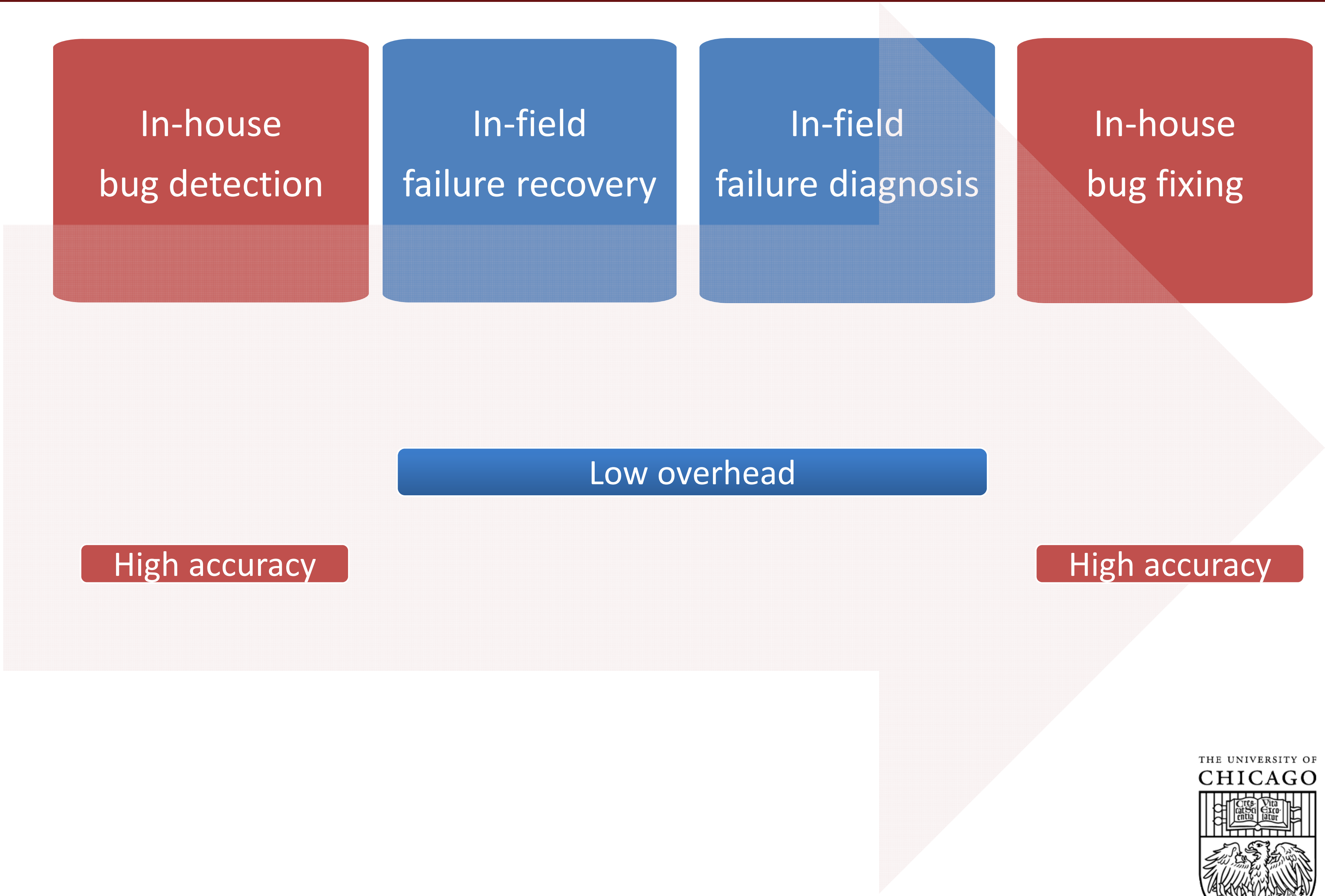
Production-Run Failures Diagnosis for Concurrency Bugs

Shan Lu

University of Chicago

Different aspects of fighting bugs

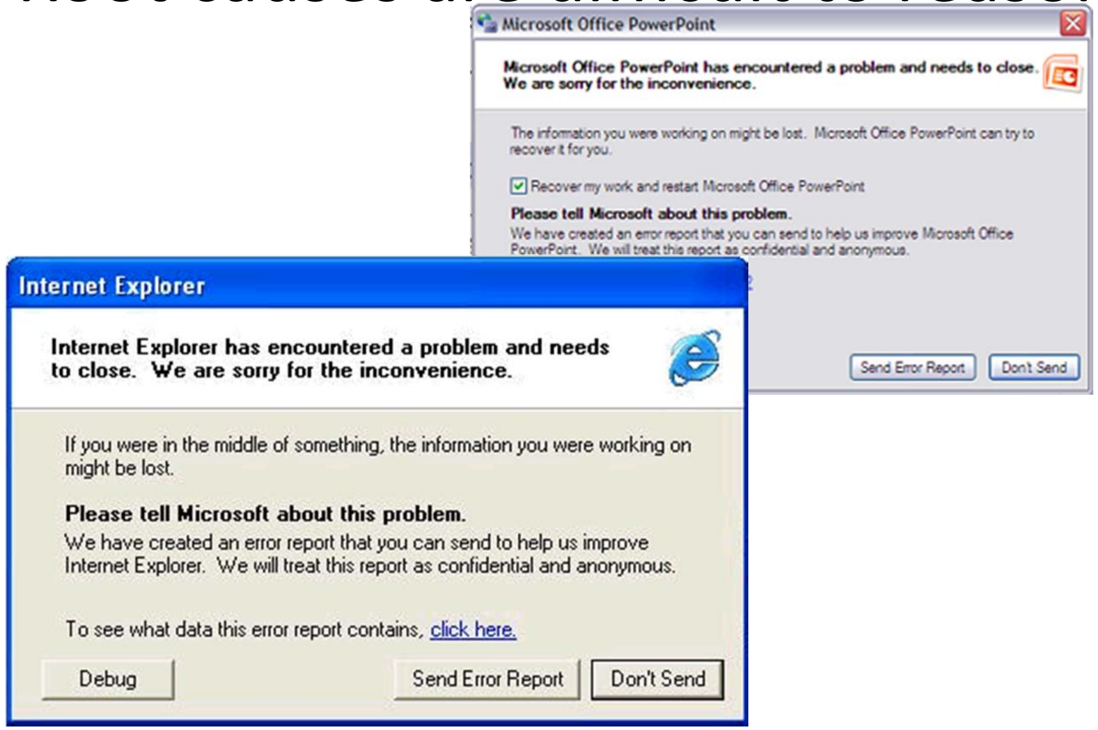


Slide 2

SL41 ideally, this should be a cycle, but ...
Shan Lu, 2014-1-7

Failure diagnosis is challenging

- Limited information
- Failures are difficult to repeat
- Root causes are difficult to reason about



Microsoft Office PowerPoint

Microsoft Office PowerPoint has encountered a problem and needs to close. We are sorry for the inconvenience.

The information you were working on might be lost. Microsoft Office PowerPoint can try to recover it for you.

☑ Recover my work and restart Microsoft Office PowerPoint

Please tell Microsoft about this problem.

We have created an error report that you can send to help us improve Microsoft Office PowerPoint. We will treat this report as confidential and anonymous.

Internet Explorer

Internet Explorer has encountered a problem and needs to close. We are sorry for the inconvenience.

If you were in the middle of something, the information you were working on might be lost.

Please tell Microsoft about this problem.

We have created an error report that you can send to help us improve Internet Explorer. We will treat this report as confidential and anonymous.

To see what data this error report contains, click here.

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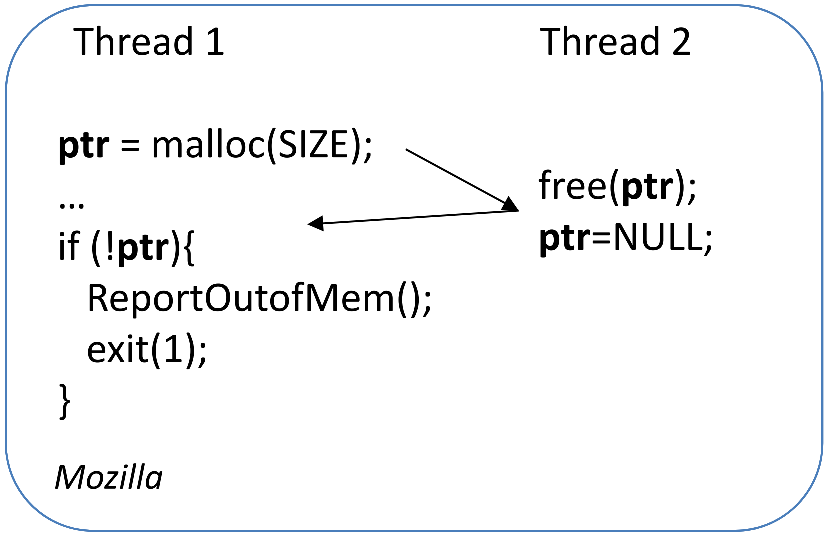
Slide 3

SL35 if i have time, i can turn these into developers quotes
Shan Lu, 2014-1-15

A15

Example



Thread 1

```
ptr = malloc(SIZE);
…
if (!ptr){
  ReportOutofMem();
  exit(1);
}
```

Thread 2

```
free(ptr);
ptr=NULL;
```

Mozilla

Slide 4

A15	i need to replace this with Joy's version Administratr, 2014-3-5

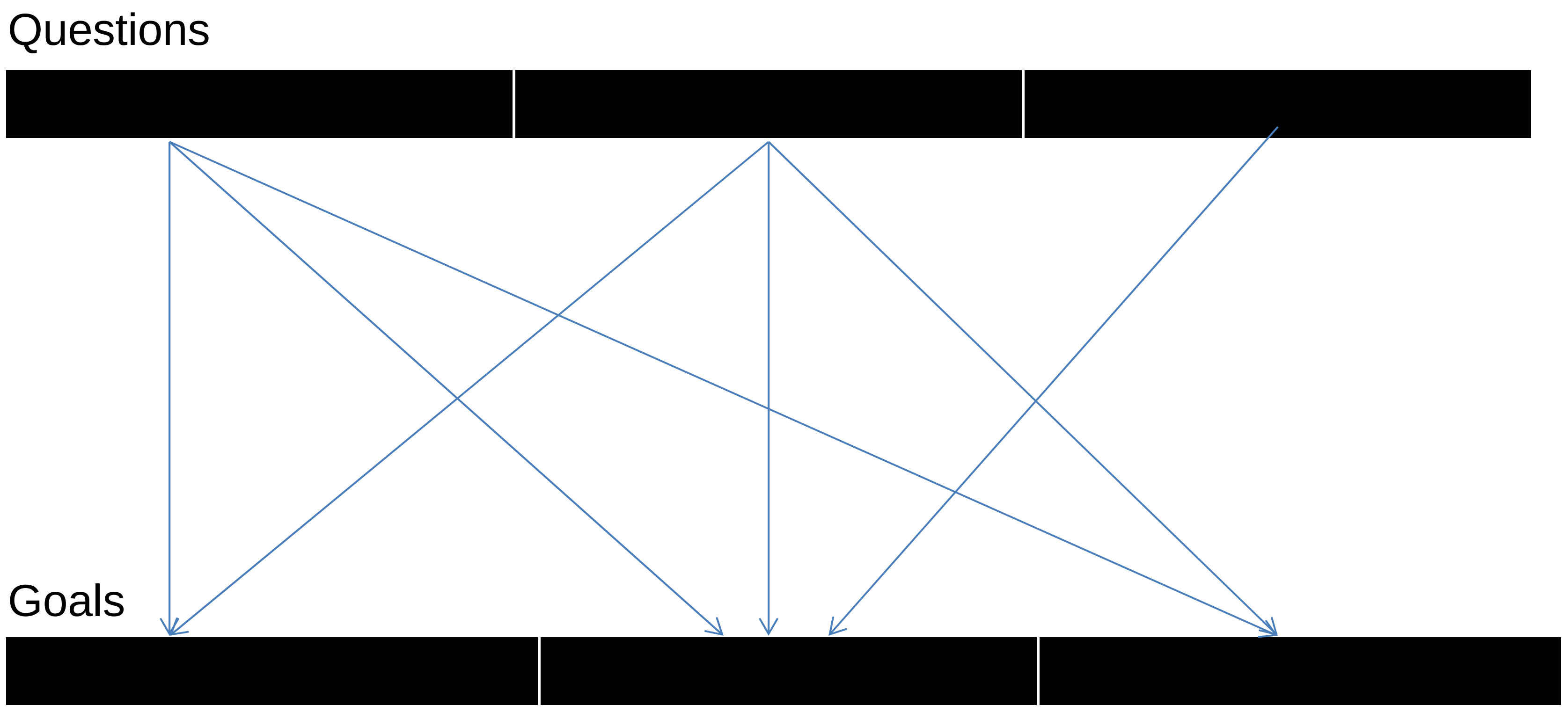
Example

```
InitState(...){
    table = New();


    if (table == NULL) {
        ReportOutOfMemory();
        return JS_FALSE;
    }
}


ReportOutOfMemory(){
  error("out of memory");
}
```

