Resilience

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Plan du cours d'aujourd'hui

Finishing your PhD on time

In a hypothetical future, in a galaxy far far away, you decided to do a PhD.

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- Thanks to the lack of budget in research, your laptop is very old: it crashes often.
- You chose to write your thesis using a WYSIWYG software which takes approx 3 minutes to save (while freezing your laptop obviously).. Too many figures.

What do you do?

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Solution: Write your thesis in Latex, faster to save (but it's too late now)

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- Solution 1: You choose to save your work every 3h.
  - Mid-afternoon of Day 3, your laptop crashes. You have lost 1.5h of work.

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What do you do?

- Solution 1: You choose to save your work every 3h.
  - Mid-afternoon of Day 3, your laptop crashes. You have lost 1.5h of work.
- Solution 2: You choose to save your work every half-hour.
  - No crash during the next three consecutive days.

Which solution is best?

Plan

Exascale platforms (courtesy Jack Dongarra)

Potential System Architecture with a cap of $200M and 20MW

Systems	2011 K computer	2019	Difference Today & 2019
System peak	**10.5 Pflop/s**	**1 Eflop/s**	**O(100)**
Power	**12.7 MW**	**~20 MW**	
System memory	1.6 PB	32 - 64 PB	O(10)
Node performance	128 GF	1,2 or 15TF	O(10) – O(100)
Node memory BW	64 GB/s	2 - 4TB/s	O(100)
Node concurrency	8	O(1k) or 10k	O(100) – O(1000)
Total Node Interconnect BW	20 GB/s	200-400GB/s	O(10)
System size (nodes)	88,124	O(100,000) or O(1M)	O(10) – O(100)
Total concurrency	705,024	O(billion)	O(1,000)
MTTI	days	O(1 day)	- O(10)

Exascale platforms (courtesy C. Engelmann & S. Scott)

Toward Exascale Computing (My Roadmap)

Based on proposed DOE roadmap with MTTI adjusted to scale linearly

Systems	2009	2011	2015	2018
System peak	2 Peta	20 Peta	100-200 Peta	1 Exa
System memory	0.3 PB	1.6 PB	5 PB	10 PB
Node performance	125 GF	200GF	200-400 GF	1-10TF
Node memory BW	25 GB/s	40 GB/s	100 GB/s	200-400 GB/s
Node concurrency	12	32	O(100)	O(1000)
Interconnect BW	1.5 GB/s	22 GB/s	25 GB/s	50 GB/s
System size (nodes)	18,700	100,000	500,000	O(million)
Total concurrency	225,000	3,200,000	O(50,000,000)	O(billion)
Storage	15 PB	30 PB	150 PB	300 PB
IO	0.2 TB/s	2 TB/s	10 TB/s	20 TB/s
MTTI	4 days	19 h 4 min	3 h 52 min	1 h 56 min
Power	6 MW	~10MW	~10 MW	~20 MW

- Hierarchical
  - 10^5 or 10^6 nodes
  - Each node equipped with 10^4 or 10^3 cores

- Failure-prone

MTBF – one node	1 year	10 years	120 years
MTBF – platform of 10^6 nodes	30sec	5mn	1h

More nodes ⇒ Shorter MTBF (Mean Time Between Failures)

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  - Each node equipped with ... or 10^3 cores

