# Two-level checkpointing and partial verifications for linear task graphs

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# Computing at Exascale

Exascale platform:

- $10^5$ or $10^6$ nodes, each equipped with $10^2$ or $10^3$ cores
- Shorter Mean Time Between Failures (MTBF) $\mu$

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

| | | | |
|---|---|---|---|
| MTBF (individual node) | 1 year | 10 years | 120 years |
| MTBF (platform of $10^6$ nodes) | 30 sec | 5 mn | 1 h |

**Need more reliable components!!**

**Need more resilient techniques!!!**

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# Two main sources of errors

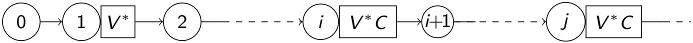
- Fail-stop errors: instantaneous error detection, e.g., resource crash
- Silent errors (aka silent data corruptions), e.g., soft faults in L1 cache, ALU, double bit flip
  - Silent error is detected only when corrupted data is activated, which could happen long after its occurrence ☹
  - Detection latency is problematic

  - Before each checkpoint, run some verification mechanism (checksum, ECC, coherence tests, TMR, etc)
  - Silent error is detected by verification $\Rightarrow$ checkpoint always valid ☺

**Verified checkpoints, rollback and recovery**

# One step further and partial verifications

- Perform several verifications before each checkpoint:
  - Pro: silent error is detected earlier in the pattern ☺
  - Con: additional overhead in error-free executions ☹




- 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., $V < V^*$ ☺

How many intermediate verifications to use and the positions?

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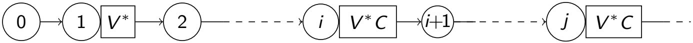


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# Two-level checkpointing

- Silent errors: use of a lightweight mechanism of in-memory checkpoints $C_M$
- Local copies lost in case of fail-stop errors: use (less frequent) copies on stable storage (classical disk checkpoints) $C_D$
- Always $C_M$ before $C_D$: little overhead, enforced in practice
- Always $V^*$ before $C_M$: all checkpoints are valid
- Verifications, memory copies and I/O transfers protected from errors

# Outline

1. Problem statement
2. Theoretical analysis
3. Performance evaluation
4. Conclusion

# Application and errors

- Linear chain of tasks $T_1, T_2, \ldots, T_n$
- Each task $T_i$ has a weight $w_i$ (computational load)
- $W_{i,j} = \sum_{k=i+1}^{j} w_k$: time to execute tasks $T_{i+1}$ to $T_j$

- Subject to fail-stop and silent errors, independent and following a *Poisson process* with arrival rates $\lambda_f$ and $\lambda_s$
- $p^f_{i,j} = 1 - e^{-\lambda_f W_{i,j}}$: probability of having at least a fail-stop error while executing $T_{i+1}$ to $T_j$
- $p^s_{i,j} = 1 - e^{-\lambda_s W_{i,j}}$: idem for silent errors

# Resilience parameters and objective

- Cost of disk checkpointing $C_D$, cost of disk recovery $R_D$
- Cost of memory checkpointing $C_M$, cost of memory recovery $R_M$
- For simplicity, $R_M$ included in $R_D$

- Cost $V^*$ for guaranteed verification
- $V$ for partial verification, with recall $r$, and $g = 1 - r$ is the proportion of undetected errosrs

$\Rightarrow$ Decide where to place disk checkpoints, memory checkpoints, guaranteed verifications and partial verifications, in order to minimize the **expected execution time** (or makespan) of the application

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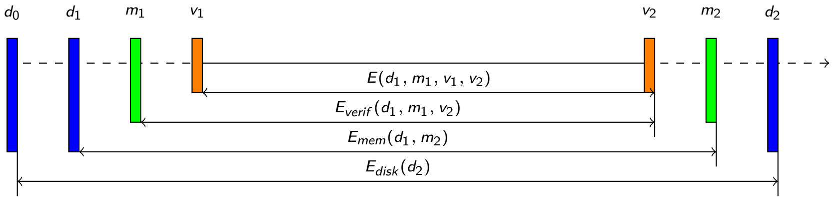
# Dynamic programming algorithm

Several dynamic programming levels:

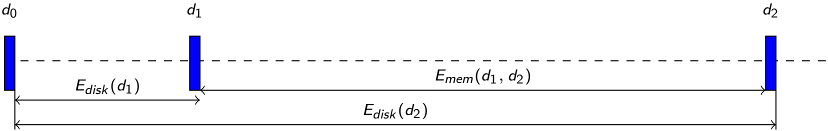
- First decide where to place disk checkpoints
- Then memory checkpoints between any two disk checkpoints
- And finally, guaranteed or partial verifications between any two memory checkpoints

- Compute the expected execution time between any two verifications



# Without partial verifications

## Placing disk checkpoints:



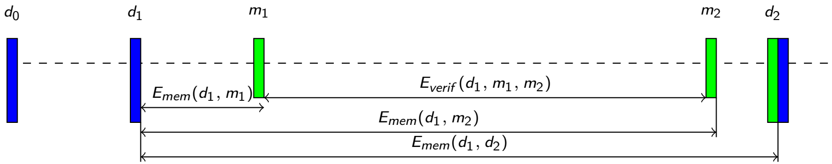

- $E_{disk}(d_2)$: expected time needed to successfully execute tasks $T_1$ to $T_{d_2}$, where $T_{d_2}$ is followed by $V^* C_M C_D$:

$$E_{disk}(d_2) = \min_{0 \leq d_1 < d_2} \{E_{disk}(d_1) + E_{mem}(d_1, d_2) + C_D\}$$

- Objective: $E_{disk}(n)$
- Initialization: $E_{disk}(0) = 0$

# Without partial verifications

## Placing memory checkpoints:



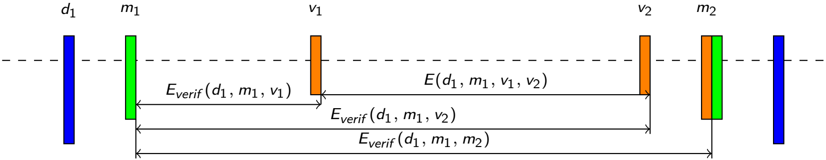

- $E_{mem}(d_1, m_2)$: expected time needed to successfully execute tasks $T_{d_1+1}$ to $T_{m_2}$, where $T_{d_1}$ is followed by $V^* C_M C_D$ and $T_{m_2}$ is followed by $V^* C_M$:

$$E_{mem}(d_1, m_2) = \min_{d_1 \leq m_1 < m_2} \{E_{mem}(d_1, m_1) + E_{verif}(d_1, m_1, m_2) + C_M\}$$

- Initialization: $E_{mem}(d_1, d_1) = 0$

# Without partial verifications

## Placing additional guaranteed verifications:




- $E_{verif}(d_1, m_1, v_2)$: expected time needed to successfully execute tasks $T_{m_1+1}$ to $T_{v_2}$, where $T_{d_1}$ is followed by $V^* C_M C_D$, $T_{m_1}$ is followed by $V^* C_M$, $T_{v_2}$ is followed by $V^*$:

$$E_{verif}(d_1, m_1, v_2) = \min_{m_1 \le v_1 < v_2} \{E_{verif}(d_1, m_1, v_1) + E(d_1, m_1, v_1, v_2)\}$$

- Initialization: $E_{verif}(d_1, m_1, m_1) = 0$

# Without partial verifications

Expected execution time between two verifications $E(d_1, m_1, v_1, v_2)$, knowing positions of last $C_D$ and last $C_M$:

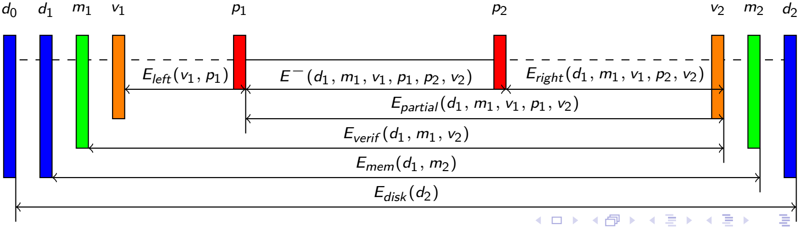
- If $p^f_{v_1,v_2}$, recover from $C_D$
- Otherwise, if $p^s_{v_1,v_2}$, detect error at $v_2$ and recover from $C_M$

$$
\begin{aligned}
&E(d_1, m_1, v_1, v_2) = \\
&p^f_{v_1,v_2}\left(T^{\text{lost}}_{v_1,v_2} + R_D + E_{mem}(d_1, m_1) + E_{verif}(d_1, m_1, v_1) + E(d_1, m_1, v_1, v_2)\right) \\
&+ \left(1 - p^f_{v_1,v_2}\right)\Big(W_{v_1,v_2} + V^* \\
&\qquad + p^s_{v_1,v_2}\left(R_M + E_{verif}(d_1, m_1, v_1) + E(d_1, m_1, v_1, v_2)\right)\Big)
\end{aligned}
$$

