Detecting and Fixing Concurrency Bugs

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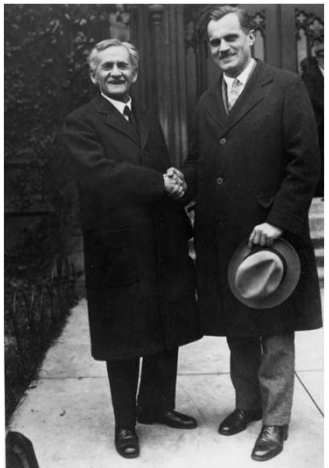
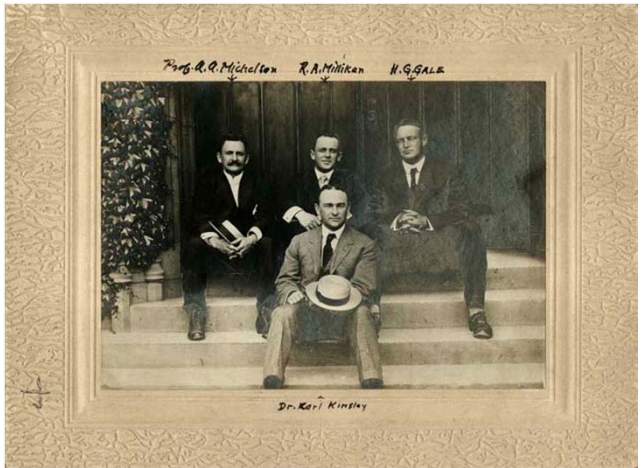
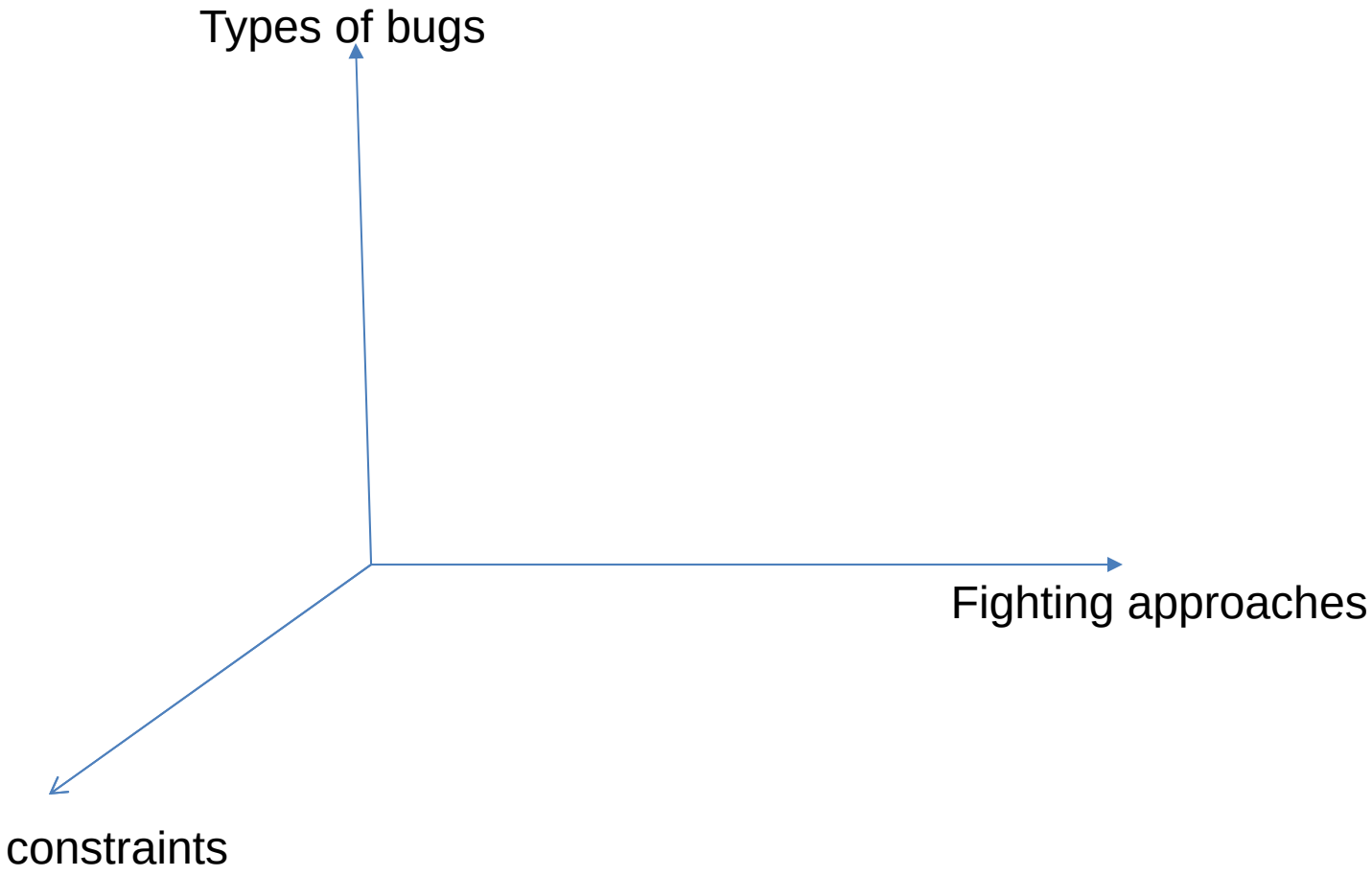