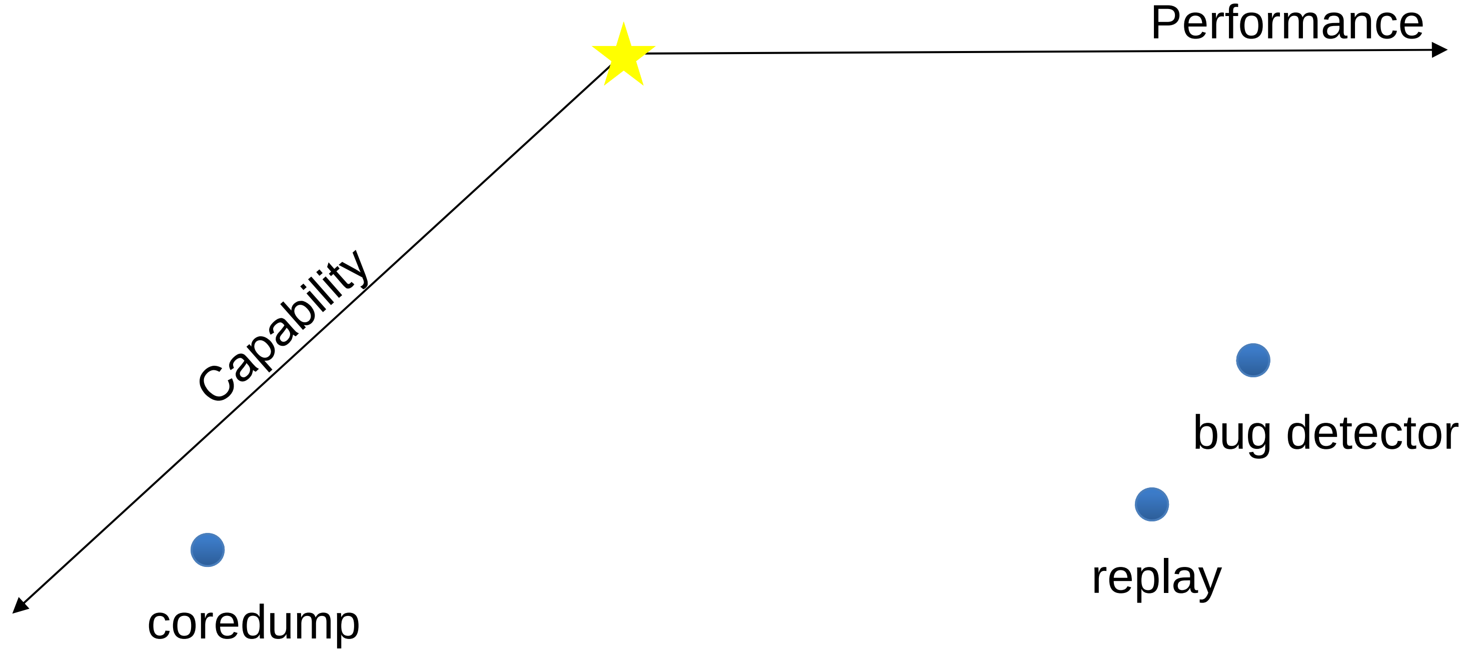
****.js*
out of memory

CALL STACK
ReportOutofMemory()
InitState()
…
main()

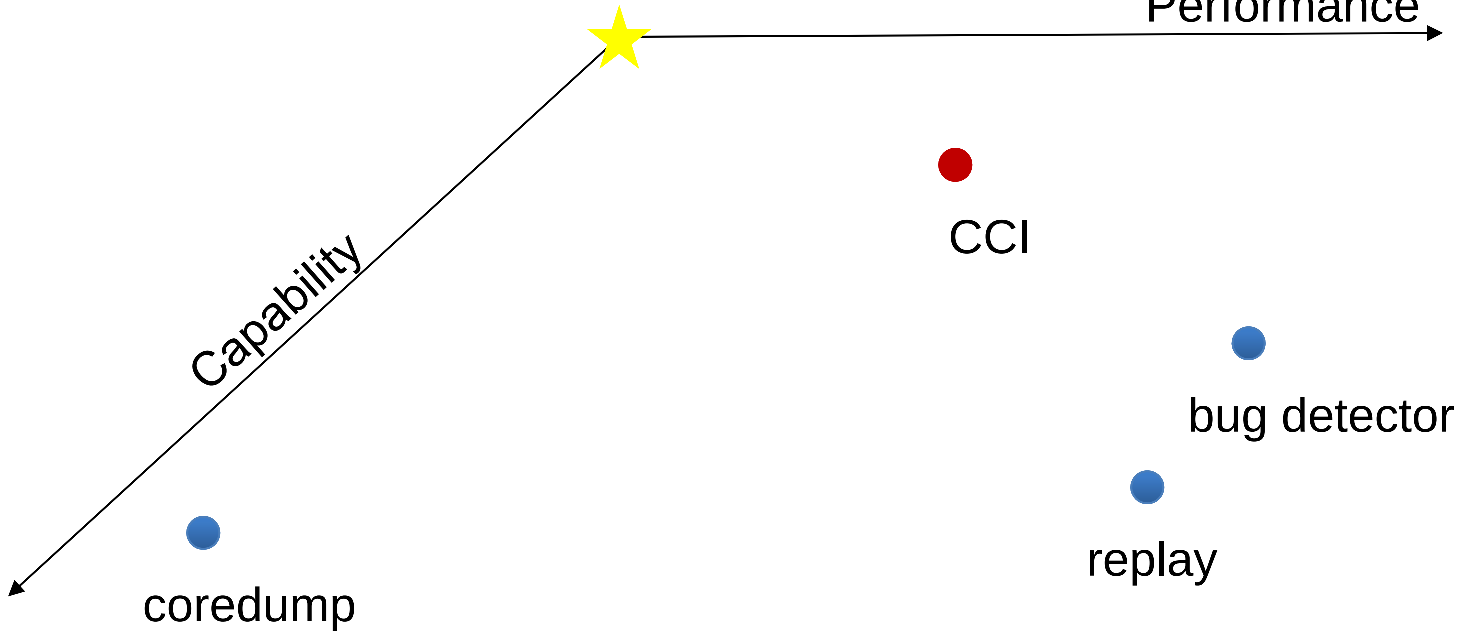
Design space



Previous work



Our work



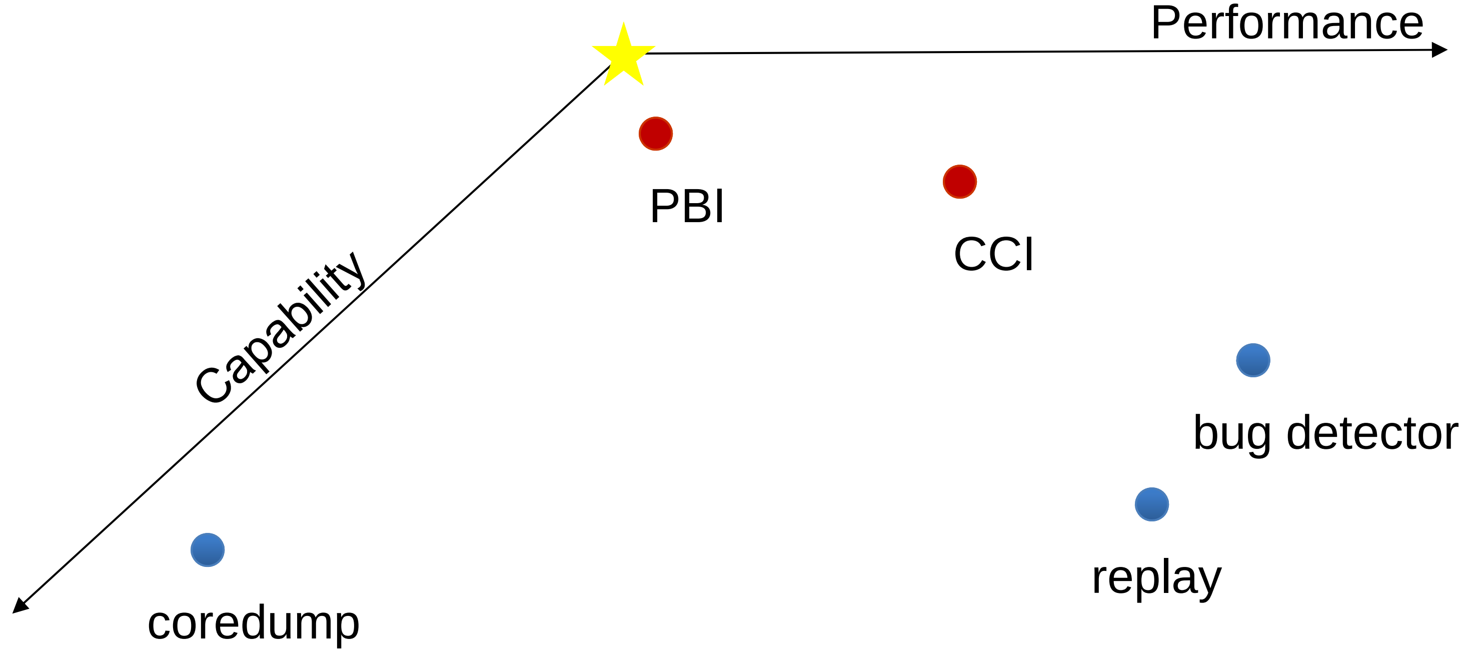
Slide 8

A14

simplify these. put
statistical approach, compiler, cause-pattern
hardware support
hardware extension, effect-pattern
in one text box, keep growing.

change the cloud shape. simplify both the slide and the script
Administratr, 2014-3-4

Our work

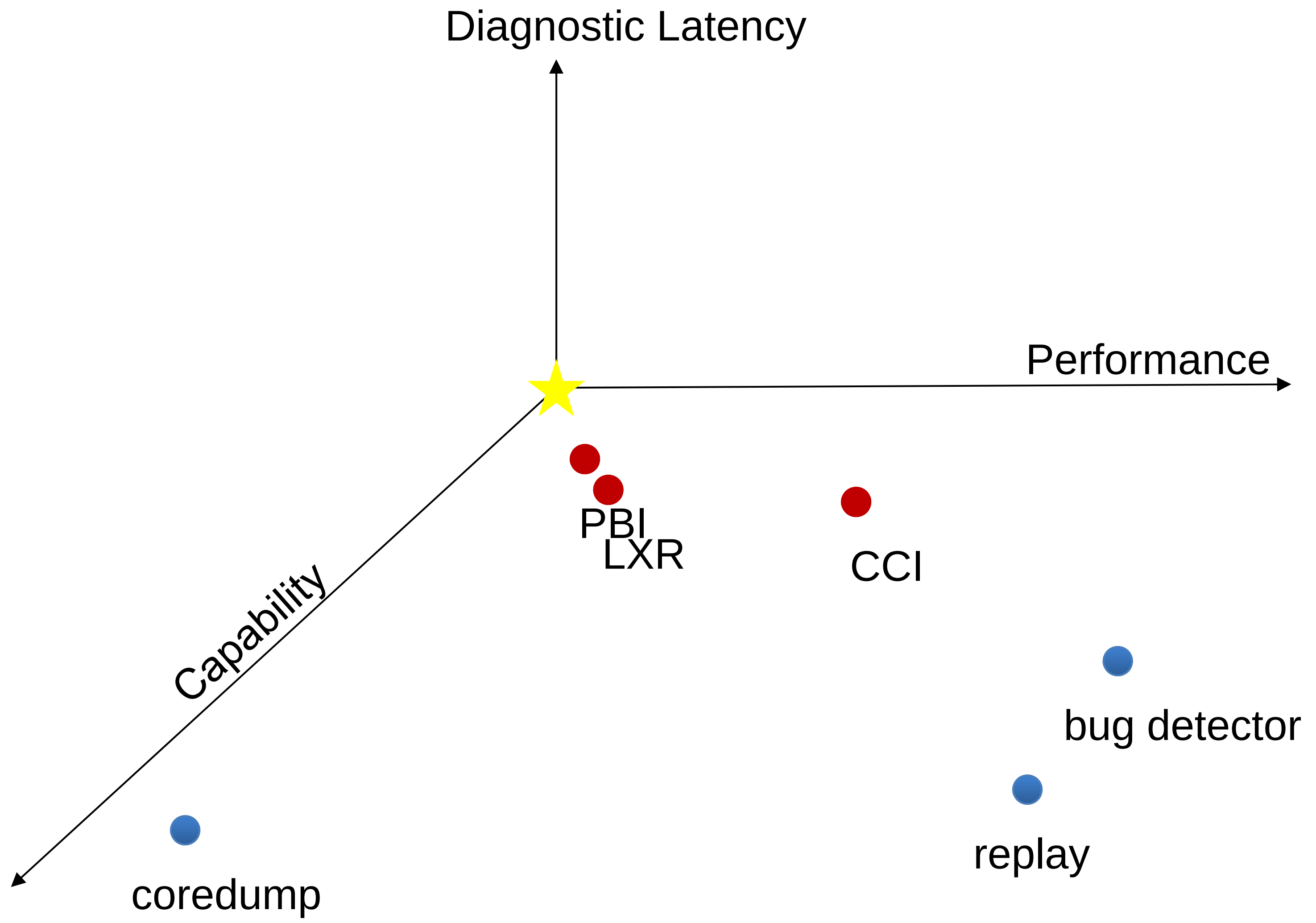

Performance
Capability
PBI
CCI
bug detector
replay
coredump

Slide 9

SL31 maybe i should put 4-d/3-d coordinates here, and change the tables following

Shan Lu, 2014-1-15

Our work


Diagnostic Latency
Performance
Capability
PBI
LXR
CCI
bug detector
replay
coredump

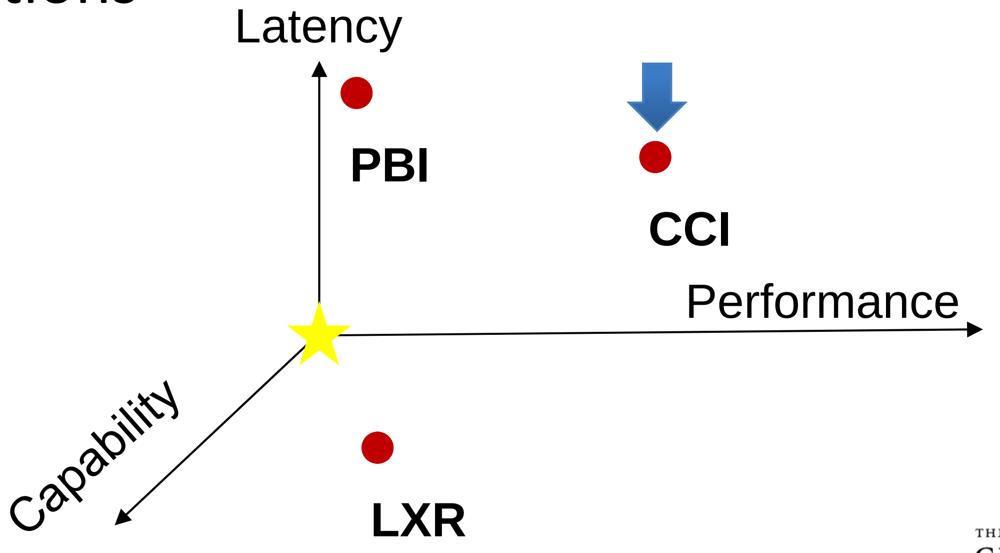
Slide 10

SL31 maybe i should put 4-d/3-d coordinates here, and change the tables following

Shan Lu, 2014-1-15

Outline

- Overview
- Production-run failure diagnosis
  - What is the problem
  - What are our solutions
- Conclusion



Slide 11

SL33 change the bullets texts. things like "compiler-based" is strange.
Shan Lu, 2014-1-15

How to do better than state-of-art?

