Fault Tolerance in Numerical Library Routines

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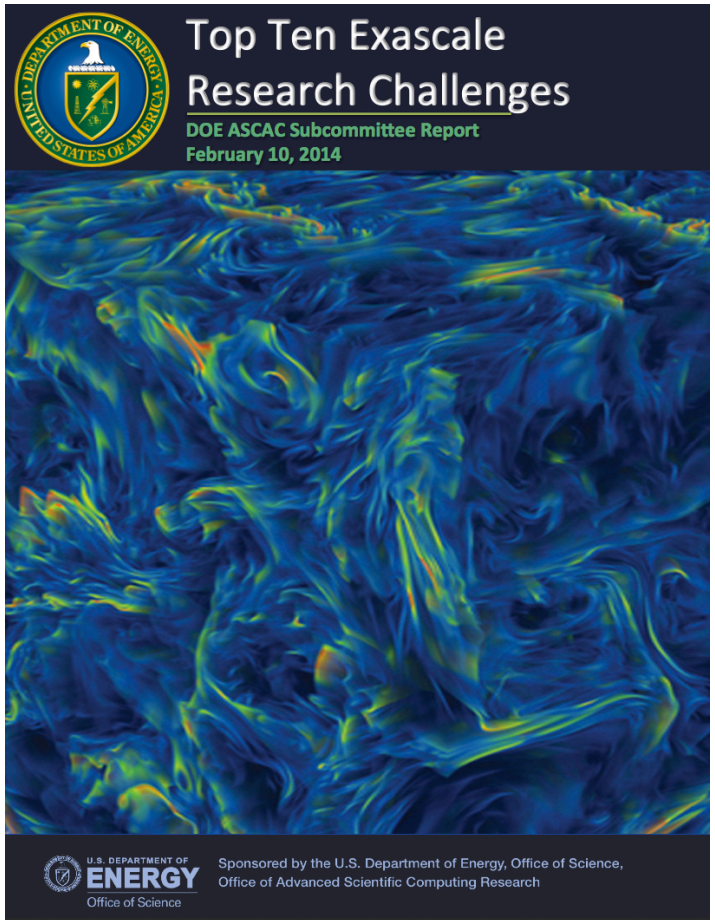
Top 10 Challenges to Exascale

In a recent report U.S. Department of Energy identified ten research challenges (Google "Top 10 Challenges to Exascale")



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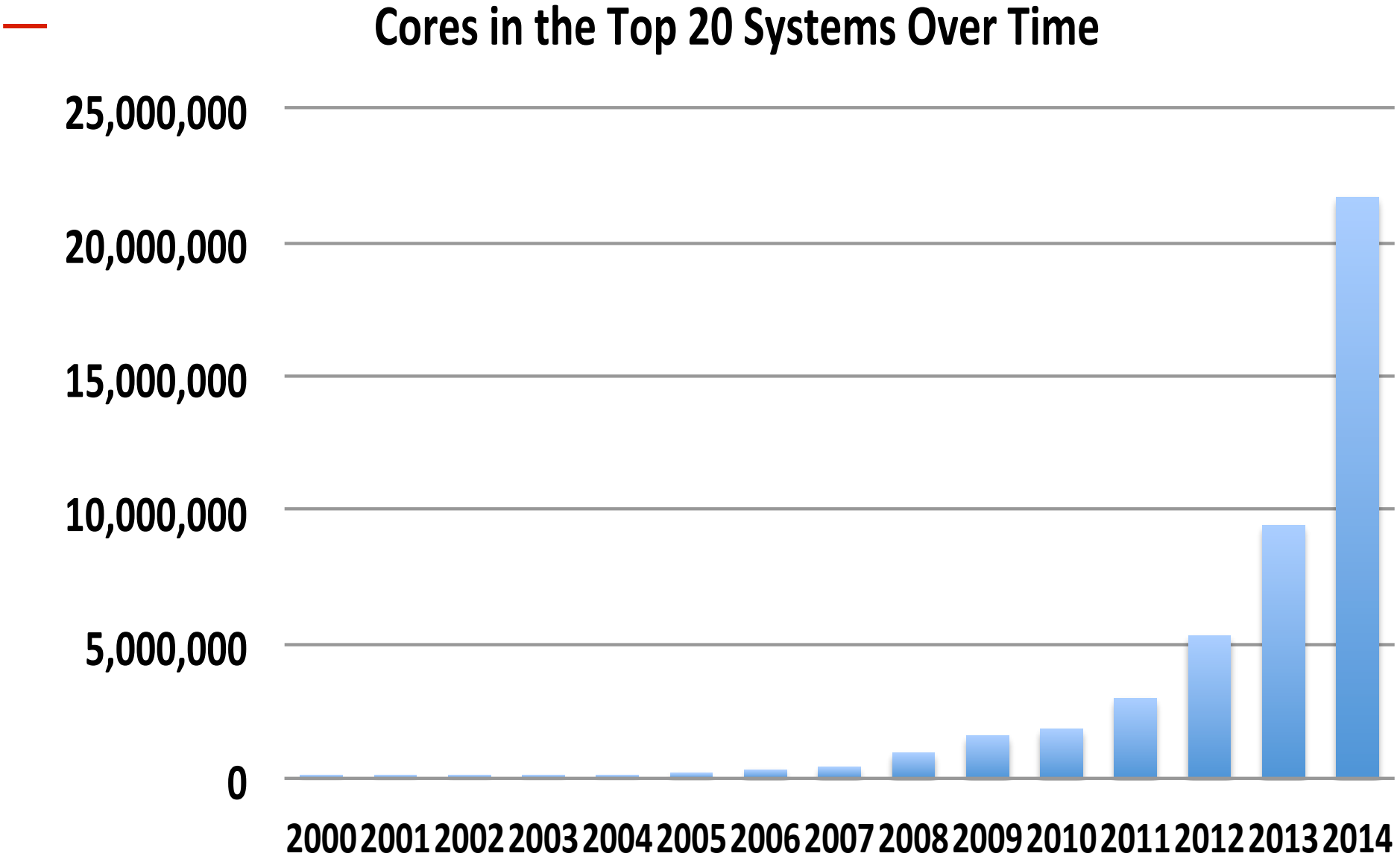
Top 10 Challenges to Exascale

1. **Energy efficiency:**
   - Creating more energy efficient circuit, power, and cooling technologies.
2. **Interconnect technology:**
   - Increasing the performance and energy efficiency of data movement.
3. **Memory Technology:**
   - Integrating advanced memory technologies to improve both capacity and bandwidth.
4. **Scalable System Software:**
   - Developing scalable system software that is power and resilience aware.
5. **Programming systems:**
   - Inventing new programming environments that express massive parallelism, data locality, and resilience
6. **Data management:**
   - Creating data management software that can handle the volume, velocity and diversity of data that is anticipated.
7. **Exascale Algorithms:**
   - Reformulating science problems and refactoring their solution algorithms for exascale systems.
8. **Algorithms for discovery, design, and decision:**
   - Facilitating mathematical optimization and uncertainty quantification for exascale discovery, design, and decision making.
9. **Resilience and correctness:**
   - Ensuring correct scientific computation in face of faults, reproducibility, and algorithm verification challenges.
10. **Scientific productivity:**
    - Increasing the productivity of computational scientists with new software engineering tools and environments.
    - Unless researcher productivity increases, the time to solution may be dominated by application development, not computation.

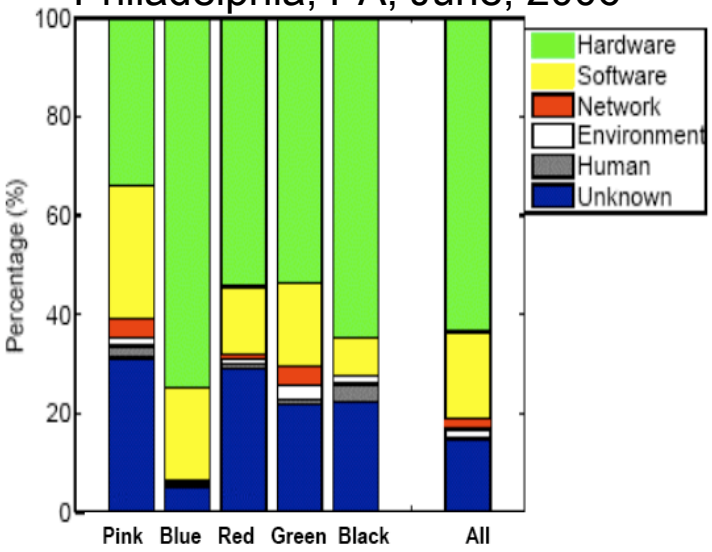

Cores in the Top 20 Systems Over Time
25,000,000
20,000,000
15,000,000
10,000,000
5,000,000
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

Motivation

Types of faults:

- Power outage (voltage regulator failure, etc.)
- Hard errors (broken component: memory, network, core, disk, etc.)
- Soft errors (bit flip in memory, logic, bus)
- OS error (buffer overrun, deadlock, etc.)
- System Software error (service malfunction, tin
- Administrator error (Human)
- User errors (Human)

G. Gibson, Proc of the DSN2006, Philadelphia, PA, June, 2006



Relative frequency of root cause by system type.

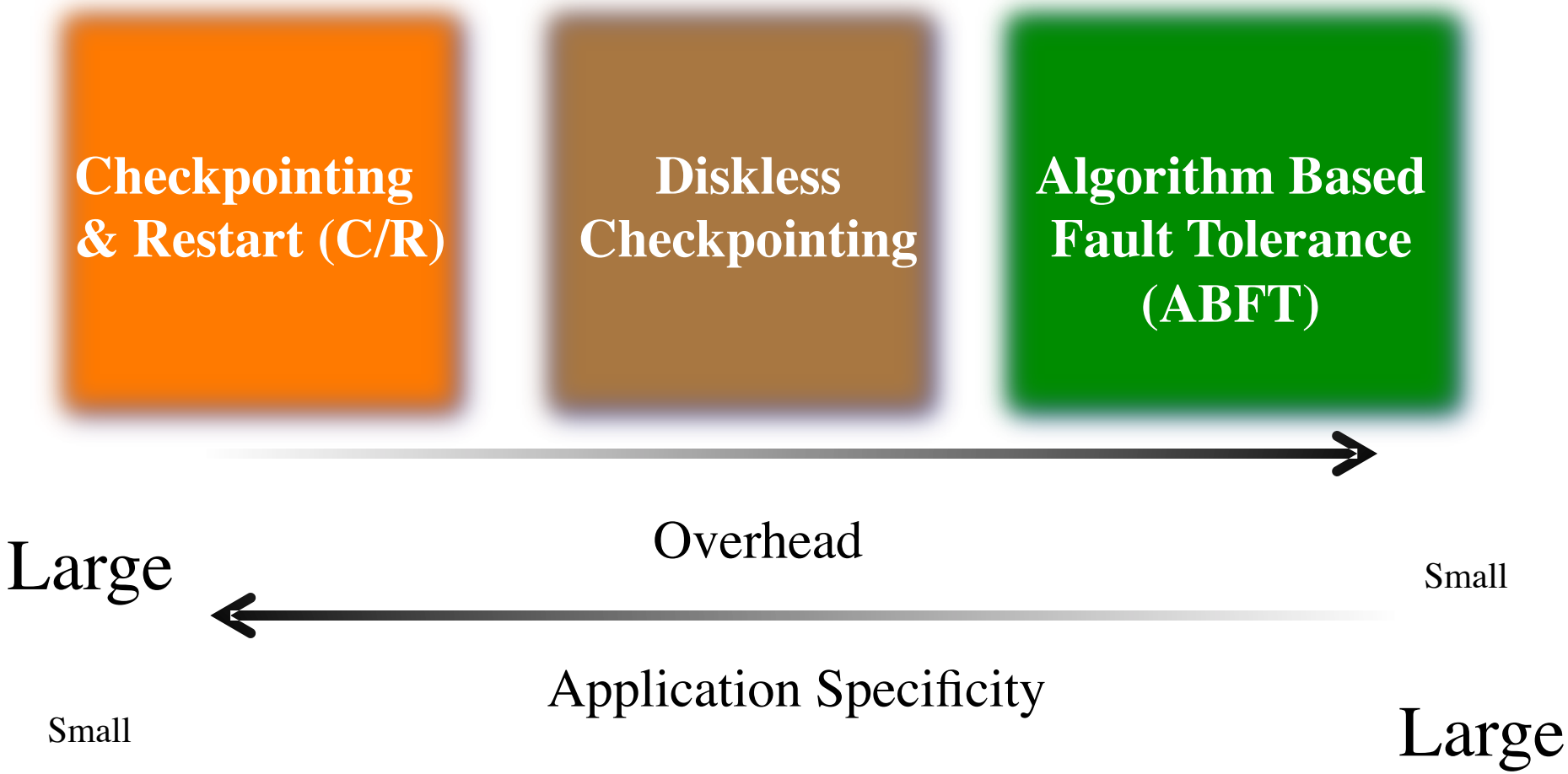
Classes of faults:

