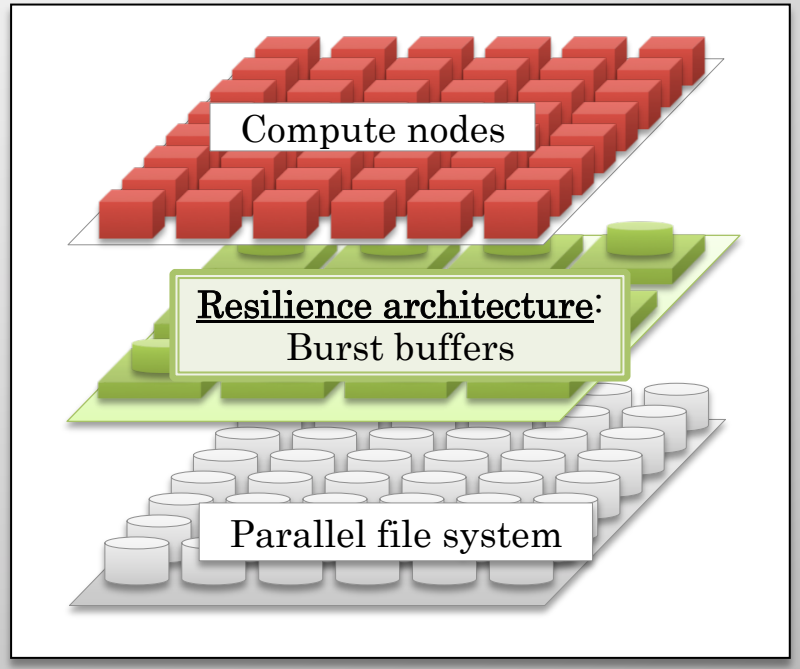
- Resilience architecture and model
  - Software level approaches are not enough

  ⇒ Architecture using *Burst buffer [CCGrid2014]*



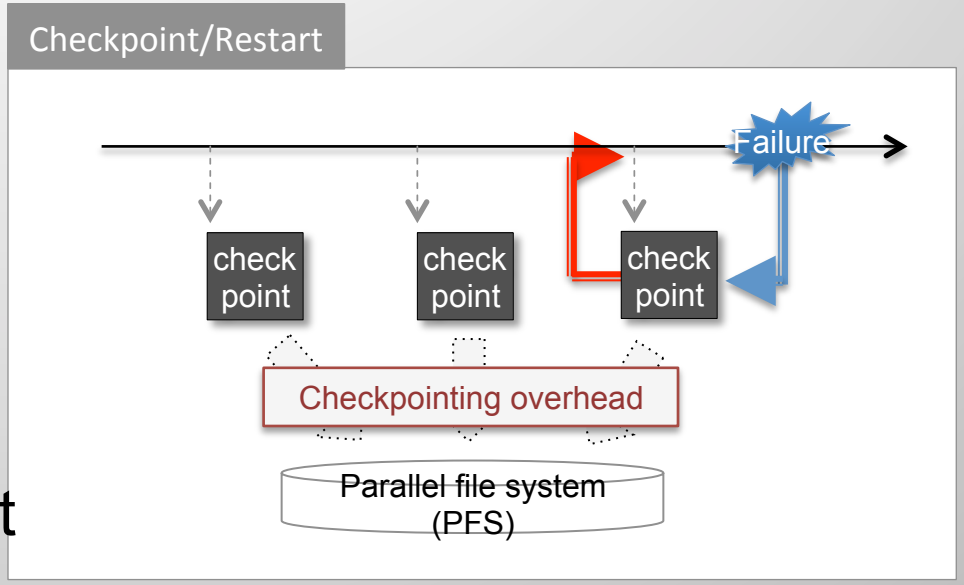
Burst buffer storage architecture

- Burst buffer
  - A new tier in storage hierarchies
  - Absorb bursty I/O requests from applications
  - Fill performance gap between node-local storage and PFSs in both latency and bandwidth
- If you write checkpoints to burst buffers,
  - Faster checkpoint/restart time than PFS
  - More reliable than storing on compute nodes



Checkpoint/Restart (Software-Lv.)

- Idea of Checkpoint/Restart
  - Checkpoint
    - Periodically save snapshots of an application state to PFS
  - Restart
    - On a failure, restart the execution from the latest checkpoint

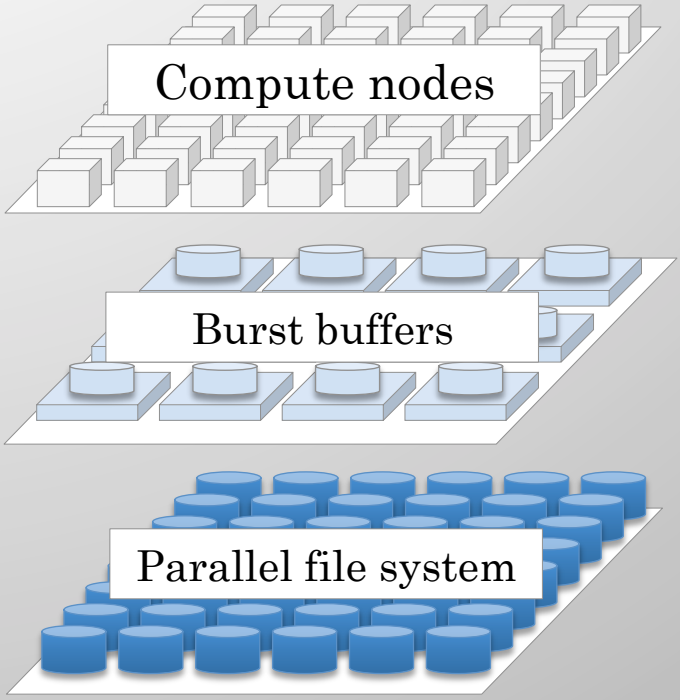


- Improved Checkpoint/Restart
  - Multi-level checkpointing [1]
  - Asynchronous checkpointing [2]
  - In-memory diskless checkpointing [3]
- We found that software-level approaches may be limited in increasing resiliency at extreme scale

[1] A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, “Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System (SC 10)
[2] Kento Sato, Adam Moody, Kathryn Mohror, Todd Gamblin, Bronis R. de Supinski, Naoya Maruyama and Satoshi Matsuoka, "Design and Modeling of a Non-blocking Checkpointing System", SC12
[3] Kento Sato, Adam Moody, Kathryn Mohror, Todd Gamblin, Bronis R. de Supinski, Naoya Maruyama and Satoshi Matsuoka, "FMI: Fault Tolerant Messaging Interface for Fast and Transparent Recovery", IPDPS2014

Storage architectures

- We consider architecture-level approaches
- Burst buffer
  - A new tier in storage hierarchies
  - Absorb bursty I/O requests from applications
  - Fill performance gap between node-local storage and PFSs in both latency and bandwidth
- If you write checkpoints to burst buffers,
  - Faster checkpoint/restart time than PFS
  - More reliable than storing on compute nodes

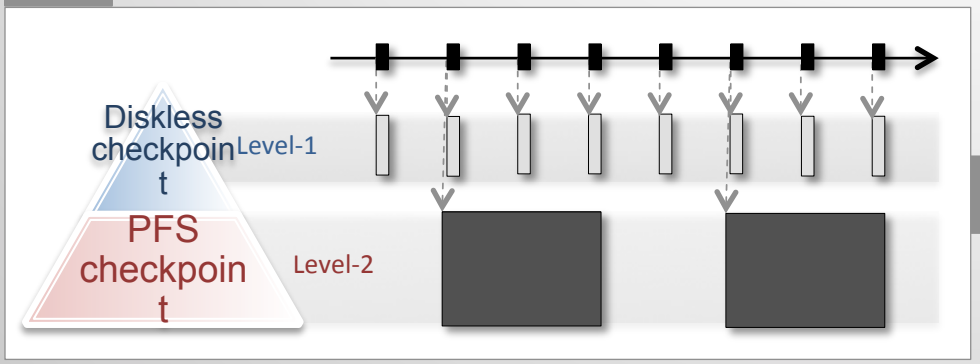


- However,…
  - Adding burst buffer nodes may increase total system size, and failure rates accordingly
    - It's not clear if burst buffers improve overall system efficiency
  - Because burst buffers also connect to networks, the burst buffers may still be a bottleneck

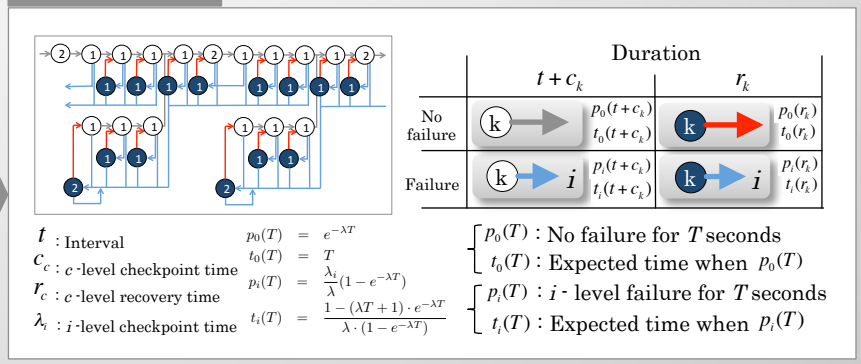
[4] Doraimani, Shyamala and Iamnitchi, Adriana, "File Grouping for Scientific Data Management: Lessons from Experimenting with Real Traces", HPDC '08

Multi-level Checkpoint/Restart (MLC/R) [SC10, 12]

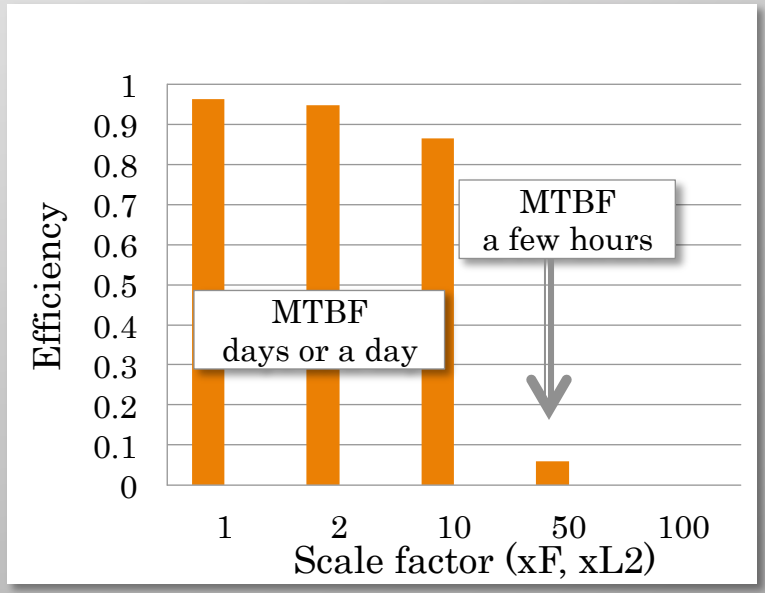
MLC



MLC model



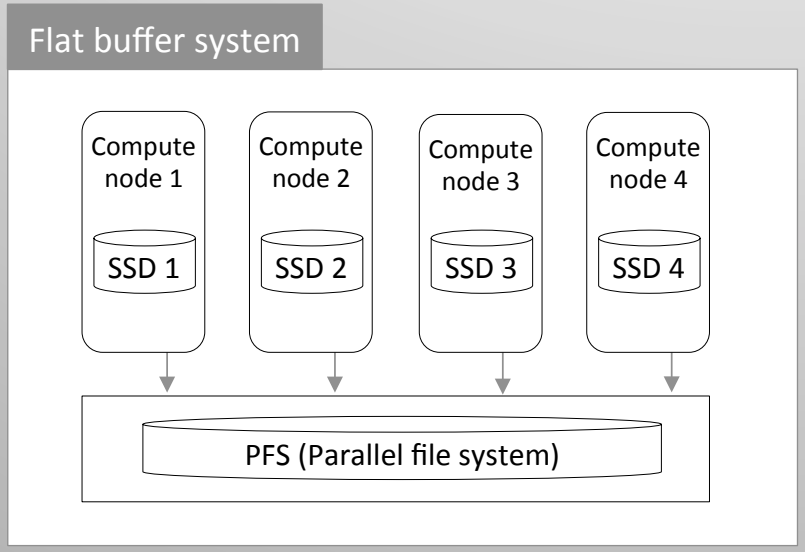
- MLC hierarchically use storage levels
  - Diskless checkpoint: Frequent for one node for a few node failure
  - PFS checkpoint: Less frequent and asynchronous for multi-node failure
- Our evaluation showed system efficiency drops to less than 10% when MTBF is a few hours

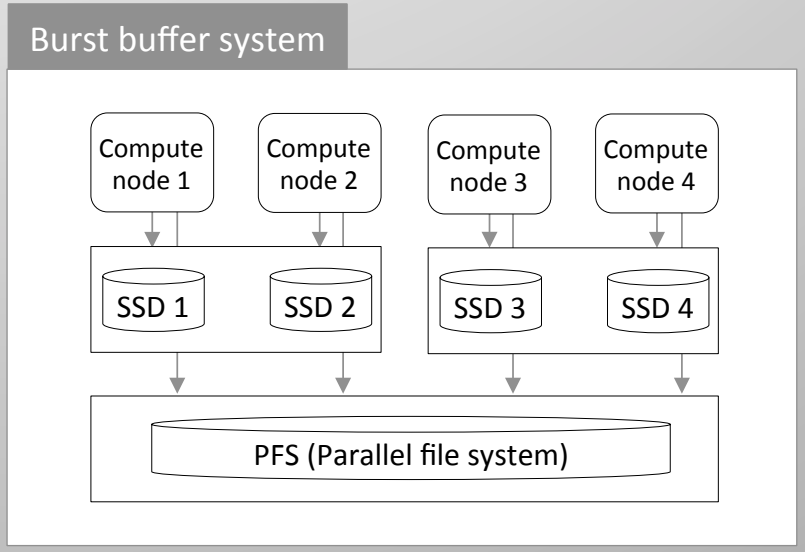


[1] A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System (SC 10)
[2] Kento Sato, Adam Moody, Kathryn Mohror, Todd Gamblin, Bronis R. de Supinski, Naoya Maruyama and Satoshi Matsuoka, "Design and Modeling of a Non-blocking Checkpointing System", SC12

