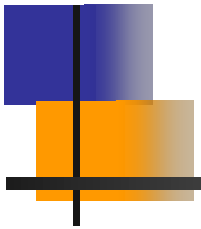
Do you have to reproduce the bug on the first replay attempt?



PRES: Probabilistic Replay with Execution Sketching on Multiprocessors

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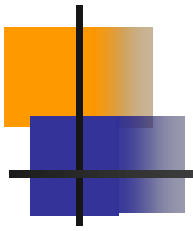
OPERA

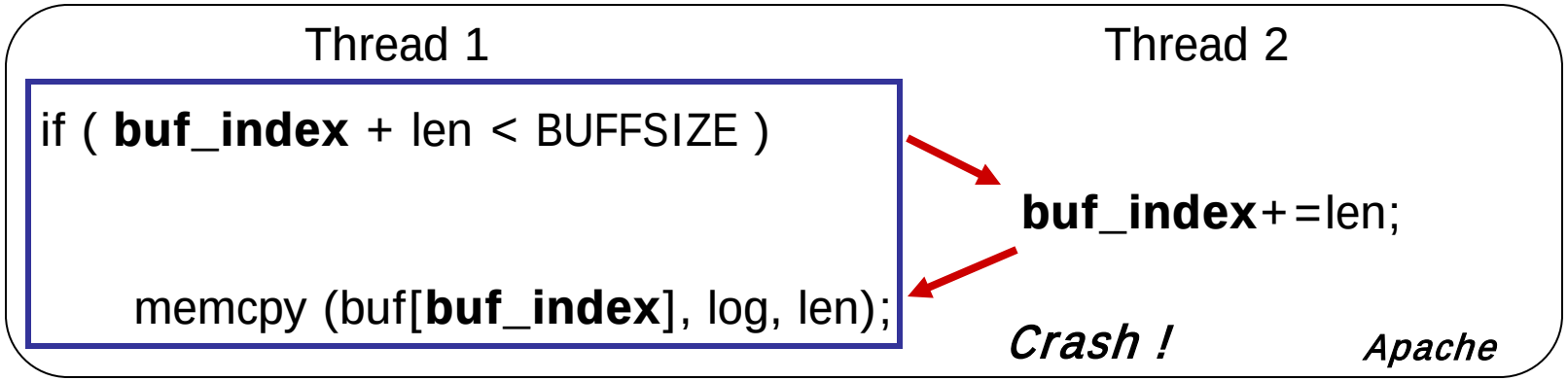


Concurrency bugs are important

- Writing concurrent program is difficult
  - Programmers are used to sequential thinking
  - → Concurrent programs are prone to bugs
- Concurrency bugs cause severe real-world problems
  - Therac-25, Northeast blackout
- Multi-core trend worsens the problem

Characteristics of Concurrency Bugs

- A concurrency bug may need a special thread interleaving to manifest

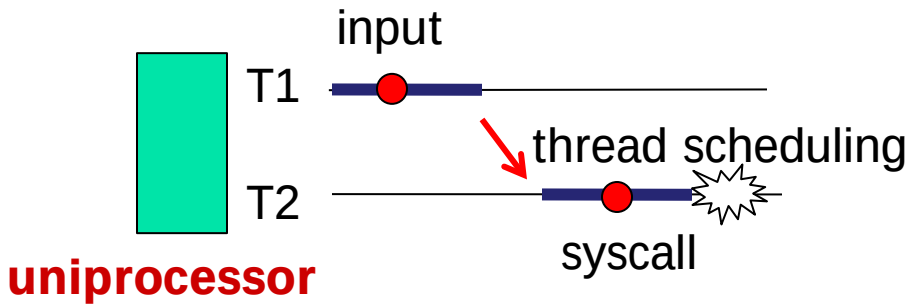


Two implications :

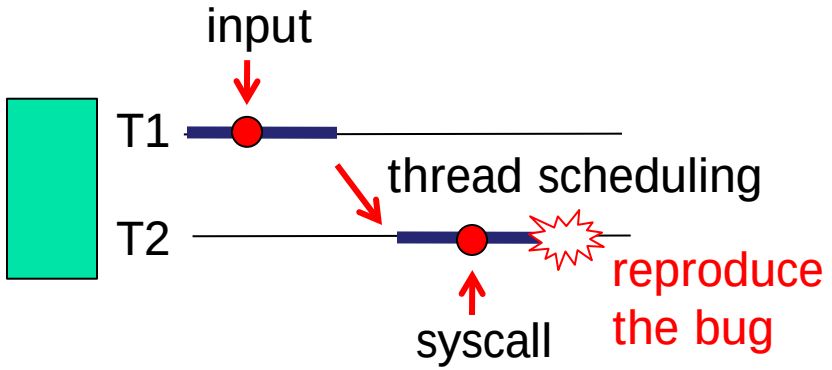
- Hard to expose a concurrency bug during testing
- Difficult to reproduce a concurrency bug for diagnosis

