Object-based Over-Decomposition Can Enable Powerful Fault Tolerance Schemes

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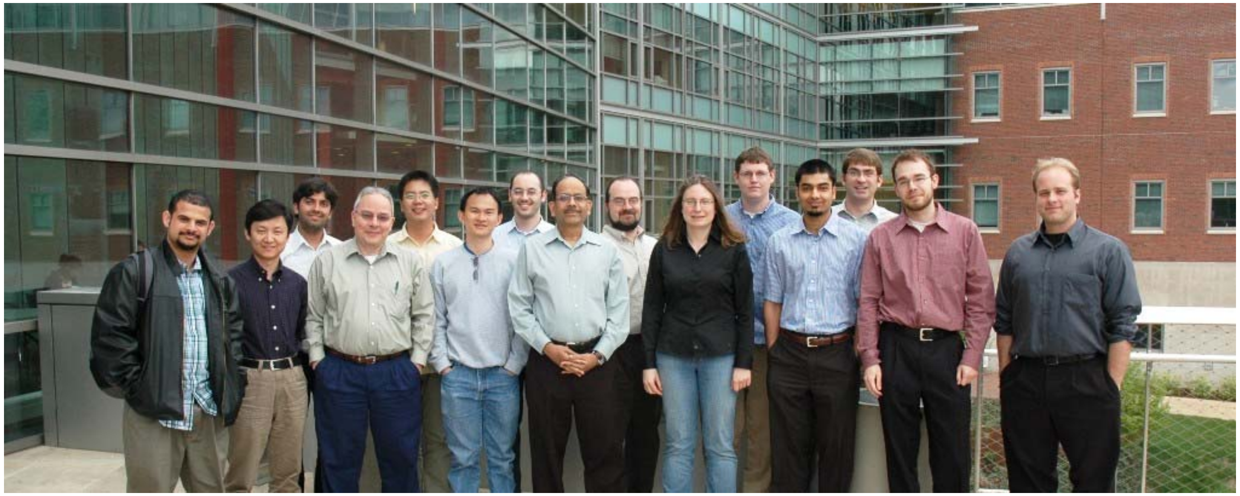
Presentation Outline

- What is object based decomposition
  - Its embodiment in Charm++ and AMPI
  - Its general benefits
  - Its features that are useful for fault tolerance schemes
- Our Fault Tolerance work in Charm++ and AMPI
  - Disk-based checkpoint/restart
  - In-memory double checkpoint/restart
  - Proactive object-migration
  - Message-logging
- Appeal for research in leveraging these features in FT research

Parallel Programming Lab - PPL

- http://charm.cs.uiuc.edu
  - Open positions ☺



PPL, April'2008

PPL Mission and Approach

- To enhance *Performance and Productivity* in programming complex parallel applications
  - Performance: scalable to thousands of processors
  - Productivity: of human programmers
  - Complex: irregular structure, dynamic variations
- Application-oriented yet CS-centered research
  - Develop enabling technology, for a wide collection of apps.
  - Embody it into easy to use abstractions
  - Implementation: Charm++
    - Object-oriented runtime infrastructure
    - Freely available for non-commercial use

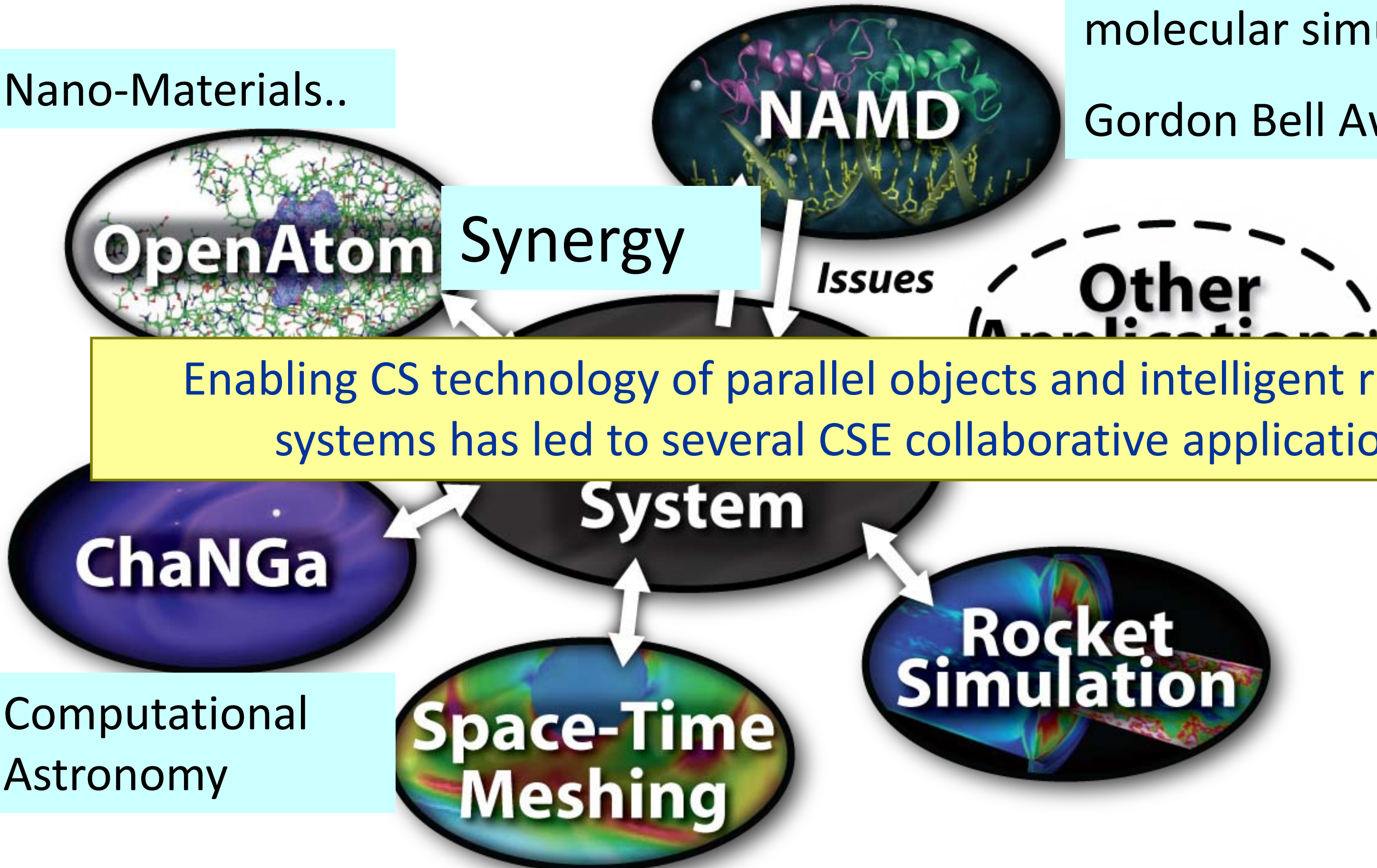
Charm++ and CSE Applications

Well-known Biophysics molecular simulations App

Gordon Bell Award, 2002

Nano-Materials..

Synergy



Enabling CS technology of parallel objects and intelligent runtime systems has led to several CSE collaborative applications