Storage designs

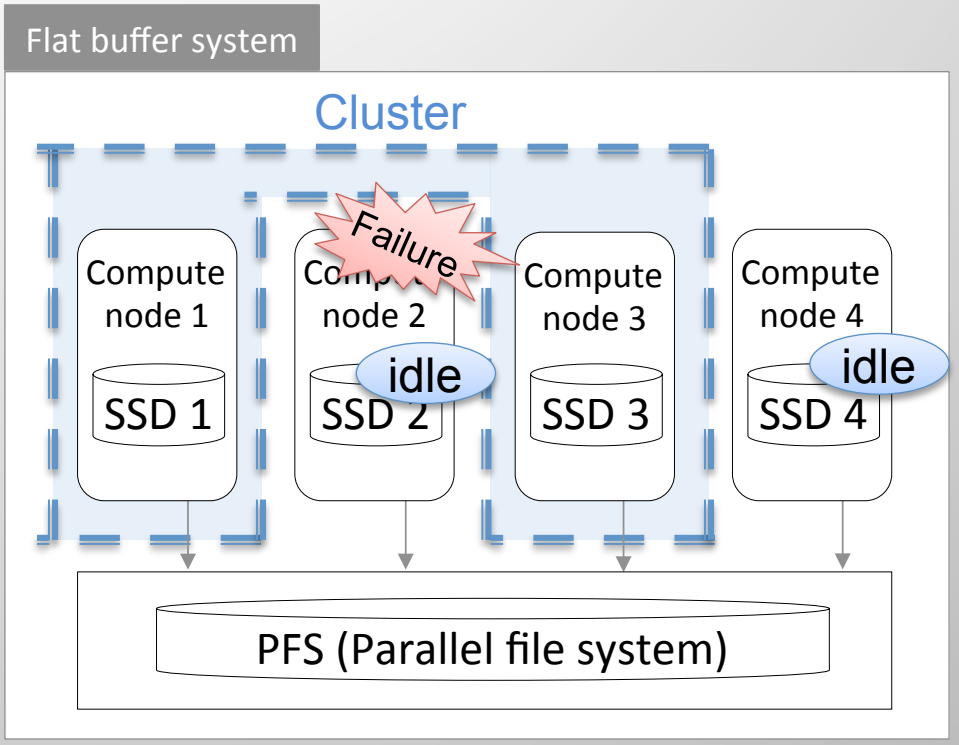
- Addition to the software-level approaches, we also explore two architecture-level approaches
  - Flat buffer system:
    - Current storage system
  - Burst buffer system:
    - Separated buffer space





Flat Buffer Systems

- Design concept
  - Each compute node has its dedicated node-local storage
  - Scalable with increasing number of compute nodes



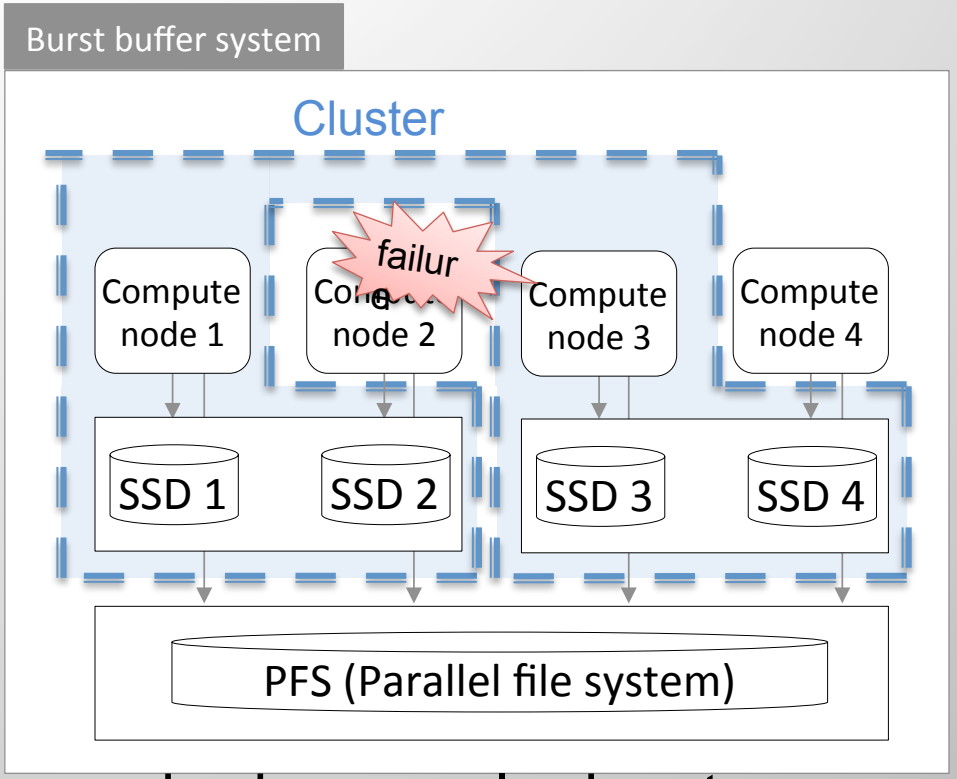
- This design has drawbacks:
  1. Unreliable checkpoint storage

     e.g.) If compute node 2 fails, a checkpoint on SSD 2 will be lost because SSD 2 is physically attached to the failed compute node 2
  2. Inefficient utilization of storage resources on uncoordinated checkpointing

     e.g.) If compute node 1 & 3 are in a same cluster, and restart from a failure, the bandwidth of SSD 2 & 4 will not be utilized

Burst Buffer Systems

- Design concept
  - A burst buffer is a storage space to bridge the gap in latency and bandwidth between node-local storage and the PFS
  - Shared by a subset of compute nodes



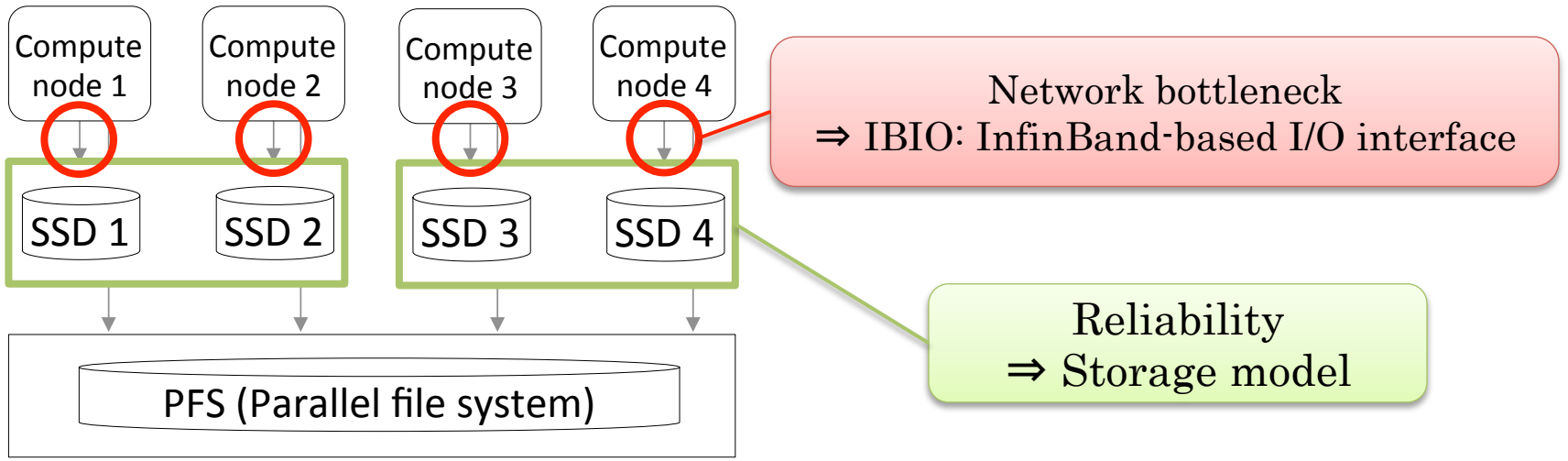
- Although additional nodes are required, several advantages
  1. More Reliable because burst buffers are located on a smaller # of nodes

     e.g.) Even if compute node 2 fails, a checkpoint of compute node 2 is accessible from the other compute node 1
  2. Efficient utilization of storage resources on uncoordinated checkpointing

     e.g.) if compute node 1 and 3 are in a same cluster, and both restart from a failure, the processes can utilize all SSD bandwidth unlike a flat buffer system

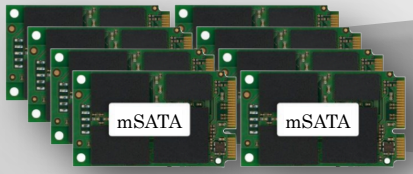
Challenges for using burst buffers

Challenges for using burst buffer system

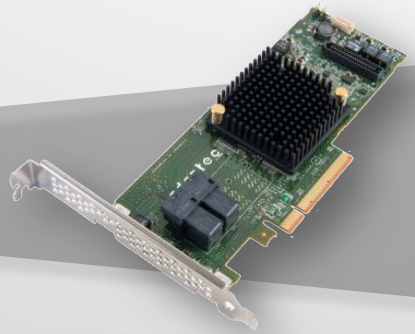


- Exploiting storage bandwidth of burst buffers
  - Burst buffers are connected to networks, networks can be bottleneck
- Analyzing reliability of systems with burst buffers
  - Adding burst buffer nodes increase total system size, and increase overall failure rate
  - System efficiency may decrease

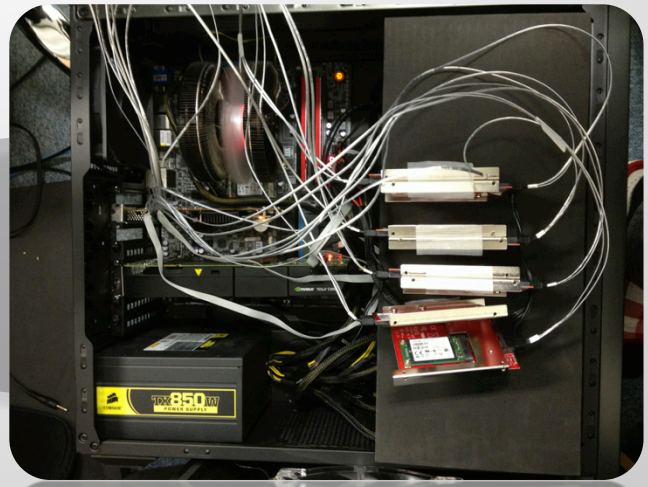
Burst buffer prototype multi-mSATA High I/O BW & cost

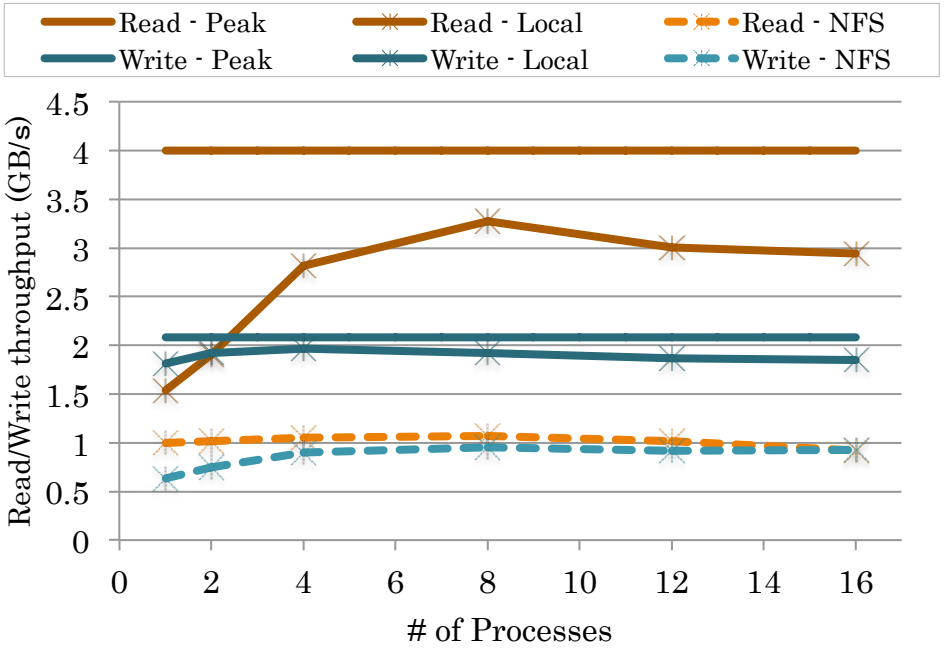


mSATA × 8
(Read: 500MB/s, Write: 260MB/s)