Deterministic Replay of Uniprocessor

- Recording non-deterministic factors and re-execution
  - Inputs (keyboards, networks, files, etc)
  - Thread scheduling
  - Return values of system calls



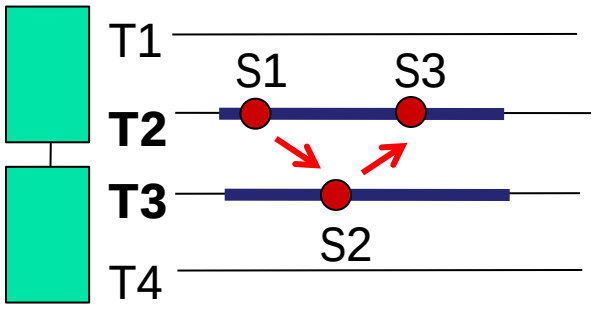
< Production run >



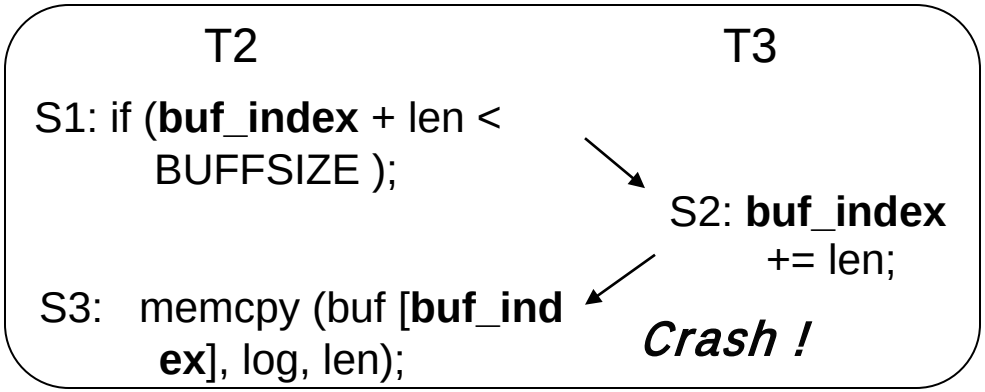
< Replay run >

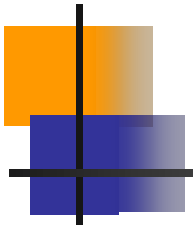
Deterministic Replay for Multiprocessors

- Much more difficult
  - Multi-threads execute simultaneously on different processors
- Extra source of non-determinism:
  - Interleaving of shared memory accesses



multiprocessor





State of the Art on Multiprocessor Replay

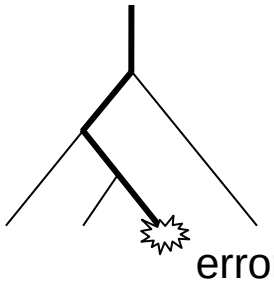
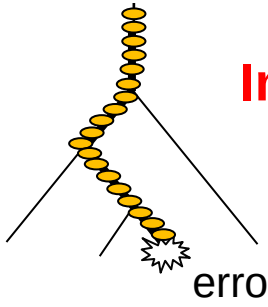
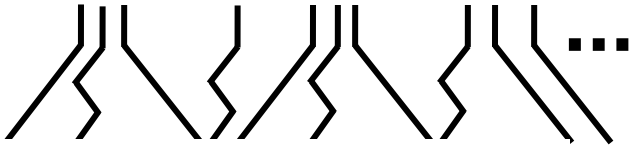
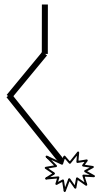
- Hardware-assisted approach
  - Recording all thread interactions with new hardware extension
    - ex) Flight Data Recorder, BugNet, Strata, RTR, DMP, Rerun, etc.

  ⇨ None of them exists in reality !

- Software-only approach
  - High production-run overhead (> 10-100X) ⇨ Not practical !
    - due to capturing the global order of shared memory accesses
    - ex) InstantReplay, Strata/s, etc.

