Design and Modeling of a Non-blocking Checkpointing System

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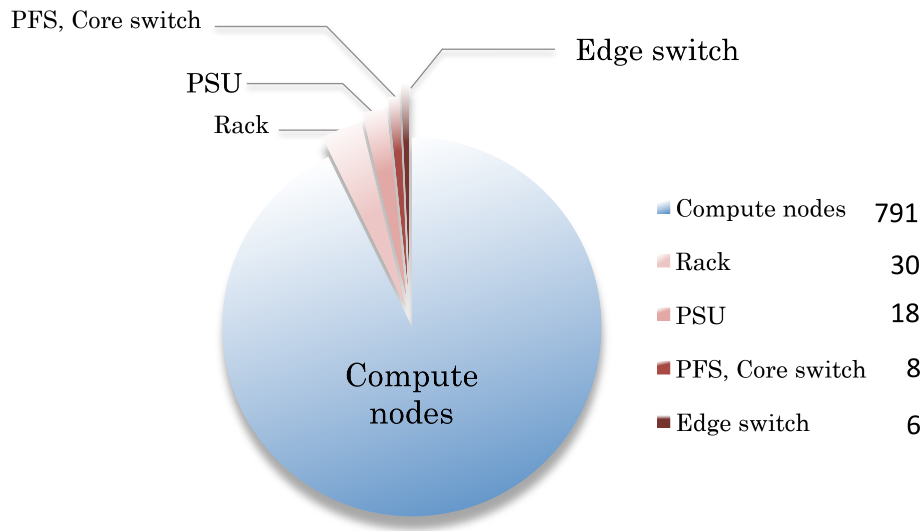
Failures on HPC systems

- Exponential growth in computational power
  - Enables finer grained scientific simulations
- Overall failures rate increases accordingly
  - Due to increasing complexity and system size



Overall MTBF
13 hours

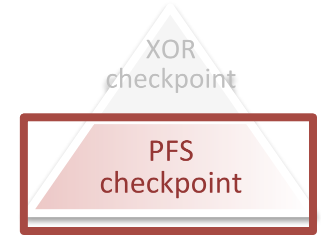
Failure analysis on TSUBAME2.0

Period: 1.5 years (Nov 1st, 2010 ~ April 6th 2012)
Observations: 962 node failures in total

TSUBAME2.0, 14th in Top500 (June 2012)

2.4 PFlops
1442 nodes
2953 CPU sockets
4264 GPUs
197 switches
58 racks

- System resiliency is becoming more important
  - Without a viable resilience strategy, applications can not run for even one day on such a large system



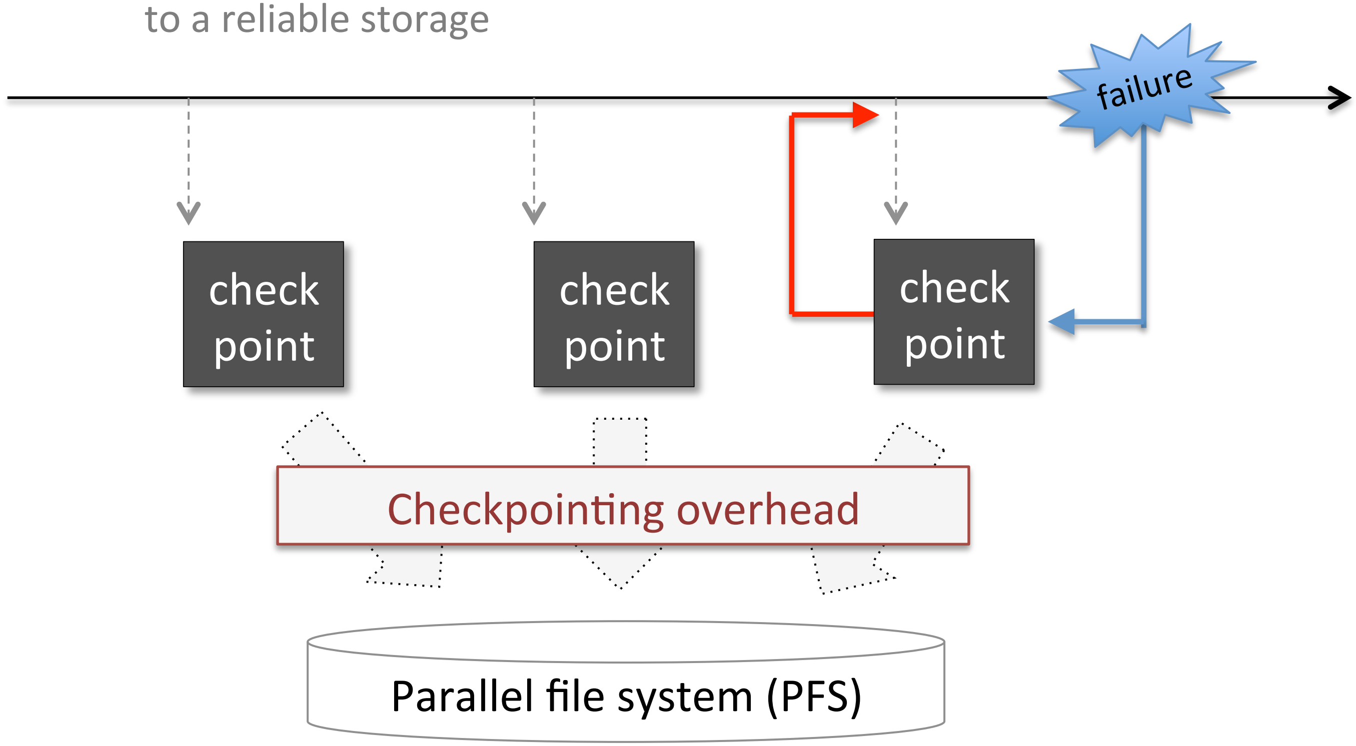
Traditional Checkpoint/Restart

Checkpoint

Periodically save a snapshot of an application state to a reliable storage

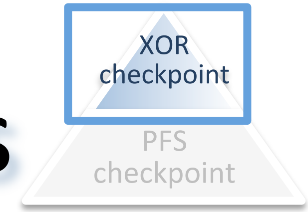
Restart

On a failure, restart the execution from the latest checkpoint

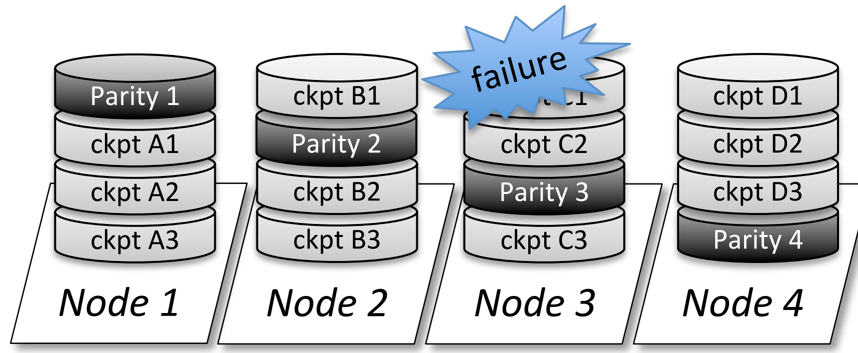


Mostly these checkpoints are stored in the most reliable storage, such as a shared parallel file system(PFS).

Scalable checkpointing methods



- Diskless checkpoint:
  - Create redundant data across local storages on compute nodes using a encoding technique such as XOR
  - Can restore lost checkpoints on a failure caused by small # of nodes like RAID-5

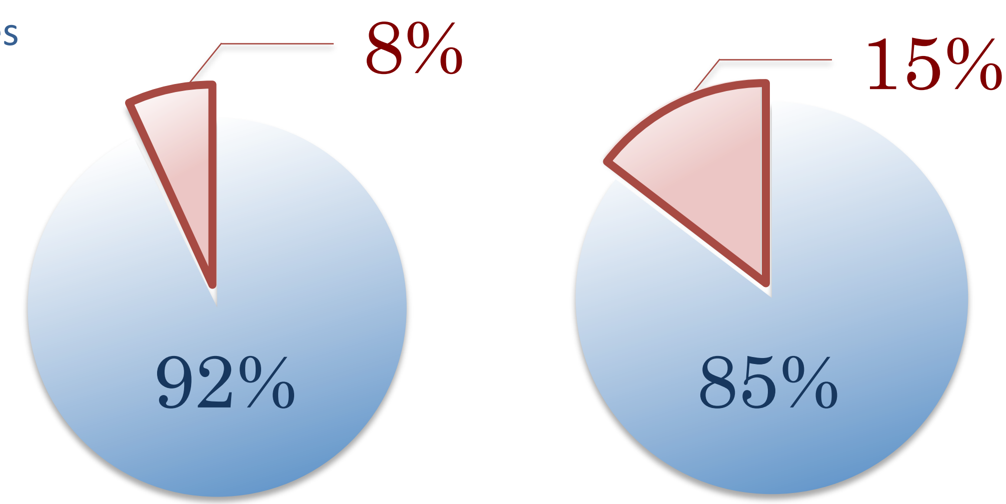


XOR encoding example

- 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

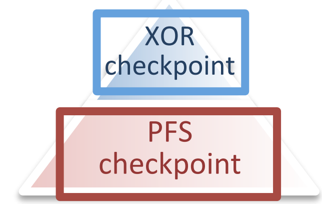
Rest of failures still require a checkpoint on a reliable PFS

LOCAL/XOR/PARTNER checkpoint
PFS checkpoint

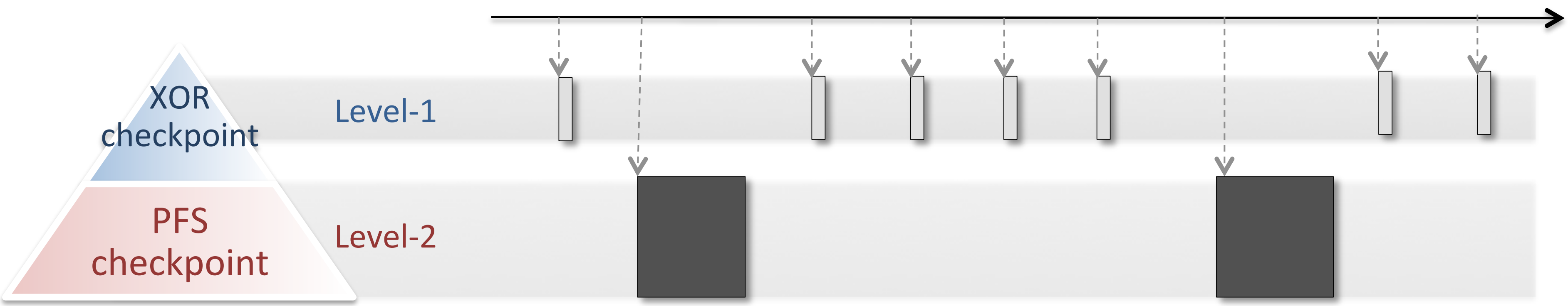


Failure analysis on TSUBAME2.0 Failure analysis on LLNL clusters

Diskless checkpoint is promising approach



Multi-level checkpointing (MLC)