- Detected and corrected (by ECC, Replication, Re-execution)
- Detected and uncorrectable (leading to application crash: fail stop)
- Undetected (leading to data corruption, application hang, etc.)

Problem Definition

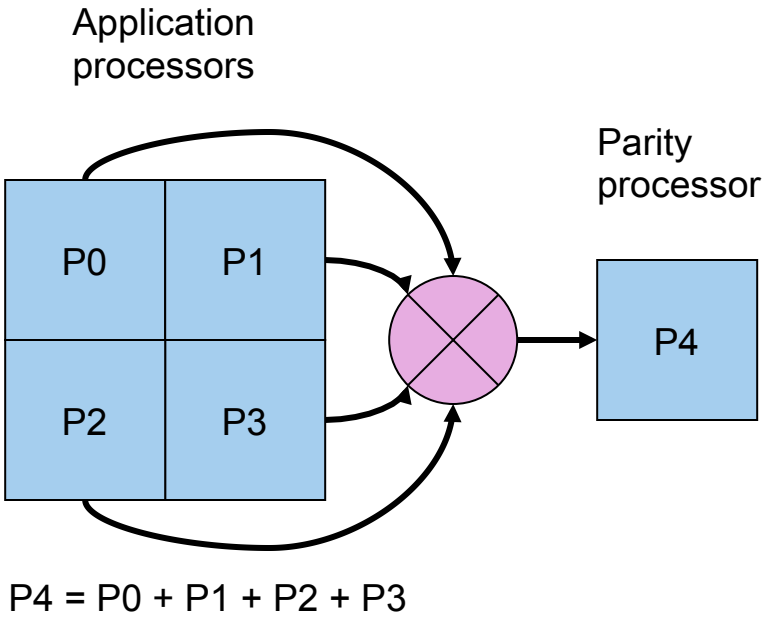
- System Errors
  - Hard Error (single, multiple)
  - Soft Error (single, multiple) (not discuss)
    - Bit flip effect
- Dense Linear Algebra
  - Direct methods: LU, Cholesky, QR, eigenvalue problems, …
  - Iterative methods
- Platforms/Applications
  - Distributed memory system
    - Eg. MPI, ScaLAPACK
  - Hybrid system with the GPGPU

Research Status Anatomy



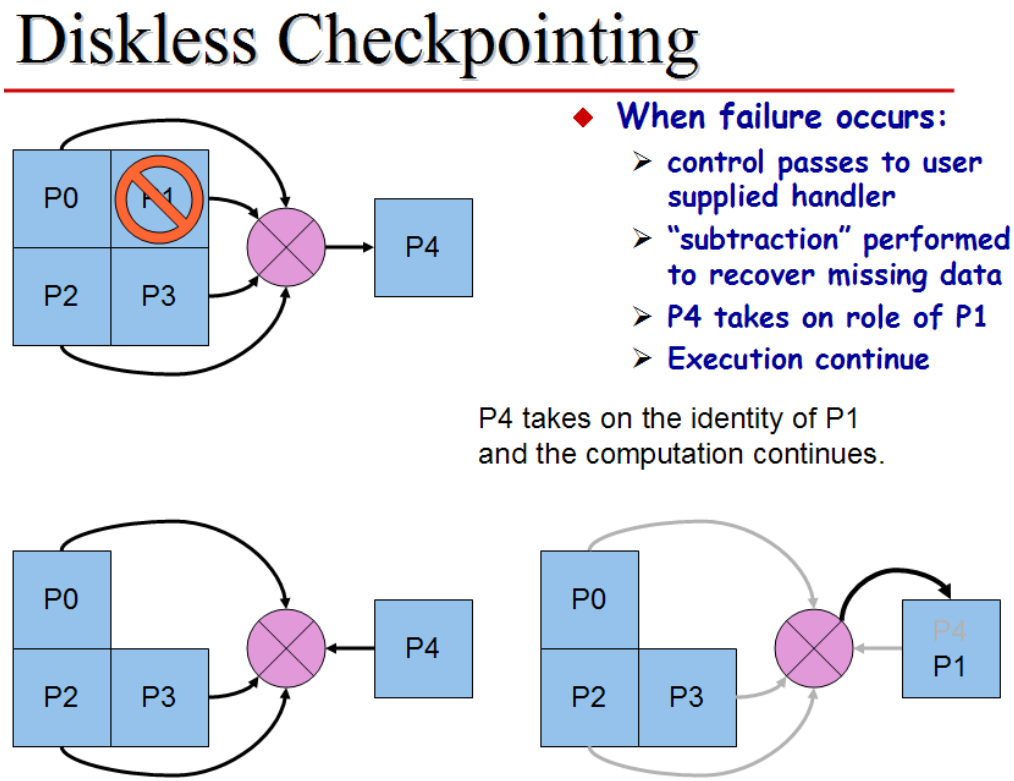
Diskless Checkpointing

- The p application processors (4 in this case) each maintain their own checkpoints locally.
- k extra processors maintain coding information so that if 1 or more processors fail, they can be replaced.
- Will describe for k=1 (parity)
- If a single processor fails, then its state may be restored from the remaining live processors



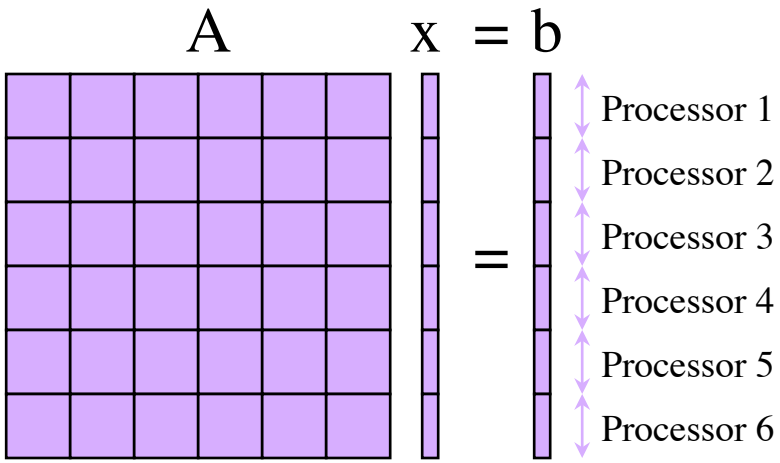
Three Ideas for Fault Tolerant Linear Algebra Algorithms

- **Lossless diskless check-pointing for iterative methods**
  - **Checksum maintained in active processors**
  - **On failure, roll back to checkpoint and continue**
  - **No lost data**



Lossy Algorithm : Basic Idea

- Let us assume that the exact solution of the system Ax=b is stored on different processors by rows



- May work well for iterative methods

Lossy Algorithm : Basic Idea

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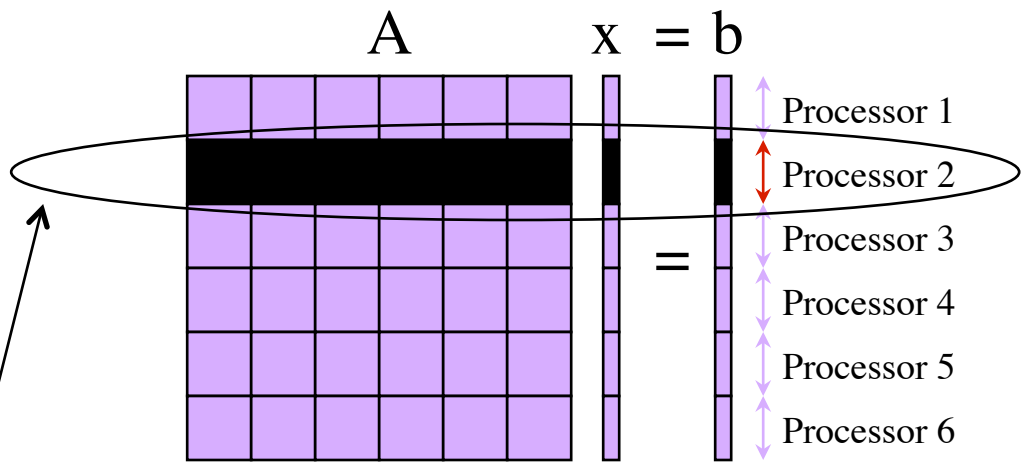
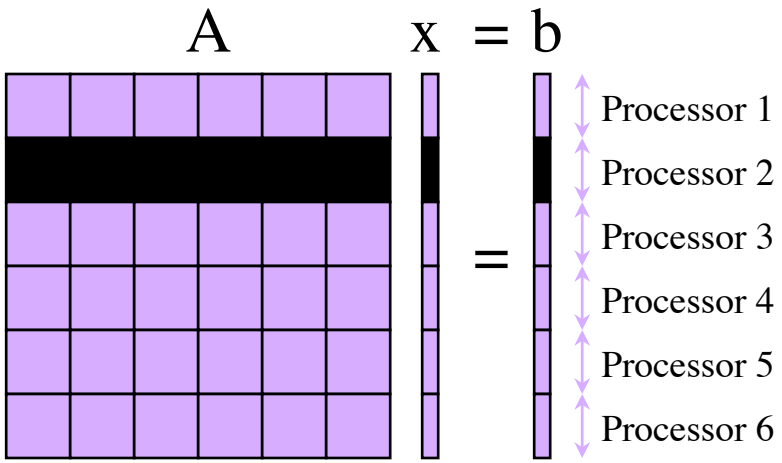


Processor 2 (e.g.) fails, all its data is lost.