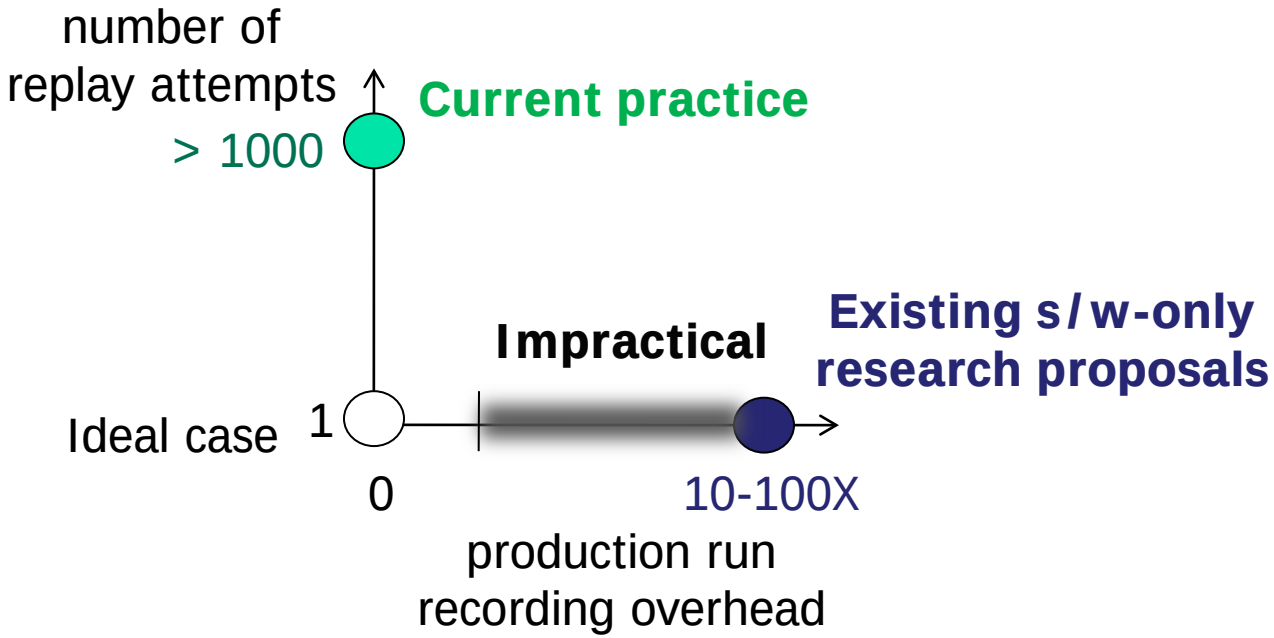
  - Recent work: SMP-Revirt
    - use page protection mechanism to optimize memory monitoring
    - >10X production-run overhead on 2 or 4 processors
    - has false sharing and page contention issues (scalability)

Contrast between Common Practice & Existing Research Proposals

	Common practice	Existing research proposals
Production run	 **0 %** overhead	 **10-100 X** slowdown
Diagnosis phase	 **>1000** replay attempts*	 the **1st** replay attempt

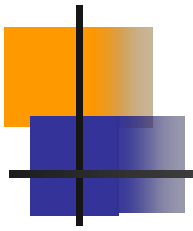
* : according to our experimental results

Observations



1) Production run performance is more critical than replay time

2) We do NOT need to reproduce a bug on the 1st replay attempt



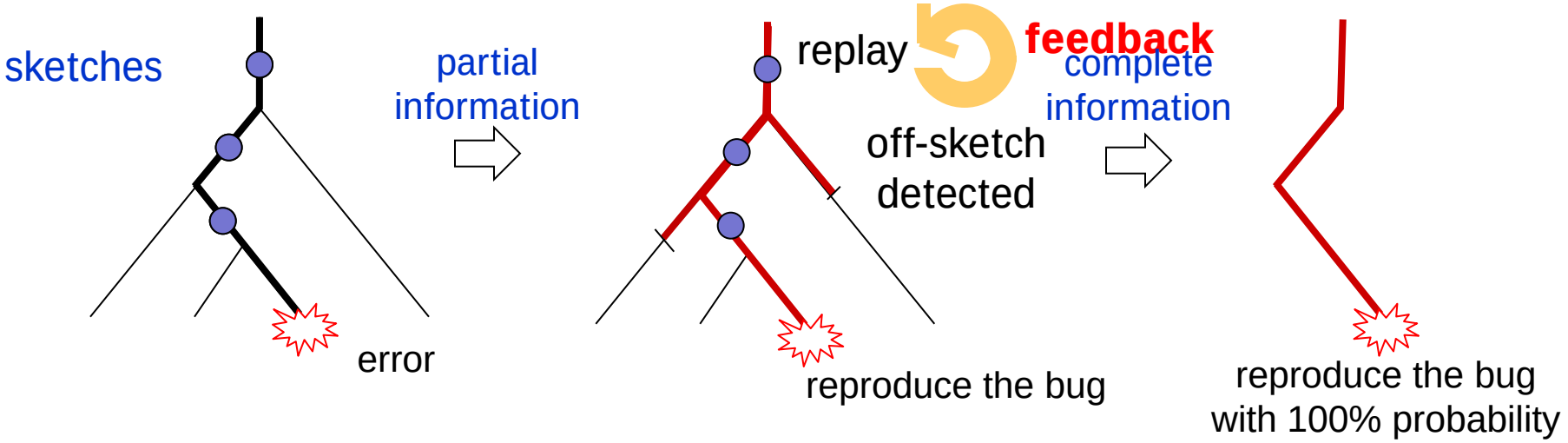
Our Idea

Probabilistic Replay with Execution Sketching (PRES)

