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Redundant Execution of HPC Applications with MR-MPI

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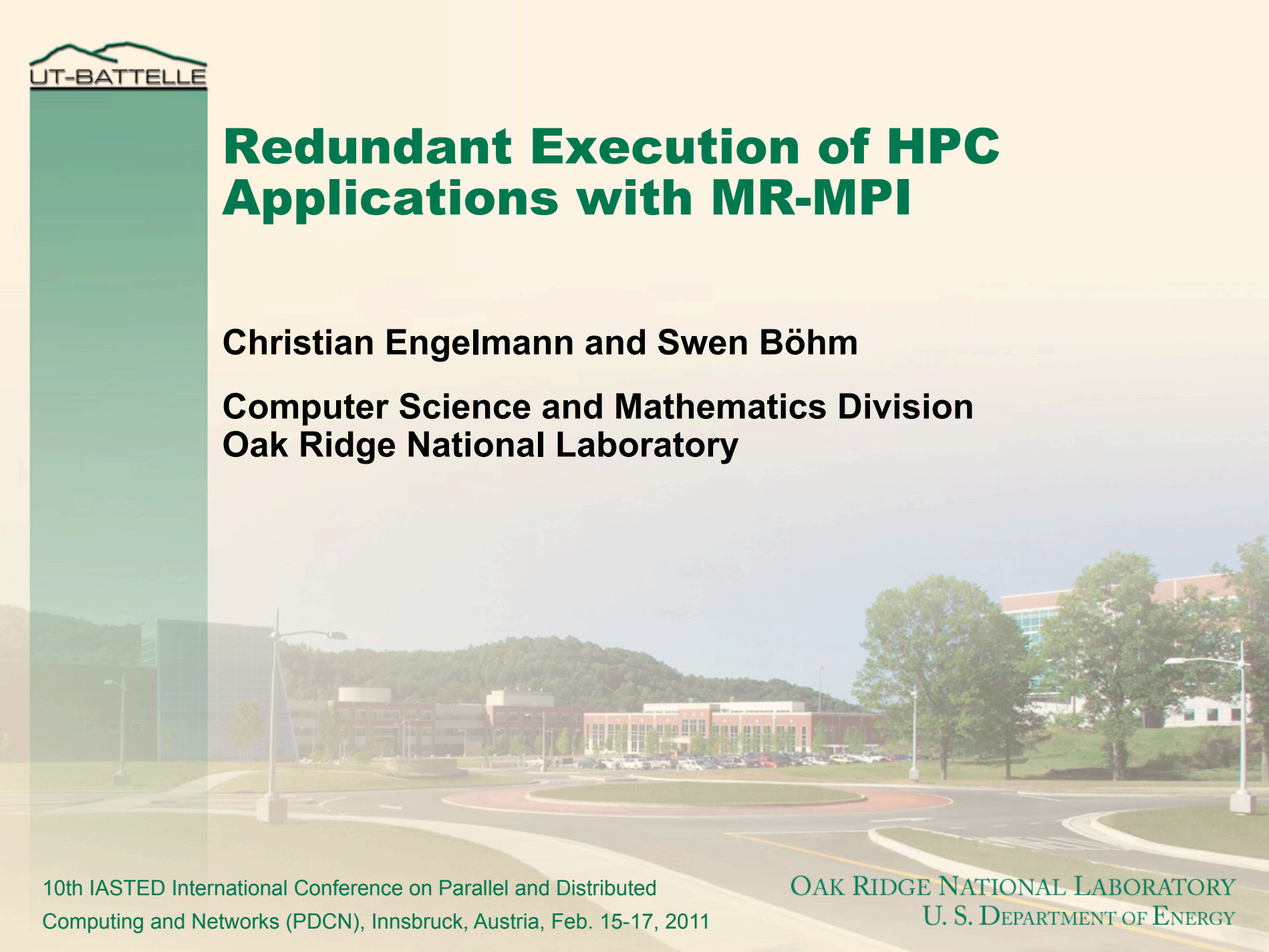