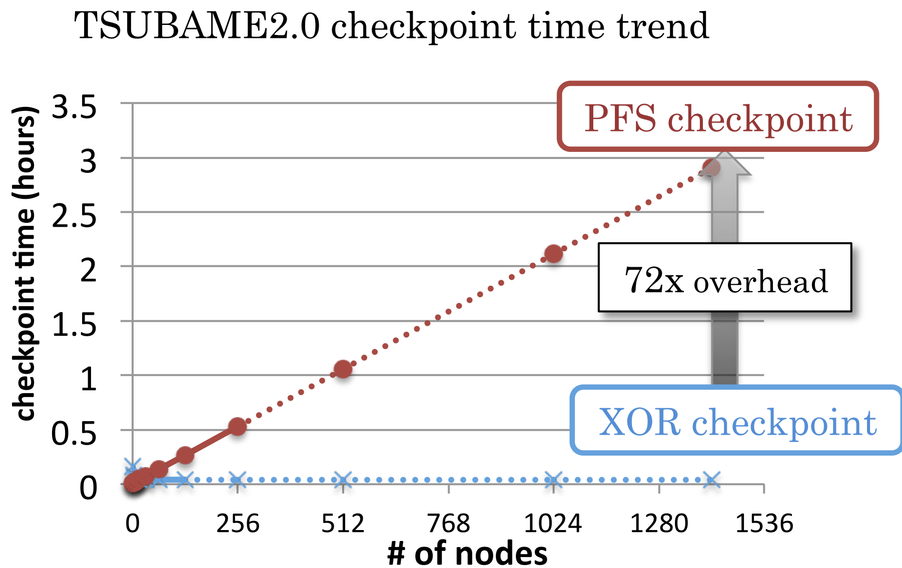
- Use storage levels hierarchically
  - XOR checkpoint: Frequently
    - for one node or a few node failure
  - PFS checkpoint: Less frequently
    - for multi-node failure
- 8x efficiency improvement
  - With MLC implementation called SCR(Scalable Checkpoint/Restart) library developed in LLNL
  - Compared to single-level checkpointing

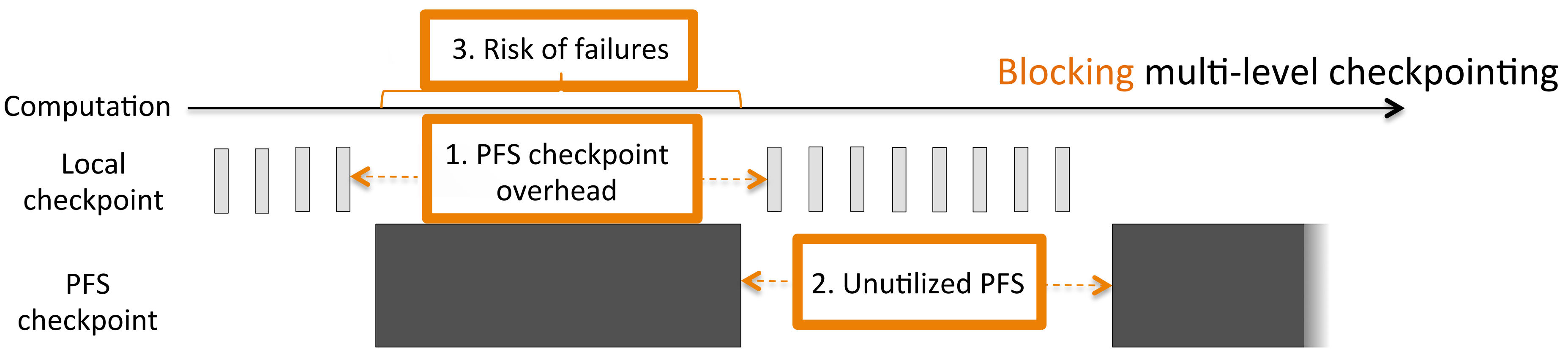
Source: A. Moody, G. Bronevetsky, K. Mohror, and B. R. de Supinski, "Design, Modeling, and Evaluation of a Scalable Multi-level Checkpointing System," in Proceedings of the 2010 ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC 10).

MLC Problems on Petascale or larger

Three potential problems

1. PFS checkpoint overhead
   – Even with MLC, PFS checkpoint still becomes big overhead
2. Inefficient PFS utilization
   – Time between PFS checkpoints becomes long, PFS is not utilized during XOR checkpoints
3. Failure during PFS checkpoint
   – At scale, prolonged PFS checkpointing has a risk of failures during checkpointing





Objective, Proposal and Contributions

- **Objective**: More efficient MLC
  - Minimize PFS checkpoint overhead
  - Improve PFS utilization
  - Reduce a risk of failure during PFS checkpoint

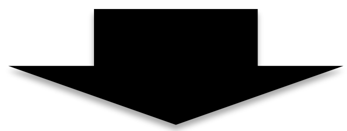
- **Proposal & Contributions**:
  - Developed an non-blocking checkpointing system as an extension for SCR library
    - PFS checkpoint with 0.5 ~ 2.5% overhead
  - Modeled the non-blocking checkpointing
    - Determine optimal multi-level checkpoint configuration
    - 1.1 ~ 1.8x efficiency on current and future systems

Outline

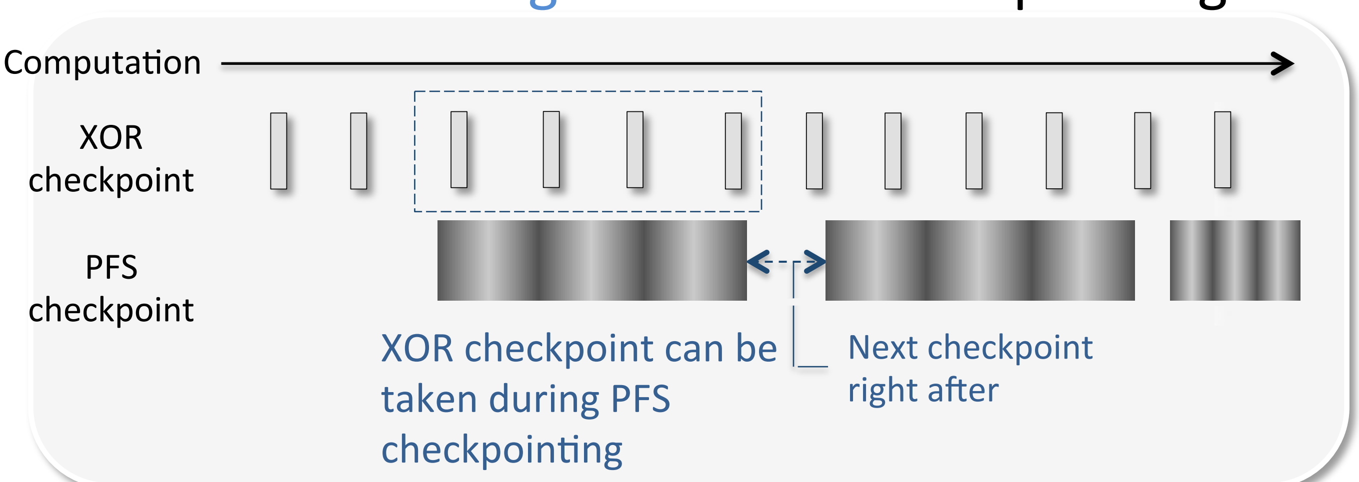
- Introduction
- Design of a Non-blocking checkpointing system
- Modeling of the Non-blocking checkpointing
- Evaluation
- Summary

Non-blocking checkpointing overview

Blocking multi-level checkpointing



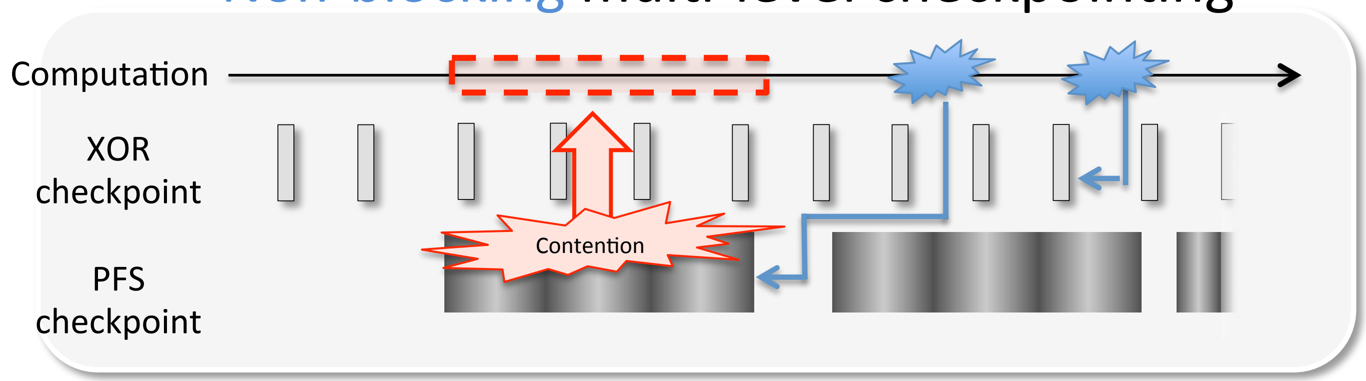
Non-blocking multi-level checkpointing



- Write PFS checkpoint in the background, minimize overhead
- By initiating next ckpt right after previous one, increase utilization
- Reduce impact of failures requiring XOR checkpoint