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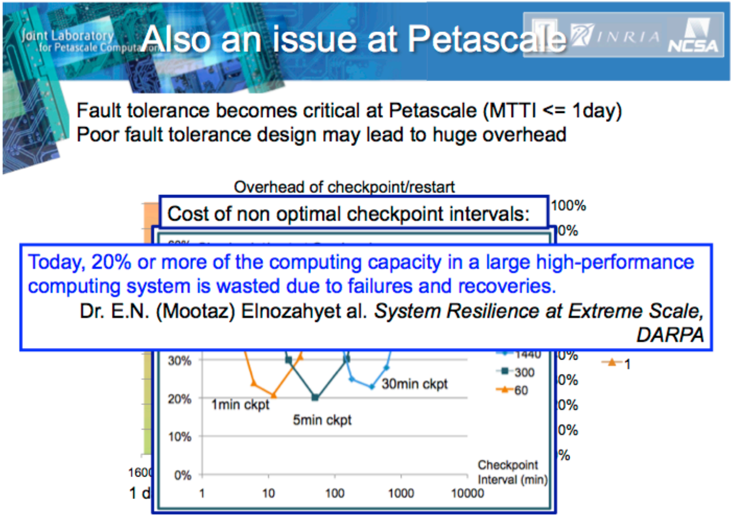
More no ... Failures)

Exascale

$\neq$ **Petascale** $\times 1000$

Plan

Even for today's platforms (courtesy F. Cappello)

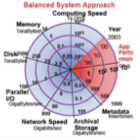


Today, 20% or more of the computing capacity in a large high-performance computing system is wasted due to failures and recoveries.

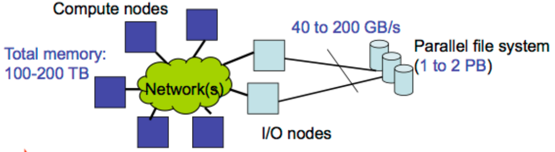
Dr. E.N. (Mootaz) Elnozahyet al. *System Resilience at Extreme Scale, DARPA*

Even for today's platforms (courtesy F. Cappello)

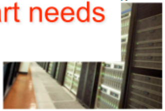
Classic approach for FT: Checkpoint-Restart



Typical "Balanced Architecture" for PetaScale Computers



RoadRunner



Without optimization, Checkpoint-Restart needs about 1h! (~30 minutes each)

Systems	Perf.	Ckpt time	Source
RoadRunner	1PF	~20 min.	Panasas
LLNL BG/L	500 TF	>20 min.	LLNL
LLNL Zeus	11TF	26 min.	LLNL
YYY BG/P	100 TF	~30 min.	YYY

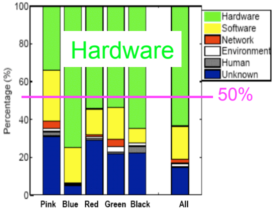
LLNL BG/L

Sources of failures

- Analysis of error and failure logs

- In 2005 (Ph. D. of CHARNG-DA LU) : "Software halts account for the most number of outages (59-84 percent), and take the shortest time to repair (0.6-1.5 hours). Hardware problems, albeit rarer, need 6.3-100.7 hours to solve."

- In 2007 (Garth Gibson, ICPP Keynote):



Relative frequency of root cause by system type.

- In 2008 (Oliner and J. Stearley, DSN Conf.):

Type	Raw Count	Raw %	Filtered Count	Filtered %
Hardware	174,586,516	98.04	1,999	18.78
Software	144,899	0.08	6,814	64.01
Indeterminate	3,350,044	1.88	1,832	17.21

Software errors: Applications, OS bug (kernel panic), communication libs, File system error and other.

Hardware errors, Disks, processors, memory, network

Conclusion: Both Hardware and Software failures have to be considered

A few definitions

- Many types of faults: software error, hardware malfunction, memory corruption
- Many possible behaviors: silent, transient, unrecoverable
- Restrict to faults that lead to application failures
- This includes all hardware faults, and some software ones
- Will use terms *fault* and *failure* interchangeably

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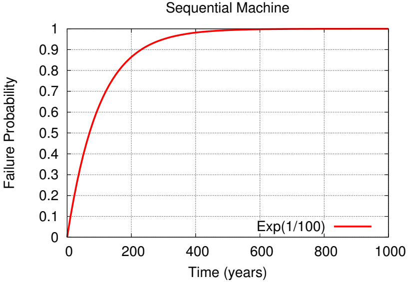
- First question: quantify the rate or frequency at which these faults strike!