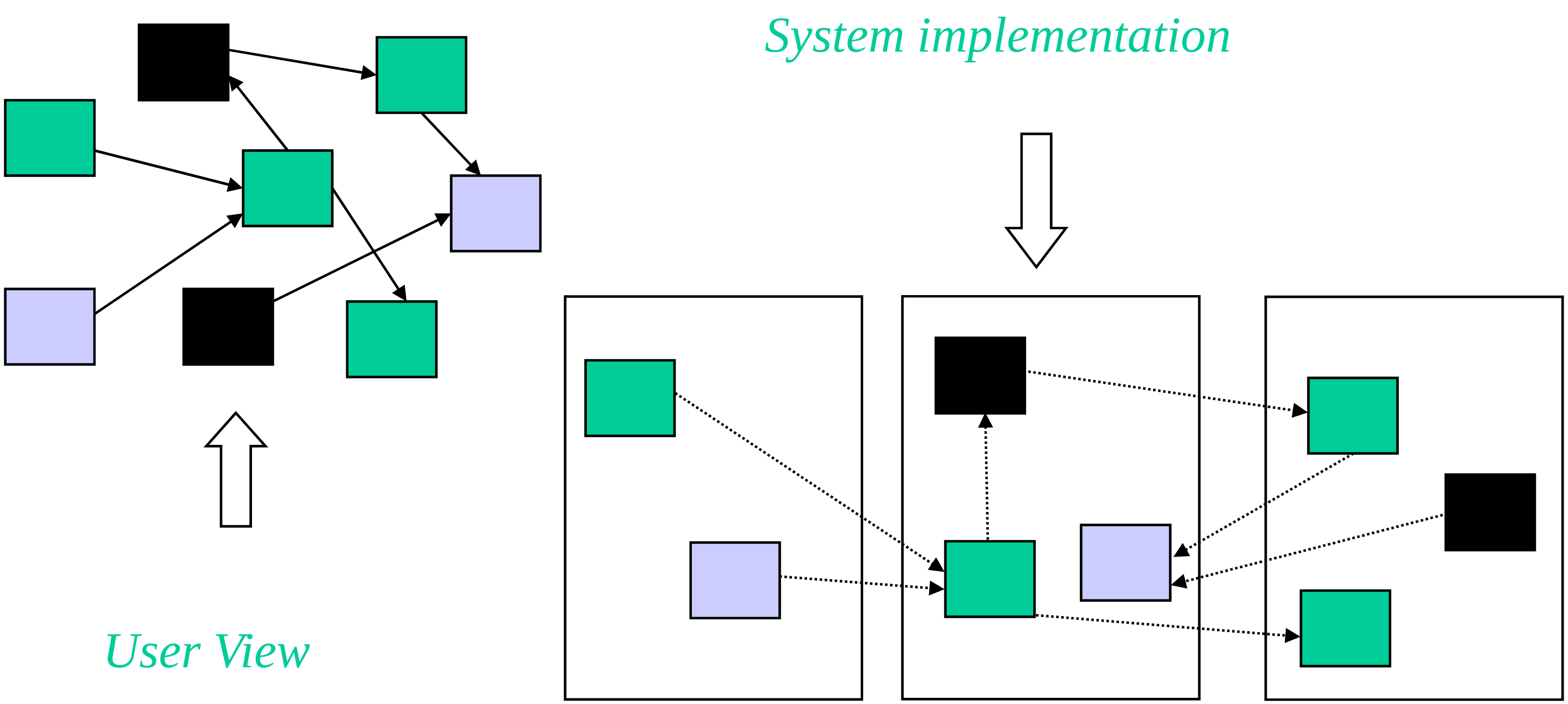
Computational Astronomy

Object based over-decomposition

- Objects:
  - Locality of data references is a critical attribute for performance
  - A parallel object can access only its own data
  - Asynchronous method invocation for accessing other's data
- Over-Decompostion
  - the programmer decompose computation into objects
    - Work units, data-units, composites
  - Let an intelligent runtime system assign objects to processors
  - RTS can change this assignment (mapping) during execution

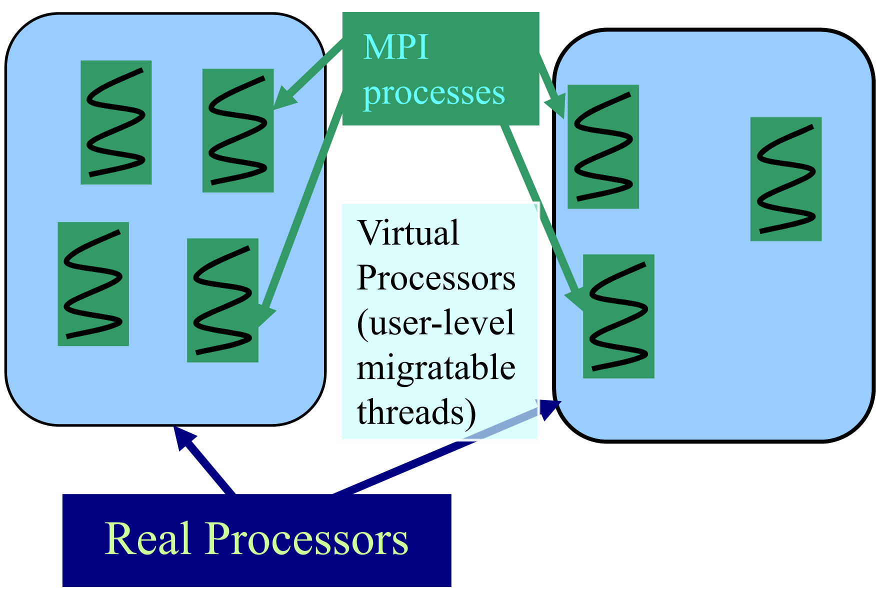
Object-based over-decomposition: Charm++

- Multiple "indexed collections" of C++ objects
- Indices can be multi-dimensional and/or sparse
- Programmer expresses communication between objects
  - with no reference to processors



Object-based over-decomposition: AMPI

- Each MPI process is implemented as a user-level thread
- Threads are light-weight, and migratable!
  - <1 microsecond contex tswitch time, potentially >100k threads per core
- Each thread is embedded in a charm+ object (chare)

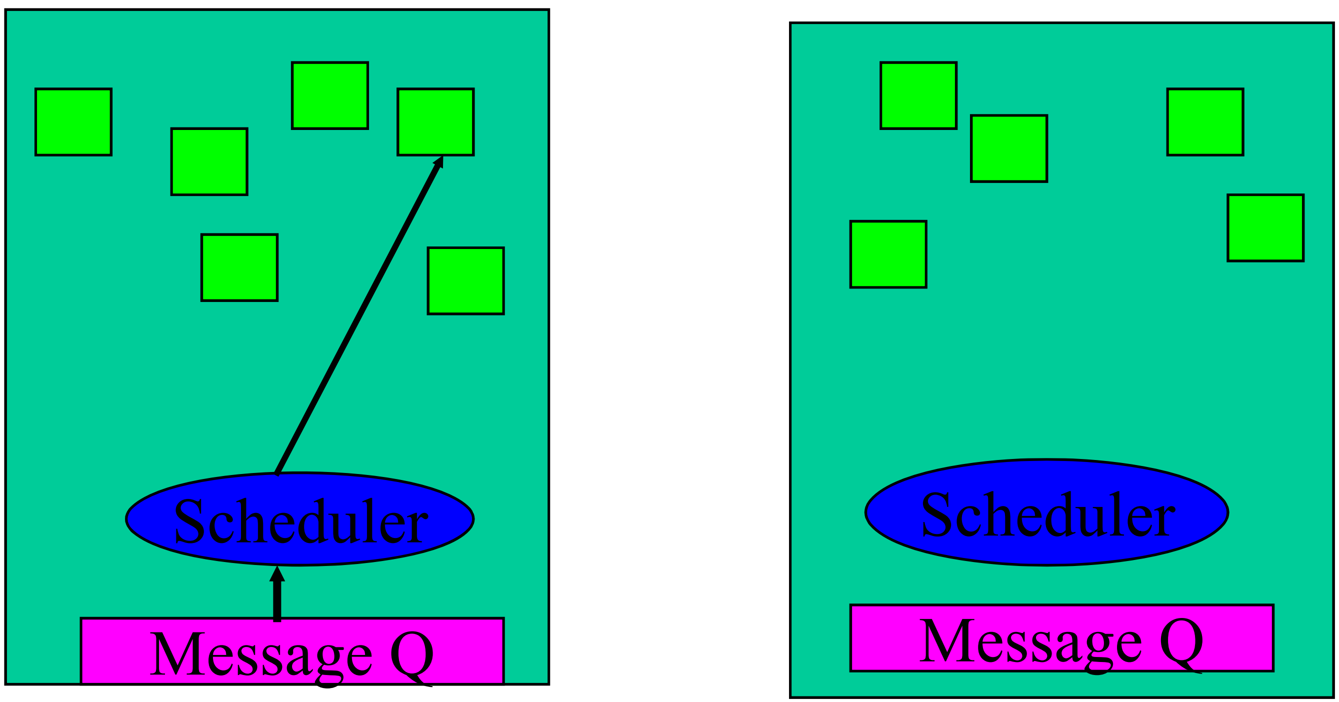


Benefits of Object-based overdecomposition

- Software engineering
  - Number of virtual processors can be independently controlled
  - Separate VPs for different modules
- Message driven execution
  - Adaptive overlap of communication
  - Predictability :
    - Automatic out-of-core
    - Prefetch to *local stores*
  - Asynchronous reductions
- Dynamic mapping
  - Heterogeneous clusters
    - Vacate, adjust to speed, share
  - **Automatic checkpointing, more advanced Fault Tolerance schemes**
  - Change set of processors used
  - Automatic dynamic load balancing
  - Communication optimization

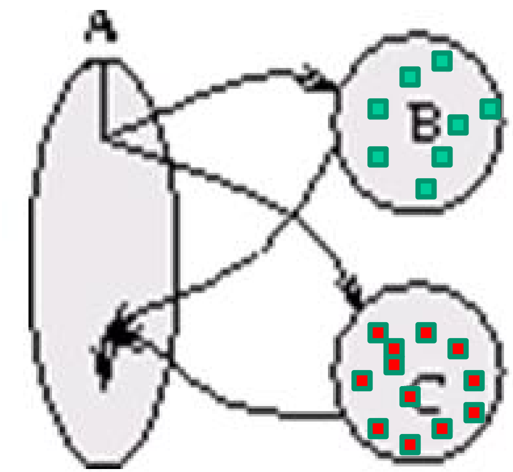
Some Relevant Properties of this approach: Message Driven Execution

Object-based Virtualization leads to *Message Driven Execution*



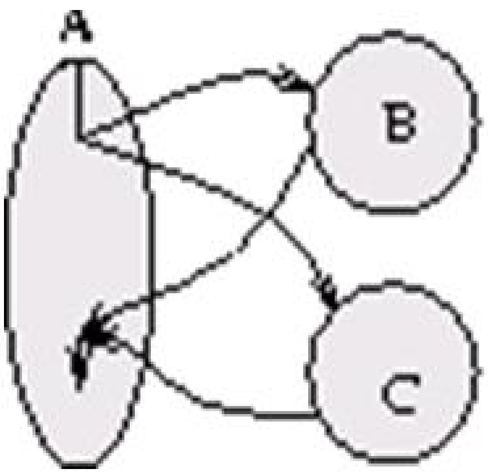
Some Relevant Properties of this approach:

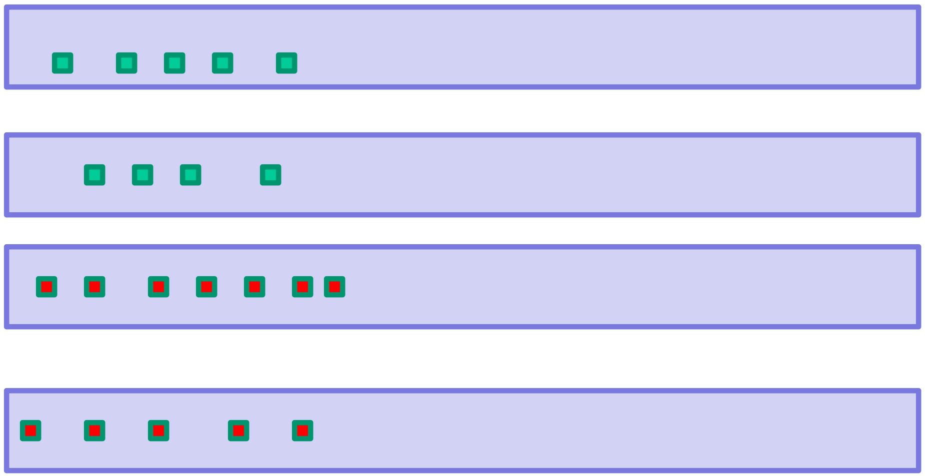
Parallel Composition:
A1; (B || C); A2



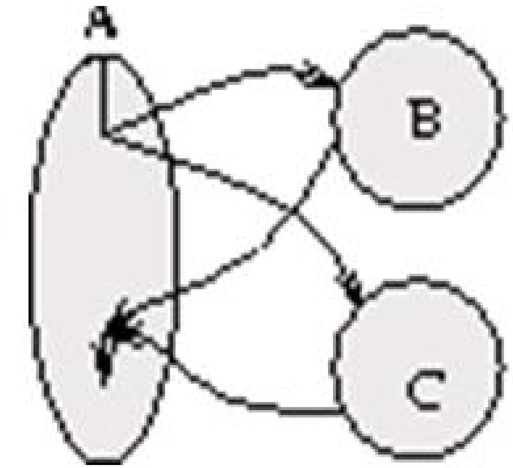
Recall: Different modules, written in different languages/paradigms, can overlap in time and on processors, without programmer having to worry about this explicitly

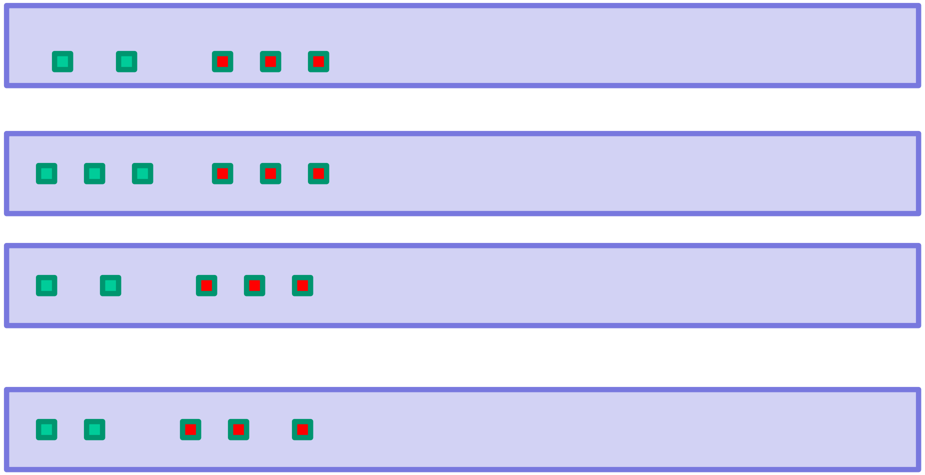
Without message-driven execution
(and virtualization), you get either:
Space-division





OR: Sequentialization



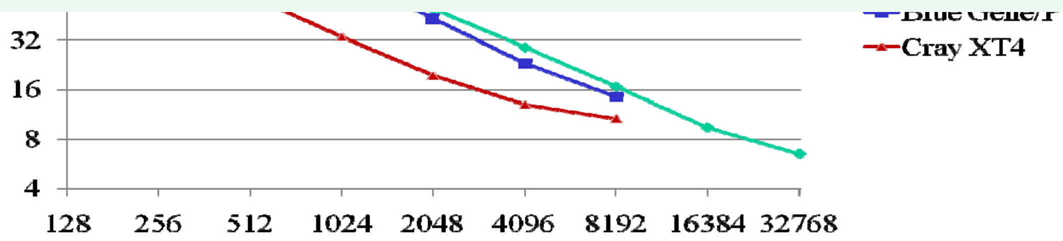


Charm++/AMPI are well established systems

- The Charm++ model has succeeded in CSE/HPC
- Because:
  - Resource management, …

15% of cycles at NCSA, 20% at PSC, were used on Charm++ apps, in a one year period

- So, work on fault tolerance for Charm++ and AMPI is directly useful to real apps



Fault Tolerance in Charm++ & AMPI

- Four Approaches Available:
  a) Disk-based checkpoint/restart
  b) In-memory double checkpoint/restart
  c) Proactive object migration
  d) Message-logging
- Common Features:
  - Based on dynamic runtime capabilities
  - Use of object-migration
  - Can be used in concert with load-balancing schemes

Disk-Based Checkpoint/Restart

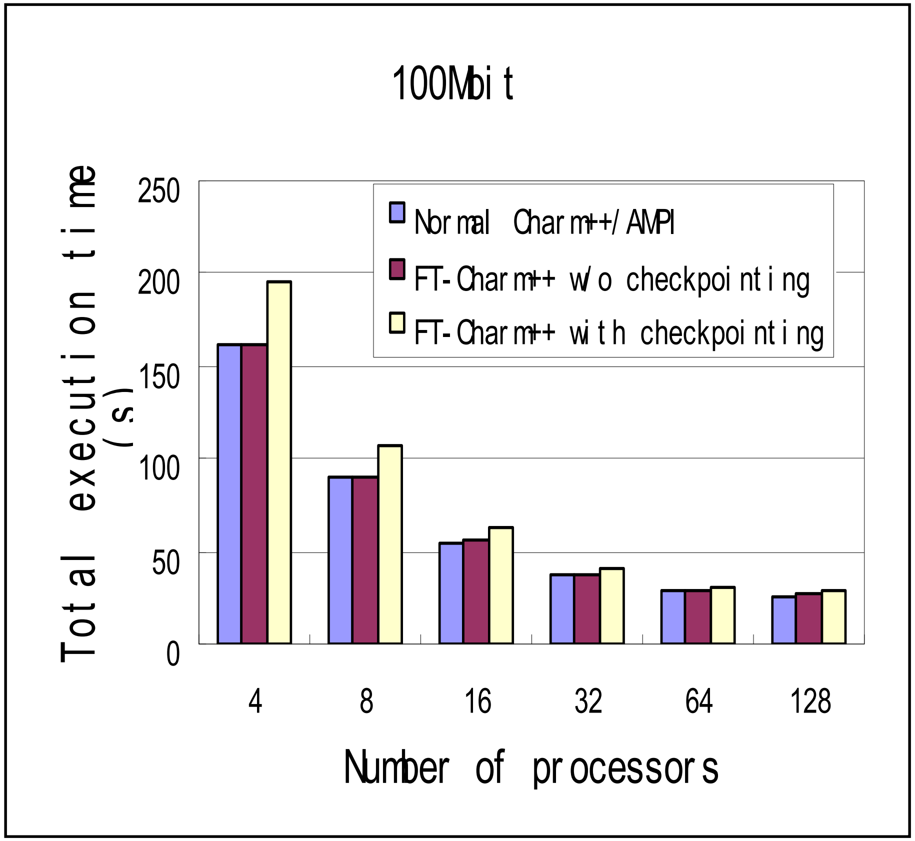
- Basic Idea:
  - Similar to traditional checkpoint/restart; "migration" to disk
- Implementation in Charm++/AMPI:
  - Blocking coordinated checkpoint: `MPI_Checkpoint(DIRNAME)`
- Pros:
  - Simple scheme, effective for common cases
  - Virtualization enables restart with any number of processors
- Cons:
  - Checkpointing and data reload operations may be slow
  - Work between last checkpoint and failure is lost
  - Job needs to be resubmitted and restarted