How to recover the lost part of x in this case?

Lossy Algorithm : Basic Idea

- **Let us assume that the exact solution of the system Ax=b is stored on different processors by rows**

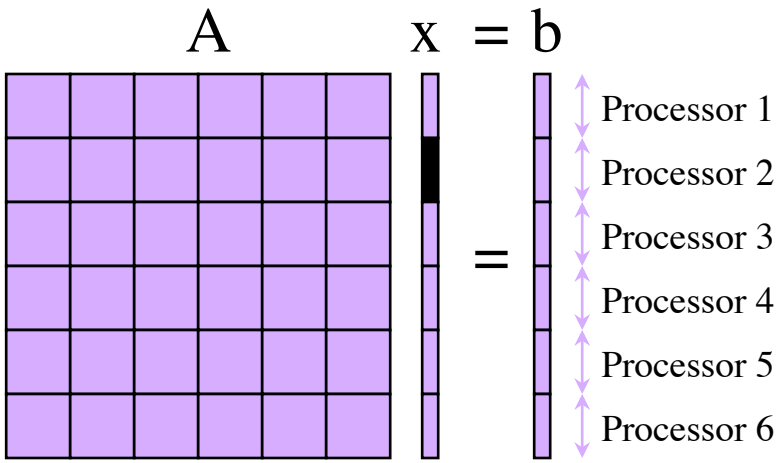


3 steps

Step 1: recover a processor and a running parallel environment (the job of the fault tolerant-MPI library)

Lossy Algorithm : Basic Idea

- **Let us assume that the exact solution of the system Ax=b is stored on different processors by rows**



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Step 1: revover a processor and a running parallel environement (the job of the fault tolerant-MPI library)

Step 2: recover A_{21} A_{22}, …, A_{n2} and b_2 (the original data) on the failed processor

Lossy Algorithm : Basic Idea

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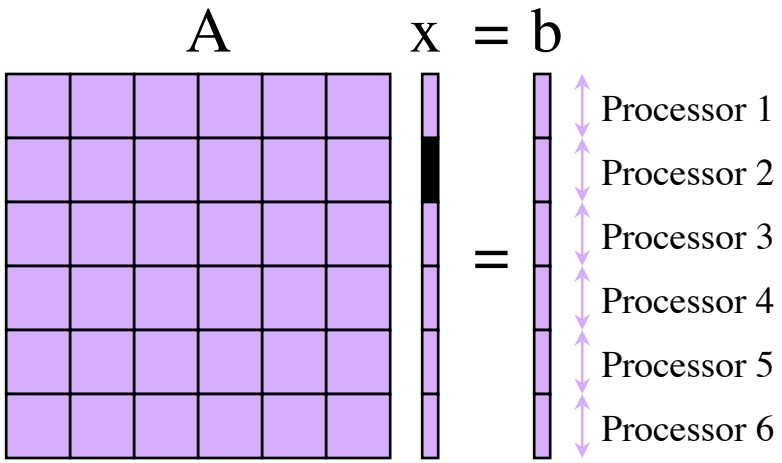


3 steps

Step 1: recover a processor and a running parallel environment (the job of the fault tolerant-MPI library)

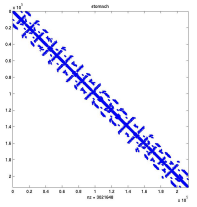
Step 2: recover A_{21} A_{22}, …, A_{n2} and b_2 (the original data) on the failed processor

Step 3: Notice that

$$A_{21} x_1 + A_{22} x_2 + \ldots + A_{2n} x_n = b_2)$$

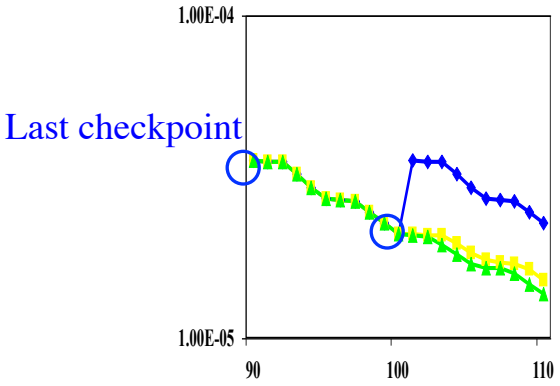
$$x_2 = A_{22}^{-1} (b_2 - \Sigma_{i \neq 2} A_{2i} x_i)$$

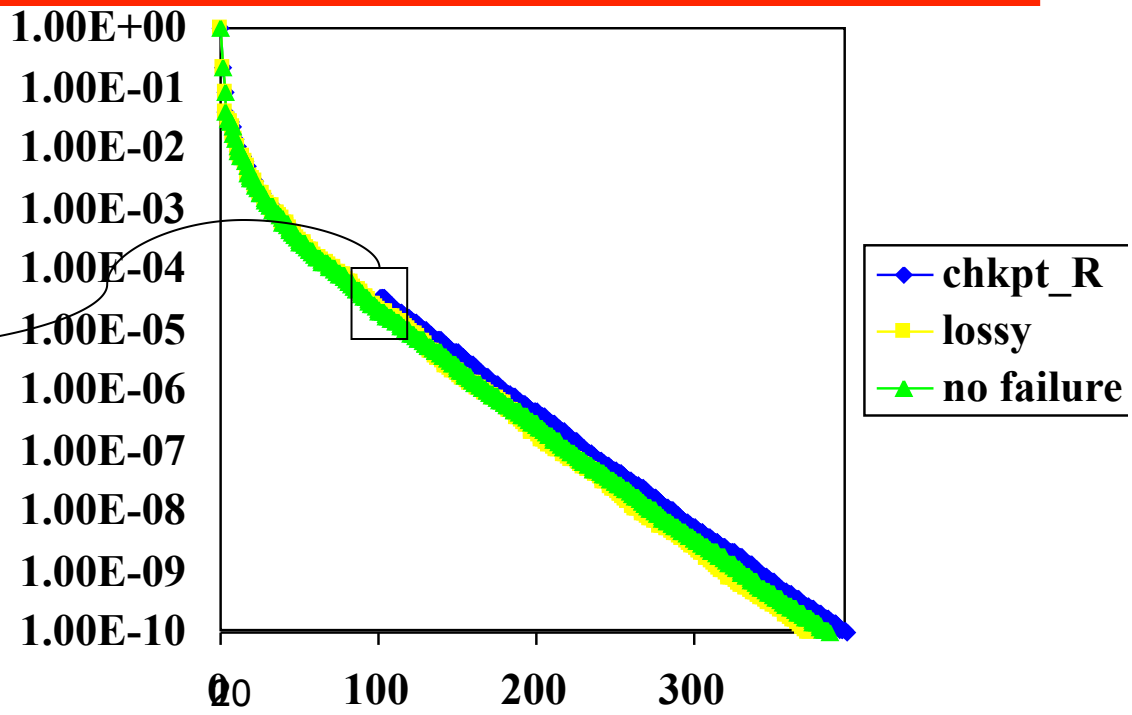
Using GMRES(30) Non Symetric Matrix



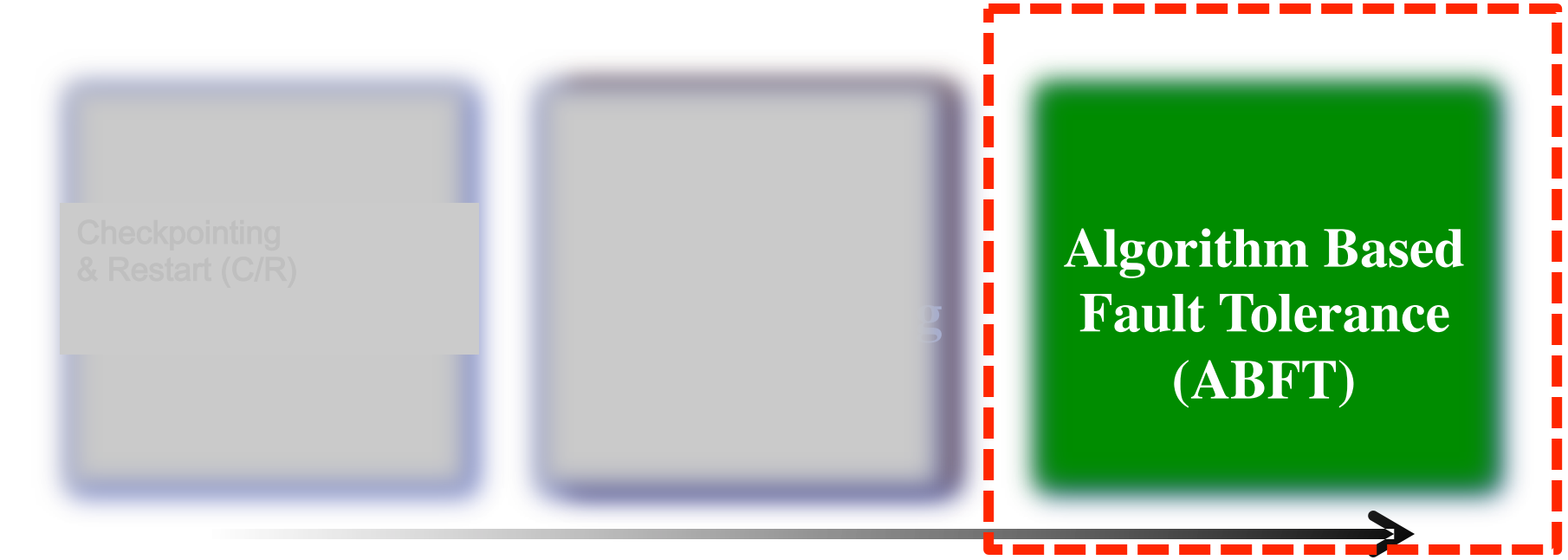
stomach; n=213,360; nnz=3,021,648; tol=10^{-10}; #procs=16; n_f=13,335; nnz=185,541									
recovery	$iter_f$	#iter	T_{Wall}	T_{Chkpt}	T_{Roll}	T_{Recov}	T_I	$T_{II,a,b}$	T_{III}
lossy	no	385	38.89						
$chkpt_R$	no	385	41.04	1.92					
lossy	100	372	42.38		1.56	5.38	1.03	0.33	3.91
$chkpt_R$	100	395	45.49	1.92	2.40	1.68	1.02	0.32	0.20

