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Reliable MPI-IO through Layout-Aware Replication

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U.S. DEPARTMENT OF ENERGY

Potential exascale system architecture: everything must scale with compute!

Systems	2009	2018	Difference
System Peak	2 Pflop/sec	1 Eflop/sec	O(1000)
Power	6 Mwatt	20 Mwatt	
System Memory	0.3 Pbytes	32-64 Pbytes	O(100)
Node Compute	125 Gflop/sec	1-15 Tflop/sec	O(10-100)
Node Memory BW	25 Gbytes/sec	2-4 Tbytes/sec	O(100)
Node Concurrency	12	O(1-10K)	O(100-1000)
Total Node Interconnect BW	3.5 Gbytes/sec	200-400 Gbytes/sec	O(100)
System Size (Nodes)	18,700	O(100,000-1M)	O(10-100)
Total Concurrency	225,000	O(1 billion)	O(10,000)
Storage	15 Pbytes	500-1000 Pbytes	O(10-100)
I/O	0.2 Tbytes/sec	60 Tbytes/sec	O(100)
MTTI	Days	O(1 day)	

Source: J. Dongarra, "Impact of Architecture and Technology for Extreme Scale on Software and Algorithm Design," Cross-cutting Technologies for Computing at the Exascale, February 2-5, 2010.

Extreme scale storage systems will be operating in a faulty environment

Checkpoint/restart is key component to achieve fault tolerance in HPC systems

Meeting rapidly growing need for disk bandwidth requires more number of disks (at 65% AGR) because disk bandwidth is growing at 20% AGR

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Hard disk failure rate is much higher (by a factor of about 15 times higher) than that expected based on MTTF information supplied by manufactures. (Schroeder and Gibson [FAST'07])

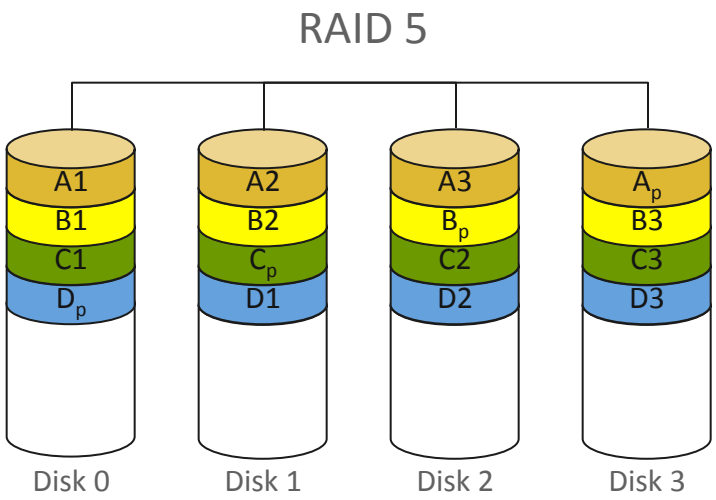
Component failures (MTTF) across several Google cells (Ford et al. [OSDI'10])

Disk	Node	Rack
10~50 years	4.3 months	10.2 yrs

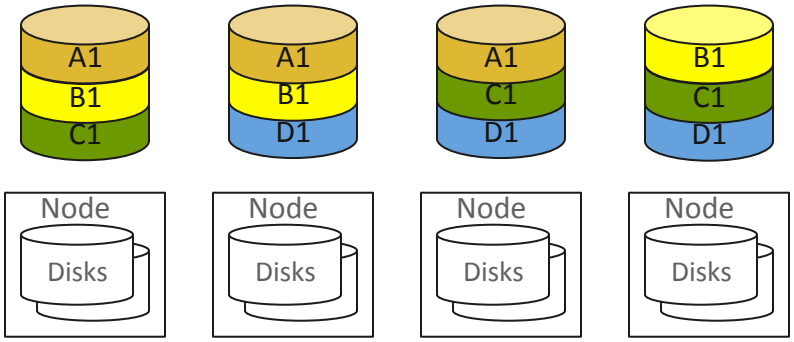
Outline

- Motivation
  - Exascale systems and reliability concern
- Prior work
  - Erasure codes vs. Replication
  - HDFS
- Block replication in MPI-IO
  - Overview
  - Layout-aware MPI Datatypes
  - Client-driven block replication
- Experimental evaluation
  - Microbenchmark and real application benchmark
- Discussion
  - limitations and possible solutions
- Related work
- Conclusion