Challenges on Non-blocking checkpointing

Non-blocking multi-level checkpointing



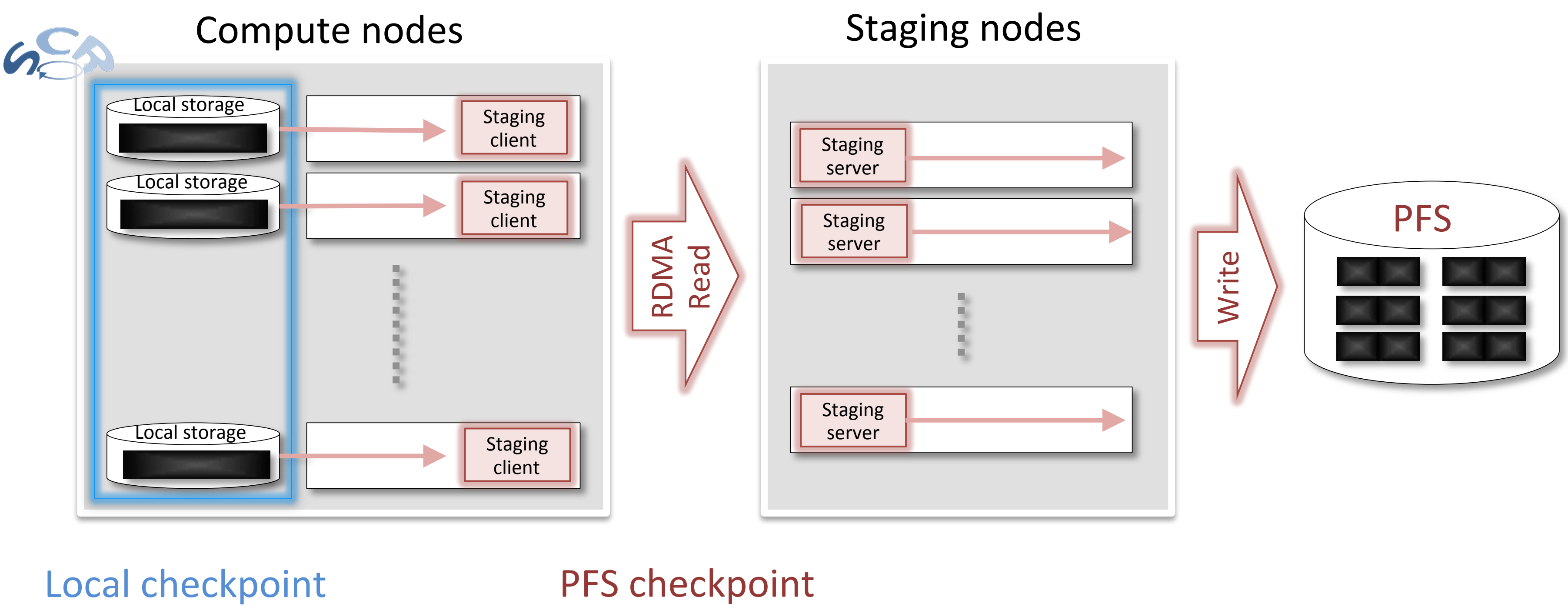
- Utilize local SSDs for the additional space
  - Write PFS checkpoint in the background which requires additional storage spaces
- Minimize resource contention
  - PFS checkpointing is running in the background, inflate the runtime due to resource contention

  ⇒ Implementation: Use RDMA with checkpoint dedicated nodes
- Optimize configuration (e.g. checkpoint interval)
  - On a failure requiring PFS , need "complete PFS checkpoint"
  - On a failure requiring XOR, need to restore both XOR & PFS ckpt being written

  ⇒ Modeling: Model a non-blocking multi-level checkpoint

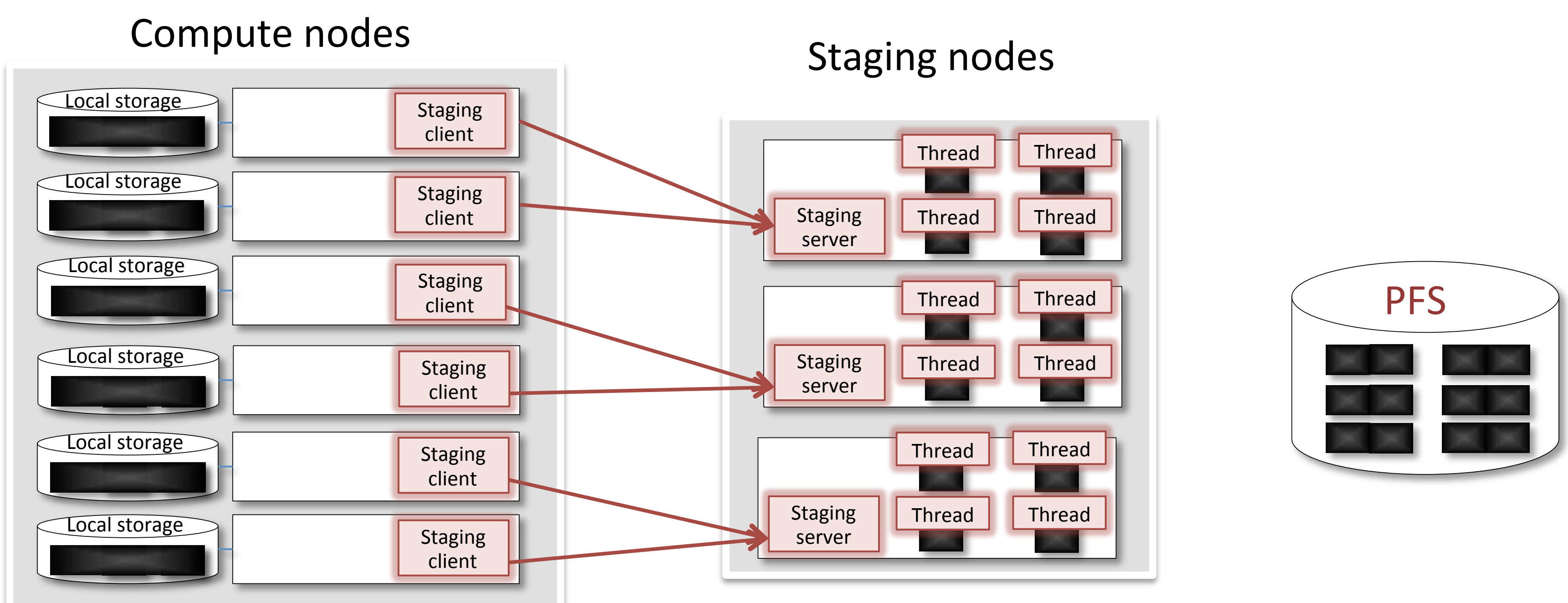
Non-blocking checkpointing overview

- Between compute nodes and PFS, use staging nodes
  - Dedicated extra nodes for transferring local checkpoints written by a SCR library
  - Read checkpoints from compute nodes using RDMA, write out to a PFS



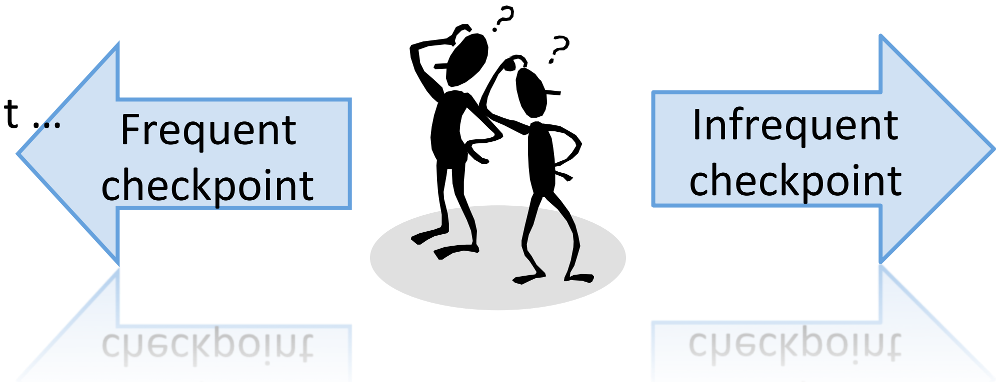
Non-blocking checkpointing using RDMA

1. Local storages to Local memory
   – After SCR writes checkpoint to a local storage, staging clients running on compute nodes read chunks of the checkpoint from the local storage to a buffer memory
2. Local memory to Remote memory
   – Send RDMA Read requests to a mapped staging server running on a staging node, staging server read the checkpoints from the buffer using RDMA
3. Remote memory to PFS
   – Data writer threads running on Staging nodes write checkpoint chunks to PFS in parallel



Modeling of Non-blocking checkpoint

more resilient but …
huge overhead



Low overhead but …
less resilient

Outline

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more resilient but …
huge overhead

Frequent checkpoint

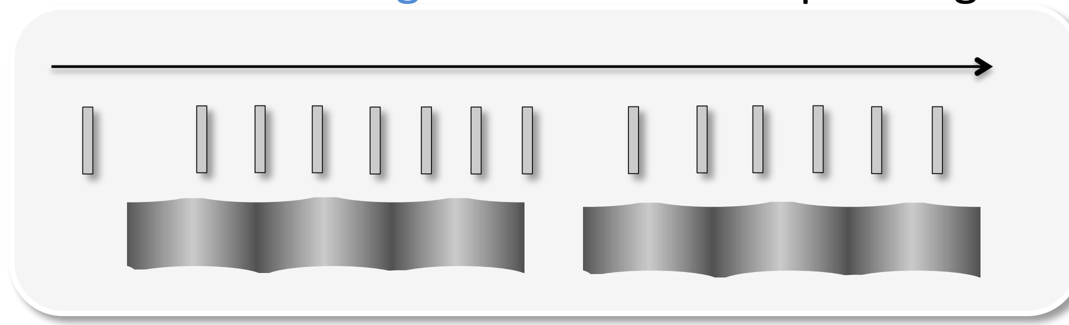
Infrequent checkpoint

Low overhead but …
less resilient

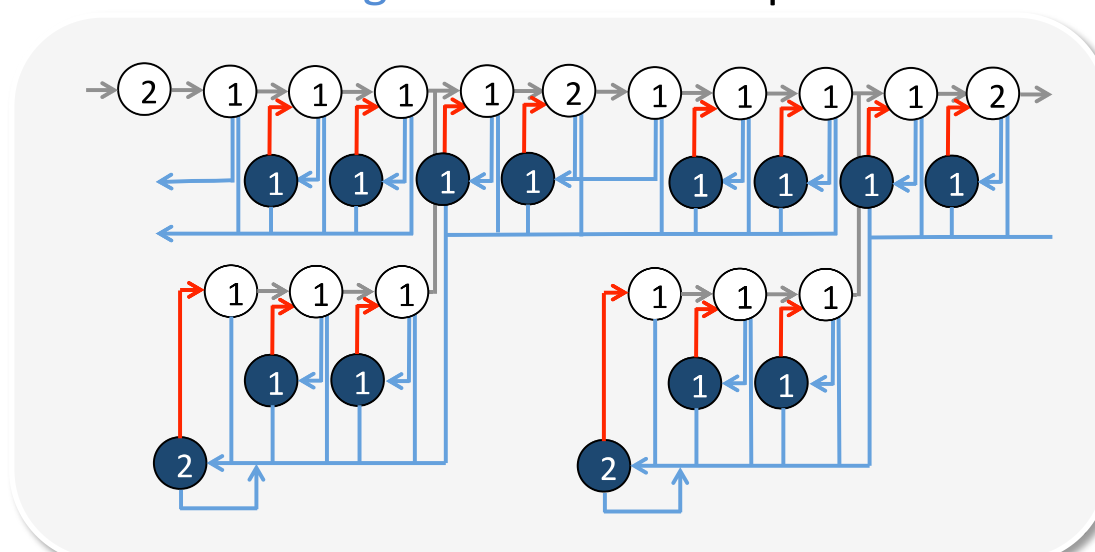
Non-blocking MLC model overview

- Describe an application's state transitions as Markov model
- Input (each level of ..)
  - Checkpoint time
  - Restart time
  - Failure rate
  - Interval
- Output
  - Expected runtime
- Find checkpoint intervals that minimize runtime

