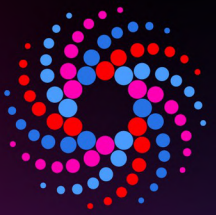


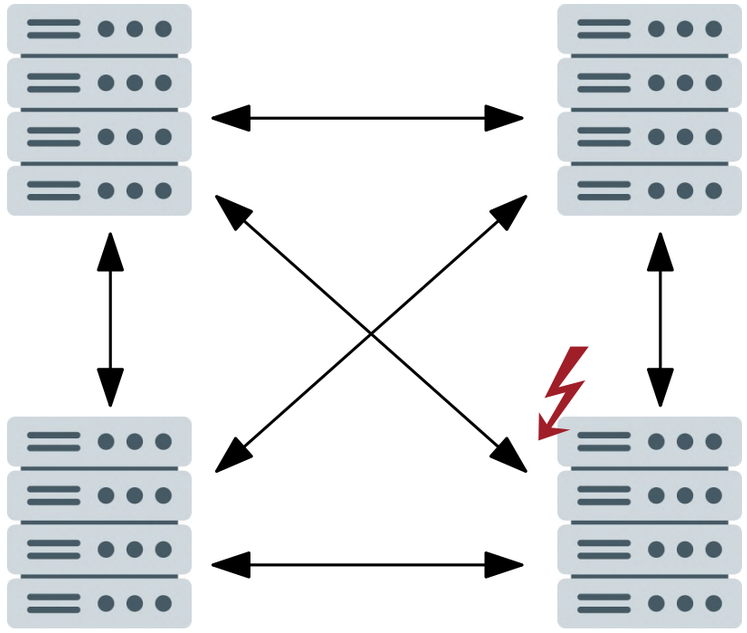
SC22
Dallas, TX | hpc accelerates.

ReStore: In-Memory REplicated STORagE for Rapid Recovery

Lukas Hübner, Demian Hespe, Peter Sanders, Alexandros Stamatakis

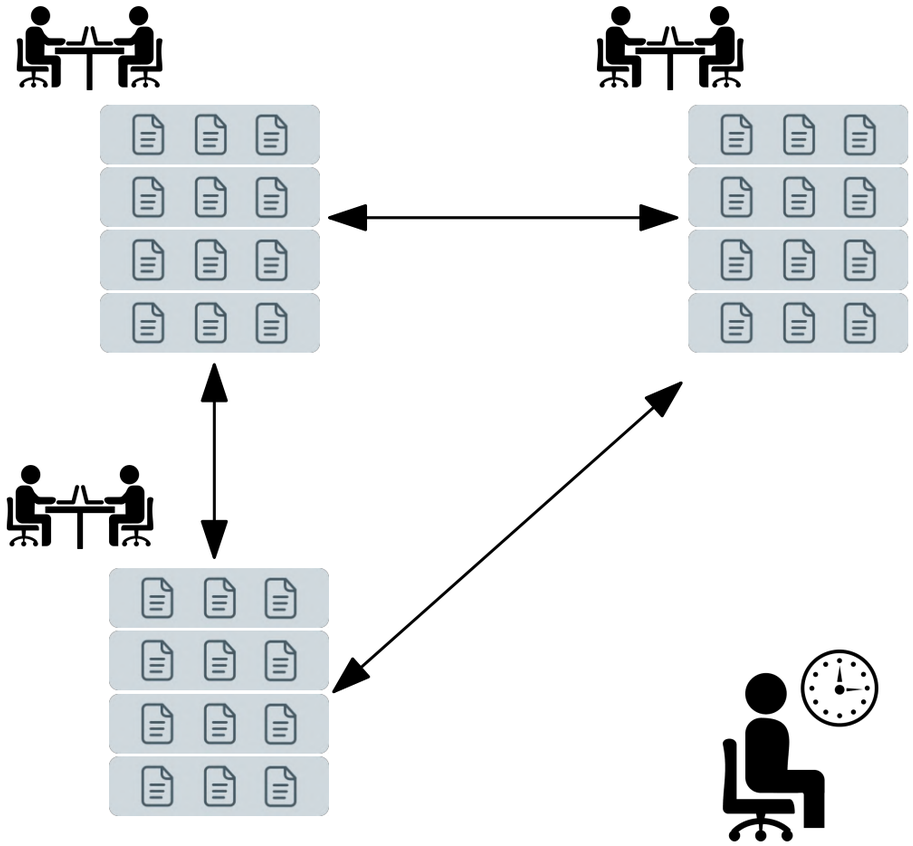
Motivation

- fail-stop faults
- More CPUs→ more faults → more recoveries
- Lower operational voltage of CPUs → less energy used, more faults
- Node failure → reload *dynamic* program state and *static* (e.g., input) data
- The parallel file system is a bottleneck



Shrinking vs Substituting Recovery

Substituting Recovery



Shrinking Recovery

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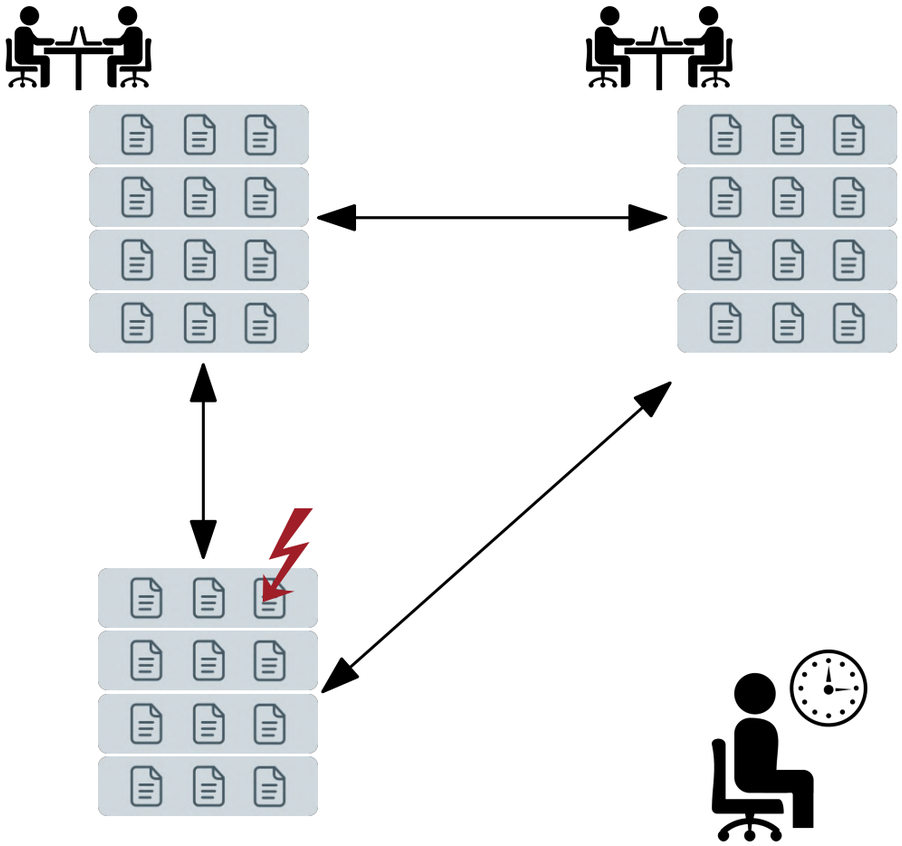

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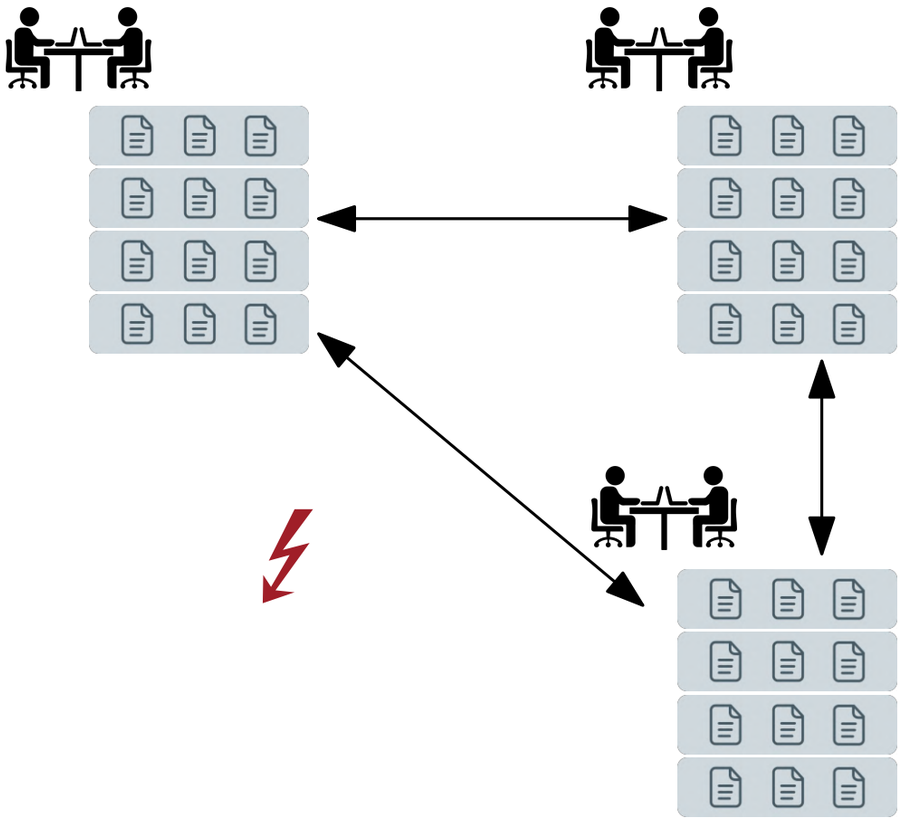

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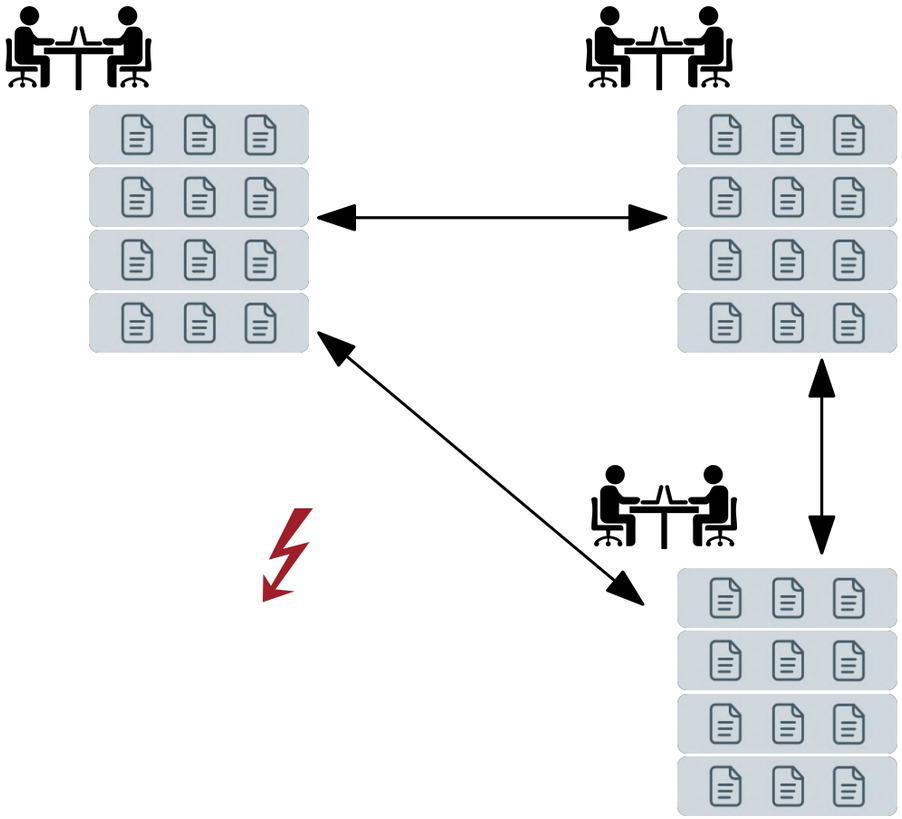