$chkpt_R$ every GMRES restart, 30 iterations





Research Status Anatomy



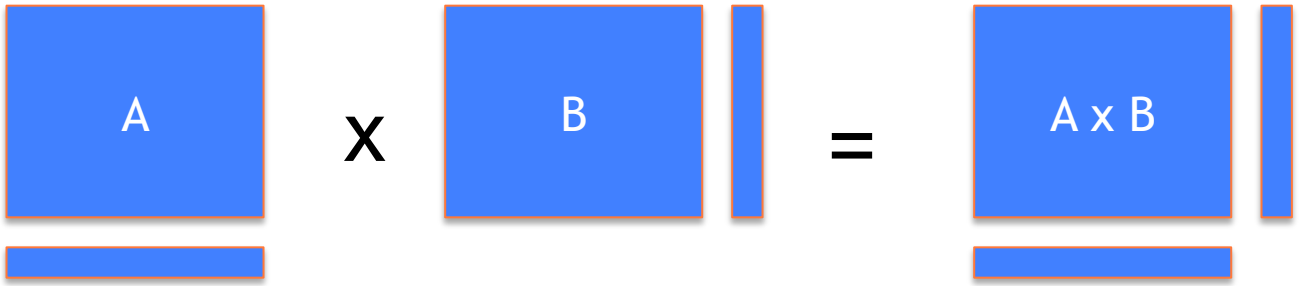
Motivation

- Algorithm Based Fault Tolerance
  - Handle failures at the application level
  - User knows more, can do better
- Mix of different techniques
  - Checkpointing (few data)
  - Transactions
  - Replication
  - Classical ABFT checksumming

Techniques for Error Protection and Failure Recovery

- **Algorithm-Based Fault Tolerance**
  - **KH Huang & Jacob Abraham, ABFT for Matrix Operations, IEEE Trans. Computers. 01/1984;**
    - **Implementation on systolic arrays**
  - **Takes advantage of additional mathematical relationship(s)**
    - **Already present in algorithm**
    - **Introduced (cheaply, if possible) by ABFT**
  - **Goal of this work is to do an implementation that could be carried out on a complete numerical library such as ScaLAPACK.**

Algorithm Based Fault Tolerance (ABFT)



$$\begin{bmatrix} A \\ G^T A \end{bmatrix} \times \begin{bmatrix} B & BG \end{bmatrix} = \begin{bmatrix} AB & ABG \\ G^T AB & G^T ABG \end{bmatrix}$$

G^T

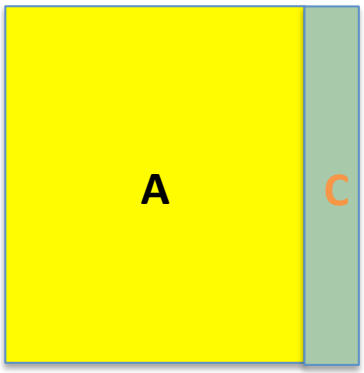
Algorithm-based fault tolerance for matrix operations, Huang, K.H. and Abraham, 1984

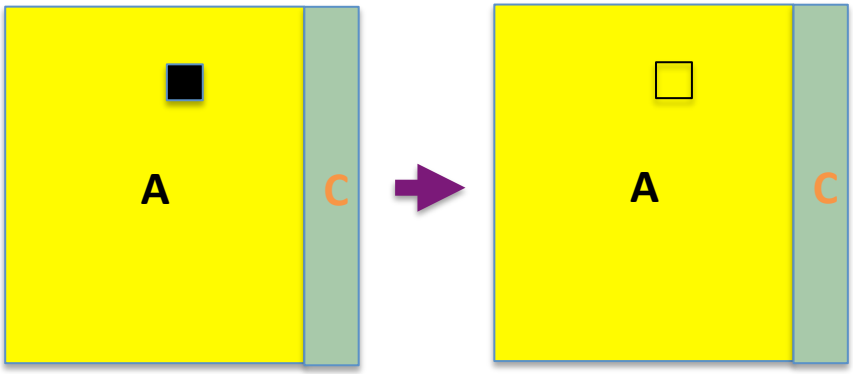
ABFT Idea

- C matrix contains a checksum (row summations) of A
- Checksums introduce redundancy (resilience) to the algorithm

$$C_i = \sum_j A_{ij}$$

$$A_{ij} = C_i - \sum_{k \neq j} A_{ik}$$





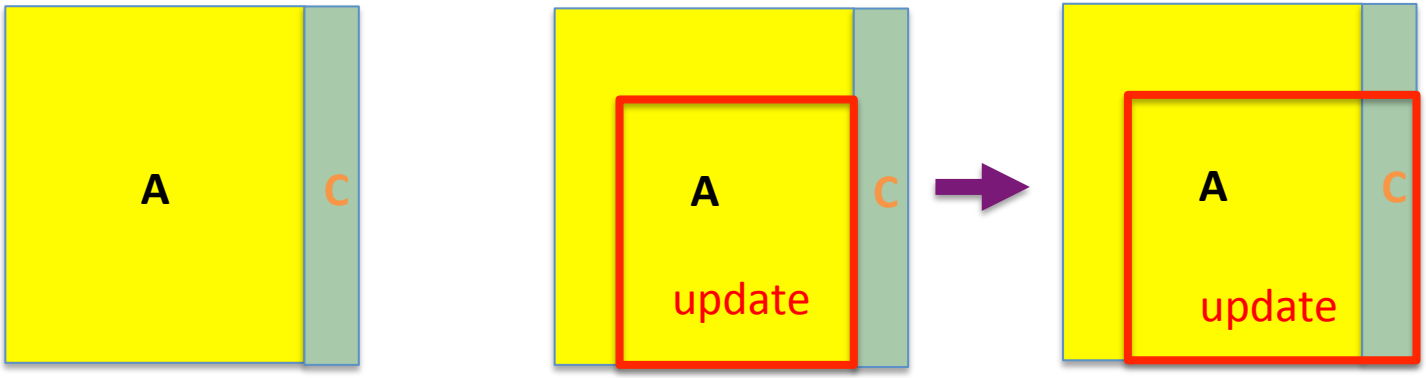
In case of failure, checksum inversion allows to restore the missing value

ABFT Idea

- C matrix contains a checksum (row summations) of A
- Checksums remain mathematically invariant!

$$C_i = \sum_j A_{ij}$$

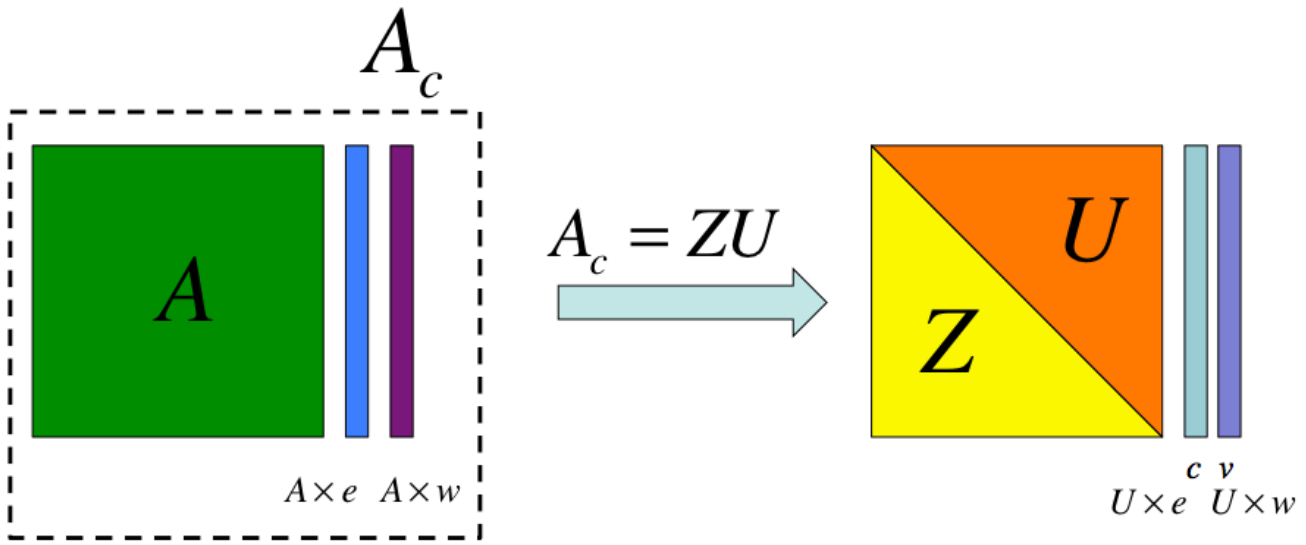
*The **Same algorithm** updates both the **trailing matrix AND** the **checksums***



$$Update(\sum_j A_{ij}) = \sum_j Update(A_{ij})$$

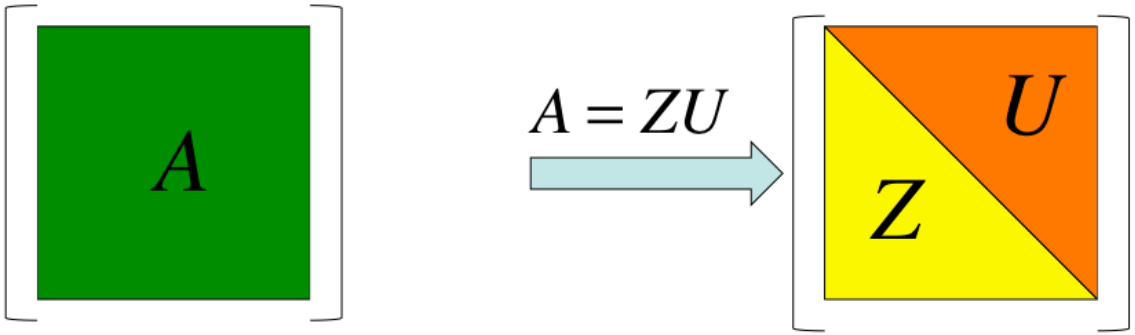
Algorithm Based Fault Tolerance

- Before the factorization starts, a checksum is taken and Algorithm Based Fault Tolerance (ABFT) is used to carry the checksum along with the computation.