Non-blocking multi-level checkpointing

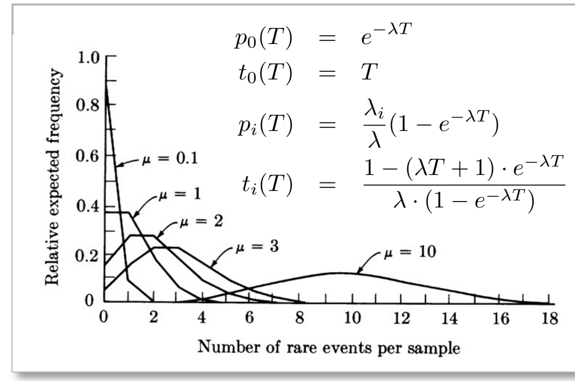


Non-blocking multi-level checkpoint model



Assumptions on the model

- Independent and identically distributed failure rate & Poisson distribution
  - One failure does not increase the probability of successive failures



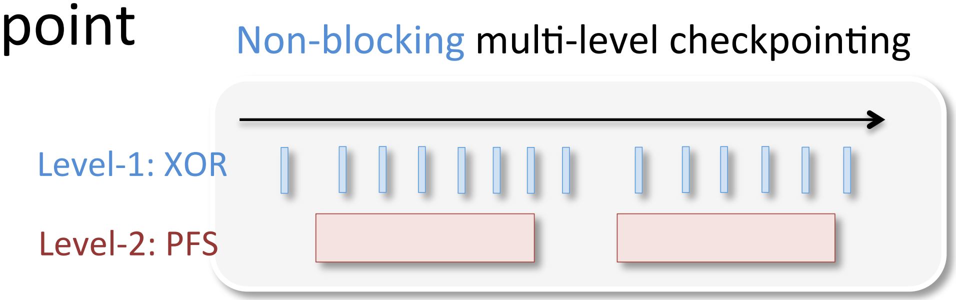
- Stable write & read performance
  - Checkpoint/Restart time significantly does not change during overall the runtime

- Failure on Level-k recovery => Level-($k+1$) checkpoint
  - Another one node failure during XOR recovery requires a PFS checkpoint
  - Assume PFS checkpoint can retry infinitely

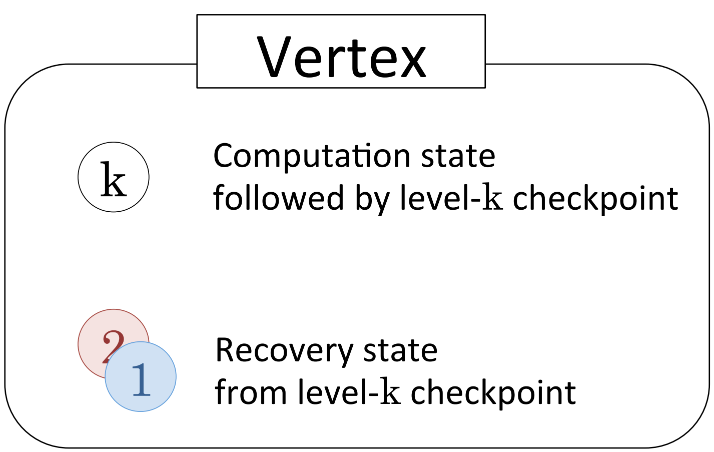
- Saved checkpoints are never lost on non-failed nodes and a PFS
  - Guarantee failed job can restart from the latest checkpoint

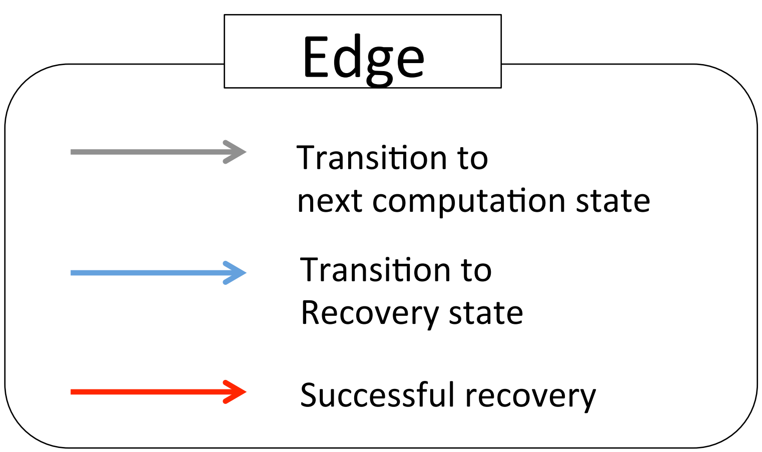
Two-level checkpoint example

- For simplicity, two-level checkpoint
  - Level-1: XOR checkpoint
  - Level-2: PFS checkpoint



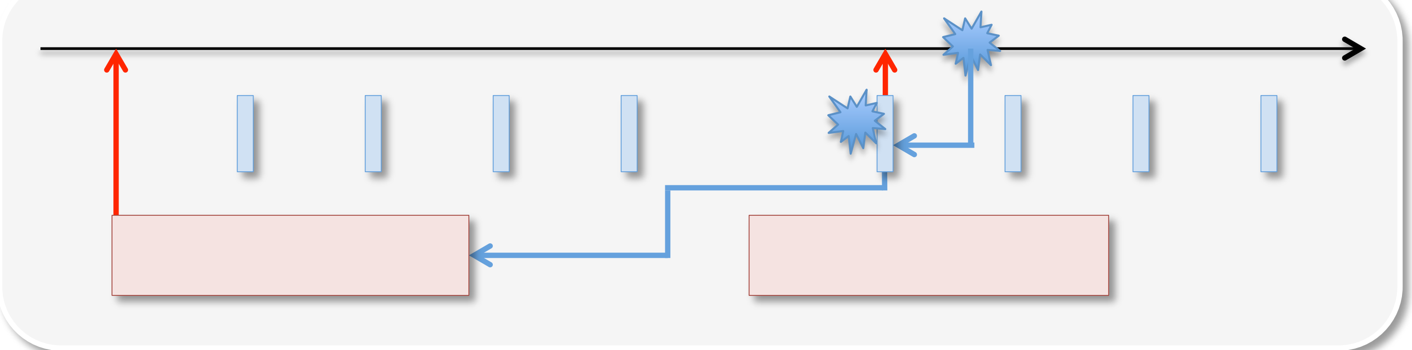
- Describe state transitions as Markov model