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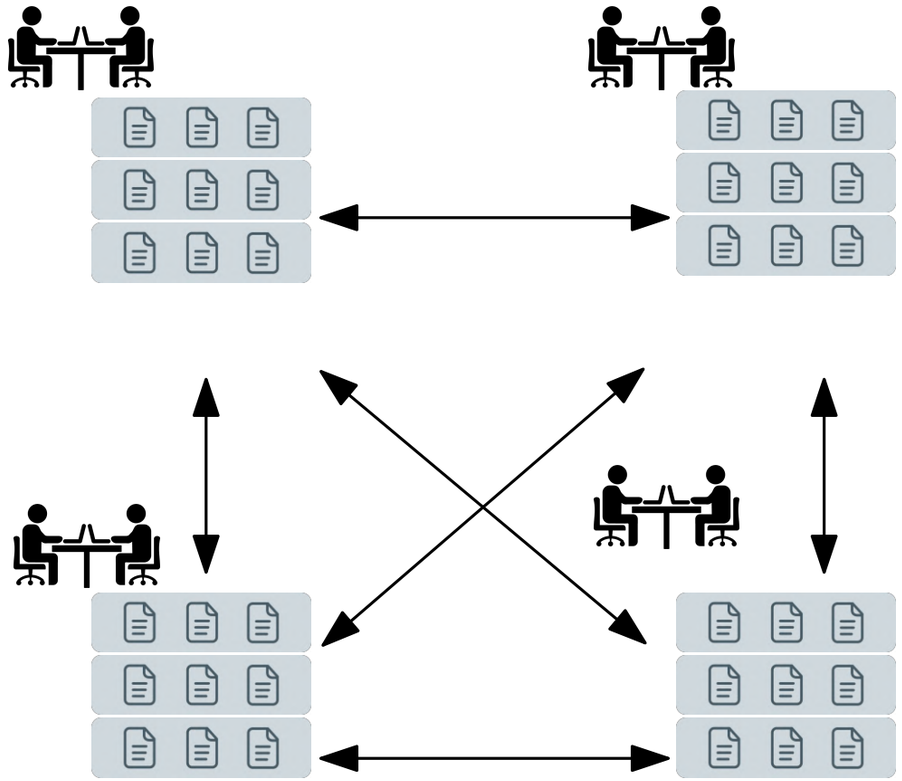

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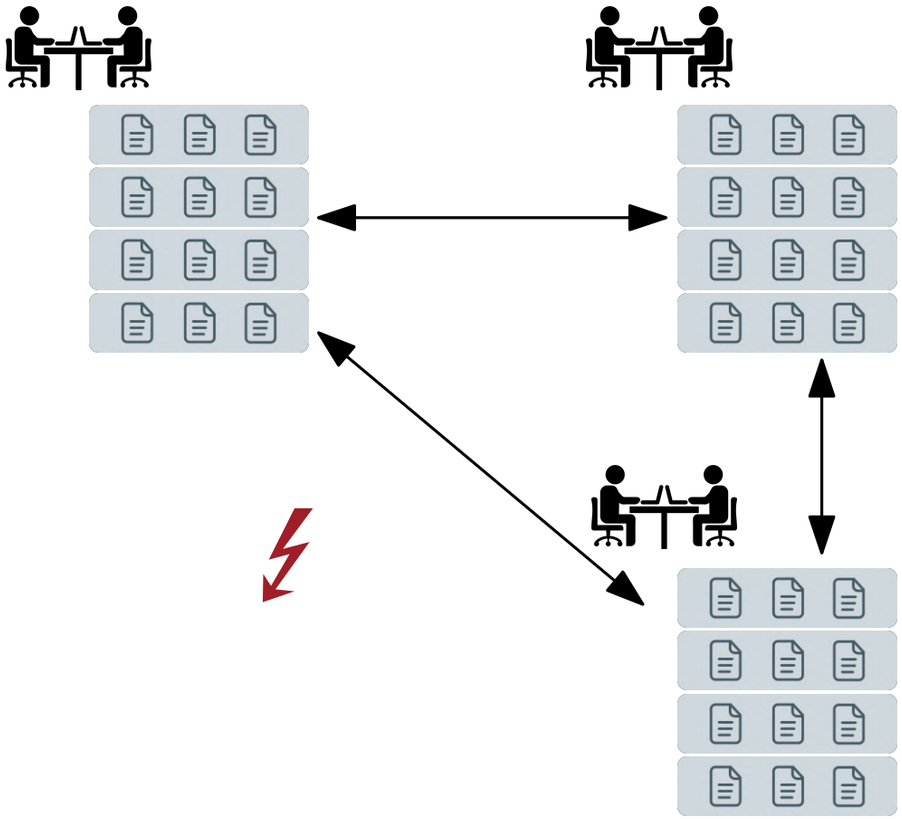

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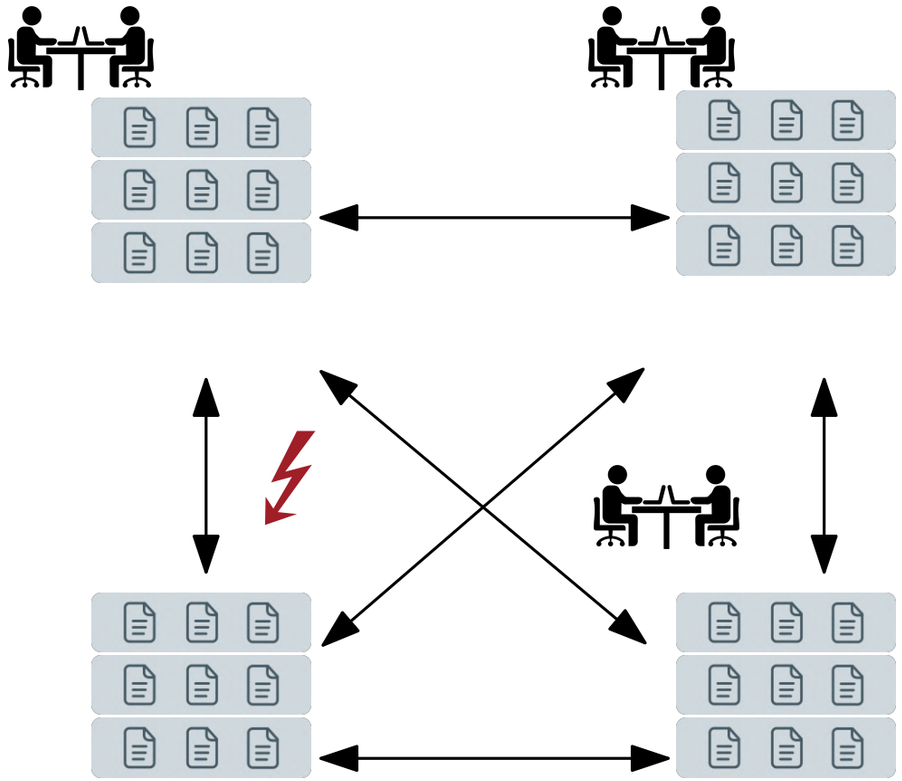

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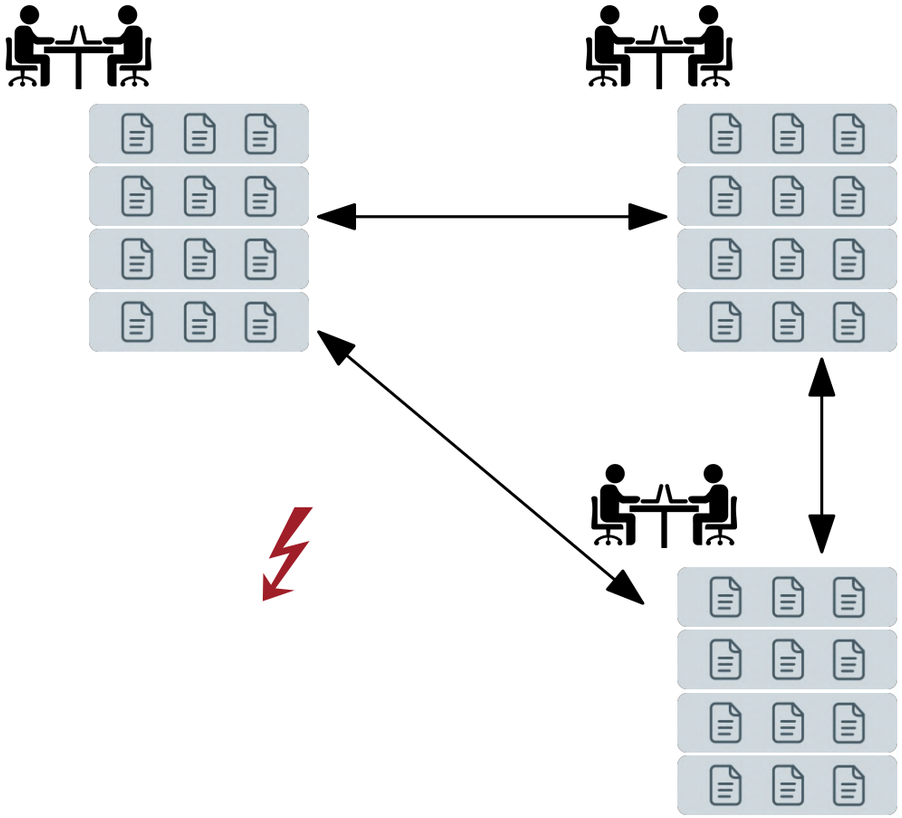

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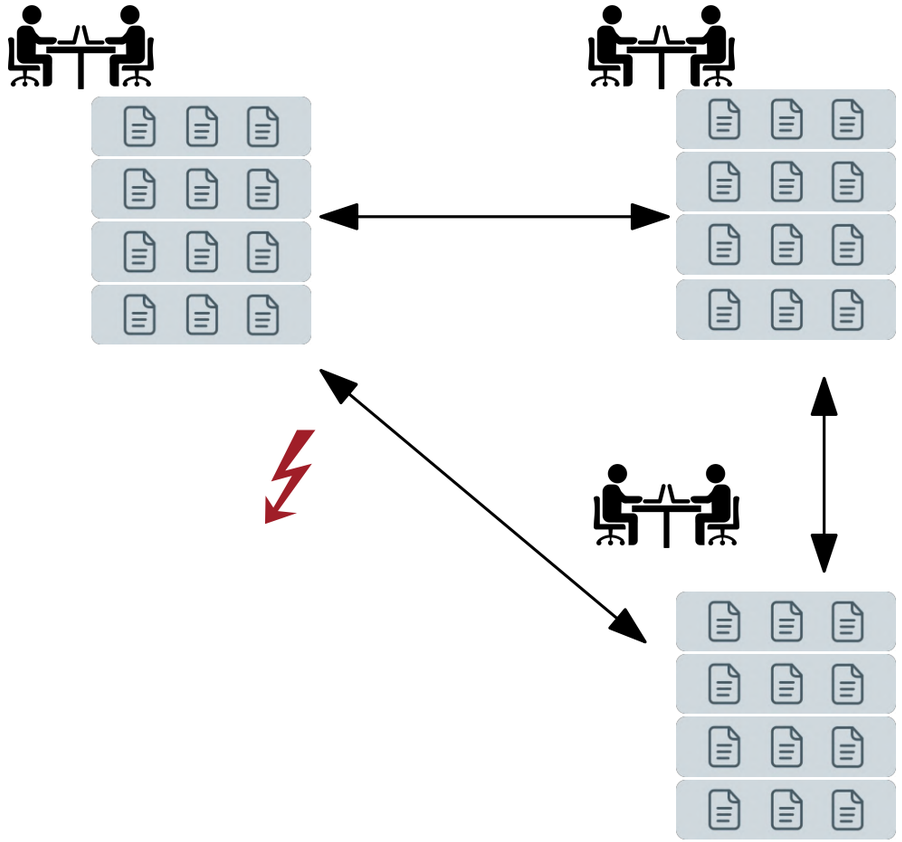