- Compute $T^{\text{lost}}_{v_1,v_2} = \frac{1}{\lambda_f} - \frac{W_{v_1,v_2}}{e^{\lambda_f W_{v_1,v_2}} - 1}$ and simplify

# And with partial verifications?

- Probability $g$ that error remains undetected after partial verification
- Need to account fo time lost executing following tasks until error is detected: compute first values at the right of the current interval
- $E_{partial}(d_1, m_1, v_1, p_1, v_2)$: expected time needed to execute all tasks $T_{p_1+1}$ to $T_{v_2}$, tries all positions $p_2$ for next partial verification
- $E_{partial}(d_1, m_1, v_1, p_1, v_2)$ calls recursively $E_{partial}(d_1, m_1, v_1, p_2, v_2)$
- To compute $E^-(d_1, m1, v_1, p_1, p_2, v_2)$, need to know $E_{left}(v_1, p_1)$ and $E_{right}(d_1, m_1, v_1, p_2, v_2)$; $E_{right}$ can be computed, and $E_{left}$ accounted for separately (independent on nb of partial verifs)



# Outline

# Simulation settings

- Identical recovery and checkpoint costs: $R_D = C_D$ and $R_M = C_M$
- $V^* = C_M$ (check all data in memory), $V = \frac{V^*}{100}$ and $r = 0.8$
- Work $W = 25000$ seconds, distributed between up to $n = 50$ tasks:
  - *Uniform*: all tasks share the same cost $\frac{W}{n}$ (matrix multiplication, iterative stencil kernels)
  - *Decrease*: task $T_i$ has cost $\alpha(n+1-i)^2$, where $\alpha \approx \frac{3W}{n^3}$ (dense matrix solvers)
  - *HighLow*: set of identical tasks with large costs followed by tasks with small costs
- Platforms used to evaluate Scalable Checkpoint/Restart (SCR) library (Moody et al.):

| platform | #nodes | $\lambda_f$ | $\lambda_s$ | $C_D$ | $C_M$ |
|---|---|---|---|---|---|
| Hera | 256 | 9.46e-7 | 3.38e-6 | 300$s$ | 15.4$s$ |
| Atlas | 512 | 5.19e-7 | 7.78e-6 | 439$s$ | 9.1$s$ |
| Coastal | 1024 | 4.02e-7 | 2.01e-6 | 1051$s$ | 4.5$s$ |
| Coastal SSD | 1024 | 4.02e-7 | 2.01e-6 | 2500$s$ | 180.0$s$ |