No failure & Level-"1" failure case

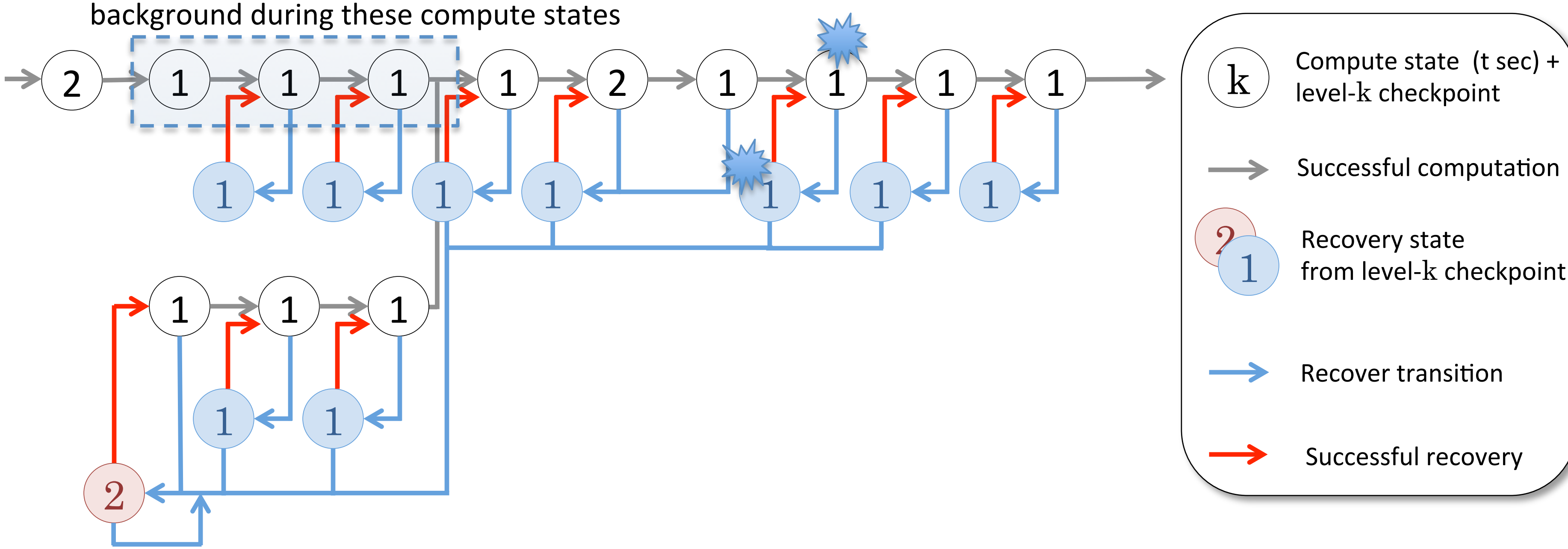
Level-"1" failure



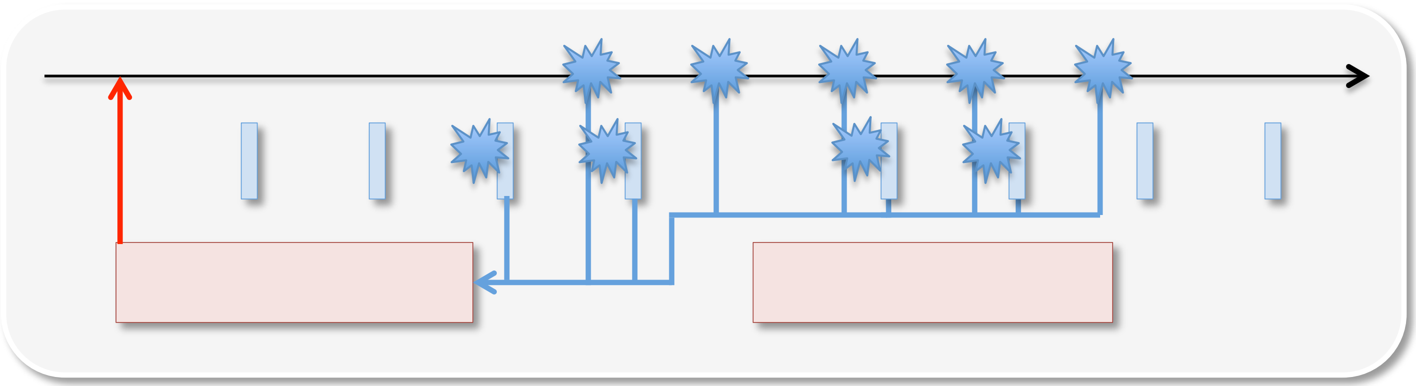
L-2 ckpt: L-1 ckpt

= 1: 4

PFS checkpointing is running in the background during these compute states

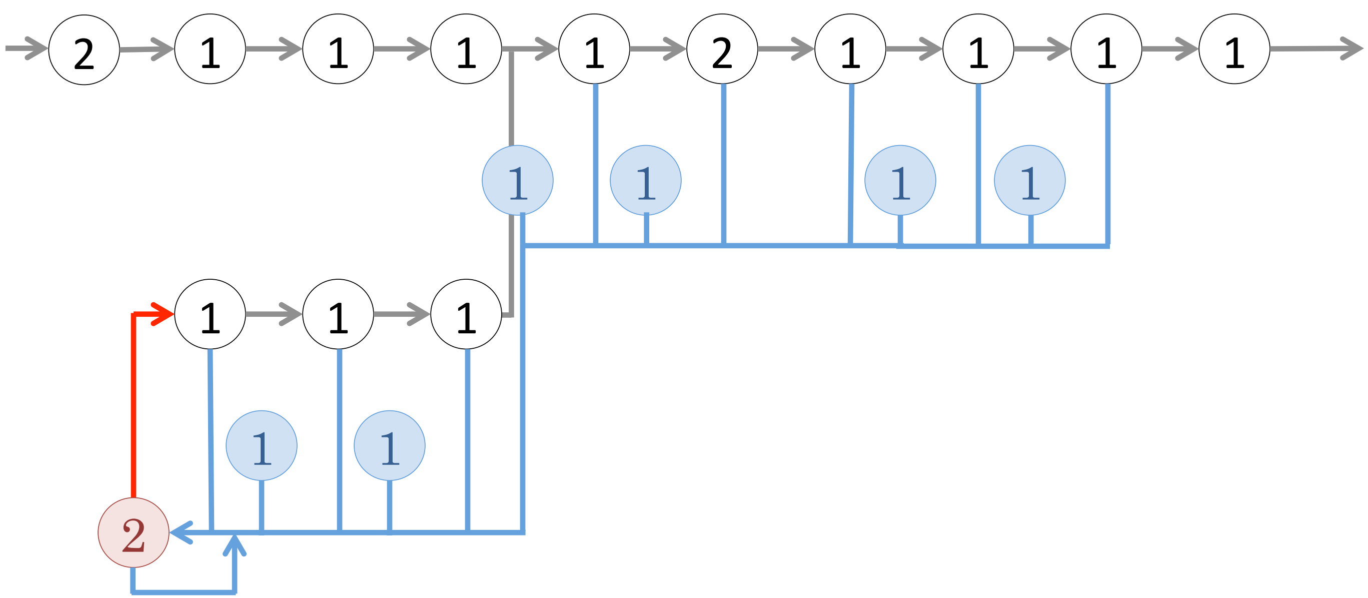


Level-"2" failure case



L-2 ckpt: L-1 ckpt

= 1: 4



k Compute state (t sec) + level-k checkpoint

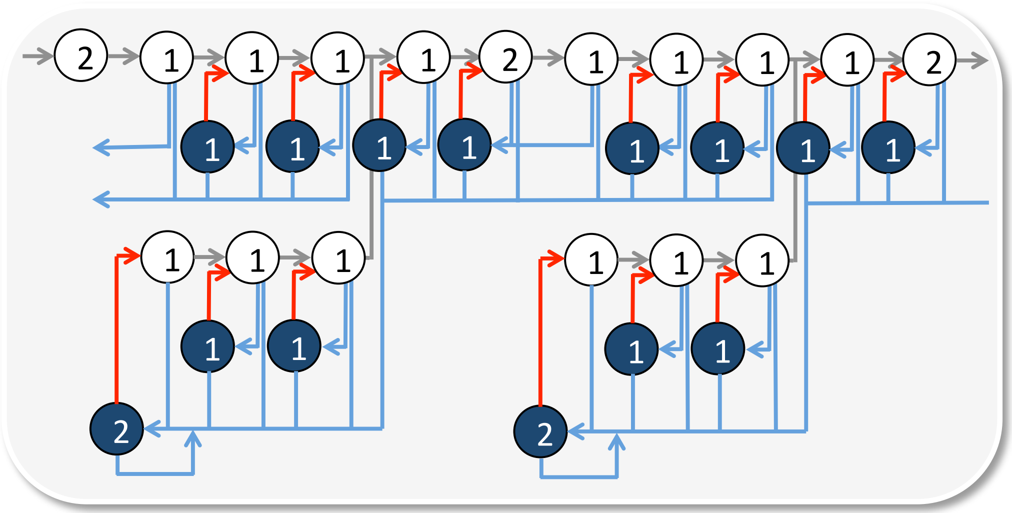
Successful computation

Recovery state from level-k checkpoint

Recover transition

Successful recovery

How to calculate $expected\_runtime$?



t : Interval

c_c : c -level checkpoint time

r_c : c -level recovery time

	Duration: $t + c_k$		Duration: r_k	
No failure	k	$p_0(t+c_k)$ $t_0(t+c_k)$	k	$p_0(r_k)$ $t_0(r_k)$
Failure	k i	$p_i(t+c_k)$ $t_i(t+c_k)$	k i	$p_i(r_k)$ $t_i(r_k)$

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

λ_i : i -level checkpoint time

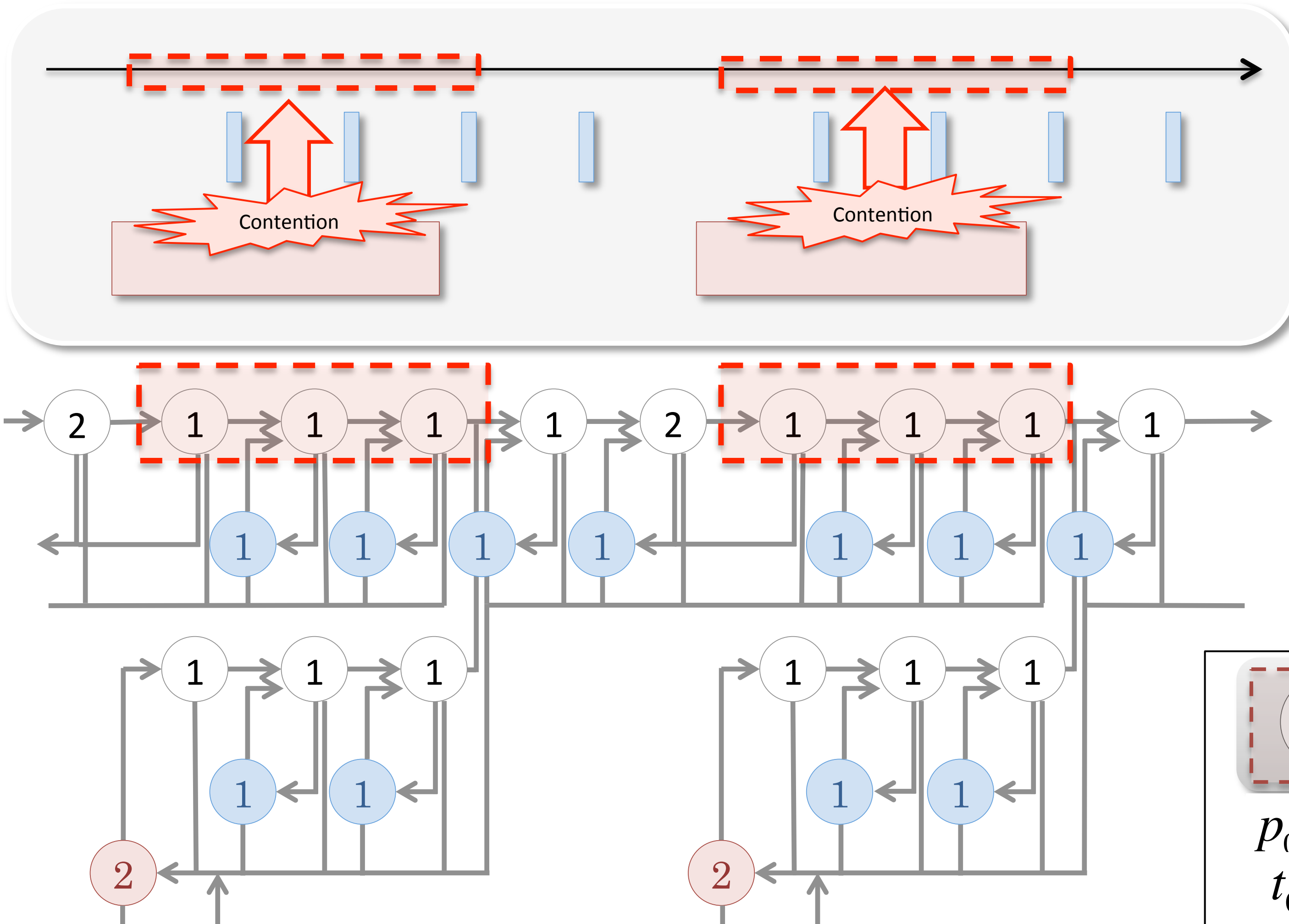
$\lambda = \sum \lambda_i$

- $p_0(T)$: No failure for T seconds
- $t_0(T)$: Expected time when $p_0(T)$

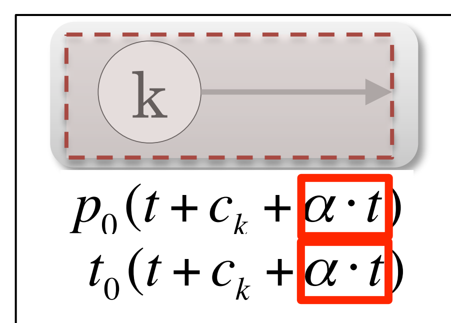
- $p_i(T)$: i - level failure for T seconds
- $t_i(T)$: Expected time when $p_i(T)$