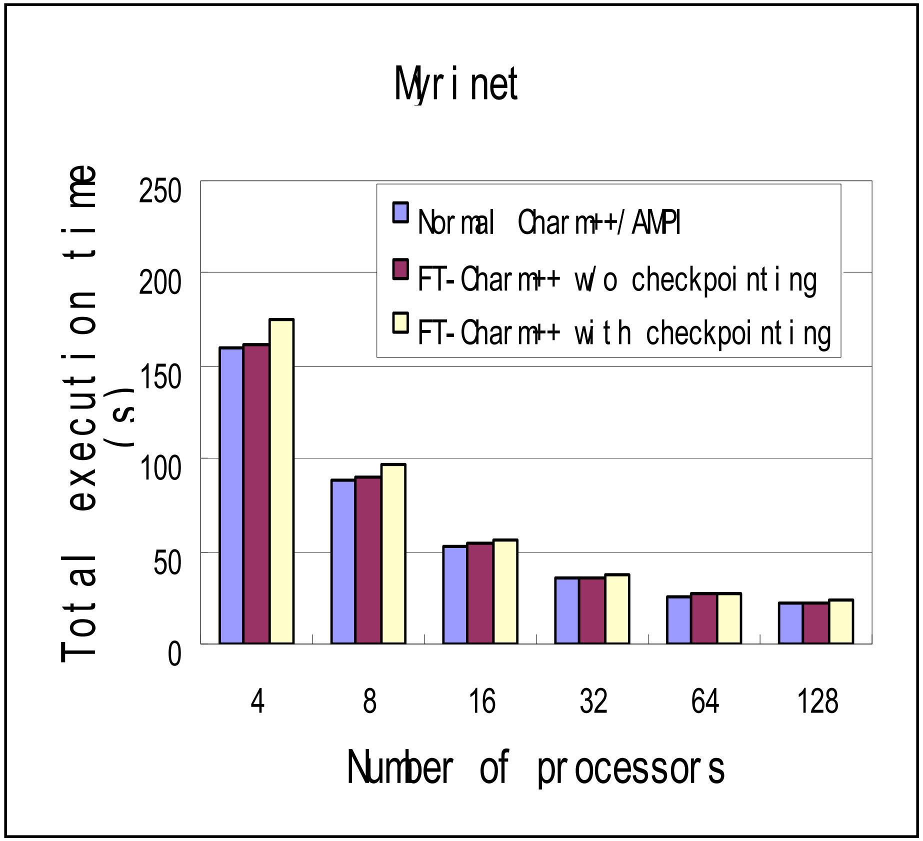
In-Memory Double Checkpoint/Restart

- Basic Idea:
  - Avoid overhead of disk access for keeping saved data
  - Allow user to define what makes up the state data
- Implementation in Charm++/AMPI:
  - Coordinated checkpoint
  - Each object maintains <u>two</u> checkpoints:
    - on local processor's memory
    - on remote *buddy* processor's memory
  - A *dummy* process is created to replace crashed process
  - New process starts recovery on other processors
    - use buddy's checkpoint to recreate state of failing processor
    - perform load balance after restart

In-Memory Double Checkpoint/Restart (cont.)

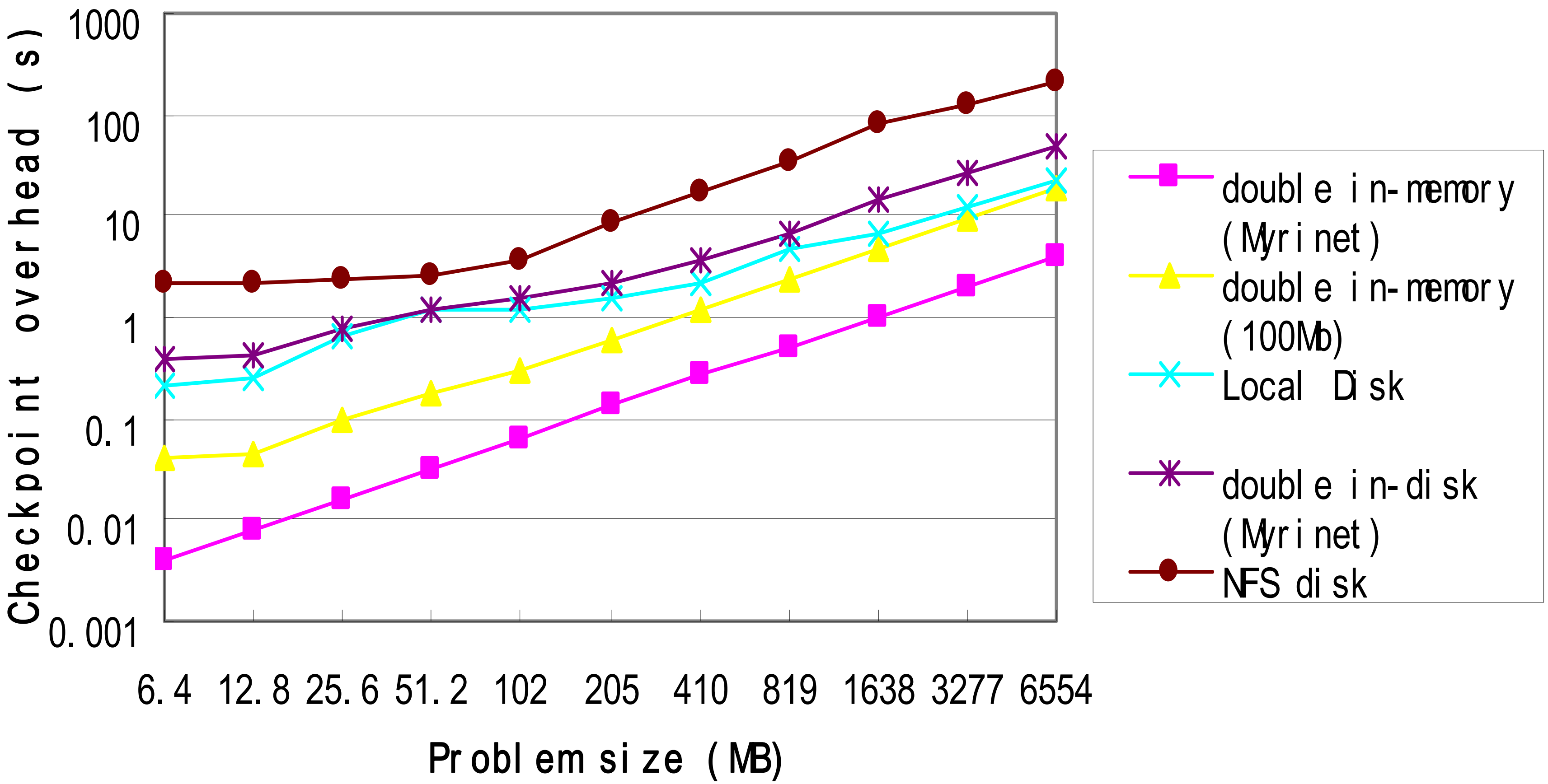
- Evaluation of Checkpointing Overhead:
  - 3D-Jacobi code in AMPI, 200 MB data, IA-32 cluster
  - Execution of 100 iterations, 8 checkpoints taken





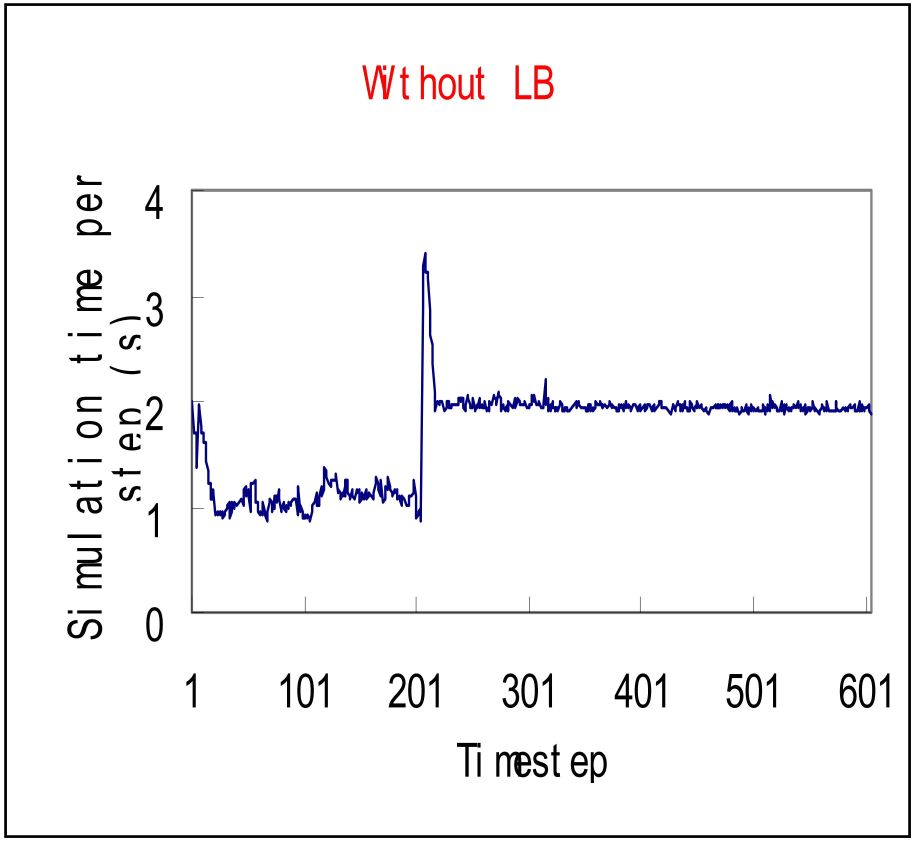
In-Memory Double Checkpoint/Restart (cont.)

