Multi-level checkpointing and silent data corruption

Anne Benoit [2], Franck Cappello [1], Aurélien Cavelan [2], Sheng Di [1], Hongyang Sun [2], Yves Robert [2], Frédéric Vivien [2]

[1] Argonne National Laboratory [2] INRIA

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Fail-stop errors

Characteristics

- Component failure (node, network, power, ...)
- Application fails and data is lost

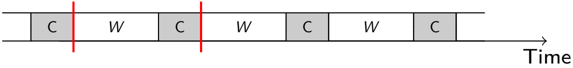
Fault rate proportional to number of components

- 2013: *Preprod.* Blue Waters requires repairs $\approx$ 4 hours [2, 1]
- 2014: Titan loses a node every $\approx$ 1.5 days [2, 3, 1]
- 2014: Blue Waters loses $\approx$ 2 nodes per day [1]

Coping with fail-stop errors

Instantaneous error detection

Standard approach: Periodic checkpoint, rollback, and recovery:



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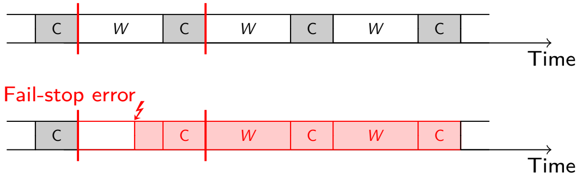

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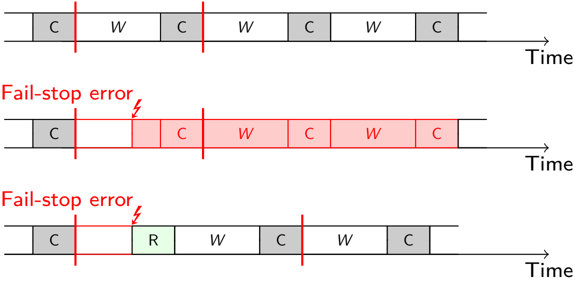
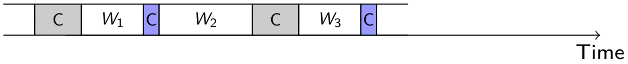


Multi-Level Checkpointing

- Different kinds of checkpoints: local disk storage, partner-copy, Reed-Solomon encoding technique, file system
- Different kinds of errors: node failure, router failure, etc.
- Each checkpoint has a cost and some resilience capabilities



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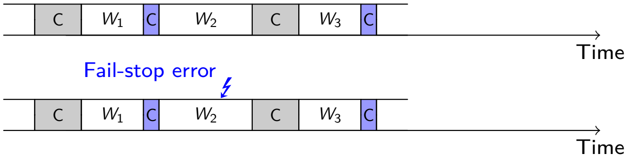

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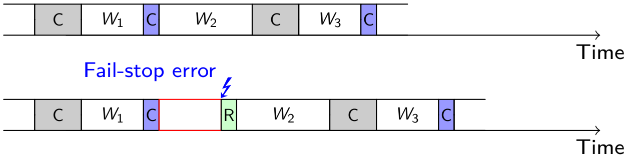

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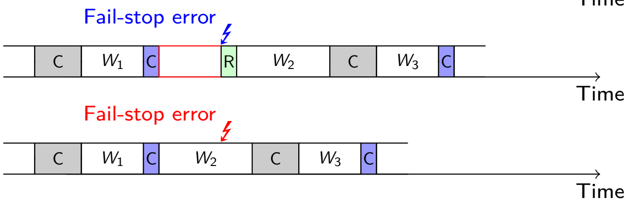

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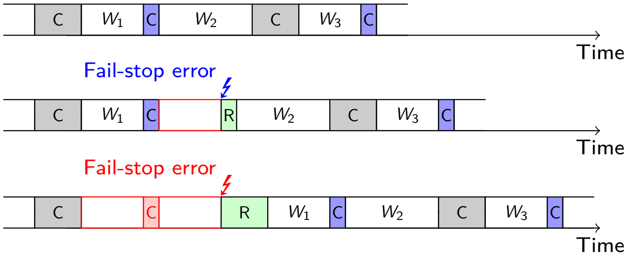