Plan

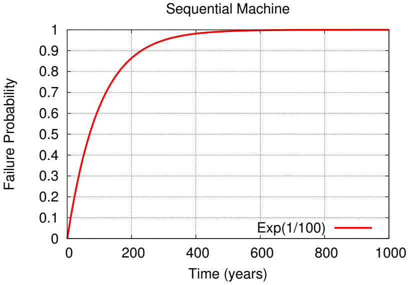
Failure distributions: (1) Exponential



Exp(λ): Exponential distribution law of parameter λ:

- Probability density function (pdf): $f(t) = \lambda e^{-\lambda t} dt$ for $t \geq 0$
- Cumulative distribution function (cdf): $F(t) = 1 - e^{-\lambda t}$
- Mean: $\mu = \frac{1}{\lambda}$

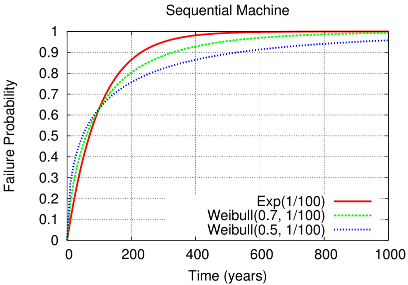
Failure distributions: (1) Exponential



X random variable for $Exp(\lambda)$ failure inter-arrival times:

- $\mathbb{P}(X \leq t) = 1 - e^{-\lambda t} dt$ (by definition)
- Memoryless property: $\mathbb{P}(X \geq t + s \,|\, X \geq s) = \mathbb{P}(X \geq t)$ (for all $t, s \geq 0$): at any instant, time to next failure does not depend upon time elapsed since last failure
- Mean Time Between Failures (MTBF) $\mu = \mathbb{E}(X) = \frac{1}{\lambda}$

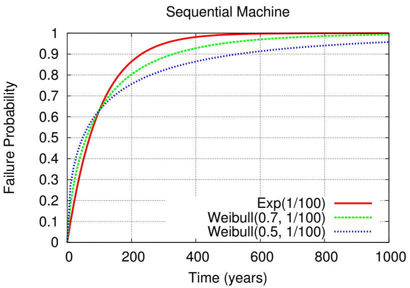
Failure distributions: (2) Weibull



Weibull(k, λ): Weibull distribution law of shape parameter k and scale parameter λ:

- Pdf: $f(t) = k\lambda(t\lambda)^{k-1}e^{-(\lambda t)^k}dt$ for $t \geq 0$
- Cdf: $F(t) = 1 - e^{-(\lambda t)^k}$
- Mean: $\mu = \frac{1}{\lambda}\Gamma(1 + \frac{1}{k})$

Failure distributions: (2) Weibull



X random variable for $Weibull(k, \lambda)$ failure inter-arrival times:

- If $k < 1$: failure rate decreases with time
  "infant mortality": defective items fail early
- If $k = 1$: $Weibull(1, \lambda) = Exp(\lambda)$ constant failure time

Failure distributions: (3) with several processors

- Processor (or node): any entity subject to failures
  $\Rightarrow$ approach agnostic to granularity

- If the MTBF is μ with one processor,
  what is its value with p processors?

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- Processor (or node): any entity subject to failures
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- If the MTBF is μ with one processor,
  what is its value with p processors?