What to collect	How to collect	How to use the collected

Performance	Capability	Latency

How to do better than state-of-art?

What to collect	How to collect	How to use the collected
	Sampling	

Performance	Capability	Latency

How to do better than state-of-art?

What to collect	How to collect	How to use the collected
	Sampling	Cooperative statistical analysis

Performance	Capability	Latency

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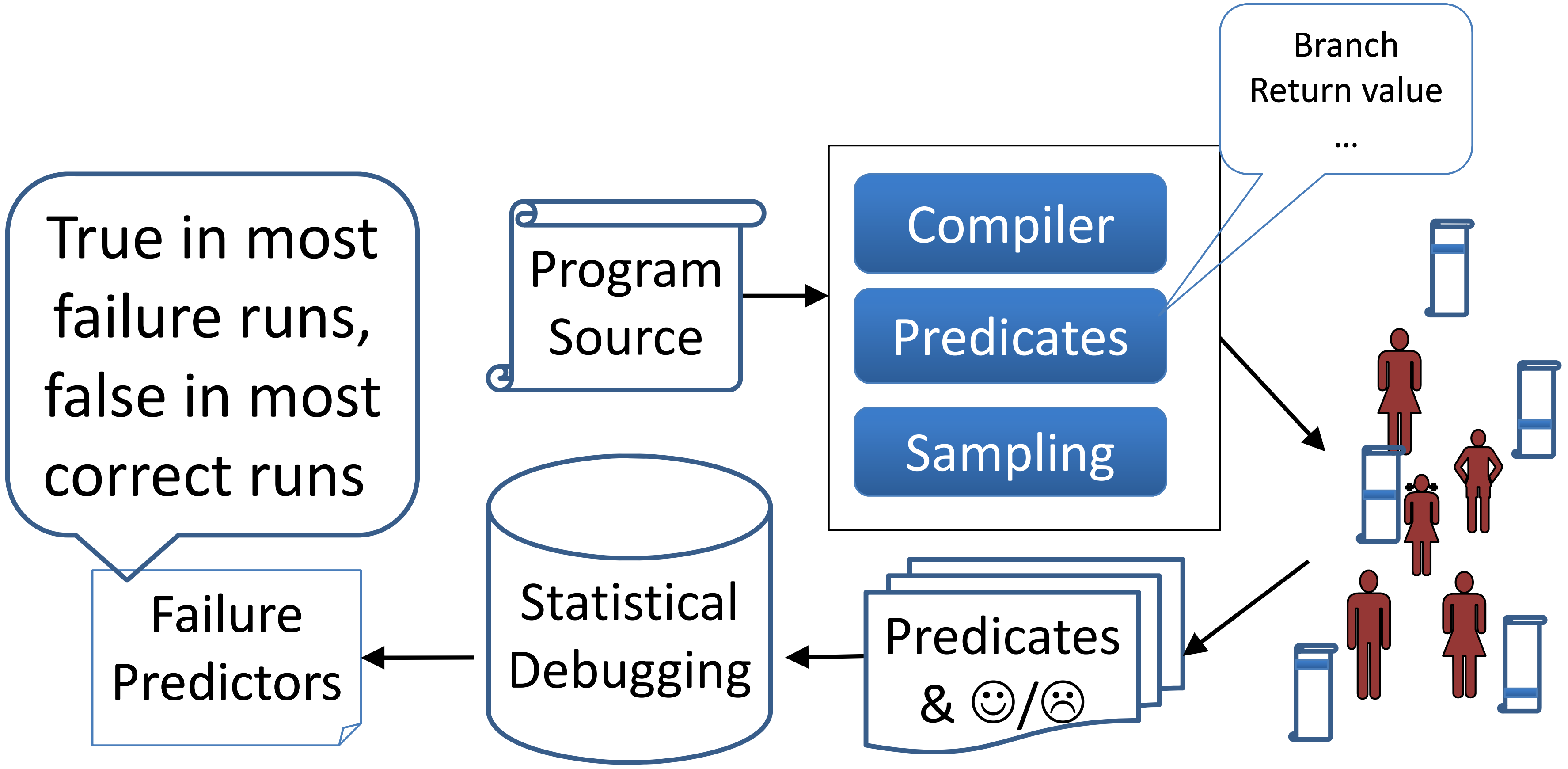
SL20 SL34

Cooperative Bug Isolation (CBI)



Performance	Capability
Good	??

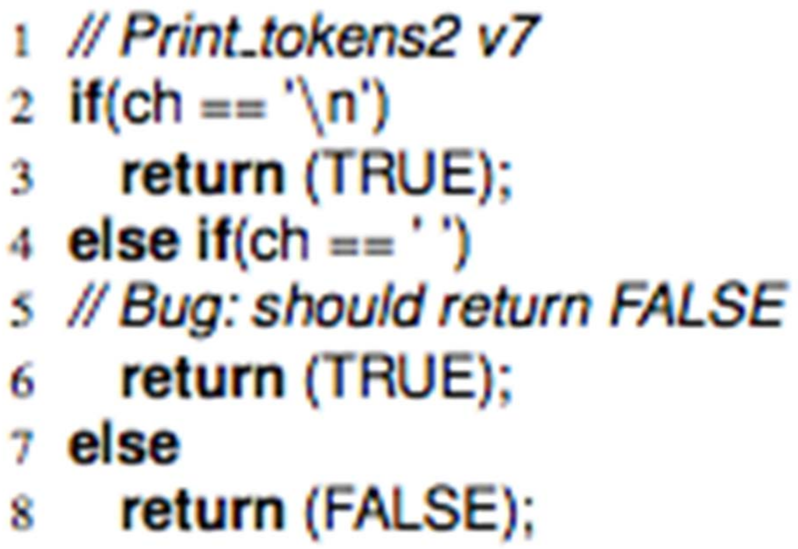
Slide 15

SL20	do i need to provide a sequential bug diagnosis example? Shan Lu, 2014-1-10
SL34	should i add an overview slide before this saying: challenges; solutions: apply xxx to concurrency bug diagnosis. Shan Lu, 2014-1-15

A long story about CBI

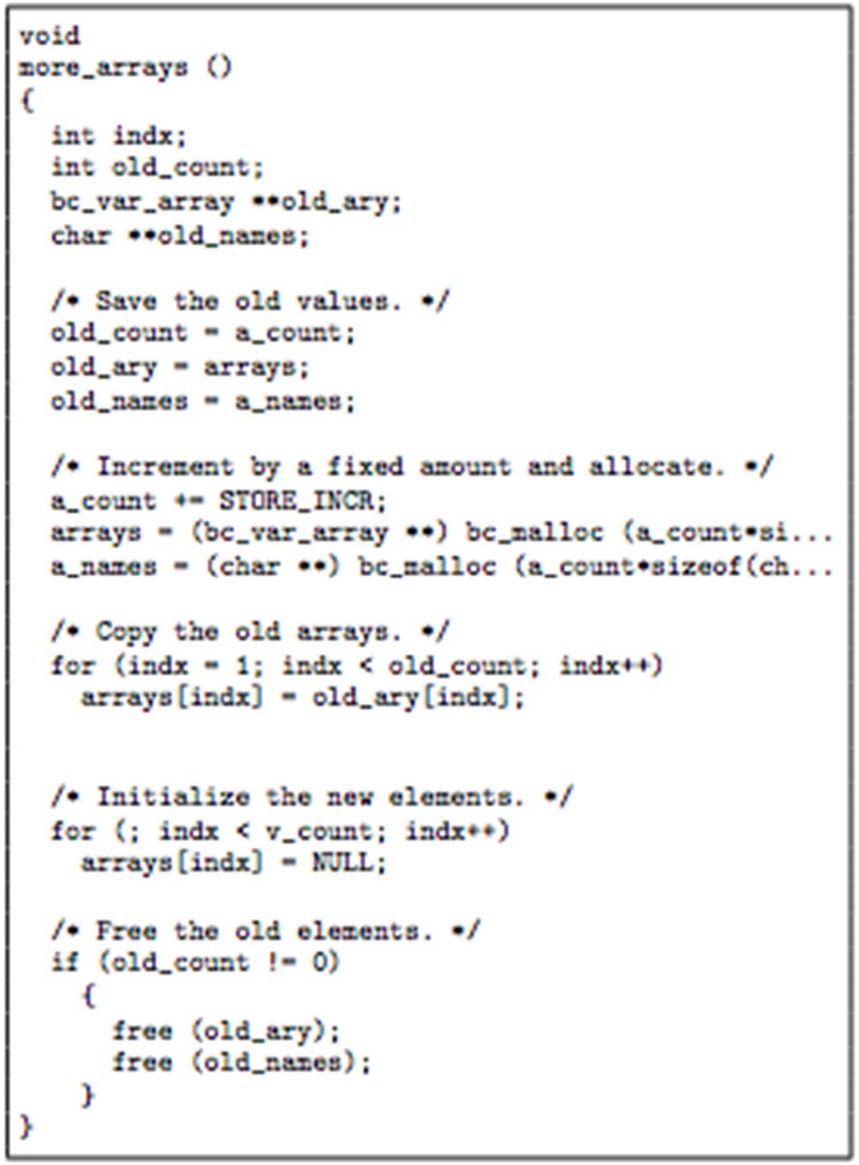
- Statistical fault localization, delta debugging
- Sampling based statistical fault localization

An example



```
// Print_tokens2 v7
if(ch == '\n')
    return (TRUE);
else if(ch == ' ')
// Bug: should return FALSE
    return (TRUE);
else
    return (FALSE);
```

Another example



```
void
more_arrays ()
{
  int indx;
  int old_count;
  bc_var_array **old_ary;
  char **old_names;

  /* Save the old values. */
  old_count = a_count;
  old_ary = arrays;
  old_names = a_names;

  /* Increment by a fixed amount and allocate. */
  a_count += STORE_INCR;
  arrays = (bc_var_array **) bc_malloc (a_count*si...
  a_names = (char **) bc_malloc (a_count*sizeof(ch...

  /* Copy the old arrays. */
  for (indx = 1; indx < old_count; indx++)
    arrays[indx] = old_ary[indx];


  /* Initialize the new elements. */
  for (; indx < v_count; indx++)
    arrays[indx] = NULL;

  /* Free the old elements. */
  if (old_count != 0)
    {
      free (old_ary);
      free (old_names);
    }
}
```

Does it work for concurrency bugs?

Thread 1

```
ptr = malloc(SIZE);
…
if (!ptr){ //b
  ReportOutofMem();
  exit(1);
}
```

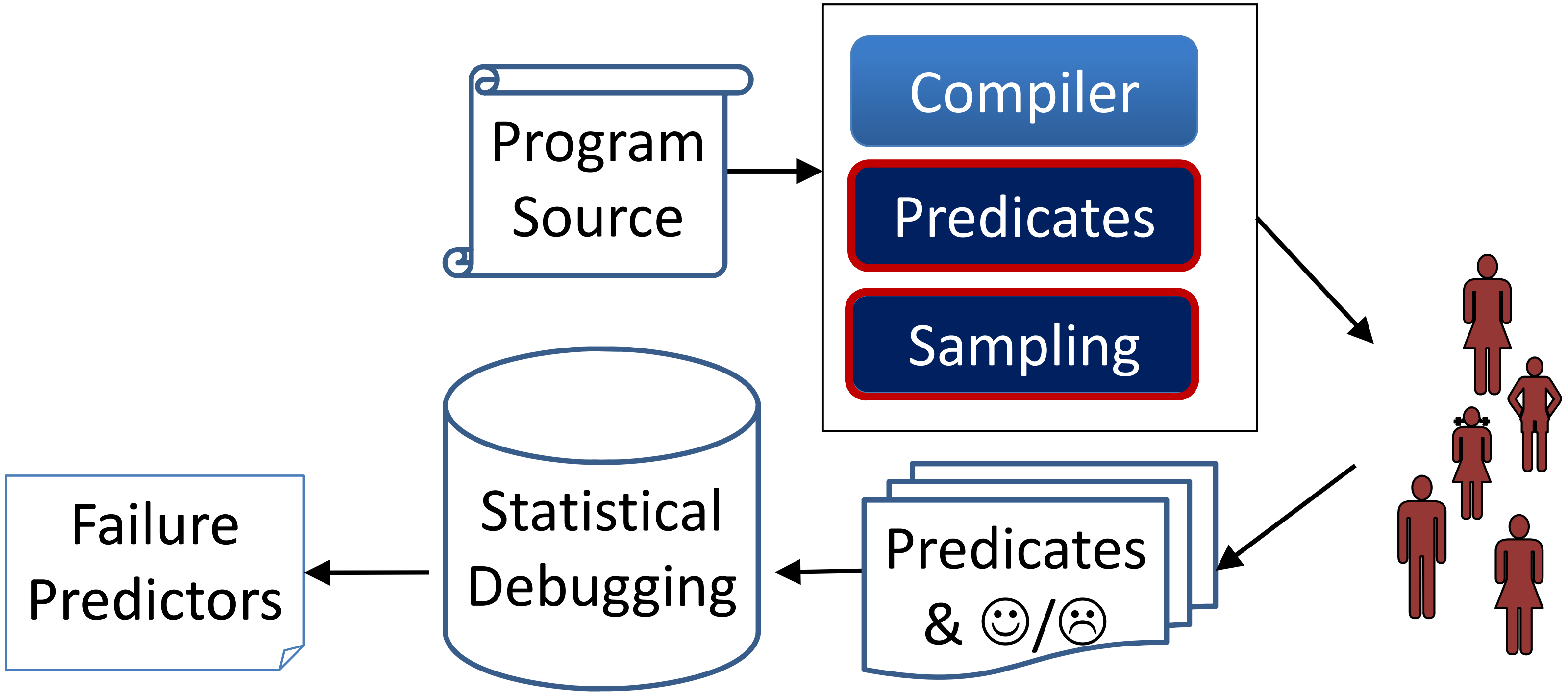
Thread 2

```
free(ptr);
ptr=NULL;
```

Predicate
…
taken$_b$
!taken$_b$
…

Why does CBI not work?