Erasure codes vs. replication



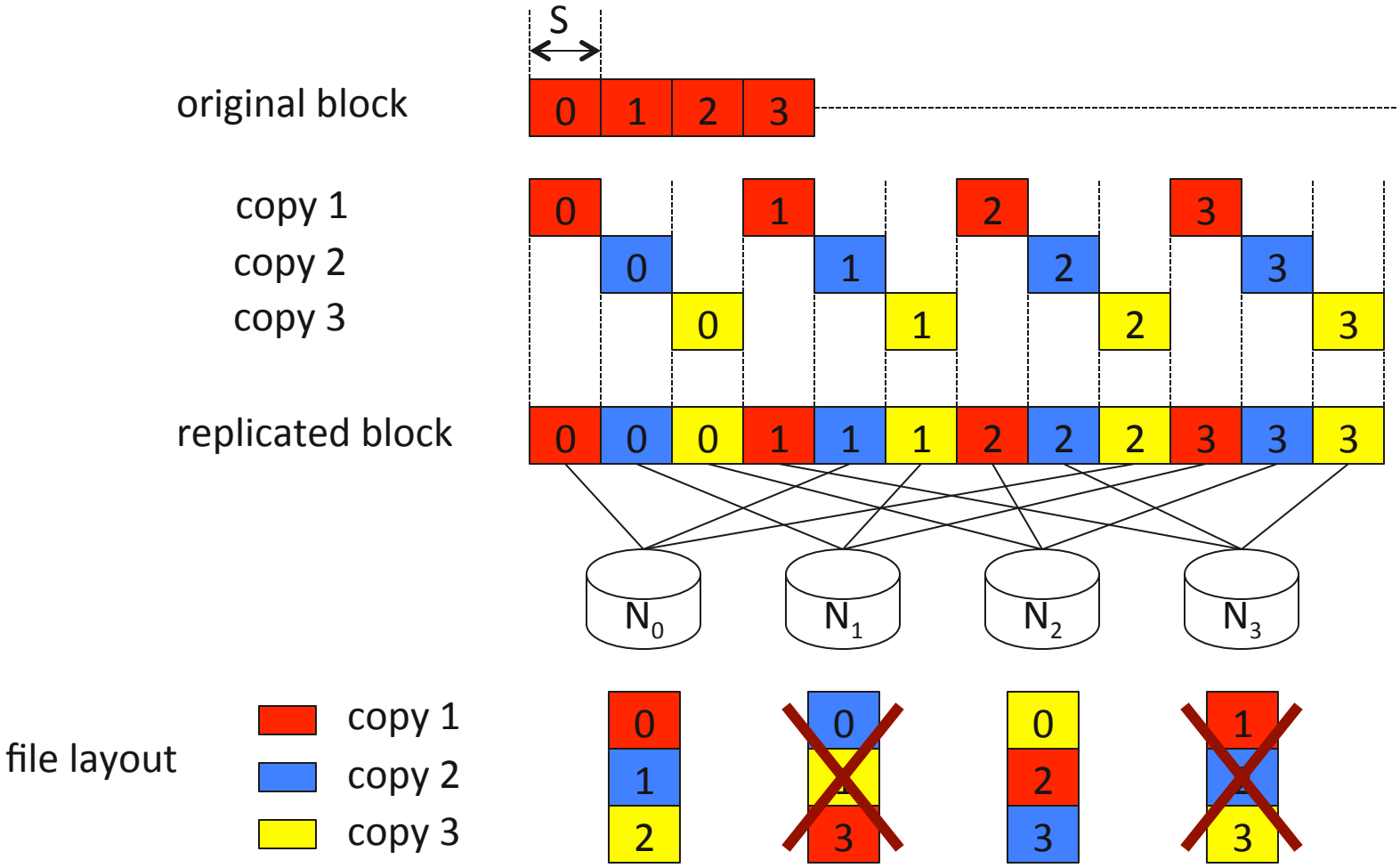
- Typically underneath the parallel file systems
- Works at a fine block granularity
- High cost to purchase hardware disk arrays
- Needs to read two or more of the remaining blocks for rebuilding



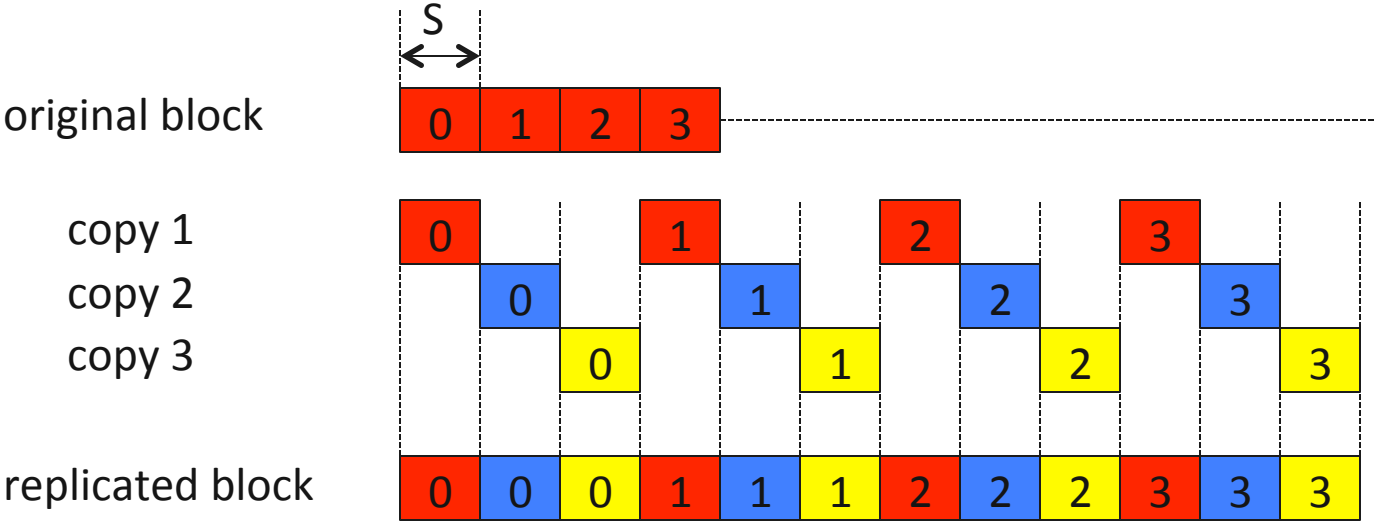
- Recently used in distributed file systems for MapReduce/Hadoop, e.g., HDFS, GFS
- Coarse block granularity, 64MB in HDFS
- Requires only one copy for rebuilding
- High storage overhead, e.g., 200%

We want to emulate replication within MPI-IO!

Block replication in a single file across stripe boundaries



We use MPI datatypes for representing each replica



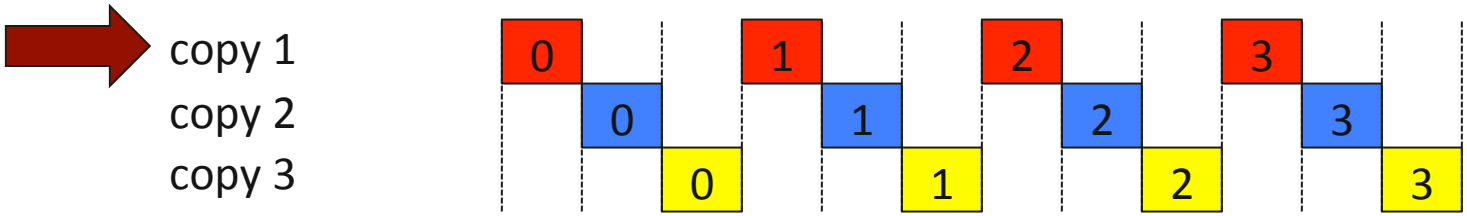
$$D_{orig} = \{(s_0, d_0), (s_1, d_1), \cdots, (s_{n-1}, d_{n-1})\}$$

$$D_{copy1} = \{(s_0, d_0), (s_1, d_1 + 3S), \cdots, (s_{n-1}, d_{n-1} + 3S * (n-1))\}$$

$$D_{copy2} = \{(s_0, d_0 + S), (s_1, d_1 + S + 3S), \cdots, (s_{n-1}, d_{n-1} + S + 3S * (n-1))\}$$

$$D_{copy3} = \{(s_0, d_0 + 2S), (s_1, d_1 + 2S + 3S), \cdots, (s_{n-1}, d_{n-1} + 2S + 3S * (n-1))\}$$

MPI derived dataypes and fileview



MPI-IO allows users to access several noncontiguous pieces of data by defining file views with derived datatypes.