- Well, it depends ☹

With rejuvenation

- Rebooting all p processors after a failure
- Platform failure distribution
  $\Rightarrow$ minimum of p IID processor distributions
- With p distributions $Exp(\lambda)$:

$$\min\left(Exp(\lambda_1), Exp(\lambda_2)\right) = Exp(\lambda_1 + \lambda_2)$$

$$\mu = \frac{1}{\lambda} \Rightarrow \mu_p = \frac{\mu}{p}$$

- With p distributions $Weibull(k, \lambda)$:

$$\min_{1..p}\left(Weibull(k, \lambda)\right) = Weibull(k, p^{1/k}\lambda)$$

$$\mu = \frac{1}{\lambda}\Gamma(1 + \frac{1}{k}) \Rightarrow \mu_p = \frac{\mu}{p^{1/k}}$$

Without rejuvenation (= real life)

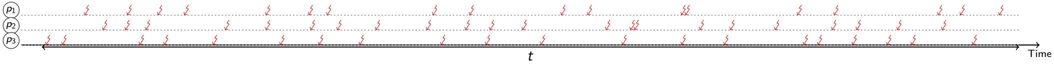
- Rebooting only faulty processor
- Platform failure distribution
  $\Rightarrow$ superposition of p IID processor distributions
  $\Rightarrow$ IID only for Exponential
- Define μ_p by

$$\lim_{F \to +\infty} \frac{n(F)}{F} = \frac{1}{\mu_p}$$

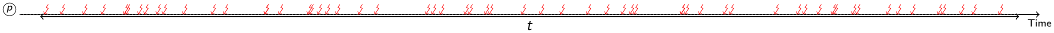
$n(F)$ = number of platform failures until time F is exceeded

Theorem: $\mu_p = \dfrac{\mu}{p}$ for arbitrary distributions

Intuition



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



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

Theorem: $\mu_p = \frac{\mu}{p}$ for arbitrary distributions

With one processor:

- $n(F)$ = number of failures until time F is exceeded
- X_i iid random variables for inter-arrival times, with $\mathbb{E}(X_i) = \mu$
- $\sum_{i=1}^{n(F)-1} X_i \leq F \leq \sum_{i=1}^{n(F)} X_i$
- Wald's equation: $(\mathbb{E}(n(F)) - 1)\mu \leq F \leq \mathbb{E}(n(F))\,\mu$
- $\lim_{F \to +\infty} \frac{\mathbb{E}(n(F))}{F} = \frac{1}{\mu}$

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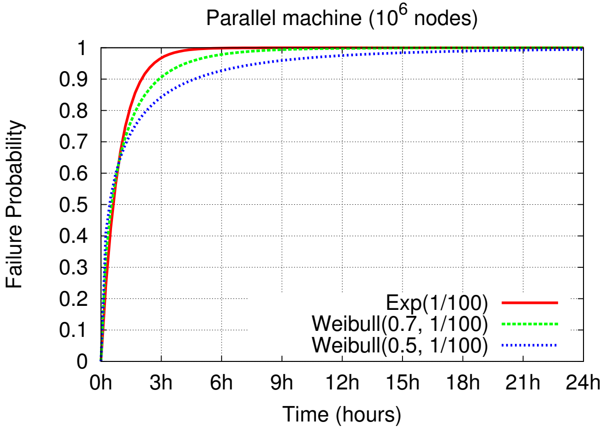
With p processors:

- $n(F)$ = number of platform failures until time F is exceeded
- $n_q(F)$ = number of those failures that strike processor q
- $n_q(F) + 1$ = number of failures on processor q until time F is exceeded (except for processor with last-failure)
- $\lim_{F\to+\infty} \frac{n_q(F)}{F} = \frac{1}{\mu}$ as above
- $\lim_{F\to+\infty} \frac{n(F)}{F} = \frac{1}{\mu_p}$ by definition
- Hence $\mu_p = \frac{\mu}{p}$ because $n(F) = \sum_{q=1}^{p} n_q(F)$

Values from the literature

- MTBF of one processor: between 1 and 125 years
- Shape parameters for Weibull: $k = 0.5$ or $k = 0.7$
- Failure trace archive from INRIA (http://fta.inria.fr)
- Computer Failure Data Repository from LANL (http://institutes.lanl.gov/data/fdata)

Does it matter?