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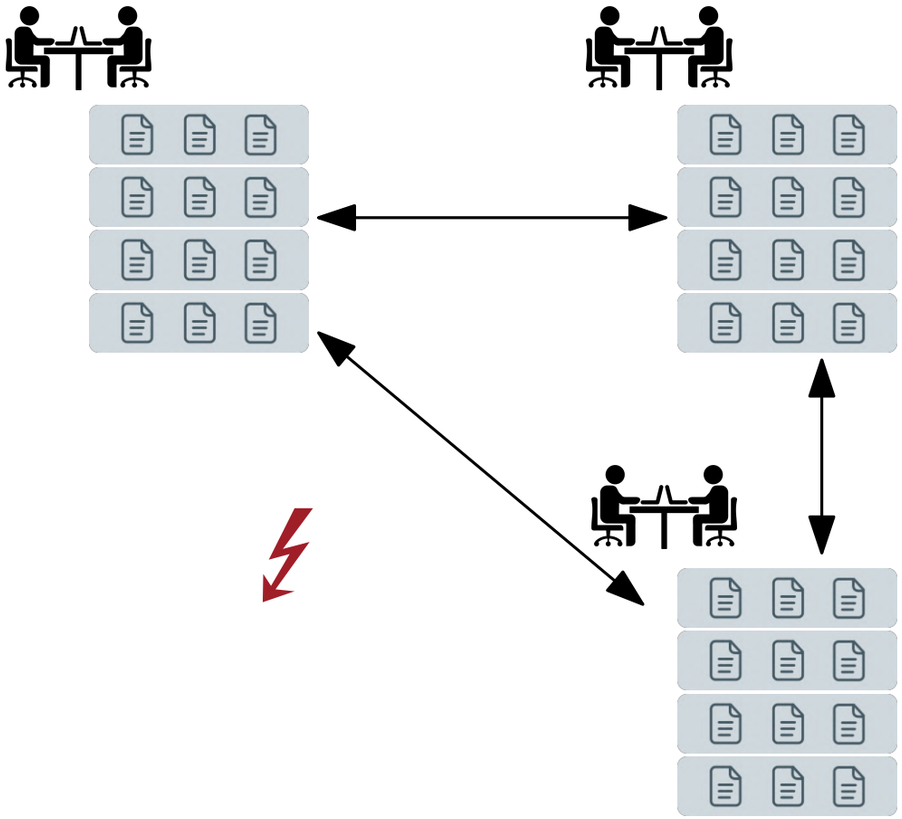
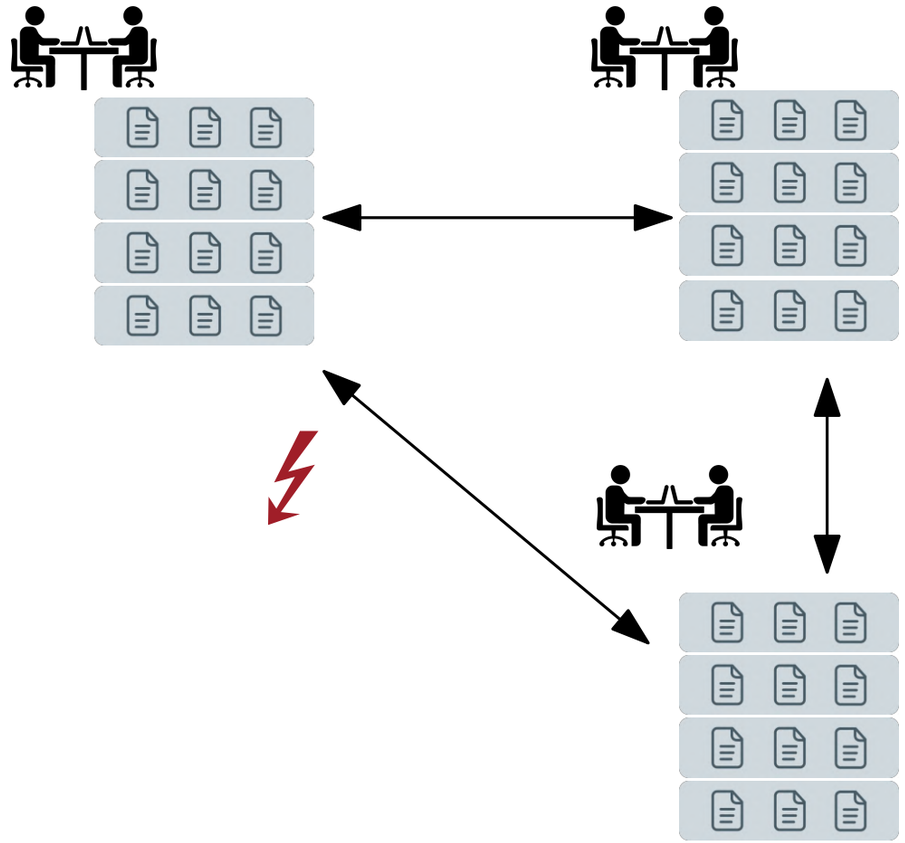


- Up to $5\,\%$ of nodes idling
- Limited number of failures supported
- Recovery time does not scale

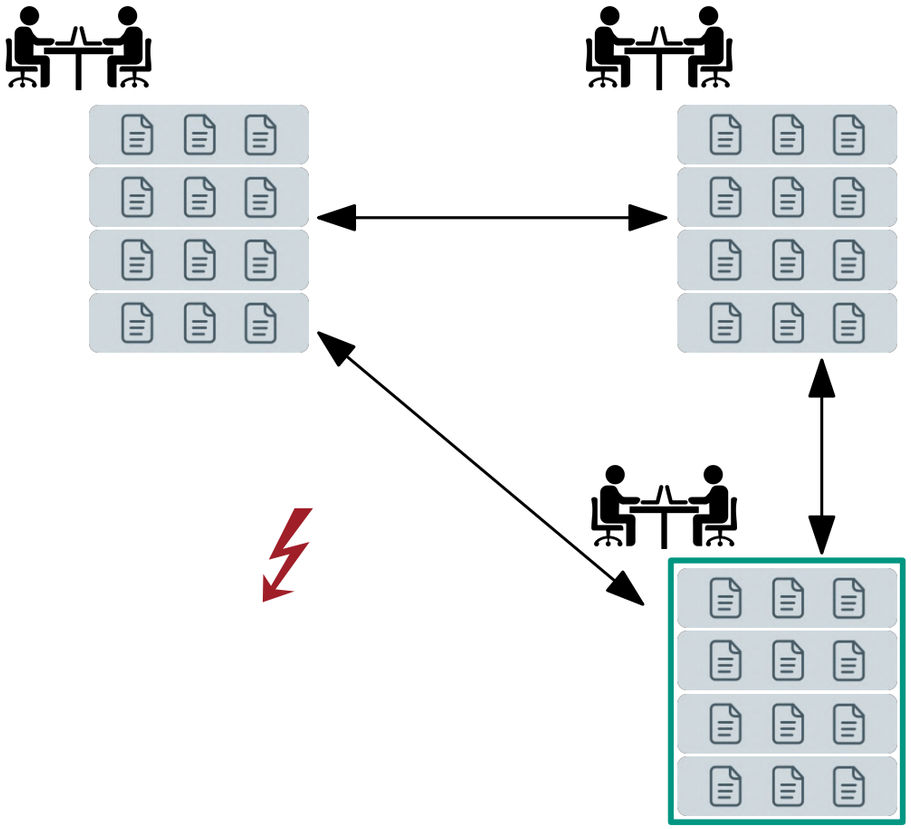
Shrinking Recovery



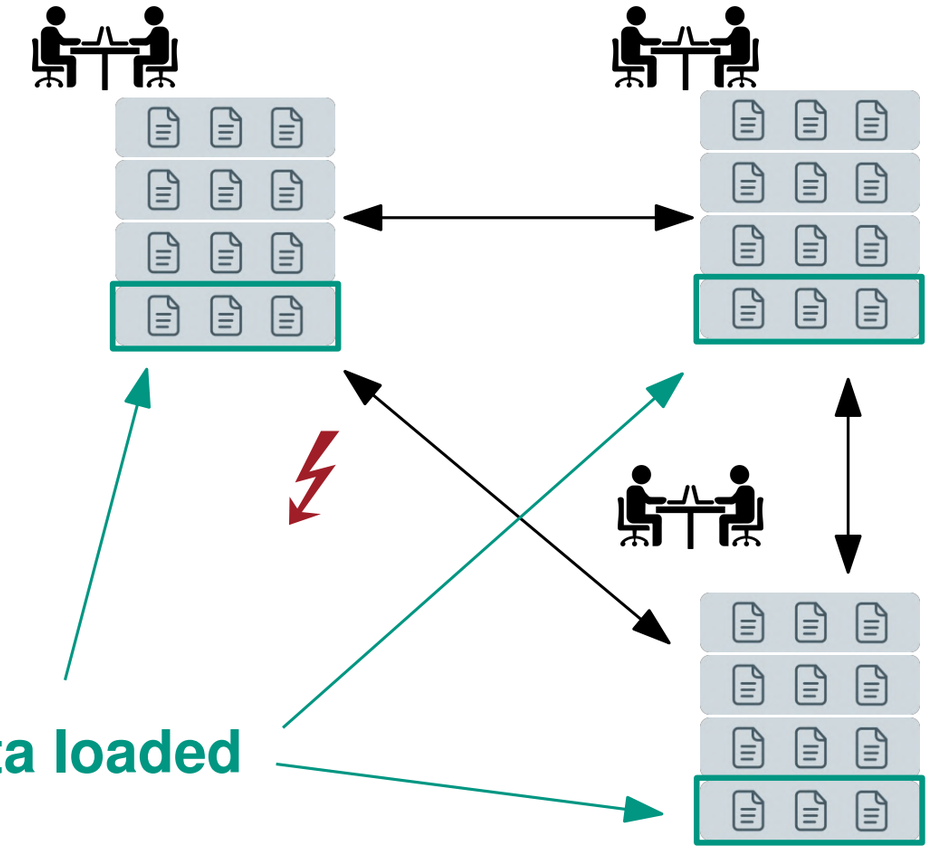
- All nodes participate in computation
- Unlimited number of failures supported
- Recovery time scales with $1/p$

Shrinking vs Substituting Recovery

Substituting Recovery



Shrinking Recovery



Single PE receives all messages
→ **bottleneck**

Design Goals

ReStore

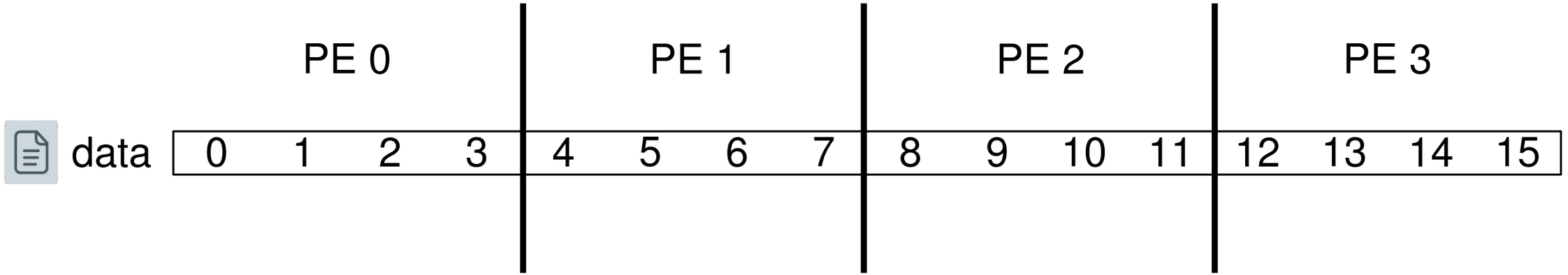
- **in-memory** access to the parallel file system is a bottleneck
- **no spare nodes required** spare nodes are wasted resources
- **no checkpointing nodes required** checkpoint nodes are wasted resources
- **scalable recovery** $\in \mathcal{O}(1/p)$ time per failure
- **arbitrary replication level** more flexibility and robustness
- **rapid recovery** that's what we needed for our application

Related Work

	ftRMA	Fenix	SCR	Lu	GPI_CP	*ReStore*
Features						
in-memory checkpointing	✓	✓	✗	✓	✓	✓
substituting recovery	✓	✓	✓	✓	✓	✓
shrinking recovery	✗	✗	✗	✗	✗	✓
all nodes participate in computation	✗[2]	(✓)[1]	(✓)[1]	✗[2]	(✓)[1]	✓
scaleable recovery	✗	✗	✗	✗	✗	✓
programming model	MPI RDMA	MPI	MPI	MPI	PGAS/GPI	MPI

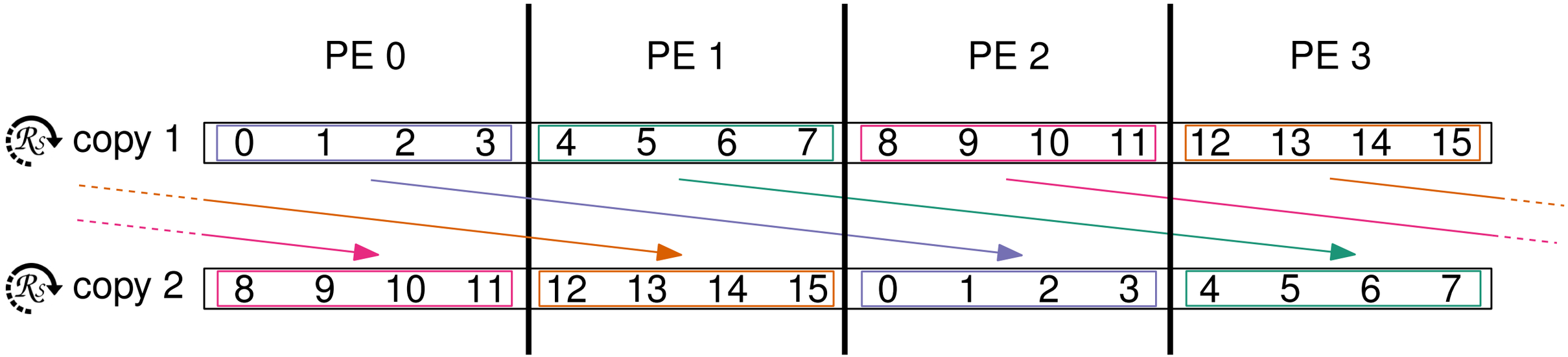
[1] Need for nodes idling until they replace a failing node
[2] Additionally, some nodes used solely to store checkpoints

