A Fast Restart Mechanism for Checkpointing in Networked Environments

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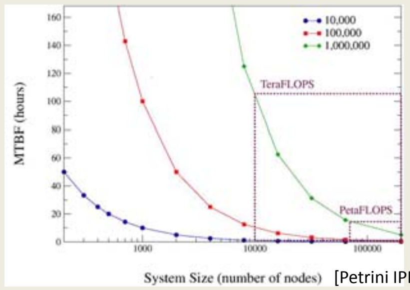
Outline

- Motivation
- FREM: a Fast REstart Mechanism
  - Design & implementation
- Experiments
- Summary

Reliability Crisis

- Failures are inevitable in large-scale systems
  - MTBF drops dramatically in large systems



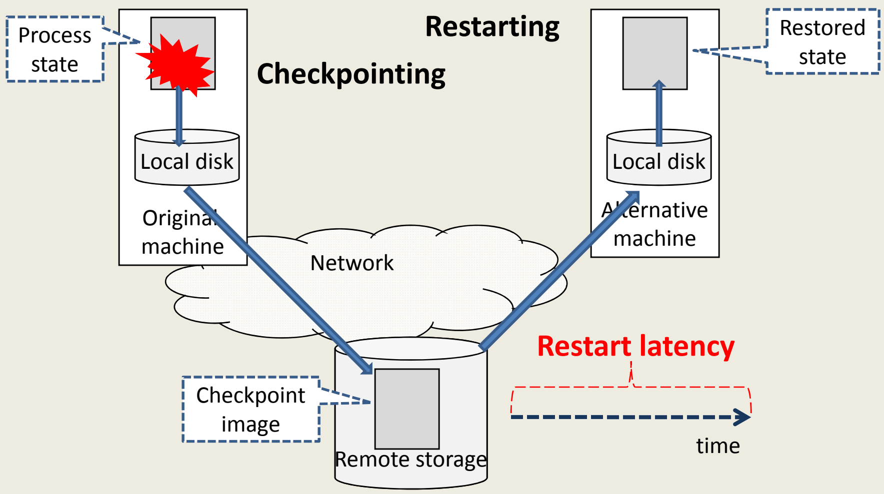
[Petrini IPDPS'04]

- Long-running programs are forced to restart more frequently

Checkpoint/Recovery

- C/R saves program state onto stable storage
  - Reduce rollback cost after restart
  - In networked systems, enable remote process restart on alternative resource
- C/R is not a silver bullet!
  - Extensive studies on reducing checkpointing overhead & determining an optimal frequency
  - Little work on optimizing its restart

An Illustrative Example

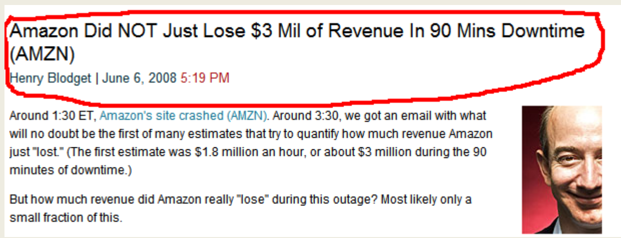


Problem Statement

- Currently, a restart requires the entire checkpoint image before it can proceed
  - Substantial restart latency in networked environments
  - Network transmission and I/O operation time
- Insatiable data demand from applications leads to larger checkpoint size
  - Thus, longer restart latency

The Pain of Restart Latency

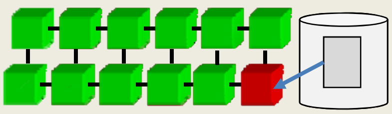
- Restart latency directly contributes to program downtime
  - Avail = (up time)/(up time + down time)


Amazon Did NOT Just Lose $3 Mil of Revenue In 90 Mins Downtime (AMZN)

Henry Blodget | June 6, 2008 5:19 PM

Around 1:30 ET, Amazon's site crashed (AMZN). Around 3:30, we got an email with what will no doubt be the first of many estimates that try to quantify how much revenue Amazon just "lost." (The first estimate was $1.8 million an hour, or about $3 million during the 90 minutes of downtime.)

But how much revenue did Amazon really "lose" during this outage? Most likely only a small fraction of this.



Parallel jobs make it worse:
all processes stall during restart!