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Motivation

- Large-scale 1 PFlop/s systems are here
  - #1 NSCT Tianhe-1A: 2.566 PFlop/s, 186,368 cores
  - #2 ORNL Jaguar XT5: 1.759 PFlop/s, 224,162 cores
  - #3 NSCS Nebulae: 1.271 PFlop/s, 120,640 cores
  - #4 GSIC Tsubame 2.0: 1.192 PFlop/s, 73,278 cores
  - #5 LBNL Hopper: 1.054 PFlop/s, 153,408 cores
  - #6 CEA Tera 100: 1.050 PFlop/s, 138,368 cores
  - #7 LANL Roadrunner: 1.042 PFlop/s, 122,400 cores
- The trend is toward even larger-scale systems
  - End of processor frequency scaling ➔ Node/core scaling

Proposed Exascale Initiative Road Map
(one of many versions)

Systems	2009	2011	2015	2018
System peak	2 Peta	20 Peta	100-200 Peta	1 Exa
System memory	0.3 PB	1.6 PB	5 PB	10 PB
Node performance	125 GF	200GF	200-400 GF	1-10TF
Node memory BW	25 GB/s	40 GB/s	100 GB/s	200-400 GB/s
Node concurrency	12	32	O(100)	O(1000)
Interconnect BW	1.5 GB/s	22 GB/s	25 GB/s	50 GB/s
System size (nodes)	18,700	100,000	500,000	O(million)
Total concurrency	225,000	3,200,000	O(50,000,000)	O(billion)
Storage	15 PB	30 PB	150 PB	300 PB
IO	0.2 TB/s	2 TB/s	10 TB/s	20 TB/s
MTTI	days	days	days	O(1 day)
Power	6 MW	~10MW	~10 MW	~20 MW

Resilience Issues in Extreme-scale HPC

- Significant growth in component count (up to 50x nodes expected) results in correspondingly higher error rate
- Smaller circuit sizes and lower voltages increase soft error vulnerability (bit flips caused by thermal and voltage variations as well as radiation)
- Hardware fault detection and recovery is limited by power consumption requirements and production costs
- Heterogeneous architectures (CPU & GPU cores) add more complexity to fault detection and recovery
- Power management cycling decreases component lifetimes due to thermal and mechanical stresses

Risks of the Business as Usual Approach

- Increased error rate requires more frequent checkpoint/ restart, thus lowering efficiency (application progress)
- Memory to I/O ratio improves due to less memory/node, but concurrency for coordination and scheduling increases significantly (up to 50x nodes, 444x cores)
- Current application-level checkpoint/restart to a parallel file system is becoming less efficient and soon obsolete
- Missing strategy for silent data/code corruption will cause applications to produce erroneous results or hang

Objectives

- Address the deficiencies of recovery-oriented HPC
- Instead of rollback recovery, focus on redundancy
- Center on a software-only approach at the system software layer that is completely transparent
- Aim at redundancy at the Message Passing Interface layer

Related Work (1/2)