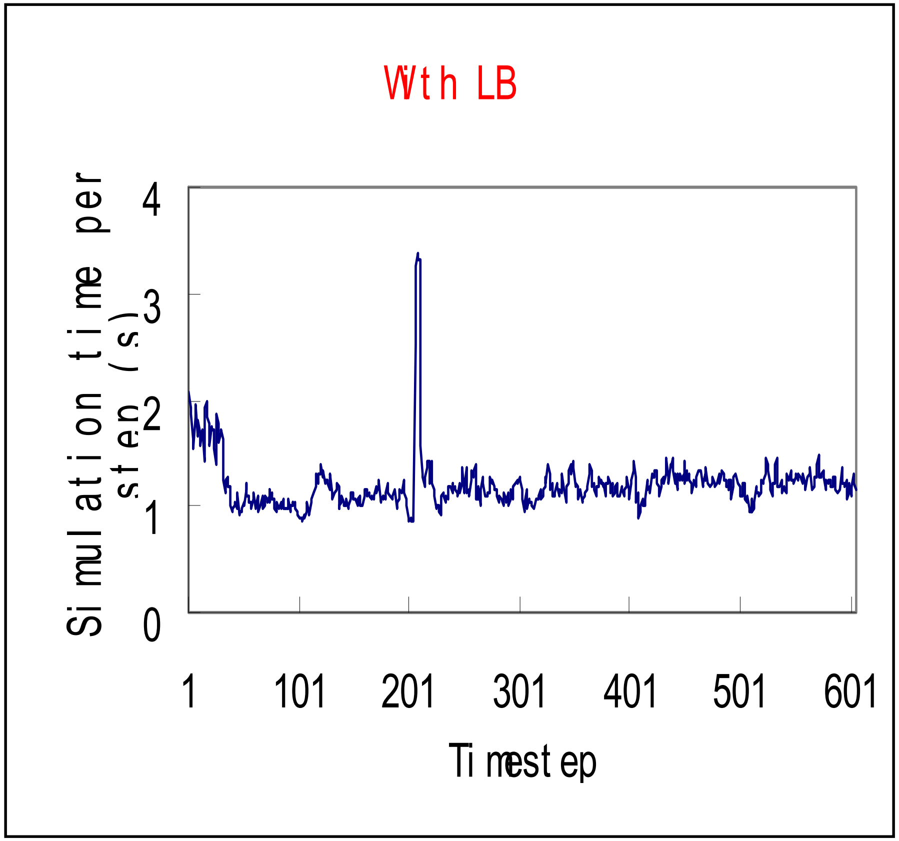
- Comparison to disk-based checkpointing:



In-Memory Double Checkpoint/Restart (cont.)

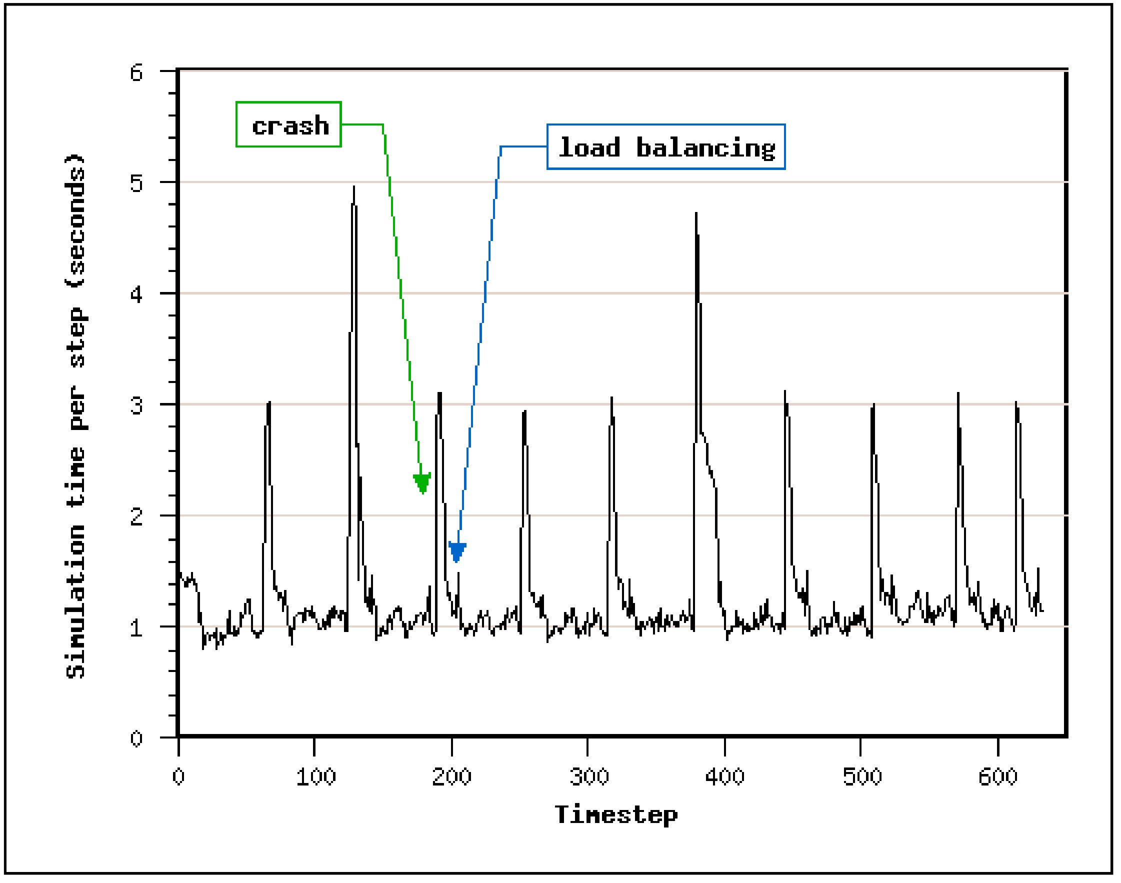
- Recovery Performance:
  - Molecular Dynamics LeanMD code, 92K atoms, P=128
  - Load Balancing (LB) effect after failure:





In-Memory Double Checkpoint/Restart (cont.)

- Application Performance:
  - Molecular Dynamics LeanMD code, 92K atoms, P=128
  - Checkpointing every 10 timesteps; 10 crashes inserted:



In-Memory Double Checkpoint/Restart (cont.)

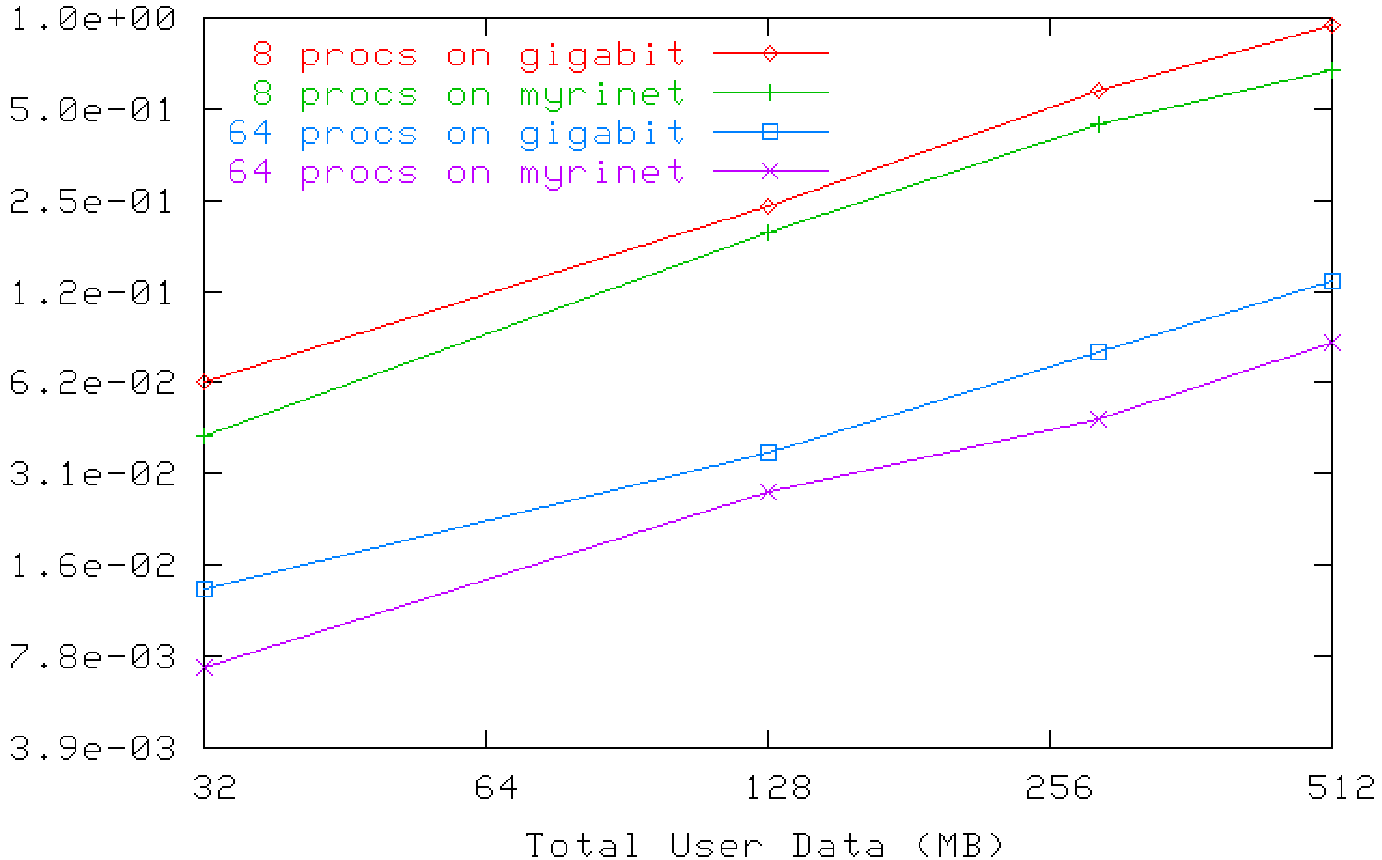
- Pros:
  - Faster checkpointing than disk-based
  - Reading of saved data also faster
  - Only one processor fetches checkpoint across network
- Cons:
  - Memory overhead may be high
  - All processors are rolled back, despite individual failure
  - All the work since last checkpoint is redone by every processor
- Publications:
  - Zheng, Huang & Kale: ACM-SIGOPS, April 2006
  - Zheng, Shi & Kale: IEEE-Cluster'2004, Sep.2004