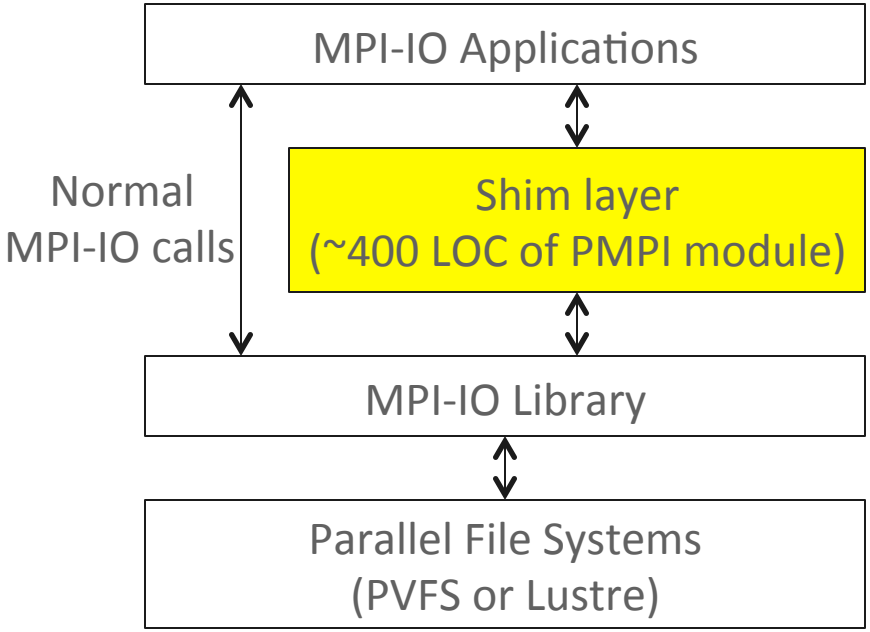
$$D_{copy1} = \{(s_0, d_0), (s_1, d_1 + 3S), \cdots, (s_{n-1}, d_{n-1} + 3S * (n-1))\}$$

```
ncount = 4;
blocklens[ncount] = {S, S, S, S};
offsets[ncount] = {0, 3S, 6S, 9S};

MPI_Type_create_hindexed (ncount, blocklens[], offsets[],
                          old_type, &newtype);
MPI_Type_commit (&newtype);


MPI_File_set_view (fh, 0, old_type, newtype, …);
MPI_File_write (fh, buf, count, old_type, &status);
```

Replication is done transparently

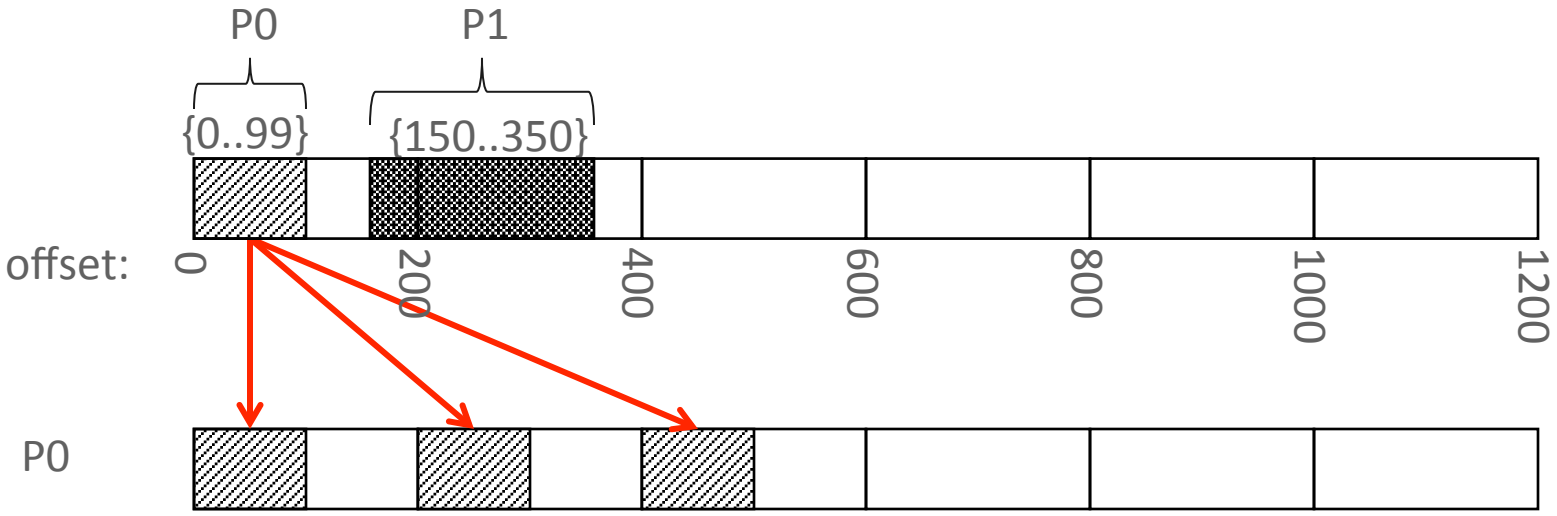



```
MPI_Info_set (info, "RF", "3");
MPI_File_write(fh, buf, count,
                   MPI_INT, &status);
```

```
MPI_File_write(…)
{
  create 3 derived datatypes;
  for(i=0; i<RF; i++)
  {
    MPI_File_set_view(…);
    PMPI_File_write(…);
  }
}
```