FREM: A Fast REstart Mechanism

- Provide a quick restart through *latency hiding*
  - Overlapping process execution with checkpoint image retrieval
- Based on two key observations
  - Data locality: only a small portion of the checkpoint image is immediately needed after resurrection
  - Predictable pattern: data access patterns of restart from checkpoint can be known

Main Idea

1) Post-checkpoint tracking
   - Record the *touch set* following each CKP within the *tracking window*
     - Touch set: defined as the intersection of the process address space saved in the checkpoint and its working set
     - It shows which data is immediately needed for restart from the image file
2) Fast restarting
   - Restart the process as soon as the touch set is retrieved
   - Overlap the process execution with data retrieval of the remaining image

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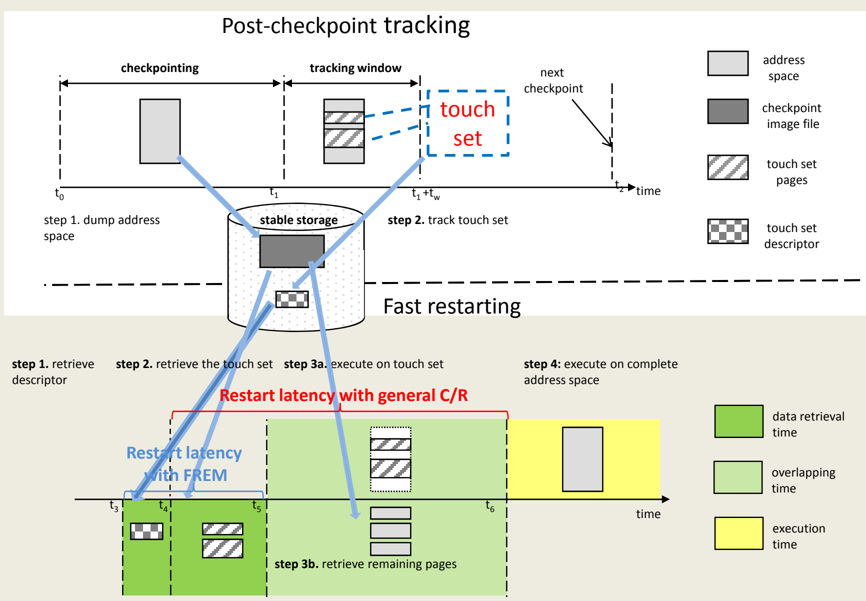

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Technical Challenges

1) How to accurately identify the touch set?
2) How to appropriately set the tracking window?
3) How to effectively load the partial image?

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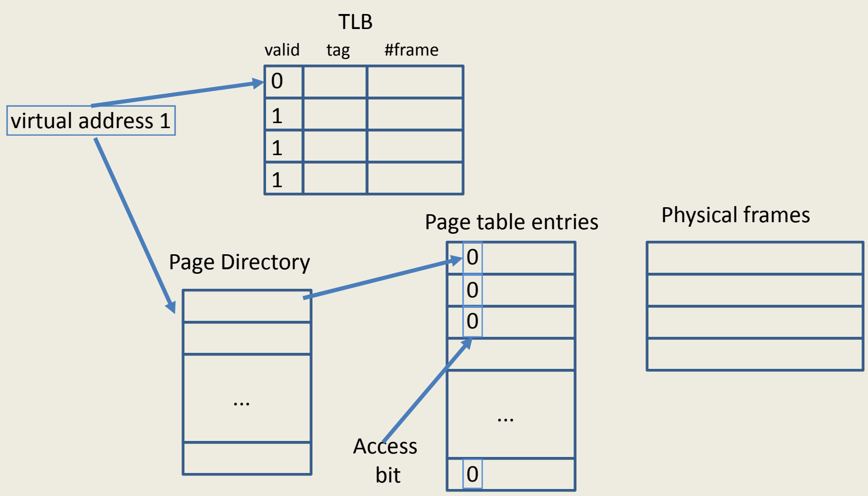
Identifying Touch Set

- Find out the data that is immediately needed for restart from the image file
- Two types of errors
  - False negative – a page of interest is missed
  - False positive – a page not interested is included
- Sources of inaccuracy:
  - Hardware bypassing, page swapping, dynamic memory usage

