Optimization problems in the presence of failures on large-scale parallel systems

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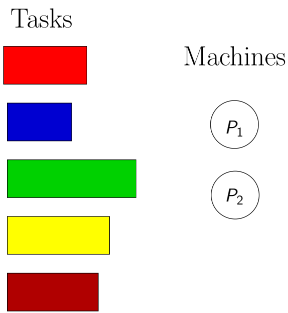
Motivation

Optimization problems: focus on scheduling, i.e., allocating resources to applications to optimize some performance metrics

- Resources: Large-scale distributed systems with millions of components
- Applications: Parallel applications, expressed as a set of tasks, or divisible application with some work to complete
- Performance metrics: Of course we are concerned with the performance of the applications, but also with resilience and energy consumption

Classical scheduling problems



Objectives:

- Minimizing total execution time (C_{max})
- Minimizing weighted sum of execution times $\sum_i w_i C_i$

Results: NP-completeness, algorithms, approximation algorithms, (in-)approximation bounds

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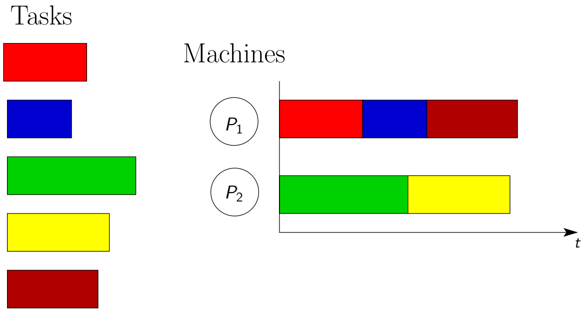

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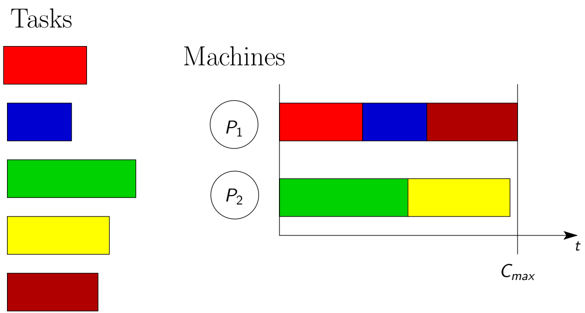

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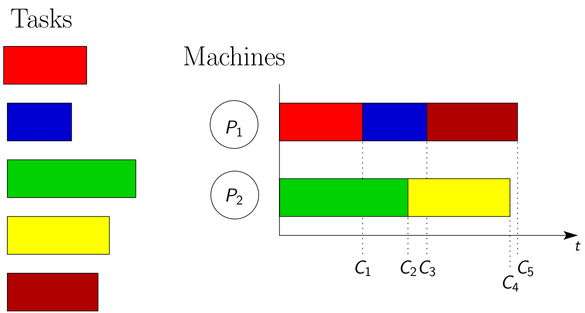

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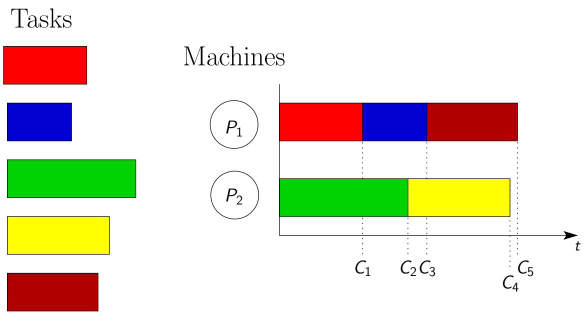

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Dealing with failures

- Consider one processor (e.g. in your laptop)
  - Mean Time Between Failures (MTBF) = 100 years
  - (Almost) no failures in practice ☺

  Why bother about failures?

- **Theorem:** The MTBF decreases linearly with the number of processors!
  With 36500 processors:
  - MTBF = 1 day
  - A failure every day on average!

A large simulation can run for weeks, hence it will face failures ☹

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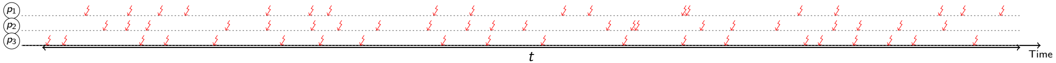
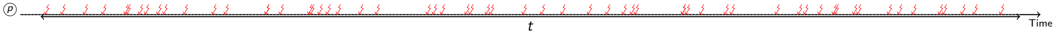
Intuition



If three processors have around 20 faults during a time t $(MTBF_{processor} = \frac{t}{20})$...

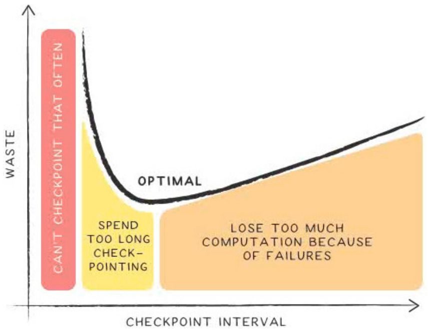


...during the same time, the platform has around 60 faults $(MTBF_{platform} = \frac{t}{60})$

So, how to deal with failures?