Proactive Object Migration

- Basic Idea:
  - Use knowledge about impending faults
  - Migrate objects away from processors that may fail soon
  - Fall back to checkpoint/restart when faults not predicted
- Implementation in Charm++/AMPI:
  - Each object has a unique index
  - Each object is mapped to a *home* processor
    - objects need not reside on home processor
    - home processor knows how to reach the object
  - Upon getting a warning, evacuate the processor
    - reassign mapping of objects to new home processors
    - send objects away, to their home processors

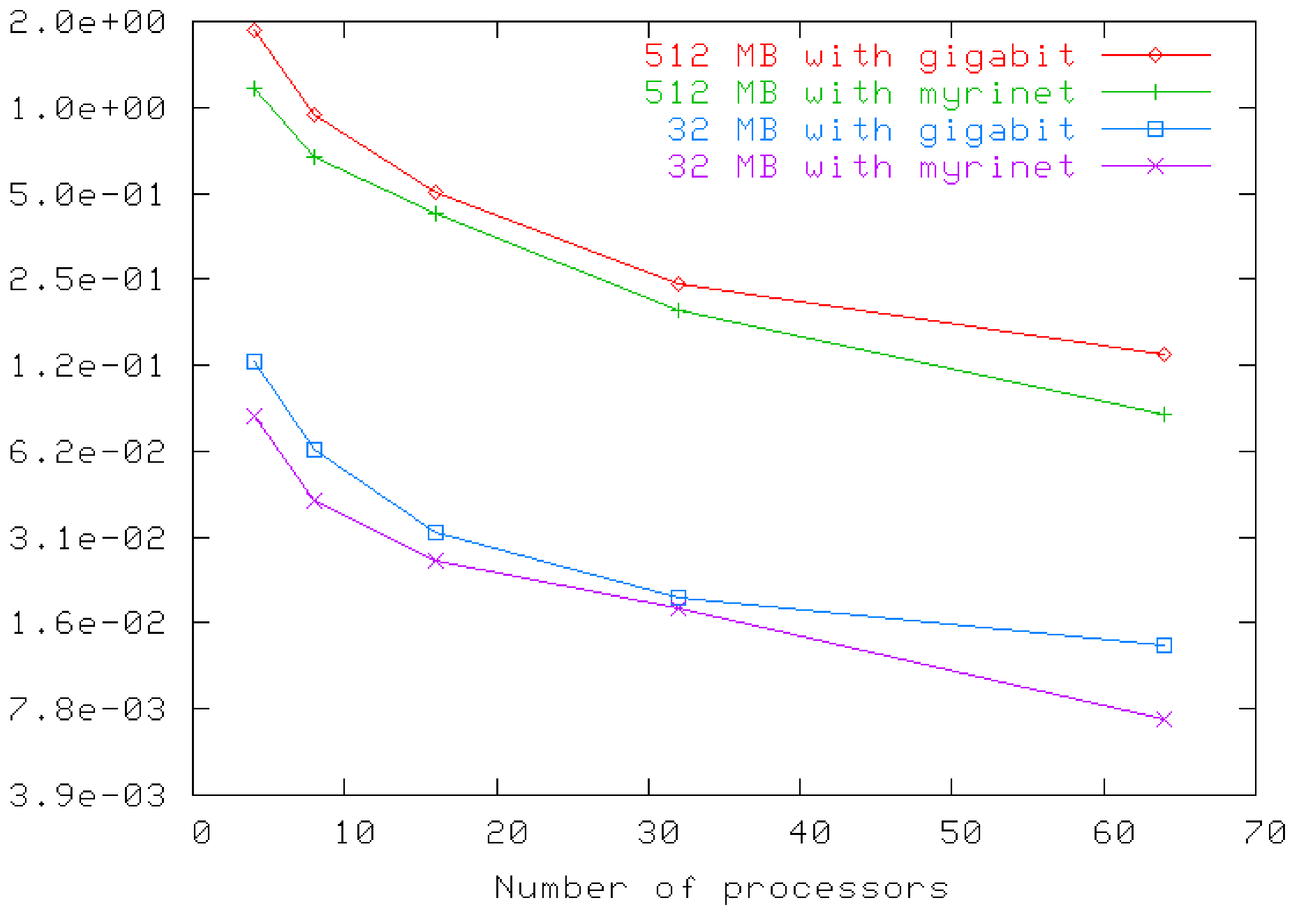
Proactive Object Migration (cont.)

- Evacuation time as a function of data size:
  - 5-point stencil code in Charm++, IA-32 cluster



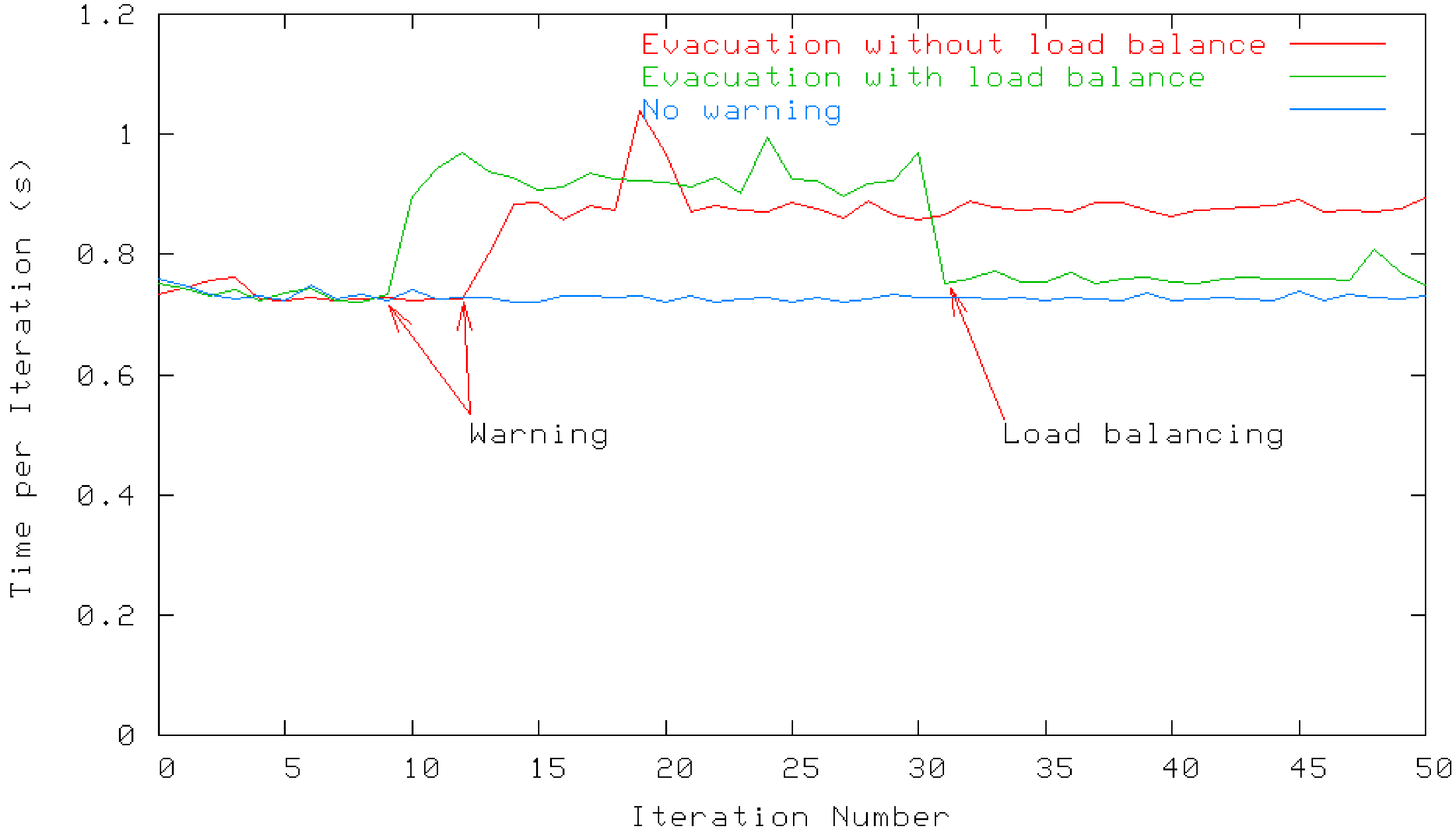
Proactive Object Migration (cont.)

- Evacuation time as a function of #processors:
  - 5-point stencil code in Charm++, IA-32 cluster



Proactive Object Migration (cont.)

- Performance of an MPI application
  - Sweep3d code, 150x150x150 dataset, P=32, 1 warning



Proactive Object Migration (cont.)