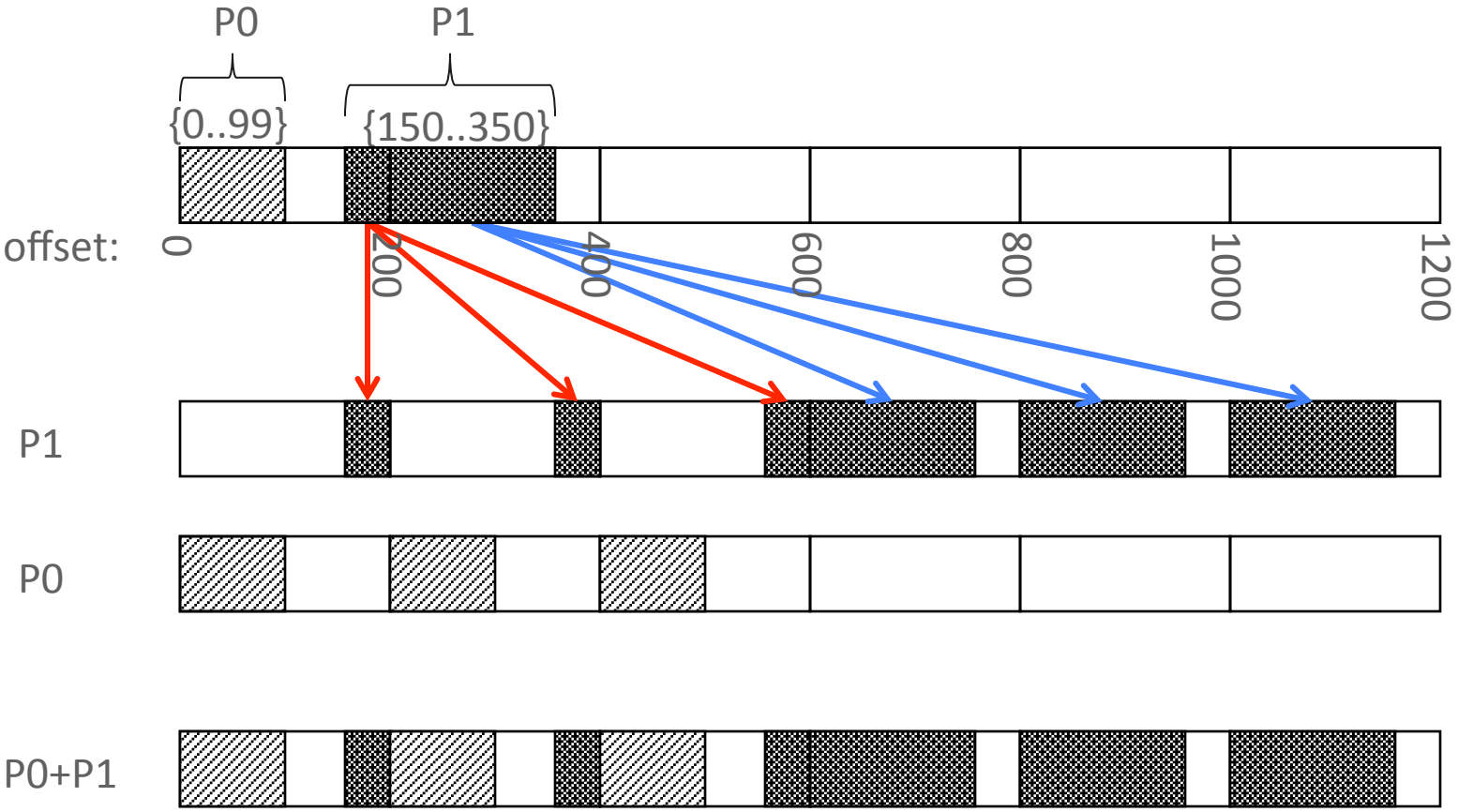
Example

Assuming stripe size = 200 bytes,
Rank 0 (P0) writes 100 bytes at offset 0, and
Rank 1 (P1) writes 200 bytes at offset 150

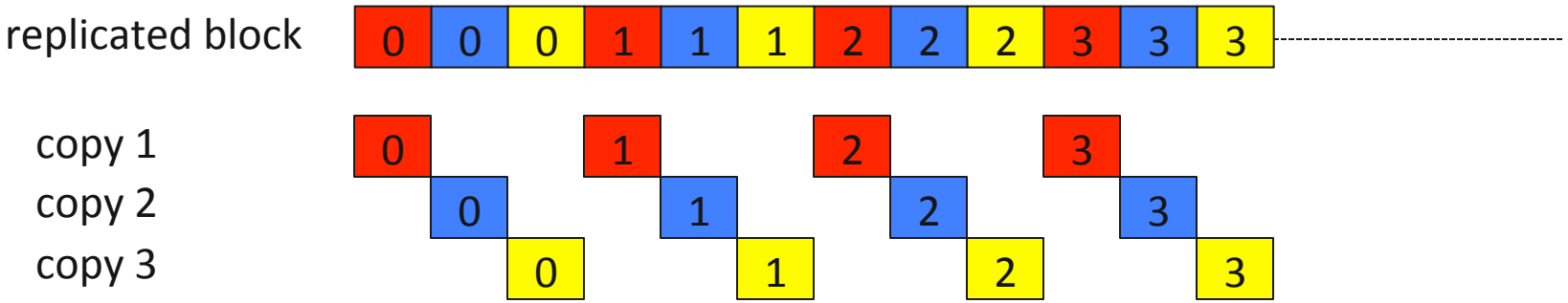


Example - cont'd

Assuming stripe size = 200 bytes,
Rank 0 (P0) writes 100 bytes at offset 0, and
Rank 1 (P1) writes 200 bytes at offset 150



How to deal with reads?