Basic Data Distribution



- Data distributed across PEs
- Data divided into blocks
- Blocks addressable via IDs

Basic Data Distribution



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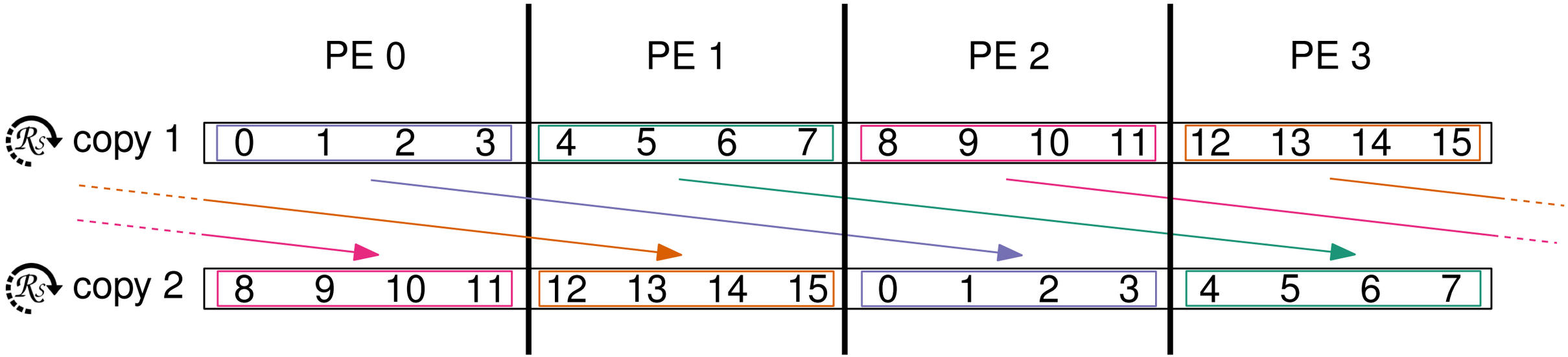
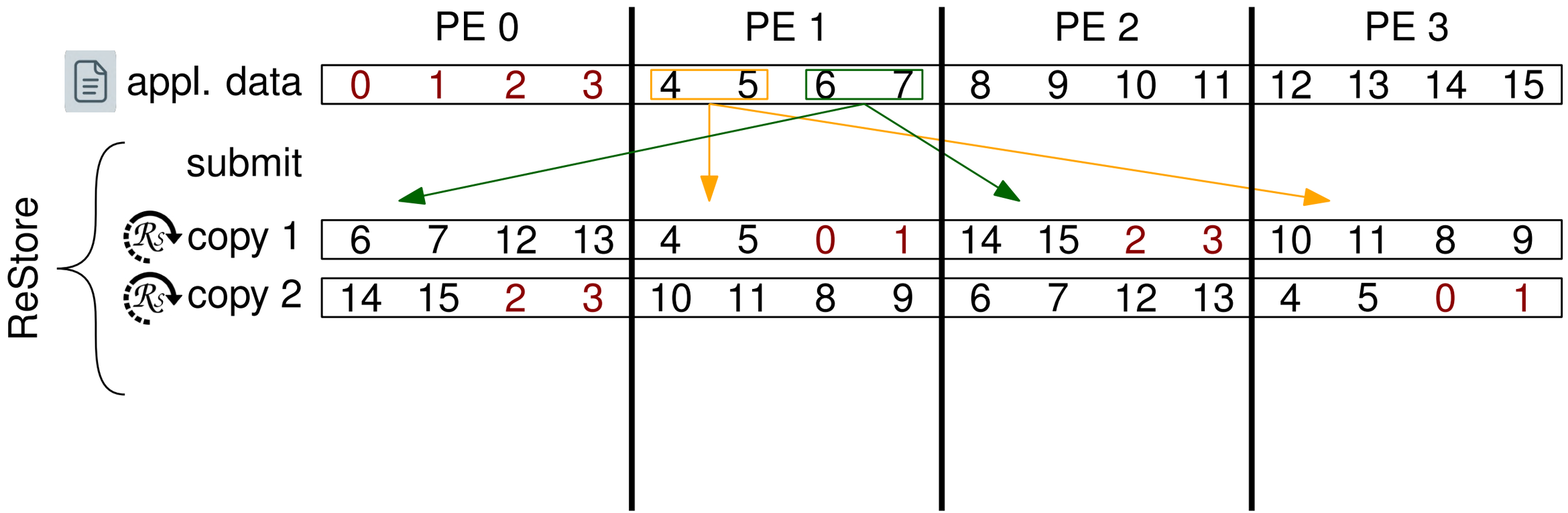


On recovery: $r = 2$ sending nodes $\rightarrow$ bottleneck

Data Distribution for Faster Recovery

- **Idea:** Break up access pattern using a random permutation for the block IDs
- More PEs serving data after failure
- Too many PEs serving data $\rightarrow$ messages too small
- Empirical optimum: Permute $256\,\mathrm{KiB}$ together



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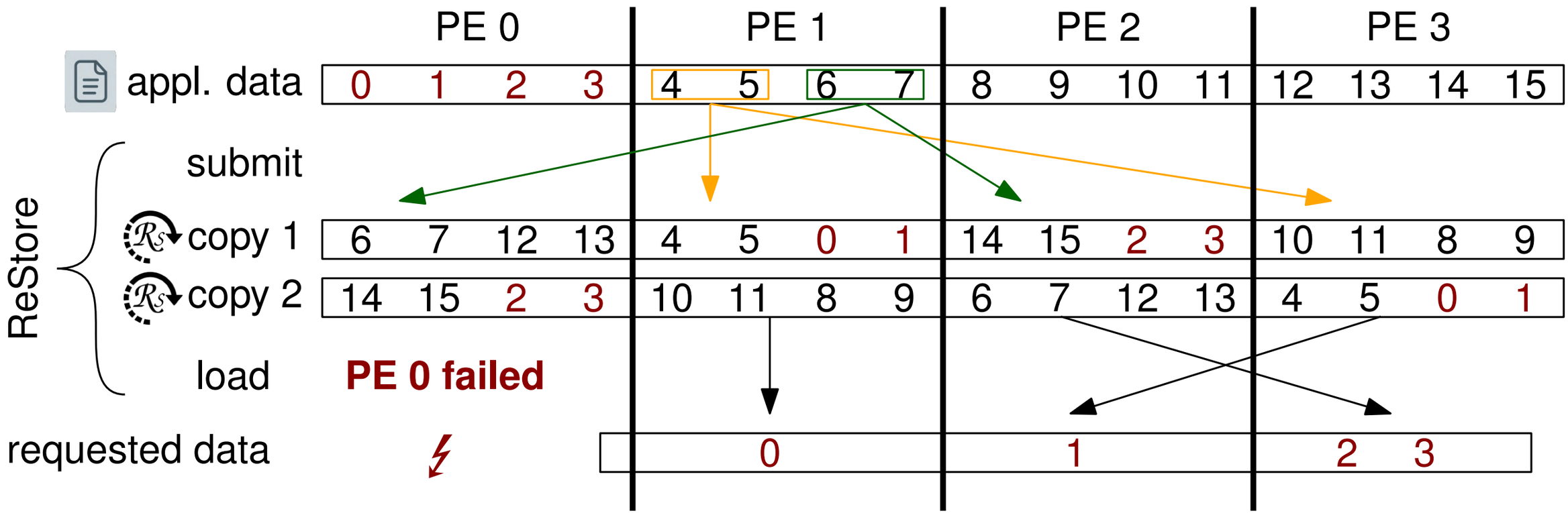

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ReStore: In-Memory REplicated STORagE for Rapid Recovery
HITS • Computational Molecular Evolution
KIT • Institute of Theoretical Informatics

Implementation and Experimental Setup

Implementation

- C++; header-only; modern CMake
- https://github.com/ReStoreCpp/ReStore

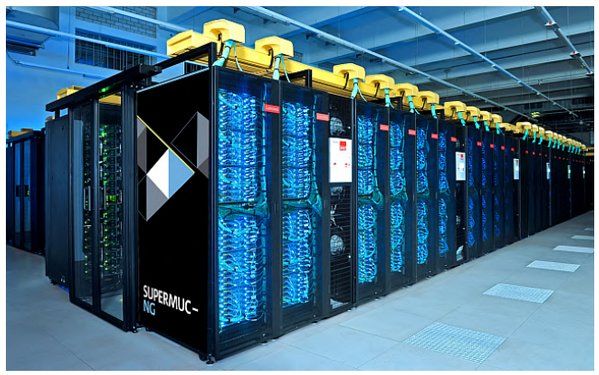
ReStore

Experimental Setup

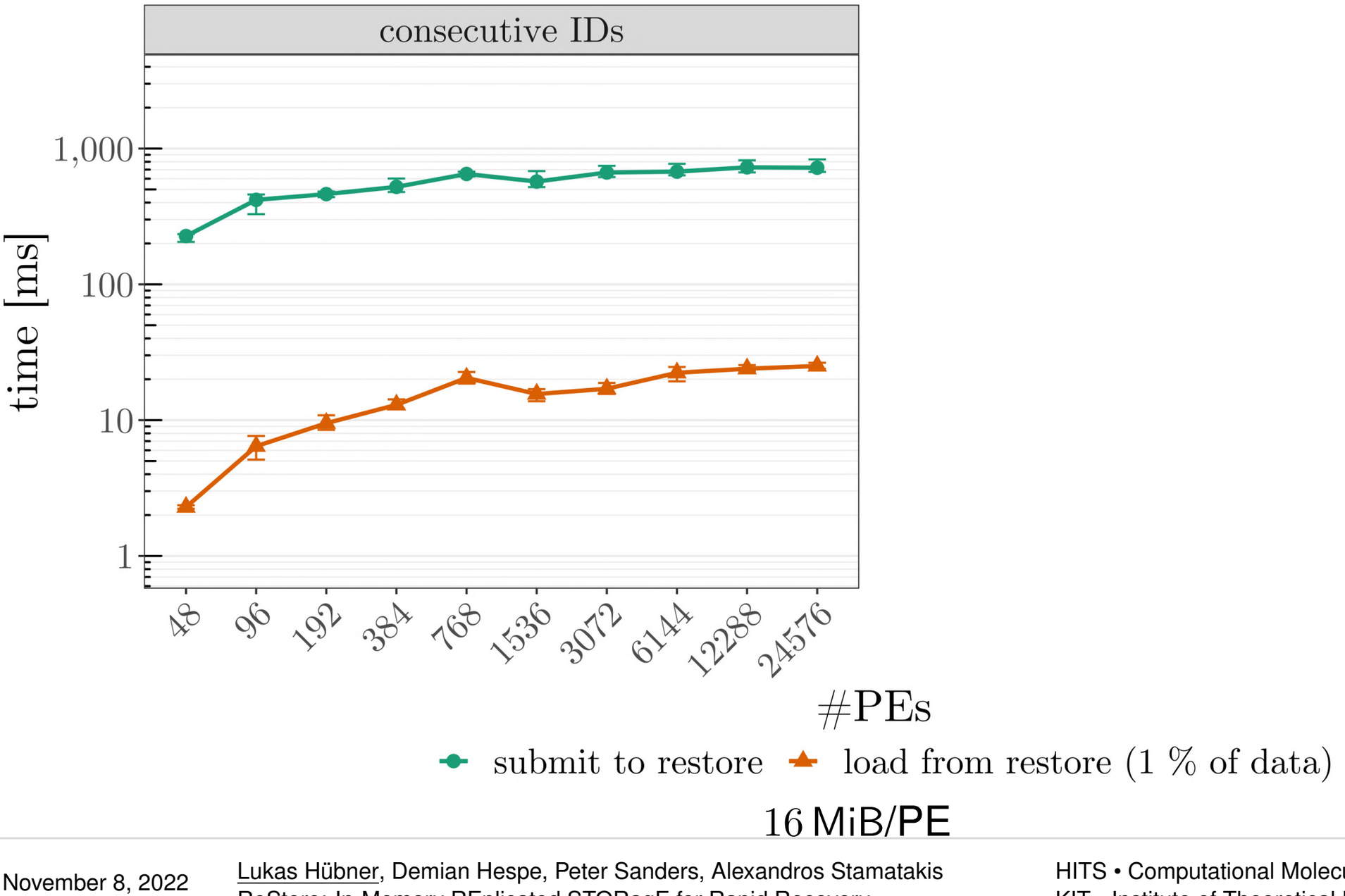
- SuperMUC-NG
- 10 repetitions per experiment
- MPI Implementation: OpenMPI during experiments, ULFM during unit tests

RAxML-NG

- Existing bioinformatics tool
- Real-world application, cited $50\,000$+ times
- Checkpointing dynamic data part of previous work
- Slow loading of input data from parallel file system $\rightarrow$ ReStore