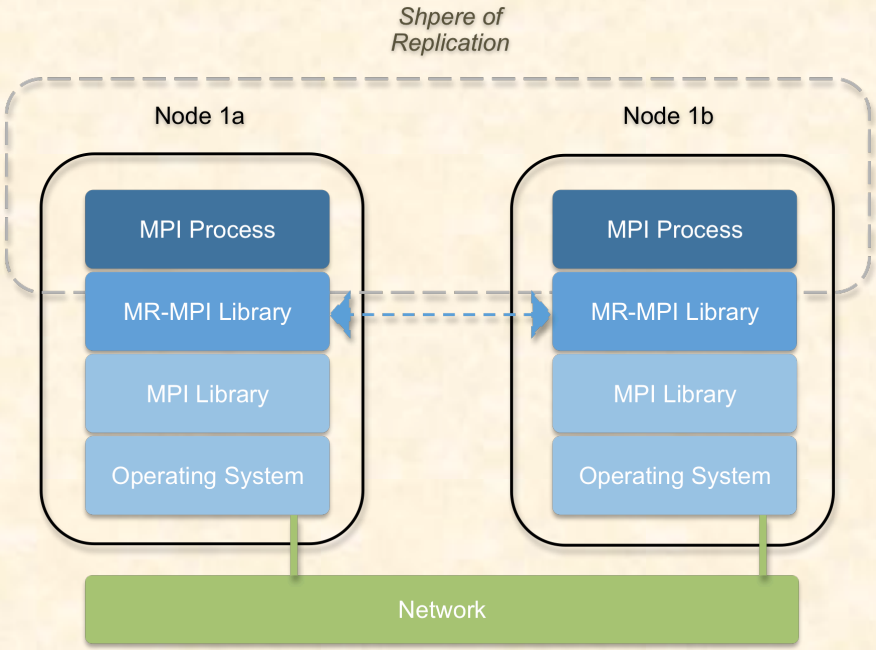
- Modular redundancy has been used to ensure availability and reliability in information technology, aerospace and command & control systems for decades
- Our 2009 availability analysis made the case for redundancy in HPC
  - Compute node mean-time to failure (MTTF) can be lowered by a factor of 100-1,000 for dual redundancy and by 1,000-10,000 for triple redundancy without lowering overall system MTTF
  - Compute node MTTF can be lowered by a factor of 1,000-1,0000 for dynamic dual redundancy and by 10,000-100,000 for dynamic triple redundancy

Related Work (2/2)

- Redundant execution with rMPI
  - Using the MPI profiling layer PMPI to intercept all MPI calls from an application and to hide all redundancy mechanisms
  - Similar, parallel effort to MR-MPI that has different features and limitations
- Redundant execution with VolpexMPI
  - MPI library implemented from scratch that supports redundancy in its communication layer
  - Similar, parallel effort to MR-MPI that has different features and limitations
- Redundant Execution with MMPI
  - Recent study of MPI redundancy protocols

Technical Approach

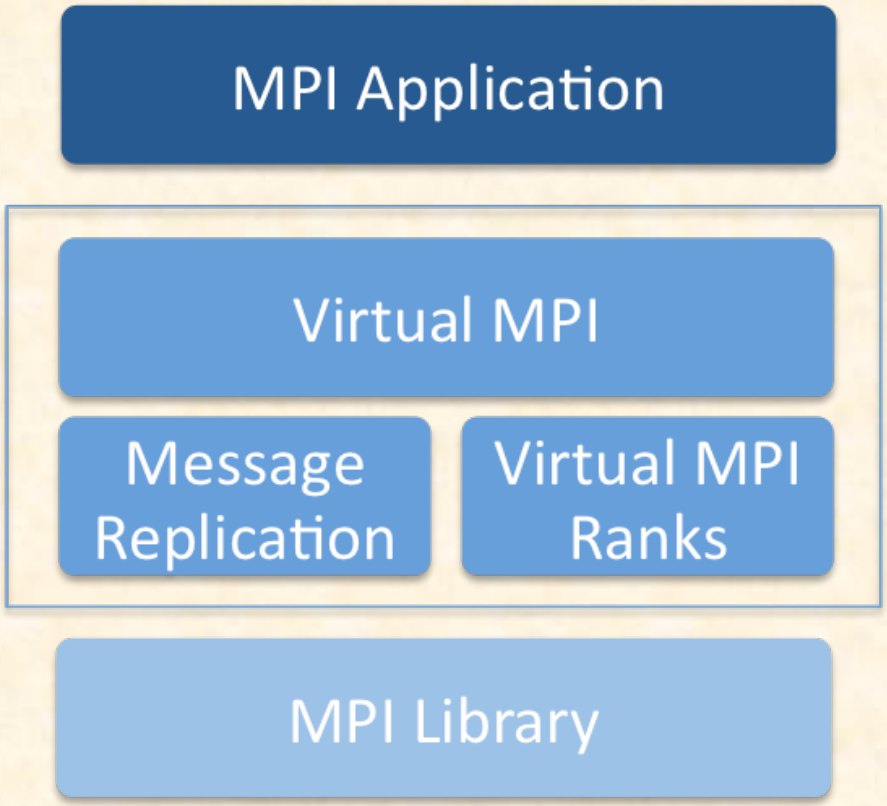
- Aim at MPI redundancy similar to rMPI/VolpexMPI
- Redundant execution of MPI processes:
  - On the same processor
  - On different processors
  - On different compute nodes
- Input replication and output comparison between the MPI library and the app
- Fault model: fail-stop
- MPI/platform independent