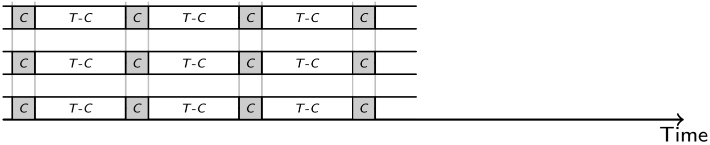
After infant mortality and before aging,
instantaneous failure rate of computer platforms is almost constant

Summary for the road

- MTBF key parameter and $\mu_p = \frac{\mu}{p}$ ☺
- Exponential distribution OK for most purposes ☺
- Assume failure independence while not (completely) true ☹

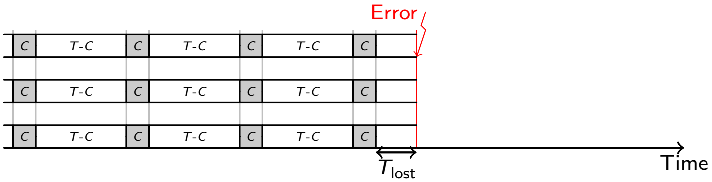
Plan

Periodic checkpointing, definitions



- Periodic checkpointing policy of period T
- Time to checkpoint C
- Time lost in case of a failure T_{lost}
- Downtime D
- Time for recovery R

Periodic checkpointing, definitions



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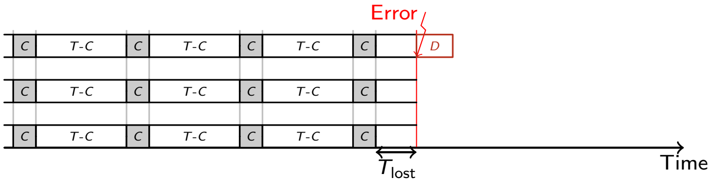

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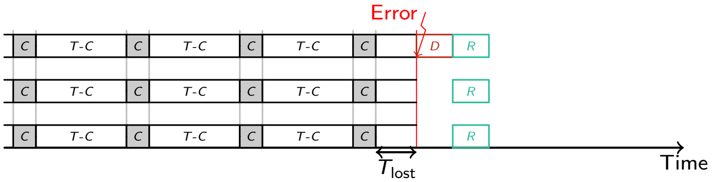

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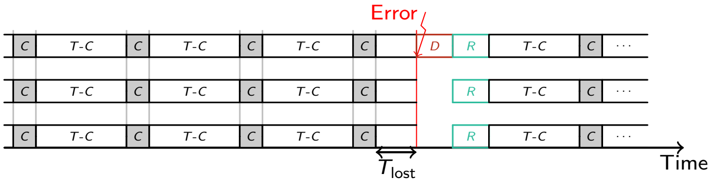

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Motivational example (1)

Strategies

1. Only one checkpoint at the end of the execution;
2. Three checkpoints during the execution, after every 10 minutes of work;
3. Five checkpoints during the execution, after every 6 minutes of work.

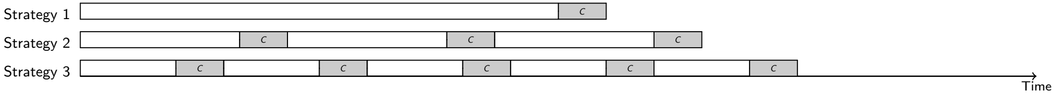
Scenarios

(A) A large time between faults (in this example, no fault during the execution);

(B) A medium time between faults (only one fault at the 19th minute);

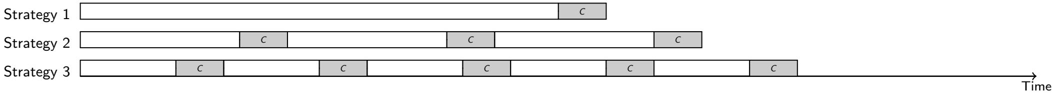
(C) A small time between faults (one fault at the 19th, 42th , and 62th minutes.).