Adaptec RAID × 1





Node specification

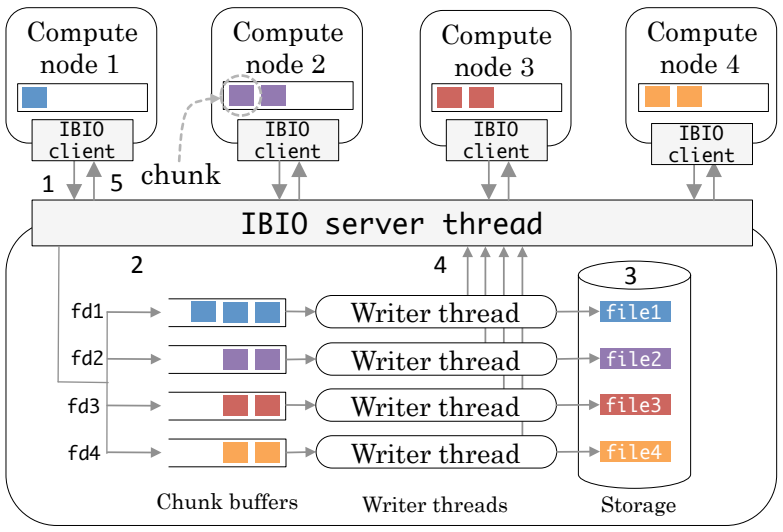
CPU	Intel Core i7-3770K CPU (3.50GHz x 4 cores)
Memory	Cetus DDR3-1600 (16GB)
M/B	GIGABYTE GA-Z77X-UD5H
SSD	Crucial m4 msata 256GB CT256M4SSD3 (Peak read: 500MB/s, Peak write: 260MB/s)
SATA converter	KOUTECH IO-ASS110 mSATA to 2.5' SATA Device Converter with Metal Fram
RAID Card	Adaptec RAID 7805Q ASR-7805Q Single

Interconnect :Mellanox FDR HCA (Model No.: MCX354A-FCBT)

IBIO: InfiniBand-based I/O interface

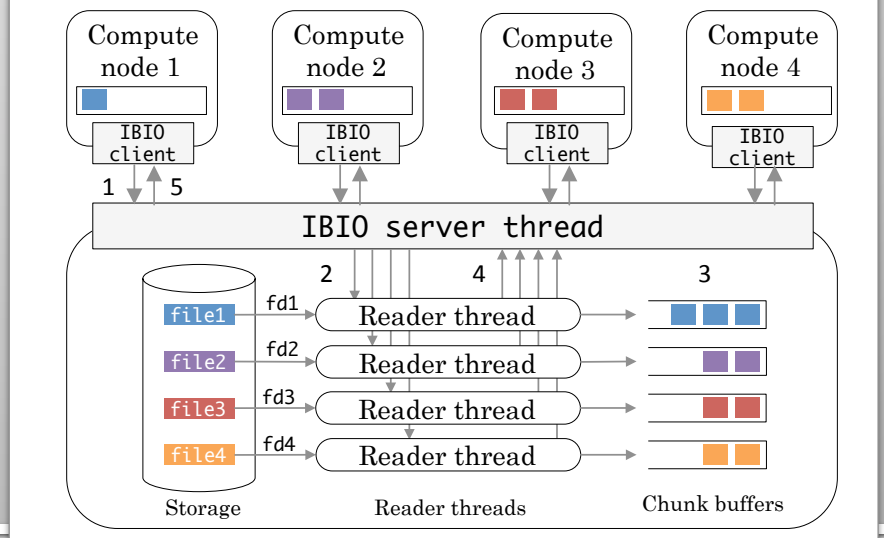
- Provide POSIX I/O-like interfaces
  - open, read, write and close
  - Client can open any files on any servers
    - open("hostname:/path/to/file", mode)
- IBIO use ibverbs for communication between clients and servers
  - Exploit network bandwidth of infiniBand

IBIO write



IBIO write: four IBIO clients and one IBIO server

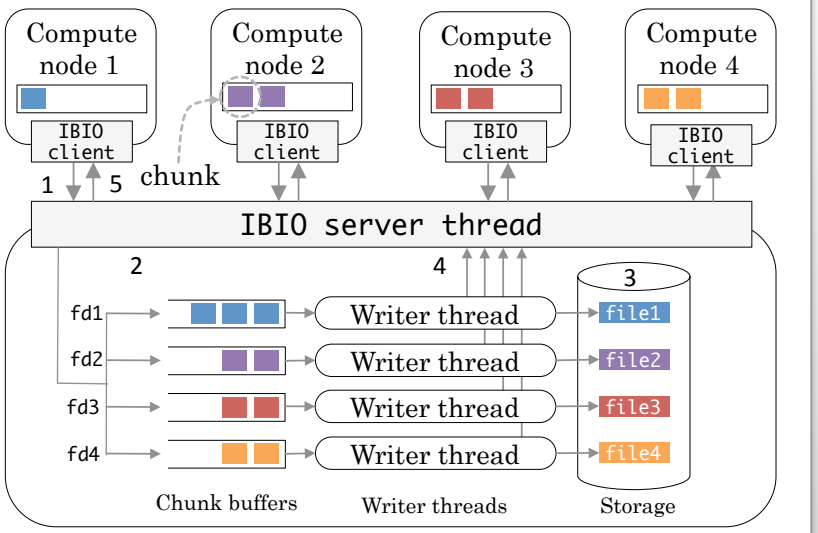
IBIO read



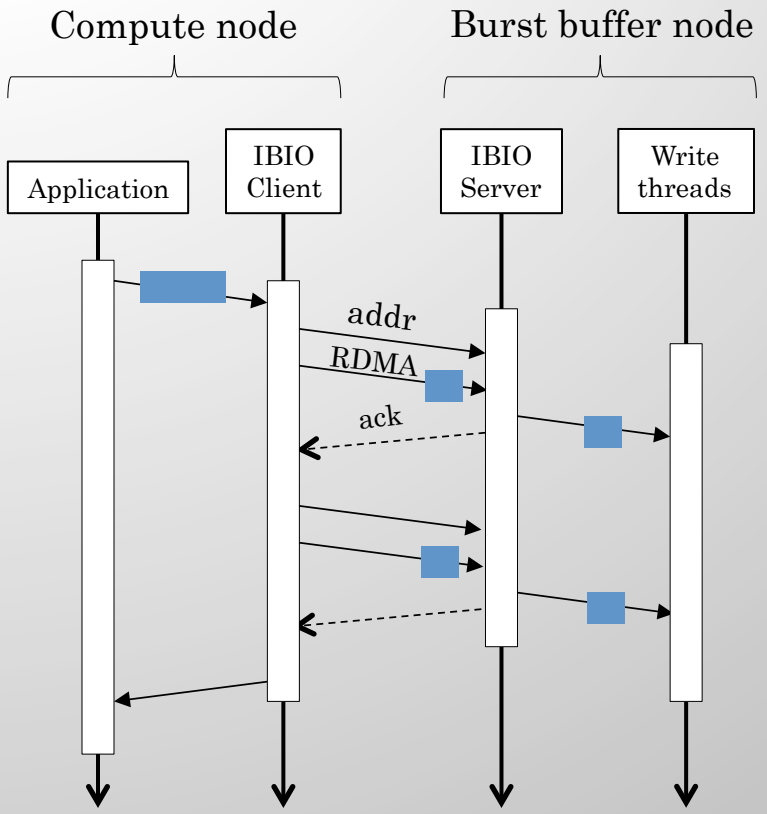
IBIO read: four IBIO clients and one IBIO server

IBIO write/read

IBIO write

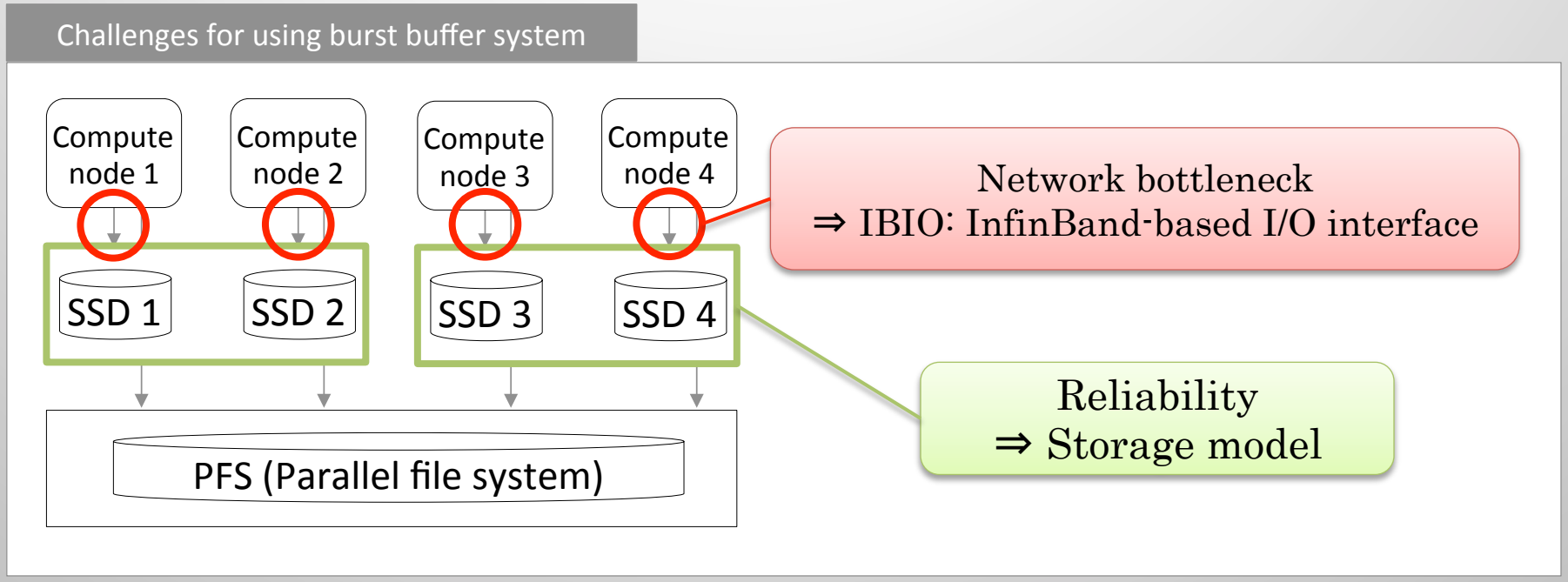


IBIO write: four IBIO clients and one IBIO server



- IBIO write
  1. Application call IBIO client function with data to write
  2. IBIO client divides the data into chunks, then send the address to IBIO server for RDMA
  3. IBIO server issues RDMA read to the address, and reply ack
  4. Continues until all chunks are sent, and return to application
  5. Writer threads asynchronously write received data to storage
- IBIO read
  - Reads chunks by reader threads and send to clients in the same way as IBIO write by using RDMA

Challenges for using burst buffers



- Exploiting storage bandwidth of burst buffers
  - Burst buffers are connected to networks, networks can be bottleneck
- Analyzing reliability of systems with burst buffers
  - Adding burst buffer nodes increase total system size
  - System efficiency may decrease due to Increased overall failure by added burst buffers

Modeling overview

- To find out the best checkpoint/restart strategy for systems with burst buffers, we model checkpointing strategies

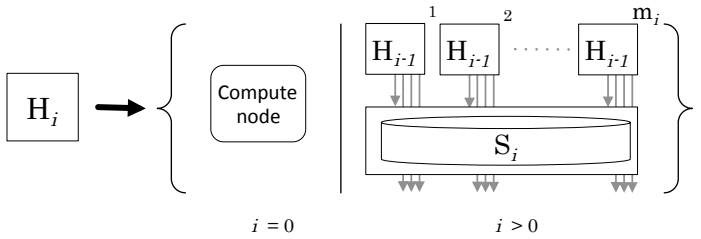
C/R strategy model

$$O_i = \begin{cases} C_i + E_i & \text{(Sync.)} \\ I_i & \text{(Async.)} \end{cases} \qquad L_i = C_i + E_i$$

$$C_i \text{ or } R_i = \frac{\text{< C/R date size / node >} \times \text{<\# of C/R nodes per } S_i^* \text{ >}}{\text{< write perf. (} w_i \text{) > or <read perf. (} r_i \text{) >}}$$

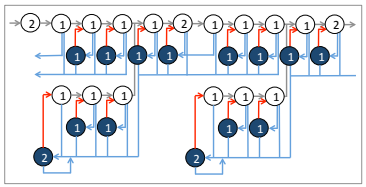
+

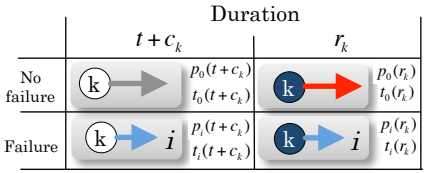
Recursive structured storage model



Storage Model: $H_N\{m_1, m_2, \ldots, m_N\}$

MLC model [2]





t : Interval
c_c : c-level checkpoint time
r_c : c-level recovery time
λ_i : i-level checkpoint time

$$p_0(T) = e^{-\lambda T}$$
$$t_0(T) = T$$
$$p_i(T) = \frac{\lambda_i}{\lambda}(1 - e^{-\lambda T})$$
$$t_i(T) = \frac{1 - (\lambda T + 1) \cdot e^{-\lambda T}}{\lambda \cdot (1 - e^{-\lambda T})}$$

$p_0(T)$: No failure for T seconds
$t_0(T)$: Expected time when $p_0(T)$
$p_i(T)$: i - level failure for T seconds
$t_i(T)$: Expected time when $p_i(T)$

Efficiency

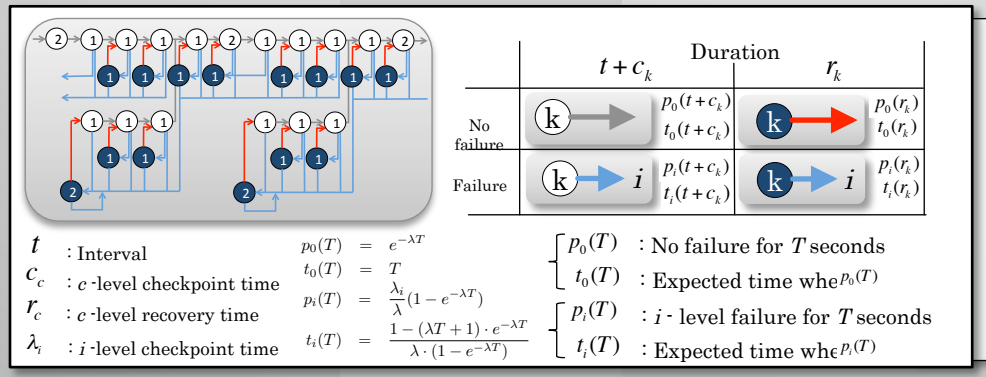
Fraction of time an application spends only in useful computation