Design (1/2)

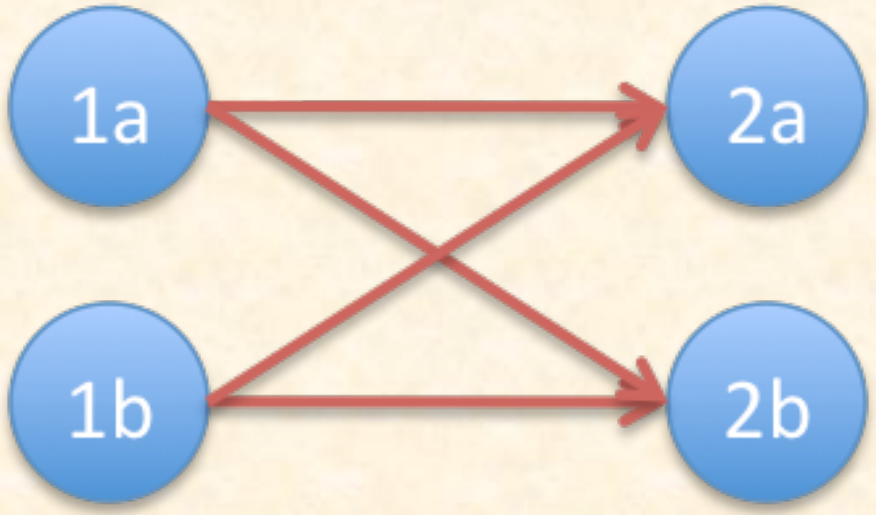
- Utilize PMPI to intercept MPI calls from the app. and to hide redundancy
- MRMPI is a C library with 53 C/Fortran MPI calls
- To run an application with redundancy, simply:
  - Link it with libmrmpi
  - Execute:

    mpirun -np <nprocs>
    <application>
    -mrmpi-np <vprocs>



Design (2/2)

- r * m native MPI ranks:
  - r ranks visible to the app.
  - m: replication degree
  - <nprocs> = r*m
  - <vprocs> = r
- Message replication
- Master-failover for non-determinism, e.g. for MPI_Wtime()
- Partial replication is supported statically



Implementation (1/2)

- MR-MPI core relies on redundant non-blocking p2p communication
  - Tracking of redundant MPI communication requests
- Blocking MR-MPI p2p calls use the non-blocking calls
- Non-determinism:
  - Lowest replica executes first and then tells others
  - Next replica in-line takes over if lowest fails
  - MPI_Wtime(), MPI_Probe(), MPI_Test…()
- Collectives use MR-MPI p2p calls and the recently added MPI_Reduce_local()
  - Linear implementations

Implementation (2/2)