Evaluating ID Randomization



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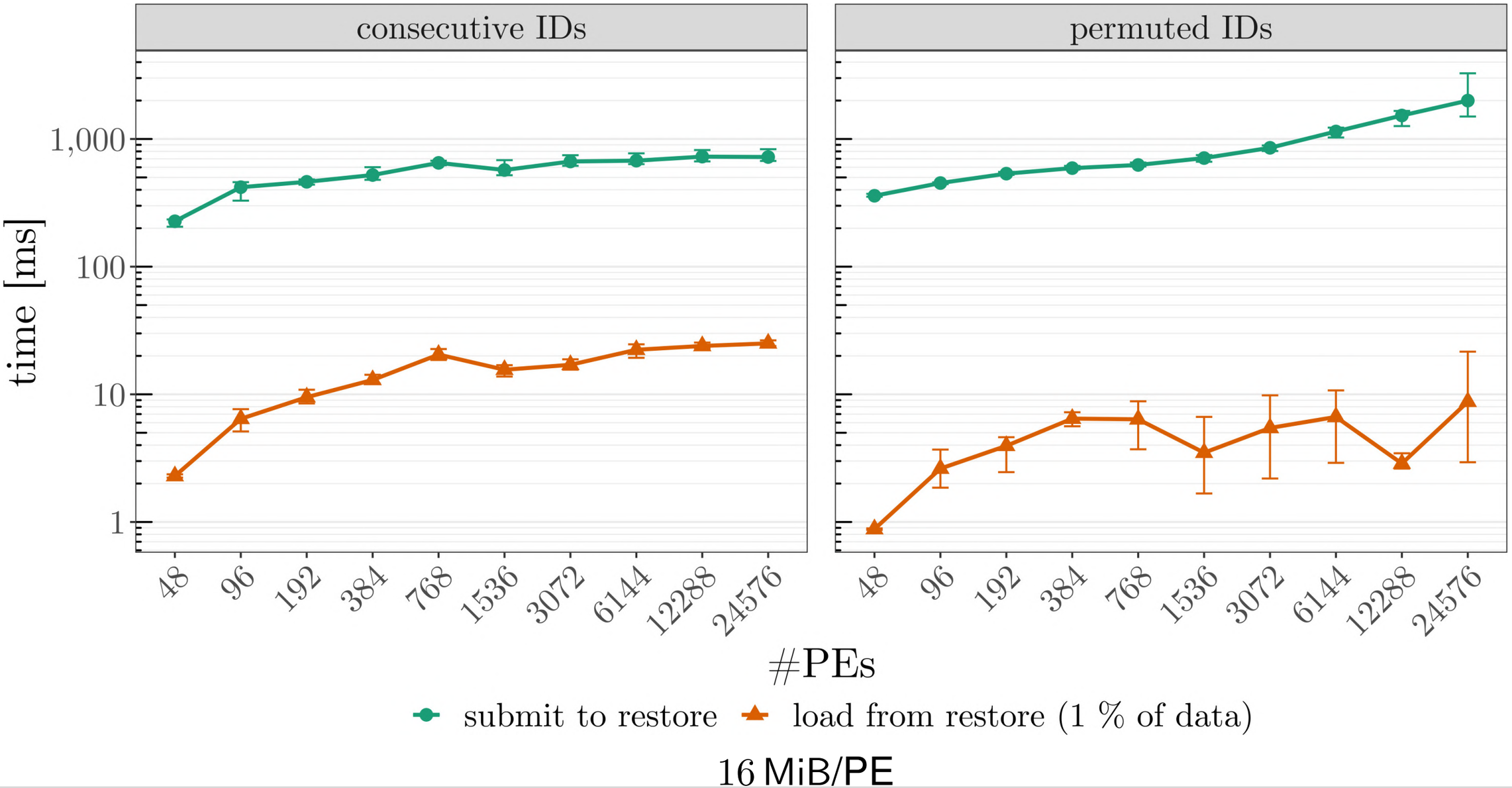
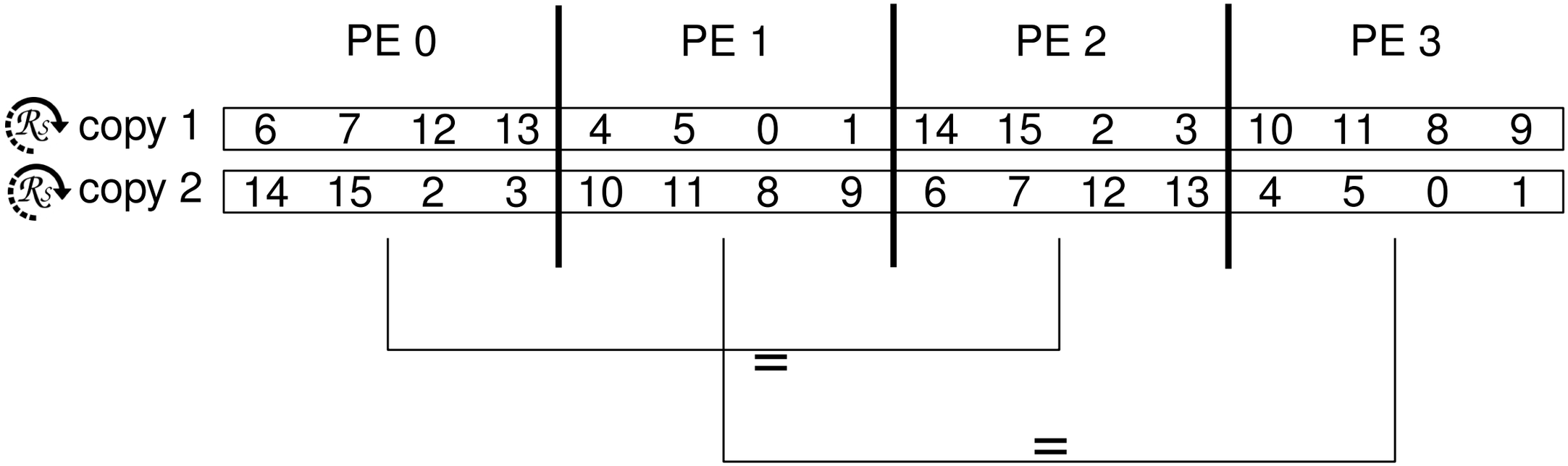


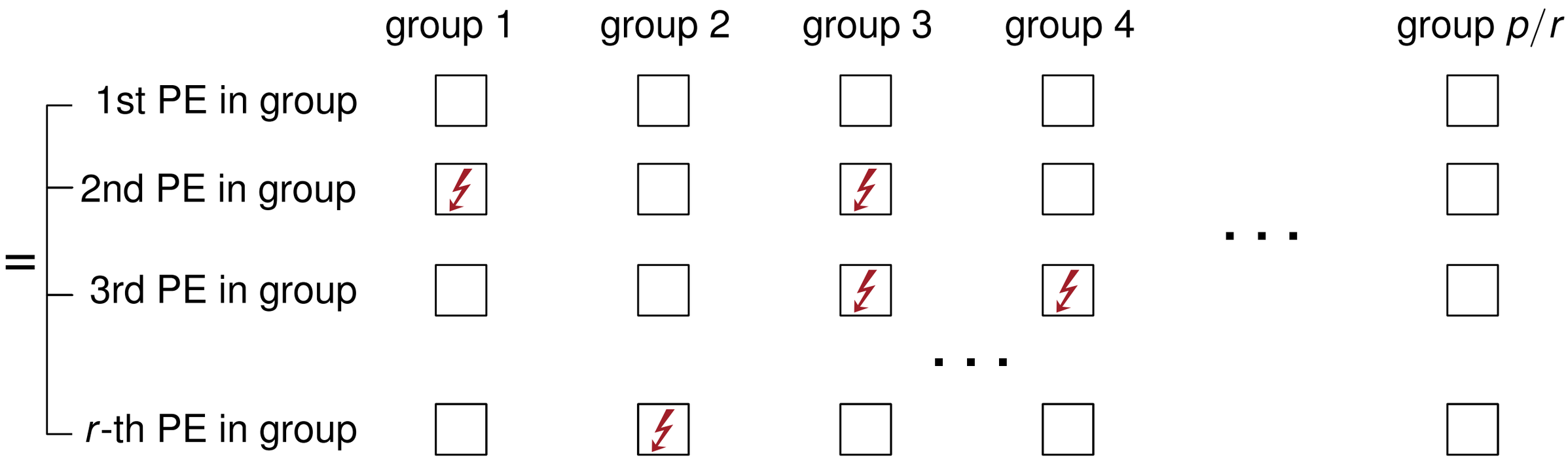
Probability of Irrecoverable Data Loss

Number of replicas r divides number of PEs p
$\rightarrow$ *groups* of PEs storing the same data



Probability of Irrecoverable Data Loss

Given f failures, what is the probability, that all PEs of any group failed?



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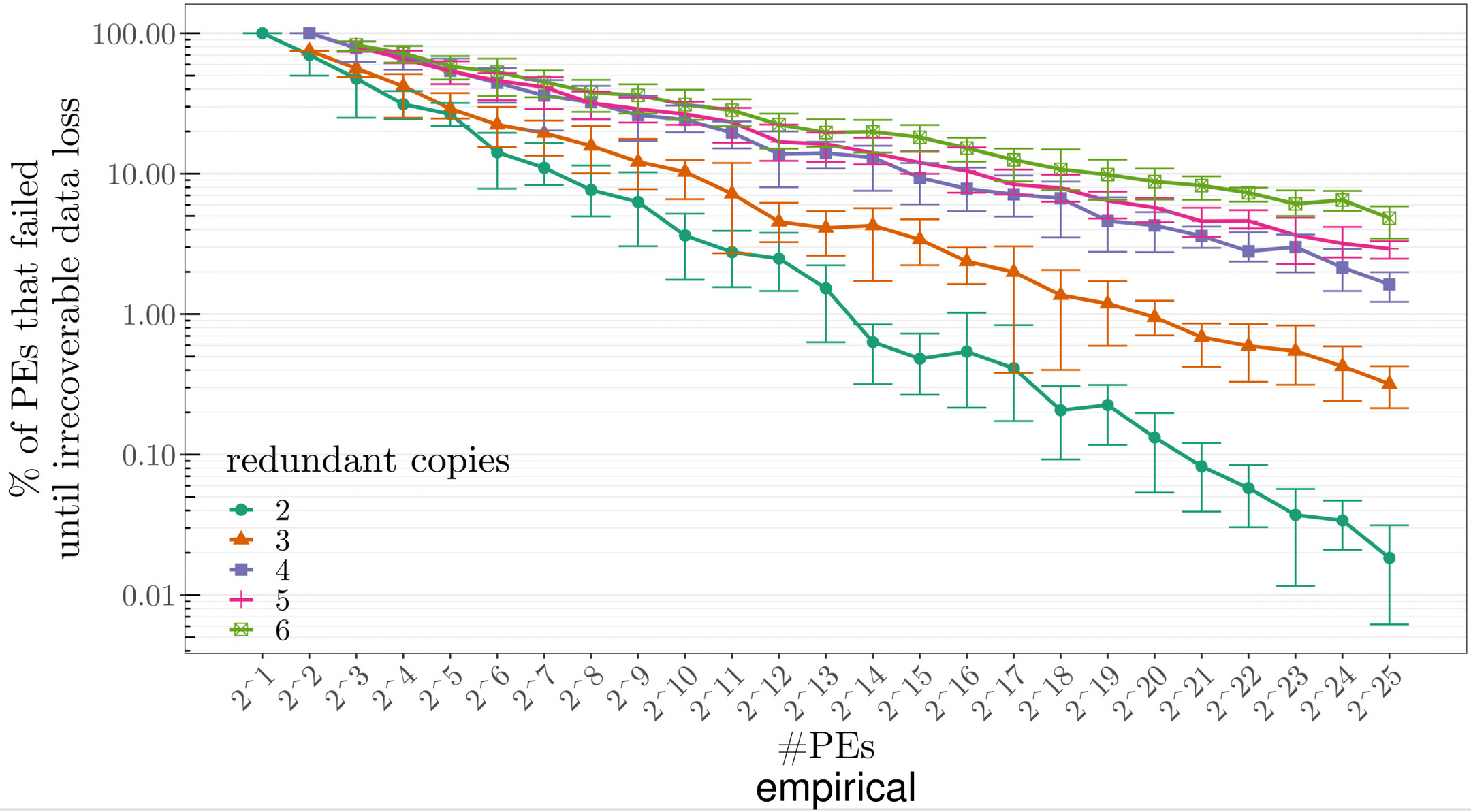