[2] Kento Sato, Adam Moody, Kathryn Mohror, Todd Gamblin, Bronis R. de Supinski, Naoya Maruyama and Satoshi Matsuoka, "Design and Modeling of a Non-blocking Checkpointing System", SC12

Multi-level Asynchronous C/R Model [SC12]

- Optimize checkpoint intervals and compute checkpoint/ restart "*Efficiency*" using Markov model
  - Vertex: Compute state OR Checkpointing state OR Recovery state
  - Edge: Completion of each state

$$L_{i=1\ldots N} \quad O_{i=1\ldots N} \quad R_{i=1\ldots N} \quad F_{i=1\ldots N}$$



- Input: Each level of
  - L_i : Checkpoint Latency
  - O_i : Checkpoint overhead
  - R_i : Restart time
  - F_i : Failure rate
- Output: *"Efficiency"*

Efficiency

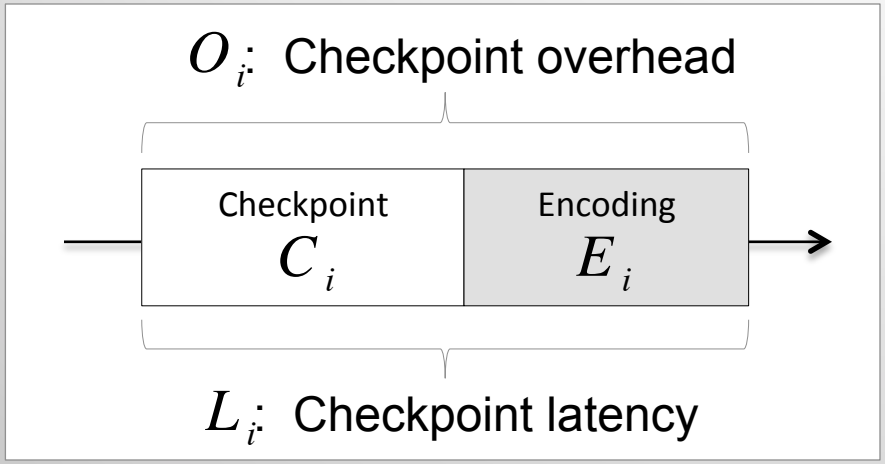
Efficiency

Fraction of time an application spends only in computation in optimal checkpoint interval

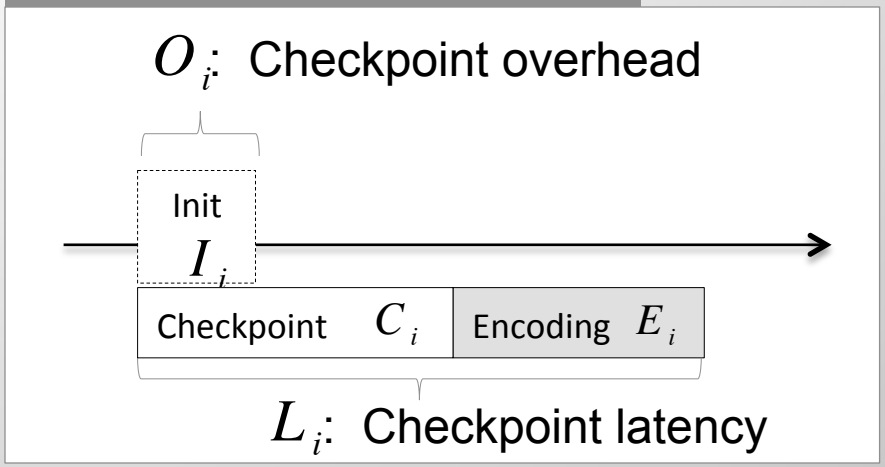
[2] Kento Sato, Adam Moody, Kathryn Mohror, Todd Gamblin, Bronis R. de Supinski, Naoya Maruyama and Satoshi Matsuoka, "Design and Modeling of a Non-blocking Checkpointing System", SC12

Modeling of C/R Strategies

Synchronous checkpointing (Diskless C/R)



Asynchronous checkpointing (PFS)



- L_i : Checkpoint Latency
  - Time to complete a checkpoint (C_i) and encoding (E_i)

$$L_i = C_i + E_i$$

- O_i : Checkpoint overhead
  - The increased execution time of an application

$$O_i = \begin{cases} C_i + E_i & \text{(Sync.)} \\ I_i & \text{(Async.)} \end{cases}$$

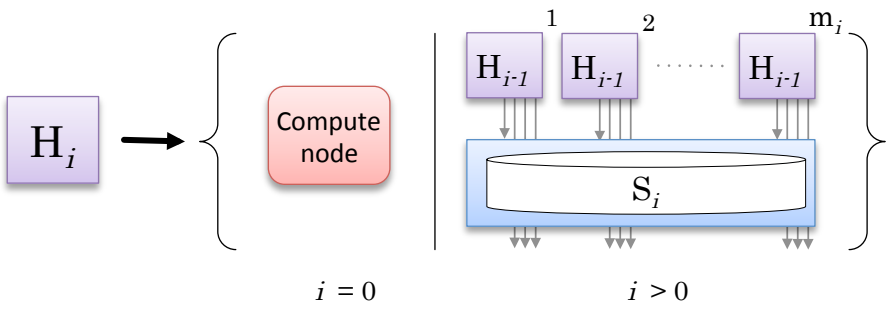
- C_i & R_i : Checkpoint/Restart time

$$C_i \text{ or } R_i = \frac{\text{< C/R data size / node >} \times \text{<\# of C/R nodes per } S_i^* \text{>}}{\text{< write perf. (} w_i \text{) > or <read perf. (} r_i \text{) >}}$$

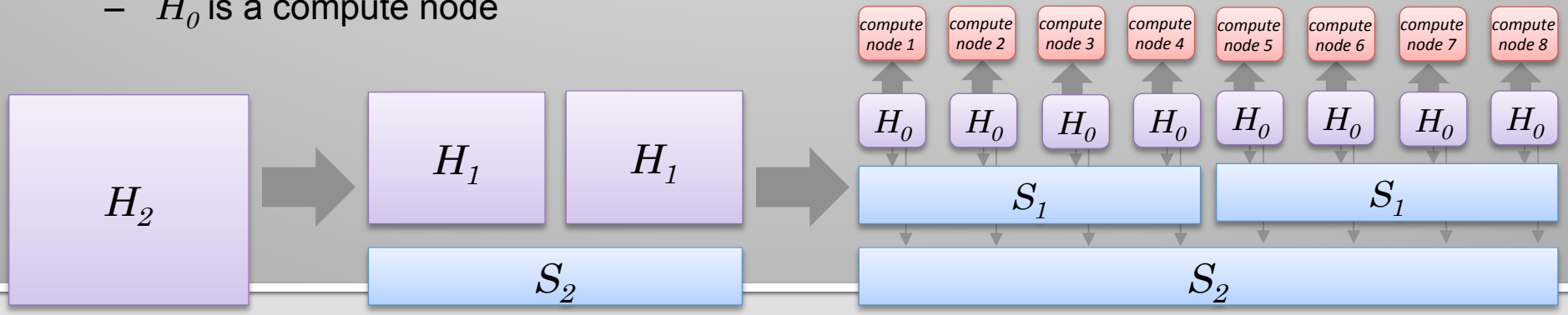
Recursive Structured Storage Model

- Generalization of storage architectures with "*context-free grammar*"
  - A tier i hierarchical entity (H_i), has a storage (S_i)shared by (m_i) upper hierarchical entities (H_{i-1})
  - $H_{i=0}$ is a compute node
  - $H_N\{m_1, m_2, \ldots, m_N\}$

Recursive structured storage model



- e.g.) $H_2\{4, 2\}$
  - H_2 has an S_2 shared by 2 H_1
  - H_1 has an S_1 shared by 4 H_0
  - H_0 is a compute node



Recursive Structured Storage Model (cont'd)

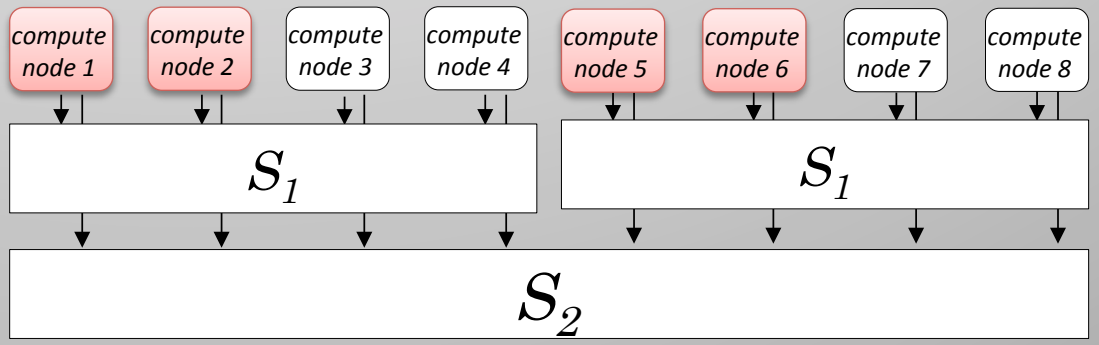
- The number of nodes accessing to S_i

$$\text{<\# of C/R nodes per } S_i\text{>} = \frac{K}{\text{<\# of } S_i\text{>}}$$

$$\text{<\# of } S_i\text{>} = \begin{cases} \Pi^{N}_{k=i+1} m_k & (i < N) \\ 1 & (i = N) \end{cases}$$

K : C/R cluster size

- e.g.) $K = 4$
  - # of C/R nodes per S_1
    - 4/2 = 2 nodes
  - # of C/R nodes per S_2
    - *4/1 = 4* nodes



Evaluation

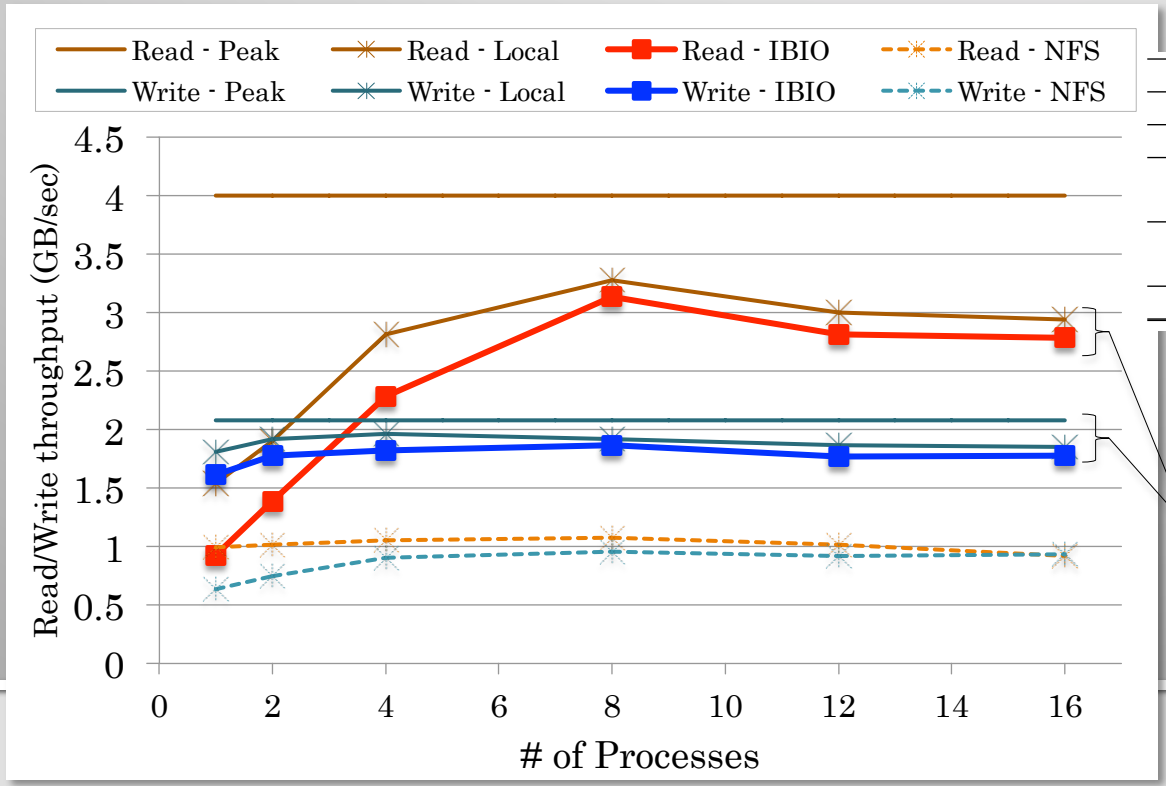
- IBIO performance
- Simulation

Sequential IBIO read/write performance

- Set chunk size to 64MB for both IBIO and NFS to maximize the throughputs

mSATA × 8
(Read: 500MB/s,
Write: 260MB/s)