Motivational example (2)



Large MTBF: there are no or very few faults. Checkpointing is too expensive. The first strategy wins.

Motivational example (2)



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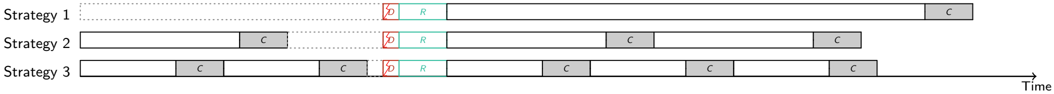
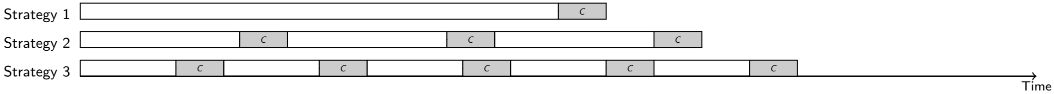


Medium MTBF: there are more faults. It is good to checkpoint, but not too frequently, because of the corresponding overhead. The second strategy wins.

Motivational example (2)



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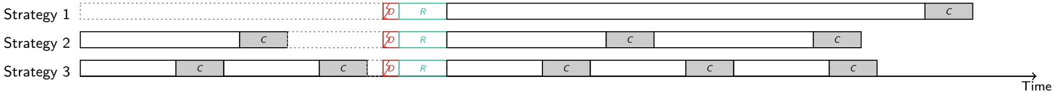

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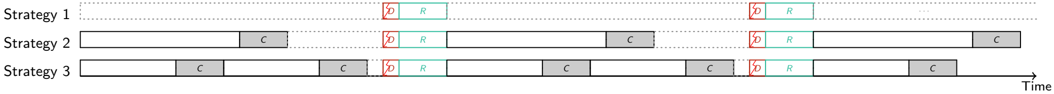


Small MTBF: there are many faults. The cost of the checkpoints is paid off because the time lost due to faults is dramatically reduced. The third strategy wins.

Optimization objective

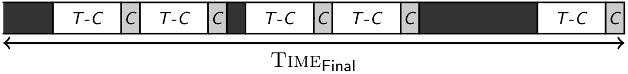
Waste: Fraction of time not spent for useful computations. If an application needs $\textsc{Time}_{\mathsf{base}}$ volume of compute, and the final execution time is $\textsc{Time}_{\mathsf{final}}$:

$$\textsc{Waste} = \frac{\textsc{Time}_{\mathsf{Final}} - \textsc{Time}_{\mathsf{base}}}{\textsc{Time}_{\mathsf{Final}}}$$

Equivalent to minimizing $\textsc{Time}_{\mathsf{Final}}$: $(1 - \textsc{Waste})\textsc{Time}_{\mathsf{Final}} = \textsc{Time}_{\mathsf{base}}$, but more convenient (get rid of notion of Time, and end of computation).

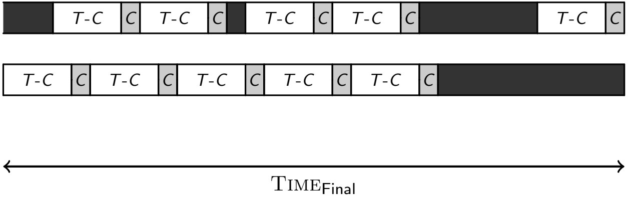
Plan

Waste?



An execution. Black intervals correspond to work destroyed by faults, downtimes, and recoveries.

Waste?