- Record only partial information during production run
  ⇨ **Low recording overhead**
- Push the complexity to diagnosis time
- Leverage **feedback** from unsuccessful replays

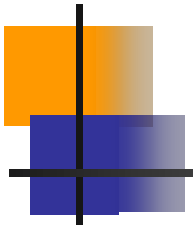
PRES Overview

- Probabilistic Replay via Execution Sketching (PRES)



Sketch recording during production run	Partial-Information based replay (PI-Replay)	Diagnosis phase

- Recording partial information (sketch) during production run
- Reproducing a bug, not the original execution



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  - Partial-Information based replayer
  - Monitor
  - Feedback generator
- Evaluation
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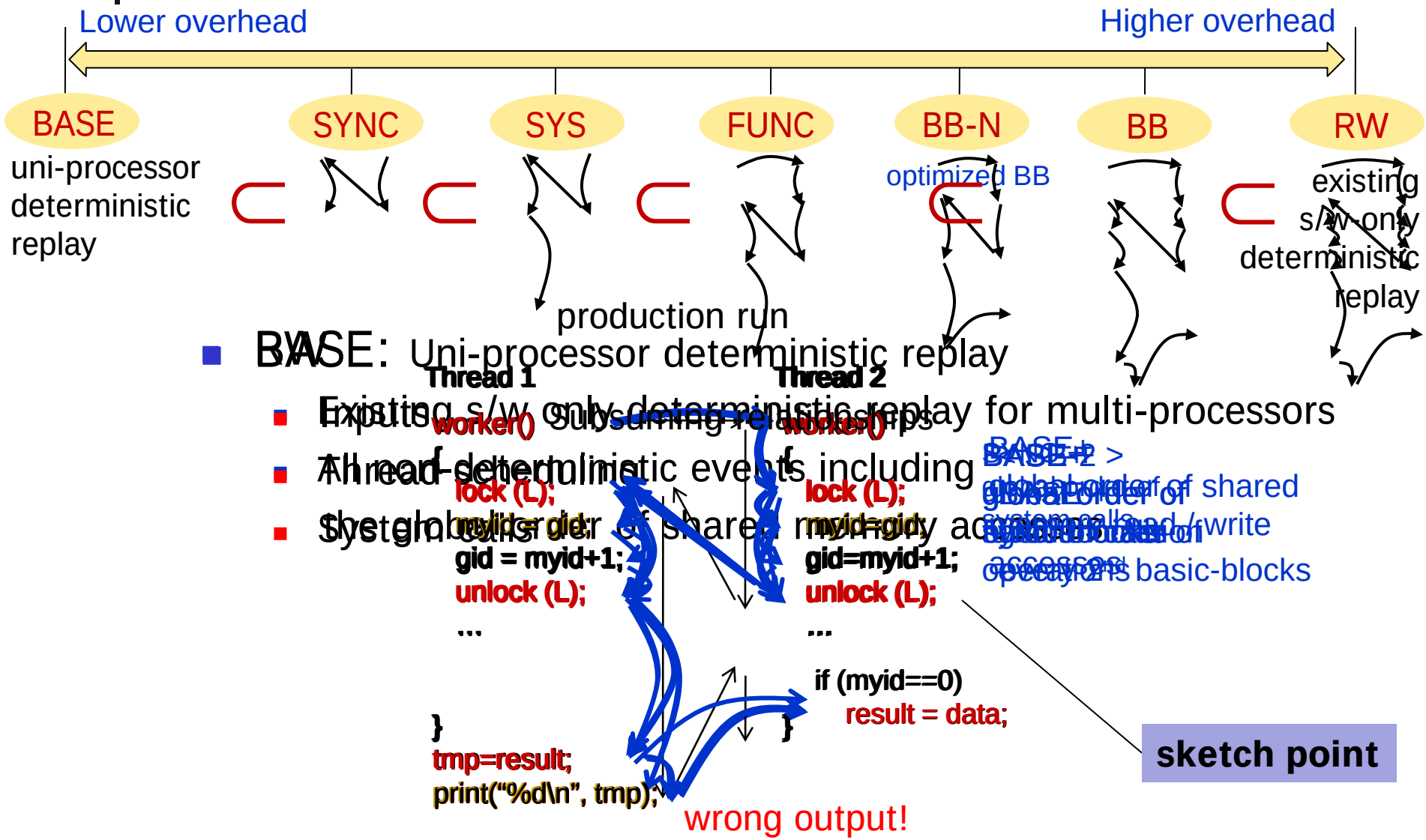
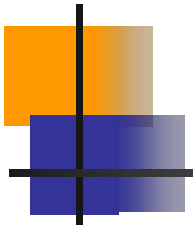
Sketch Recording