Cooperative Con-Bug Isolation (CCI)



Performance	Capability
Mixed	Good

What to collect? (predicate design)

Slide 21

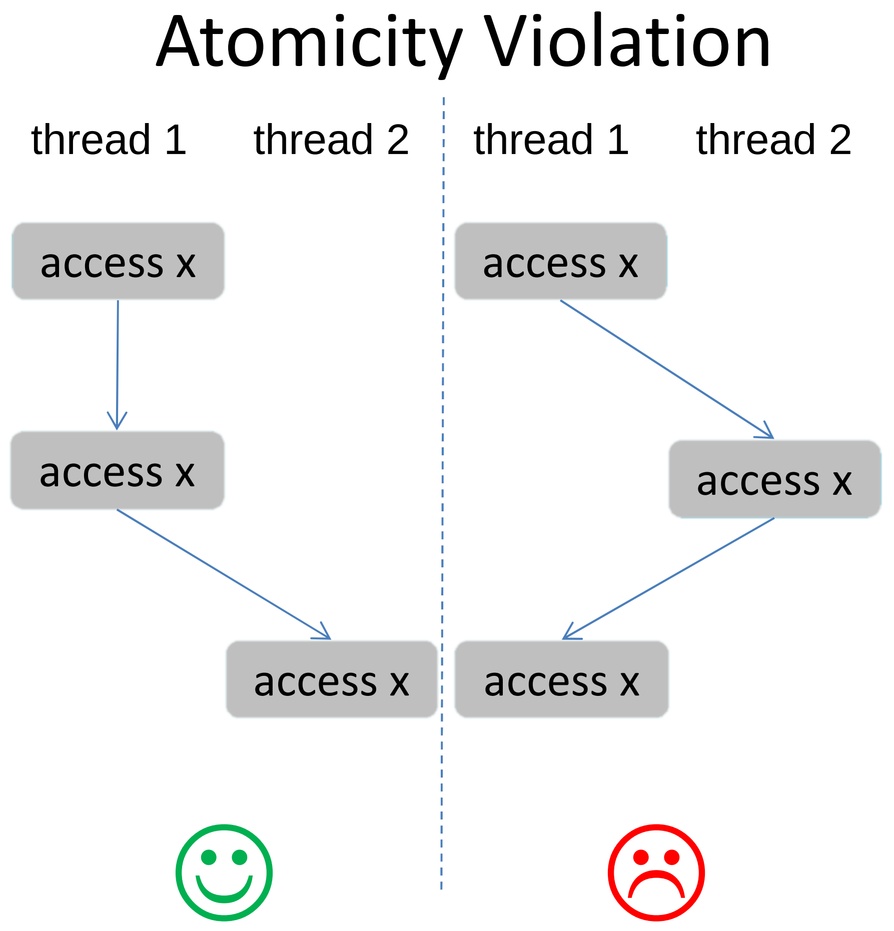
SL42	i need to redraw this to be consistent with earlier ... Shan Lu, 2014-1-16

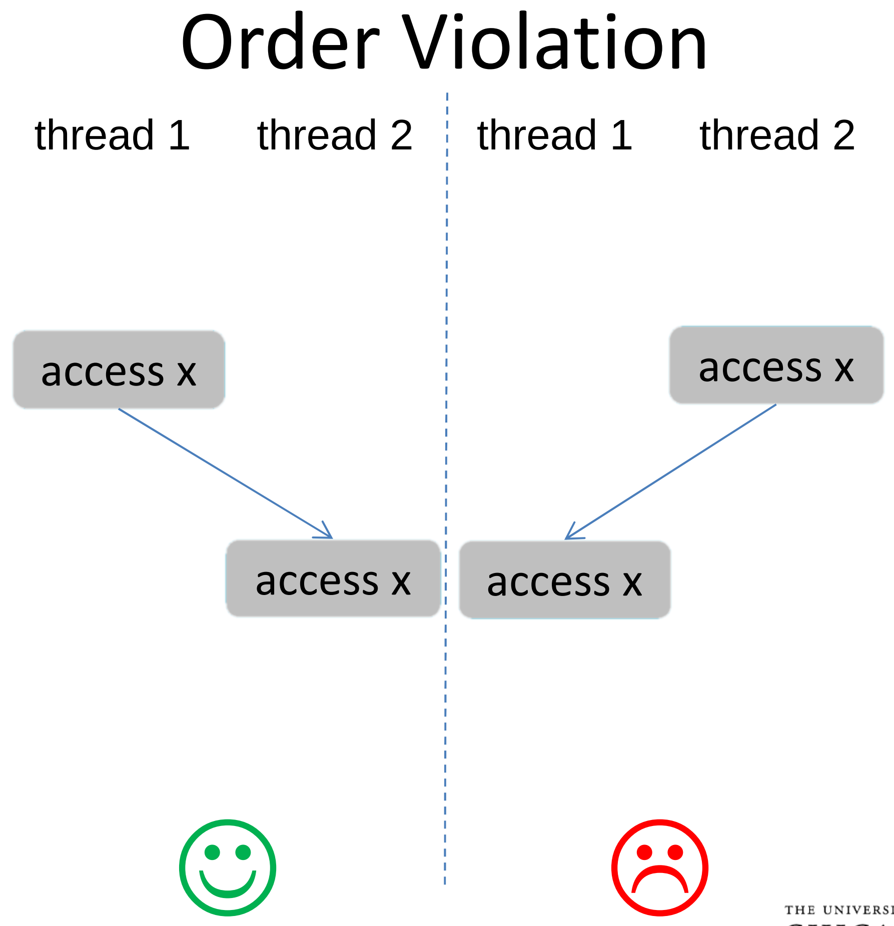
Concurrency bug root cause patterns

Atomicity Violation

Order Violation

Concurrency bug root cause patterns

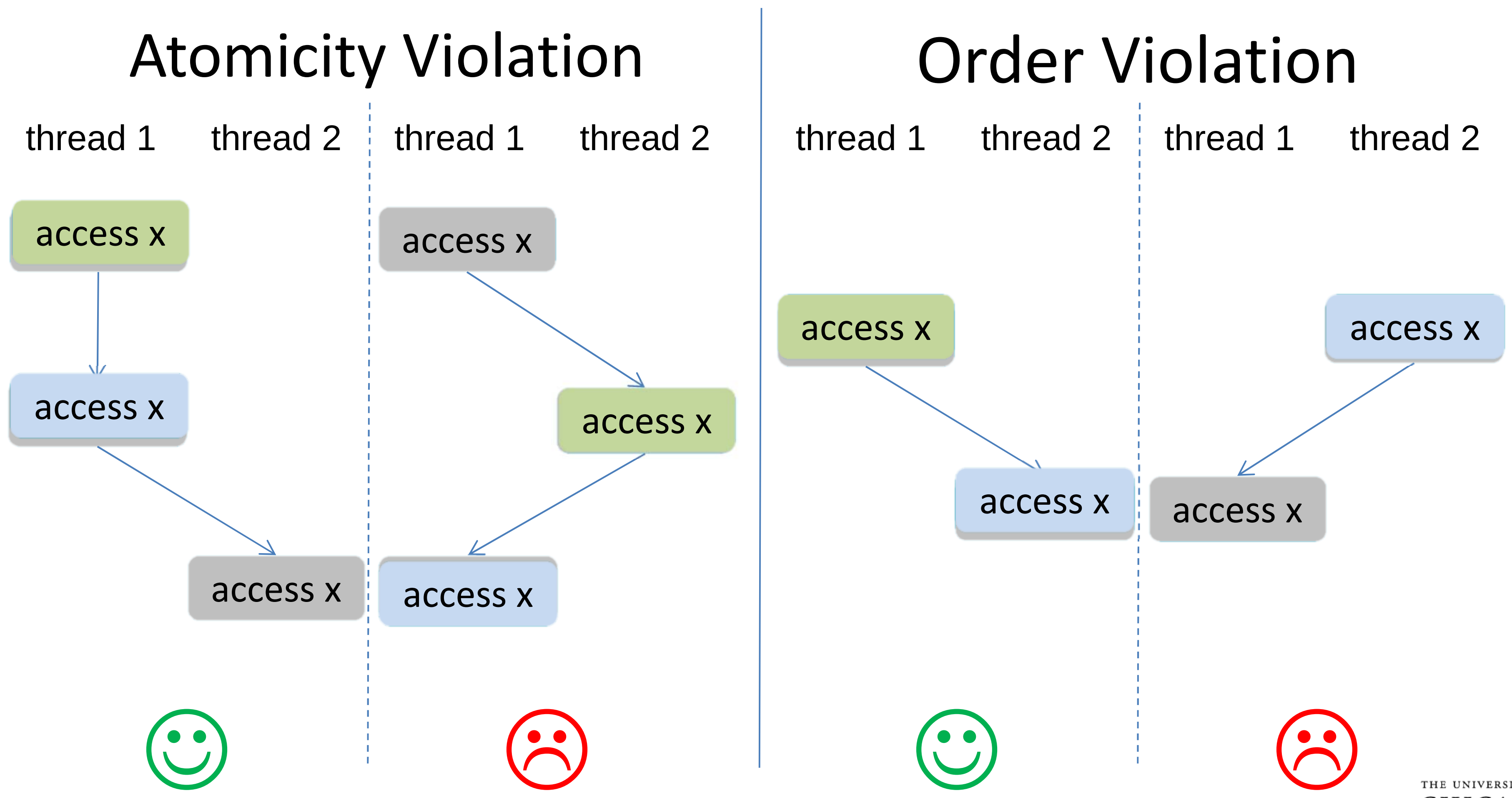




CCI-Prev predicate

Whether two successive accesses to a memory location were by two distinct threads or one thread

CCI-Prev can reflect root causes



Is CCI-Prev useful? (Example)

Thread 1

```
ptr = malloc(SIZE);
…
if (!ptr){
  ReportOutofMem();
  exit(1);
}
```

Thread 2

```
free(ptr);
ptr=NULL;
```

Mozilla

Example (correct runs)

thread 1

thread 2

```
…
free (ptr);
ptr=NULL;
…
```

```
…
ptr = malloc (SIZE);
…
if (!ptr) {
    ReportOutofMem();
    exit(1);
}
```

l

Predicate	☺	☹
…		
$remote_l$	0	0
$local_l$	1	0
…		

☺

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Example (failure run)

thread 1

```
…
ptr = malloc (SIZE);
```

thread 2

```
…
free (ptr);
ptr=NULL;
…
```

```
…
I  if (!ptr) {
      ReportOutofMem();
      exit(1);
   }
```

Predicate	☺	☹
…		
remote$_I$	0	1
local$_I$	1	0
…		

☹

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How to evaluate?

thread 1

```
…
ptr = malloc (SIZE);
```

thread 2

```
…
free (ptr);
ptr=NULL;
…
```

```
  lock(glock);
  remote = test_and_insert(& ptr, curTid);
  record(I, remote);
I temp = ptr;
  unlock(glock);

  if (!temp) {
    ReportOutofMem();
    exit(1);
  }
```