Note: when ZU is QR factorization, Z is not lower triangular

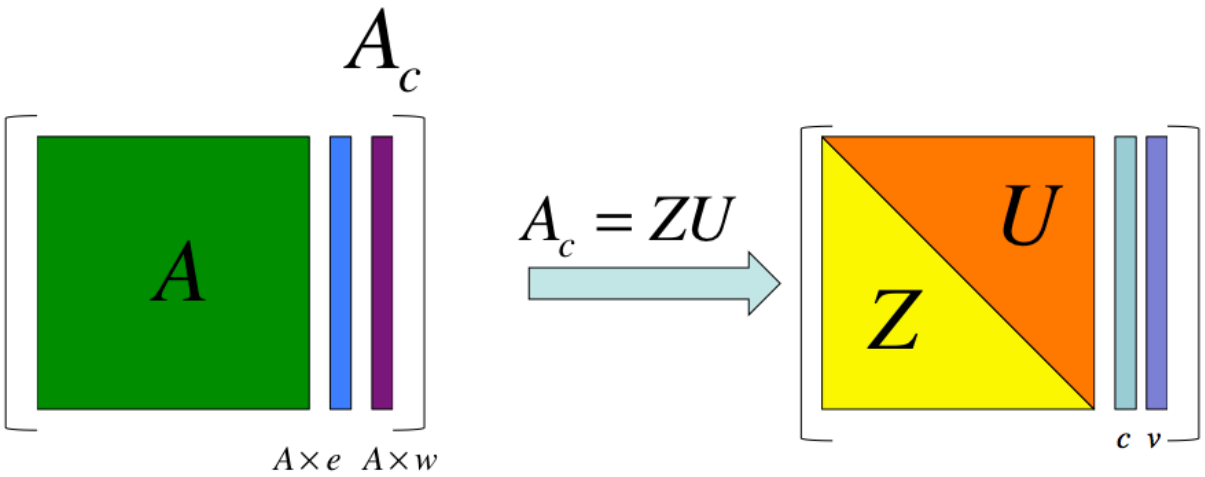
Checksum in ABFT



Generator, *G =(e, w)*

$$e = \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \quad w = \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix}$$

w_i random number



$$A_c = (A, Ae, Aw)$$

$$A_c = Z(U, c, v)$$

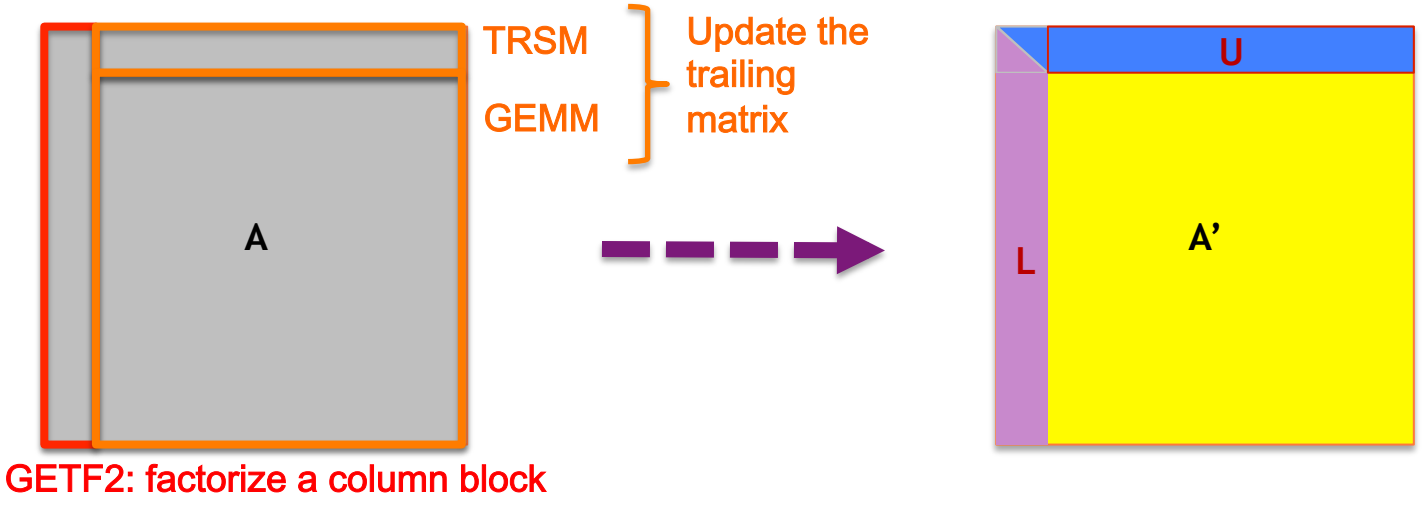
$$c = Ue$$

$$v = Uw$$

Dense Factorization

$$\begin{bmatrix} L & A & P & A & C & K \\ L & -A & P & -A & C & -K \\ L & A & P & A & -C & -K \\ L & -A & P & -A & -C & K \\ L & A & -P & -A & C & K \\ L & -A & -P & A & C & -K \end{bmatrix}$$

- **Recursive block LU (ScaLapack)**
  - Want to solve Ax=b (hard)
  - Transform A into LU factorization
  - Solve Ly=Pb, then Ux=y (easy)



GETF2: factorize a column block

Dense Factorization

L	A	P	A	C	K
L	-A	P	-A	C	-K
L	A	P	A	-C	-K
L	-A	P	-A	-C	K
L	A	-P	-A	C	K
L	-A	-P	A	C	-K

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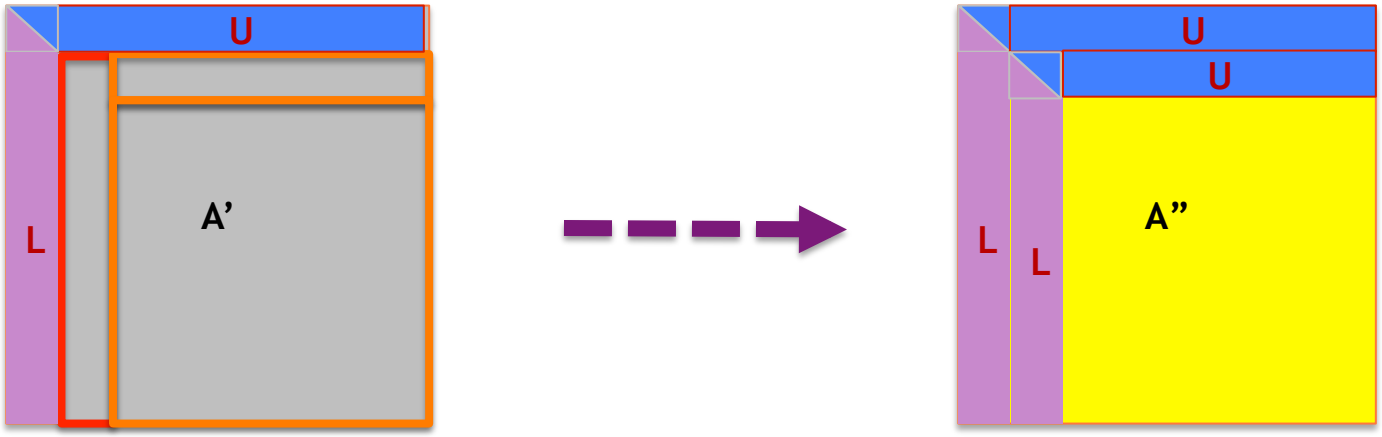
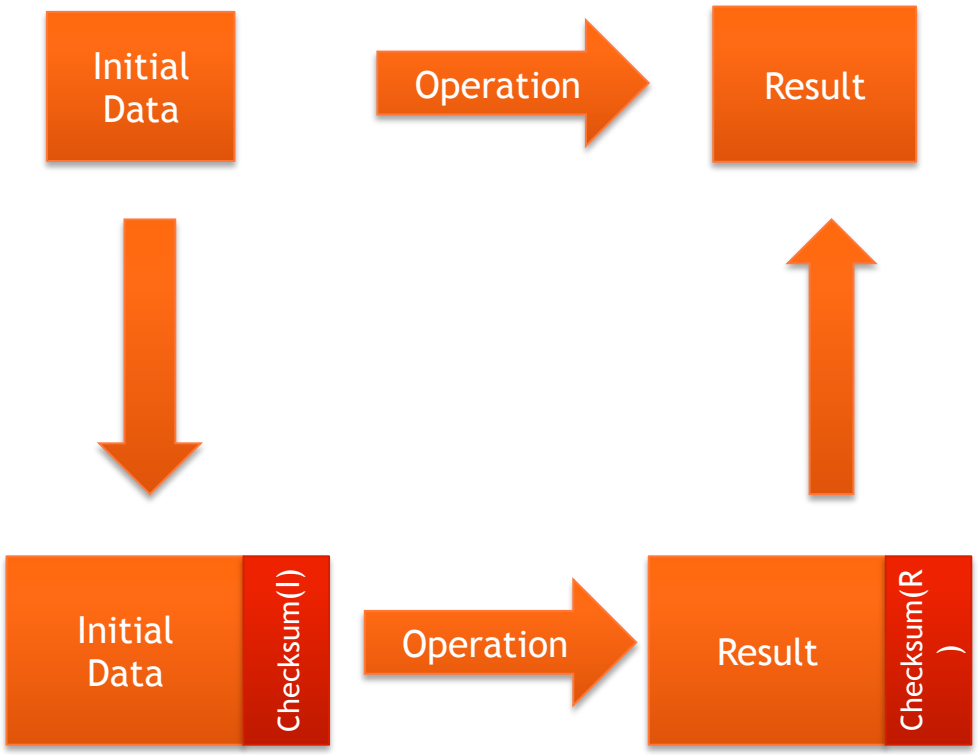


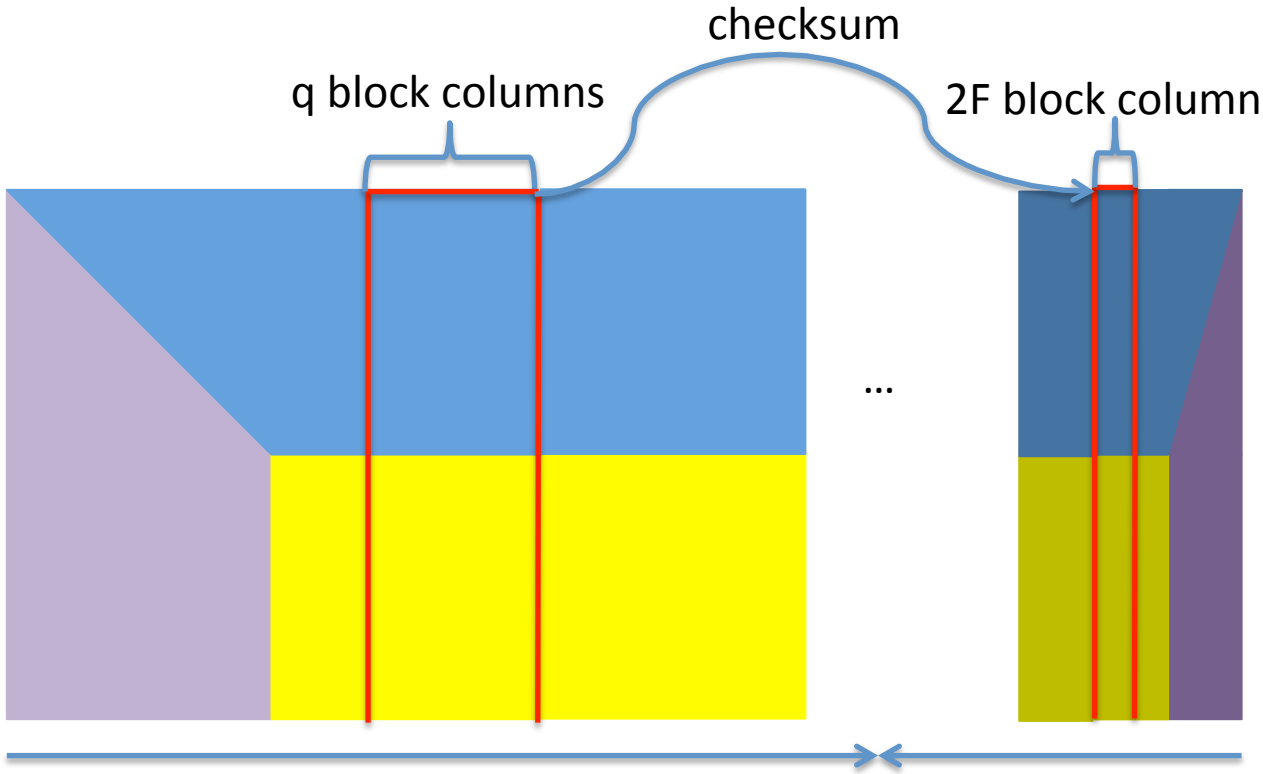
Principle of ABFT

- Data is distributed
- Result is distributed
- The operation preserves the checksum properties