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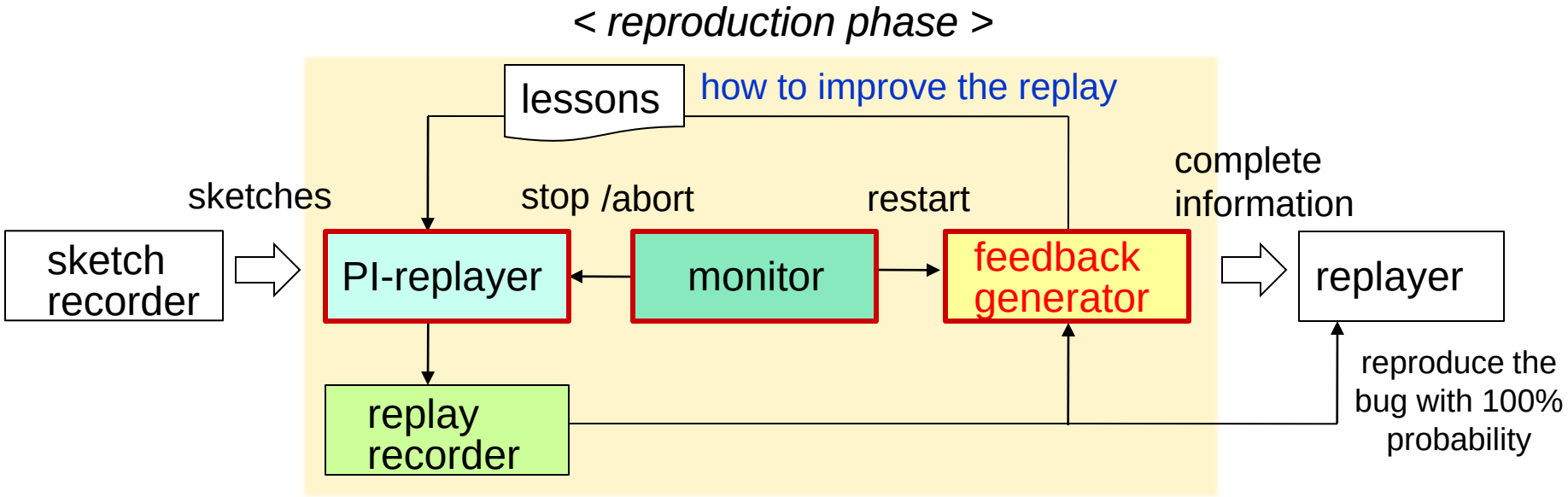
Partial Information-based Replay

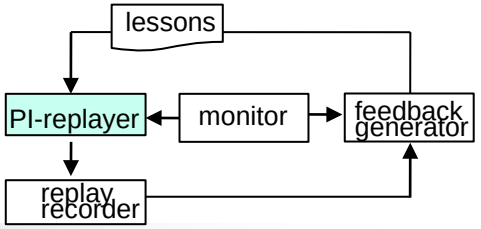
- Process of bug reproduction phase



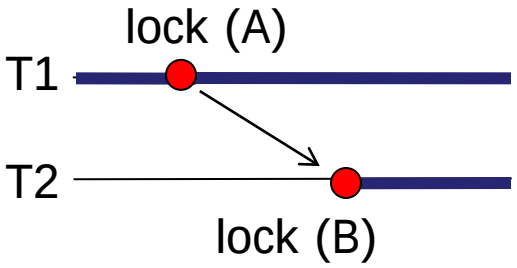
Monitor is used for:

- Detecting successful bug reproduction
- Detecting off-sketch path: deviates from sketches

PI-replayer

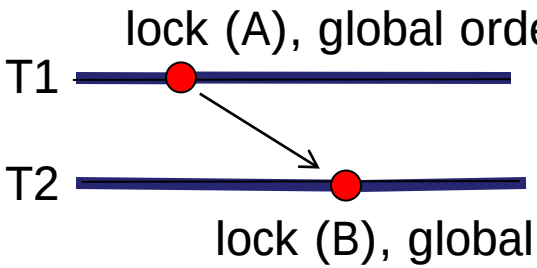


- Partial-Information based replayer
  - Consults the execution sketch to enforce observed global orders
  - Right before re-executing a sketch point, make sure that all prior points from other threads have been executed