Failures usually handled by adding redundancy:

- Replicate the work (for instance, use only half of the processors, and the other half is used to redo the same computation)
- Checkpoint the application: Periodically save the state of the application on stable storage, so that we can restart in case of failure without loosing everything



Another crucial issue: Energy consumption

"The internet begins with coal"

- Nowadays: more than 90 billion kilowatt-hours of electricity a year; requires 34 giant (500 megawatt) coal-powered plants, and produces huge CO_2 emissions
- Explosion of artificial intelligence; AI is hungry for processing power! Need to double data centers in next four years
  $\rightarrow$ how to get enough power?
- Failures: Redundant work consumes even more energy

Energy and power awareness $\rightsquigarrow$ crucial for both environmental and economical reasons

Outline

1. Checkpointing for resilience
   - How to cope with errors?
   - Optimization objective and optimal period
   - Optimal period when accounting for energy consumption

2. Combining checkpoint with replication
   - Replication analysis
   - Simulations

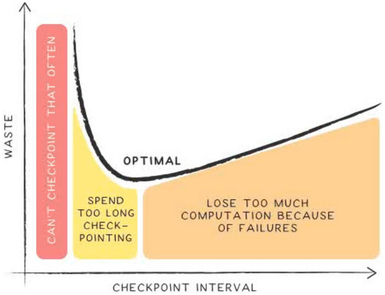
3. Back to task scheduling

4. Summary and need for trade-offs

Introduction to resilience

- Fail-stop errors:
  - Component failures (node, network, power, ...)
  - Application fails and data is lost
- Silent data corruptions:
  - Bit flip (Disk, RAM, Cache, Bus, ...)
  - Detection is not immediate, and we may get wrong results

How often should we checkpoint to minimize the waste, i.e., the time lost because of resilience techniques and failures?



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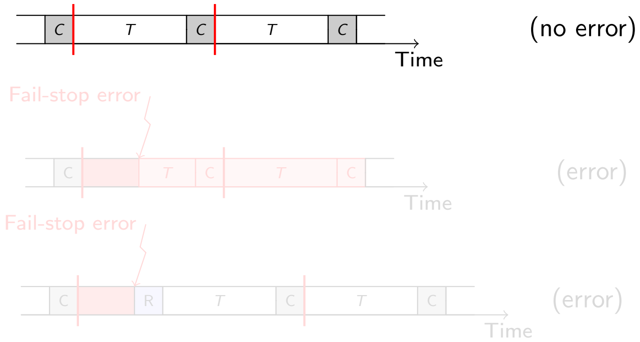
Coping with fail-stop errors

Periodic checkpoint, rollback, and recovery:



- Coordinated checkpointing (the platform is a giant macro-processor)
- Assume instantaneous interruption and detection
- Rollback to last checkpoint and re-execute

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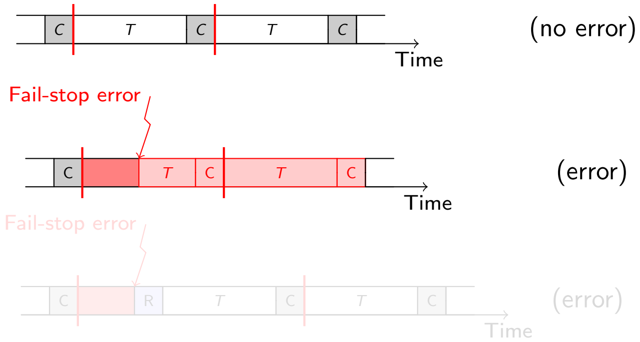

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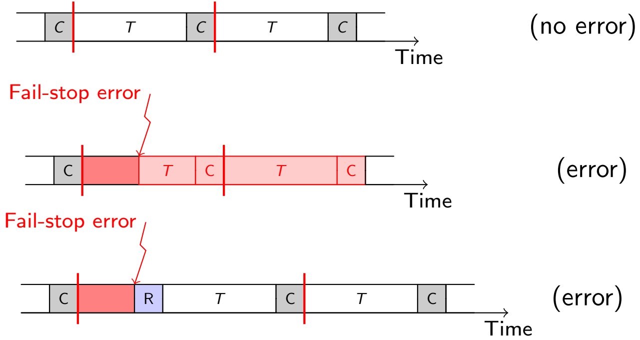

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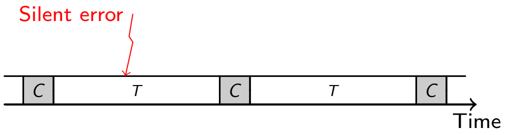
Coping with silent errors

Silent error = detection latency

Error is detected only when corrupted data is activated

Same approach?



Keep multiple checkpoints?

Which checkpoint to recover from?

Need an active method to detect silent errors!

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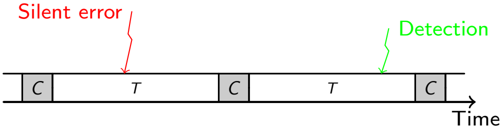

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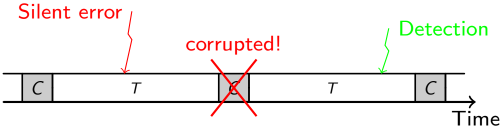

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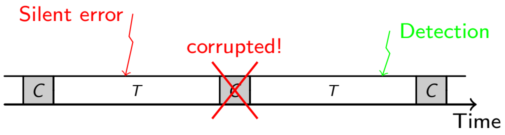

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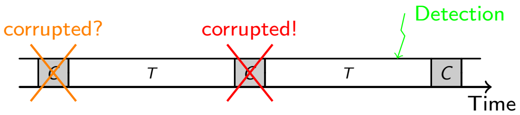

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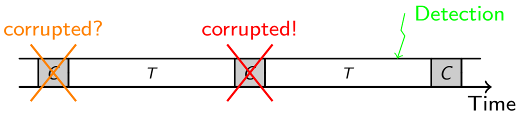

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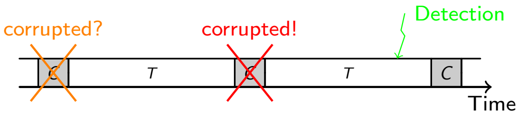

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Methods for detecting silent errors

General-purpose approaches

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

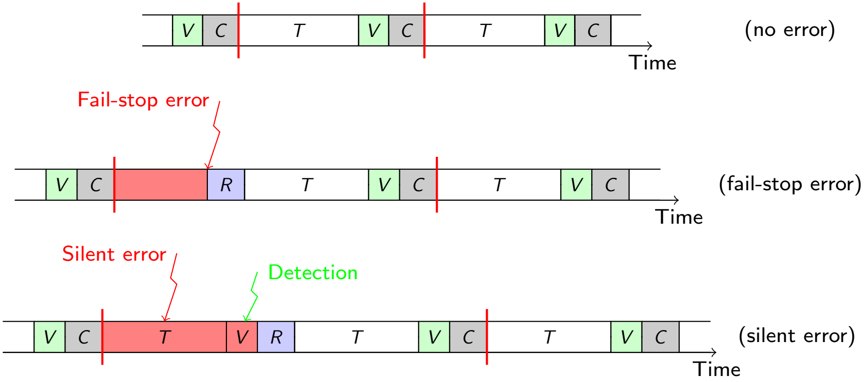
Application-specific approaches

- 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 fail-stop and silent errors



What is the optimal checkpointing period?