- Apply the operation on Data + Checksum
- In case of failure, recover the missing data by inverting the checksum



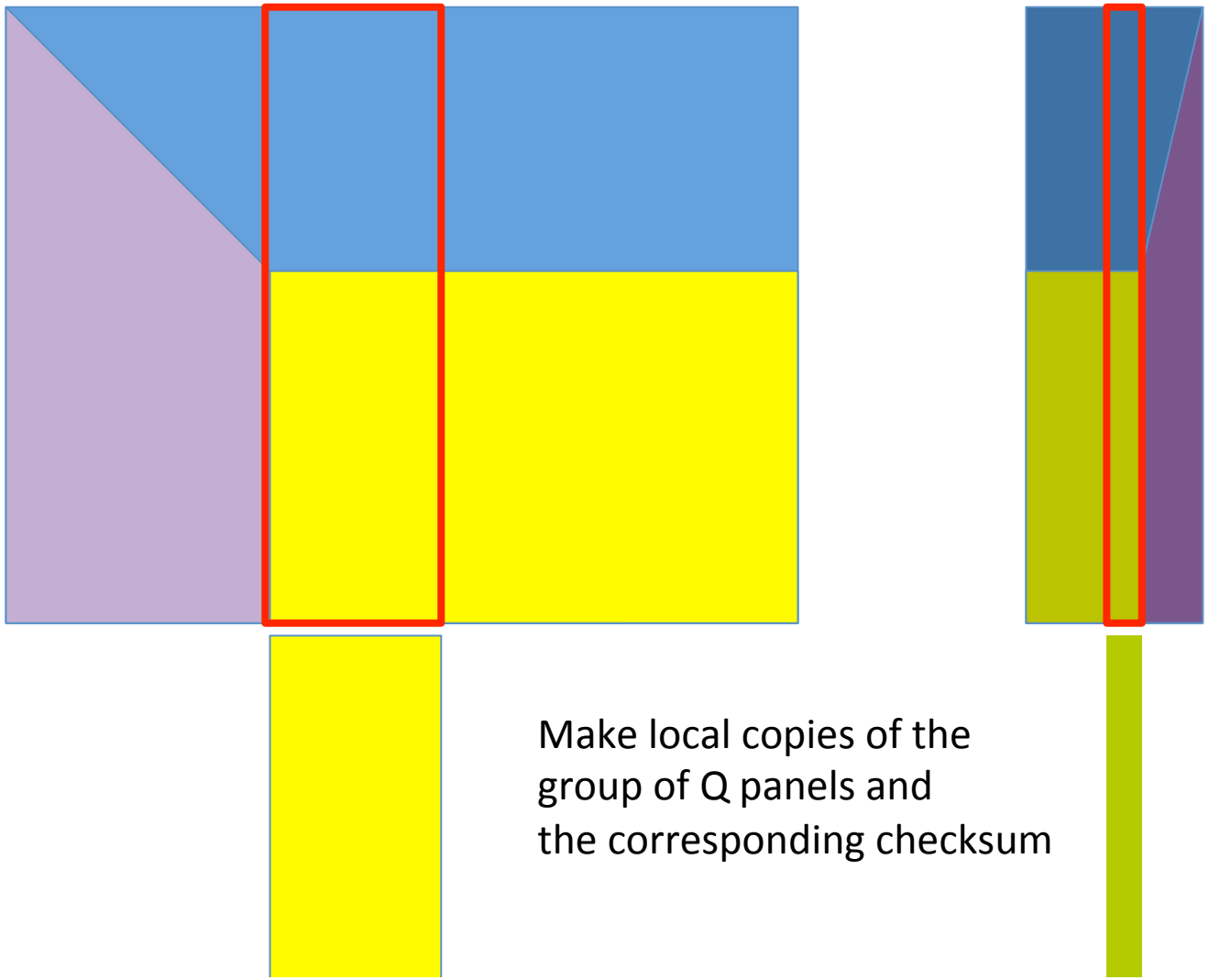
Reverse Neighboring Scheme



The matrix of size M x N,
Blocked in blocks of mb x nb
And distributed over a 2D process grid of pxq
is extended with $\frac{2F \times N}{q \times nb}$ block columns to store a checksum
that will allow to tolerate up to F simultaneous faults on the same row

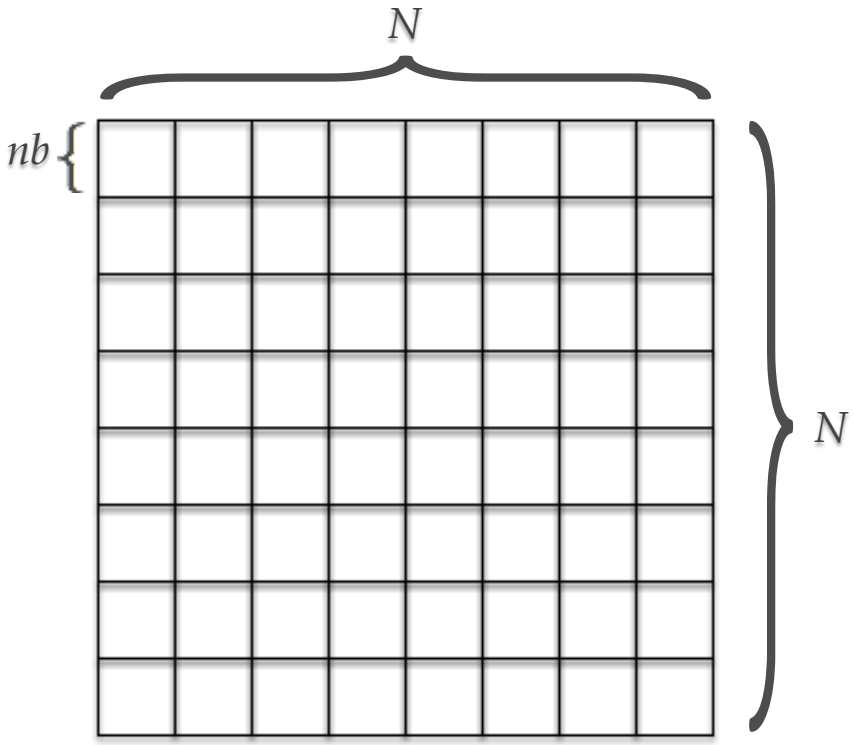
Group of Q panels

Corresponding Checksum

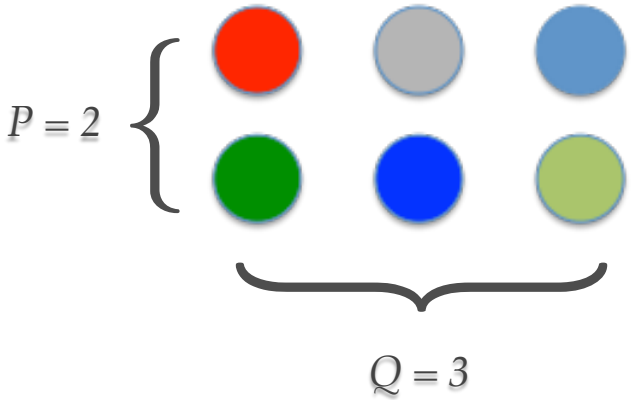


Make local copies of the
group of Q panels and
the corresponding checksum

2-D Block Cyclic Data Distribution

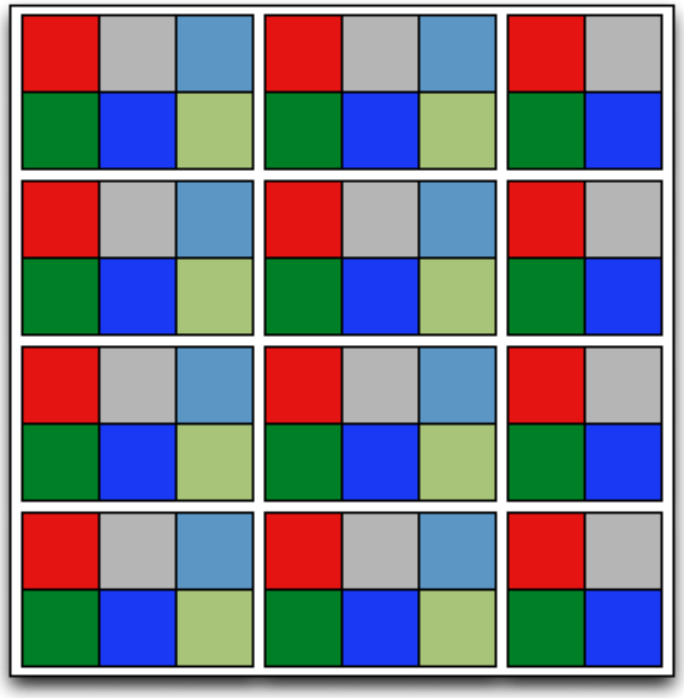


An NxN matrix partitioned into $nb \times nb$ blocks

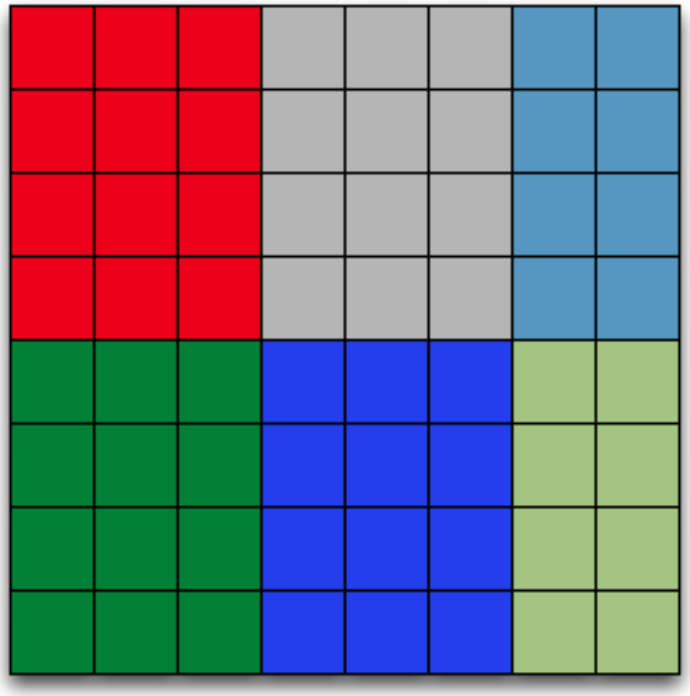


A PxQ processor gird (P = 2, Q = 3)

