SC3260 / SC5260

Fault-tolerant Techniques for HPC

Lecture by: Ana Gainaru

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Slides heavily based on the SC tutorial given by George Bosilca
`https://fault-tolerance.org/downloads/sc14tutorial.pdf`

Failures and Faults in HPC

Top ranked supercomputers in the US (June 2017)

Rank	Name	Laboratory	Technology	Cores	PFlops/s	MTBF
4	Titan	ORNL	Cray XK7	560,640	17.59	$\approx$ 1 day
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Fail-stop errors Node failure, resource crashes

Silent errors or silent data corruptions (SDCs) Double bit flips, soft faults

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Exascale computing (1000 PFlops/s)

- Larger core count: millions or even billions of cores
- Shorter Mean Time Between Failures (MTBF) μ

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Coping with faults

- Build more reliable hardware!
- Make applications more fault tolerant!
- Design better resilience techniques/algorithms!

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Exascale platforms

- **Hierarchical**
  - 10^5 or 10^6 nodes
  - Each node equipped with 10^4 or 10^3 cores
- **Failure-prone**

MTBF – one node	1 year	10 years	120 years
MTBF – platform of 10^6 nodes	30sec	5mn	1h

More nodes → Shorter MTBF (Mean Time Between Failures)

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Exascale $\neq$ Petascale x 1000 !!

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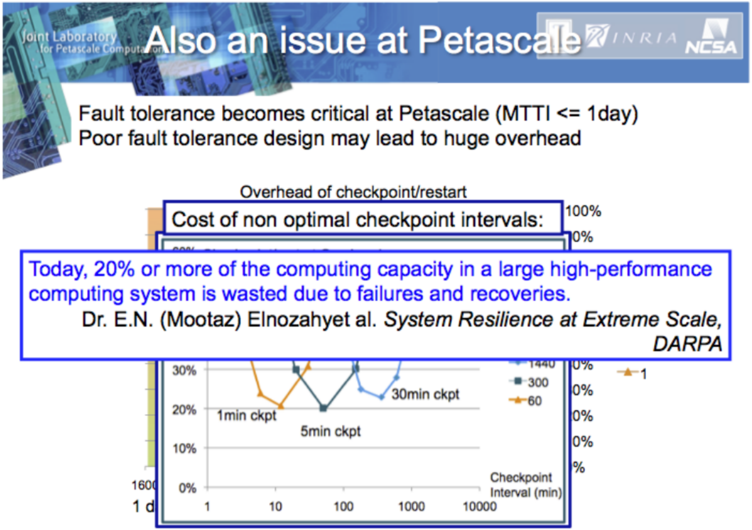
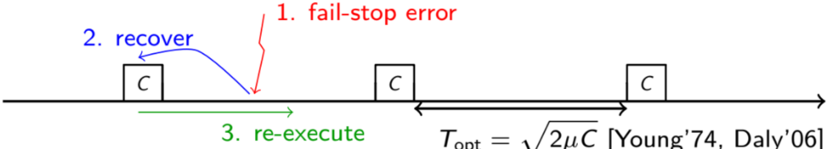
Even for today's platforms (courtesy F. Cappello)



Classic Resilience Techniques for HPC

Fail-stop errors (instantaneous error detection)
Standard approach periodic checkpointing, rollback and recovery



$T_{\text{opt}} = \sqrt{2\mu C}$ [Young'74, Daly'06]

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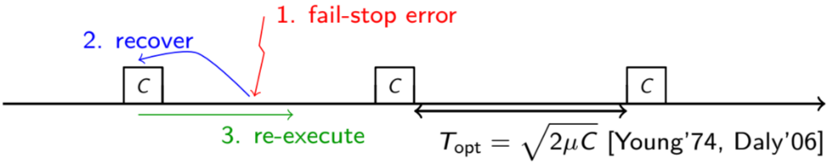

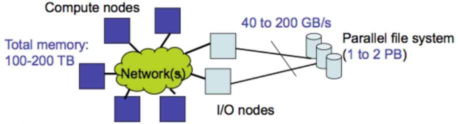

Without optimizations, currently C/R could take up to one hour !