About course assignment

- Study 5 bugs in an open-source application's Bugzilla
  - Pick the keyword you like
  - Pick the application you like (or use cbs …)
  - Write the following for each bug
    - What is the bug root cause (fault)
    - What errors might be caused by the bug
    - What is the failure symptom of this bug
    - What is the fix strategy of developers
    - Can this bug be automatically detected? Exposed during testing? Automatically diagnosed or fixed?
- You can work in group


Types of bugs
Fighting approaches
constraints

Different types of bugs

- Memory bugs
  - Memory leaks
  - Buffer overflow
  - Null-ptr dereference
  - Uninitialized read
- Semantic bugs
- Concurrency bugs
- Performance/energy bugs

Faults in linux: ten years later. ASPLOS'11
Bug Characteristics in Open Source Software. EMSE'13

Don’t hesitate to ask me questions!

Background

Thread

Concurrency Bugs

Thread vs. Process

- Process – resource management unit
  - Nothing is shared among processes, except …
  - Parent & child share initial image

- Thread – execution/scheduling unit
  - The address space is completely* shared among threads under the same process

See example code

Sources of non-determinism

- race.c

- On single-core machines
  - System event non-determinism
- On multi-core machines
  - System event non-determinism
  - (Parallel) hardware on-determinism

Thread synchronization (I)

- Lock
  - Enforce mutual exclusion
- Condition variable
  - Enforce pair-wise ordering

- What is needed to synchronize …?

(1) *Thread 1* x++; *Thread 2* x++;

(2) *Thread 1* p=malloc(10); *Thread 2* *p=10;

Thread synchronization (II)

- Semaphore
  - A counter (can be initialized with any positive value)
  - P (acquire one piece of resource)
  - V (release one piece of resource)

- What is needed to synchronize …?

(1) *Thread 1* x++; *Thread 2* x++;

(2) *Thread 1* p=malloc(10); *Thread 2* *p=10;

Thread APIs

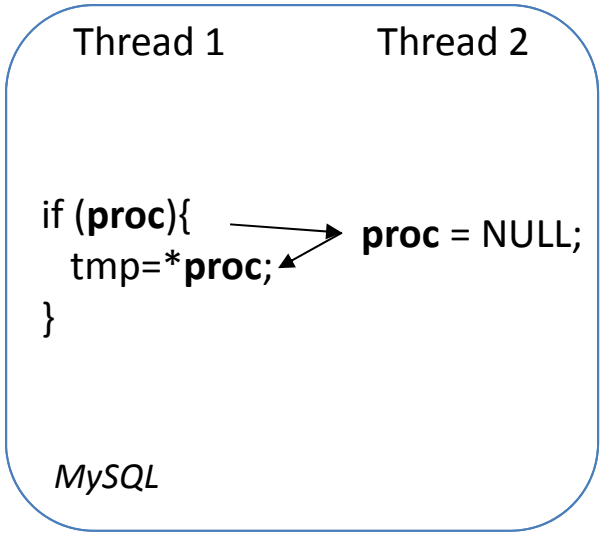
- pthread_create
- pthread_join
- pthread_mutex_lock
- pthread_mutex_unlock
- pthread_cond_wait
- pthread_cond_signal
- …