< Production run >

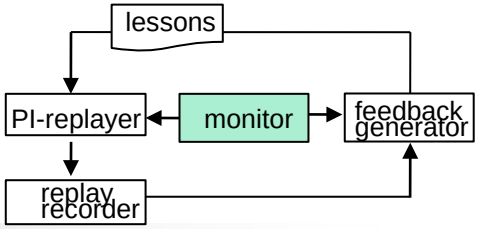
SYNC sketches
T1 : lock A, global order 1
T2 : lock B, global order 2



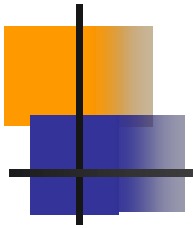
wait for T1 to execute lock A first

< Replay run >

Monitor



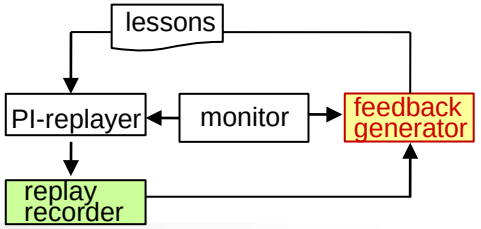
- Detect successful bug reproduction
  - Crash failure - PRES can catch exceptions
  - Deadlock - a periodic timer to check for progress
  - Incorrect results - programmer needs to provide conditions for checking
  - Can leverage testing oracles and existing bug detection tools
- Detect unsuccessful replay
  - Compare against the execution sketch from the original execution
  - Prevent from giving useless replay efforts on a wrong path



What if a replay attempt fails?

- Replay it again!
  - Restart from the beginning or the previous checkpoint
- Shall we do something different next time?
  - Random approach: just leave it to fate
  - Systematic approach
    - Actively learn from previous mistakes

Feedback Generator (1/2)



- Why previous replays cannot reproduce a bug?
  - Some un-recorded data races execute in different orders

Production run

```
Thread 1                    Thread 2
worker()                    worker()
{                           {
   …                           …
                               if (myid==0)
                                 result = data;
}                           }
tmp = result;
printf("%d\n", tmp);
```

1st replay attempt

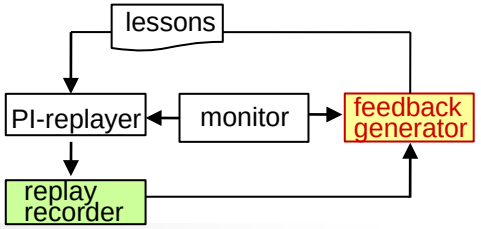
```
Thread 1                    Thread 2
worker()                    worker()
{                           {
   …                           …
}
tmp = result;               if (myid==0)
printf("%d\n", tmp);          result = data;
                            }
```

fail to reproduce the bug!

< FUNC sketches >

This original order is not recorded in the sketch

Feedback Generator (2/2)



- Steps

replay recorder

⇩ R/W traces

Identifying dynamic race pairs

⇩ initial candidates

Filtering order-determined races

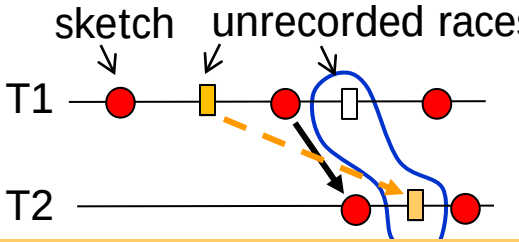
⇩ suspect races

Selecting suspect

⇩ one race

Starting next replay

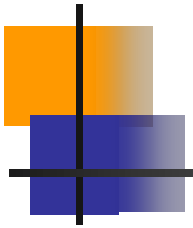
- use happens-before race detector



The race order is already implied by the order of sketch points

- close-to-failure-first, depth-first

- deterministically execute until the suspect race pair
- flip the race order



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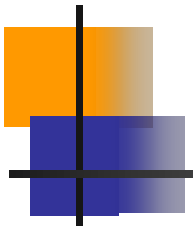


Methodology

- Implement PRES using Pin
- 8-core Xeon machine
- 11 evaluated applications
  - 4 server applications (Apache, MySQL, Cherokee, OpenLDAP)
  - 3 desktop applications (Mozilla, PBzip2, Transmission)
  - 4 scientific computing applications (Barnes, Radiosity, FMM, LU)
- 13 real-world concurrency bugs
  - 6 Atomicity violation bugs (single- and multi-variable bugs)
  - 4 Order violation bugs
  - 3 Deadlock bugs

Recording Overhead (1/2)