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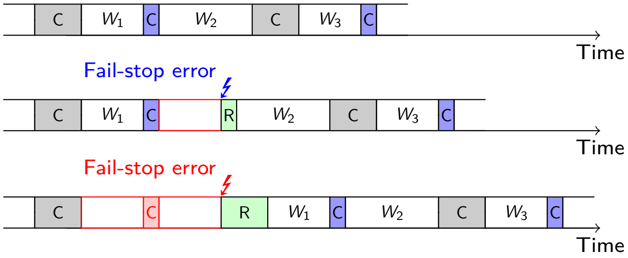

When should we checkpoint? Using which mechanism?

Two-level checkpointing: assumptions

Two types of faults

- Type-1: follow an exponential distribution of failure rate λ_1
- Type-2: follow an exponential distribution of failure rate λ_2

Two types of checkpoints

- Type-2 checkpoints take time C_2 (recovery R_2)
  Enables recovery from type-1 and type-2 faults

- Type-1 checkpoints take time C_1 (recovery R_1)
  Enables recovery from type-1 faults

Two-level checkpointing: assumptions

Two types of faults

- Type-1: follow an exponential distribution of failure rate λ_1
- Type-2: follow an exponential distribution of failure rate λ_2
  More dramatic faults

Two types of checkpoints

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  More expensive checkpoints
- Type-1 checkpoints take time C_1 (recovery R_1)
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Two-level checkpointing: assumptions

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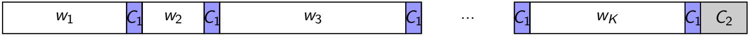
Other assumptions

- Fault of type-i is followed by a *downtime* and a type-i recovery
- No faults during recoveries

Execution time of a pattern

- Pattern: work of some size W divided in K chunks



- Objective: overhead minimization

$$\text{OVERHEAD}(\text{PATTERN}(K, W, w_1, ..., w_K)) = \frac{\mathbb{E}(\text{PATTERN}(K, W, w_1, ..., w_K))}{W} - 1$$

- First property:
  Execution time is minimized when all chunks have same size

Unknown job length: optimal solution

- Chunks have size w_{opt} where:

$$N(w_{opt})\ln(N(w_{opt})) = \lambda L w_{opt}(e^{\lambda(w_{opt}+C_1)} - 1)$$

- There are K chunks in a pattern where:

$$\beta\lambda K w_{opt} e^{\lambda(w_{opt}+C_1)}(1 + L(e^{\lambda(w_{opt}+C_1)} - 1))^{K-1} = \alpha + \frac{\beta}{L}(1 + L(e^{\lambda(w_{opt}+C_1)} - 1))^{K}$$

- Missing notations
  $N(w) = 1 + L(e^{\lambda(w+C_1)} - 1)$, $L = \frac{\lambda_2}{\lambda}$, $\lambda = \lambda_1 + \lambda_2$,
  $\alpha = \mathcal{R}(e^{\lambda C_2} - 1) - \frac{\beta}{L}$, $\beta = \mathcal{R}(1 + L(e^{\lambda C_2} - 1))$,
  $\mathcal{R} = \frac{1+\lambda_1 R_1+\lambda_2 R_2}{\lambda} + D$
- Ugly implicit equations: solve them numerically!

Known job length: optimal solution

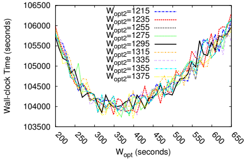
- Total size of job: $\mathcal{W}_{total}$
- Chunks have same w_{opt} size than previously
- There are p^* patterns where:

$$p^* = \frac{\mathcal{W}_{total} \ln(N(w_{opt}))}{\left(\mathbb{L}\left(\frac{\alpha L}{\beta e}\right) + 1\right) w_{opt}}$$

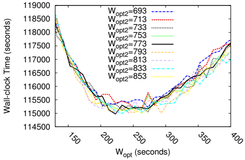
  with the same notations as previously
  and $\mathbb{L}(z) = x$ if $xe^x = z$.