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Sources of failures

- Many types of faults: software error, hardware malfunction, memory corruption
  - Software errors: Applications, OS bug (kernel panic), communication libs, File system error, etc
  - Hardware errors: Disks, processors, memory, network
- Many possible behaviors: silent, transient, unrecoverable
- **Restrict to faults that lead to application failures**
  - This includes most hardware faults, and some software ones
- Will use terms fault and failure interchangeably
- **Silent errors (SDC) addressed later in the lecture**

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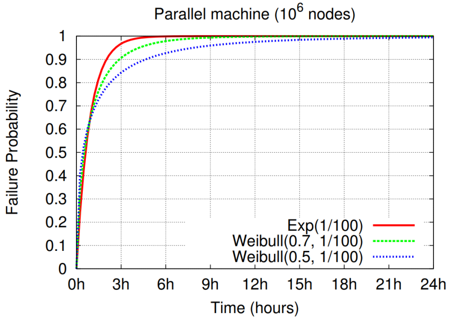
Values from real systems

- MTBF of one processor: between 1 and 125 years
- MTBF for systems: between several hours to one day



Failure trace archive from INRIA (`http://fta.inria.fr`)

Computer Failure Data Repository from LANL (`http://institutes.lanl.gov/data/fdata`)

Process Checkpointing

Goal

Save the current state of the process

- FT Protocols save a possible state of the parallel application

Two techniques

- User-level checkpointing
- System-level checkpointing

- Blocking call
- Asynchronous call

User-level checkpointing

User code serializes the state of the process in a file

- Usually small(er than system-level checkpointing)
- Portability
- Diversity of use

- Hard to implement if preemptive checkpointing is needed
- Loss of the functions call stack
  - code full of jumps
  - loss of internal library state

FTI (Fault Tolerance Interface)

Multi-level checkpointing tool for MPI applications

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System-level checkpointing

- Different possible implementations: OS syscall; dynamic library; compiler assisted
- Create a serial file that can be loaded in a process image. Usually on the same architecture, same OS, same software environment.

- **Entirely transparent**
- Preemptive (often needed for library-level checkpointing)

- Lack of portability
- Large size of checkpoint ($\approx$ memory footprint)

BLCR

Requires linking with the code

CRIU

User-space tool that can freeze a running container (or an individual application) and checkpoint its state to disk

Blocking / Asynchronous call

Blocking Checkpointing

- Relatively intuitive: checkpoint(filename)
- Cost: no process activity during the whole checkpoint operation.
- Can be linear in the size of memory and in the size of modified files

Asynchronous Checkpointing

- System-level approach: make use of copy on write of fork syscall
- User-level approach: critical sections, when needed

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Storage

Remote Reliable Storage

- Intuitive. I/O intensive. Disk usage.

Memory Hierarchy

- local memory
- local disk (SSD, HDD)
- remote disk
  - Scalable Checkpoint Restart Library
  - FTI

Checkpoint is valid when finished on reliable storage

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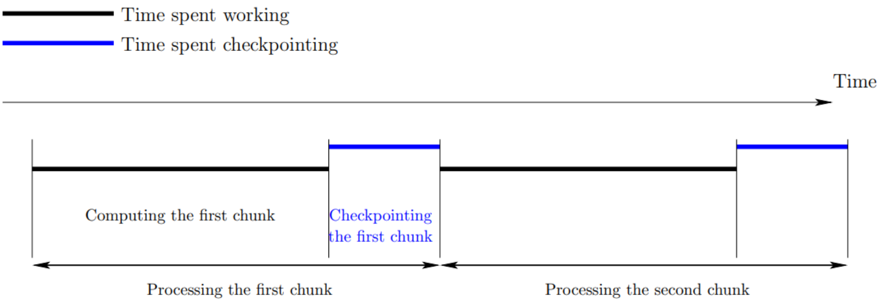
How to use checkpointing for your application?