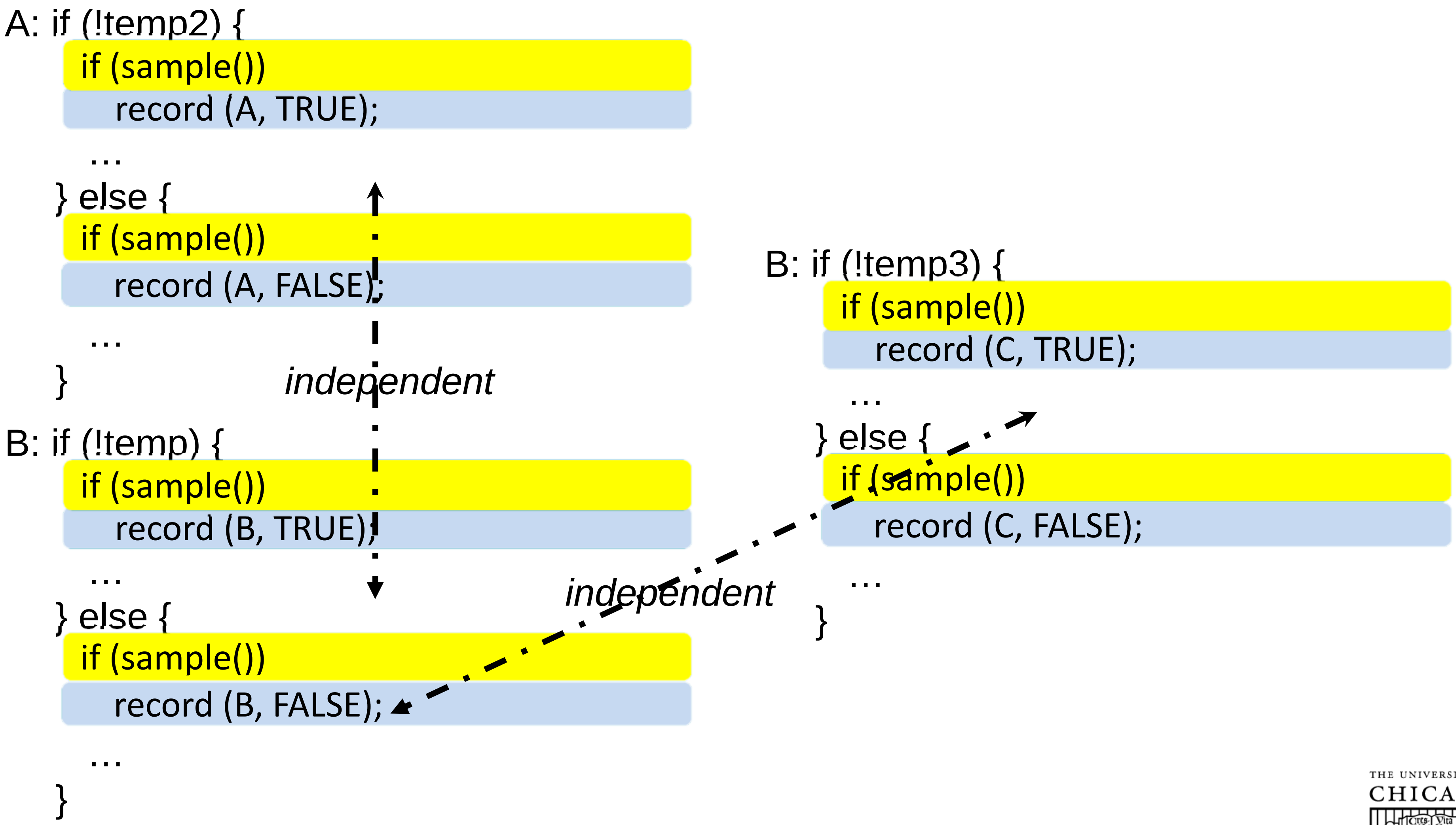
Predicate	☺	☹
…		
remote_I	0	1
local_I	1	0
…		

a global hash table

address	ThreadID
…	…
& ***ptr***	1
…	…

How to sample?

How to sample branch predicates?



```
A: if (!temp2) {
     if (sample())
        record (A, TRUE);
     …
   } else {
     if (sample())
        record (A, FALSE);
     …
   }
B: if (!temp) {
     if (sample())
        record (B, TRUE);
     …
   } else {
     if (sample())
        record (B, FALSE);
     …
   }
```

```
B: if (!temp3) {
     if (sample())
        record (C, TRUE);
     …
   } else {
     if (sample())
        record (C, FALSE);
     …
   }
```

How to sample CCI-Prev?

thread 1

```
…
ptr = malloc (SIZE);
```

thread 2

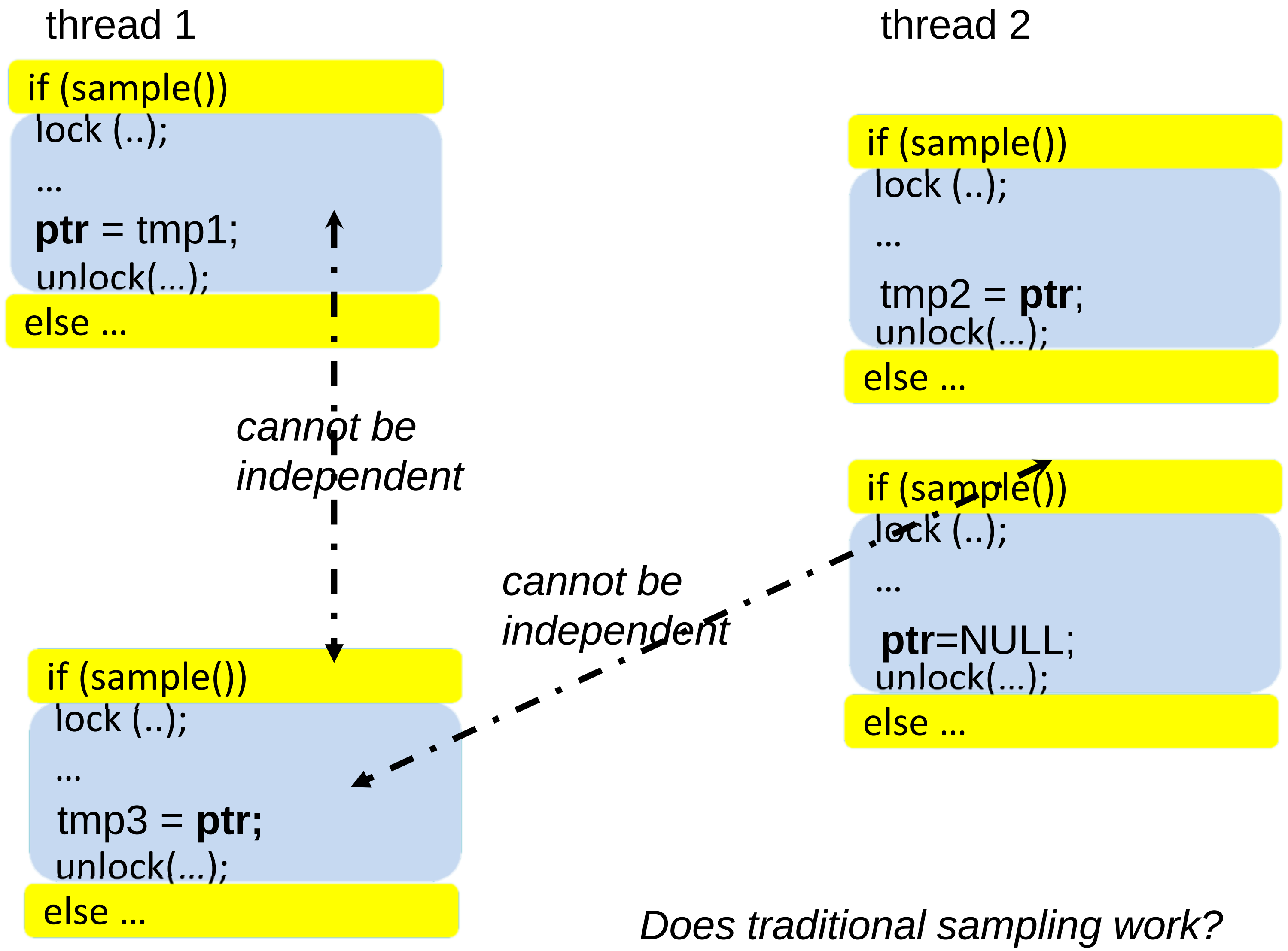
```
…
free (ptr);
ptr=NULL;
…
```

thread 1

```
…
if (!ptr) {
   ReportOutofMem();
   exit(1);
}
```

Does traditional sampling work?

How to sample CCI-Prev?



thread 1

```
if (sample())
lock (..);
…
ptr = tmp1;
unlock(…);
else …
```

```
if (sample())
lock (..);
…
tmp3 = ptr;
unlock(…);
else …
```

thread 2

```
if (sample())
lock (..);
…
 tmp2 = ptr;
unlock(…);
else …
```

```
if (sample())
lock (..);
…
 ptr=NULL;
unlock(…);
else …
```

Does traditional sampling work? **NO!**

Thread-coordinated, bursty sampling

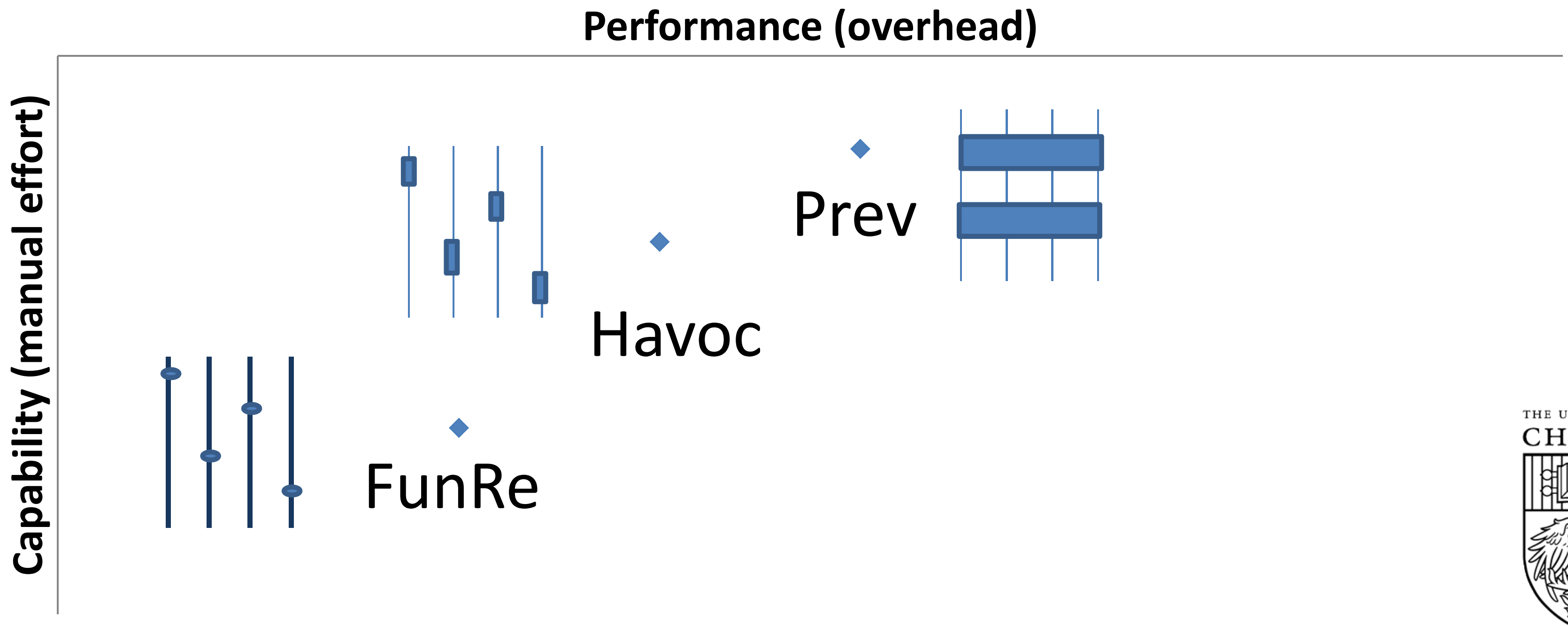
thread 1

```
if (sample())
 lock (...);
 ...
 ptr = tmp1;
 unlock(...);
else ...

 if (sample())
  lock (...);
  ...
  tmp3 = ptr;
  unlock(...);
 else ...
```

thread 2

```
if (sample())
 lock (...);
 ...
 tmp2 = ptr;
 unlock(...);
else ...

if (sample())
 lock (...);
 ...
 ptr=NULL;
 unlock(...);
else ...
```

Other predicates



Evaluation methodology

Program
Apache-1
Apache-2
Cherokee
FFT
LU
Mozilla-JS-1
Mozilla-JS-2
Mozilla-JS-3
PBZIP2

CIL-based static code instrumentor

1/100 sampling rate, ~3000 runs in total (failure:success~1:1)

Diagnosis capability (w/ sampling)

Program	CCI-Prev
Apache-1	✓ top1
Apache-2	✓ top1
Cherokee	✗
FFT	✓ top1
LU	✓ top1
Mozilla-JS-1	✗
Mozilla-JS-2	✓ top1
Mozilla-JS-3	✓ top2
PBZIP2	✓ top1

1/1000 sampling rate, ~3000 runs in total (failure:success~1:1)

Diagnosis performance (overhead)

	Prev	
	No Sampling	Sampling
Apache-1	62.6%	**1.9%**
Apache-2	**8.4%**	**0.5%**
Cherokee	19.1%	**0.3%**
FFT	169 %	24.0%
LU	57857 %	949 %
Mozilla-JS	11311 %	606 %
PBZIP2	**0.2%**	**0.2%**