- Ugly implicit equations: solve them numerically!

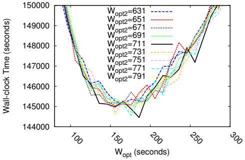
Assessment through simulations



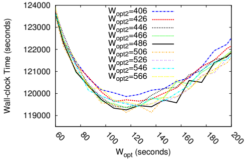
Case 1



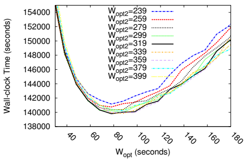
Case 2



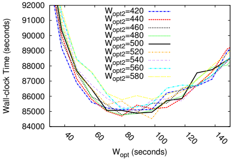
Case 3



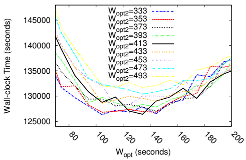
Case 4



Case 5



Case 6



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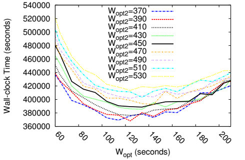
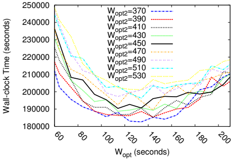


Case 8



Case 9

Conclusion so far

- We know how to use efficiently two-level checkpointing under fail-stop failures
- What about silent data corruption?

Second kind of errors: silent data corruption

Characteristics

- Bit flip (Disk, RAM, Cache, Bus, ...)
- Problems: detection latency, potentially wrong results

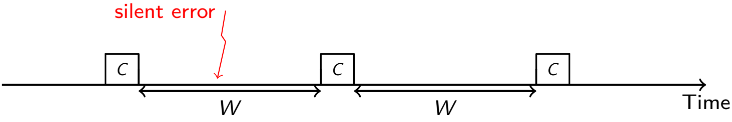
Cosmic rays do produce errors

- 2002: *Unprotected address bus* ASCI Q at Los Alamos National Laboratory could not run more than one hour [3]
- 2003: *No ECC* Virginia Tech 1,100 Apple Power Mac G5 supercomputer could not boot [3]
- 2010: *ECC protected* Jaguar saw 350 bit-flips/min [3]
- 2010: *ECC protected* Jaguar saw 1 double-bit error/day [3]
- 2014: Titan: *reported* $>$ 1 double-bit error per week [4]

Coping with Silent Errors

Main problem: detection latency

Question: can we follow the same approach?



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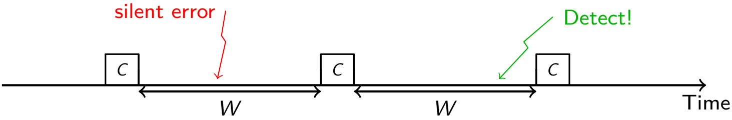

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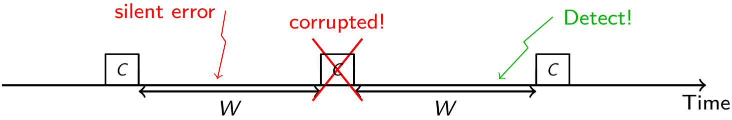

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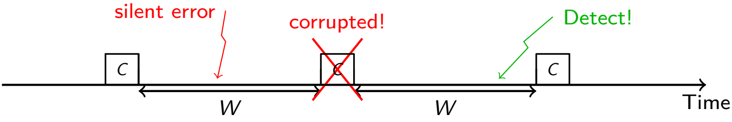

Keep multiple checkpoints?

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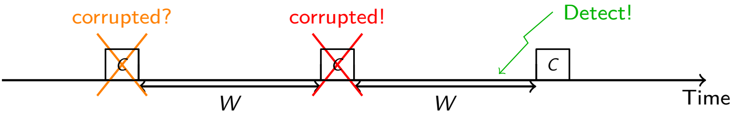

Keep multiple checkpoints?