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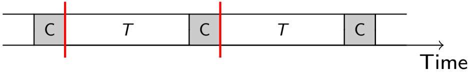
Optimization objective (1/2)



- T is the **pattern length** (time without failures)
- C is the checkpoint cost
- $\mathbb{E}(T)$ is the expected execution time of the pattern

By definition, the overhead of the pattern is defined as:

$$\mathbb{H}(T) = \frac{\mathbb{E}(T)}{T} - 1$$

The overhead measures the fraction of **extra time** due to:

- Checkpoints
- Recoveries and re-executions (failures)

The goal is to minimize the quantity: $\mathbb{H}(T)$

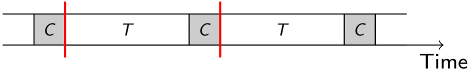
Optimization objective (2/2)

- Goal: Find the **optimal pattern length** T^*, so that the overhead is minimized
- Overhead: $\mathbb{H}(T) = \frac{\mathbb{E}(T)}{T} - 1$

1. Compute expected execution time $\mathbb{E}(T)$ (exact formula)
2. Compute overhead $\mathbb{H}(T)$ (first-order approximation)
3. Derive optimal T^*: fail-stop errors
4. Derive optimal T^*: silent errors
5. Derive optimal T^*: both

1. Expected execution time $\mathbb{E}(T)$

- T: Pattern length; C: Checkpoint time; R: Recovery time
- $\lambda^f = \frac{1}{\mu^f}$: Fail-stop error rate



(no error)

$$\mathbb{E}(T) = \mathbb{P}_{no-error}\,(T + C)$$

$$+$$

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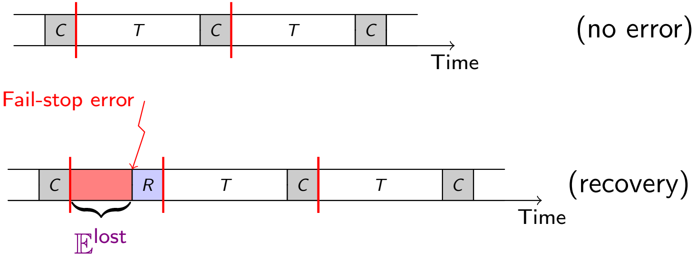

$$\mathbb{E}(T) = \mathbb{P}_{no-error}\,(T + C) + \mathbb{P}_{error}\left(\mathbb{E}^{lost} + R + \mathbb{E}(T)\right)$$

1. Expected execution time $\mathbb{E}(T)$

Assume that failures follow an **exponential distribution** $\text{Exp}(\lambda^f)$

- Independent errors (memoryless property)

There is at least one error before time t with probability:

$$\mathbb{P}(X \leq t) = 1 - e^{-\lambda^f t} \quad \text{(cdf)}$$

Probability of failure / no-failure

- $\mathbb{P}_{error} = 1 - e^{-\lambda^f T}$
- $\mathbb{P}_{no-error} = e^{-\lambda^f T}$

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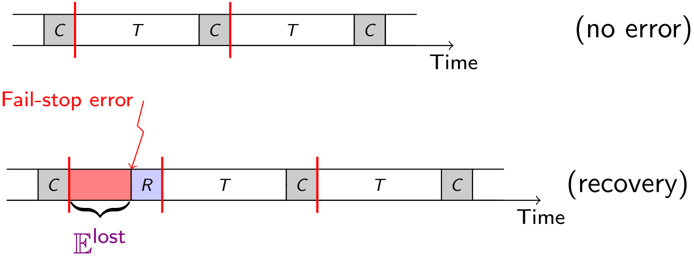

$$\mathbb{E}(T) = e^{-\lambda^f T}(T+C) + (1 - e^{-\lambda^f T})\left(\mathbb{E}^{\text{lost}} + R + \mathbb{E}(T)\right)$$

$$= T + C + (e^{\lambda^f T} - 1)\left(\mathbb{E}^{\text{lost}} + R\right)$$

$\mathbb{E}^{\text{lost}}$ is the time lost when the failure strikes:

$$\mathbb{E}^{\text{lost}} = \int_0^\infty t\mathbb{P}(X = t | X < T)dt = \frac{1}{\lambda^f} - \frac{T}{e^{\lambda^f T} - 1} = \frac{T}{2} + o(\lambda^f T)$$

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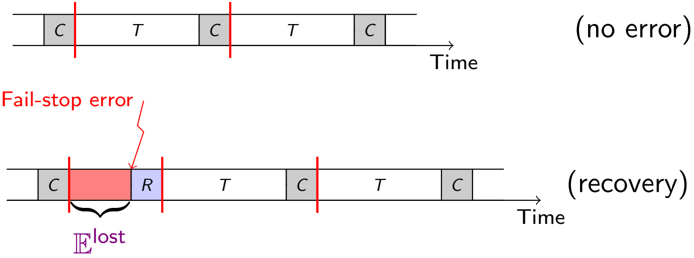

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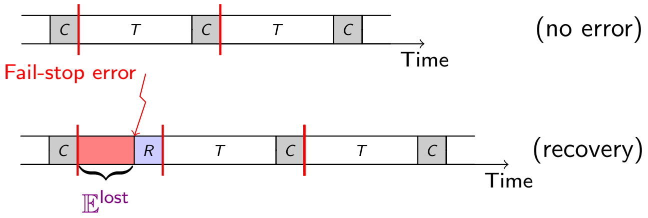