Overhead factor: α

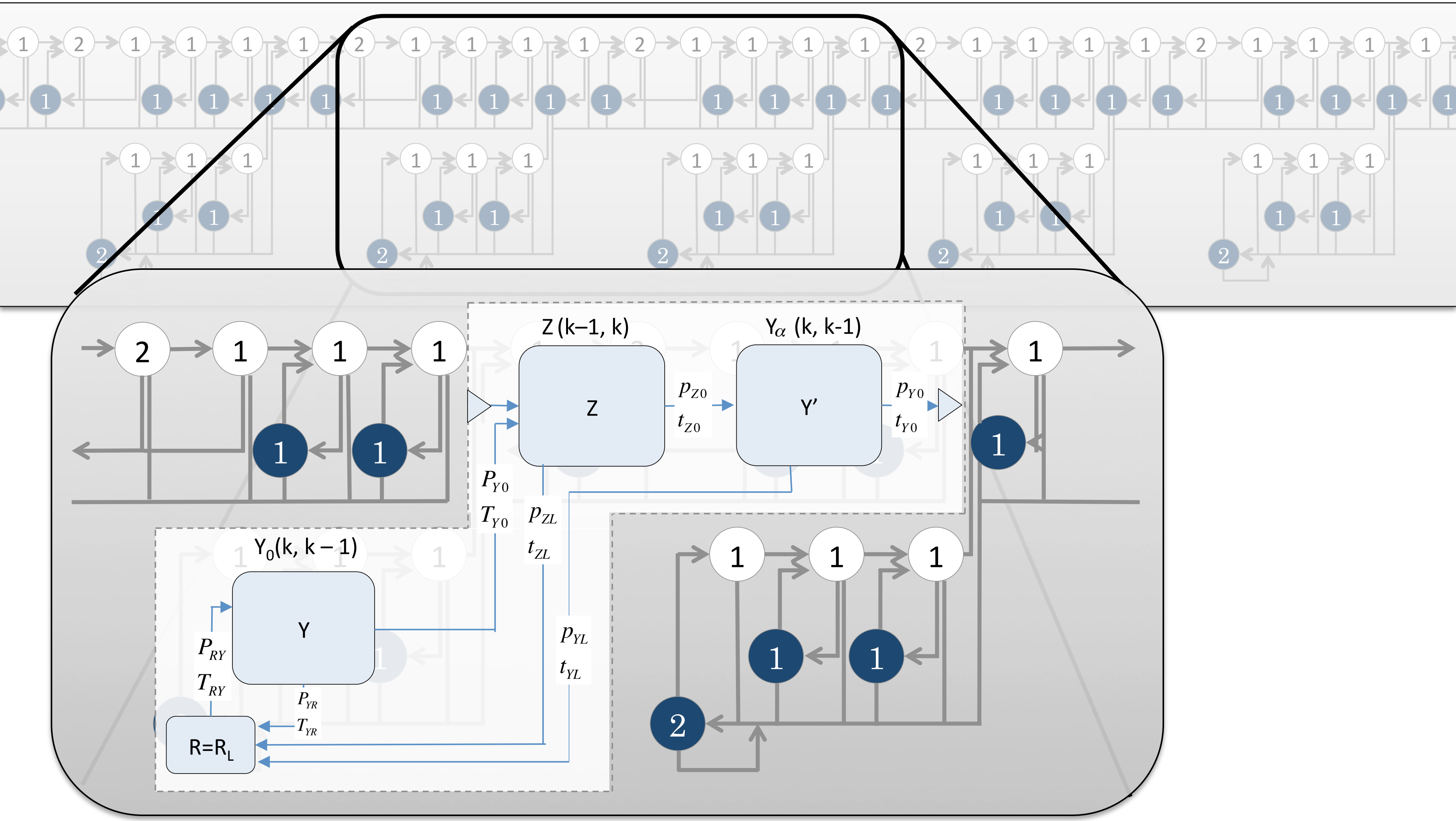
- Quantify an overhead by our proposed non-blocking checkpointing system



During these compute states PFS checkpointing is running in the background, inflate the runtime due to resource contention



Arbitrary N - level checkpointing model

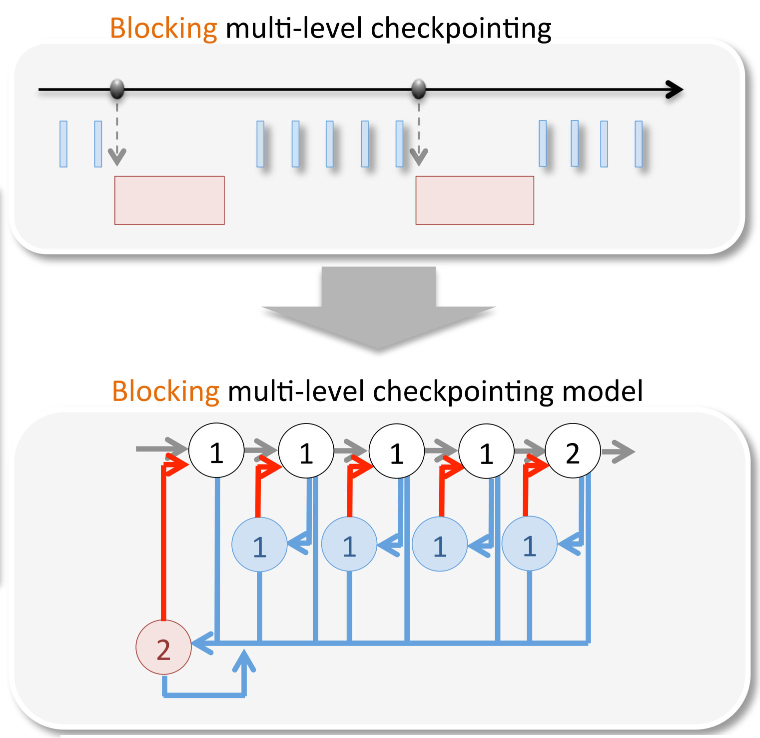


Non-blocking vs. Blocking MLC checkpointing

- **Benchmark**: Himeno benchmark
  - Stencil application solving Poisson's equation using Jacobi iteration method
- **Target System**:
  TSUBAME2.0 Thin nodes (1408 nodes)

CPU	Intel Xeon X5670 2.93GHz (6cores x 2 sockets)
Memory	DDR3 1333MHz (58GB)
Network	Mellanox Technologie Dual rail QDR Infiniband 4x (80Gbps)
Local storage	120GB Intel SSD (RAID0/60GBx2)
PFS	Lustre (/work0)

- **Checkpoint Level**: Two-level
  - Level-1: XOR using local SSD
  - Level-2: PFS using Lustre



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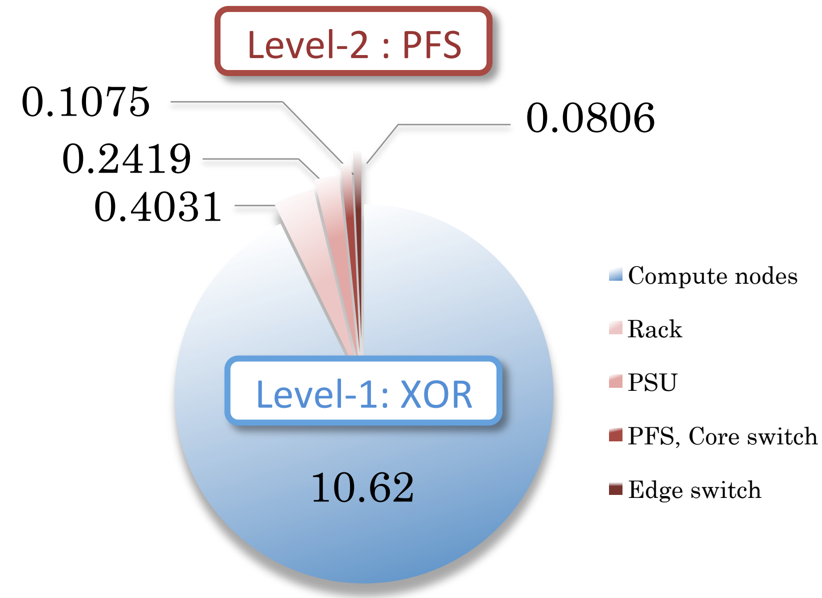
Model Parameters

- **<u>Failure rates</u>**
  - 1.5 years (Nov 1st 2010 ~ Apr 6th 2012) failure history