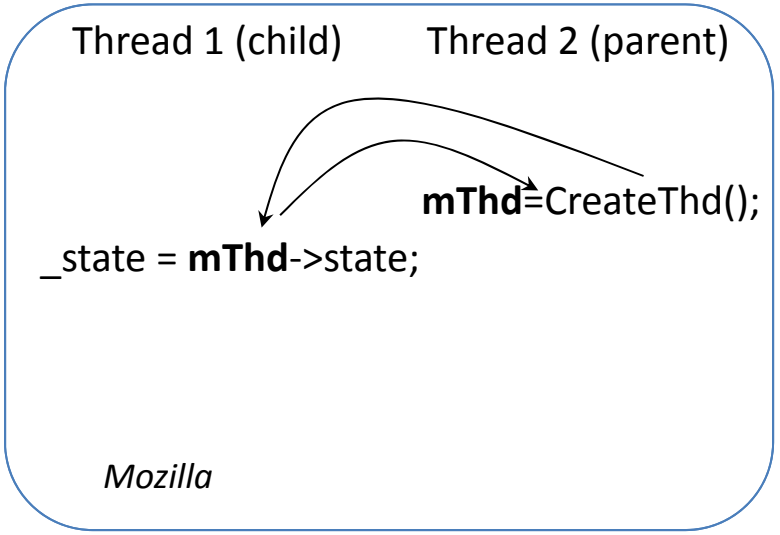
Other way of parallel execution

- Shared memory vs. message passing

What are concurrency bugs?

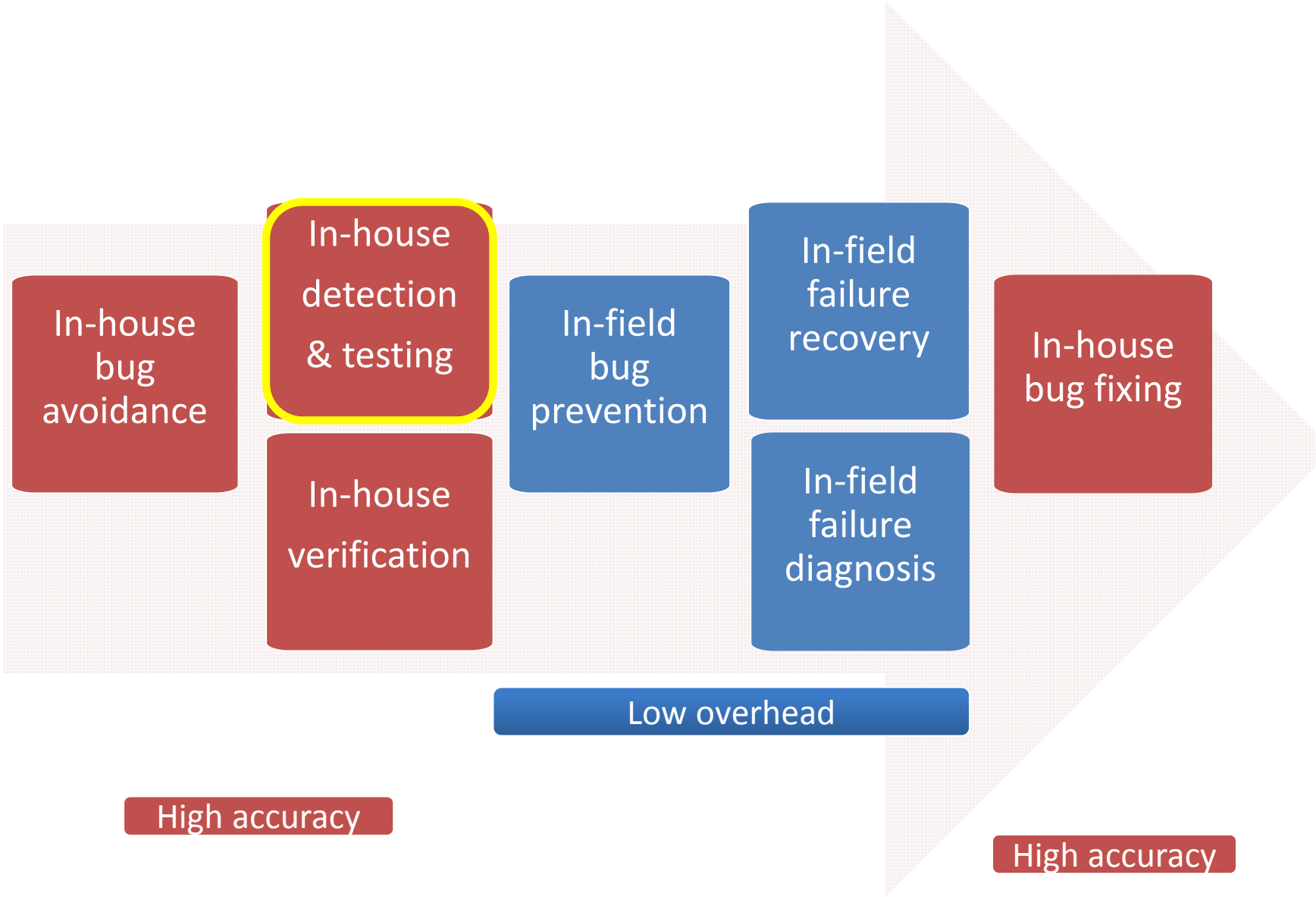
- Untimely accesses among threads (buggy interleavings)