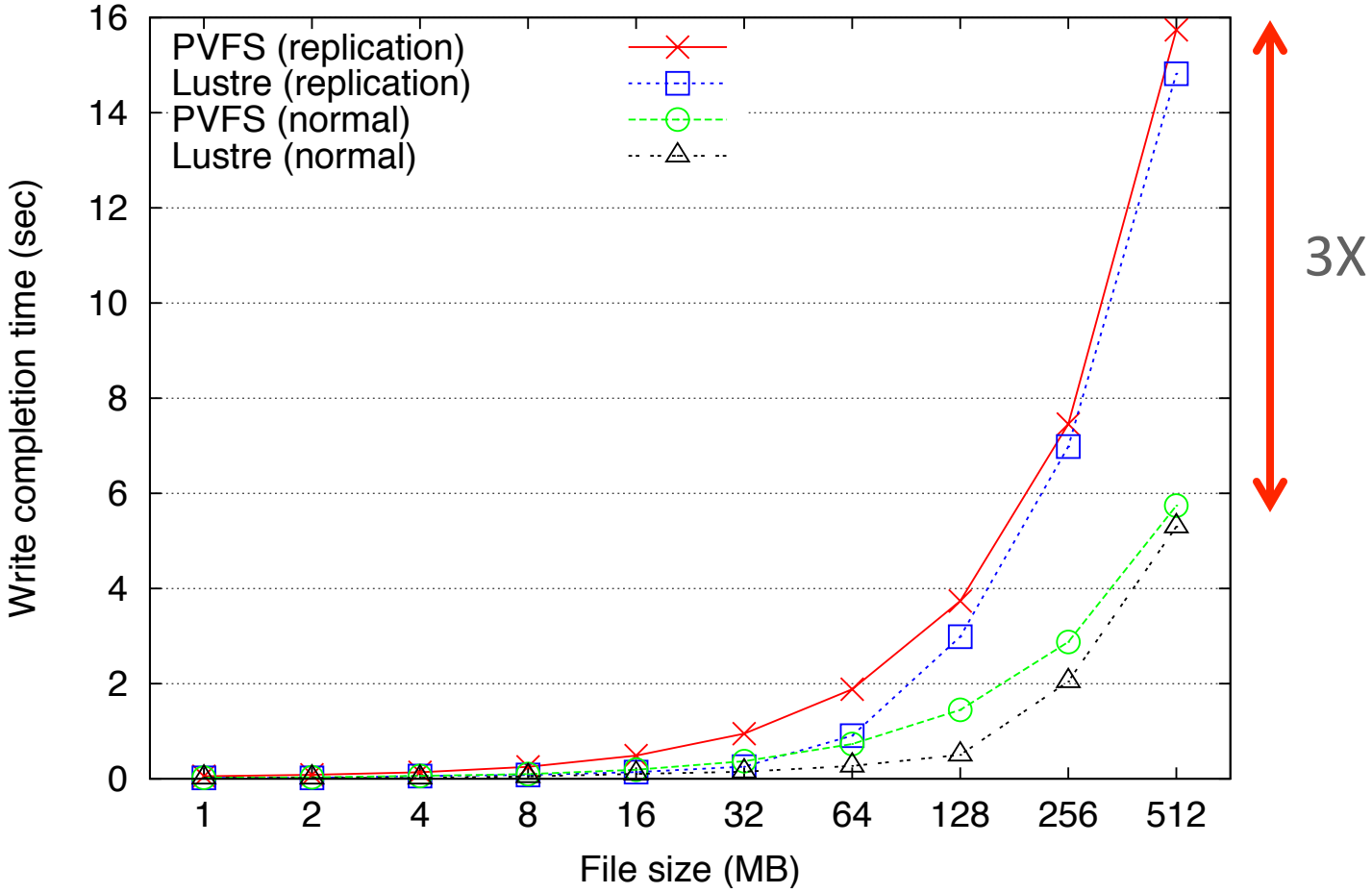



```
MPI_File_read(...)
{
  /* try copy 1 */
  MPI_File_set_view(fh_shadow, 0, ..., hindextype[0], ...);
  PMPI_File_read(fh_shadow, buf, nints, MPI_INT, &status);
  if (status == ERROR)
  {
    /* try copy 2 */
    MPI_File_set_view(fh_shadow, 0, ..., hindextype[1], ...);
    PMPI_File_read(fh_shadow, buf, nints, MPI_INT, &status);
    if (status == ERROR) {
      /* try copy 3 (last) */
      MPI_File_set_view(fh_shadow, 0, ..., hindextype[2], ...);
      PMPI_File_read(fh_shadow, buf, nints, MPI_INT, &status);
    }
  }
}
```