Hardware Bypassing – TLB

- TLB Miss: OK



Hardware Bypassing – TLB

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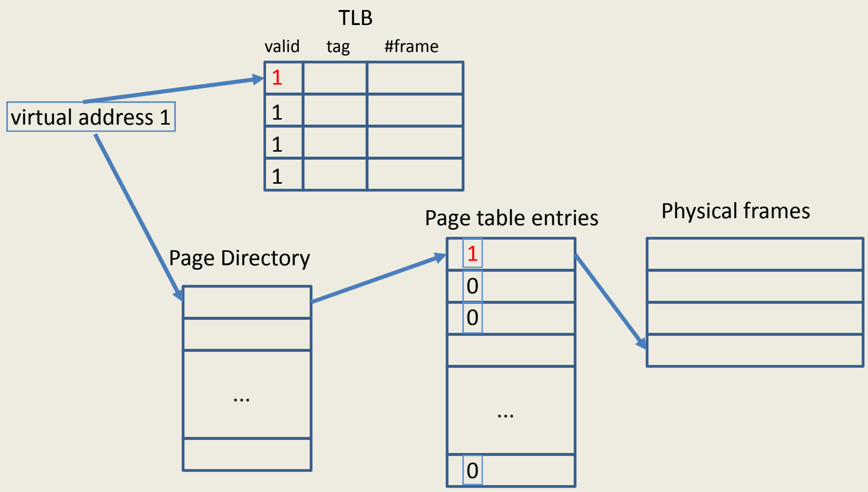

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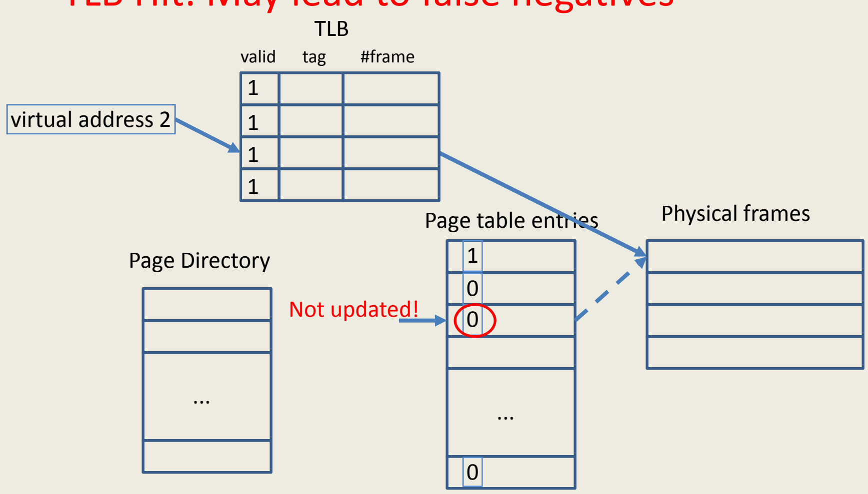
Hardware Bypassing – TLB

- TLB Hit: May lead to false negatives



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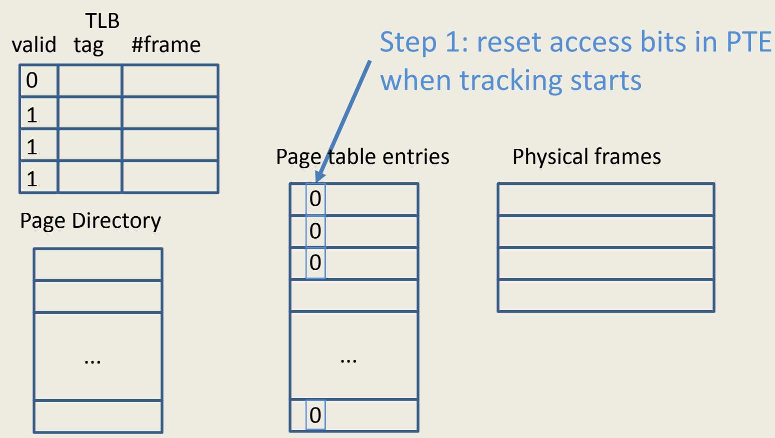
Hardware Bypassing – TLB

- Solution: invalidate TLB entry to enforce TLB miss



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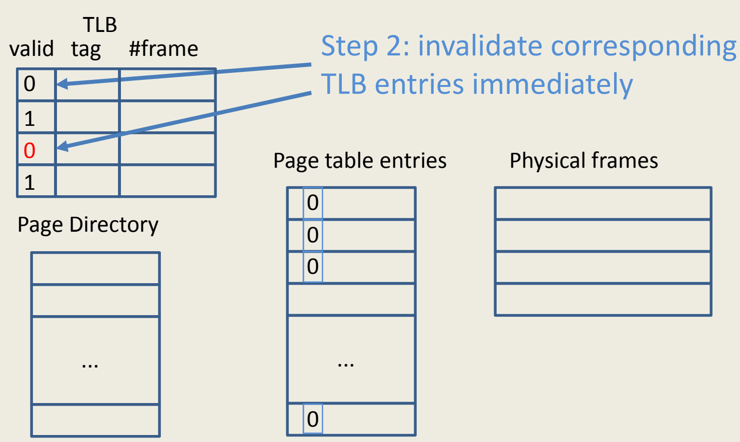