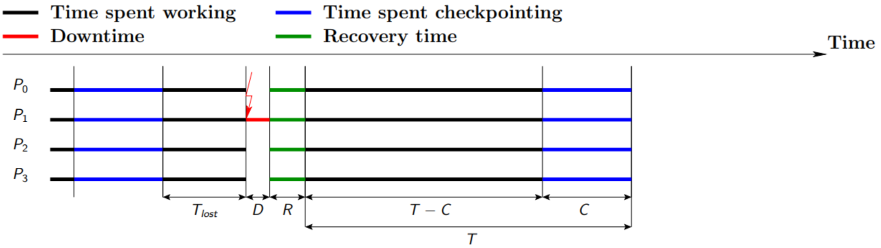
1. Choose the checkpoiting tool that fits your application
   - Do you have access to the code of the application?
   - What is the memory footprint?
   - How much time do you want to invest in changing your application?
   - What overhead is acceptable?
   - Is there a plugin in SLURM capable of taking checkpoints for you?
2. Choose the storage space for your application
   - Permanent storage or local memory
3. Choose how often you take checkpoints

Checkpointing cost



Blocking model: while a checkpoint is taken, no computation can be performed

Checkpointing cost



Time lost

- Downtime required to fix the error
- Time it takes to restart the application
- Average lost time is half the time between two checkpoints

- In addition to the time to take the checkpoints

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Checkpointing interval

Optimization problem

- Studied by multiple research projects
  - Failure rate of different hardware components
  - Application behavior
- **Daly's optimal checkpoint sequence from 2006 is still valid**

  $\sqrt{2\mu C}$

Lesson learned for fail-stop failures

- Tsubame 2: 962 failures during last 18 months so μ = 13 hrs
- Blue Waters: 2-3 node failures per day
- Titan: a few failures per day
- Tianhe 2: wouldn't say

$$T_{\text{opt}} = \sqrt{2\mu C} \quad \Rightarrow \quad \textsc{Waste}[opt] \approx \sqrt{\frac{2C}{\mu}}$$

Petascale:	$C = 20$ min	$\mu = 24$ hrs	$\Rightarrow \textsc{Waste}[opt] = 17\%$
Scale by 10:	$C = 20$ min	$\mu = 2.4$ hrs	$\Rightarrow \textsc{Waste}[opt] = 53\%$
Scale by 100:	$C = 20$ min	$\mu = 0.24$ hrs	$\Rightarrow \textsc{Waste}[opt] = 100\%$

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Fault tolerant MPI

Message Passing Interface Most popular middleware for multi-node programming in HPC

> **MPI Standard 3.0, p. 21, l. 24:25**
>
> This document does not specify the state of a computation after an erroneous MPI call has occurred.

Open MPI (`http://www.open-mpi.org`) **MPICH** (`http://www.mcs.anl.gov/mpi/mpich/`)

- Default: on failure detection, the runtime kills all processes. Can be de-activated by a runtime switch
- Errors might be reported to MPI processes. In that case MPI might be partly usable.

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MPI-Next-FT proposal: ULFM

Goal

Resume Communication Capability for MPI (and nothing more)

- Error reporting indicates impossibility to carry an operation
  - State of MPI is unchanged for operations that can continue (i.e. if they do not involve a dead process)
- Errors are non uniformly returned
  - (Otherwise, synchronizing semantic is altered drastically with high performance impact)

New APIs

- REVOKE allows to resolve non-uniform error status
- SHRINK allows to rebuild error-free communicators

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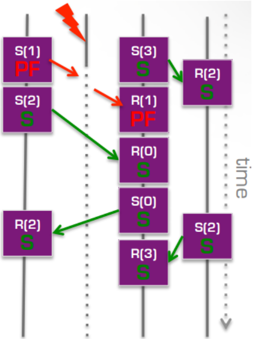
MPI-Next-FT proposal: ULFM



Errors are visible only for operations that cannot complete

Error Reporting

- Operations that cannot complete return `ERR_PROC_FAILED`, or `ERR_PENDING` if appropriate
- State of MPI Objects is unchanged (communicators etc.)
- Operations that can be completed return `MPI_SUCCESS` point to point operations between non-failed ranks can continue