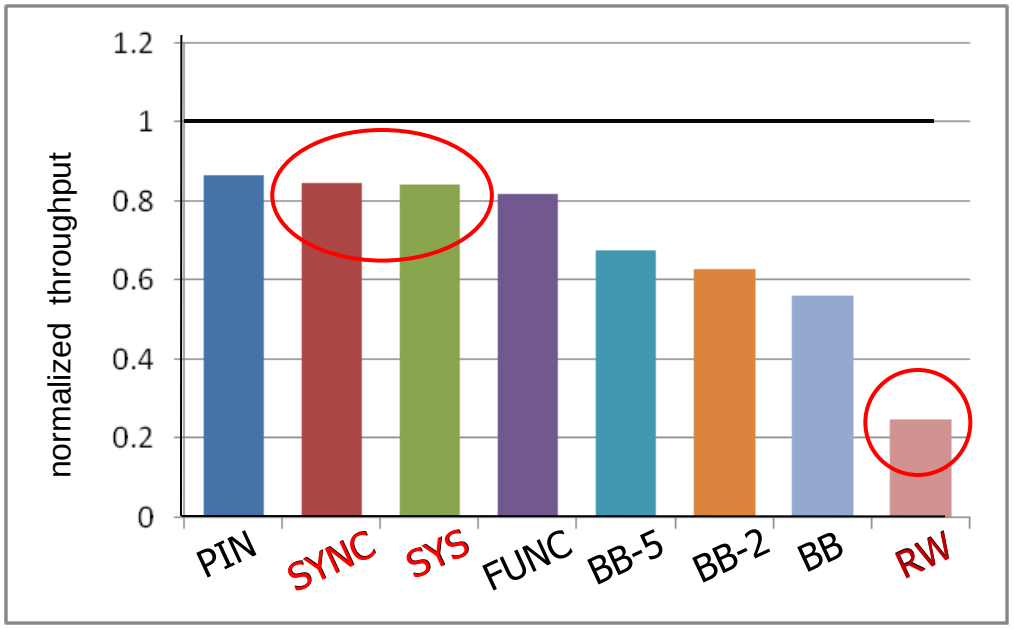
- Non-server applications

Application	PIN	SYNC	SYS	FUNC	BB-5	BB-2	BB	RW
			Desktop Applications (overhead %)					
Mozilla	32.5	59.5	60.6	83.8	598.0	858.8	1213.9	3093.5
PBZip2	17.4	**18.0**	**18.0**	18.4	595.4	1066.6	1977.9	**27009.7**
Transmission	5.9	14.5	21.3	32.7	30.3	33.9	41.9	71.8
			Scientific Applications (overhead %)					
Barnes	2.5	6.5	6.8	427.7	424.2	1122.3	2351.0	28702.2
Radiosity	16.0	16.1	16.1	779.0	480.3	1181.7	2425.5	27209.6

- RW : up to around 280 times slowdown
- SYNC, SYS : Good for performance critical applications
  - 6-60% overhead

Recording Overhead (2/2)

- Server application



MySQL

- SYNC, SYS : 3 times higher than RW throughput

Number of Replay Attempts

NO : not reproduced within 1000 tries

Appli-cation	Bug type	Base	SYNC	SYS	FUNC	BB-5	BB-2	BB	RW
			Server Applications						
Apache	Atom.	NO	96	28	7	8	7	1	1
MySQL	Atom.	NO	3	3	2	3	2	1	1
Cherokee	Atom.	NO	33	22	24	25	8	7	1
OpenLDAP	Deadlock	NO	1	1	1	1	1	1	1
			Desktop Applications						
Mozilla	Multi-v	NO	3	3	3	4	4	3	1
PBZip2	Atom.	NO	3	3	2	4	3	3	1
Transm.	Order	NO	2	2	2	2	2	2	1
			Scientific Applications						
Barnes	Order	NO	10	10	1	74	19	1	1
Radiosity	Order	NO	**NO**	**NO**	152	5	1	1	1

reproduce 12 out of 13 bugs mostly within 10 attempts

Reproduce all 13 bugs mostly within 5 attempts

Benefit of Feedback Generation

NO : not reproduced within 1000 tries

Application		SYNC	SYS	FUNC	BB-5	BB-2	BB
Apache	**w/**	96	28	7	8	7	1
	w/o	**NO**	**NO**	**NO**	**NO**	754	1
PBZip2	**w/**	3	3	2	4	3	3
	w/o	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Barnes	**w/**	10	10	1	74	19	1
	w/o	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**

- Low-overhead sketches (SYNC and SYS) can be used to reproduce concurrency bugs only because of our PI-replayer that leverages feedback

- The random approach does NOT work!