Hardware Bypassing – DMA

- Hardware devices access system memory for reading/writing independently of the CPU
  - Direct I/O, zero copy optimization

- Solution: include the mapped DMA pages in the touch set

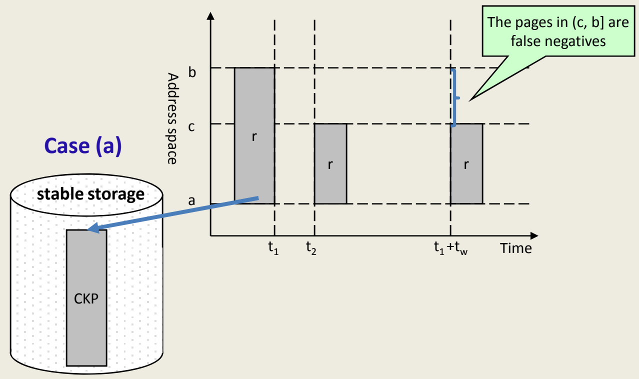
Page Swapping

- OS page swapping may cause false negatives
  - Page swapping algorithm clears the access bits when do the page table walk

- Solution: intercept *kswapd* to record the page per swapping

Dynamic Memory Usage

- Complications incurred by dynamic memory usage



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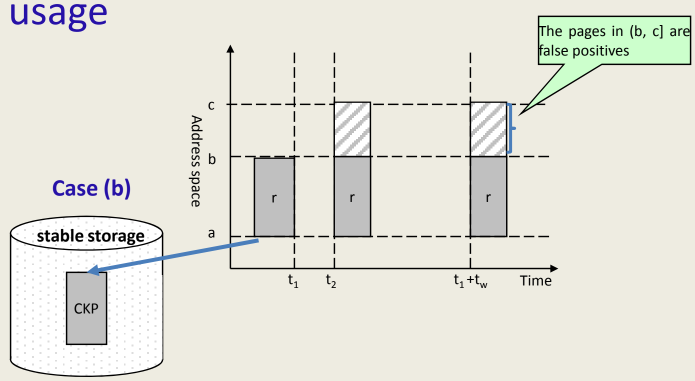

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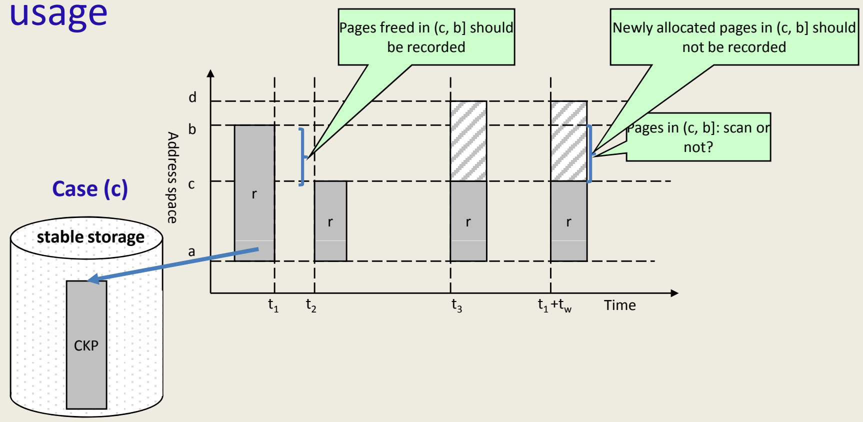


Dynamic Memory Usage

- Observation:
  - The touch set is always a subset of the checkpoint image, which monotonically decreases
- Solution
  - Record the pages saved in the checkpoint image as the *candidate pages*;
  - Intercept *do_munmap* to capture memory shrinking
  - Scan the intersection of the *candidate pages* and the pages to be freed
  - Update the *candidate pages* to exclude the intersection

Experiments

- A prototype implementation with the BLCR tool in Linux 2.6.22
  - Use a red-black tree for fast touch set tracking
  - Instrument the kernel in a non-intrusive way
- FREM-enhanced BLCR vs. BLCR
  - Evaluated with the SPEC CPU2006 suite
  - Two network settings