2-D Block Cyclic Data Distribution



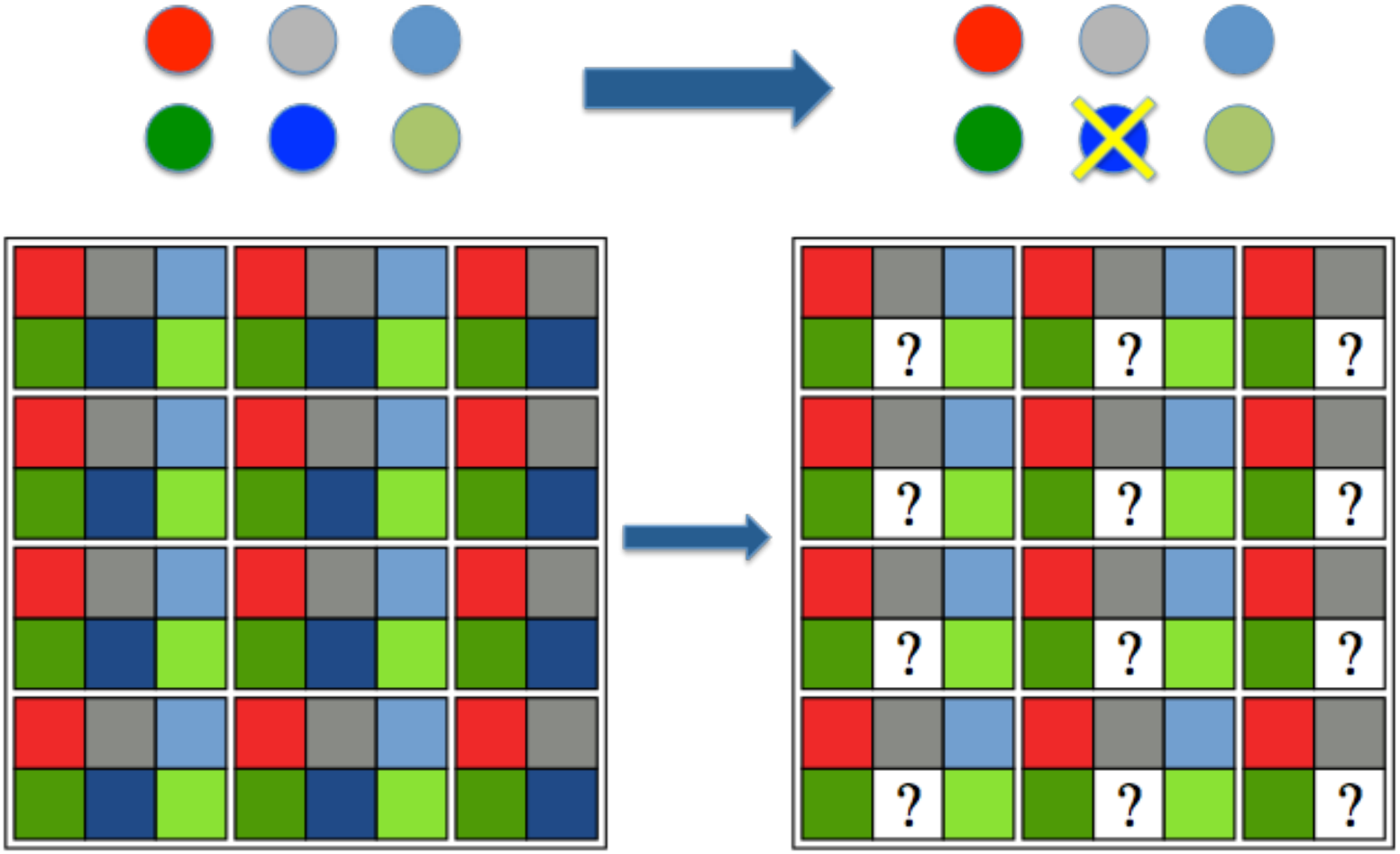
Matrix view



Process view

P x Q process grid (2x3)

Failure Model



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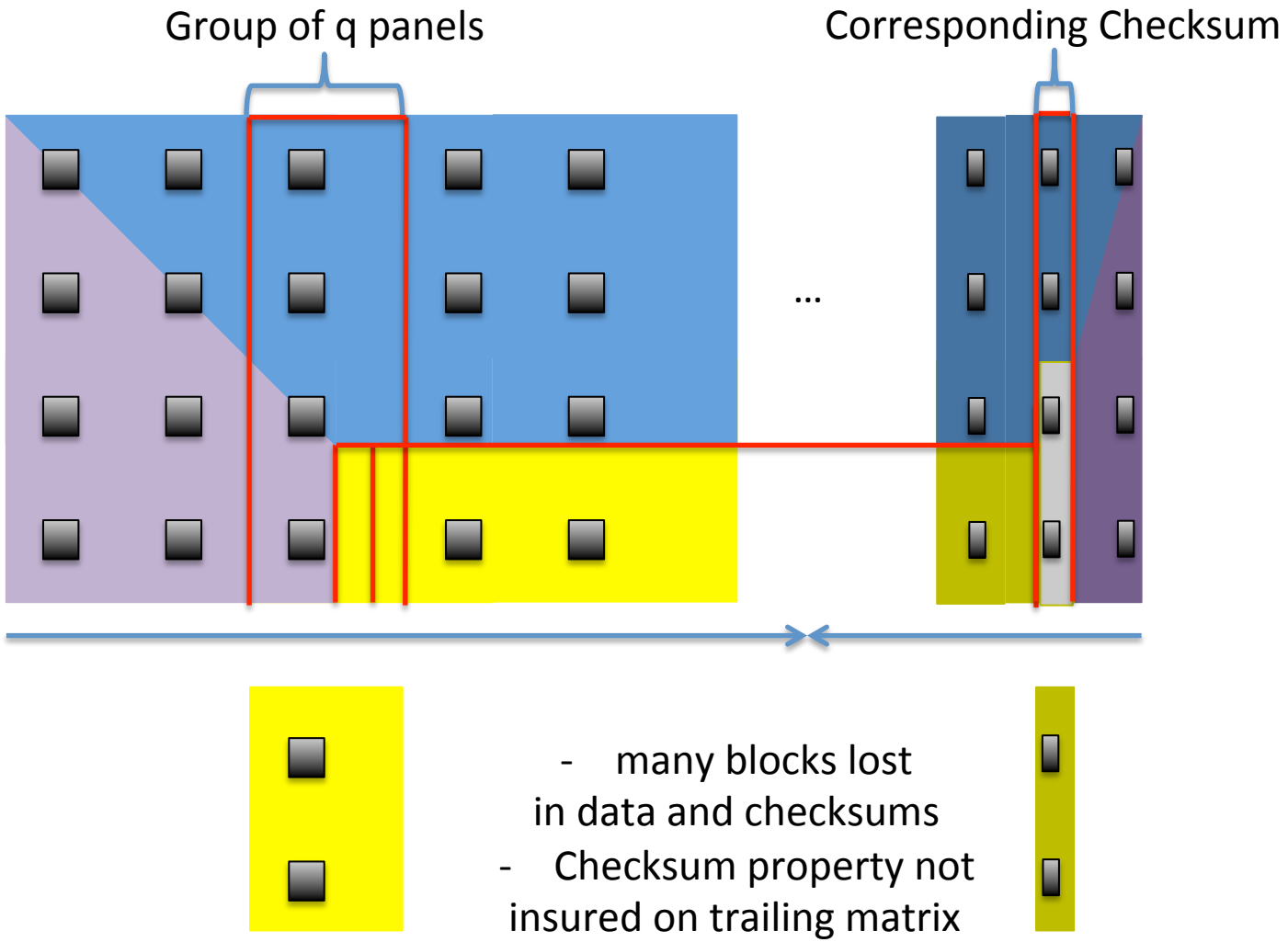
In case of Failure