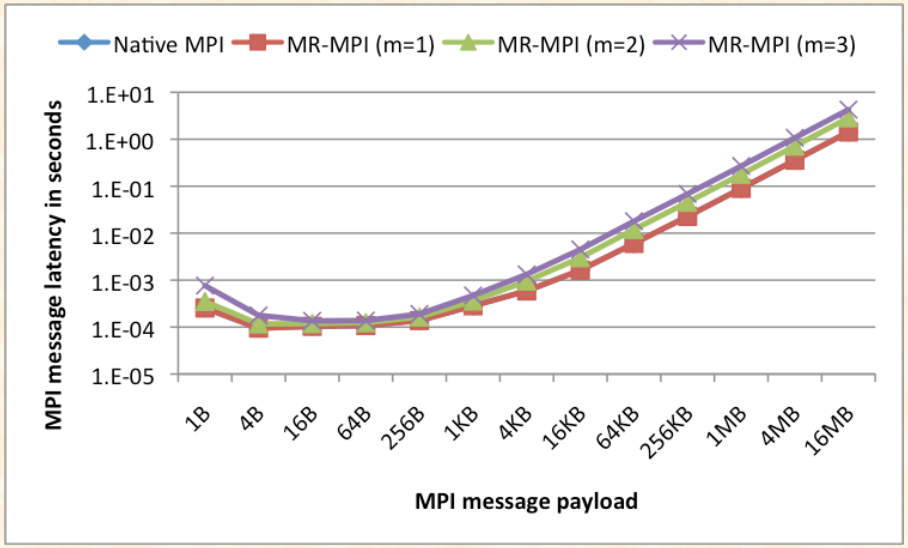
- MPI communicators & groups:
  - Fixed mapping of ranks
  - Utilize native MPI calls and maintain mapping
  - MPI_Comm_split(), MPI_Group_intersection(), …
- Fortran calls use C variants and MPI_..._f2c/c2f()
  - Support for 32-bit Fortran and 64-bit C compiler mix
- GNU autotools-based distribution
- Fully documented source, including Doxygen
- Tested on/with:
  - Mac OS X 10.5 and Linux
  - Open MPI 1.5rc3
  - NPB 3.3.1
  - GNU C and Fortran comp.

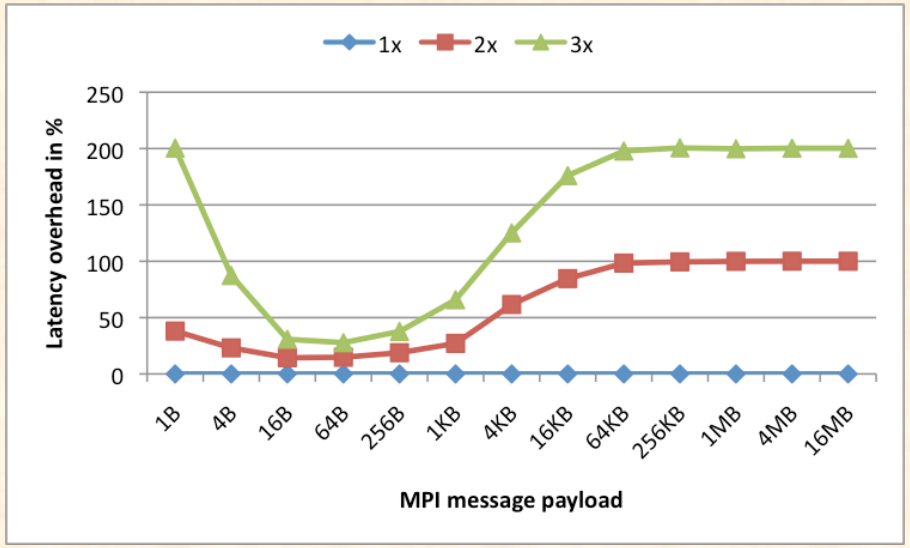
Experimental Results

- Test environment #1:
  - 32-node (32-core) cluster
  - Intel Pentium 4 2GHz per node
  - 0.75GB RAM/node
  - Fast Ethernet (100Mbps)
  - Ubuntu 8.04 32-bit Linux
  - Without swap
  - Open MPI 1.5.rc3
  - p2p latency benchmark
  - NAS parallel benchmark suite 3.3.1
- Test environment #2:
  - 16-node (128-core) cluster
  - Two 4-core AMD Opteron 2378 2.4GHz per node
  - 8GB RAM/node
  - Gigabit Ethernet (1Gbps)
  - Ubuntu 10.04 64-bit Linux
  - With swap
  - Open MPI 1.5.rc3
  - NAS parallel benchmark suite 3.3.1