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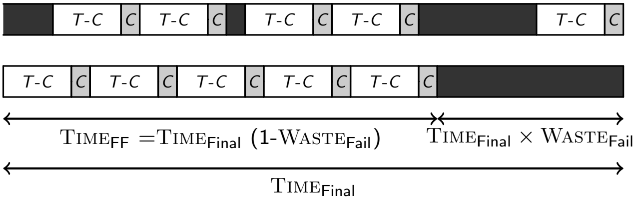

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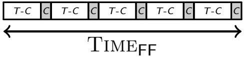
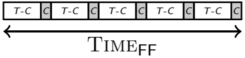
Waste in a fault-free execution



- $\text{TIME}_{\text{base}}$: application base time
- TIME_{FF}: with periodic checkpoints but failure-free

$$\text{TIME}_{\text{FF}} = \text{TIME}_{\text{base}} + \#checkpoints \times C$$

Waste in a fault-free execution



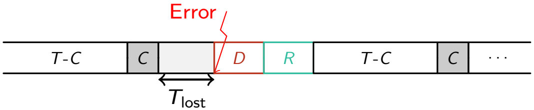
- $\textsc{Time}_{\mathsf{base}}$: application base time
- $\textsc{Time}_{\mathsf{FF}}$: with periodic checkpoints but failure-free

$$\textsc{Time}_{\mathsf{FF}} = \textsc{Time}_{\mathsf{base}} + \#checkpoints \times C$$

$$\#checkpoints = \left\lceil \frac{\textsc{Time}_{\mathsf{base}}}{T - C} \right\rceil \approx \frac{\textsc{Time}_{\mathsf{base}}}{T - C} \text{ (valid for large jobs)}$$

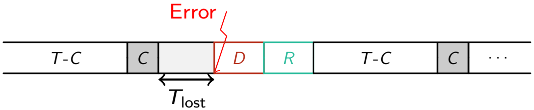
$$\textsc{Waste}_{\mathsf{FF}} = \frac{\textsc{Time}_{\mathsf{FF}} - \textsc{Time}_{\mathsf{base}}}{\textsc{Time}_{\mathsf{FF}}} = \frac{C}{T}$$

Waste due to failures



$$\text{TIME}_{\text{Final}} = \text{TIME}_{\text{FF}} + N_{\text{faults}}\,(T_{\text{lost}} + D + R)$$

Waste due to failures

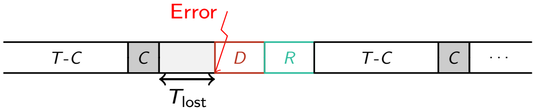


$$\text{TIME}_{\text{Final}} = \text{TIME}_{\text{FF}} + N_{\text{faults}}\,(T_{\text{lost}} + D + R)$$

$$\text{TIME}_{\text{Final}} = \text{TIME}_{\text{FF}} + \frac{\text{TIME}_{\text{Final}}}{\mu}\,(T/2 + D + R)$$

$\Rightarrow$ Instants when periods begin and failures strike are independent

Waste due to failures



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$$\text{WASTE}_{\text{Fail}} = \frac{\text{TIME}_{\text{Final}} - \text{TIME}_{\text{FF}}}{\text{TIME}_{\text{Final}}} = \frac{1}{\mu}\,(T/2 + D + R)$$

Total waste

$$\text{Waste} = \frac{\text{Time}_{\text{Final}} - \text{Time}_{\text{base}}}{\text{Time}_{\text{Final}}}$$

Reminder

- $\text{Time}_{\text{base}}$: application base time
- Time_{FF}: with periodic checkpoints but failure-free
- $\text{Time}_{\text{Final}}$: final time

$$1 - \text{Waste} = (1 - \text{Waste}_{\text{FF}})(1 - \text{Waste}_{\text{Fail}})$$

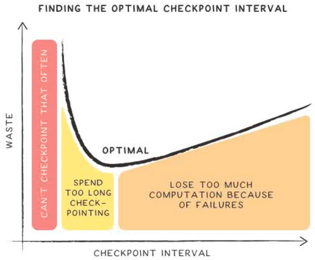
$$\text{Waste} = \frac{C}{T} + \left(1 - \frac{C}{T}\right)\frac{1}{\mu}\left(D + R + \frac{T}{2}\right)$$