We use Taylor series to approximate $e^{-\lambda^f T}$ up to first-order terms:

$$e^{-\lambda^f T} = 1 - \lambda^f T + o(\lambda^f T)$$

Works well provided that $\lambda^f << T, C, R$:

$$\mathbb{E}(T) = T + C + \lambda^f T \left(\frac{T}{2} + R\right) + o(\lambda^f T)$$

Finally, we get the overhead of the pattern: $\mathbb{H}(T) = \frac{C}{T} + \lambda^f \frac{T}{2} + o(\lambda^f T)$

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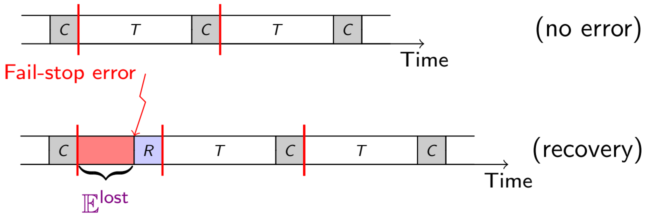

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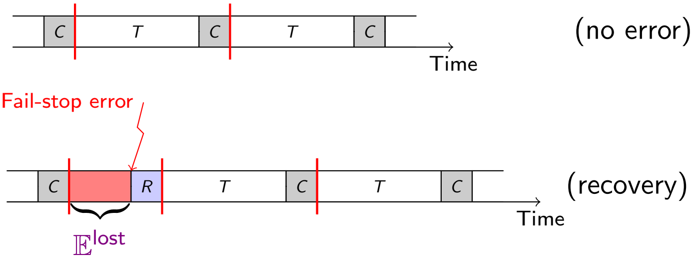

$$\mathbb{H}(T) = \frac{C}{T} + \lambda^f \frac{T}{2} + o(\lambda^f T)$$

We solve: $\frac{\partial \mathbb{H}(T)}{\partial T} = -\frac{C}{T^2} + \frac{\lambda^f}{2} = 0$

Finally, we retrieve:

$$T^* = \sqrt{\frac{2C}{\lambda^f}} = \sqrt{2\mu^f C}$$

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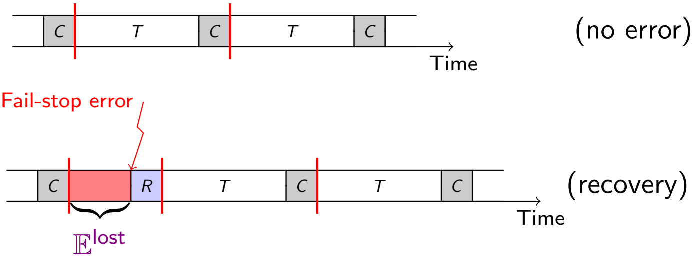

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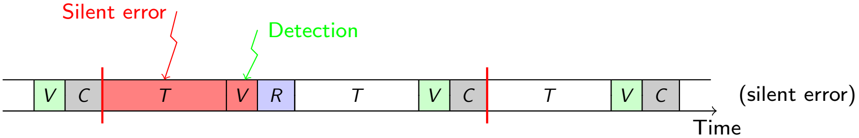

Similar to fail-stop except:

- $\lambda^f \rightarrow \lambda^s$
- $\mathbb{E}^{\text{lost}} = T$
- V: verification time

Using the same approach:

$$\mathbb{H}(T) = \frac{C+V}{T} + \underbrace{\lambda^s T}_{\textit{silent}} + o(\lambda^s T)$$

5. Derive optimal T^*: Both errors

$$\mathbb{H}(T) = \frac{C+V}{T} + \underbrace{\lambda^f \frac{T}{2}}_{fail-stop} + \underbrace{\lambda^s T}_{silent} + o(\lambda T)$$

First-order approximations [Young 1974, Daly 2006, AB et al. 2016]

	Fail-stop errors	Silent errors	Both errors
Pattern	$T+C$	$T+V+C$	$T+V+C$
Optimal T^*	$\sqrt{\frac{C}{\frac{\lambda^f}{2}}}$	$\sqrt{\frac{V+C}{\lambda^s}}$	$\sqrt{\frac{V+C}{\lambda^s+\frac{\lambda^f}{2}}}$
Overhead $\mathbb{H}^*$	$2\sqrt{\frac{\lambda^f}{2}C}$	$2\sqrt{\lambda^s(V+C)}$	$2\sqrt{\left(\lambda^s+\frac{\lambda^f}{2}\right)(V+C)}$

Is this optimal for energy consumption?

5. Derive optimal T^*: Both errors

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Energy model (1/2)

- Modern processors equipped with dynamic voltage and frequency scaling (DVFS) capability
- Power consumption of processing unit is $P_{idle} + \kappa\sigma^3$, where $\kappa > 0$ and σ is the processing speed
- Error rate: May also depend on processing speed
  - $\lambda(\sigma)$ follows a U-shaped curve
  - increases exponentially with decreased processing speed σ
  - increases also with increased speed because of high temperature

Energy model (2/2)

- Total power consumption depends on:
  - P_{idle}: static power dissipated when platform is on (even idle)
  - $P_{cpu}(\sigma)$: dynamic power spent by operating CPU at speed σ
  - P_{io}: dynamic power spent by I/O transfers (checkpoints and recoveries)

- Computation and verification: power depends upon σ (total time $T_{cpu}(\sigma)$)
- Checkpointing and recovering: I/O transfers (total time T_{io})
- Total energy consumption:

$$Energy(\sigma) = T_{cpu}(\sigma)(P_{idle} + P_{cpu}(\sigma)) + T_{io}(P_{idle} + P_{io})$$

  - Checkpoint: $E^C = C(P_{idle} + P_{io})$
  - Recover: $E^R = R(P_{idle} + P_{io})$
  - Verify at speed σ: $E^V(\sigma) = V(\sigma)(P_{idle} + P_{cpu}(\sigma))$