Adaptec RAID × 1



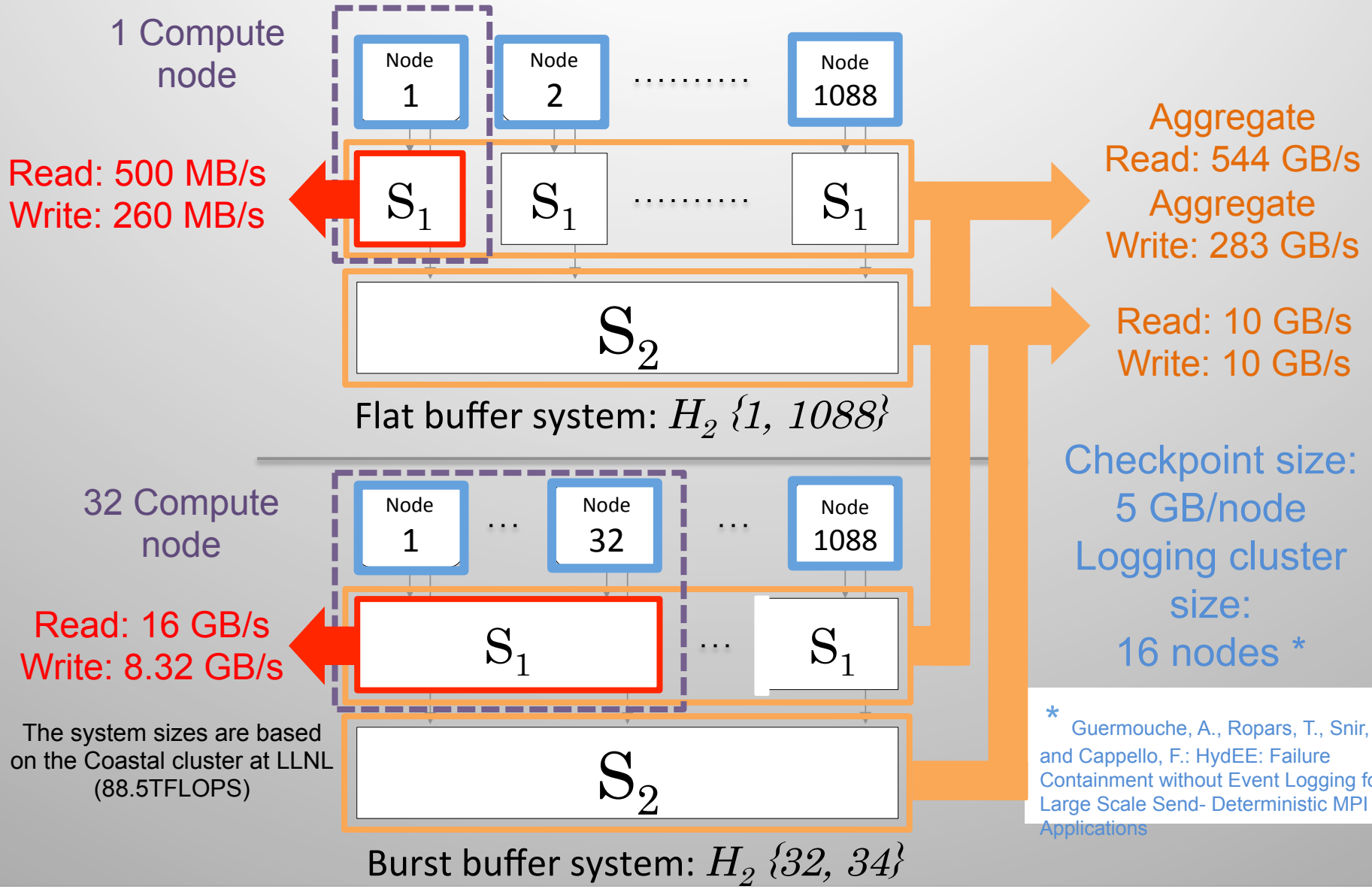
Node specification

CPU	Intel Core i7-3770K CPU (3.50GHz x 4 cores)
Memory	Cetus DDR3-1600 (16GB)
M/B	GIGABYTE GA-Z77X-UD5H
SSD	Crucial m4 msata 256GB CT256M4SSD3 (Peak read: 500MB/s, Peak write: 260MB/s)
SATA converter	KOUTECH IO-ASS110 mSATA to 2.5' SATA Device Converter with Metal Fram
RAID Card	Adaptec RAID 7805Q ASR-7805Q Single

Interconnect :Mellanox FDR HCA (Model No.: MCX354A-FCBT)

IBIO achieve the same remote read/write performance as the local read/write performance by using RDMA

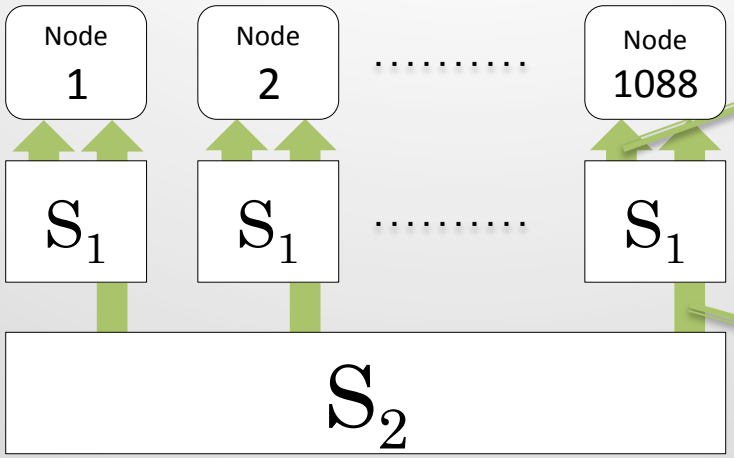
Experimental setup



The system sizes are based on the Coastal cluster at LLNL (88.5TFLOPS)

* Guermouche, A., Ropars, T., Snir, M. and Cappello, F.: HydEE: Failure Containment without Event Logging for Large Scale Send- Deterministic MPI Applications

Experimental setup



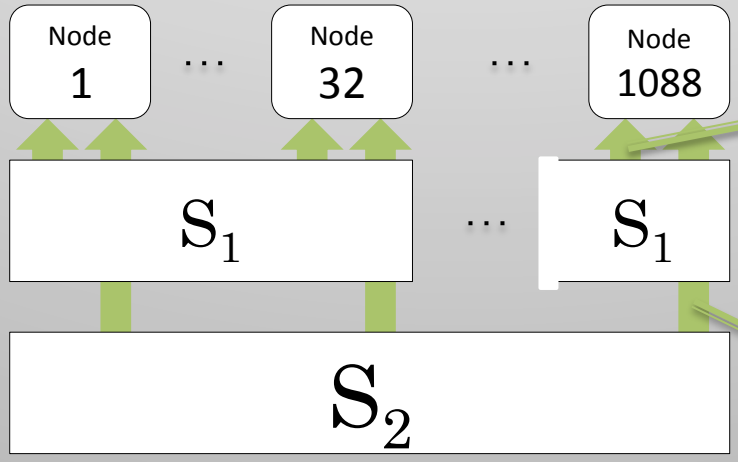
Level 1
(XOR checkpoint required)
2.14×10^{-6}

Level 2
(PFS checkpoint required)
4.28×10^{-7}

Flat buffer system: $H_2\{1, 1088\}$

Estimated failure rates are based on failure analysis on the Coastal cluster at LLNL (88.5TFLOPS) [1]

[1] A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System (SC 10)



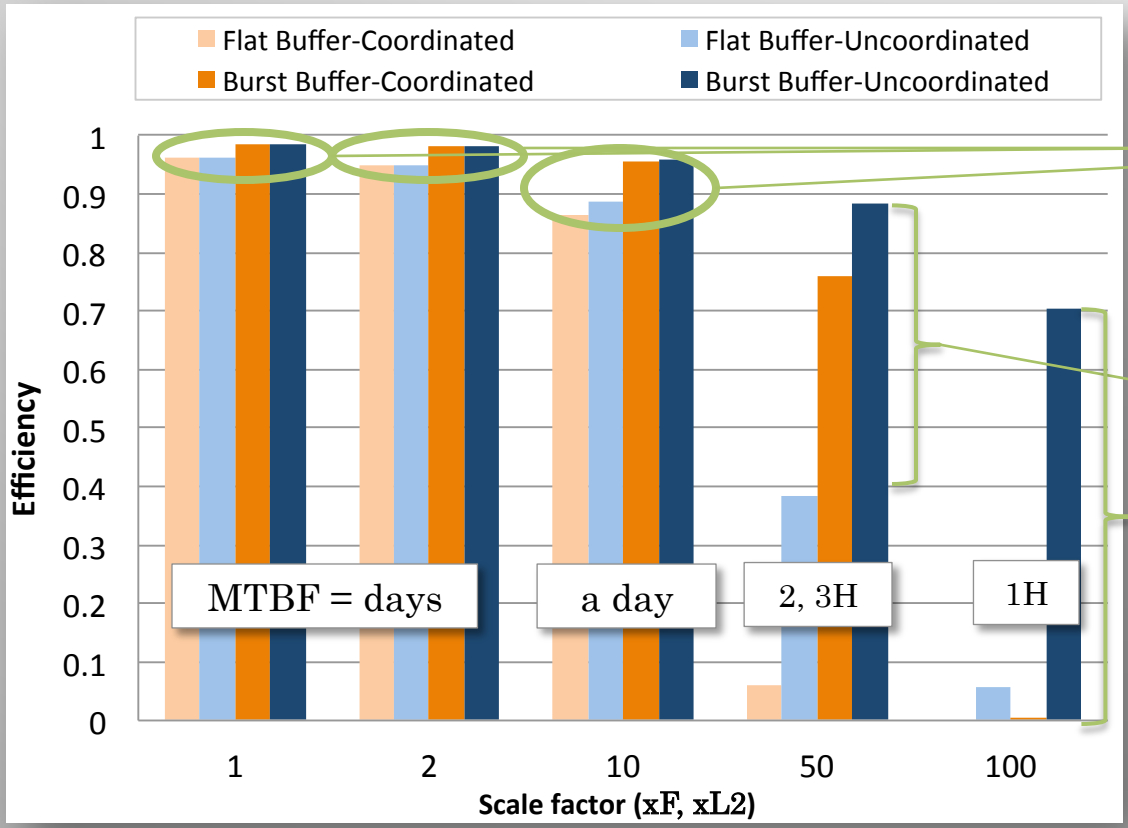
Level 1
(XOR checkpoint required)
2.63×10^{-6}

Level 2
(PFS checkpoint required)
1.33×10^{-8}

Burst buffer system: $H_2\{32, 34\}$

Efficiency with Increasing Failure Rates and Checkpoint Costs

- Assuming there is no message logging overhead



In days or a day of MTBF, there is no big efficiency differences

In a few hours of MTBF, with burst buffers, systems can still achieve high efficiency

Even in a hour of MTBF, with uncoordinated, systems can still achieve 70% efficiency

⇒ Partial restart accelerate recovery time from burst buffers and PFS checkpoint

Allowable Message Logging overhead

Message logging overhead allowed in uncoordinated checkpointing to achieve a higher efficiency than coordinated checkpointing

Flat buffer		Burst buffer	
scale factor	Allowable message logging overhead	scale factor	Allowable message logging overhead
1	0.0232%	1	0.00435%
2	0.0929%	2	0.0175%
10	2.45%	10	0.468%
50	84.5%	50	42.0%
100	≈ 100	100	99.9%

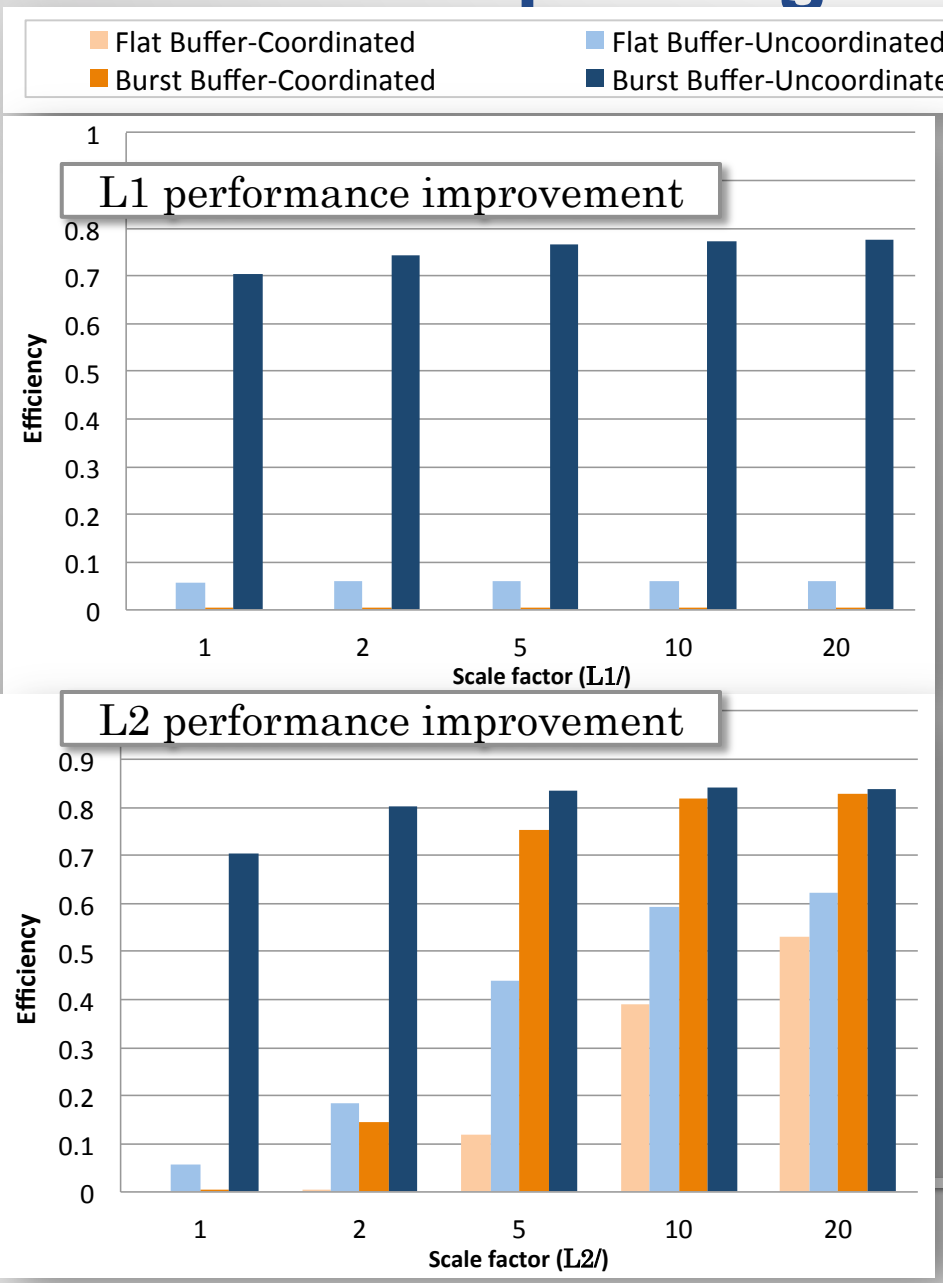
Coordinated

Uncoordinated

- Logging overhead must be relatively small, less than a few percent in days or a day of MTBF
  - In a few hours or a hour, very high message logging overheads are tolerated