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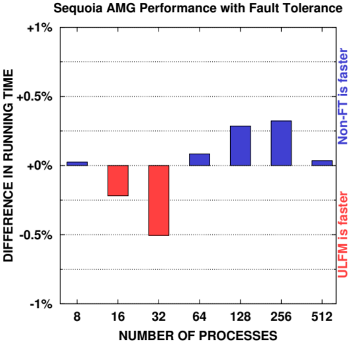
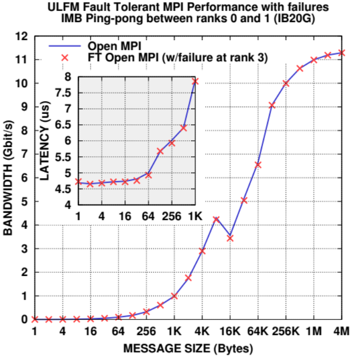
MPI-Next-FT proposal: ULFM





OpenMPI support

Branch of Open MPI (`www.open-mpi.org`)

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Application level resiliency

Applications can build customized methods for tolerating failures

- Depending on the application behavior some can mask failures all together
  - Neural networks
  - Heat equation
- Algorithm based fault tolerance
  - ABFT for Linear Algebra applications

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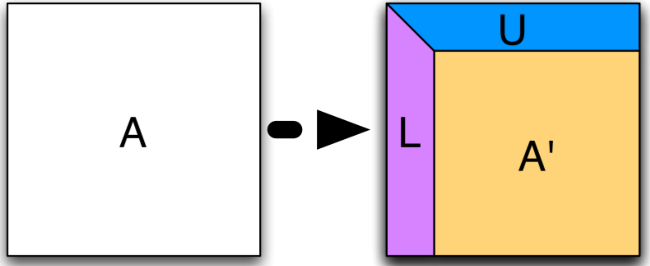
Example: block LU/QR factorization



- Solve $A \cdot x = b$ (hard)
- Transform A into a LU factorization
- Solve $L \cdot y = B \cdot b$, then $U \cdot x = y$

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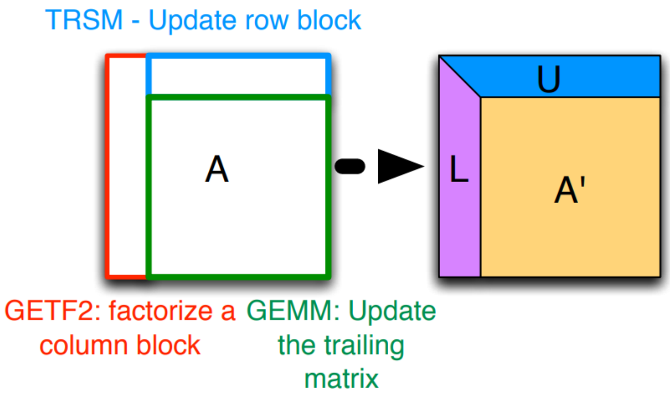
Example: block LU/QR factorization



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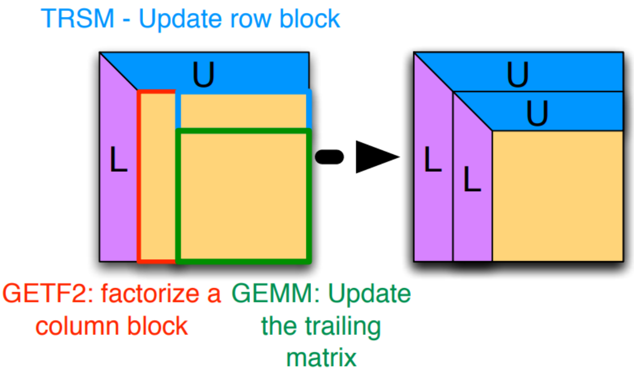