Network	Network Latency	Network Bandwidth
SLOW	200 ms	7MB/s
FAST	70 ms	32MB/s

Checkpoint image size

Restart latency

Application (input set)	W (MB)	Touch set size (MB)		RL with BLCR (s)		RL with FREM (s)	
		FAST	SLOW	FAST	SLOW	FAST	SLOW
1: astar (1)	280	34	44	49.4	80.1	6.0 (87.88%)	12.6 (84.26%)
2: bzip2 (5)	847	45	152	161.3	254.1	8.6 (94.64%)	45.6 (82.04%)
3: bzip2 (6)	609	64	244	109.3	176.0	11.5 (89.49%)	70.5 (59.97%)
4: dealII	239	12	28	31.0	57.2	1.6 (94.80%)	6.8 (88.13%)
5: gamess (1)	629	5	9	112.0	180.9	0.8 (99.28%)	2.6 (98.57%)
6: gcc (4)	311	48	82	53.4	87.6	11.6 (78.20%)	23.0 (73.75%)
7: gcc (6)	771	216	211	136.7	221.2	38.2 (72.05%)	60.6 (72.62%)
8: lbm	409	402	402	73.6	118.5	72.3 (1.80%)	116.3 (1.80%)
9: mcf	839	394	827	151.0	242.8	70.9 (53.03%)	239.5 (1.37%)
10: perl (1)	171	31	50	24.7	43.5	4.4 (82.16%)	12.8 (70.66%)
11: soplex (2)	490	186	191	89.3	142.9	33.9 (62.05%)	55.7 (61.06%)
12: wrf	685	37	346	117.8	192.9	54.5 (53.78%)	97.9 (49.25%)

Runtime Overhead during Post-Checkpoint Tracking (in milliseconds)

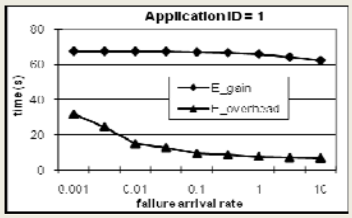
Application (input set)	Scan time	Search and insertion time	Descriptor I/O time	Tracking overhead
1: astar (1)	18.747	13.517	1.360	33.632
2: bzip2 (5)	48.790	0.257	0.184	49.231
3: bzip2 (6)	38.763	0.448	0.149	39.360
4: dealII	4.663	1.718	0.220	6.601
5: gamese (1)	36.711	1.678	0.298	38.687
6: gcc (4)	29.297	4.641	0.549	34.487
7: gcc (6)	43.734	14.954	1.488	60.176
8: lbm	21.832	0.462	0.119	22.413
9: mcf	3.390	0.175	0.161	34.234
10: perl (1)	18.573	13.630	1.350	33.553
11: soplex (2)	29.749	14.359	1.459	45.566
12: wrf	41.594	4.643	0.608	46.845

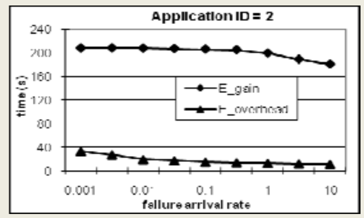
Runtime Overhead during Fast Restart (in seconds)

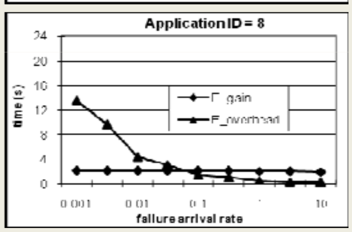
Application (input set)	Remaining image (MB)	Duration of overlapping	Fast restart overhead
1: astar (1)	162	19	7.1
2: bzip2 (5)	476	55	13.1
3: bzip2 (6)	250	48	11.8
4: dealII	144	14	10.2
5: gamese (1)	424	60	21.7
6: gcc (4)	157	19	10.6
7: gcc (6)	560	77	22.7
8: lbm	5	0.8	0.1
9: mcf	8	1.4	0.3
10: perl (1)	83	12	6.9
11: soplex (2)	205	30	4.8
12: wrf	231	35	7.8

Performance Evaluation

- statistically evaluate application performance between two restarts







E_{gain}= expected restart improvement between 2 restarts;
$E_{overhead}$=expected runtime overhead introduced between 2 restarts

Related Work

- Existing work on fast restart
  - OS, Database, Internet services, ...
  - *The novelty of FREM is its ability to reduce restart latency by recording data accesses after CKP*
- Traditional work on C/R
  - Focus on checkpoint optimization, e.g., determining an optimal checkpoint frequency
  - *FREM complements these studies*
- Demand paging
  - *FREM selectively restores the pages needed by tracking data access patterns*

Summary

- Have presented a novel mechanism for fast recovery of C/R applications
  - Through a user-transparent system support
- Have demonstrated its effectiveness
  - FREM can reduce process restart latency by 61.96% on average
- Future work
  - Adaptive tracking window estimation
  - Better image loading mechanism
  - Integration with checkpointing tools

Questions?

FENCE Project Website:

http://www.cs.iit.edu/~zlan/fence.html