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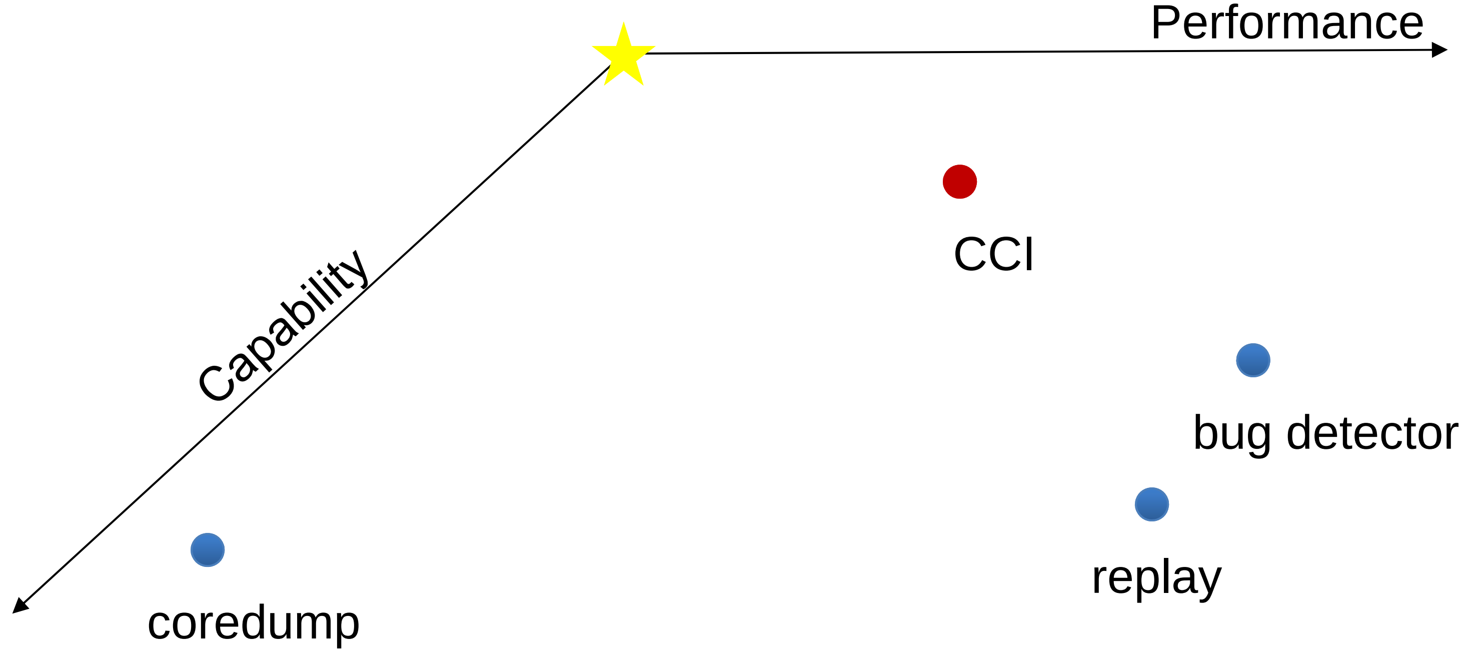
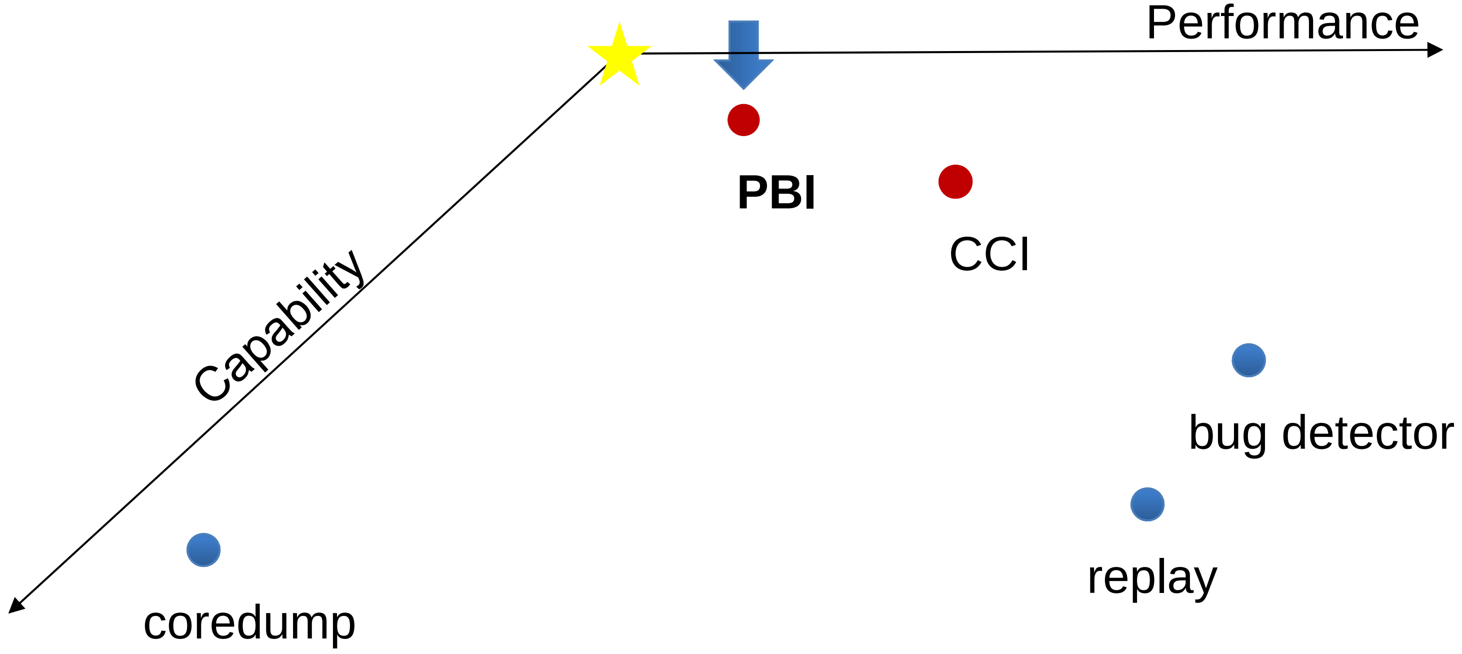
Are we done?



SL33

Outline



Slide 40

SL33 change the bullets texts. things like "compiler-based" is strange.
Shan Lu, 2014-1-15

How to do better than CCI?

What to collect	How to collect	How to use the collected
CCI-Prev …	Sampling	Cooperative statistical analysis

Performance	Capability	Latency

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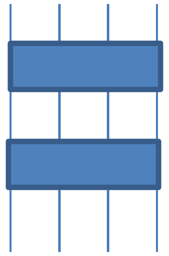
How to do better than CCI?

What to collect	How to collect	How to use the collected
	Sampling	

Slow sampling infrastructure

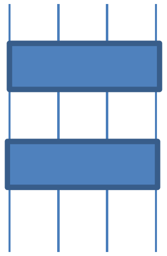


Performance	Capability	Latency

How to do better than CCI?

What to collect	How to collect	How to use the collected
	Sampling	

Slow sampling infrastructure
Inaccurate evaluation



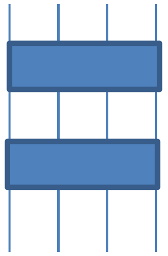
Performance	Capability	Latency

How to do better than CCI?

What to collect	How to collect	How to use the collected
	Hardware-based evaluation & sampling	

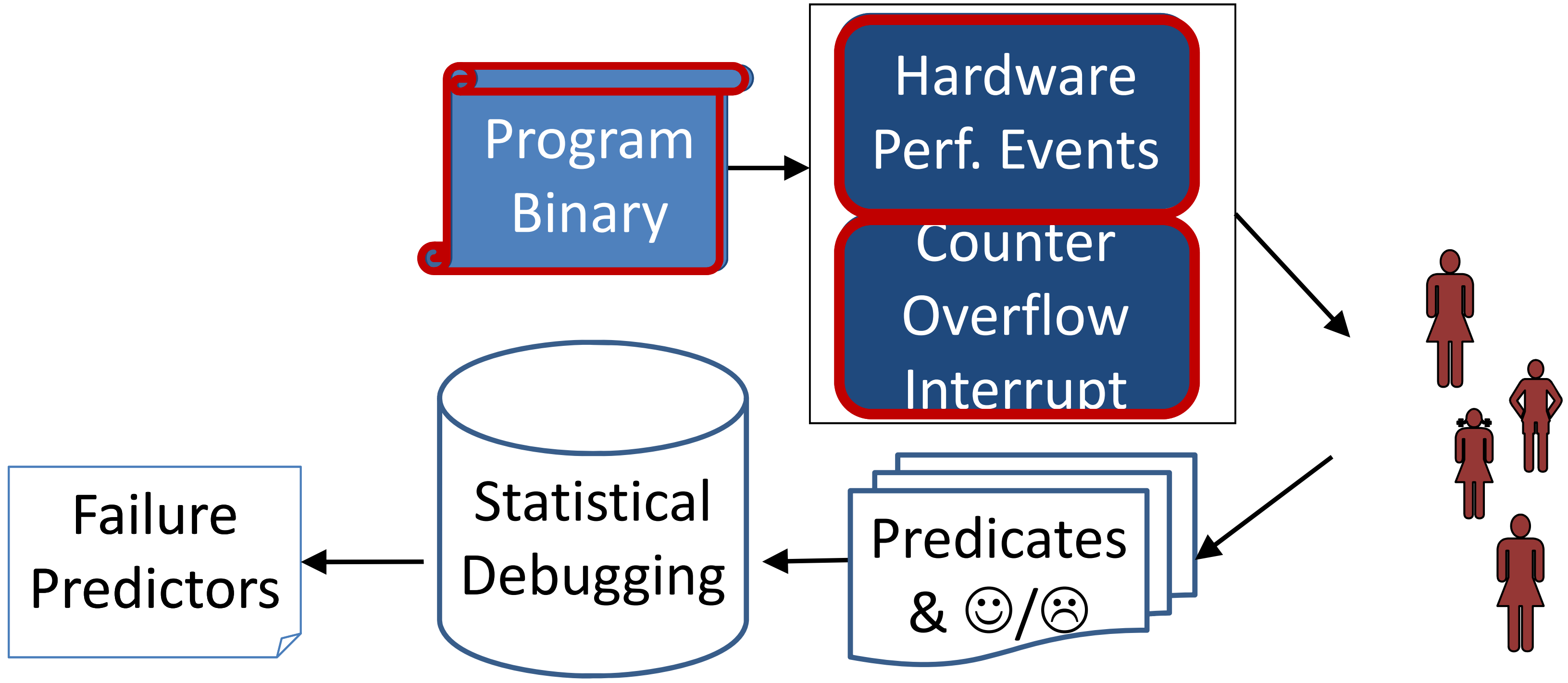
~~Slow sampling infrastructure~~

~~Inaccurate evaluation~~



Performance	Capability	Latency

PerfCnt-based Bug Isolation (PBI)



Performance	Capability	Code Size	Change Hardware?
Good (<5% overhead)	Good	No Change	NO!

Slide 45

SL38 should i bring in secret sauce here?
Shan Lu, 2014-1-16

Hardware Performance Counters

- Registers monitor hardware performance events
  - 1—8 registers per core
  - Each register can contain an event count
  - Large collection of hardware events
    - Instructions retired, TLB misses, cache misses, etc.
- Traditional usage
  - Hardware testing/profiling

How can this help diagnose software failures?

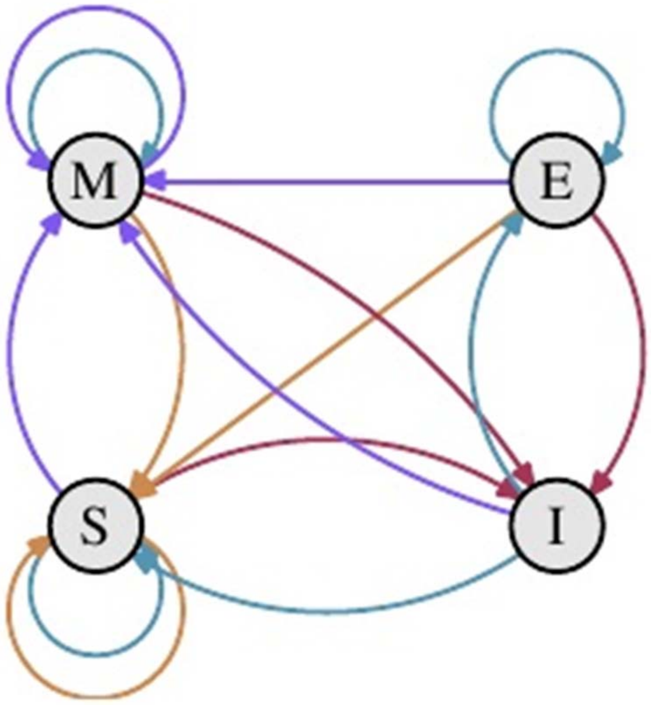
What to collect?

Which event can reflect root causes?

- L1 data cache cache-coherence events

It tracks which cache-coherence state (M/E/S/I) an instruction observes

Modified
Exclusive
Shared
Invalid



Local read
Local write
Remote read
Remote write

Is cache-coherence event useful?