Bi-criteria problem

Linear combination of execution time and energy consumption:

$$a \cdot Time + b \cdot Energy$$

Theorem

Application subject to both fail-stop and silent errors

Minimize $a \cdot Time + b \cdot Energy$

The optimal checkpointing period is $T^*(\sigma) = \sqrt{\frac{2(V(\sigma)+C_e(\sigma))}{\lambda^f(\sigma)+2\lambda^s(\sigma)}}$,

where $C_e(\sigma) = \frac{a+b(P_{idle}+P_{io})}{a+b(P_{idle}+P_{cpu}(\sigma))} C$

Similar optimal period as without energy, but account for new parameters!

$$T^* = \sqrt{\frac{2(V+C)}{\lambda^f+2\lambda^s}}$$

Bi-criteria problem

Linear combination of execution time and energy consumption:

$$a \cdot Time + b \cdot Energy$$

Theorem

Application subject to both fail-stop and silent errors
Minimize $a \cdot Time + b \cdot Energy$
The optimal checkpointing period is $T^*(\sigma) = \sqrt{\frac{2(V(\sigma)+C_e(\sigma))}{\lambda^f(\sigma)+2\lambda^s(\sigma)}}$,
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Outline

1. Checkpointing for resilience
   - How to cope with errors?
   - Optimization objective and optimal period
   - Optimal period when accounting for energy consumption
2. Combining checkpoint with replication
   - Replication analysis
   - Simulations
3. Back to task scheduling
4. Summary and need for trade-offs

When Amdahl meets Young/Daly

Error-free speedup with P processors and α sequential fraction:

Amdahl's Law: $S(P) = \frac{1}{\alpha + \frac{1-\alpha}{P}}$

- Bounded above by $1/\alpha$
- Strictly increasing function of P

Allocating more processors on an error-prone platform?

- Higher error-free speedup ☺
- More errors/faults ☹
  - More frequent checkpointing ☹
    - More resilience overhead ☹

We can compute optimal processor allocation and checkpointing interval!

How is replication used?

On a Q-processor platform, application is replicated n times:

- **Duplication**: each replica has $P = Q/2$ processors
- **Triplication**: each replica has $P = Q/3$ processors
- **General case**: each replica has $P = Q/n$ processors

Having more replicas on an error-prone platform?

- Lower error-free speedup ☹
- More resilient ☺
  - Smaller checkpointing frequency ☺
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Optimal replication level, processor allocation per replica, and checkpointing interval?

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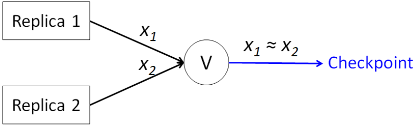
Why is replication useful?

- **Error detection (duplication)**:



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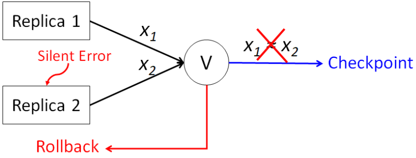

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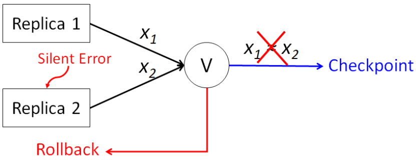

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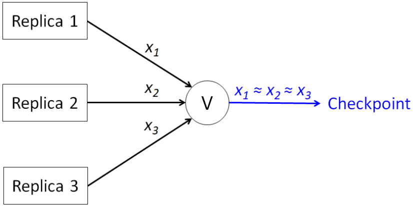

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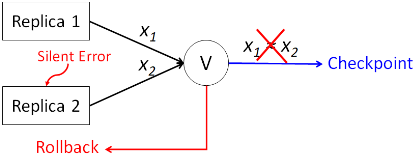

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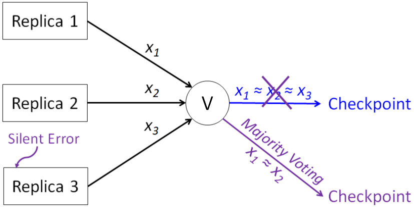

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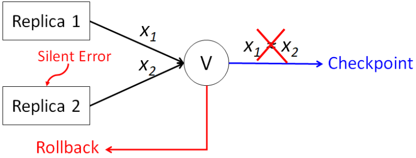

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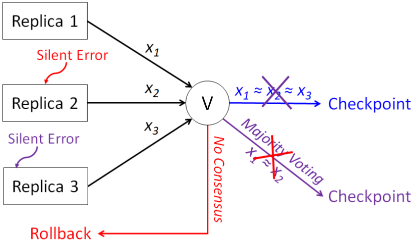
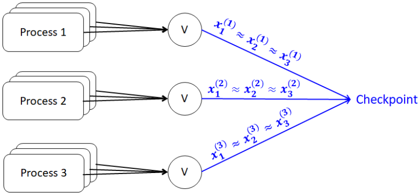


Outline

Two replication modes

- **Process replication**:



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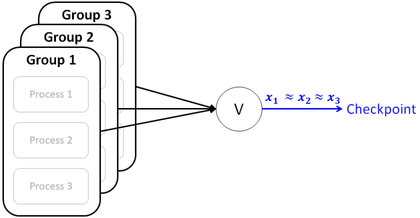

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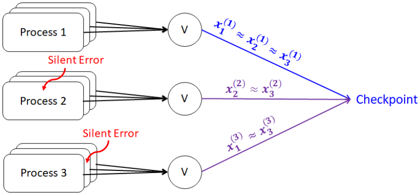

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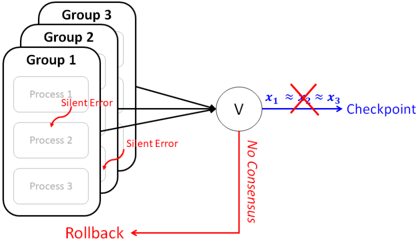

Probability of failure

Independent process error distribution:

- Exponential $Exp(\lambda)$, $\lambda = 1/\mu$ (Memoryless)
- *Error probability of one process during T time of computation:*

$$\mathbb{P}(T) = 1 - e^{-\lambda T}$$

Process triplication:

- *Failure probability of any triplicated process:*

$$\mathbb{P}_3^{\text{prc}}(T,1) = \binom{3}{2}\Big(1 - \mathbb{P}(T)\Big)\mathbb{P}(T)^2 + \mathbb{P}(T)^3$$

$$= 3e^{-\lambda T}\left(1 - e^{-\lambda T}\right)^2 + \left(1 - e^{-\lambda T}\right)^3 = 1 - 3e^{-2\lambda T} + 2e^{-3\lambda T}$$

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$$\mathbb{P}_3^{\text{prc}}(T,P) = 1 - \mathbb{P}(\text{“No process fails”})$$

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$$\mathbb{P}_1^{\text{grp}}(T,P) = 1 - \mathbb{P}(\text{“No process in group fails”}) = 1 - (1-\mathbb{P}(T))^P = 1 - e^{-\lambda PT}$$

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Two observations

Observation 1 (Implementation)

- **Process replication** is more resilient than group replication (assuming same overhead)
- **Group replication** is easier to implement by treating an application as a blackbox

Observation 2 (Analysis)

Following two scenarios are equivalent w.r.t. failure probability:

- **Group replication** with n replicas, where each replica has P processes and each process has error rate λ
- **Process replication** with one process, which has error rate λP and which is replicated n times

Benefit of analysis: $\text{Group}(n, P, \lambda) \rightarrow \text{Process}(n, 1, \lambda P)$

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Analysis steps

Maximize error-aware speedup

$$\mathbb{S}_n(T,P) = \frac{S(P)}{\mathbb{E}_n(T,P)/T}$$

1. Derive failure probability $\mathbb{P}_n^{\text{prc}}(T,P)$ or $\mathbb{P}_n^{\text{grp}}(T,P)$ — exact
2. Compute expected execution time $\mathbb{E}_n(T,P)$ — exact
3. Compute first-order approx. of error-aware speedup $\mathbb{S}_n(T,P)$
4. Derive optimal T_{opt}, P_{opt} and get $\mathbb{S}_n(T_{\text{opt}},P_{\text{opt}})$
5. Choose right replication level n

Analytical results

Duplication:
On a platform with Q processors and checkpointing cost C, the optimal resilience parameters for *process/group duplication* are:

$$P_{opt} = \min\left\{\frac{Q}{2}, \left(\frac{1}{2}\left(\frac{1-\alpha}{\alpha}\right)^2 \frac{1}{C\lambda}\right)^{\frac{1}{3}}\right\}$$

$$T_{opt} = \left(\frac{C}{2\lambda P_{opt}}\right)^{\frac{1}{2}}$$

$$\mathbb{S}_{opt} = \frac{S(P_{opt})}{1 + 2(2\lambda C P_{opt})^{\frac{1}{2}}}$$

Triplication & (n,k)-replication (k-out-of-n replica consensus):
similar results but different for process and group, less practical for $n > 3$

- For $\alpha > 0$, not necessarily use up all available Q processors
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Results comparison

For fully parallel jobs, i.e., $\alpha = 0$ (similar for $\alpha > 0$)

- Duplication v.s. Process triplication

$$P_{\text{opt}} = \frac{Q}{2} \qquad P_{\text{opt}} = \frac{Q}{3} \qquad \text{(Processors} \downarrow\text{)}$$

$$T_{\text{opt}} = \sqrt{\frac{C}{\lambda Q}} \qquad T_{\text{opt}} = \sqrt[3]{\frac{C}{2\lambda^2 Q}} \qquad \text{(Chkpt interval} \uparrow\text{)}$$

$$\mathbb{S}_{\text{opt}} = \frac{Q/2}{1 + 2\sqrt{\lambda C Q}} \qquad \mathbb{S}_{\text{opt}} = \frac{Q/3}{1 + 3\sqrt[3]{\left(\frac{\lambda C}{2}\right)^2 Q}} \qquad \text{(Exp. speedup??)}$$

- Process triplication v.s. Group triplication

$$P_{\text{opt}} = \frac{Q}{3} \qquad P_{\text{opt}} = \frac{Q}{3} \qquad \text{(Processors} =\text{)}$$

$$T_{\text{opt}} = \sqrt[3]{\frac{C}{2\lambda^2 Q}} \qquad T_{\text{opt}} = \sqrt[3]{\frac{3C}{2(\lambda Q)^2}} \qquad \text{(Chkpt interval} \downarrow\text{)}$$

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Duplication	Process triplication	
$P_{opt} = \frac{Q}{2}$	$P_{opt} = \frac{Q}{3}$	(Processors ↓)
$T_{opt} = \sqrt{\frac{C}{\lambda Q}}$	$T_{opt} = \sqrt[3]{\frac{C}{2\lambda^2 Q}}$	(Chkpt interval ↑)
$\mathbb{S}_{opt} = \frac{Q/2}{1 + 2\sqrt{\lambda C Q}}$	$\mathbb{S}_{opt} = \frac{Q/3}{1 + 3\sqrt[3]{\left(\frac{\lambda C}{2}\right)^2 Q}}$	(Exp. speedup??)