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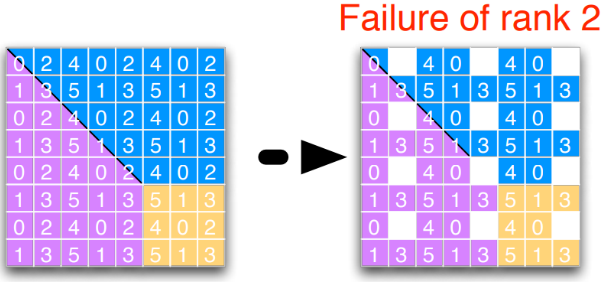

- 2D Block Cyclic Distribution (here 2 x 3)
- A single failure → many data elements will be lost

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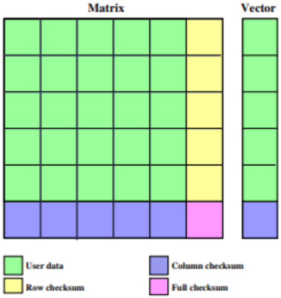
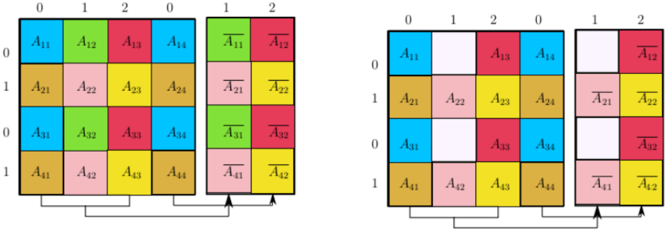
How do checksum work?





(a) Original matrix with the associated checksums

(b) Fault in process (0,1)

- For vector matrix multiplication, compute row/column wise checksum
- For LU factorization naive implementations will fail

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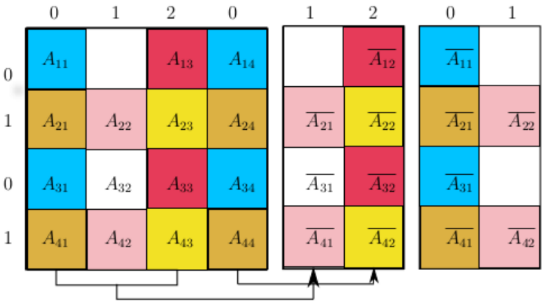
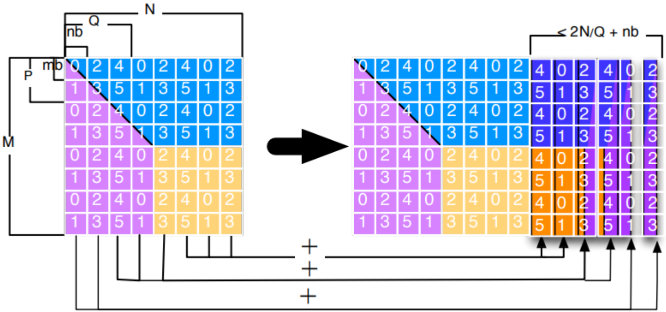
Checksum for LU



- Replication is needed

Algorithm Based Fault Tolerant QR decomposition



- Checksum: invertible operation on the data of the row / column
- Checksum blocks are doubled, to allow recovery when data and checksum are lost together

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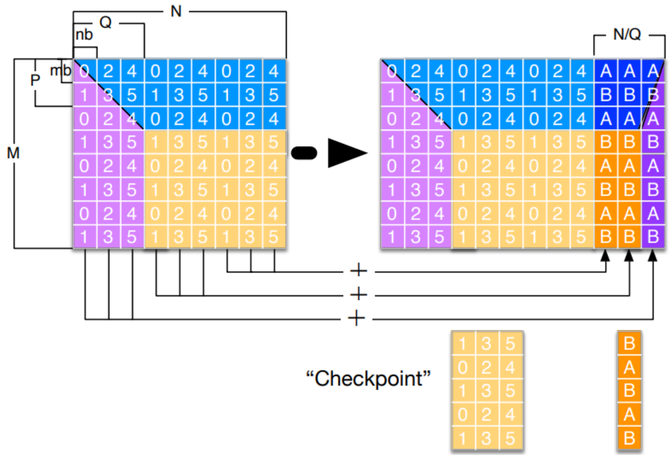
Algorithm Based Fault Tolerant QR decomposition