It is important to fight con. bugs

Different aspects of fighting bugs



Outline

- What are concurrency bugs
- Concurrency bug detection
- Concurrency bug exposing
- Concurrency bug fixing
- Others
- Conclusion

Outline

- What are concurrency bugs
- Concurrency bug detection
- Concurrency bug exposing
- Concurrency bug fixing
- Others
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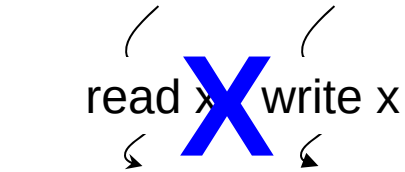
The key challenges

- What type of interleavings is buggy?

- Large state space
- False positives
- False negatives
- Overhead

Data race

- Definition



Dinning'90,Netzer'91, Choi'91,
Savage'97, Larus'98, Choi'02,
O'Callahan'03, Yu'05, Aiken'06

- Does this pattern match our examples?
- How to get rid of a data race?

How to detect data races?

- How do I know the execution of two accesses are concurrent?

- What does basic run-time monitoring tell us?

count ++; <thread 1>

… //millions of instructions in between

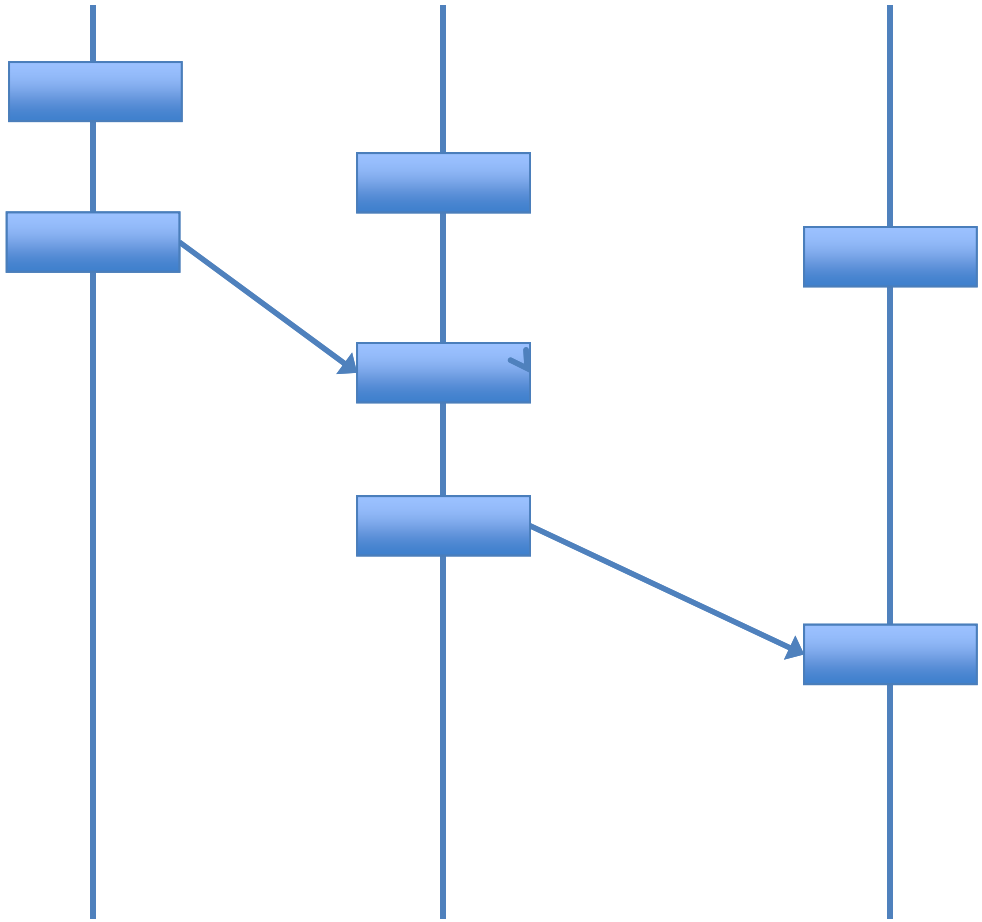
count++; <therad 2>

Physical time vs. logical time

- From Leslie Lamport
- What ordering do we know for sure in a distributed environment?