Thread 1

```
ptr = malloc(SIZE);
…
if (!ptr){
  ReportOutofMem();
  exit(1);
}
```

Mozilla

Thread 2

```
free(ptr);
ptr=NULL;
```

Example (correct runs)

thread 1 (core 1)

Modified

thread 2 (core 2)

Invalid

```
…
free (ptr);
ptr=NULL;
…
```

```
…
ptr = malloc (SIZE);
…
I: if (!ptr) {
      ReportOutofMem();
      exit(1);
   }
```

Predicate	☺	☹
…		
M_I	1	0
E_I	0	0
S_I	0	0
I_I	0	0
…		

☺

Concurrency Bug from Apache HTTP Server

Example (failure run)

thread 1 (core 1)

Invalid

```
ptr = malloc (SIZE);
```

thread 2 (core 2)

Modified

```
…
free (ptr);
ptr=NULL;
…
```

```
…
if (!ptr) {
   ReportOutofMem();
   exit(1);
}
```

Predicate	☺	☹
…		
M_I	1	0
E_I	0	0
S_I	0	0
I_I	0	1
…		

☹

Concurrency Bug from Apache HTTP Server

Useful for Atomicity Violations

Bug Type	FAILURE PREDICTOR
WWR Violation	INVALID
RWR Violation	INVALID
RWW Violation	INVALID
WRW Violation	SHARED

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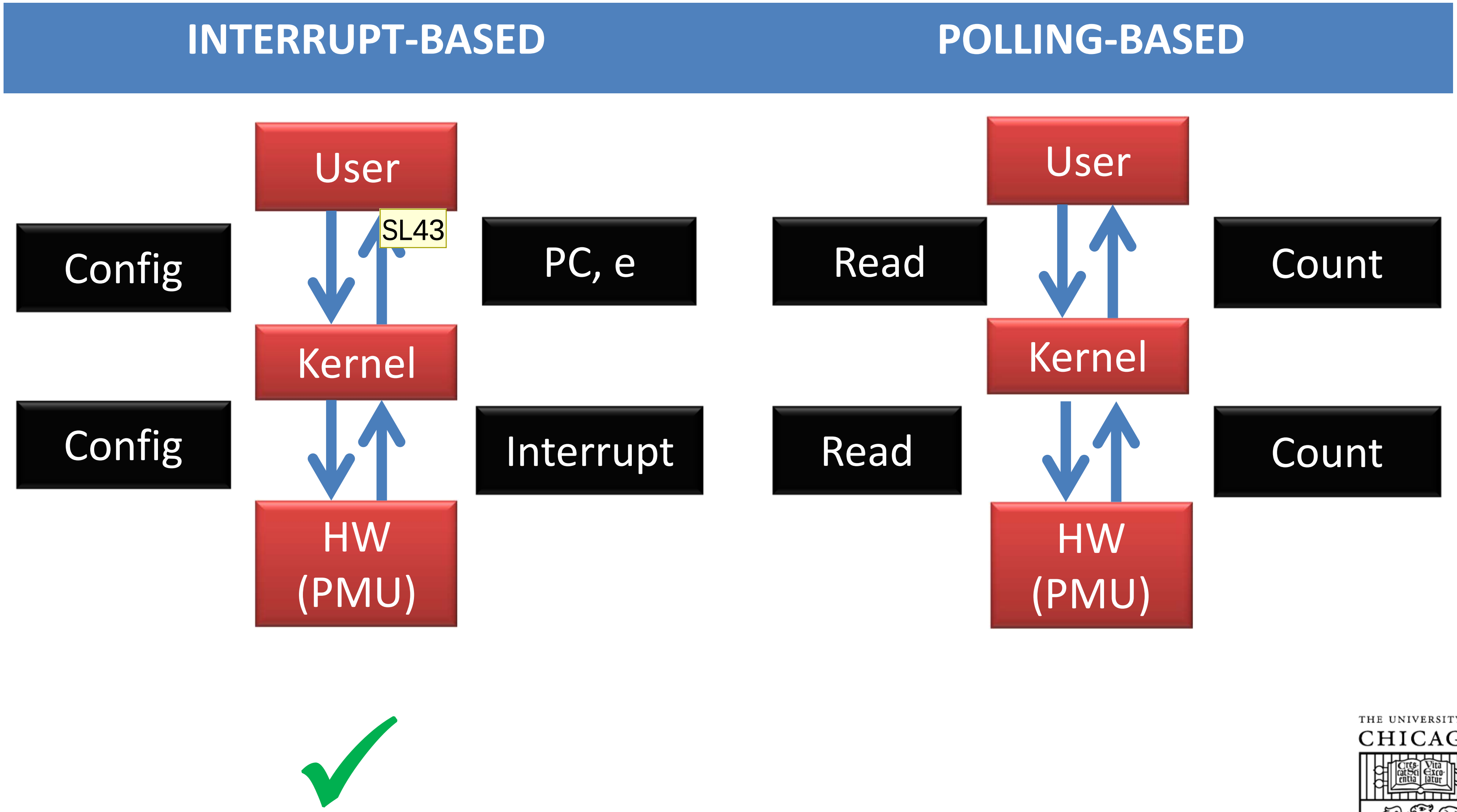
Useful for order violations

Bug Type	FAILURE PREDICTOR
Read-too-early	EXCLUSIVE (!INVALID)
Read-too-late	INVALID

How to evaluate & sample?

Which performance events occur at a specific instruction?

Accessing performance counters



Slide 55

SL43 double check if polling needs to go through kernel
Shan Lu, 2014-1-16

More details of counter access

```
perf record –event=<code> -c <sampling_rate>
<program monitored>
```

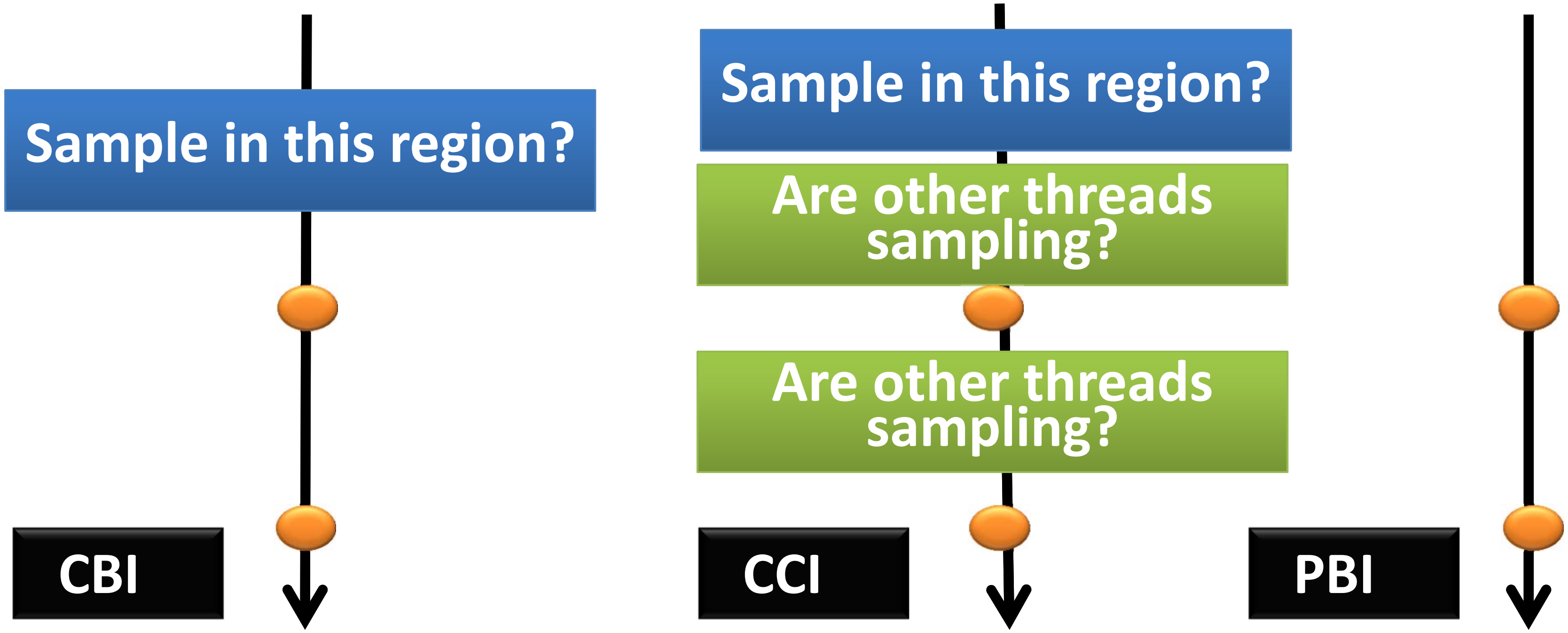
Log Id	APP	Core	Performance Event	Instruction	Function
1	Httpd	2	0x140 (Invalid)	401c3b	decrement _refcnt

Beyond concurrency bugs

- Which event?
  - Branch taken/non-taken event
- How to evaluate & sample?
  - Performance counter overflow interrupt

PBI vs. CBI/CCI (Qualitative)

- Performance



- Diagnostic capability
  - Discontinuous monitoring (CCI/CBI)
  - Continuous monitoring (PBI)
  - PBI differentiates interleaving reads from writes

Evaluation methodology

Program
Apache-1
Apache-2
Cherokee
FFT
LU
Mozilla-JS-1
Mozilla-JS-2
Mozilla-JS-3
MySQL-1
MySQL-2
PBZIP2

1/100 sampling rate, ~1000 runs in total (failure:success~1:1)

Diagnosis capability (w/ sampling)

Program	CCI-Prev
Apache-1	✓ top1
Apache-2	✓ top1
Cherokee	✗
FFT	✓ top1
LU	✓ top1
Mozilla-JS-1	✗
Mozilla-JS-2	✓ top1
Mozilla-JS-3	✓ top2
MySQL-1	-
MySQL-2	-
PBZIP2	✓ top1

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Diagnosis capability (w/ sampling)

Program	CCI-Prev	PBI
Apache-1	✓ top1	✓ top1
Apache-2	✓ top1	✓ top1
Cherokee	✘	✓ top1
FFT	✓ top1	✓ top1
LU	✓ top1	✓ top1
Mozilla-JS-1	✘	✓ top1
Mozilla-JS-2	✓ top1	✓ top1
Mozilla-JS-3	✓ top2	✓ top1
MySQL-1	-	✓ top1
MySQL-2	-	✓ top1
PBZIP2	✓ top1	✓ top1

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Diagnosis capability (w/ sampling)

Program	CCI-Prev	PBI
Apache-1	✓ top1	✓ top1-I
Apache-2	✓ top1	✓ top1-I
Cherokee	✗	✓ top1-I
FFT	✓ top1	✓ top1-E
LU	✓ top1	✓ top1-E
Mozilla-JS-1	✗	✓ top1-I
Mozilla-JS-2	✓ top1	✓ top1-I
Mozilla-JS-3	✓ top2	✓ top1-I
MySQL-1	-	✓ top1-S
MySQL-2	-	✓ top1-S
PBZIP2	✓ top1	✓ top1-I

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Diagnosis performance (overhead)

Program	CCI-Prev	PBI
Apache-1	1.90%	0.40%
Apache-2	0.40%	0.40%
Cherokee	0.00%	0.50%
FFT	121%	1.00%
LU	285%	0.80%
Mozilla-JS-1	800%	1.50%
Mozilla-JS-2	432%	1.20%
Mozilla-JS-3	969%	0.60%
MySQL-1	-	3.80%
MySQL-2	-	1.20%
PBZIP2	1.40%	8.40%

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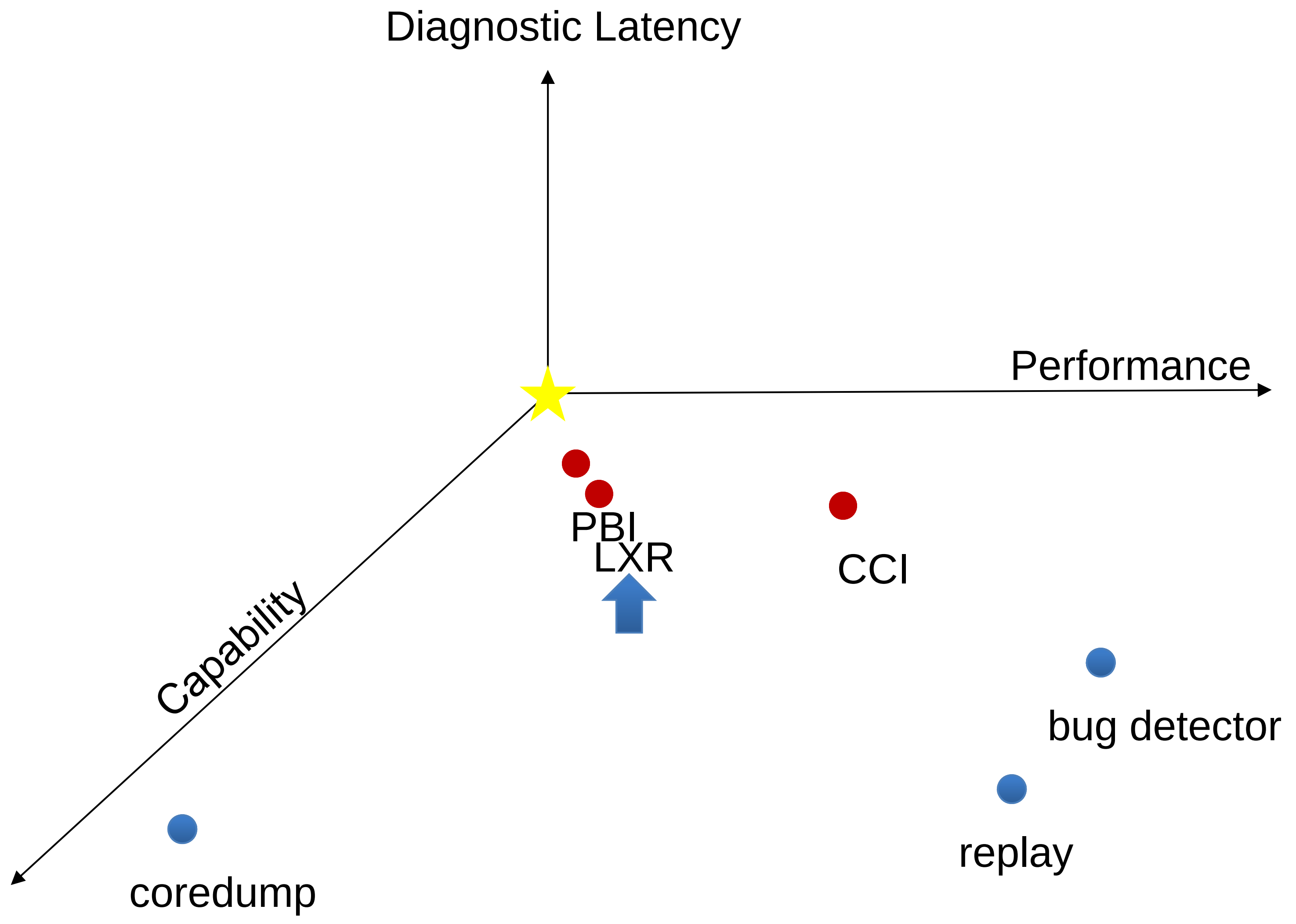
Sequential-bug failure diagnosis results are also good!