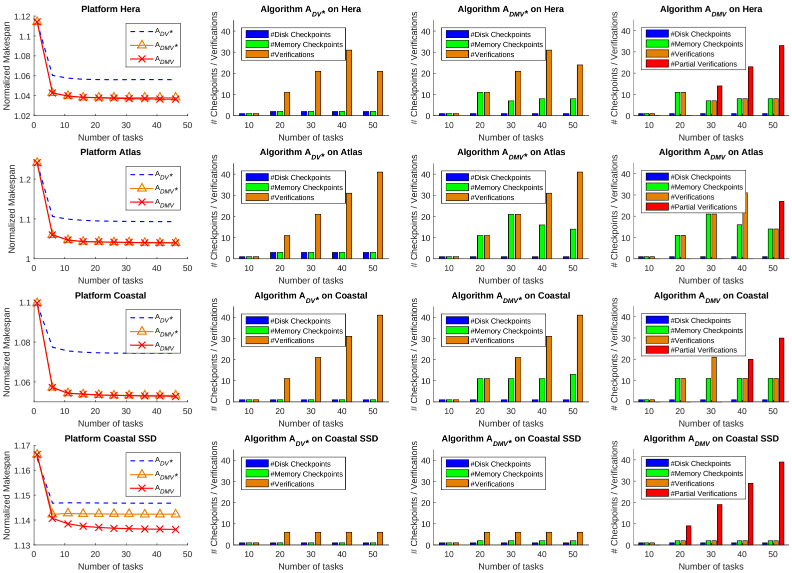



Figure: Performance of the three algorithms with *uniform* distribution

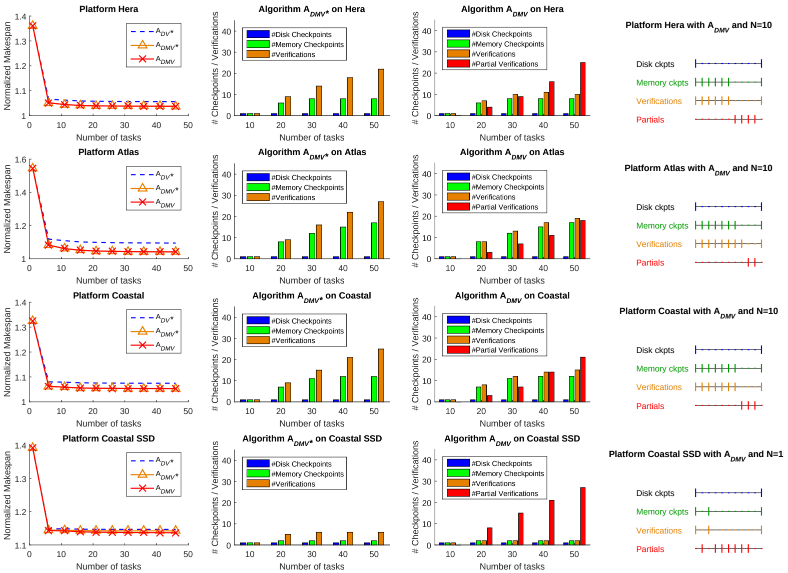



Figure: Performance of the three algorithms with *decrease* distribution

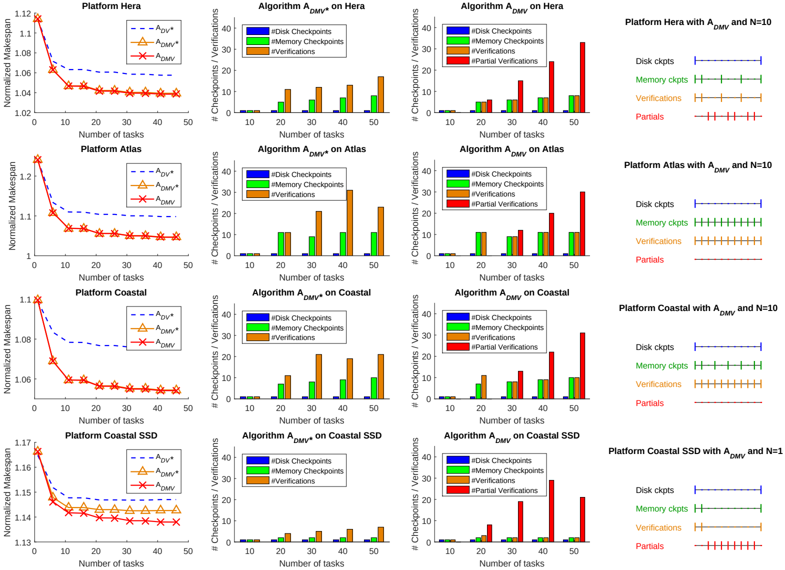



Figure: Performance of the three algorithms with *highlow* distribution

# Summary of simulations

- More tasks → better performance
- Single-level algorithm: Guaranteed verifications everywhere, except with too many tasks ($n = 50$ on Hera) or cost of verification too high (Coastal SSD)
- Two-level algorithms: Use of memory checkpoints drastically reduces makespan
- With partial verifications: Need to use a lot of them (smaller recall): useful only when enough tasks; limited impact, except for Coastal SSD with higher checkpointing and verification costs

# Outline

# Conclusion

- Two-level checkpointing scheme to cope with fail-stop and silent errors
- Combines disk/memory checkpoints with guaranteed/partial verifications
- Theoretically: multi-level polynomial-time dynamic programming algorithm for linear chains ($O(n^6)$)
- Practically: benefit of combined approach with realistic parameters, fast in practice

Future directions

- Usefulness of the approach on general application workflows
- Need of efficient polynomial-time heuristics

Research report RR-8794 available at `graal.ens-lyon.fr/~abenoit`