- Logical time based on causality/happens-before relationship
  - Vector timestamp
  - Scalar timestamp

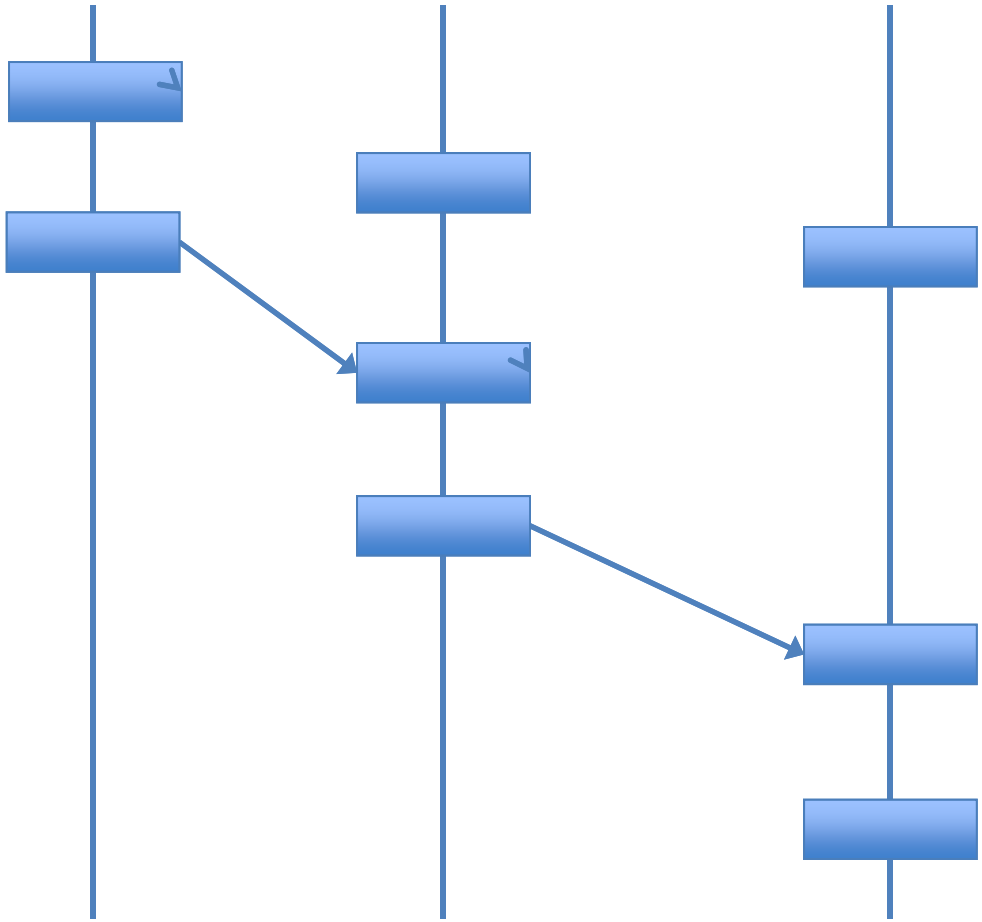
What ordering is guaranteed?



Logical time

- Operations within one thread are (happens-before) ordered following program semantics
- Message sending is (happens-before) ordered before message receiving
- Ordering is transitive
  - A→B, B→C ➔A→C