Results: P2P Latency #1

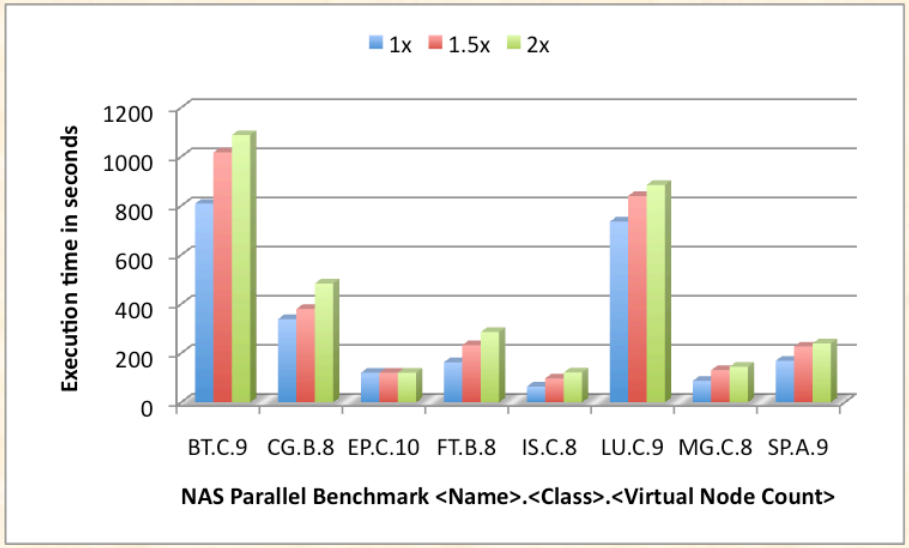
- High impact of message replication on p2p latency
- MRMPI-internal overlap due to non-blocking calls: 4B-4KB