Waste is minimized for

$$T = \sqrt{2(\mu - (D + R))C}$$

WRAP UP

- Capping periods, and enforcing a lower bound on MTBF $\Rightarrow$ mandatory for mathematical rigor ☹
- Not needed for practical purposes ☺
  - actual job execution uses optimal value
  - account for multiple faults by re-executing work until success
- Approach surprisingly robust ☺



Plan

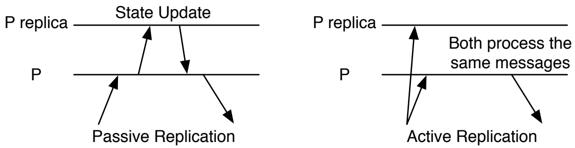
Your time to work

- Back to your thesis
- Saving periodically is a pain: you get interrupted in important paragraphs and then lose your train of thoughts.
- You would rather save at the end of sections.
- Let's assume you know how many sections you are going to write, and what their sizes are going to be.

- Propose a model for this new problem
- Solve it!

Plan

Replication

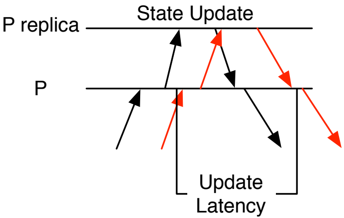


Idea

- Each process is replicated on a resource that has small chance to be hit by the same failure as its replica
- In case of failure, one of the replicas will continue working, while the other recovers
- Passive Replication / Active Replication

Passive Replication

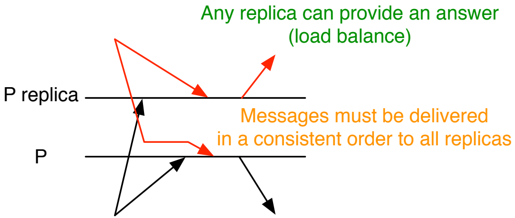
Replication



Challenges

- Passive replication: latency of state update
- Active replication: ordering of decision → internal additional communications

Replication

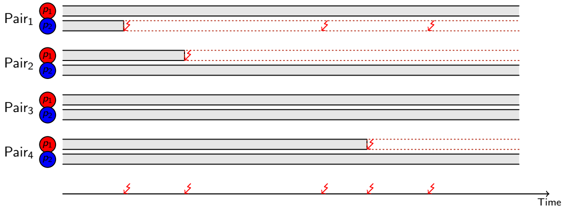


Challenges

- Passive replication: latency of state update
- Active replication: ordering of decision → internal additional communications

Plan

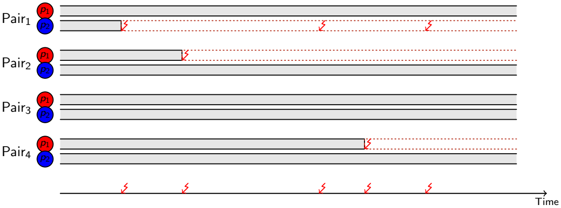
Modeling replication



Processor pairs for replication: each blue processor is paired with a red processor and they do the same work.

- How do you write the job model?
- How do you write the objective function?
- How do you compare to the checkpoint strategy?

Modeling replication



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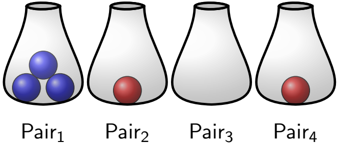

Modeling the state of the platform as a balls-into-bins problem. Colors of balls are important: $\neq$ birthday problem!

Conclusion

This was not a class about resilience but a class about scheduling ☺. If you are interested, still need to read about:

- Technical Protocols for resilience (dealing with messages etc)
- Different type of checkpointing (blocking v Asynchronous, coordinated v uncoordinated, hierarchical, in memory etc)
- Combining replication and checkpointing
- ABFT
- ...

You can see the Tutorial by Bosilca, Bouteiller, Hérault and Robert:
http://fault-tolerance.org/2018/11/09/sc18/