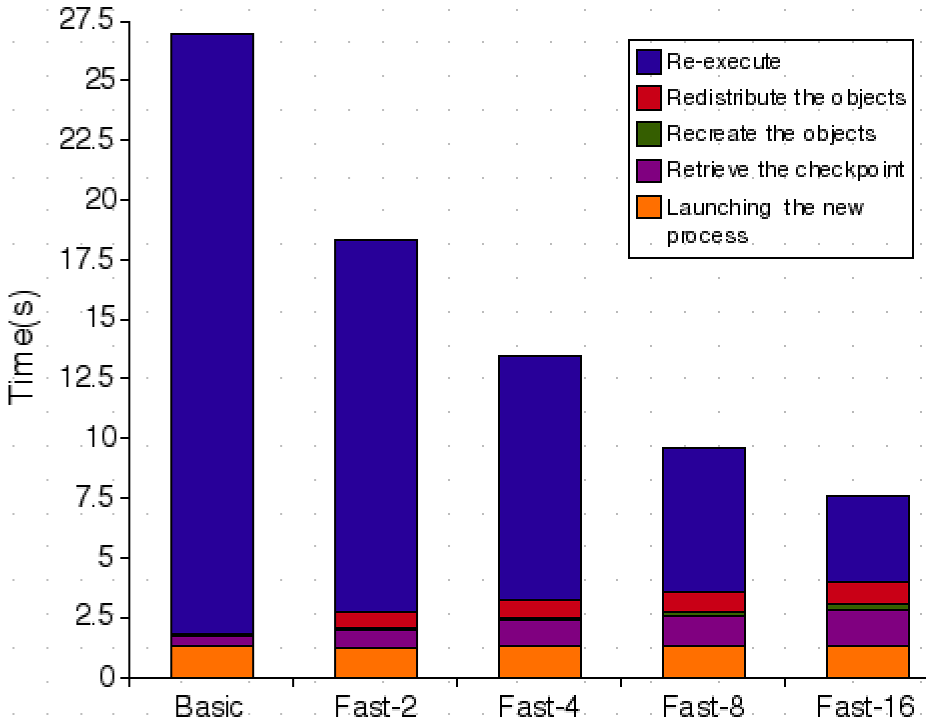
- Pros:
  - No overhead in fault-free scenario
  - Evacuation time scales well, only depends on data and network
  - No need to roll back when predicted fault happens
- Cons:
  - Effectiveness depends on fault predictability mechanism
  - Some faults may happen without advance warning
- Publications:
  - Chakravorty, Mendes & Kale: HiPC, Dec.2006
  - Chakravorty, Mendes, Kale et al: ACM-SIGOPS, April 2006

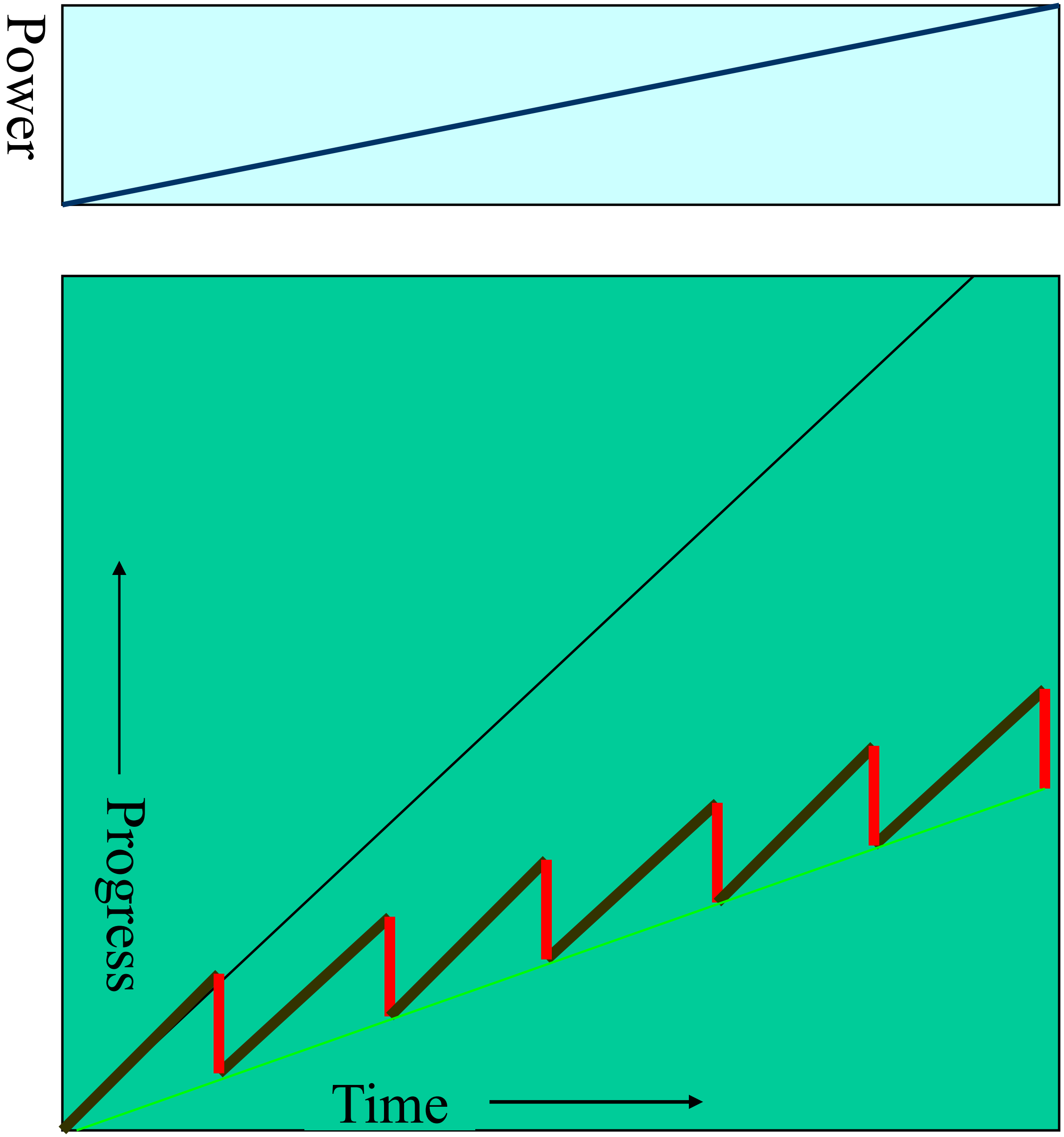
Message-Logging

- Basic Idea:
  - Messages are stored by sender during execution
  - Periodic checkpoints still maintained
  - After a crash, reprocess “recent” messages to regain state
- Implementation in Charm++/AMPI:
  - Since the state depends on the order of messages received, the protocol ensures that the new receptions occur in the same order
  - Upon failure, roll back is “localized” around failing point: no need to roll back all the processors!
  - With virtualization, work in one processor is divided across multiple virtual processors; thus, restart can be parallelized
  - Virtualization helps fault-free case as well

Message-Logging (cont.)

- Fast restart performance:
  - Test: 7-point 3D-stencil in MPI, P=32, $2 \leq VP \leq 16$
  - Checkpoint taken every 30s, failure inserted at t=27s