Experimental Methodology

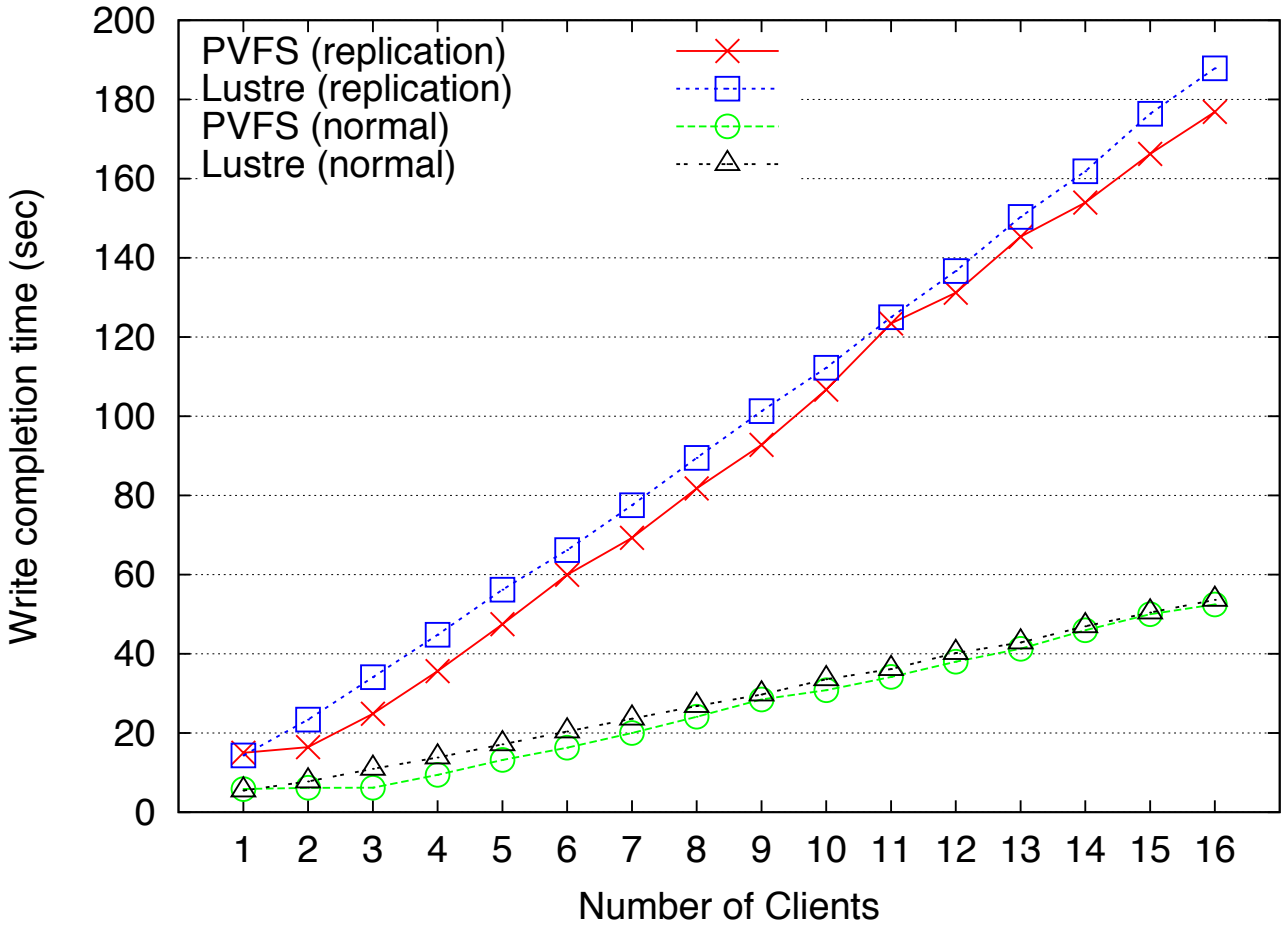
- Evaluation platform
  - A cluster of 24 nodes
    - Each node: Dual Intel Xeon Quad core 2.66 GHz, 16 GB main memory, 50 GB local storage space
  - All nodes run the Linux 2.6.22 kernel, connected thorough 1GE
  - MPI library: MPICH2-1.3.1
  - Parallel file systems: PVFS-2.8.1 and Lustre 1.6.4.2
    - Configured to use 4 storage nodes
    - Default stripe size: 1 MB
- Evaluated schemes
  - Normal: without replication
  - Replication: our MPI triplication scheme
- Evaluation metric
  - Write completion time: micro and application benchmark

Replication overhead increases w.r.t replication factor

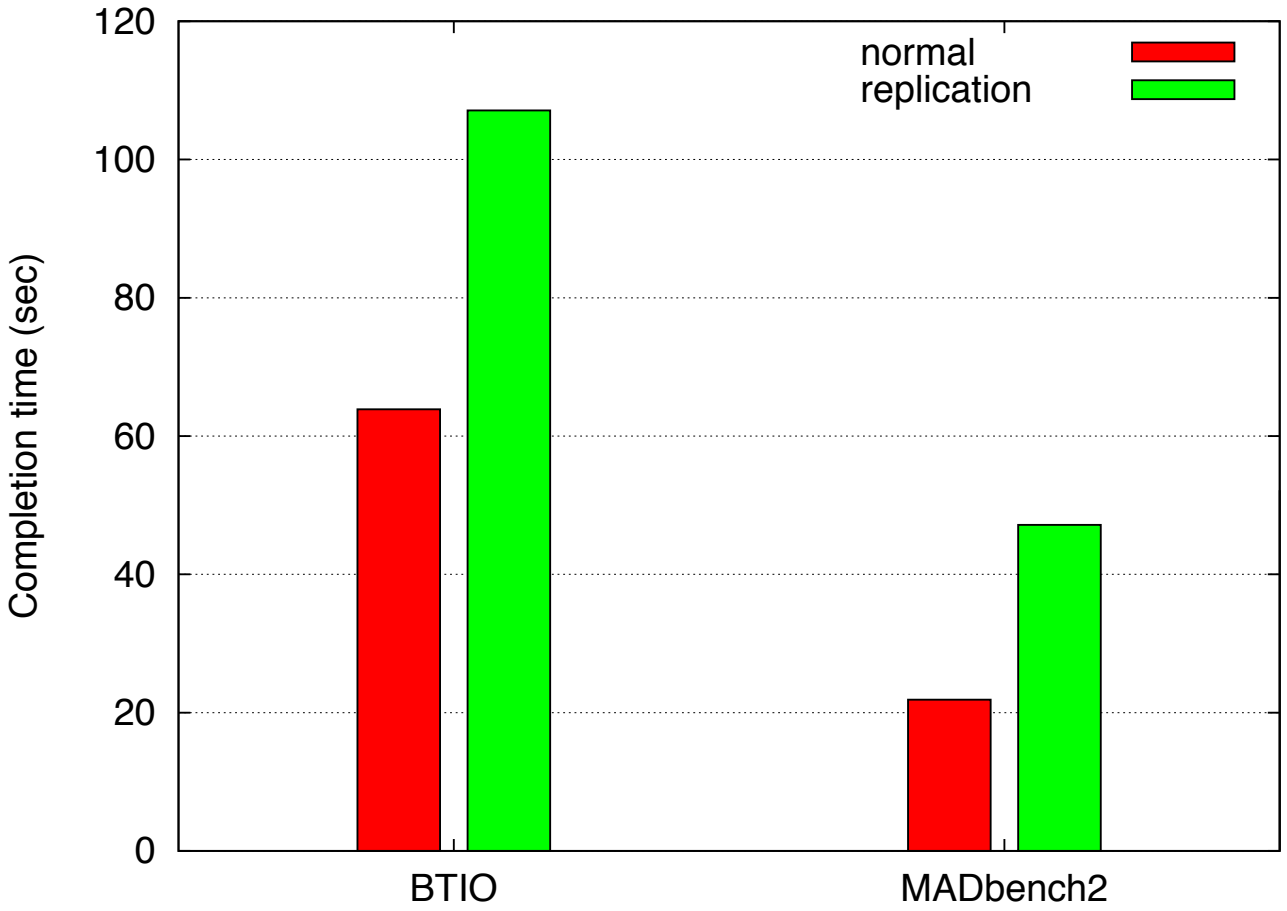


write completion time $\propto$ replication factor (3)