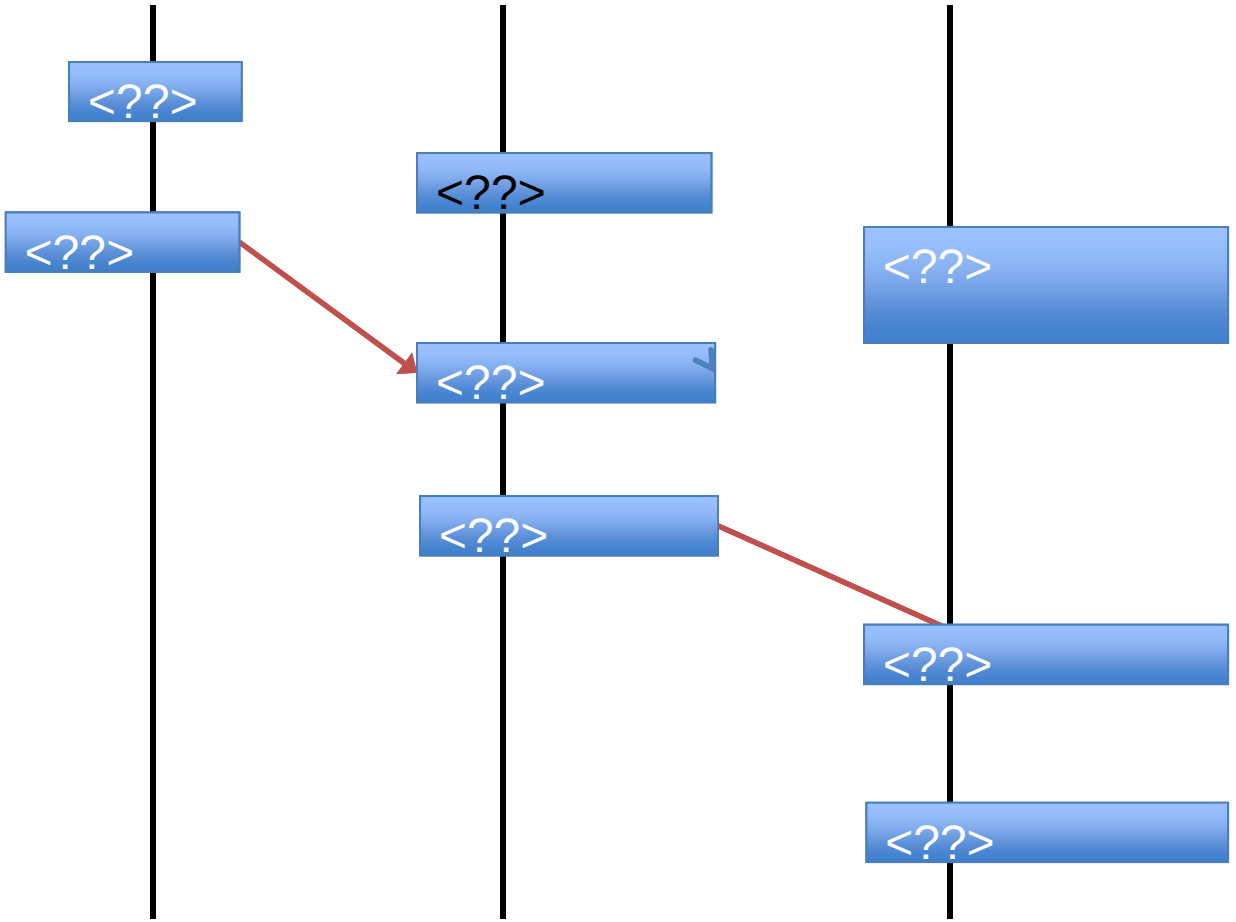
How to represent logical time?