⇒ Uncoordinated checkpointing can be more effective on future systems

Effect of Improving Storage Performance



To see which storage impact to efficiency, we increase performance of level-1 and level-2 storage while keeping MTBF a hour

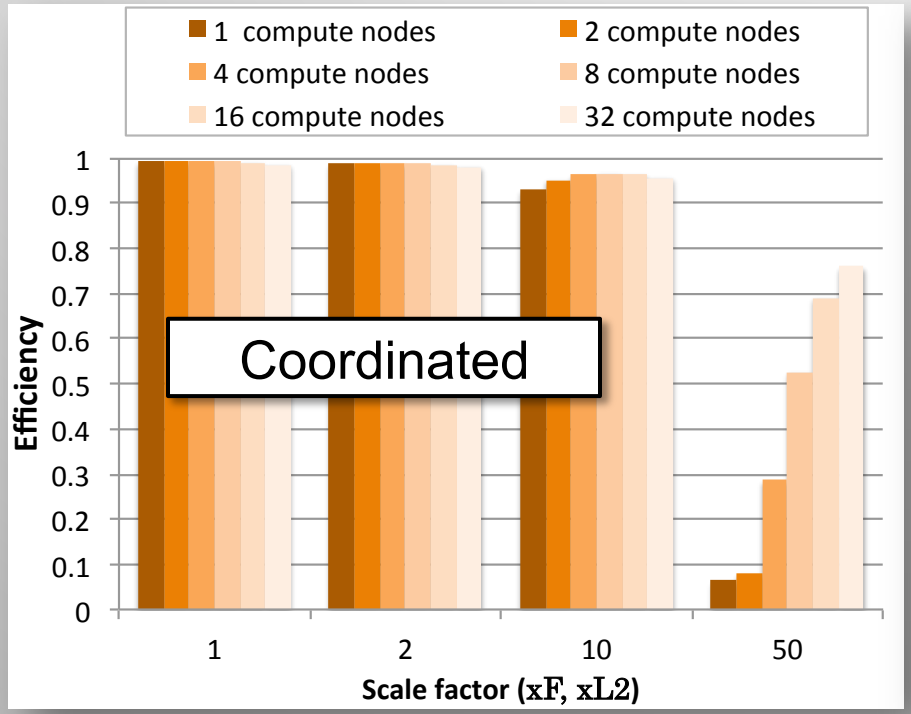
Improvement of level-1 storage performance does not impact efficiency for both flat buffer and burst buffer systems

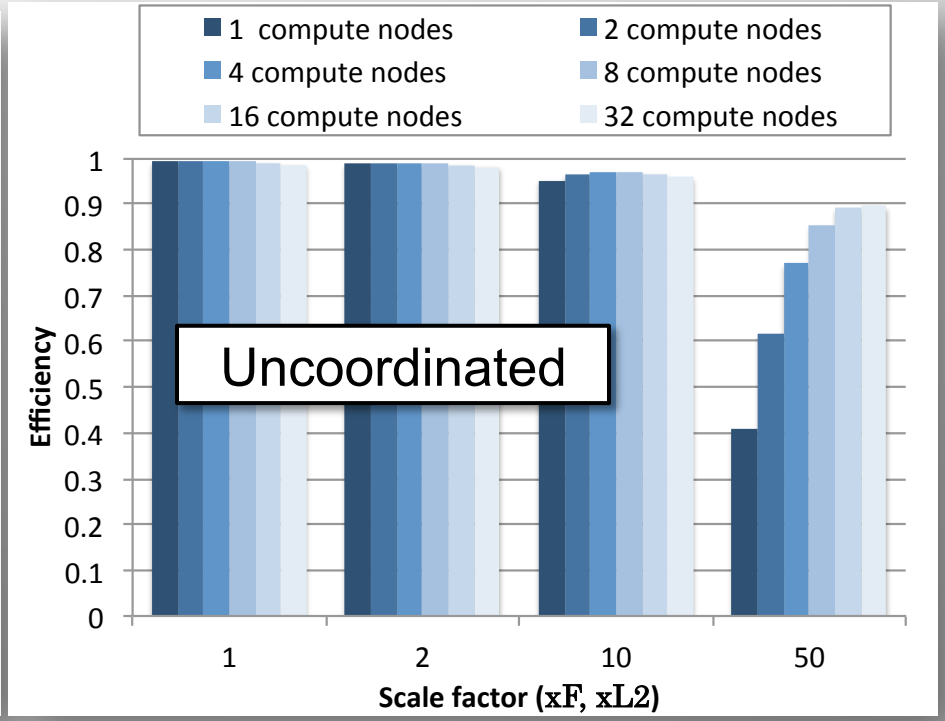
Increasing the performance of the PFS does impact system efficiency

L2 C/R overhead is a major cause of degrading efficiency, so reducing level-2 failure rate and improving level-2 C/R is critical on future systems

Ratio of Compute nodes to Burst Buffer nodes

Another thing to consider when building a burst buffer system is the ratio of compute nodes to burst buffer nodes





- The ratio is not important matter when MTBF is from a day to days
- When MTBF is a few hours, a larger number of burst buffer nodes decreases efficiency

  ⇒ Adding additional burst buffer nodes increases the failure rate which degrades system efficiency more than the efficiency gained by the increased bandwidth

Towards resilient extreme scale computing

1. Burst buffers
   - Burst buffers are beneficial for C/R at extreme scale

2. Uncoordinated C/R
   - When MTBF is days or a day, uncoordinated C/R may not be effective
   - If MTBF is a few hours or less, will be effective

3. Level-2 failure, and Level-2 performance
   - Reducing Level-2 failure and increasing Level-2 performance are critical to improve overall system efficiency

4. Fewer number of burst buffers
   - Adding additional burst buffer nodes increases the failure rate
   - May degrades system efficiency more than the efficiency gained by the increased bandwidth
   - We need to be careful a trade-off between I/O performance and reliability of burst buffers

Conclusion

- Fault tolerance is critical at extreme scale
  - Both C/R strategy and storage design are important
- We developed IBIO to maximize remote access to burst buffers, and modeled C/R strategy and storage design
- We listed up key factors to build resilient systems based on our evaluations
- We expect our findings can benefit system designers to create efficient and cost-effective systems

NEEDS FOR REDUCTION IN CHECKPOINT TIME

Checkpoint/Restart

→Store the data of memory in the disk

→High I/O cost

On TSUBAME2.5
Memory capacity：about 100TB
I/O throughput：about 20GB/s
↓
Checkpoint time：about 80min

Reduce MTBF(Mean Time Between Failure) by expansion in scale of HPC systems

- MTBF is over 30min by trial calculation On a exascale computer [※1]

If MTBF < Checkpoint time
Application may not be able to run !
↓
Needs for reduction in checkpoint time !

There are methods of reduction in checkpoint cost, incremental checkpoint etc., but we compress checkpoint

※1 : Peter Kogge, Editor & Study Lead (2008)
ExaScale Computing Study: Technology Challenges in Achieving ExaScale Systems

LOSSLESS AND LOSSY COMPRESSION

Features of lossless

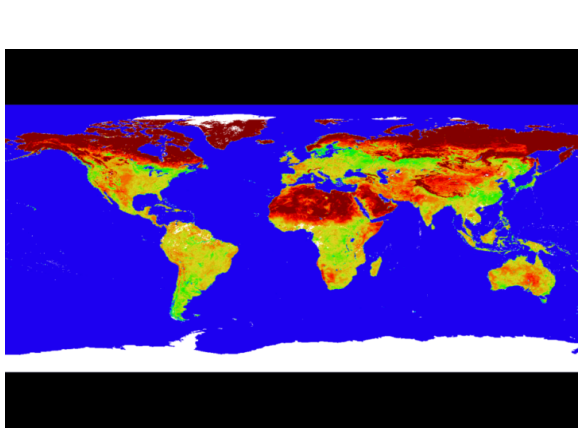
- Decompress a data without a loss
- Low compression rate without bias
  - Scientific data has a randomness

Features of lossy

- High compression rate
- introduce an error

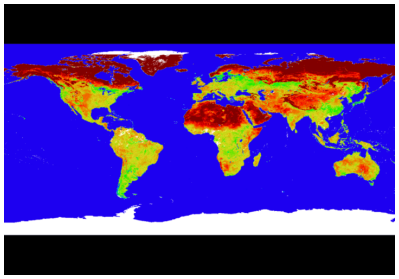
About introducing an error

- Possibility of getting equal quality result with introducing an error
- Don't apply lossy compression to a data that must not have an error(pointer etc.)



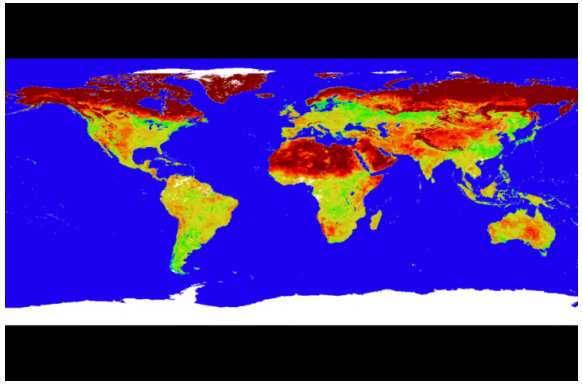
gzip 2.19MB

1/7



original 14.7MB

1/100

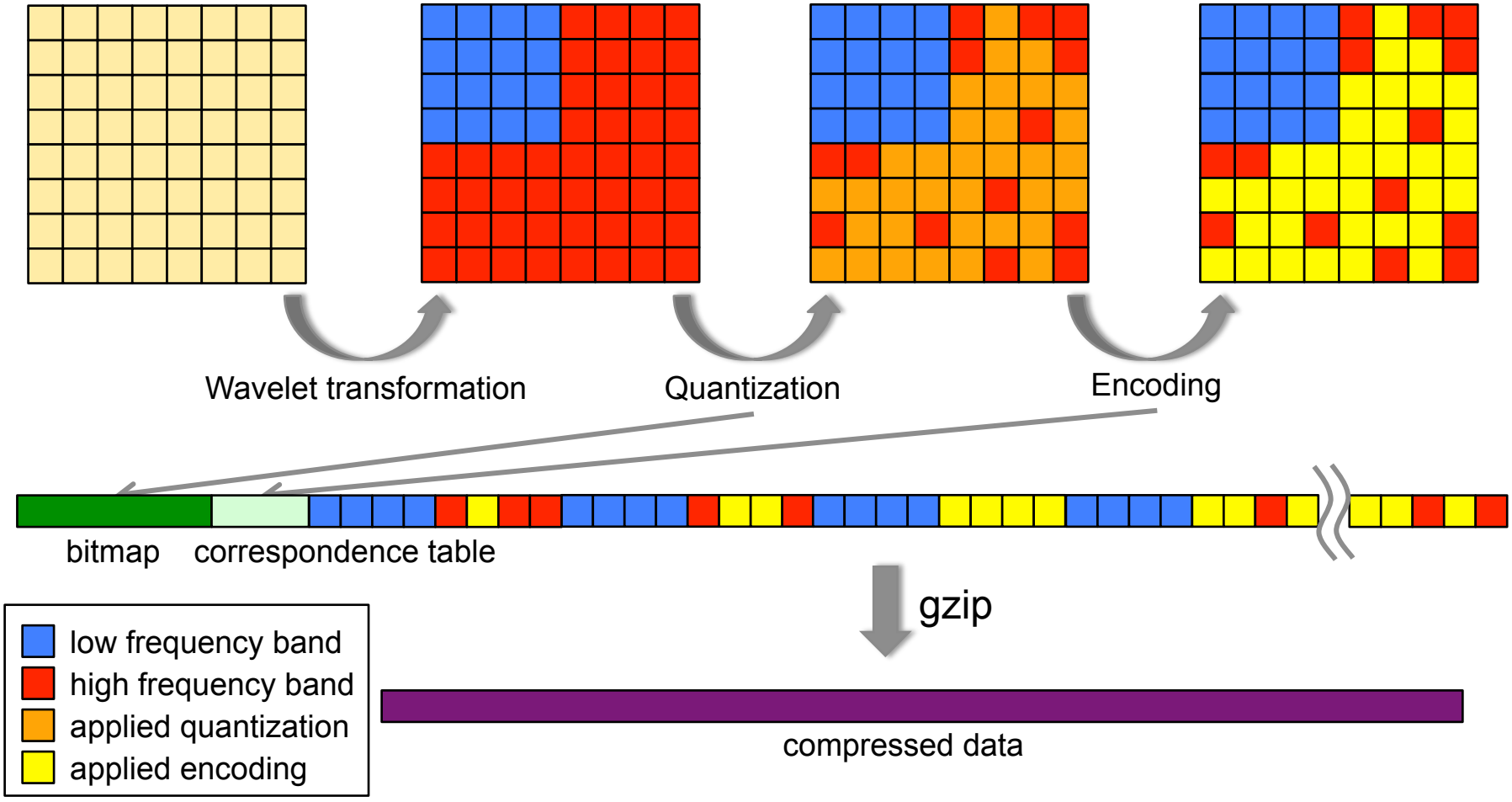


jpeg2000 0.153MB

(citation of images : http://svs.gsfc.nasa.gov/vis/a000000/a002400/a002478/)