Our replication scheme is scalable w.r.t number of clients (writers)



Real applications

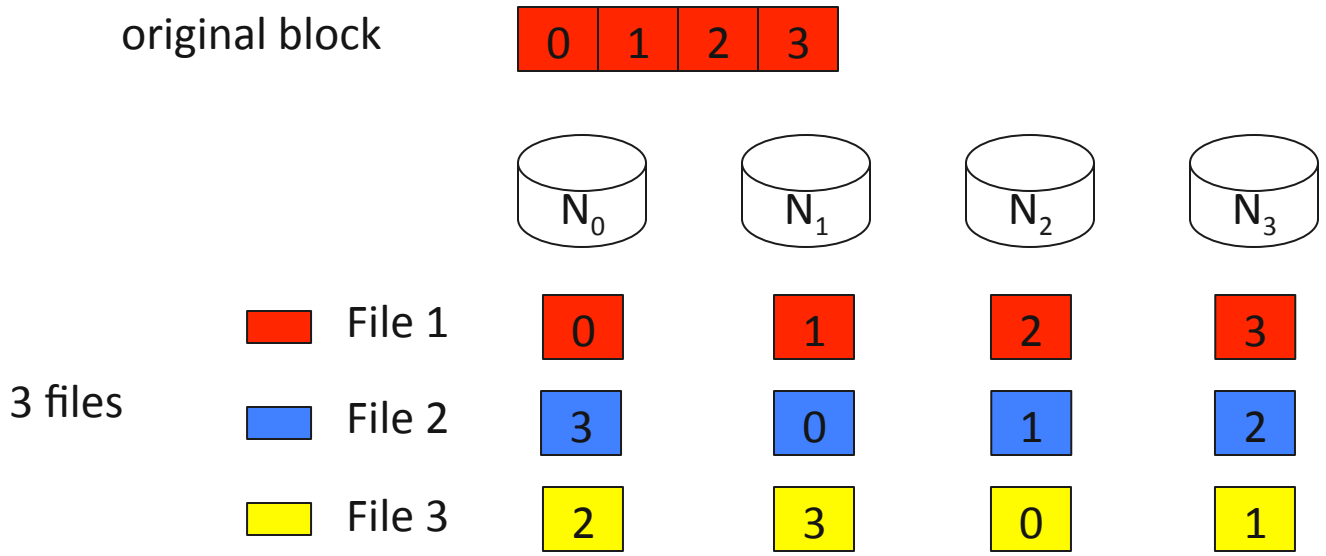


67.7% and 115.6% performance penalty for BTIO and MADbench2, respectively

Discussion

- Collective I/O
  - Current implementation works only with independent calls
    - MPI_File_write(), MPI_File_write_at(), etc.
  - Fileview conflict
    - Fileview for describing different block location ≠ Fileview for a particular process
- Storage overhead
  - Higher storage overhead than RAID
    - 25% in 8+2 RAID 6 vs. 200 %
  - Selective replication or async/delayed encoding can be used in conjunction with
- Non-blocking writes for replicas
  - Currently ROMIO does not support nonblocking I/O for strided writes
- Placing replicas in separate files
  - Replication can be done in a single file or multiple files

Example: file layouts using three files with different first data servers



It achieves the same reliability level, i.e., tolerating two disk (node) failures.

Each file stripe should start at a different file server (disk).

It does not require complex data layouts for read/write calls.

It creates 3x more files than single-file approach.

Related work

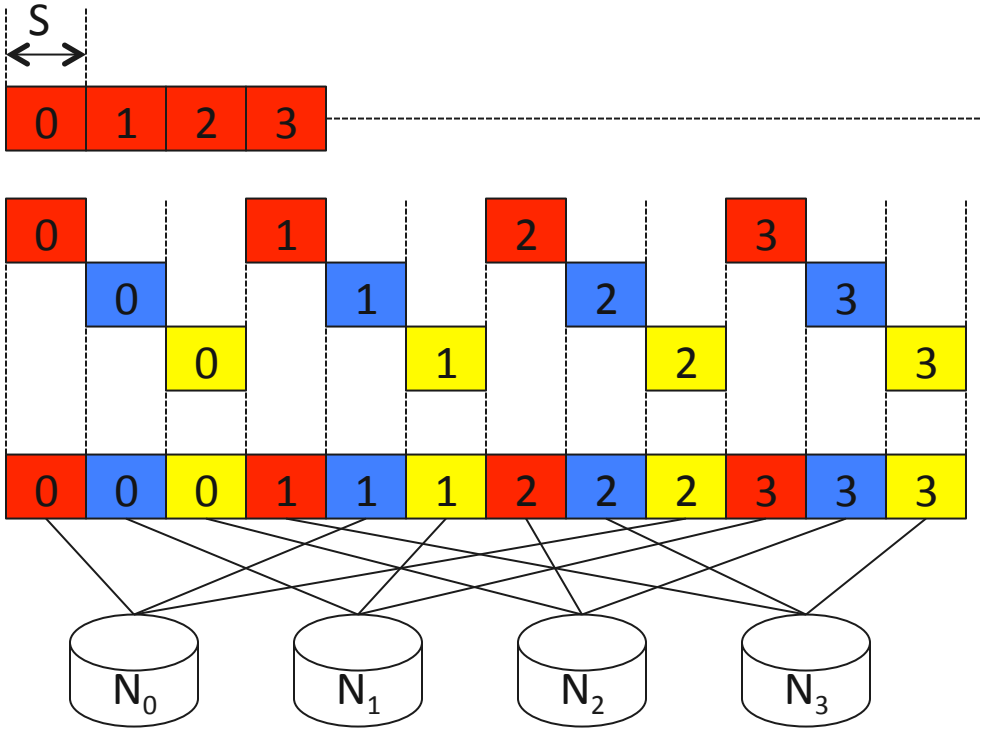
- MPI extensions for fault tolerance
  - Most are focused on providing capability of checkpointing/restart
  - FT-MPI, VolpexMPI, XOR-based double erasure codes [Wang et al.], transparent redundancy [Brightwell et al.]
  - Not providing redundancy to data stored on the storage systems
- Redundancy in MPI-IO and parallel file systems
  - Fault tolerance in MPI applications on PVFS [Calderon et al.], Data structure for continuous snapshot [Brinkmann et al.], SSpiRAL [Amer et al.]
- Data-intensive computing workloads, e.g., MapReduce/Hadoop
  - HDFS uses triplication for fault tolerance
  - Our approach is similar, but provides replication within the context of MPI-IO
- Lazy redundancy [Gropp et al.]
  - It also uses MPI datatypes to calculate parity blocks
  - It requires a modification to the ROMIO MPI-IO implementation