- Process triplication v.s. Group triplication

Process triplication	Group triplication	
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Results comparison

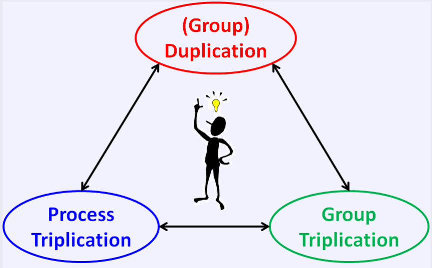
For fully parallel jobs, i.e., $\alpha = 0$ (similar for $\alpha > 0$)

- Duplication v.s. Process triplication

- Pro

Choosing right mode & level of replication

Based on analytical results, app. output structure and system/language support



$1 + 3\sqrt[3]{\left(\frac{\lambda C}{2}\right)^2 Q}$ $1 + 3\sqrt[3]{\frac{1}{3}\left(\frac{\lambda C Q}{2}\right)^2}$

Outline

Simulations

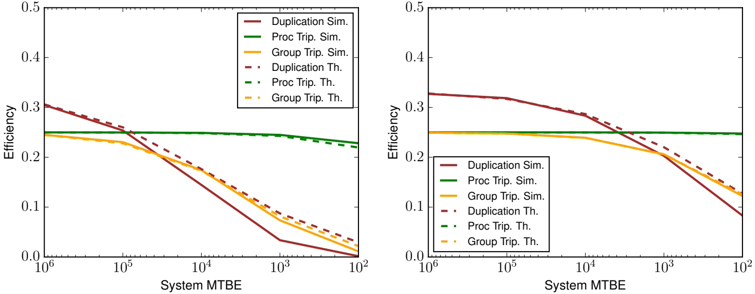
Consider a platform with $Q = 10^6$, and study

$$Efficiency = \frac{\mathbb{S}_{\text{opt}}}{Q}$$

- Impact of MTBE (Mean Time Between Errors – errors lead to failures) and checkpointing cost C
- Impact of sequential fraction α
- Impact of number of processes P

Impact of MTBE and checkpointing cost

$$\alpha = 10^{-6}$$

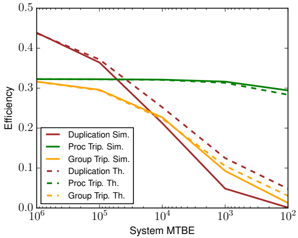


(a) $C = 1800s$ (b) $C = 60s$

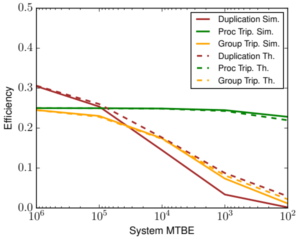
- First-order accurate except for duplication (where P is larger) and with small MTBE
- Duplication can be sufficient for large MTBE, especially for small checkpointing cost

Impact of sequential fraction

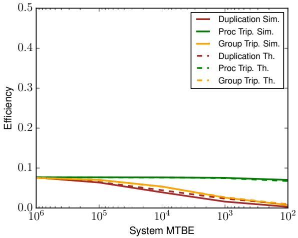
$C = 1800s$



(c) $\alpha = 10^{-7}$



(d) $\alpha = 10^{-6}$

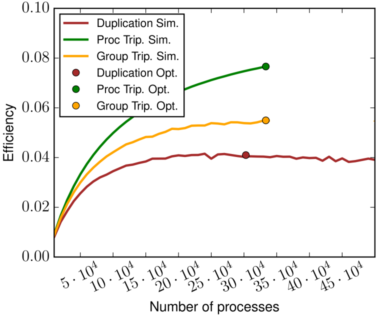


(e) $\alpha = 10^{-5}$

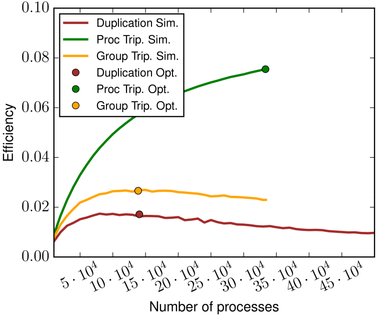
- Increased α reduces efficiency
- Increased α increases minimum MTBE for which duplication is sufficient

Impact of number of processes

$\alpha = 10^{-5}, C = 1800s$



(f) $MTBE = 10^4$



(g) $MTBE = 10^3$

- Efficiency/speedup not strictly increasing with P
- First-order P_{opt} close to actual optimum

What to remember

- "Replication + checkpointing" as a general-purpose fault- tolerance protocol for detecting/correcting silent errors in HPC
- Process replication is more resilient than group replication, but group replication is easier to implement
- Analytical solution for $P_{\text{opt}}, T_{\text{opt}}, and\ \mathbb{S}_{\text{opt}}$ and for choosing right replication mode and level

Outline

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   - Optimal period when accounting for energy consumption

2. Combining checkpoint with replication
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   - Simulations

3. Back to task scheduling

4. Summary and need for trade-offs

Chains of tasks

- High-performance computing (HPC) application: chain of tasks $T_1 \rightarrow T_2 \rightarrow \cdots \rightarrow T_n$
- Parallel tasks executed on the whole platform
- For instance: tightly-coupled computational kernels, image processing applications, ...
- Goal: efficient execution, i.e., minimize total execution time
- Checkpoints can only be done after a task has completed

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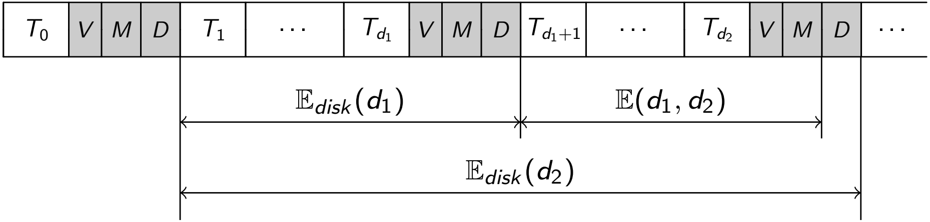
Dynamic programming algorithm without replication

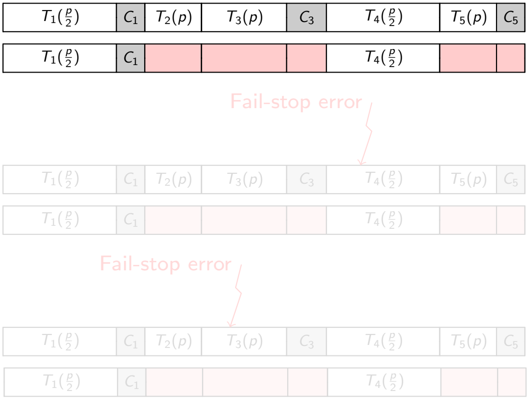
Possibility to add verification, memory checkpoint and disk checkpoint at the end of a task



$$\mathbb{E}_{disk}(d_2) = \min_{0 \le d_1 < d_2} \{\mathbb{E}_{disk}(d_1) + \mathbb{E}(d_1, d_2) + C_D\}$$