Which checkpoint to recover from?

Coping with Silent Errors

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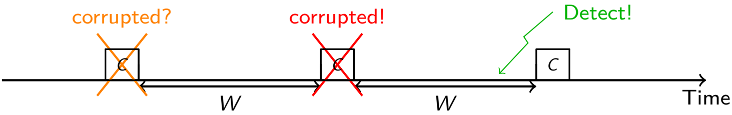


Keep multiple checkpoints?

Which checkpoint to recover from?

Need an active method to detect silent errors!

Existing Methods for Detecting Silent Errors

General-purpose approaches

- Replication [*Fiala et al. 2012*] or triple modular redundancy and voting [*Lyons and Vanderkulk 1962*]

Application-specific approaches

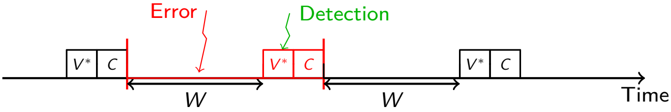
- Algorithm-based fault tolerance (ABFT): checksums in dense matrices Limited to one error detection and/or correction in practice [*Huang and Abraham 1984*]
- Partial differential equations (PDE): use lower-order scheme as verification mechanism [*Benson, Schmit and Schreiber 2014*]
- Generalized minimal residual method (GMRES): inner-outer iterations [*Hoemmen and Heroux 2011*]
- Preconditioned conjugate gradients (PCG): orthogonalization check every k iterations, re-orthogonalization if problem detected [*Sao and Vuduc 2013, Chen 2013*]

Data-analytics approaches

- Dynamic monitoring of HPC datasets based on physical laws (e.g., temperature limit, speed limit) and space or temporal proximity [*Bautista-Gomez and Cappello 2014*]
- Time-series prediction, spatial multivariate interpolation [*Di et al. 2014*]

Coping with Silent Errors

Solution: coupling checkpointing with verification

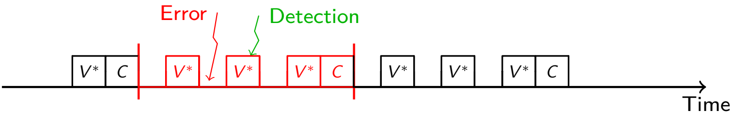


- Before each checkpoint, run some verification mechanism or error detection test
- Silent error, if any, is detected by verification
- Last checkpoint is always valid

Problem solved! But can do better than that!

One step further

Perform several verifications before each checkpoint:



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- Con: additional overhead in error-free executions
- Need to find the best trade-off

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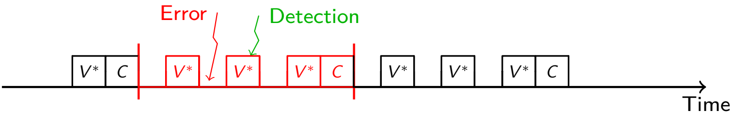
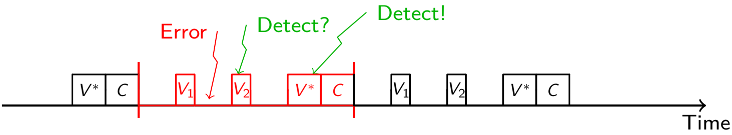


- Pro: silent error detected earlier in pattern
- Con: additional overhead in error-free executions
- Need to find the best trade-off
- Not all verification mechanisms have 100% accuracy!
  Should we use partial detectors? How?

Partial verification

Guaranteed/perfect verifications (V^*) can be very expensive!
Partial verifications (V) are available for some HPC applications!