Effects of Race Filtering

The number of dynamic benign data races to be explored

Applications	BASE	SYNC	SYS	FUNC	BB-5	BB-2	BB
Apache	54390	1072	274	33	25	25	6
MySQL	39983	2	2	2	2	1	0
Cherokee	133	86	58	16	36	7	3
Mozilla	36258	317	310	14	72	60	42
PBZip2	667	326	318	1	7	4	4
Transmission	225	240	172	6	6	6	4

- Filters out the races whose order can be inferred from sketches
- Significantly shrinks the unrecorded non-deterministic space to be explored

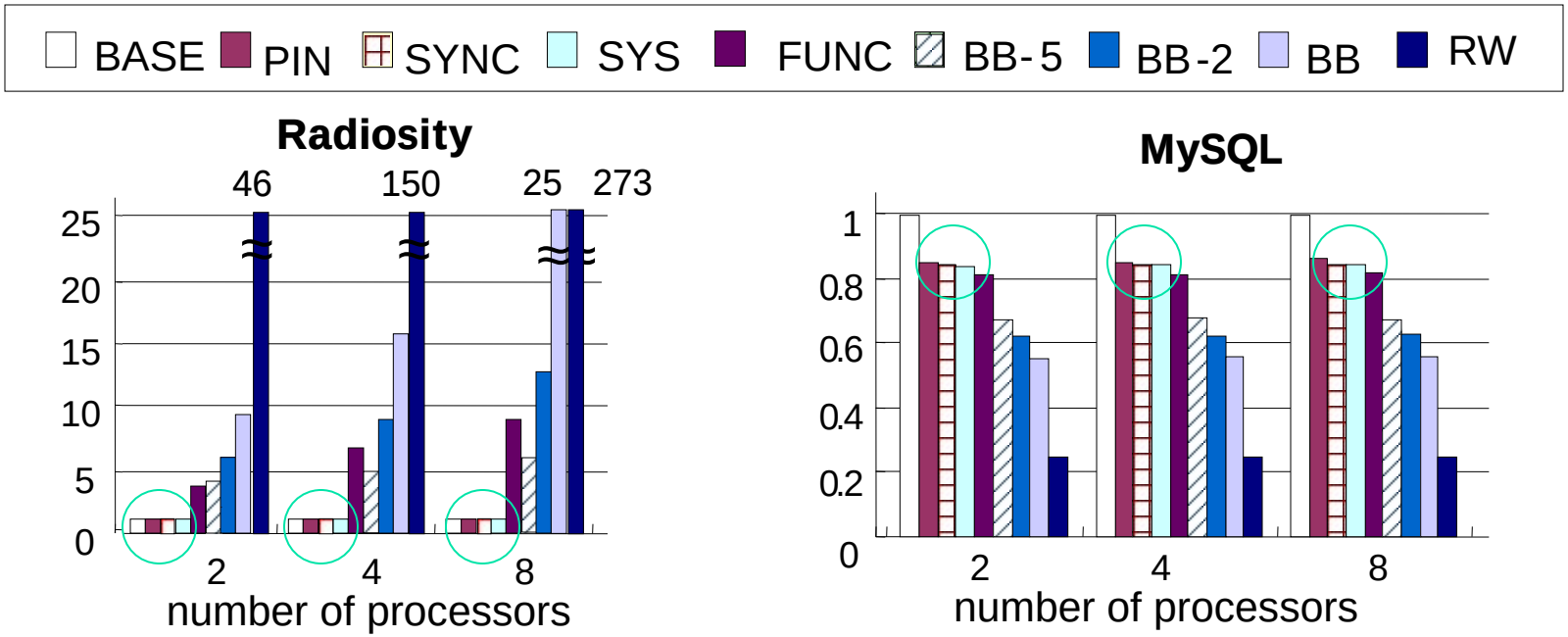
Bugs vs. Execution Reproduction

Application		SYNC	SYS	FUNC	BB-5	BB-2	BB
Mozilla	**BR**	3	3	3	4	4	3
	ER	**16**	**16**	4	4	4	3
PBZip2	**BR**	3	3	2	4	3	3
	ER	5	5	2	4	5	3

the number of replays for bug reproduction (BR)
vs. those for execution reproduction (ER)

- Reproducing the exact same execution path requires 1.6-5 times more attempts with SYS and SYNC

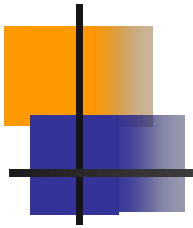
Scalability



Normalized elapse time
(the lower, the better)

Normalized throughput of a server application
(the higher, the better)

2-core : SYNC 6.2%, SYS 11.8%
(770% by SMP-Revirt)



Conclusions

- Software solutions can be practical for reproducing concurrency bugs on multiprocessor
- PRES: Probabilistic Replay via Execution Sketch
  - No need to reproduce the bug at the first attempt
  - Trade replay-time efficiency for lower recording overhead
  - PI-Replayer (that leverages feedback) makes low-overhead sketches (SYS, SYNC) useful for bug reproduction