- Initialization: $\mathbb{E}_{disk}(0) = 0$
- Objective: Compute $\mathbb{E}_{disk}(n)$
- Compute $\mathbb{E}_{disk}(0), \mathbb{E}_{disk}(1), \mathbb{E}_{disk}(2), \ldots, \mathbb{E}_{disk}(n)$ in that order
- Complexity: $O(n^2)$

Coping with fail-stop errors with replication



- The whole platform is used at all time, some tasks are replicated
- If failure hits a replicated task, no need to rollback
- Otherwise, rollback to last checkpoint and re-execute

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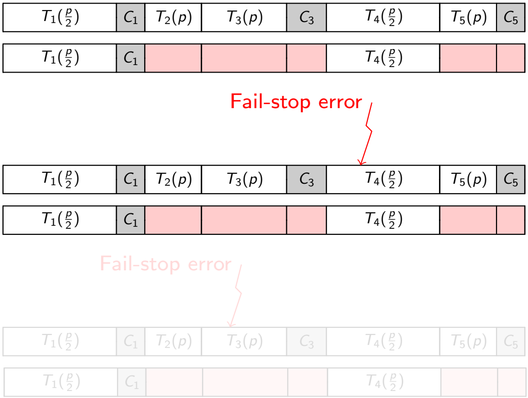

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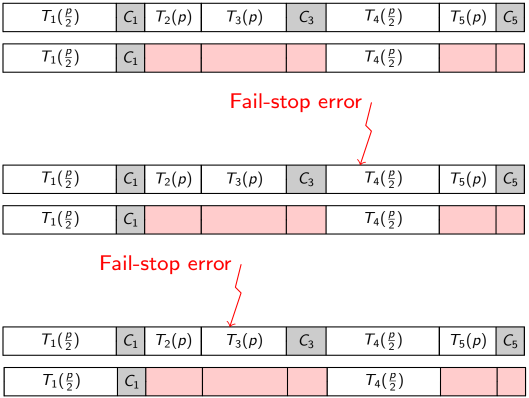

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Dynamic programming algorithm with replication

- Recursively computes expectation of optimal time required to execute tasks T_1 to T_i and then checkpoint T_i
- Distinguish whether T_i is replicated or not
- $T_{opt}^{rep}(i)$: knowing that T_i is replicated
- $T_{opt}^{norep}(i)$: knowing that T_i is not replicated
- Solution: $\min\left\{T_{opt}^{rep}(n) + C_n^{rep}, T_{opt}^{norep}(n) + C_n^{norep}\right\}$

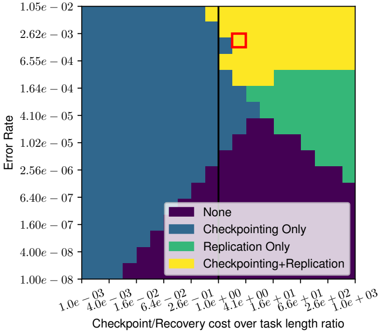
Computing $T_{opt}^{rep}(j)$: j is replicated

$$T_{opt}^{rep}(j) = \min_{1 \le i < j} \left\{ \begin{array}{l} T_{opt}^{rep}(i) + C_i^{rep} + T_{NC}^{rep,rep}(i+1,j), \\ T_{opt}^{rep}(i) + C_i^{rep} + T_{NC}^{norep,rep}(i+1,j), \\ T_{opt}^{norep}(i) + C_i^{norep} + T_{NC}^{rep,rep}(i+1,j), \\ T_{opt}^{norep}(i) + C_i^{norep} + T_{NC}^{norep,rep}(i+1,j), \\ R_1^{rep} + T_{NC}^{rep,rep}(1,j), \\ R_1^{norep} + T_{NC}^{norep,rep}(1,j) \end{array} \right\}$$

- T_i: last checkpointed task before T_j
- T_i can be replicated or not, T_{i+1} can be replicated or not
- $T_{NC}^{A,B}$: no intermediate checkpoint, first/last task replicated or not, previous task checkpointed: complicated formula but done in constant time
- Similar equation for $T_{opt}^{norep}(j)$
- Overall complexity: $O(n^2)$

Comparison to checkpoint only

- With identical tasks
- Reports occ. of checkpoints and replicas in optimal solution
- Checkpointing cost $\leq$ task length $\Rightarrow$ no replication



Summary

- Goal: Minimize execution time of linear workflows
- Decide which task to checkpoint and/or replicate
- Sophisticated dynamic programming algorithms: optimal solutions
- Even when accounting for energy: decide at which speed to execute each task
- Even with k different levels of checkpoints and partial verifications: algorithm in $O(n^{k+5})$
- Simulations: With replication, gain over checkpoint-only approach is quite significant, when checkpoint is costly and error rate is high

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Summary and need for trade-offs

- Two major challenges for Exascale systems:
  - Resilience: need to handle failures
  - Energy: need to reduce energy consumption
- The main optimization objective is often performance, such as execution time, but other criteria must be accounted for
- Many models for which we have the answer:
  - Optimal checkpointing period, with fail-stop / silent errors
  - Use of replication to detect and correct silent errors
  - When to checkpoint, replicate and verify for a chain of tasks?
- Still a lot of challenges to address, and techniques to be developed for many kinds of high-performance applications, making trade-offs between performance, reliability, and energy consumption

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Thanks...

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- ... and to Didier El-Baz and Grégoire Danoy for their kind invitation!
- A few references:

  - A. Benoit, A. Cavelan, Y. Robert, H. Sun. Assessing general-purpose algorithms to cope with fail-stop and silent errors. TOPC, 2016
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