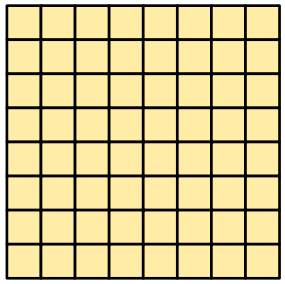
PROPOSAL APPROACH: LOSSY COMPRESSION WITH WAVELET

We apply wavelet transformation, quantization and encoding to a target data, then compress a data that is stored in proposal output format with *gzip*

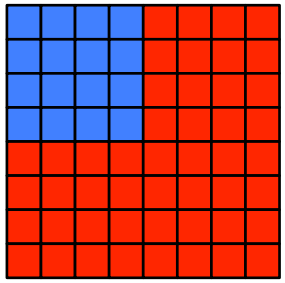


PROPOSAL APPROACH: LOSSY COMPRESSION WITH WAVELET

Wavelet transformation

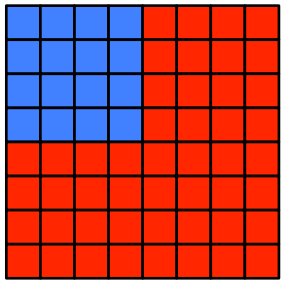


Divide original data into two subbands

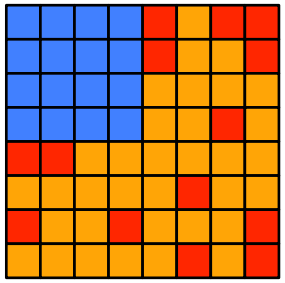


- use average
- use difference (most of these is close to zero)

Quantization

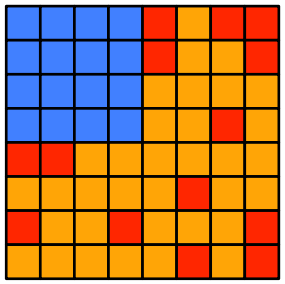


Round the *red values* into *n* kind of values

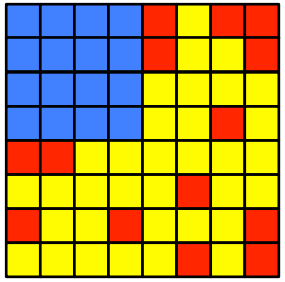


- *n* kind of values ($n = 2^0 \sim 2^7$)

Encoding



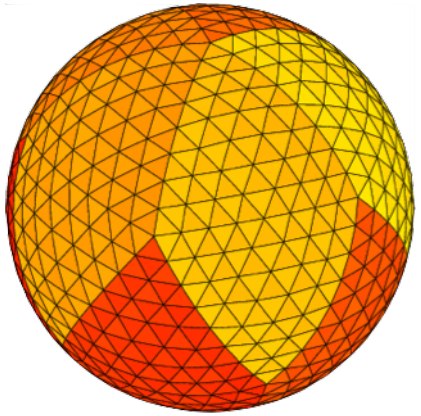
Store the *float, double* value to *char value*



- Data size reduces to 1/4 or 1/8 at this point

EVALUATION ENVIRONMENT

We apply our approach to climate simulation NICAM[M.Satoh, 2008]



- Target physical quantity are pressure, temperature and velocity.
  - 3Darray, double precision, 1156*82*2
- The data is uniform in initial state

→apply the method after 720 step from initial state?

We evaluate compression time and rate and error, while changing the number of division ($2^0 \sim 2^7$)

Machine spec

CPU	Intel Core i7-3930K 6 cores 3.20GHz
Memory size	16GB

(citation of image : HPCS2014 全球大気シミュレーションにおいて、どこまで解像度が必要か？)

EVALUATION OF COMPRESSION TIME

An assumption about compression time

- I/O throughput…20GB/s
- Checkpoint size that each process has…about 1.5MB

→Total checkpoint size…about (1.5 × # of parallelism)MB

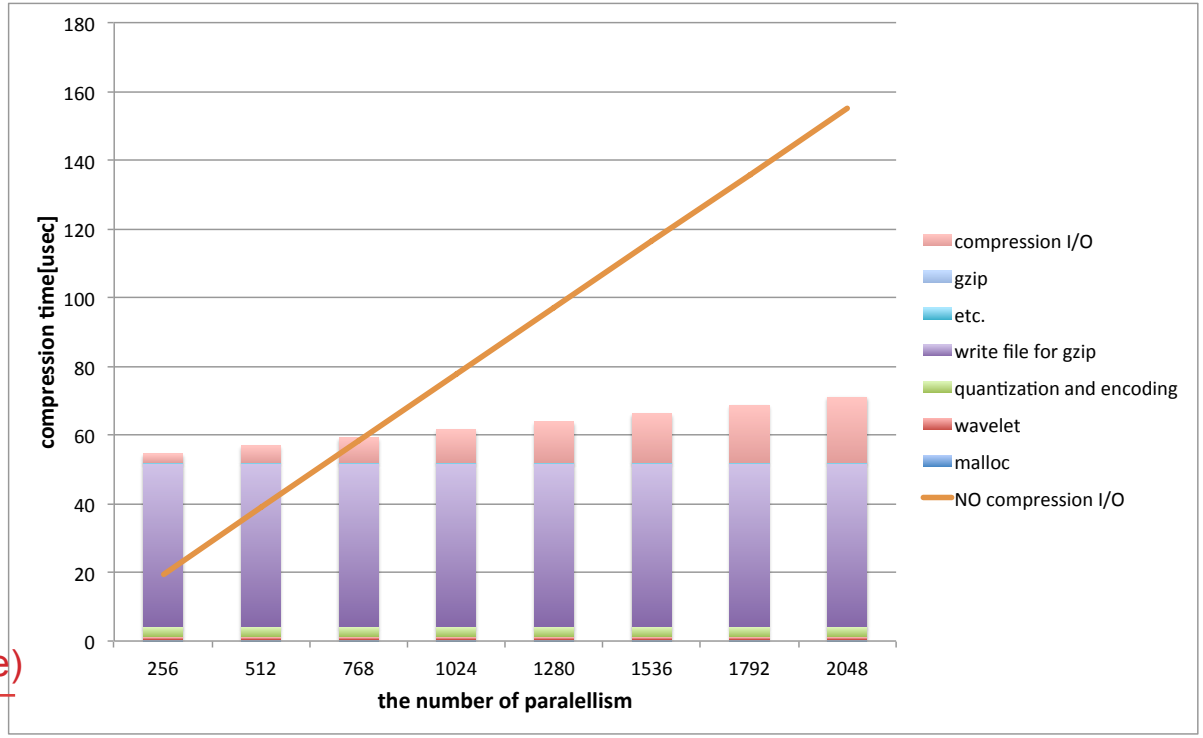
Actual survey

- Compression time
- Compression rate

Calculation from assumption

- I/O time

$$\frac{\text{Total checkpoint size}(\times\text{compression rate})}{\text{I/O Throughput}}$$



EVALUATION OF COMPRESSION TIME

An assumption about compression time

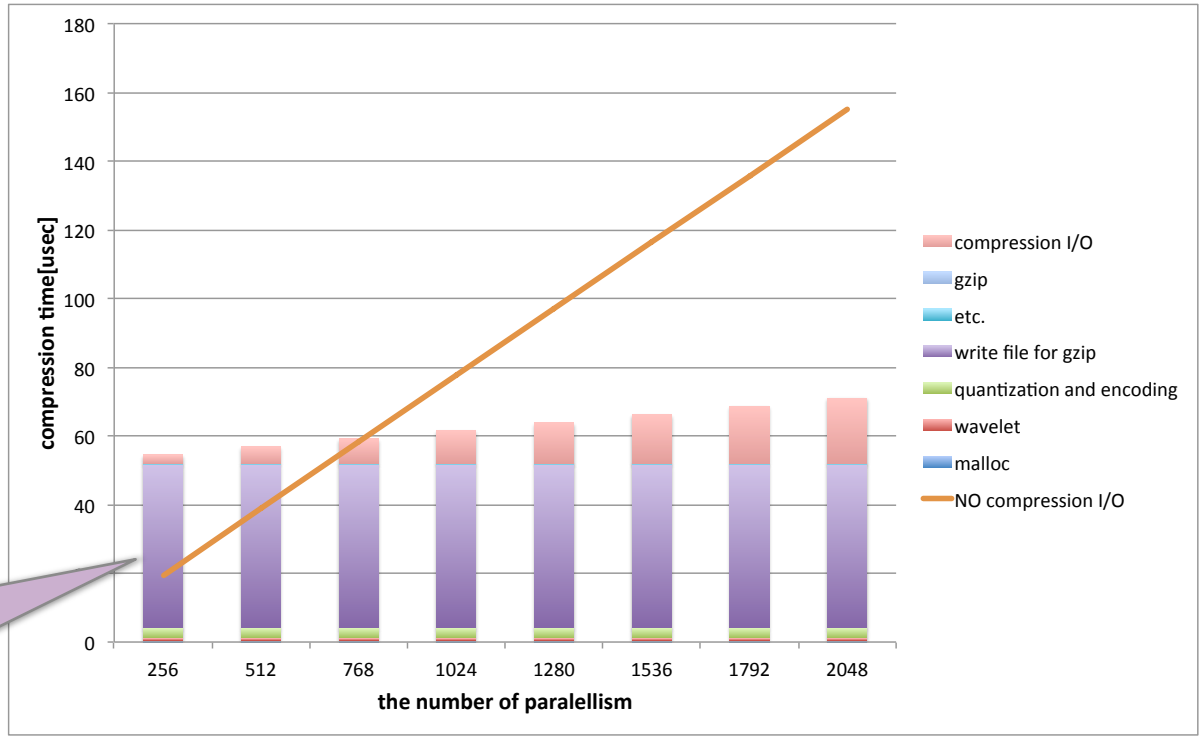
- I/O throughput…20GB/s
- Checkpoint size that each process has…about 1.5MB

  →Total checkpoint size…about (1.5 × # of parallelism)MB

Problems of gzip

- Computational complecity
- Needs for writing files

Write time can be cut if we apply gzip to the data internally



EVALUATION OF COMPRESSION TIME

I/O time reduces by about 70%, if compression time is negligible by increasing # of parallelism

An assumption about compression time

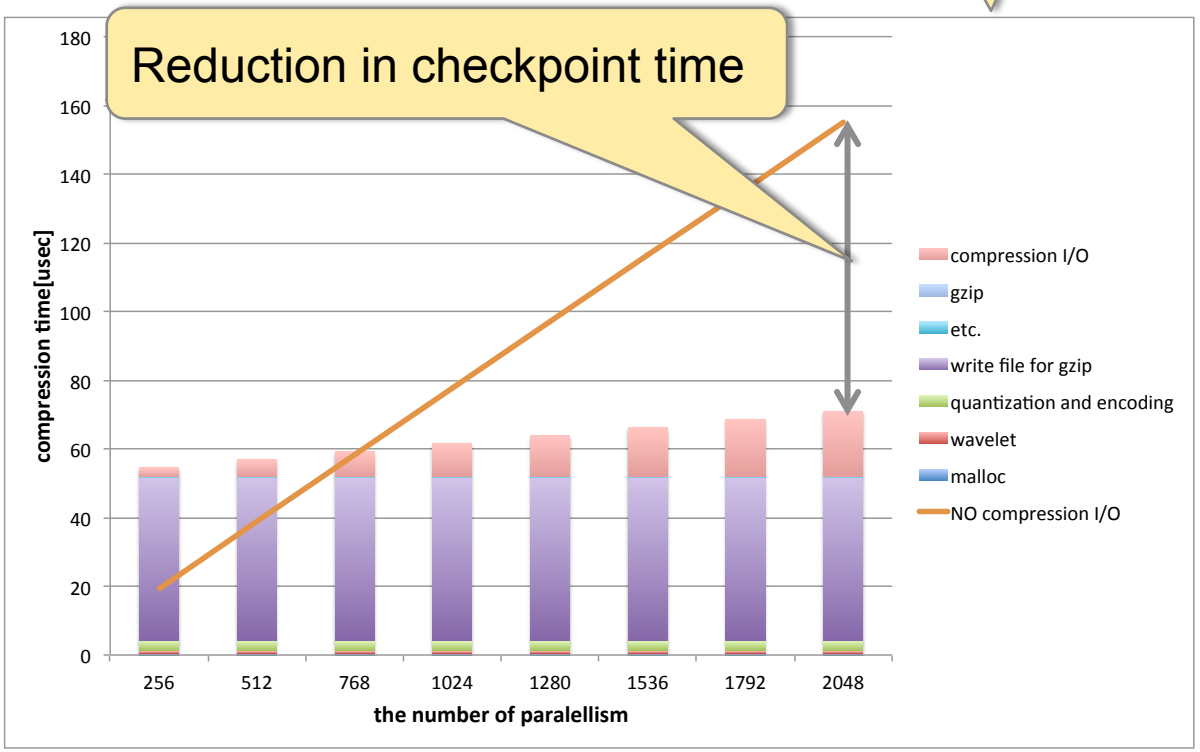
- I/O throughput…20GB/s
- Checkpoint size that each process has…about 1.5MB