- Lower accuracy: recall $r = \frac{\#\text{detected errors}}{\#\text{total errors}} < 1$
- Lower cost, i.e., $V < V^*$



The optimization problem

Two types of checkpoints

- Disk checkpoint: stable storage (slow but resilient)
- Memory checkpoint: local copy (fast but lost on fail-stop)

Checkpoint only done after guaranteed verification

Two types of responses to errors

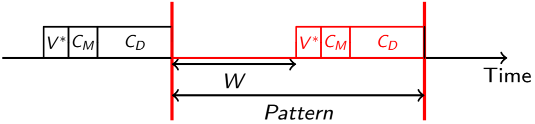
- Fail-stop error ⇒ rollback to last disk checkpoint
- Silent errors ⇒ rollback to last memory checkpoint

Goal:

- Combine everything into a single periodic pattern
- Minimize the overhead due to faults and to fault-tolerance

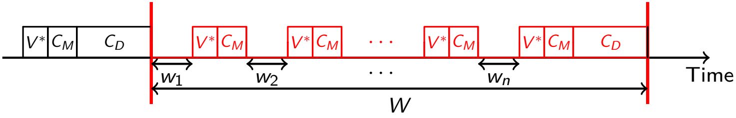
Resilience patterns (1/2)

Starting with base pattern



Pattern à la Young-Daly

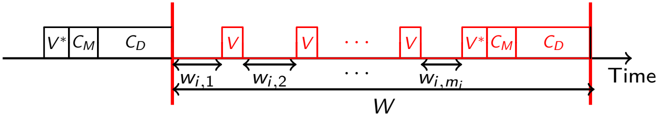
Adding verified memory checkpoints



Pattern with n segments

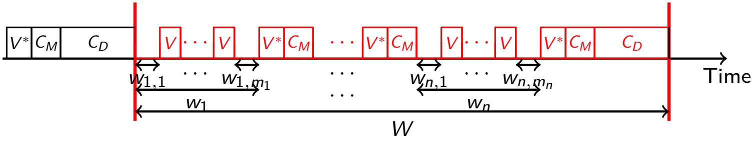
Resilience patterns (2/2)

Adding intermediate verifications between memory checkpoints



Segment w_i has m_i chunks

Putting everything together

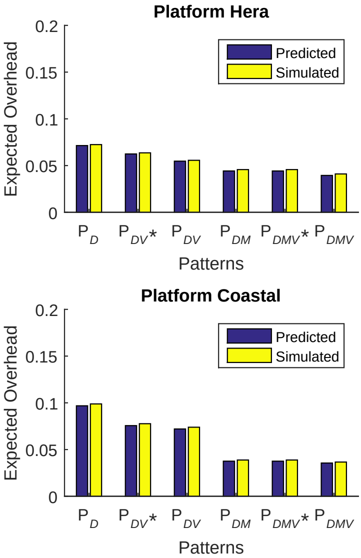


Full pattern

The optimal solution (first order approximation)