We provide a block replication within MPI-IO transparently

We use MPI derived datatypes to represent replicated file layouts.

Block replication is implemented within shim layer.

Our scheme can be used with any existing parallel file systems.



Acknowledgements

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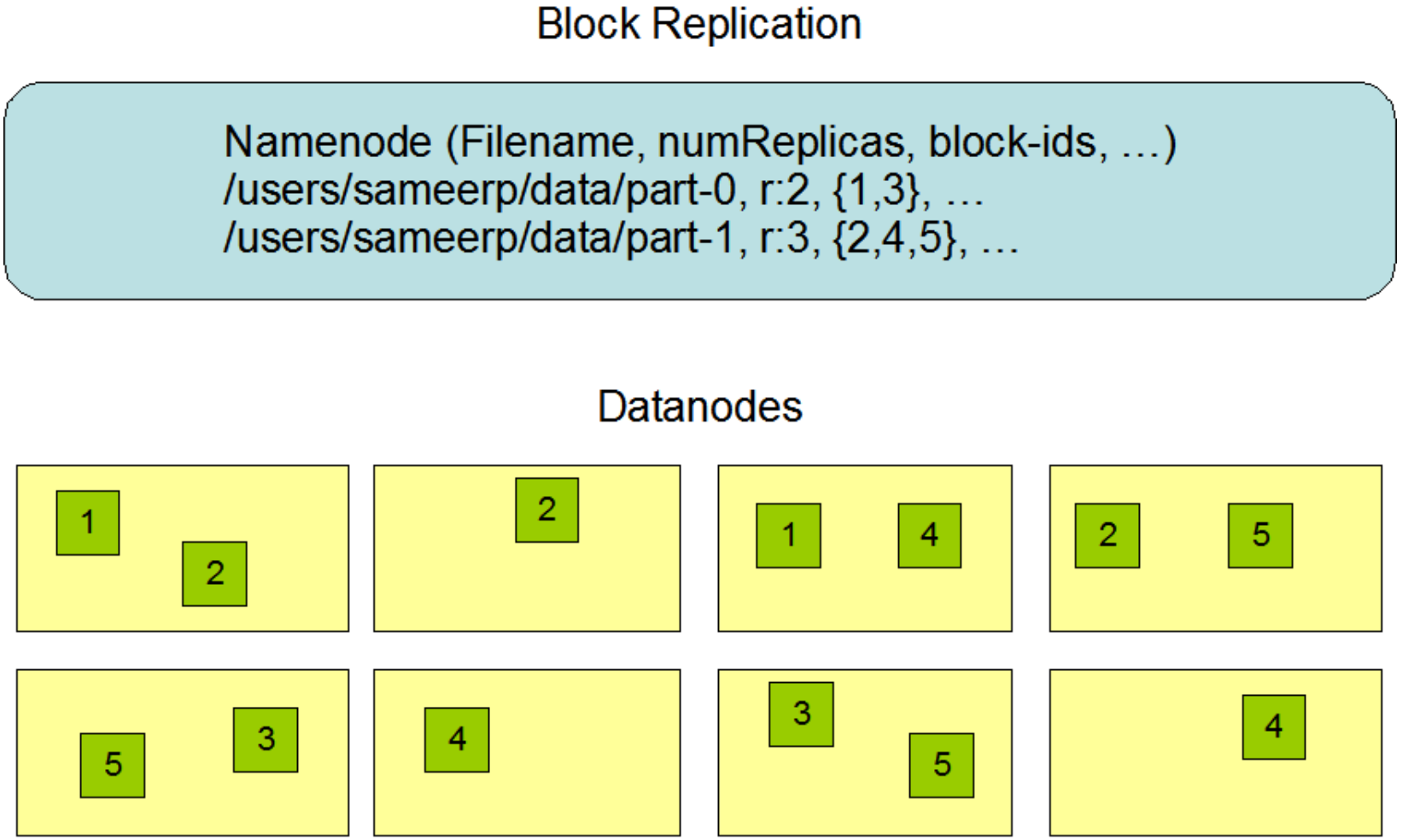
- Wei-keng Liao (NU)

Questions?

Backup slides

HDFS replicates block in a rack-aware manner



Source: http://hadoop.apache.org/common/docs/r0.18.0/hdfs_design.pdf

Application Benchmarks

Benchmark	Description	No. of Procs	Exec time	Dataset size
BTIO	- I/O version of BT (block tridiagonal) - "simple" subtype with Class A problem size (64 x 64 x 64 grid size) - 419.43 MB data to a shared file every 5th timestep out of 200 iterations	16	69.9 sec	419.43 MB
MADbench2	- MADspec data analysis code - Out-of-core matric operations - Built to generate unique (individual) file type using MPI-IO - Each process writes about 303 MB	16	21.9 sec	4,848 MB