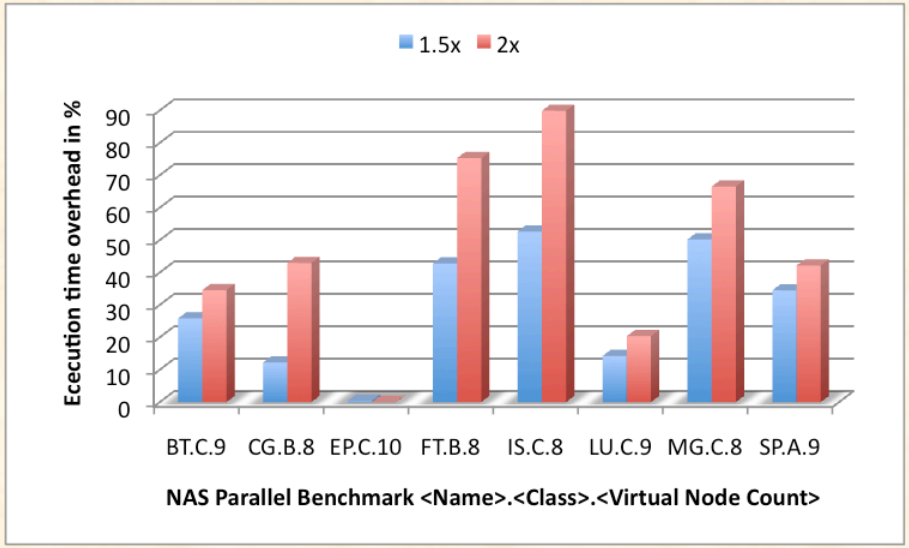




Results: NAS Parallel Benchmark Suite #1

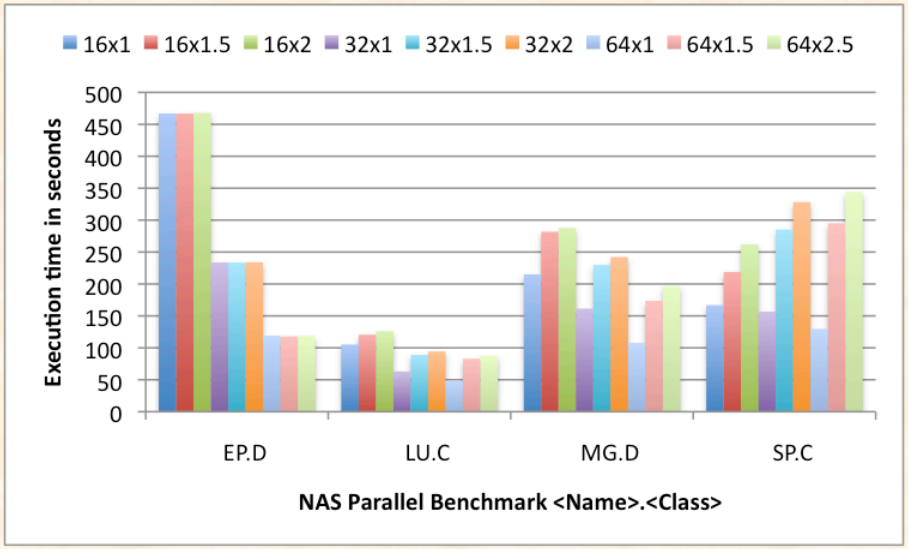
- No overhead for embarrassingly parallel (EP) benchmark
- 70-90% overhead for communication-heavy integer sort (IS) and fast Fourier transform (FT) under DMR

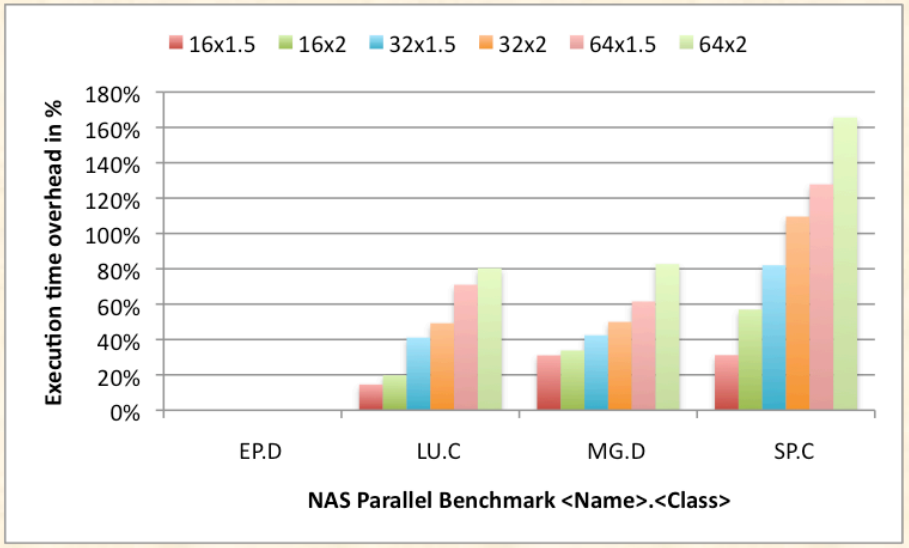




Results: NAS Parallel Benchmark Suite #2

- With increasing per-node core counts, the overhead is increasing as well
- No overhead for embarrassingly parallel (EP) benchmark





Conclusions and Future Work

- Presented the MR-MPI approach for HPC redundancy
- In contrast to rMPI, MR-MPI does not rely on a specific MPI library, such as MPICH
- MR-MPI distinguishes itself from VolpexMPI by not reimplementing the MPI layer
- The performance results clearly show the negative impact of the $O(m^2)$ messages between replicas
- MR-MPI and rMPI recently joined efforts: redMPI
- Recently added output comparison for soft error detection
- Further planned work focuses on better redundancy protocols and on POSIX file I/O under redundancy

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Questions?