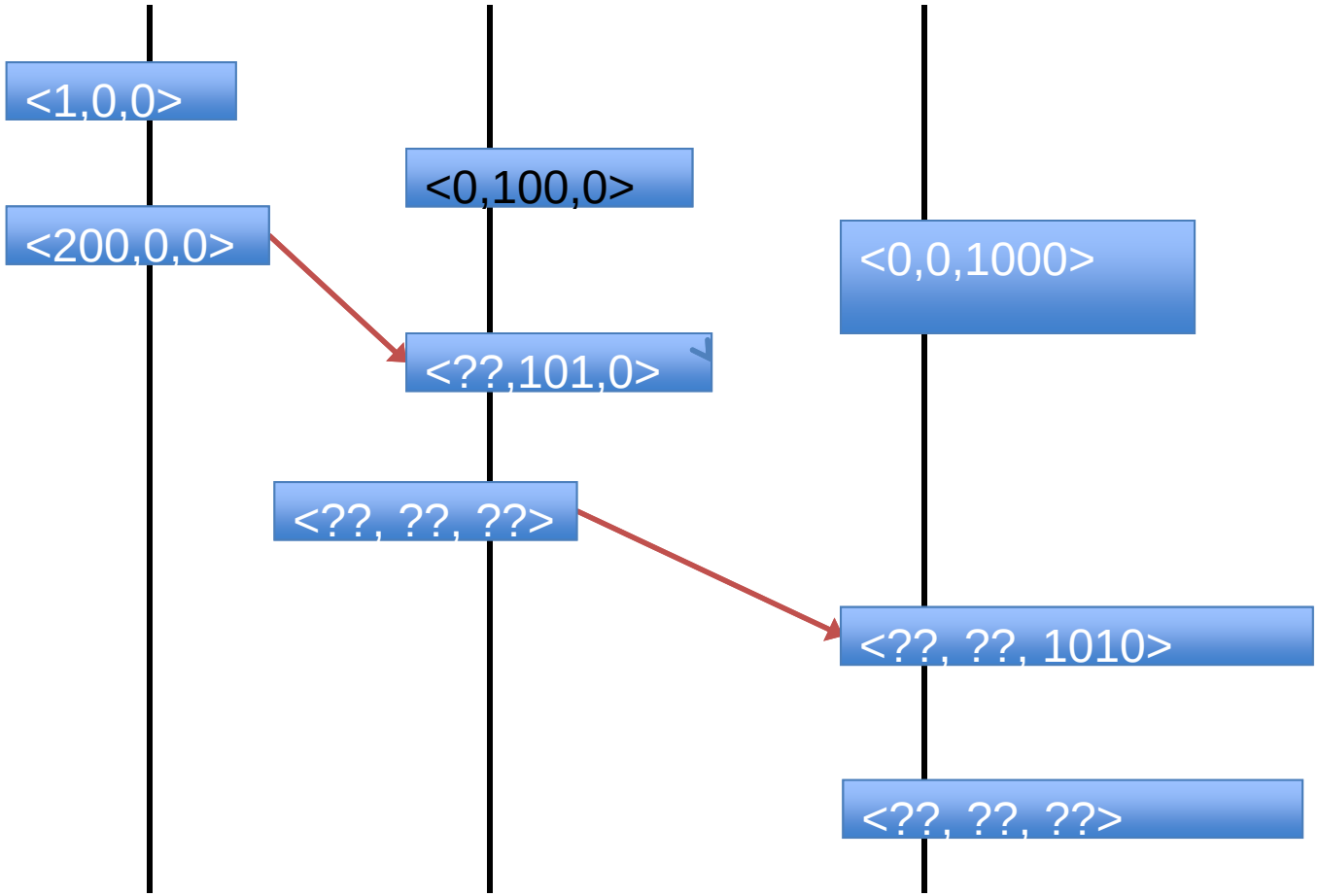
(scalar) logical clock

- Design a clock that can reflect the happens-before order
  - Increment within one process
  - Increment when receiving a message

Scalar clock



Vector clock



How to use logical time in race det?

- What is the causality relationship here?
- Example 1

Thread 1	*Thread 2*
tmp=x;	tmp=x;
x = tmp+1;	x=tmp+1;

- Example 2

Thread 1	*Thread 2 (child)*
p=malloc(10);	*p=10;
pthread_create(…)	

- Example 3 (lock)

How to detect data races?

- Happen-before algorithm
  - Use logic time-stamps to find concurrent accesses

Thread 1	Thread 2	
	lock (L);	<0,1>
	ptr=NULL;	<0,2>
	unlock(L);	<0,3>

<1,0> **ptr** = malloc(10)**;**
<2,3> lock (L);
<3,3> **ptr**[0]='a';
<4,3> unlock(L);

How to detect data races?

- Happen-before algorithm
  - Use logic time-stamps to find concurrent accesses

Thread 1	Thread 2
	ptr=NULL; <,>
	barrier(&b); <,>

<,> barrier(&b);
<,> **ptr** = malloc(10)**;**
<,> **ptr**[0]='a';

How to detect data races?

- Happen-before algorithm
  - Use logic time-stamps to find concurrent accesses

	Thread 1	Thread 2	
<1,0>	**ptr** = malloc(10)**;**		
<,>	lock (L);		
<,>	**ptr**[0]='a';		
<4,0>	unlock(L);		
		lock (L);	<4,1>
		ptr=NULL;	<4,2>
		unlock(L);	<,>

Happen-before algorithm summary

- Strength
  - Work for different types of synchronization
  - Few false positives in race detection
- Weakness
  - False negatives in race detection

How to detect data races?

- Lock-set algorithm
  - A common lock should protect all conflicting accesses to a shared variable

	Thread 1	Thread 2	
		lock (L);	
		ptr=NULL;	<L>
		unlock(L);	
</>	**ptr** = malloc(10)**;**		
	lock (L);		
<L>	**ptr**[0]='a';		
	unlock(L);		

	Thread 1	Thread 2	
</>	**ptr** = malloc(10)**;**		
	lock (L);		
<L>	**ptr**[0]='a';		
	unlock(L);		
		lock (L);	
		ptr=NULL;	<L>
		unlock(L);	

Eraser : A dynamic data race detector for multithreaded programs, TOCS'97

Lock-set algorithm summary

- Strength
  - Fewer false negatives
    - Interleaving in-sensitive
- Weakness
  - More false positives
  - Cannot handle non-lock synchronization

- How to solve the false positive problem?
  - H-B & Lockset hybrid race detection

Are we done?