Pattern	W^*	n^*	m^*	OVERHEAD(PATTERN)
P_D	$\sqrt{\frac{V^*+C_M+C_D}{\lambda_s+\frac{\lambda_f}{2}}}$	–	–	$2\sqrt{\left(\lambda_s+\frac{\lambda_f}{2}\right)(V^*+C_M+C_D)}$
P_{DV^*}	$\sqrt{\frac{m^*V^*+C_M+C_D}{\frac{1}{2}\left(1+\frac{1}{m^*}\right)\lambda_s+\frac{\lambda_f}{2}}}$	–	$\sqrt{\frac{\lambda_s}{\lambda_s+\lambda_f}\cdot\frac{C_M+C_D}{V^*}}$	$\sqrt{2(\lambda_s+\lambda_f)C_M+C_D}+\sqrt{2\lambda_s V^*}$
P_{DV}	$\sqrt{\frac{(m^*-1)V+V^*+C_M+C_D}{\frac{1}{2}\left(1+\frac{2-r}{(m^*-2)r+2}\right)\lambda_s+\frac{\lambda_f}{2}}}$	–	$2-\frac{2}{r}+\sqrt{\frac{\lambda_s}{\lambda_s+\lambda_f}}$ $\times\sqrt{\frac{2-r}{r}\left(\frac{V^*+C_M+C_D}{V}-\frac{2-r}{r}\right)}$	$\sqrt{2(\lambda_s+\lambda_f)\left(V^*-\frac{2-r}{r}V+C_M+C_D\right)}$ $+\sqrt{2\lambda_s\frac{2-r}{r}V}$
P_{DM}	$\sqrt{\frac{n^*(V^*+C_M)+C_D}{\frac{\lambda_s}{n^*}+\frac{\lambda_f}{2}}}$	$\sqrt{\frac{2\lambda_s}{\lambda_f}\cdot\frac{C_D}{V^*+C_M}}$	–	$2\sqrt{\lambda_s(V^*+C_M)}+\sqrt{2\lambda_f C_D}$
P_{DMV^*}	$\sqrt{\frac{n^*m^*V^*+n^*C_M+C_D}{\frac{1}{2}\left(1+\frac{1}{m^*}\right)\frac{\lambda_s}{n^*}+\frac{\lambda_f}{2}}}$	$\sqrt{\frac{\lambda_s}{\lambda_f}\cdot\frac{C_D}{C_M}}$	$\sqrt{\frac{C_M}{V^*}}$	$\sqrt{2\lambda_f C_D}+\sqrt{2\lambda_s C_M}+\sqrt{2\lambda_s V^*}$
P_{DMV}	$\sqrt{\frac{n^*(m^*-1)V+n^*(V^*+C_M)+C_D}{\frac{1}{2}\left(1+\frac{2-r}{(m^*-2)r+2}\right)\frac{\lambda_s}{n^*}+\frac{\lambda_f}{2}}}$	$\sqrt{\frac{\lambda_s}{\lambda_f}\cdot\frac{C_D}{V^*-\frac{2-r}{r}V+C_M}}$	$2-\frac{2}{r}$ $+\sqrt{\frac{2-r}{r}\left(\frac{V^*+C_M}{V}-\frac{2-r}{r}\right)}$	$\sqrt{2\lambda_f C_D}+\sqrt{2\lambda_s\left(V^*-\frac{2-r}{r}V+C_M\right)}$ $+\sqrt{2\lambda_s\frac{2-r}{r}V}$

Simulations



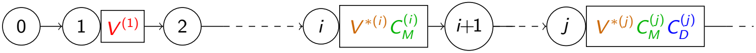
Conclusion so far

- We know how to use efficiently two-level checkpointing under fail-stop failures and silent data corruption with guaranteed verifications and partial verifications

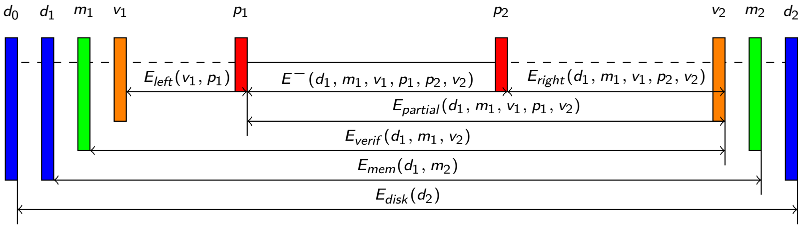
- Caveat: we assumed full freedom to place checkpoints and verifications (divisible load)
  Question: What about task graphs?

The optimization problem

- Application modeled as a linear task graph
- Checkpoints and verifications are performed in between tasks



- Question: when to take which checkpoint and verification in order to minimize the execution time?



- Optimal solution: $O(n^6)$ dynamic programming algorithm

Conclusion and perspectives

Pros

- Mix of silent and fail-stop errors
- Mix of partial and guaranteed verifications

Cons

- Results limited to 2 levels...
  ... but upcoming generalization for any number of levels!
- Exponential failure distribution

All details can be found in

- S. Di, Y. Robert, F. Vivien, and F. Cappello. Toward an Optimal Online Checkpoint Solution under a Two-Level HPC Checkpoint Model. *IEEE Transactions on Parallel and Distributed Systems*, 2016. To appear.
- A. Benoit, A. Cavelan, Y. Robert, and H. Sun. Optimal Resilience Patterns to Cope with Fail-Stop and Silent Errors. In *IPDPS'2016*, May 2016.
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ANY QUESTIONS?