- Checksum: invertible operation on the data of the row / column
- Checksum replication can be avoided by dedicating computing resources

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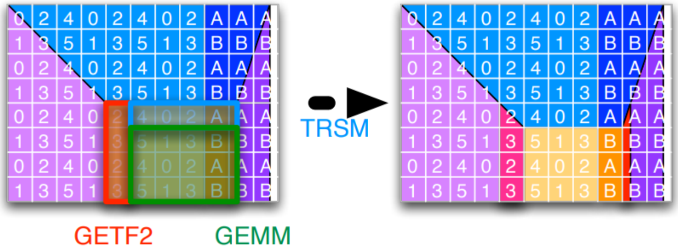
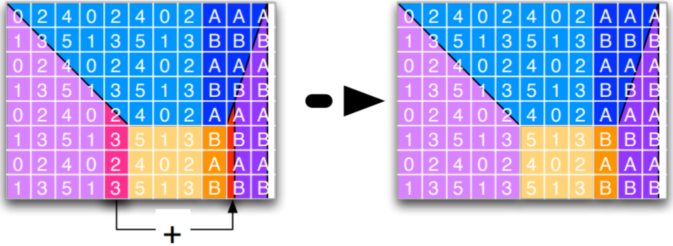
Algorithm Based Fault Tolerant QR decomposition



Idea of ABFT

Applying the operation on data and checksum preserves the checksum properties

Algorithm Based Fault Tolerant QR decomposition



Idea of ABFT

For the part of the data that is not updated this way, the checksum must be re-calculated

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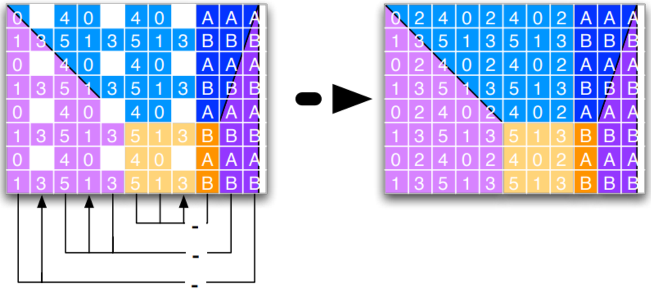
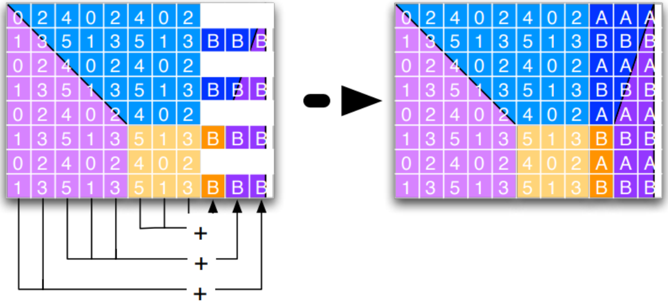
In case of a failure



- In case of failure, conclude the operation, then
  - Missing Data = Checksum - Sum(Existing Data) s

In case of a failure



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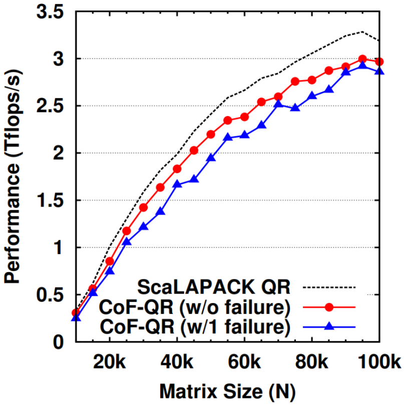
ABFT QR decomposition: performance



Open MPI; Kraken supercomputer;

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- Failures and faults in HPC
- Checkpointing
  - Theory
  - System and application level solutions currently used
- Fault tolerant MPI
- Desiging a resilient application
- Silent errors

What are silent failures?