ABFT Overheads

Matrix M x N, Blocks mb x nb, Process grid p x q

F: maximum number of ***simultaneous*** failures tolerated

Memory

$$O(\frac{F}{q} \times M \times N)$$

Matrix is extended with 2F columns every q columns

N.B. Usually F << q

Relative overheads in F/q

e.g. 2 simultaneous faults on 192x192 process grid => 1% overhead

Computation

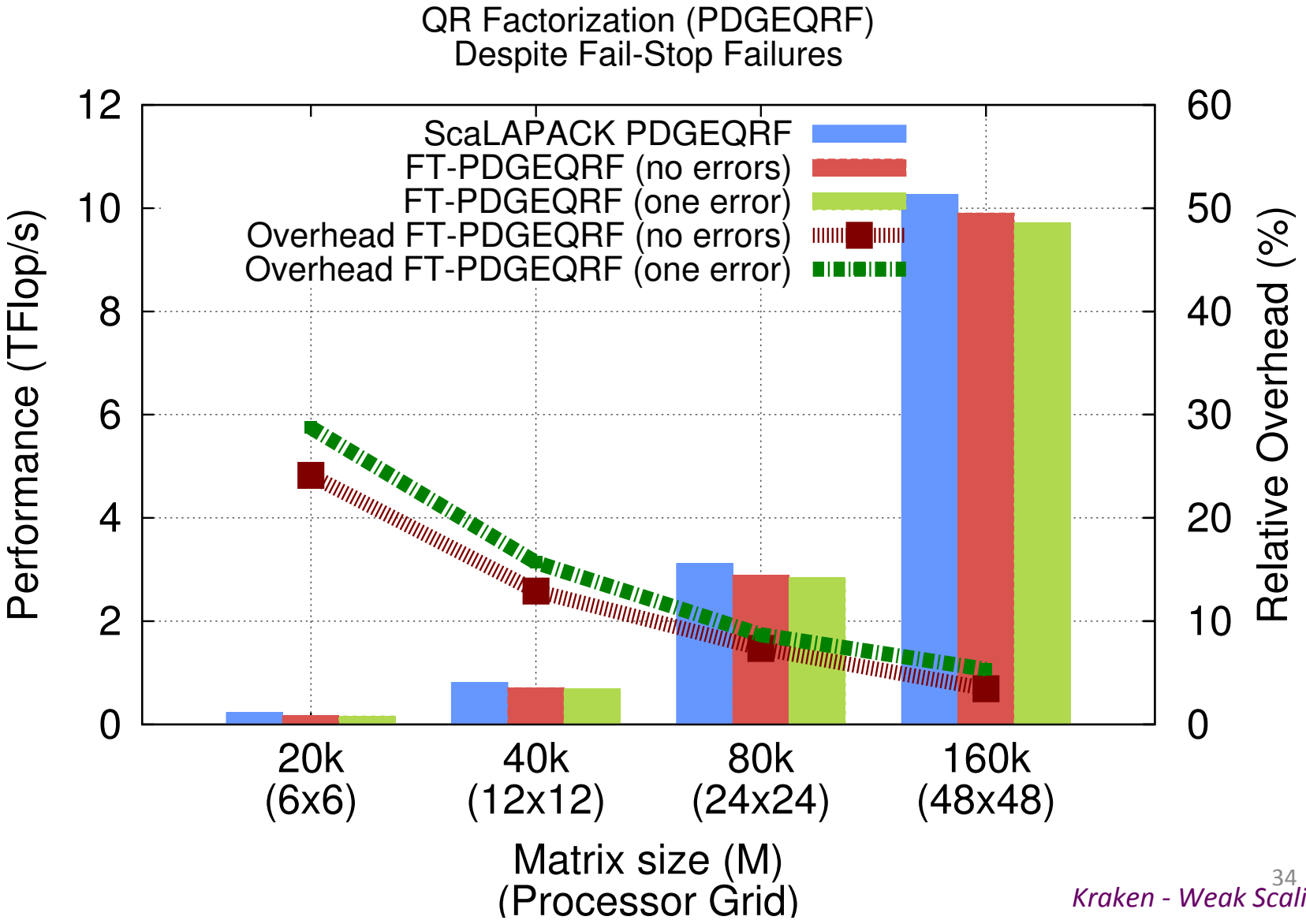
$$O(\frac{F}{q} \times M^3)$$

flops for the checksum update, and

$$O(MN)$$

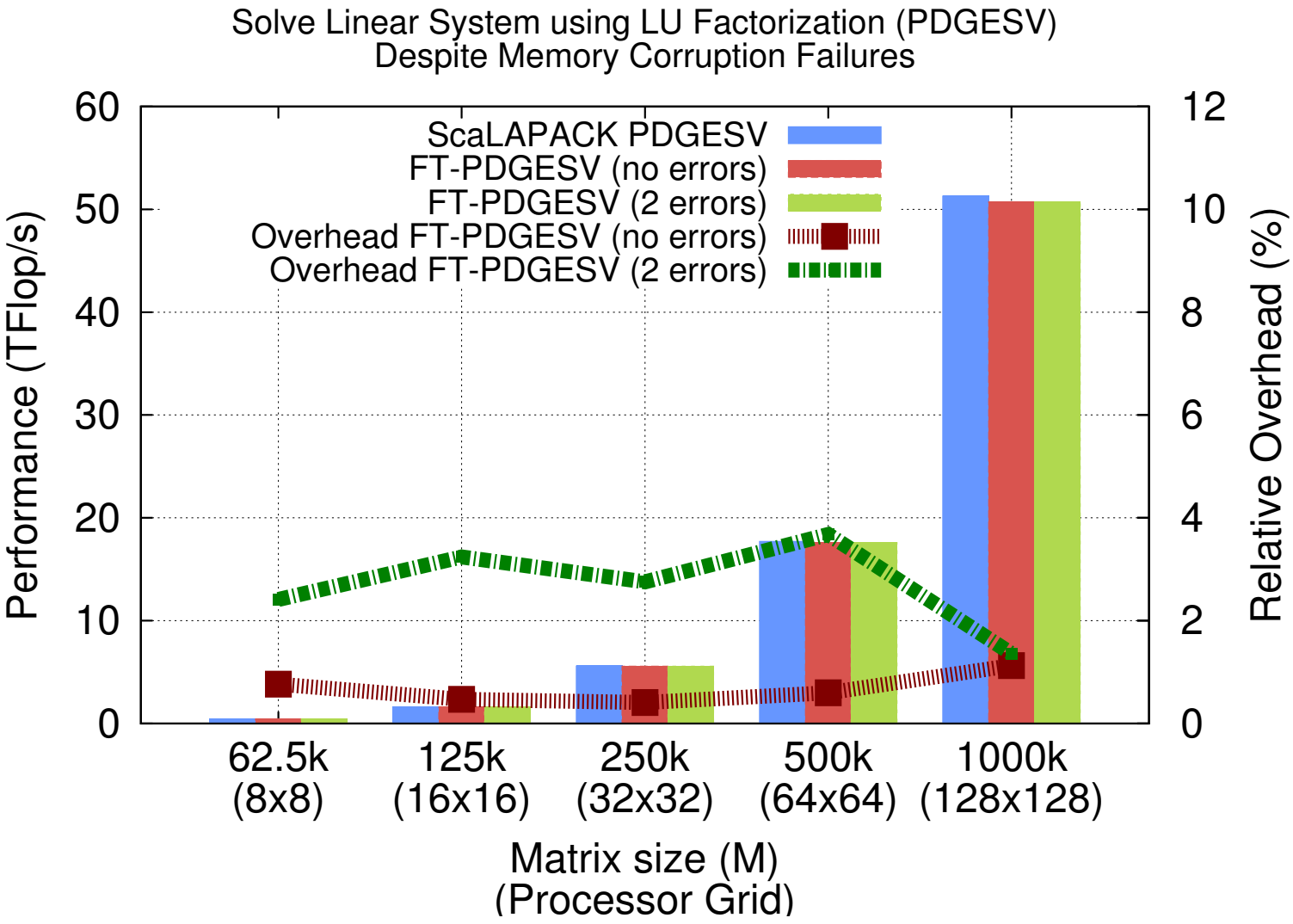
flops for the checksum creation

Performance



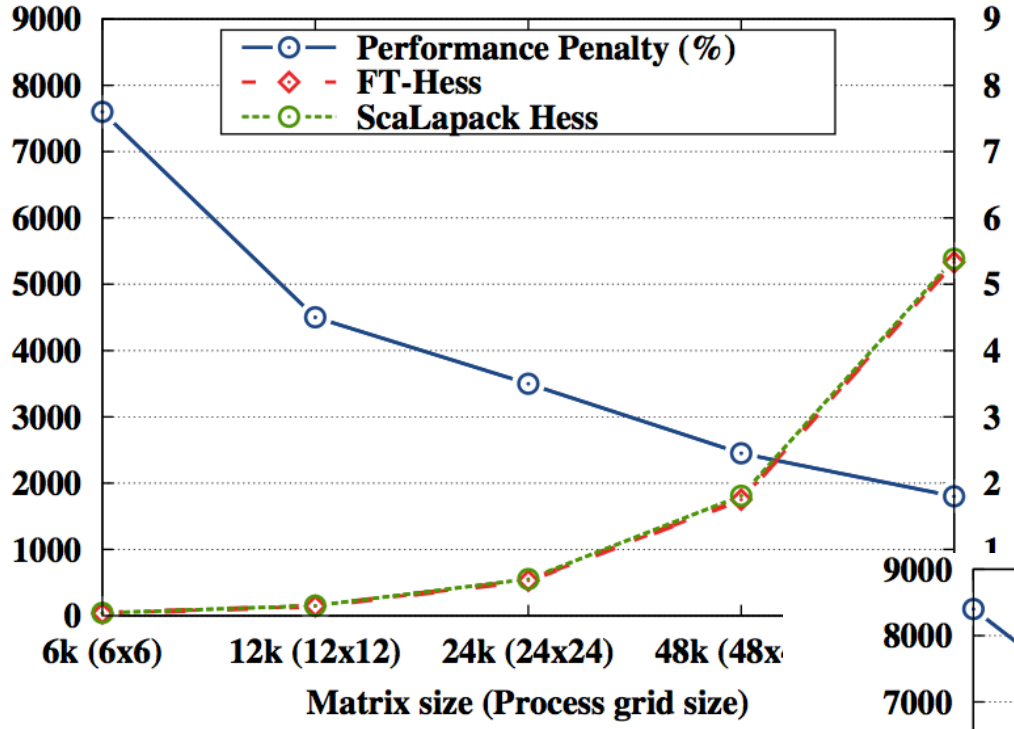
Kraken - Weak Scaling

Performance



Kraken - Weak Scaling

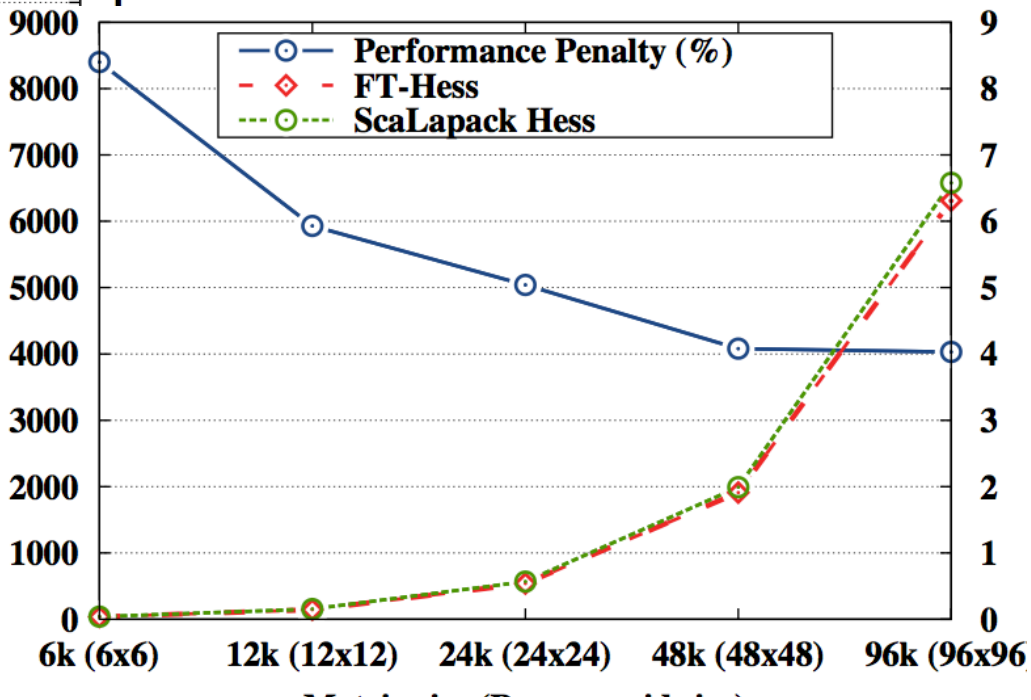
Experiment: Hessenberg Reduction



- ORNL Titan: Cray XK7
- AMD Opteron 6274
- 299,008 core
- Cray Gemini 3D Torus

No errors

1 error



Hessenberg Reduction: Recovery Error

Cores	Process grid	Fault-Tolerant	Classic (ScaLAPACK)
36	6 x 6	5.20×10^{-3}	5.01×10^{-3}
144	12 x 12	3.09×10^{-3}	2.34×10^{-3}
576	24 x 24	2.16×10^{-3}	1.17×10^{-3}
2304	48 x 48	1.36×10^{-3}	6.35×10^{-4}
9216	96 x 96	1.03×10^{-3}	3.37×10^{-4}

ULFM & FT-LA

- User Level Failure Mitigation,
  - An extension to the MPI Standard, currently under discussion by the MPI Forum, and a fault tolerant MPI implementation that let the application space be in control of failure recovery.
  - Implemented in Open-MPI and MPITCH
- FT-LA supports the following operations (in all sdcz precisions):
  - QR factorization (protection against fail-stop failures, failure of at most 1 proc at a time, both Q and R factors protected)
  - LU factorization (protection against fail-stop failures, failure of at most 1 proc at a time, both L and U factors protected)
  - See: http://icl.cs.utk.edu/ft-la/software/index.html

Collaborators / Software / Support

- **PLASMA**
  http://icl.cs.utk.edu/plasma/
- **MAGMA**
  http://icl.cs.utk.edu/magma/
- **Quark (RT for Shared Memory)**
  http://icl.cs.utk.edu/quark/
- **PaRSEC(**Parallel Runtime Scheduling and Execution Control**)**
  http://icl.cs.utk.edu/parsec/

- Collaborating partners
  University of Tennessee, Knoxville
  University of California, Berkeley
  University of Colorado, Denver

  INRIA, France
  KAUST, Saudi Arabia

These tools are being applied to a range of applications beyond dense LA:
Sparse direct, Sparse iterations methods and Fast Multipole Methods