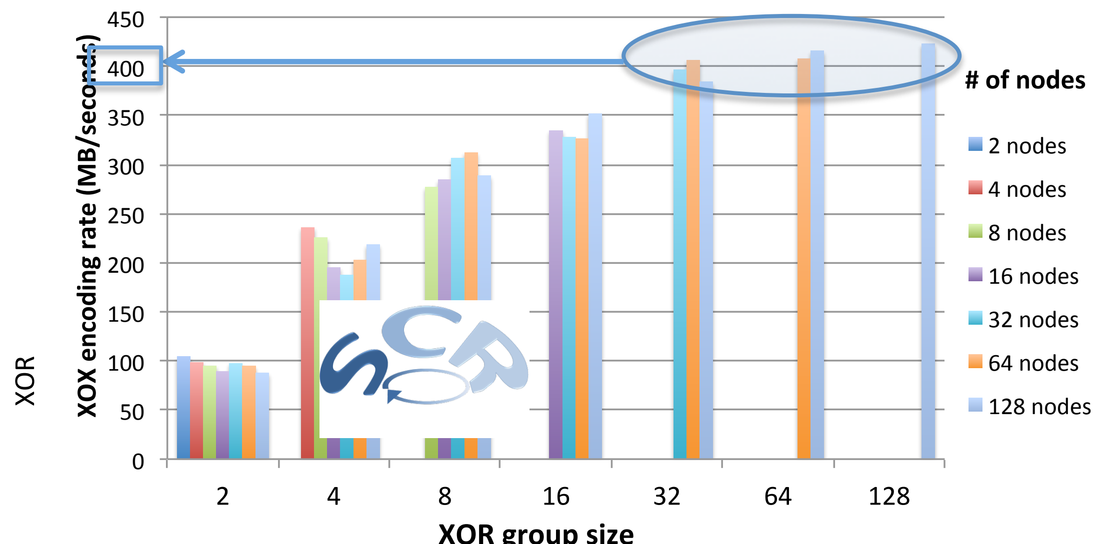


Failure rates (failures/week) on TSUBAME2.0

- **<u>Checkpoint size per node</u>**: 29GB
  - TSUBAME nodes memory: 58GB

Level-1

- **<u>XOR throughput</u>**: 400MB/s



XOR encoding performance on TSUBAME2.0 using local SSDs

Model Parameters

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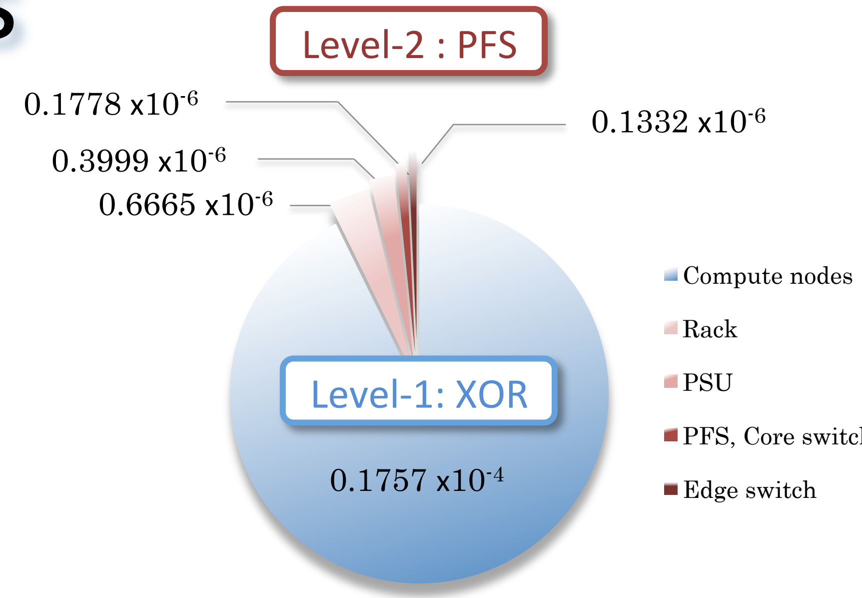
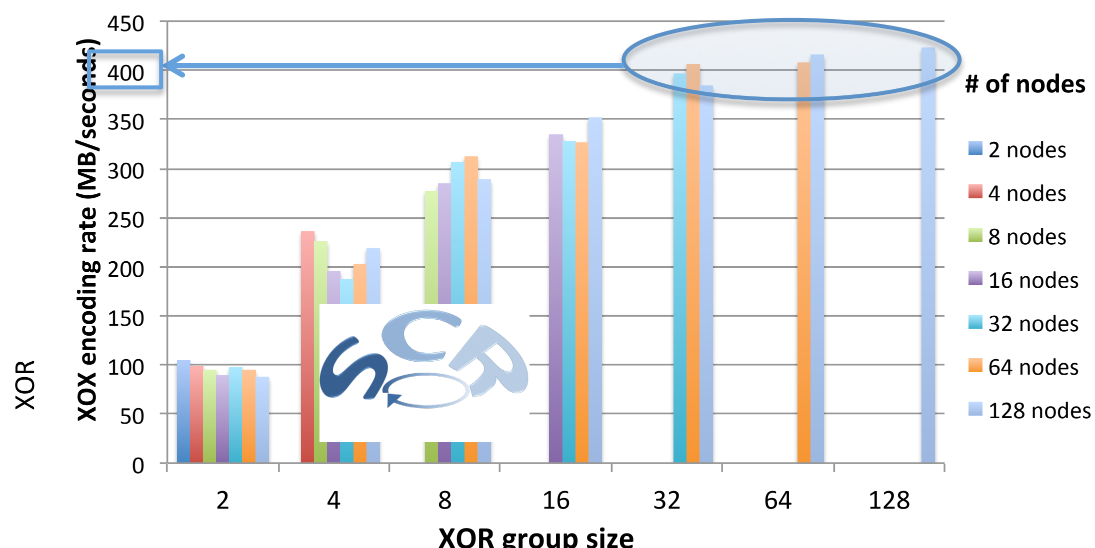


Failure rates (failures/second) on TSUBAME2.0



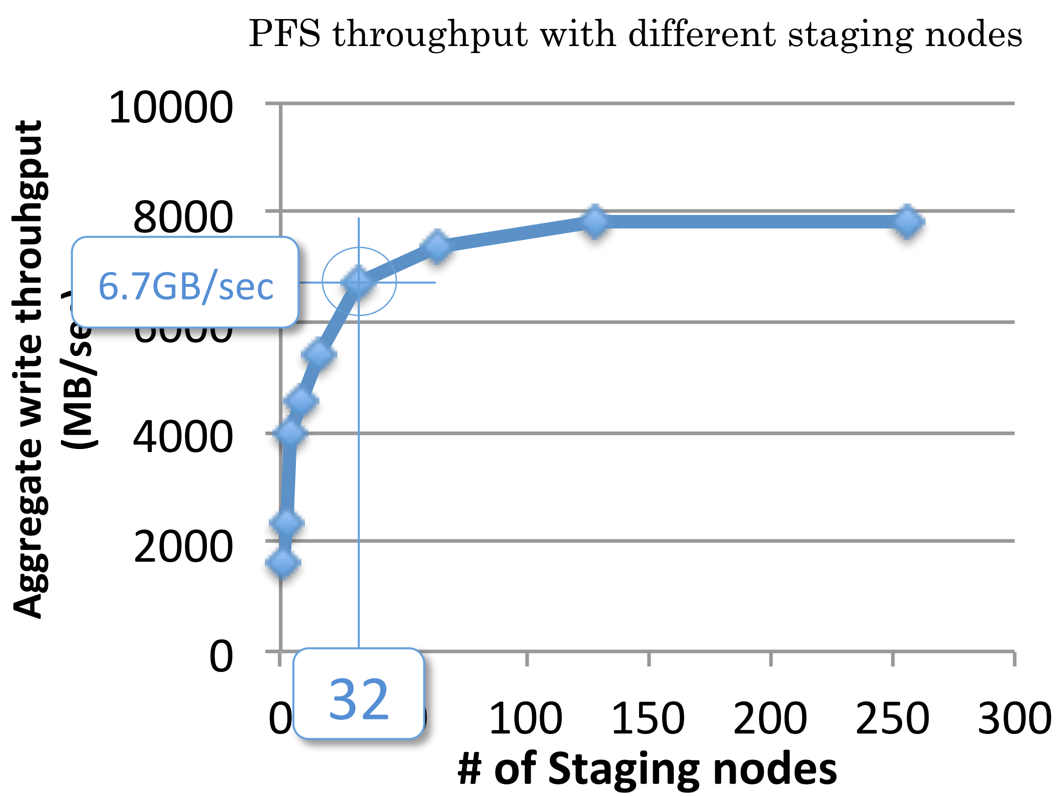
XOR encoding performance on TSUBAME2.0 using local SSDs

Staging node tuning for TSUBAME2.0

Level-2

- **# of Staging nodes**: 32 nodes
  - 2.3% of TSUBAME2.0 thin nodes (1408 nodes)
- **PFS throughput**: 6.7GB/seconds
  - 209.5 MB/seconds* per Staging node

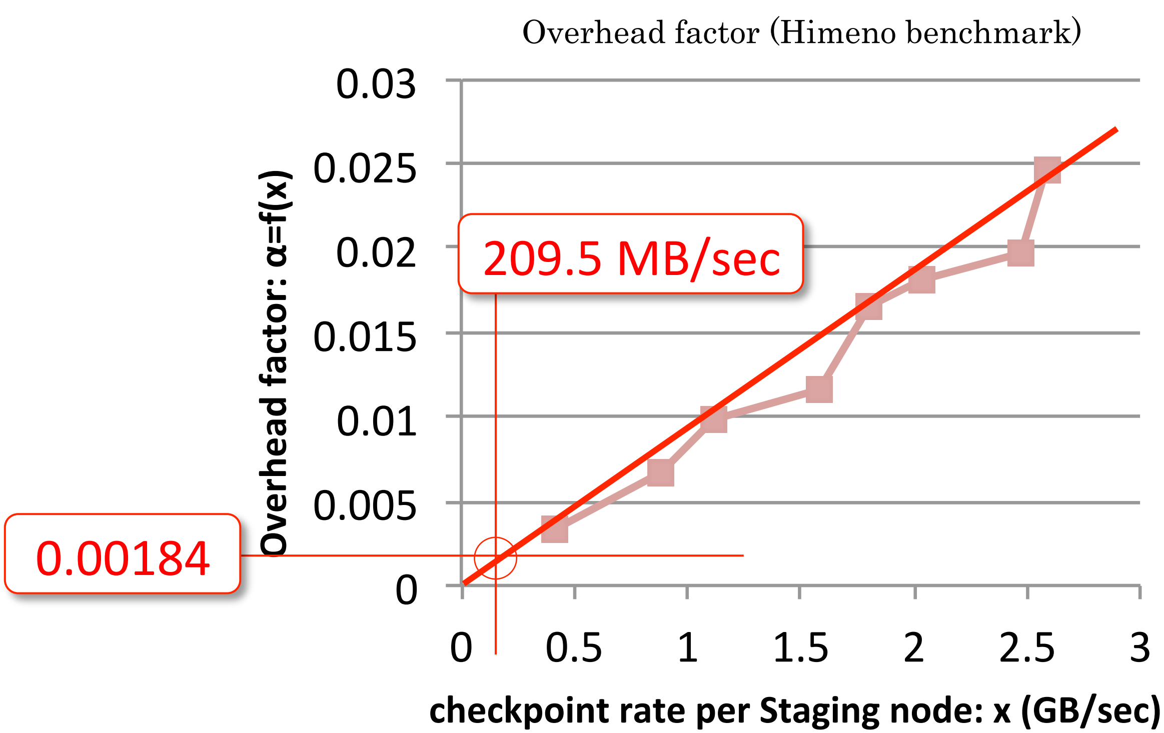
  * 6.7(GB/s) / 32(nodes) = 209.5



Overhead factor

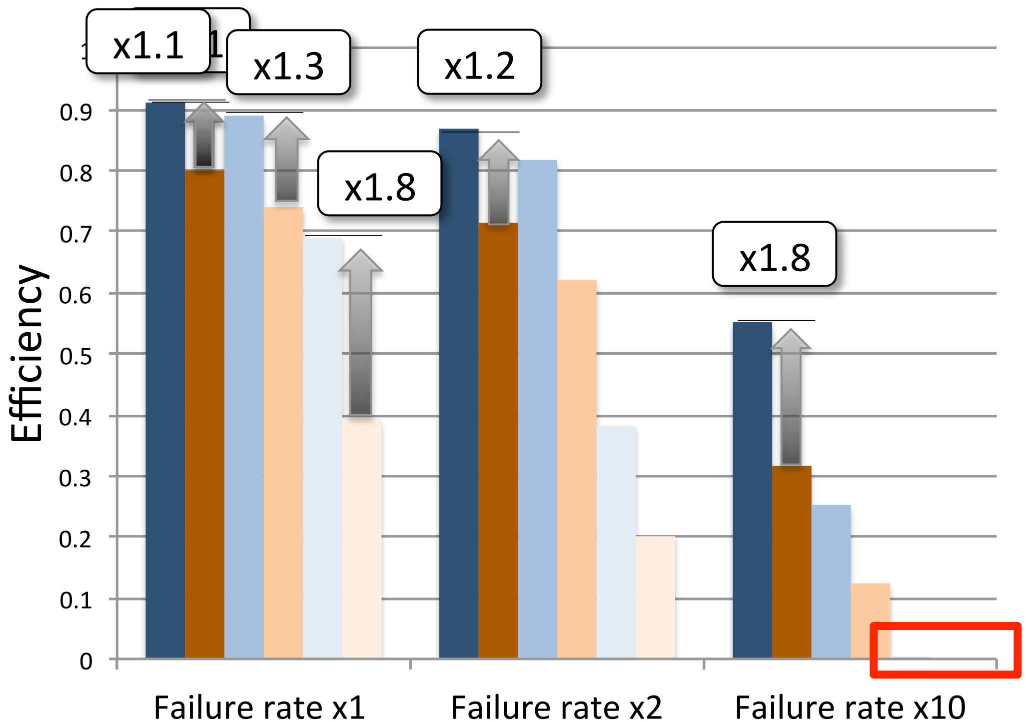
- **Overhead factor**: 0.00184 (0.184%)
  - For Himeno bechmark