SL31

Are we done?



1/100 sampling rate ➔ ~100 failures required for diagnosis

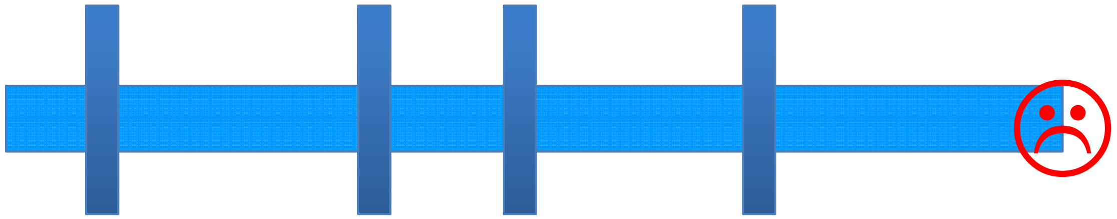
Slide 64

SL31 maybe i should put 4-d/3-d coordinates here, and change the tables following
Shan Lu, 2014-1-15

How to do better than PBI?

What to collect	How to collect	How to use the collected
	Sampling	

Missing failure-related information



High overhead

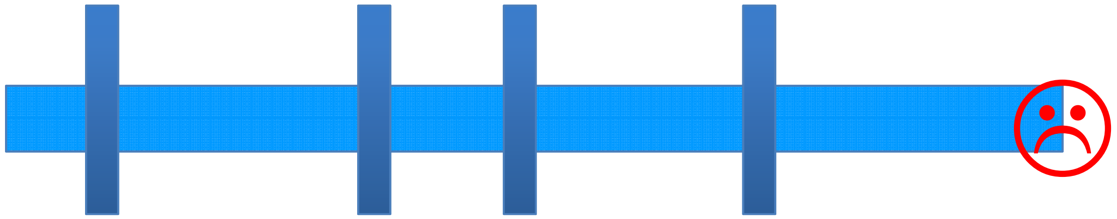
Performance	Capability	Latency

How to collect sufficient root-cause information in 1 run w/ small overhead?

How to do better than PBI?

What to collect	How to collect	How to use the collected
	Biased sampling	

Missing failure-related information



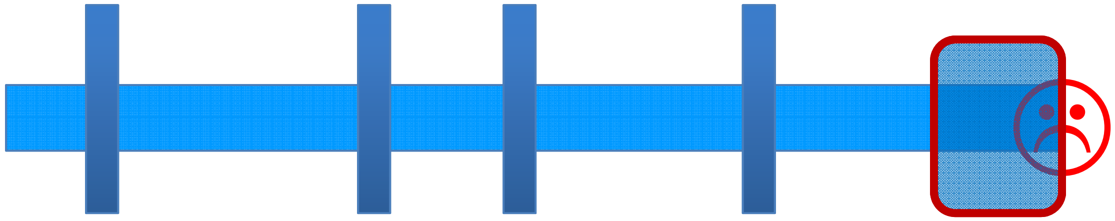
High overhead

Performance	Capability	Latency

Collect information @ likely root-cause locations

LXR – Last eXecution Record

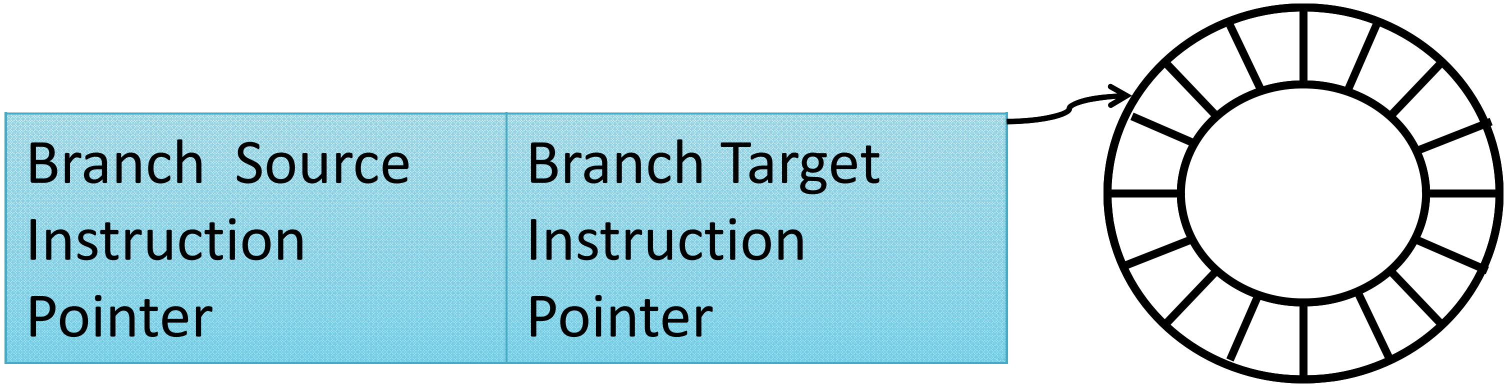
- What to collect?
  - Last few branches right before failure
  - Last few cache-coherence events right before failures
- How to collect/maintain LXR?
  - Existing* hardware support!



Performance	Capability	Code Size	Change Hardware?	Diagnosis Latency
Good (<5% overhead)	Good	Little Change	Simple Extension*	Short

Last Branch Record (LBR)

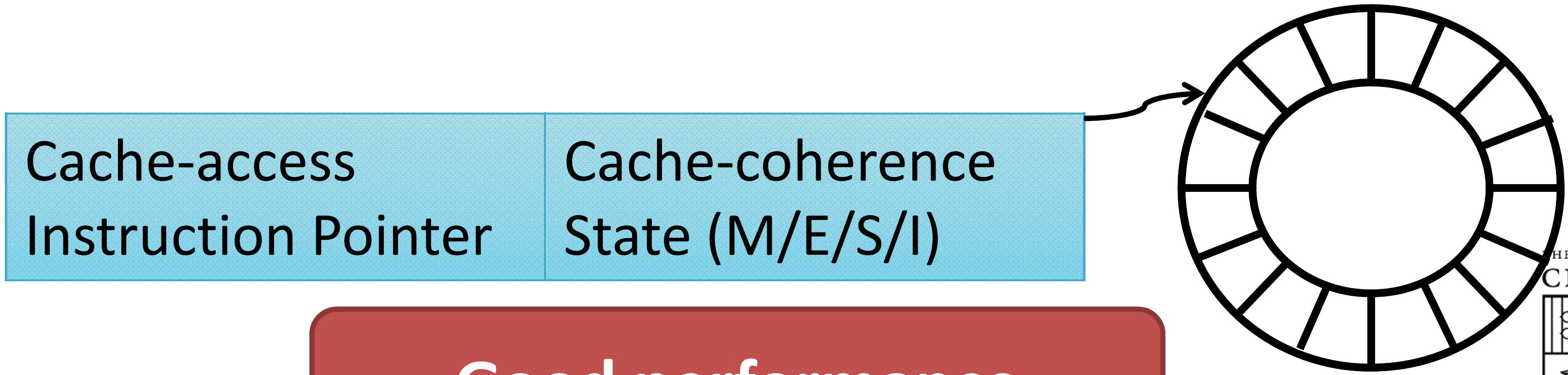
- **Existing** hardware feature
  - Store recently taken branches
  - Circular buffer with 16 entries (Intel Nehalem)
  - **Negligible** overhead


Branch Source Instruction Pointer
Branch Target Instruction Pointer

Good performance

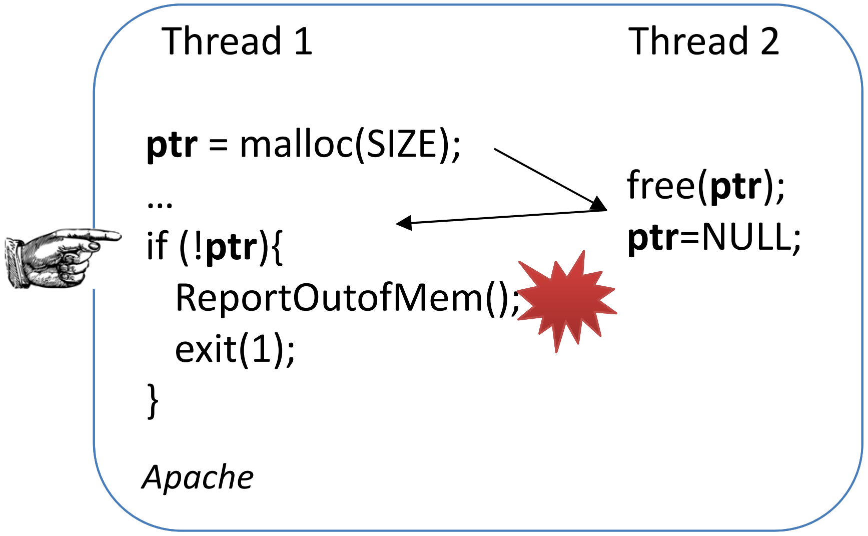
Last Cache-coherence Record (LCR)

- **Existing** hardware feature
  – Configurable cache-coherence event counting
- Extension
  – Buffer to collect this information
  – Set of recent L1 data cache access instructions
- Negligible overhead (estimated)


Cache-access Instruction Pointer
Cache-coherence State (M/E/S/I)

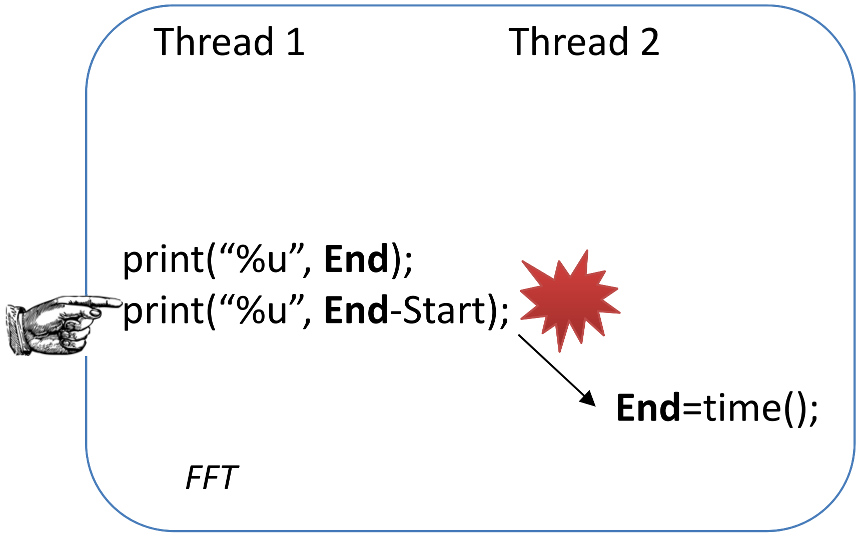
Good performance

Is LXR useful?



```
Thread 1                        Thread 2

ptr = malloc(SIZE);
...                             free(ptr);
if (!ptr){                      ptr=NULL;
  ReportOutofMem();
  exit(1);
}
```



```
Thread 1                        Thread 2

print("%u", End);
print("%u", End-Start);
                                End=time();
```

Bugs have short error-propagation distance → LXR is sufficient for failure diagnosis

Good diagnosis capability

LXR vs PBI vs CBI/CCI

	Performance	Capability	Diagnosis Latency (#-failure-runs)
LXR	<5%	23/31	1~10 failures
PBI	<5%	25/31	1000 failures
CBI/CCI	3% ~ 969%	18/31	1000 failures

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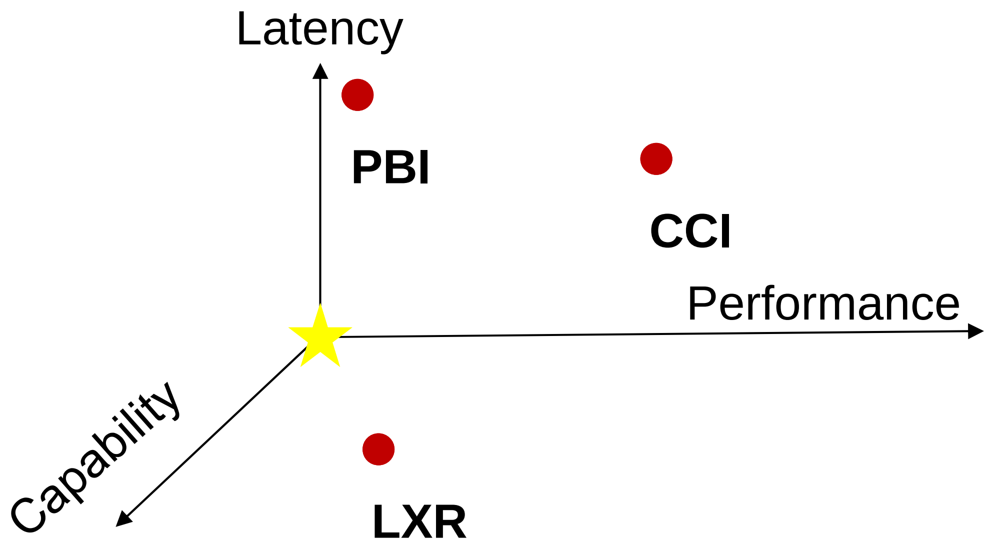
Summary


Latency
PBI
CCI
Performance
Capability
LXR