Optimal resilience patterns to cope with fail-stop and silent errors

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Why resilience?

Computing at exascale

- Larger node count: 10^5 or 10^6 nodes, each with 10^2 or 10^3 cores
- Shorter Mean Time Between Failures (MTBF) μ

Theorem: $\mu_p = \frac{\mu_{\text{ind}}}{p}$ for arbitrary distributions.

MTBF (individual node)	1 year	10 years	100 years
MTBF (platform of 10^6 nodes)	30 secs	5 mins	50 mins

Multiple error sources

- Many papers address fail-stop errors
- Many others address silent errors (or silent data corruptions)

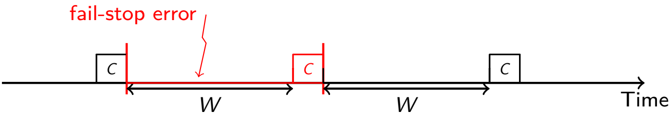
HPC applications must cope with **both** error sources! ☹

Objective: unified framework and optimal algorithmic solutions ☺

Coping with fail-stop errors

Instantaneous error detection, e.g., resource crash

Standard approach: Periodic checkpoint, rollback, and recovery:



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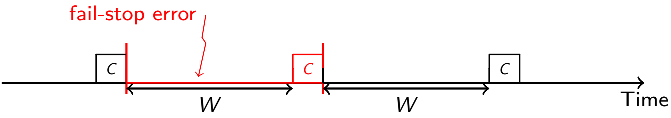


General-purpose approach! ☺

Theorem.

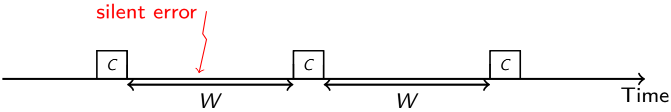
$$W^* = \sqrt{2\mu C} \quad \text{[Young 1974, Daly, 2006]}$$

μ: Platform MTBF
C: Checkpointing time

Coping with Silent Errors

Silent error detected only when corrupted data is activated
e.g., soft faults in L1 cache, ALU, double bit flip.

Main problem: detection latency
Same approach?



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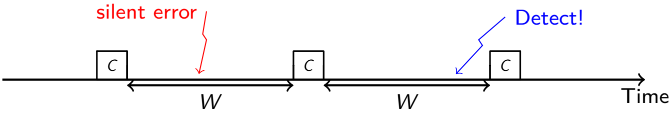

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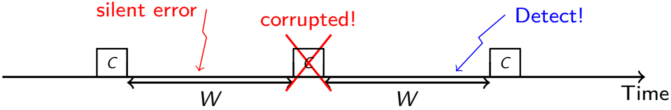

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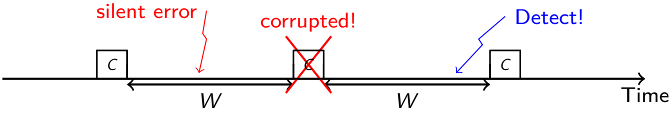

Keep multiple checkpoints?

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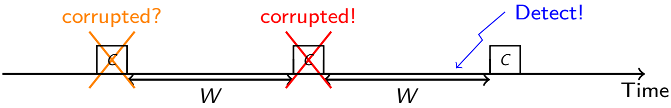

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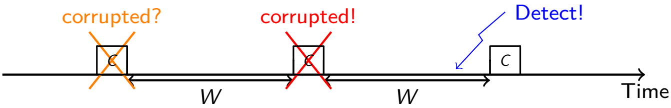

Keep multiple checkpoints?

Which checkpoint to recover from?

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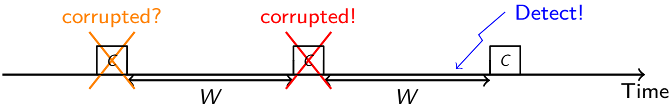


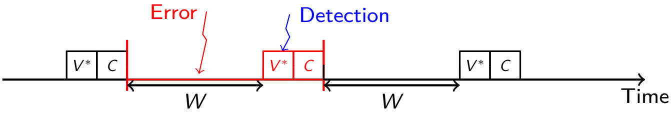
Keep multiple checkpoints?

Which checkpoint to recover from?

Need an active method to detect silent errors!