→Total checkpoint size…about (1.5 × # of parallelism)MB

Each process compress 1.5MB data in spite of # of parallelism

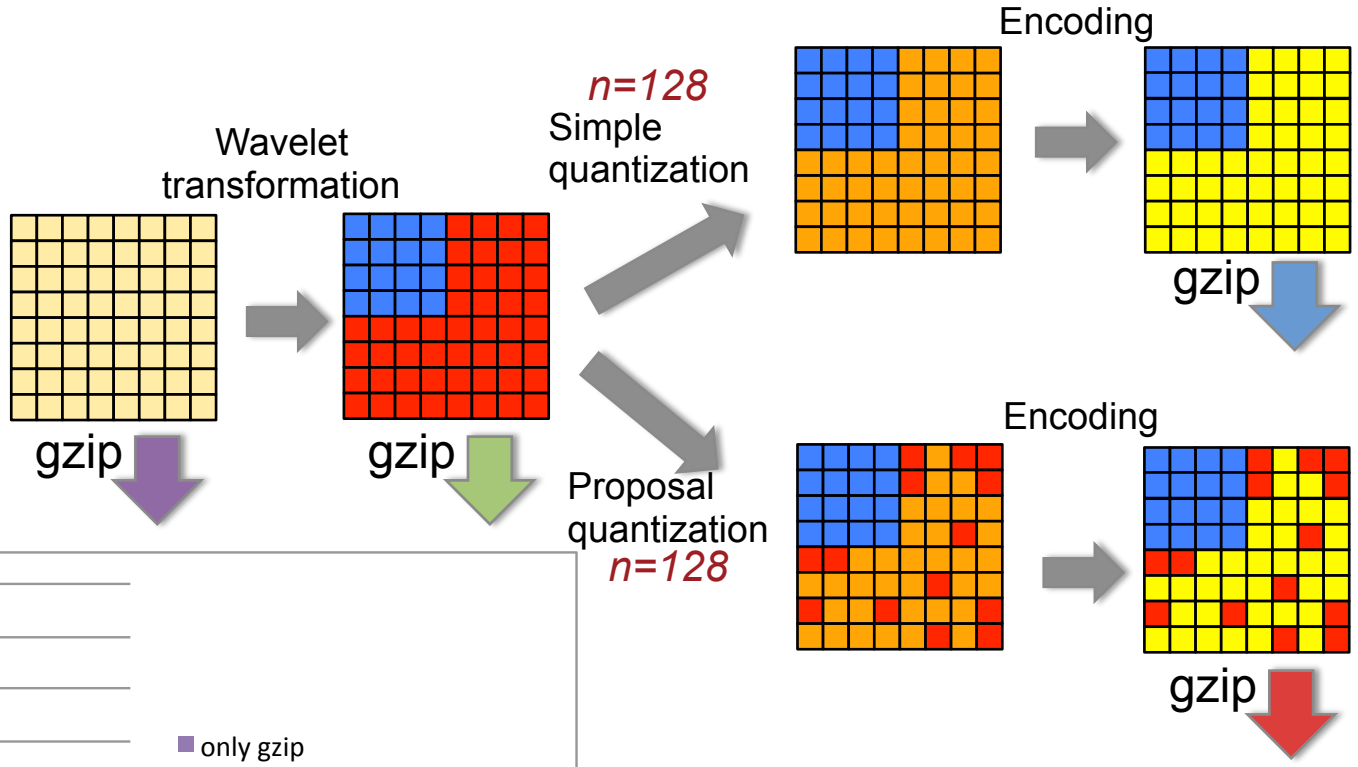
- Compression time is constant
- I/O time depends on total checkpoint size

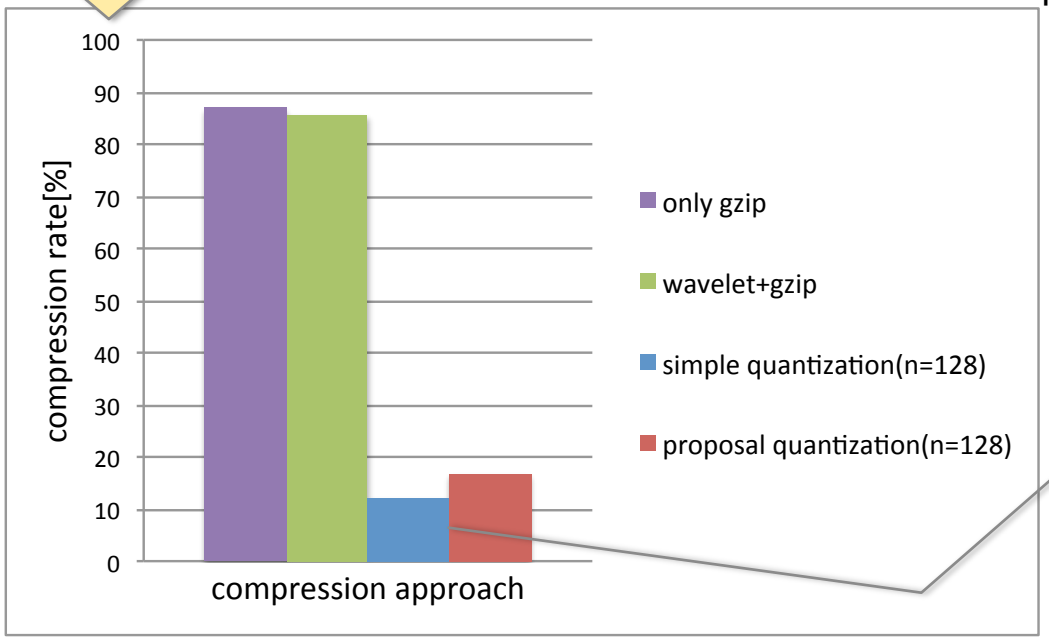
Our approach takes advantage when # of parallelism increases



COMPARISON TO WITHOUT OUR APPROACH

In comparison with only gzip, our approach reduces checkpoint size by 75%





Simple quantization achieves better compression rate, but larger error than proposal quantization

EVALUATION OF ERROR

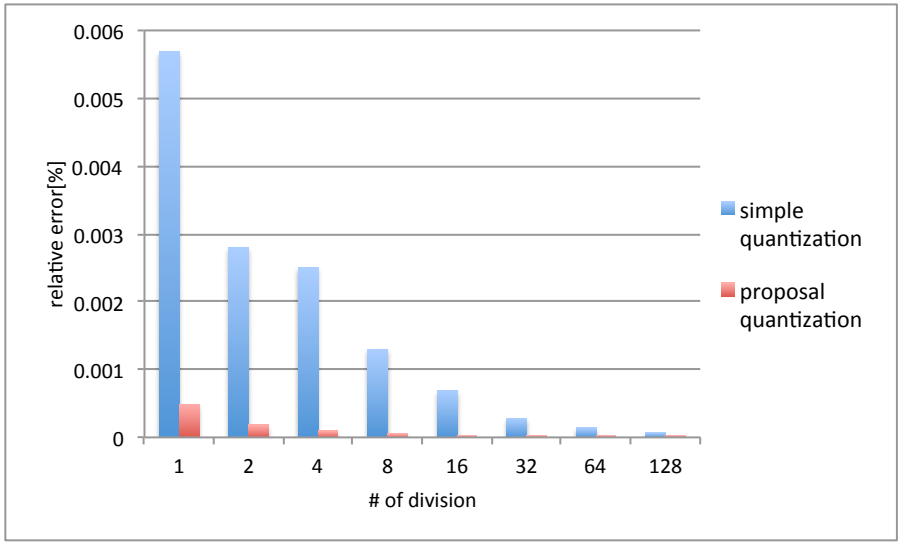
$$RE_i = \frac{x_i - \tilde{x}_i}{\max_j \{x_j\} - \min_j \{x_j\}}$$

Reduce an error with # of division(*n*) increasing

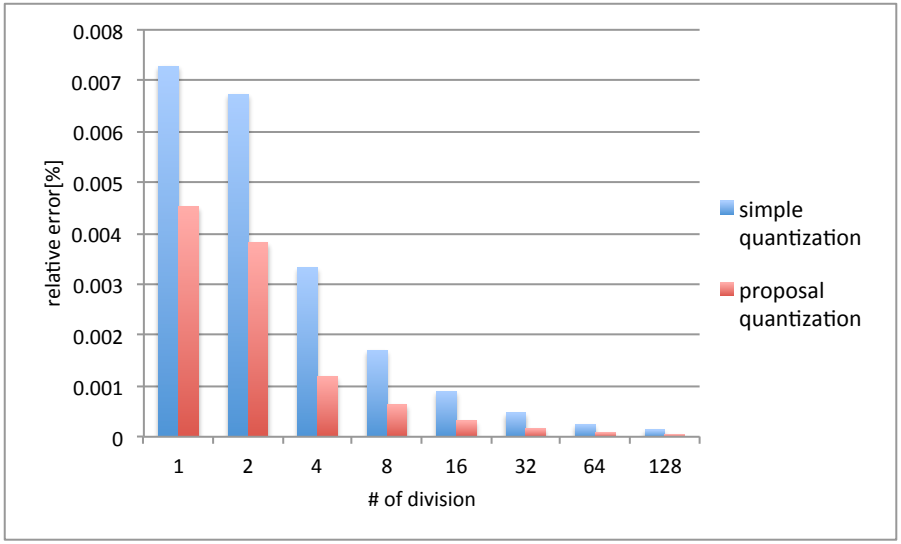
- An error reduce by about 98% at *n* = 128 compared to *n* = 1

Our quantization reduce an error in comparison with simple one

- A degree of reduction of an error is different depending on arrays



An average error on pressure array



An average error on temperature error

On all variables, maximum error is within 5%

Summary

- Resilience APIs
  - Resilient APIs in MPI is critical for fast and transparent recovery in HPC applications
- Resilient Architecture
  - Burst buffers Burst buffers are beneficial for C/R at extreme scale
  - Uncoordinated C/R
    - When MTBF is days or a day, uncoordinated C/R may not be effective
    - If MTBF is a few hours or less, will be effective
  - Level-2 failure, and Level-2 performance
    - Reducing Level-2 failure and increasing Level-2 performance are critical to improve overall system efficiency
  - Fewer number of burst buffers
    - Adding additional burst buffer nodes increases the failure rate
    - May degrades system efficiency more than the efficiency gained by the increased bandwidth
    - We need to be careful a trade-off between I/O performance and reliability of burst buffers
- Lossy data compression
  - Preliminary, but promising

Q & A

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Naoya Maruyama, RIKEN AICS


Lawrence Livermore
National Laboratory

Limitation and Future support

- FMI is an on-going project, several limitations exist

- Limited MPI functions
  - The current FMI implementation only supports a subset of MPI functions.
  - e.g.) MPI_IO

- C/R of communicators
  - Several applications dynamically split a communicator in order to balance the workloads across processes
  - Such applications change not only application state but also communicator state over the iterations

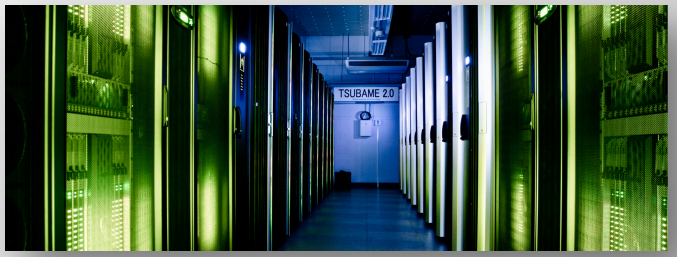
- Multi-level C/R
  - Future versions of FMI will support multilevel C/R to be able to recover from any failures occurring on HPC systems.

Failures on HPC systems

Scientific discovery

Supercomputers enable larger and higher-fidelity simulations by communication libraries

The TSUBAME supercomputer



System failure

TSUBAME2.0 experienced 962 node failures for 1.5 years (MTBF = 13 hours)

TSUBAME MTBF

Failure type	MTBF
PFS, Core switch	65.10 days
Rack	86.90 days
Edge switch	17.37 days
PSU	28.94 days
Compute node	0.658 days

Failures are already not exceptional but usual events

Goal and Contributions

- Goal:
  - Fast and Transparent recovery for extreme scale computing

- Contributions:
  - We developed Fault Tolerant Messaging Interface (FMI) enabling fast and transparent recovery
  - Experimental results show FMI incurs only a **28% overhead** with a very high **MTBF of 1 minute**

Outline

- Introduction
- Challenges for fast and transparent recovery
- FMI: Fault Tolerant Messaging Interface
  - User perspective
  - Internal implementation
- Evaluation
- Conclusion

Conclusion

- We developed Fault Tolerant Messaging Interface (FMI) for fast and transparent recovery
  - Scalable failure detection
  - Survivable messaging interface
  - Dynamic node allocation
  - Fast checkpoint/restart

- Experimental results show FMI incurs only a **28% overhead** with a very high **MTBF of 1 minute**
  - The result presents good prospect to implement resilience capability on top of other fault tolerant MPIs (e.g. ULFM & NR-MPI)

Evaluations

- Initialization
  - FMI_Init time
- Detection
- Checkpoint/restart
- Benchmark run
- Simulations for extreme scale

Goal and Contributions

- **Goal**:
  - Develop an interface to exploit bandwidth of burst buffers
  - Explore effectiveness of burst buffers
  - Find out the best C/R strategy on burst buffers

- **Contributions**:
  - Development of IBIO exploiting bandwidth to burst buffers
  - A model to evaluate system resiliency given a C/R strategy and storage configuration
  - Our experimental results show a direction to build resilient systems for extreme scale computing

Outlines

- Introduction
- Checkpoint strategies
- Storage designs
- IBIO: InfiniBand-based I/O interface
- Modeling
- Experiments
- Conclusion

Evaluations

- IBIO performance
  - Sequential read/write for C/R
- Several system efficiency evaluations