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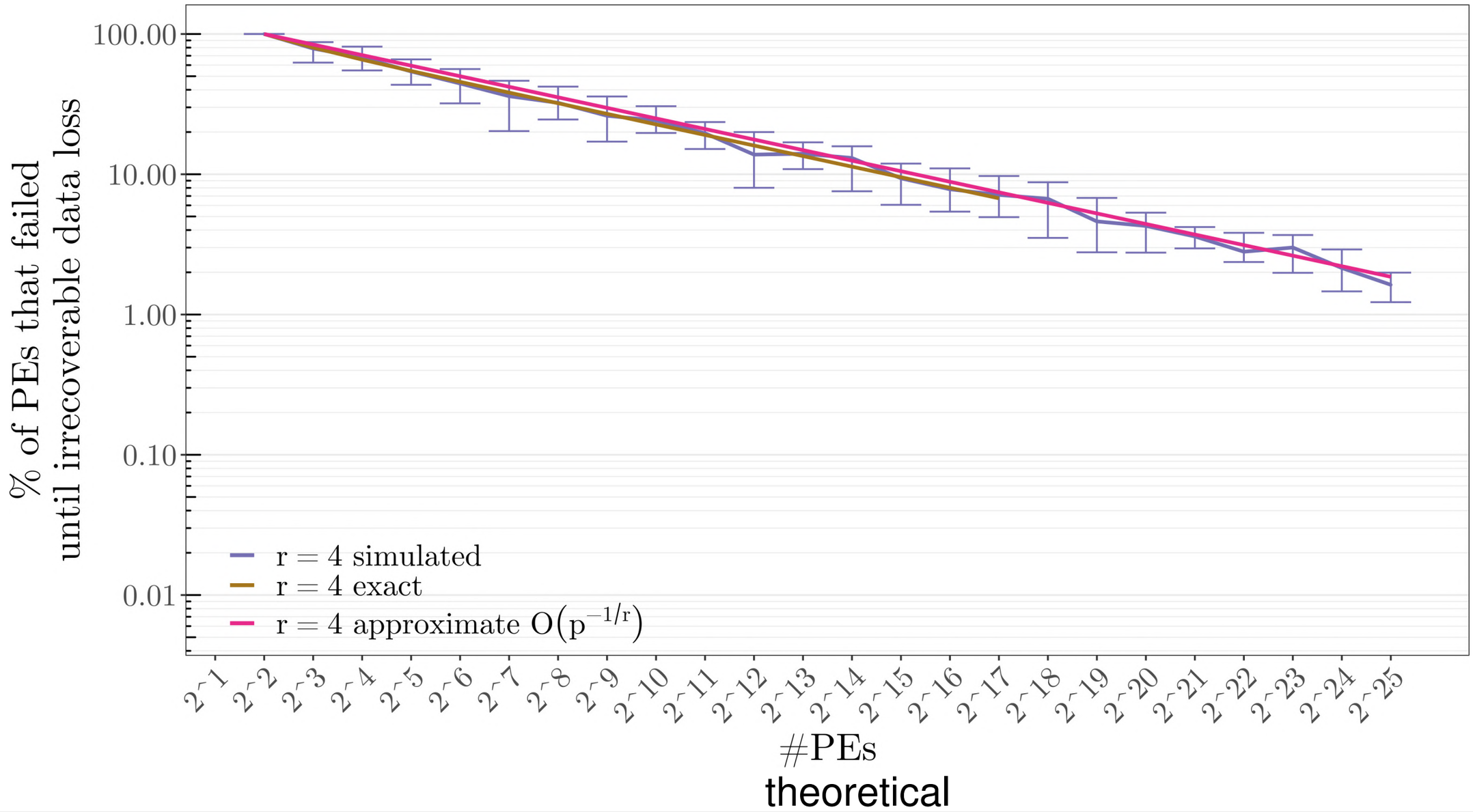
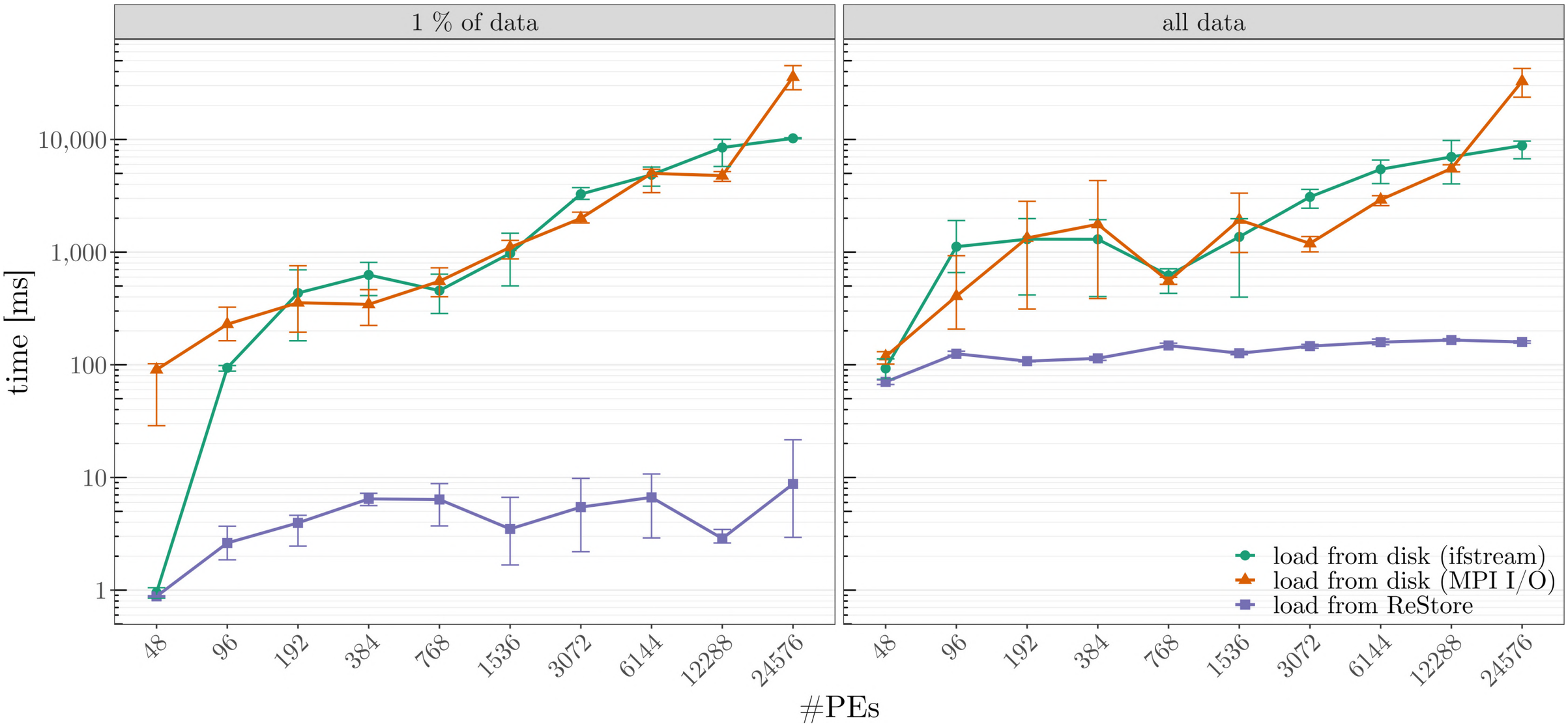
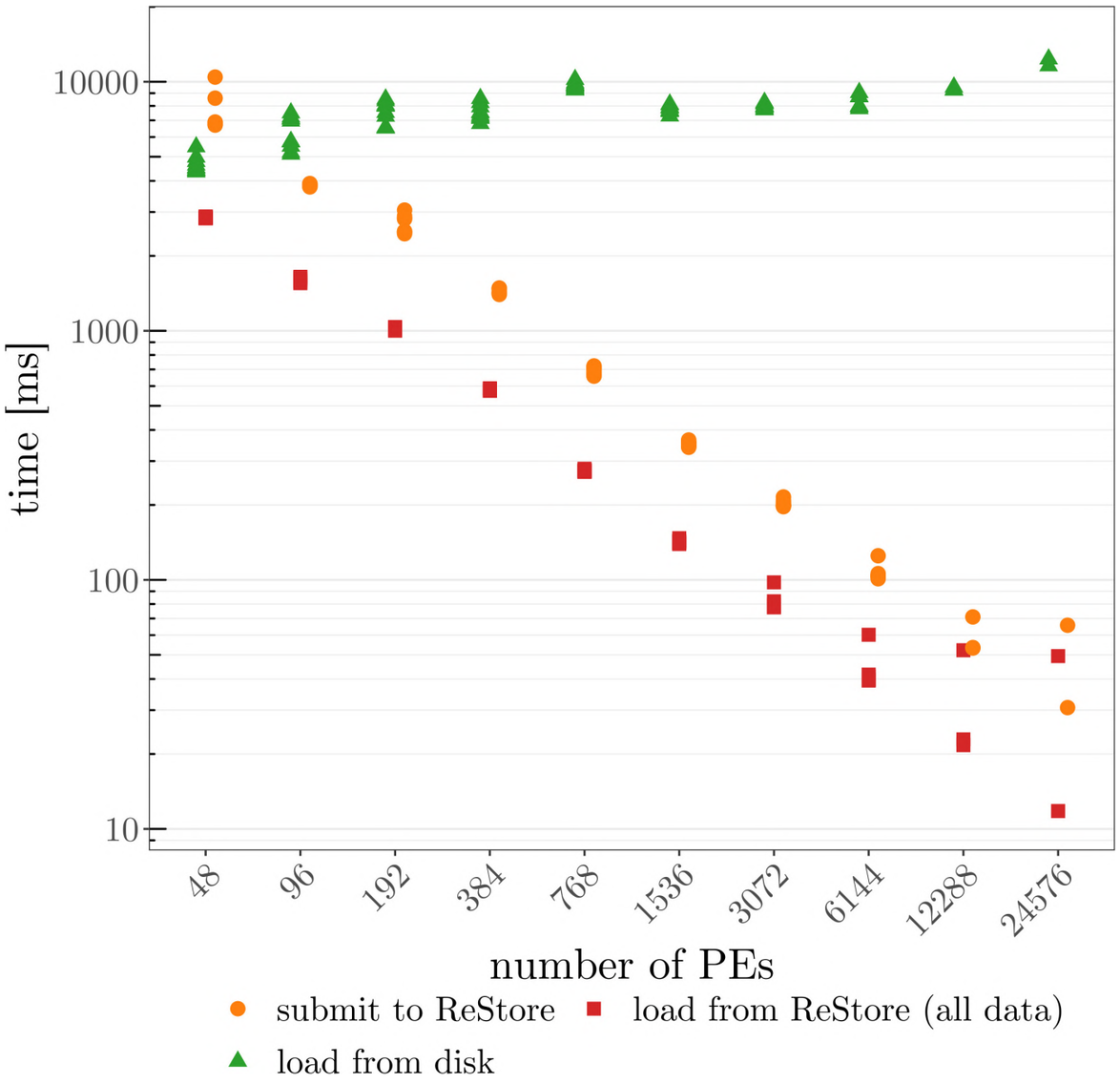


In-Memory vs. Parallel File System



16 MiB data per PE

Overhead of ReStore in RAxML-NG



19.1 GiB synthetic dataset

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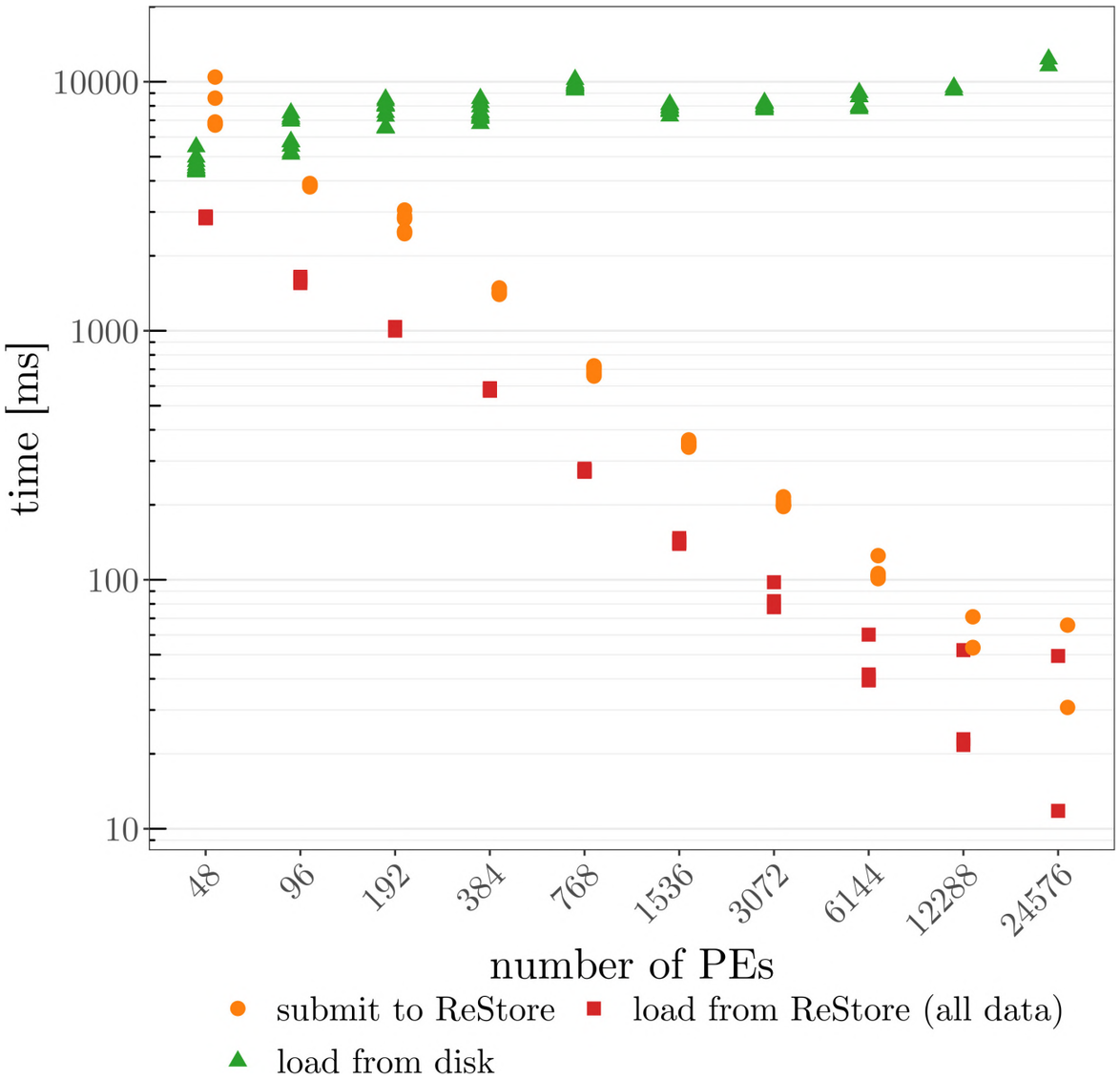