Coping with Silent Errors

Solution: coupling checkpointing with verification

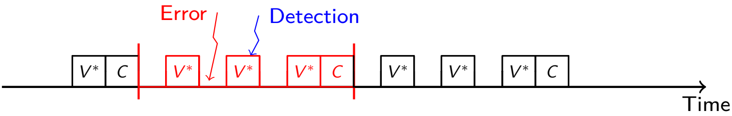


- Before each checkpoint, run some verification mechanism or error detection test
- Silent error, if any, is detected by verification
- Last checkpoint is always valid ☺

Problem solved! But can do better than that!

One step further

Perform several verifications before each checkpoint:



- Pro: silent error detected earlier in pattern ☺
- Con: additional overhead in error-free executions ☹

Seems good! ☺

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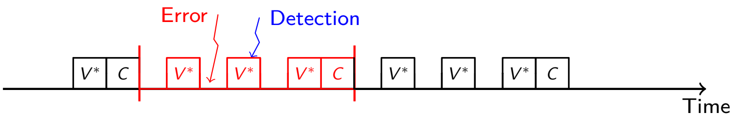

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Wait... Verifications with 100% accuracy?

Partial verification

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

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

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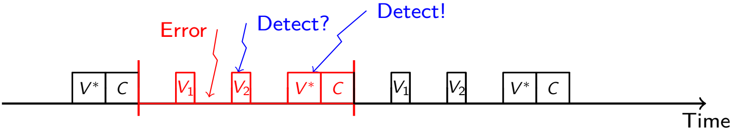

Ok! ☺

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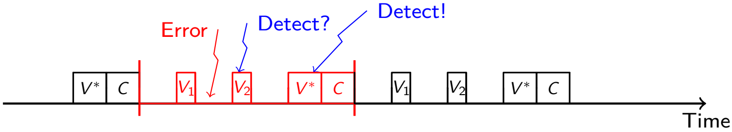

Ok! ☺

Wait... Disk checkpoints are also expensive. Can we do better?

Two-level checkpointing

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.

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

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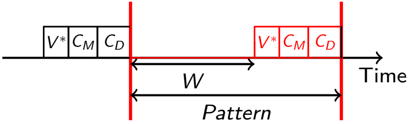
To do next:

- Combine everything into a single periodic pattern
- Minimize the expected execution time of the application

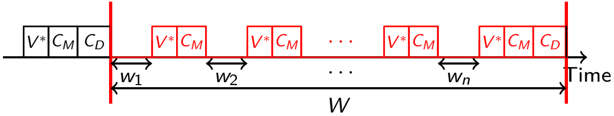
Resilience patterns (1/2)

Starting with base pattern



Pattern à la Young-Daly

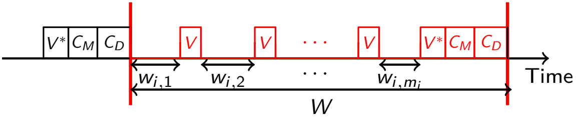
Adding verified memory checkpoints



Pattern with n segments

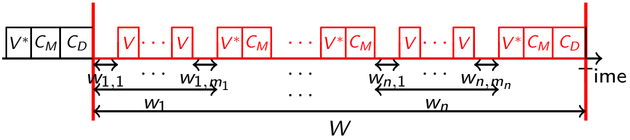
Resilience patterns (2/2)

Adding intermediate verifications between memory checkpoints



Segment w_i has m_i chunks

Putting everything together



Full pattern

Model (1/3)

Failure arrivals follow exponential law $Exp(\lambda)$, where $\lambda = 1/\mu$.

- Independant
- Memoryless

	Arrival rate	Probability of failure
fail-stop	λ_f	$p^f = 1 - e^{-\lambda_f w}$
silent	λ_s	$p^s = 1 - e^{-\lambda_s w}$

Same order.

$$\Leftrightarrow \lambda_f = \Theta(\lambda), \text{ and } \lambda_s = \Theta(\lambda)$$

where $\lambda = \lambda_f + \lambda_s = 1/\mu$ (platform MTBE)

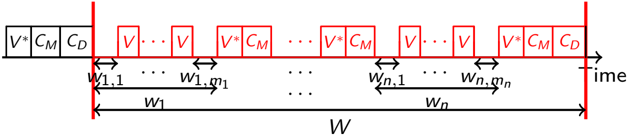
Model (2/3)

Two-level checkpointing.