RDMA ⇒ No CPU cycle, No redundant memcpy
RDMA read speed ⇒ 209.5MB/s < Network & Memory bandwidth



Efficiency: Non-blocking vs. blocking

The non-blocking method always achieves higher efficiency than the blocking method



$$Efficiency = \frac{ideal\ \ runtime}{expected\ \ runtime}$$

$ideal\ \ runtime$: No failure and No checkpoint

$expected\ \ runtime$: Computed by the models

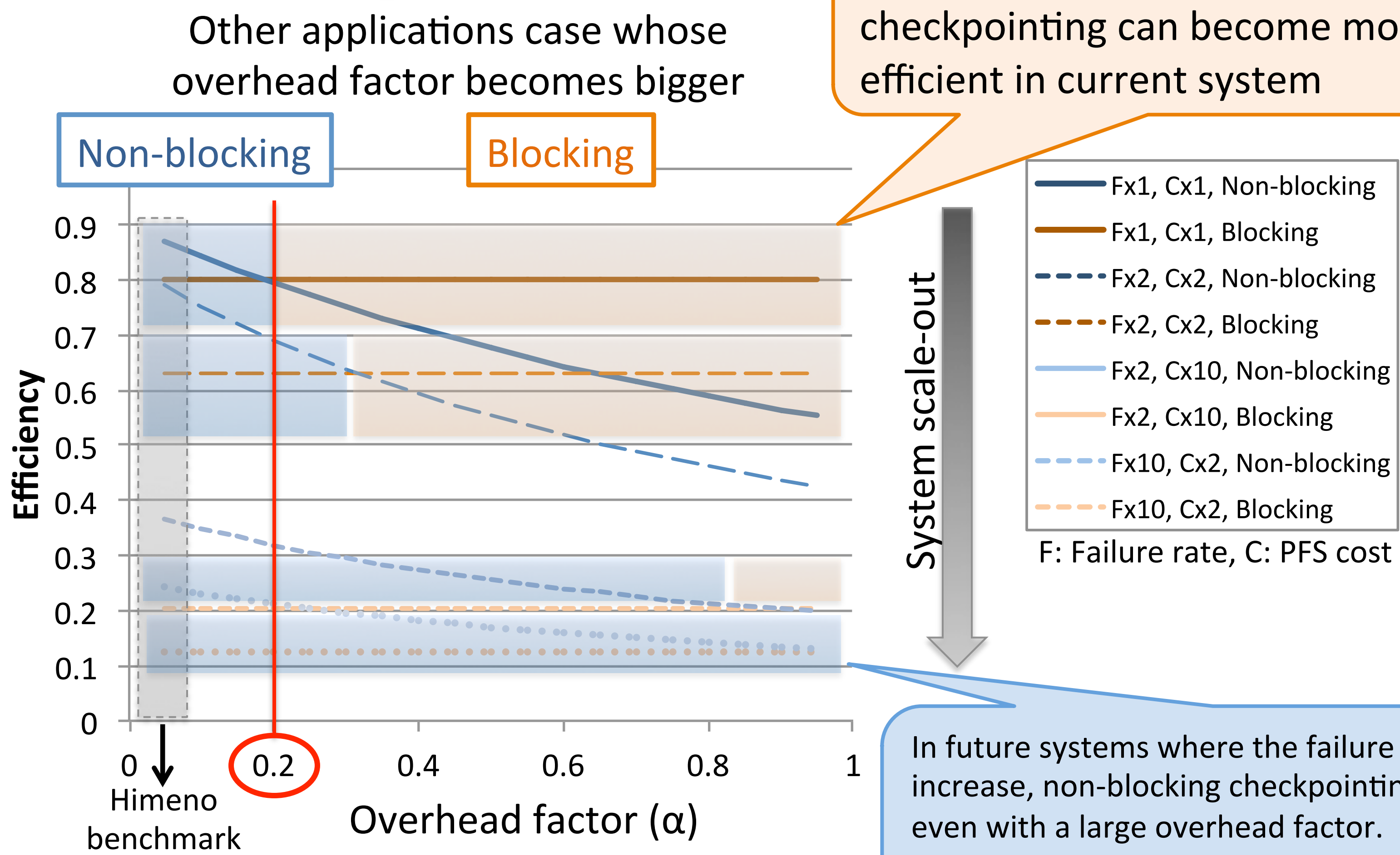
- PFS cost x1 / Non-blocking
- PFS cost x1 / Blocking
- PFS cost x2 / Non-blocking
- PFS cost x2 / Blocking
- PFS cost x10 / Non-blocking
- PFS cost x10 / Blocking

One TSUBAME2.0 node MTBF: 2.57 years
\# of Nodes: 1408 nodes

x10 scale-out →

No computation progresses !!

Overhead factor: Non-blocking vs. Blocking



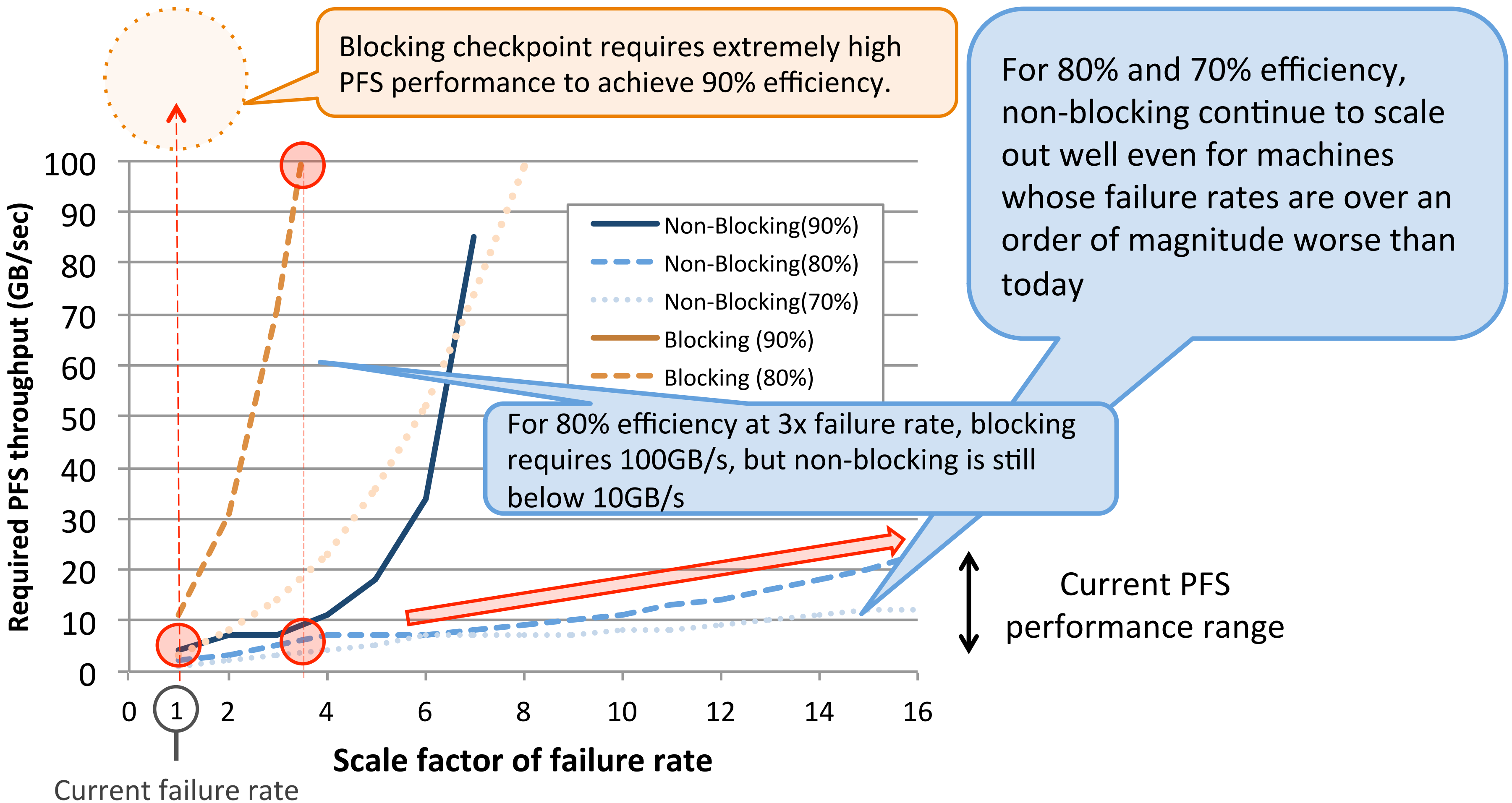
If overhead factor is over 0.2, blocking checkpointing can become more efficient in current system

In future systems where the failure rates and cost increase, non-blocking checkpointing can be effective even with a large overhead factor.
=> Blocking checkpoint overhead dominate the runtime more than overhead factor by non-blocking

Required PFS performance to meet given application efficiency

When building a reliable data center or supercomputer, two major concerns are monetary cost of the PFS and the PFS throughput required to maintain high efficiency …

=> predict required PFS performance with the models



Conclusion

- Developed an non-blocking checkpointing system
  - Write checkpoint data in the background using RDMA
- Markov model of the non-blocking checkpointing
  - Optimal multi-level checkpoint interval
  - Non-blocking v.s. Blocking checkpoint
    - Higher efficiency (1.1 ~ 1.8x) on current and future systems
  - High efficiency (up to 80%) with low PFS throughput

Q & A

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