- Instantaneous error detection $\rightarrow$ fail-stop failures, e.g. resource crash
- Silent errors (data corruption) $\rightarrow$ detection latency

Silent error detected only when the corrupt data is activated

- Includes some software faults, some hardware errors (soft errors in L1 cache), double bit flip
- Cannot always be corrected by ECC memory

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Should we be afraid? (courtesy Al Geist)

Fear of the Unknown

Hard errors – permanent component failure either HW or SW (hung or crash)

Transient errors –a blip or short term failure of either HW or SW

Silent errors – undetected errors either hard or soft, due to lack of detectors for a component or inability to detect (transient effect too short). Real danger is that answer may be incorrect but the user wouldn't know.

Statistically, silent error rates are increasing.
Are they really? Its fear of the unknown

Are silent errors really a problem
or just monsters under our bed?

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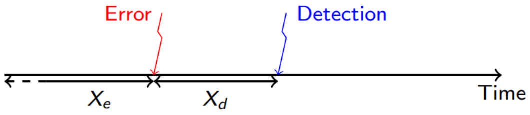
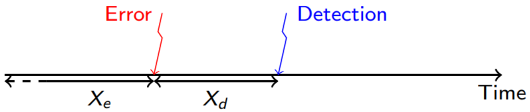
Coupling checkpointing with verification



Error and detection latency

- Last checkpoint may have saved an already corrupted state
- Possible solution: Saving k checkpoints (Lu, Zheng and Chien):
  1. Critical failure when all live checkpoints are invalid

Coupling checkpointing with verification



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       Assume unlimited storage resources
    2. Which checkpoint to roll back to?

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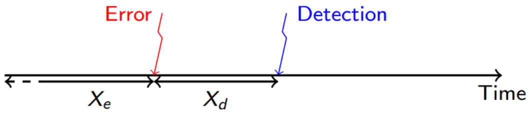
Coupling checkpointing with verification



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  2. Which checkpoint to roll back to?
     Assume verification mechanism

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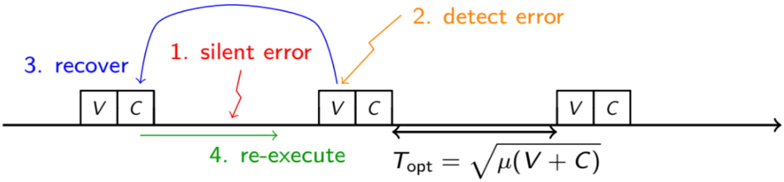
Coupling checkpointing with verification



- The most promising approach: checkpointing + verification (error detection)
- Use verification to correct some errors (ABFT)

A lot of unknowns

- Error rate? MTBE?
- Selective reliability?
- New algorithms beyond iterative? matrix-product, FFT

Conclusion

- **Multiple approaches to Fault Tolerance**
- **Application-Specific Fault Tolerance will always provide more benefits**:
  - Checkpoint Size Reduction (when needed)
  - Portability (can run on different hardware, different deployment, etc..)
  - Diversity of use (can be used to restart the execution and change parameters in the middle)
- **General Purpose Fault Tolerance is a required feature of the platforms**
  - Not every computer scientist needs to learn how to write fault-tolerant applications
- **Requirements of a more Fault-friendly programming environment**
  - MPI-Next evolution
  - Other programming environments?

Further resources

Fault-Tolerance Techniques for High-Performance Computing
Springer Book, Computer Communications and Networks series, 2015
Editors: Thomas Herault and Yves Robert

Checkpointing tools

- FTI: Fault Tolerance Interface, application level checkpoiting using multi-level storage, `https://github.com/leobago/fti`
- BLCR: Berkeley Lab Checkpoint/Restart for Linux (system level checkpointing tool), `https://crd.lbl.gov/departments/computer-science/CLaSS/research/BLCR/`
- CRIU: Checkpoint and Restore in Userspace, system level tool to checkpoint/restore Linux tasks, `https://github.com/checkpoint-restore/criu`

More info on the ABFT example
Algorithm-based fault tolerance applied to high performance computing,
Bosilca G. et al., JPDC 69, 4 (2009)

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