- C_D cost of disk checkpointing (R_D for recovery)
- C_M cost of memory checkpointing (R_M for recovery)
- V cost of partial verification (with $r < 1$)
- V^* cost of guaranteed verification (with $r = 1$)

Model (3/3)

Finding optimal pattern

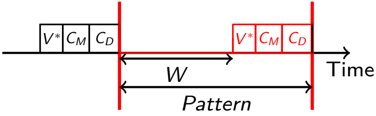


Total length	#Segments	#Chunks
W^*	n^*	m^*

Minimizing pattern overhead

$$H(P) = \frac{\mathbb{E}(\mathrm{P})}{W} - 1$$

Derivation: how?



$$\mathbb{E}(\mathrm{P}) = p^f \left(\mathbb{E}(T^{\text{lost}}) + R_D + R_M + \mathbb{E}(\mathrm{P})\right)$$
$$+ (1 - p^f)\big(W + V^* + p^s(R_M + \mathbb{E}(\mathrm{P})) + (1 - p^s)(C_M + C_D)\big)$$

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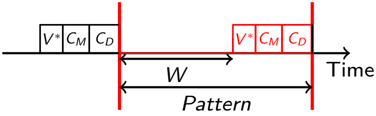

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$$H(\mathrm{P}) = \frac{\mathbb{E}(\mathrm{P})}{W} - 1 = \frac{V^* + C_M + C_D}{W} + \left(\lambda_s + \frac{\lambda_f}{2}\right) W + \lambda_s(V^* + R_M) + \lambda_f(R_M + R_D) + O(\lambda^2 W^2)$$

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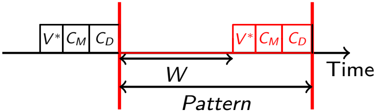

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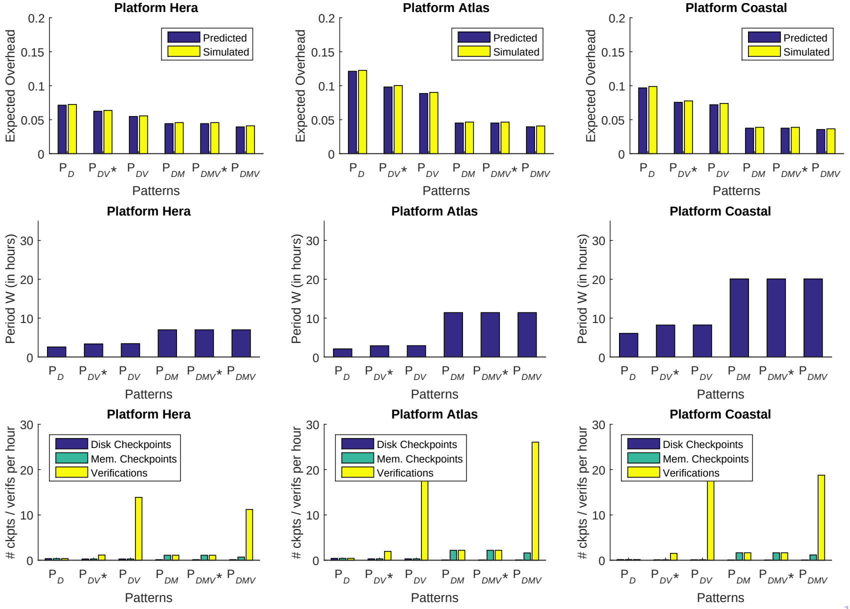
$$W^* = \sqrt{\frac{V^* + C_M + C_D}{\lambda_s + \frac{\lambda_f}{2}}}$$

$$H^*(\mathrm{P}) = 2\sqrt{\left(\lambda_s + \frac{\lambda_f}{2}\right)(V^* + C_M + C_D)} + O(\lambda)$$

Theorems

Pattern	W^*	n^*	m^*	$H^*(\mathrm{P})$
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}	$\sqrt{\frac{n^*(m^*-1)V+n^*(V^*+C_M)+C_D}{\frac{1}{2}\left(1+\frac{2-r}{(m^*-2)r+2}\right)\frac{\lambda_s}{n^*}+\frac{\lambda_f}{2}}}$	$\sqrt{\frac{\lambda_s}{\lambda_f}\cdot\frac{C_D}{V^*-\frac{2-r}{r}V+C_M}}$	$2-\frac{2}{r}$ $+\sqrt{\frac{2-r}{r}\left(\frac{V^*+C_M}{V}-\frac{2-r}{r}\right)}$	$\sqrt{2\lambda_f C_D}+\sqrt{2\lambda_s\left(V^*-\frac{2-r}{r}V+C_M\right)}$ $+\sqrt{2\lambda_s\frac{2-r}{r}V}$

Experiments



Conclusion

Unified framework

- Error and application model
- Resilience patterns
- Optimal solutions

Next

- Multilevel fail-stop errors
- Replication vs checkpointing?

Thanks!

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]