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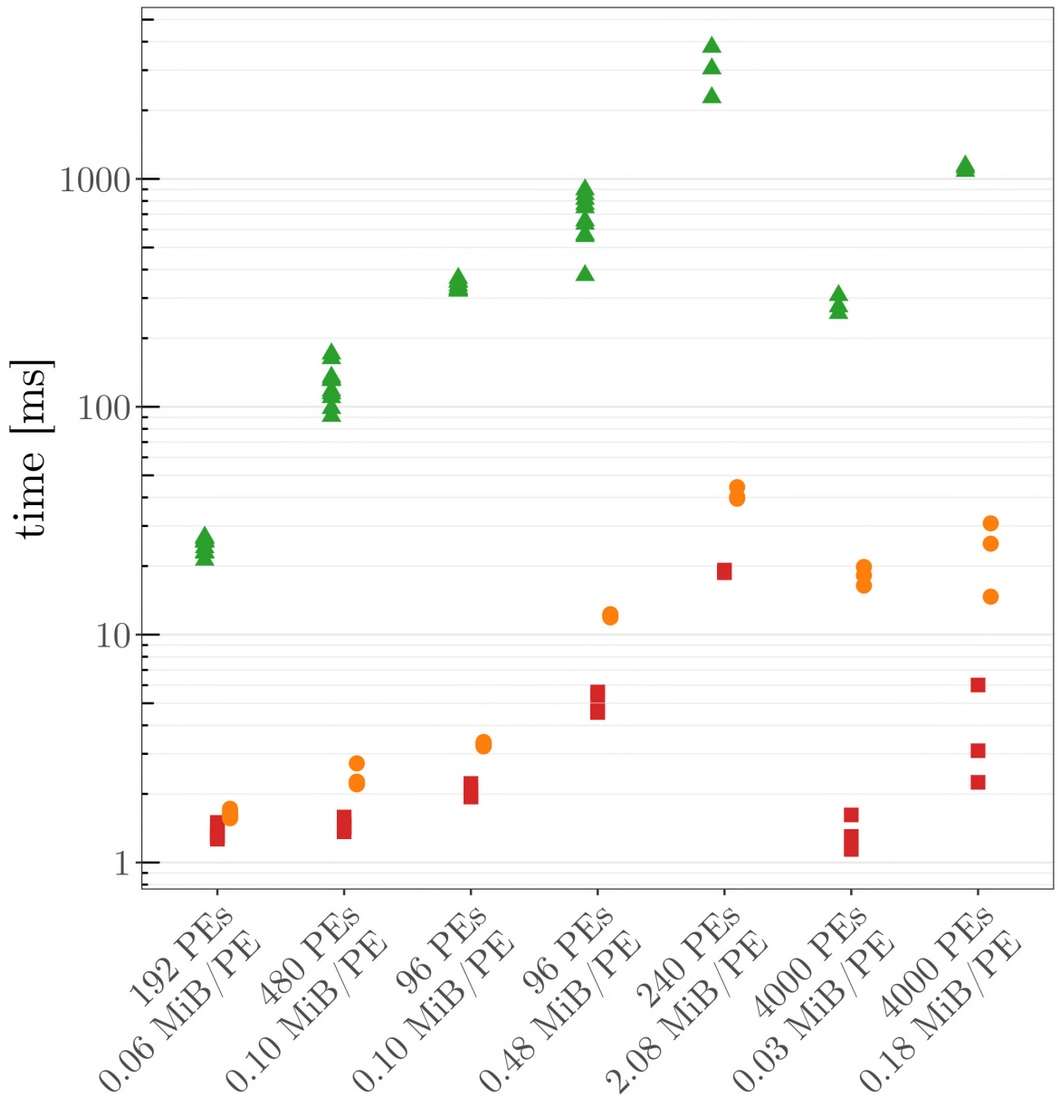
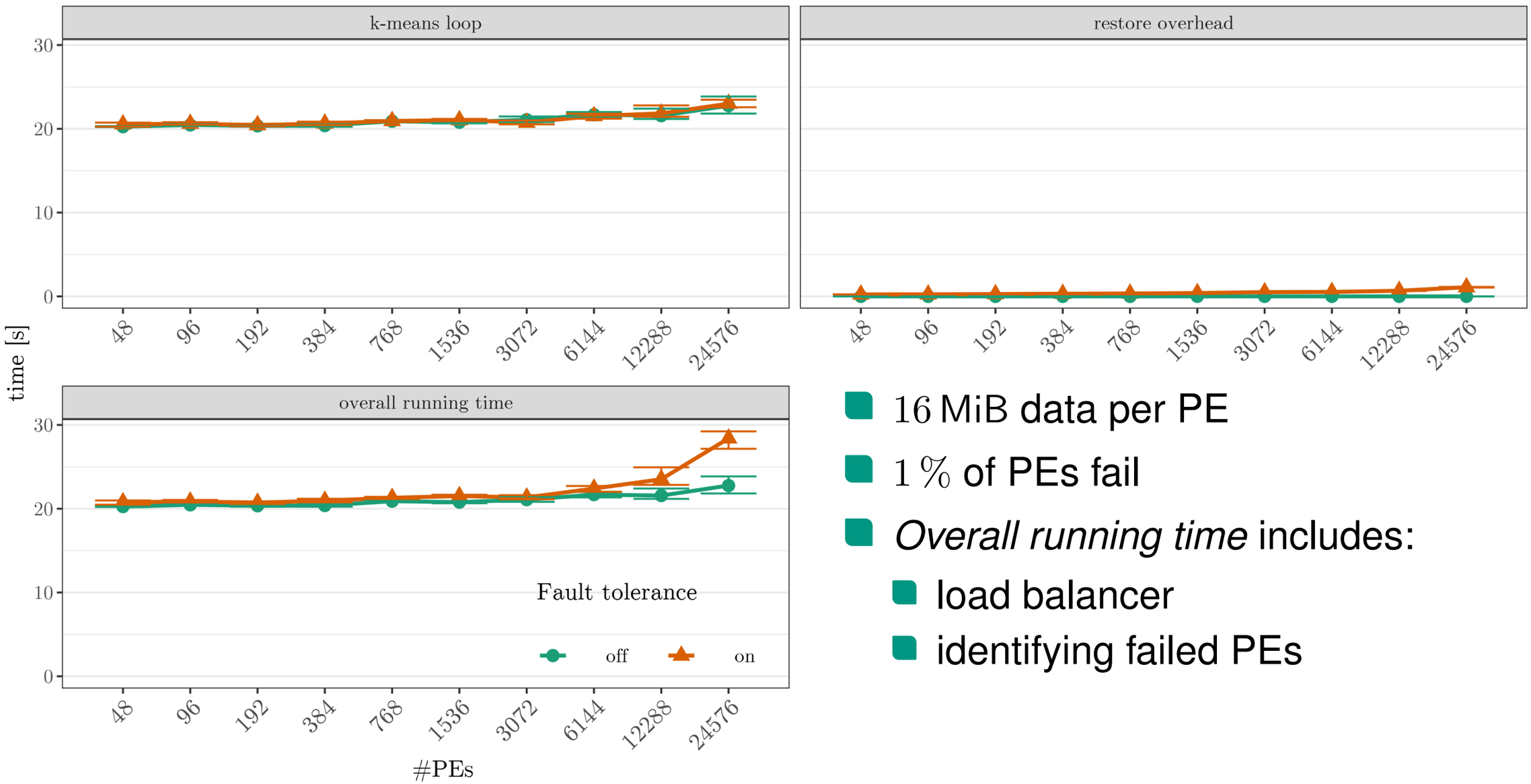


empirical datasets

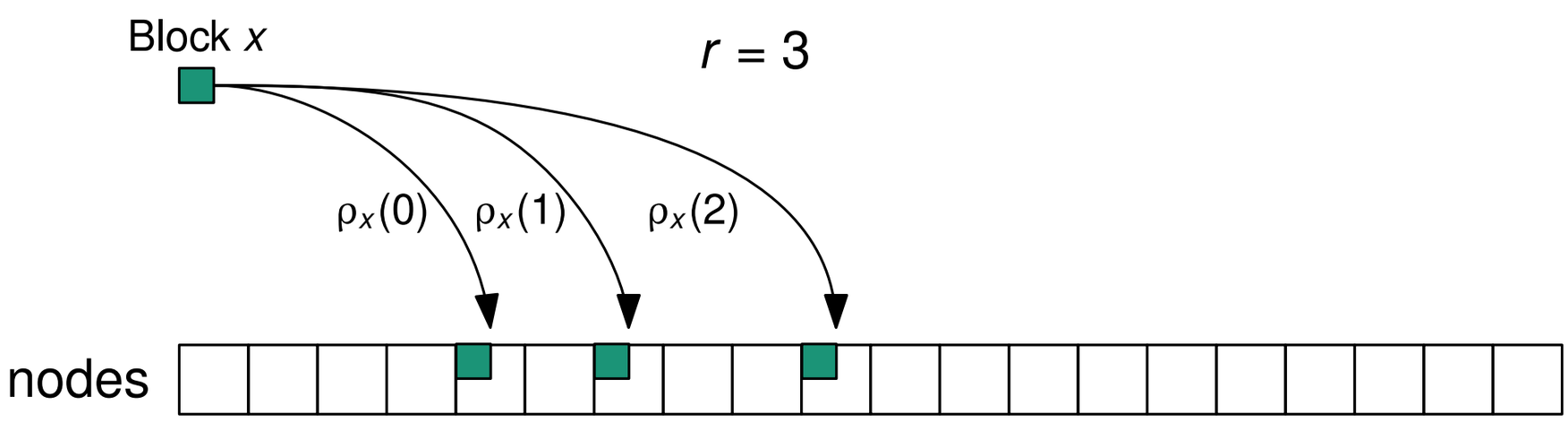
Overhead of ReStore in k-means



- 16 MiB data per PE
- 1 % of PEs fail
- *Overall running time* includes:
  - load balancer
  - identifying failed PEs

Recovering Replicas After a Node Failure

- **Goal:** Restore lost replicas after a failure; copying only the lost data
- **Idea:** For each block x, draw pseudorandom permutation ρ_x on $[0, p-1]$
- Place copies on $\rho_x(0), \rho_x(1), \ldots$
- Nodes on which this block is stored? $\mathcal{O}(r+f)$ time, $\mathcal{O}(1)$ space