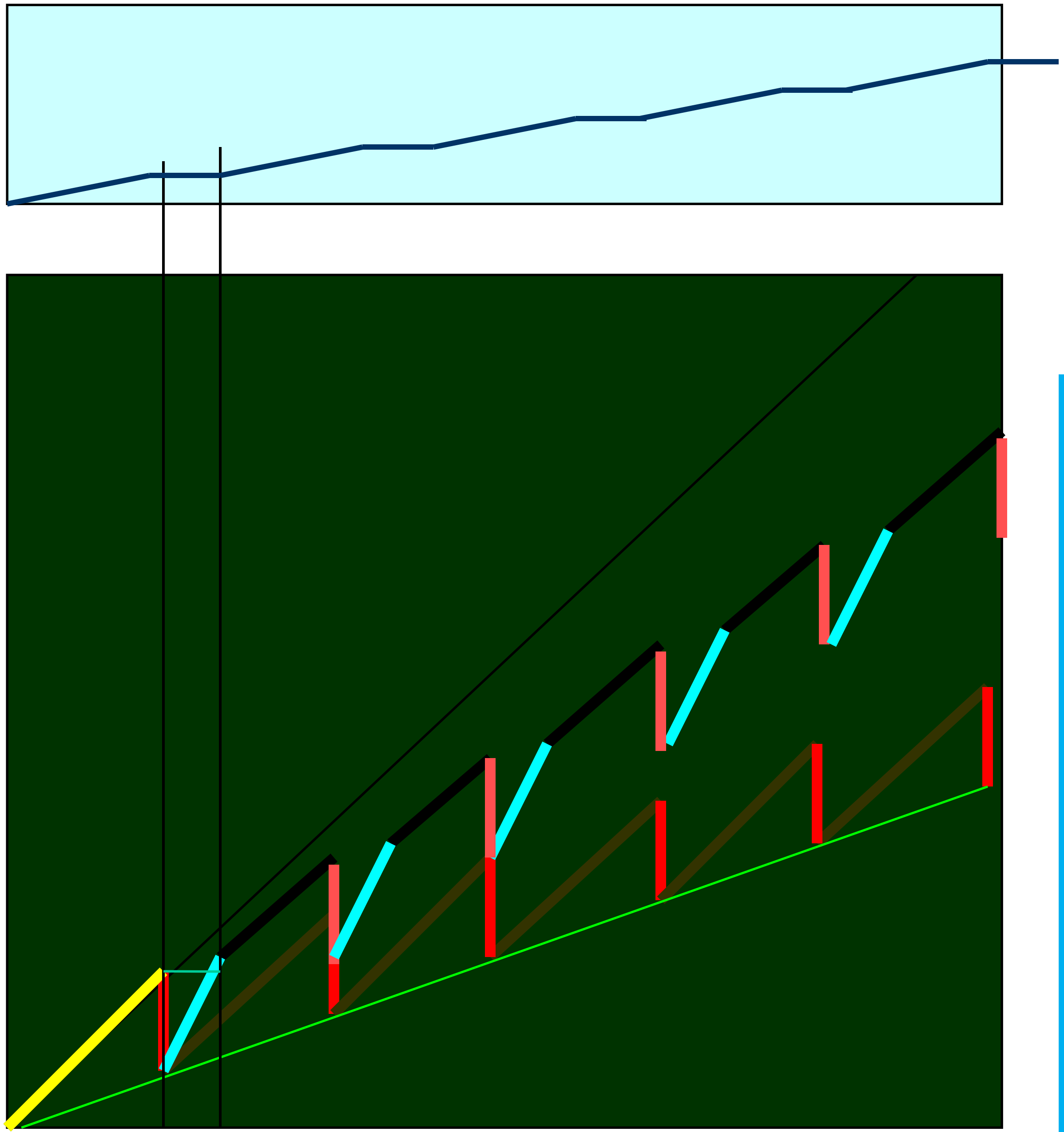




Normal Checkpoint-Resart method

Progress is slowed down with failures

Power consumption is continuous



Our Checkpoint-Resart method

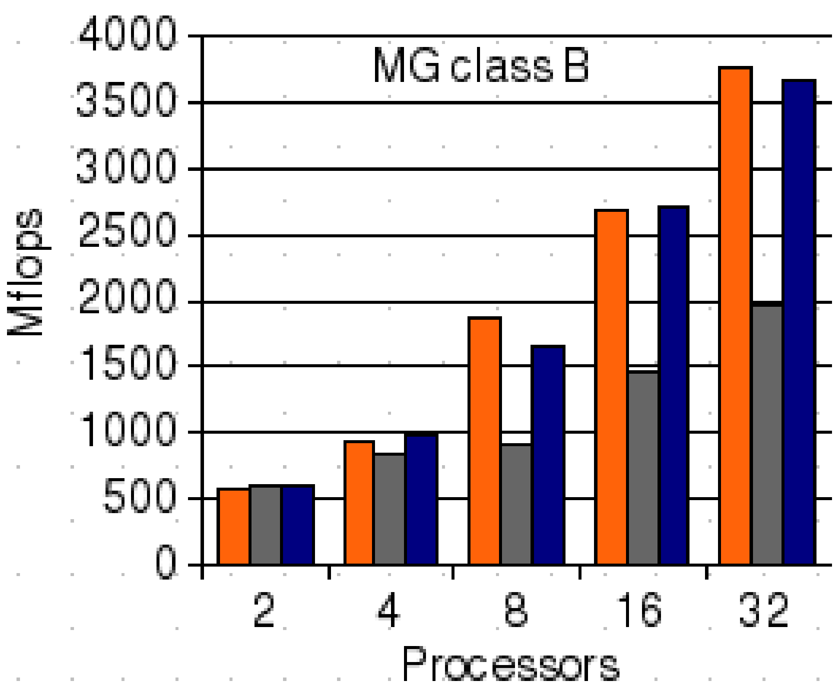
(Message logging + Object-based virtualization)

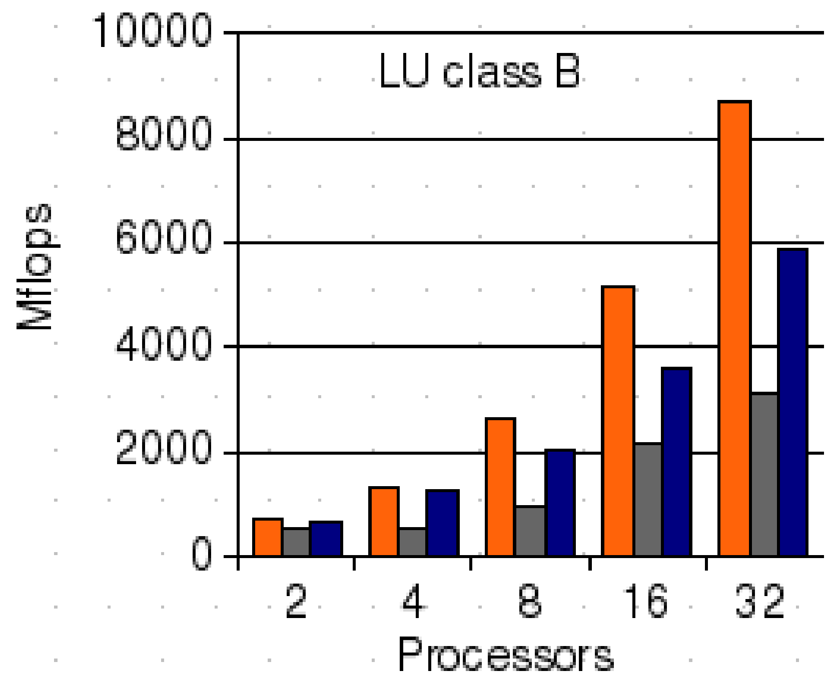
Progress is faster with failures

Power consumption is lower during recovery

Message-Logging (cont.)

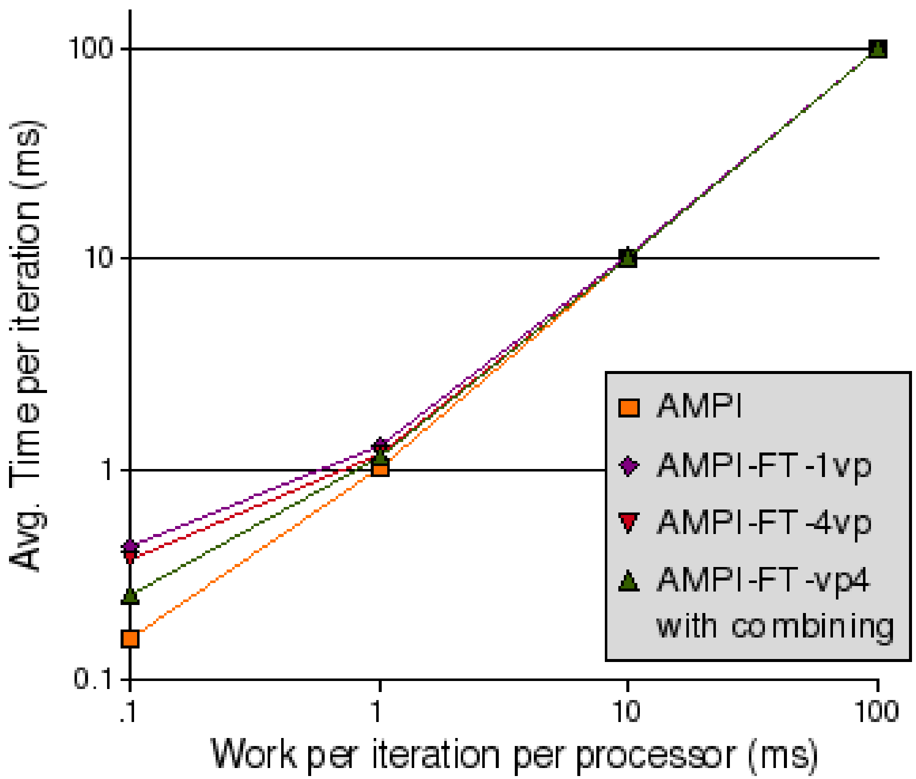
- Fault-free performance:
  - Test: NAS benchmarks, MG/LU
  - Versions: AMPI, AMPI+FT, AMPI+FT+multipleVPs





Message-Logging (cont.)

- Protocol Optimization:
  - Combine protocol messages: reduces overhead and contention
  - Test: synthetic compute/communicate benchmark



Message-Logging (cont.)

- Pros:
  - No need to roll back non-failing processors
  - Restart can be accelerated by spreading work to be redone
  - No need of stable storage
- Cons:
  - Protocol overhead is present even in fault-free scenario
  - Increase in latency may be an issue for fine-grained applications
- Publications:
  - Chakravorty: UIUC PhD Thesis, Dec.2007
  - Chakravorty & Kale: IPDPS, April 2007
  - Chakravorty & Kale: FTPDS workshop at IPDPS, April 2004

Current PPL Research Directions

- Message-Logging Scheme
  - Decrease latency overhead in protocol
  - Decrease memory overhead for checkpoints
  - Stronger coupling to load-balancing
  - Newer schemes to reduce message-logging overhead

But we are not experts in FT

- The message-driven objects model provides many benefits for fault tolerance schemes
  - Not just our schemes, but your schemes too
  - Multiple objects per processor:
    - latencies of protocols can be hidden
  - Parallel recovery by leveraging "multiple objects per processor"
  - Can combine benefits by using system level or BLCR schemes specialized to take advantage of objects (or user-level threads)
  - I am sure you can think of many new schemes
- We are willing to help
  - (without needing to be co-authors)
  - E.g. a simplified version of Charm RTS for you to use?

Messages

- We have an interesting fault tolerance schemes
  – Read about them
- We have an approach to parallel programming
  – That has benefits in the era of complex machines, and sophisticated applications
  – That is used by real apps
  – That provides beneficial features for FT schemes
  – That is available via the web
  – SO: please think about developing new FT schemes of your own for this model
- More info, papers, software: http://charm.cs.uiuc.edu
- And please pass the word on: we are hiring

PPL Funding Sources

- National Science Foundation
  - BigSim, Cosmology, Languages
- Dep. of Energy
  - Charm++ (Load-Balance, Fault-Tolerance), Quantum Chemistry
- National Institutes of Health
  - NAMD
- NCSA/NSF, NCSA/IACAT
  - Blue Waters project (Charm++, BigSim, NAMD), Applications
- Dep. of Energy / UIUC Rocket Center
  - AMPI, Applications
- NASA
  - Cosmology/Visualization