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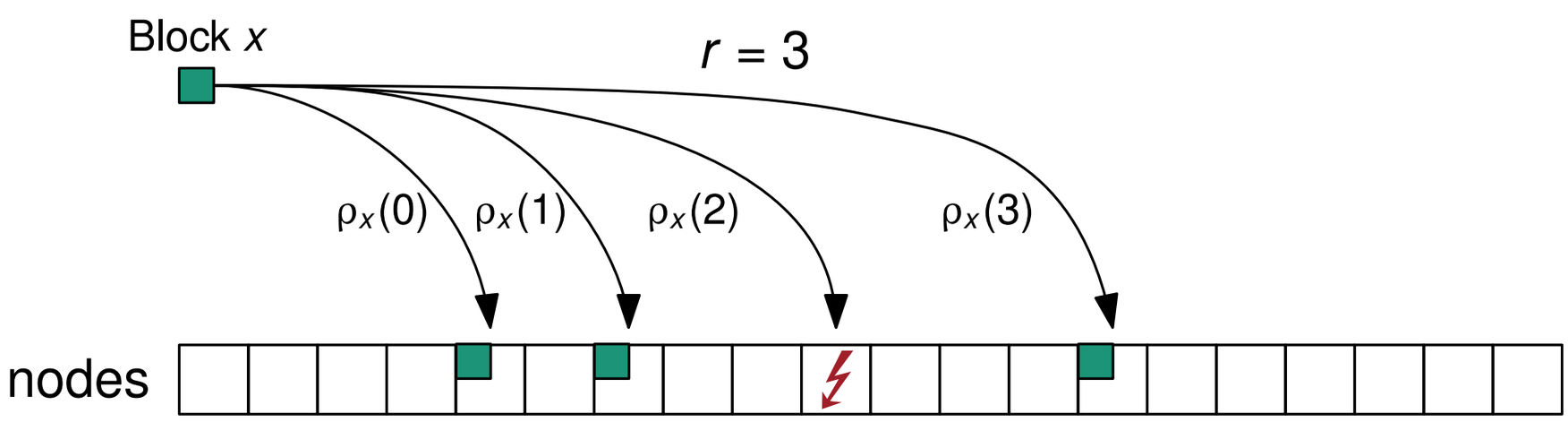

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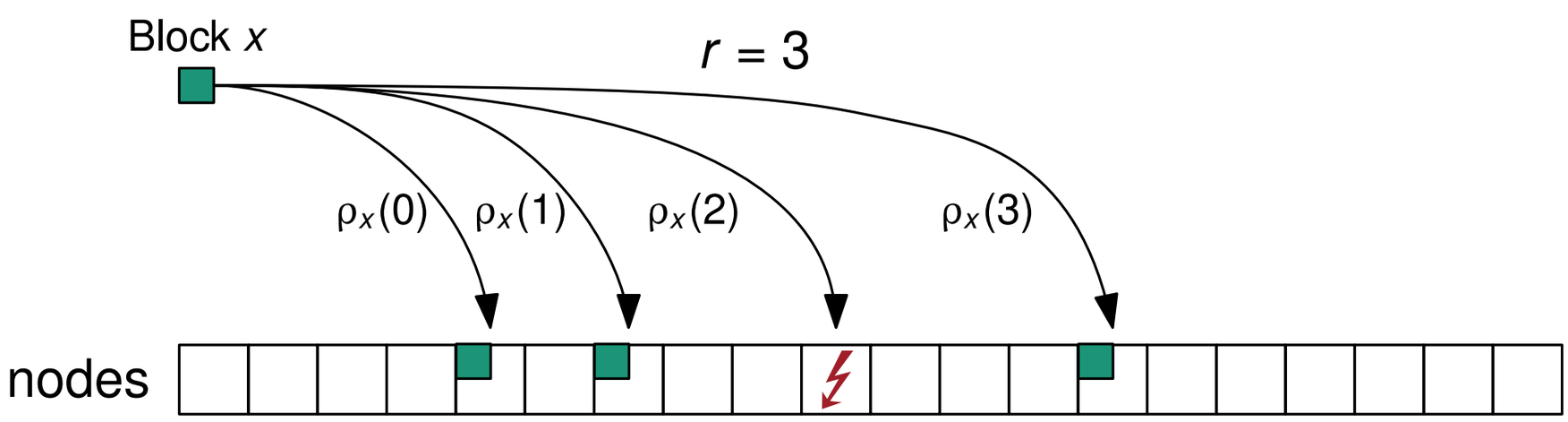


No need to redistribute any block that did not lose a replica!

Conclusion

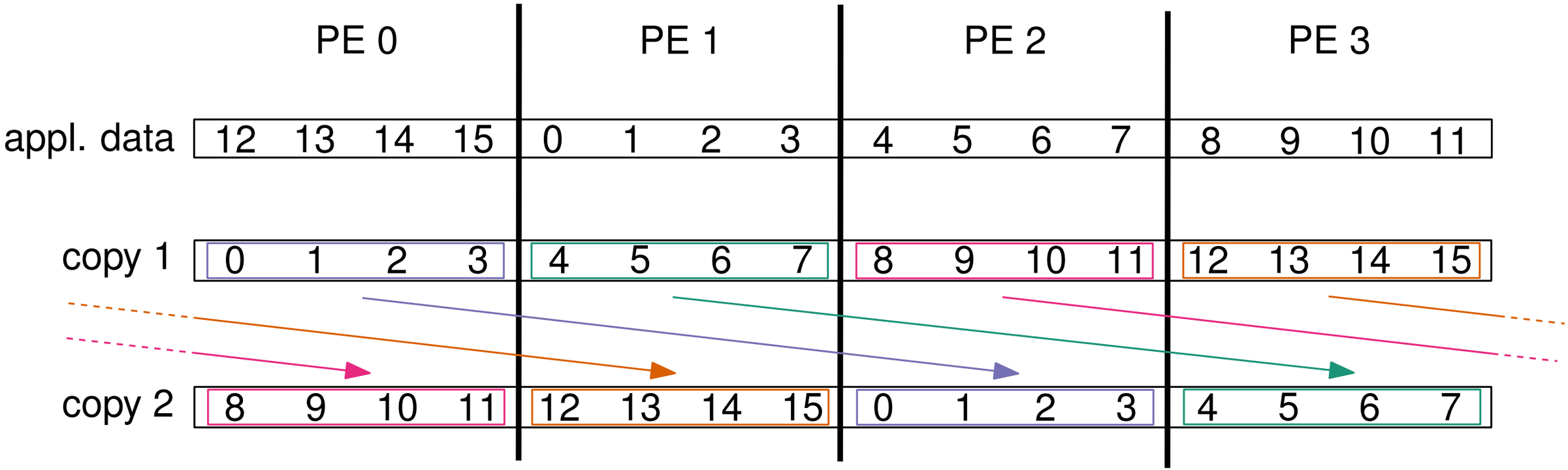
- Permutation-based data distribution enables recovery of lost data in milliseconds on tens of thousands of PEs
- First in-memory library to support shrinking recovery
- RAxML-NG's recovery performance improved by up to two orders of magnitude
- Extension to easily restore lost replicas after a failure
- Provably small probability of data loss

ReStore

https://github.com/ReStoreCpp/ReStore

Thanks for listening :-)

Basic Data Distribution



- Avoid storing the blocks needed after a failure of node *i* on node *i*
- No need to change the distribution of the application data; assigning different IDs when submitting to ReStore is sufficient

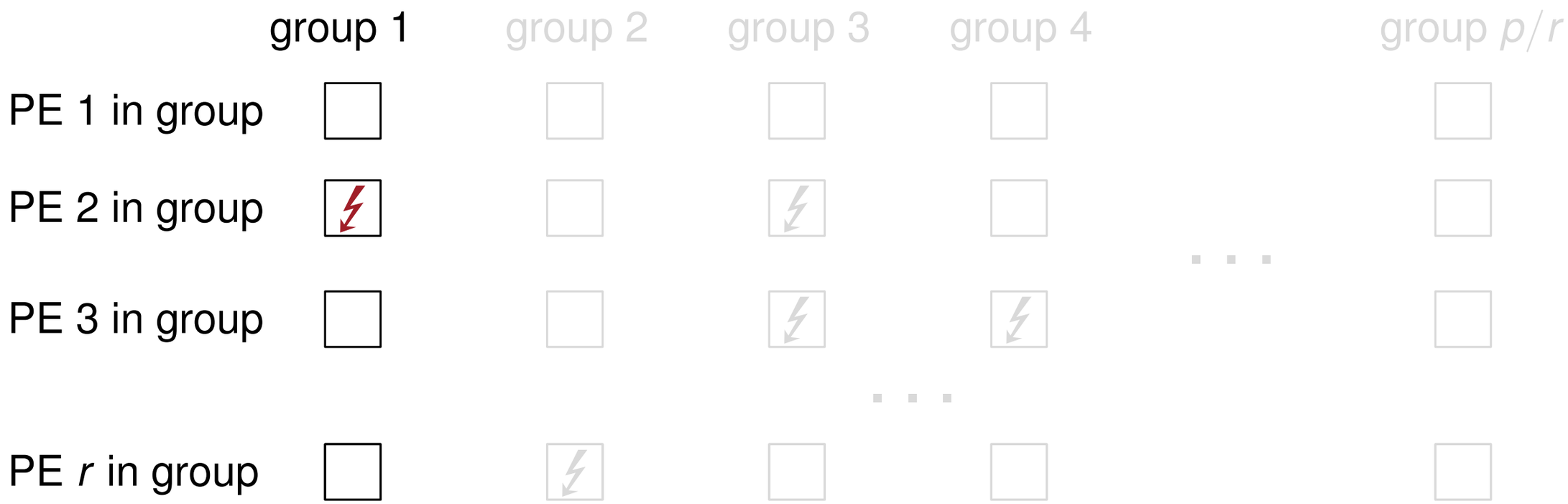
Implementation and Experimental Setup

Experimental Setup

- We benchmark on the SuperMUC-NG
- Two Intel Skylake Xeon 8174 processors with 24 cores each per node
- 96 GiB of RAM per node
- Omnipath interconnect with 100 Gbit s^{-1}
- OpenMPI as MPI implementation
- 10 repetitions per experiment

Probability of Irrecoverable Data Loss

Given f failures, what is the probability, that all copies of group 1 failed?

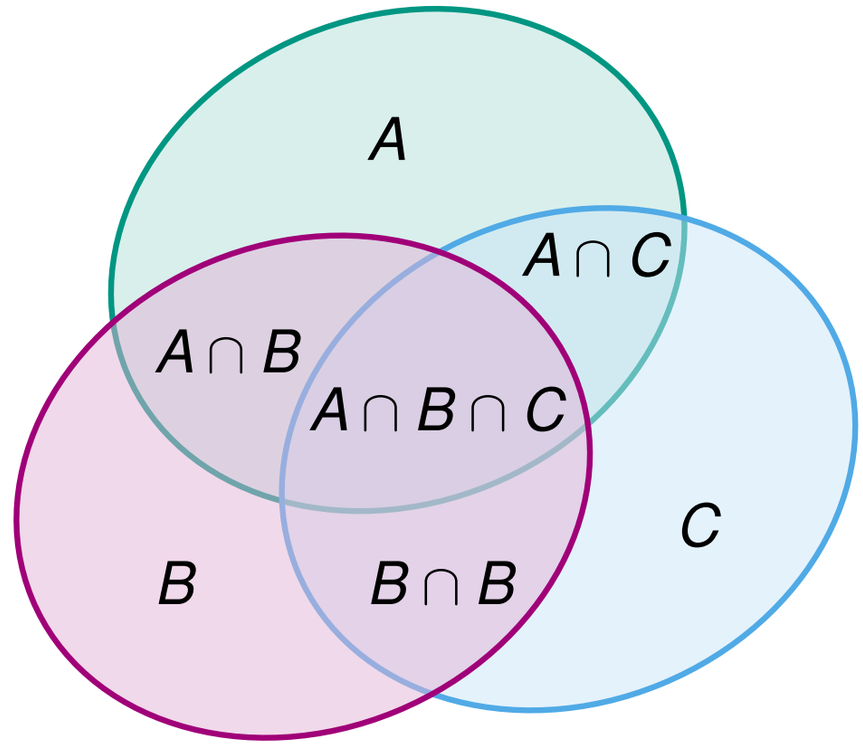


- Number of possibilities to draw f nodes from p nodes: $\binom{p}{f}$
- Number of possibilities to draw all r copies of group 1 plus $f - r$ other nodes: $\binom{p-r}{f-r}$
- $P(\text{All nodes of group 1 failed}) = \binom{p-r}{f-r} / \binom{p}{f}$

Probability of Irrecoverable Data Loss

Inclusion-exclusion principle

$$
\begin{aligned}
|A \cup B \cup C| = &|A| + |B| + |C| \\
&- |A \cap B| - |A \cap C| - |B \cap C| \\
&+ |A \cap B \cap C|
\end{aligned}
$$



Probability of Irrecoverable Data Loss

- Given f, there are $\binom{p-r}{f-r}$ configurations of failed nodes which lead to data loss
- Summing up over all groups would count certain states twice, trice, ...
- E.g., states in which *all* nodes of group 1 and group 2 failed would be counted twice

$$P_{\text{IDL}}^{\leq}(f) = \sum_{j=1}^{g} (-1)^{j+1} \binom{g}{j} \frac{\binom{p-jr}{f-jr}}{\binom{p}{f}}$$

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probability of irrecoverable data loss at failure f or any failure before $\longrightarrow$

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inclusion-exclusion principle

all combinations of $1, \ldots, j, \ldots, g$ groups in which all nodes failed

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number of configurations