- Performance
  - Huge problem
  - Solution?
- False positives
  - Huge problem
    - 90% of data races do not lead to visible failures* [PLDI'07]
  - Solution?
- False negatives

```
while (!flag) {};        flag=TRUE;
```

```
Thread 1
ptr = malloc(10);
lock (L);
ptr[0]='a';
unlock(L);
```

```
Thread 2
lock (L);
ptr=NULL;
unlock(L);
```

How to speed-up?

- Hardware support
  - Non-existing
  - Existing

- Sampling

Break

How to do better?

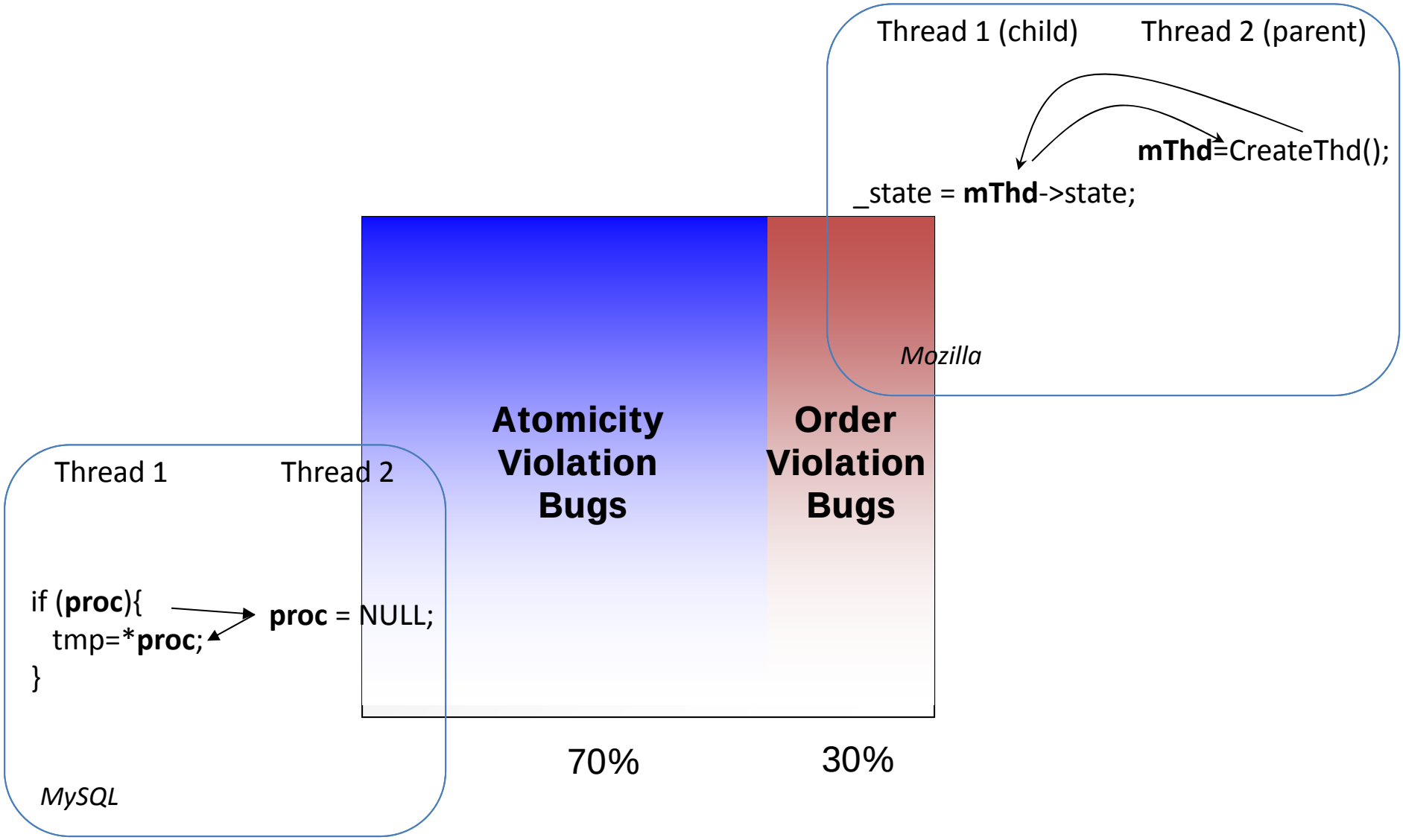
Let’s find a more accurate root-cause pattern for concurrency bugs!

Root-cause patterns

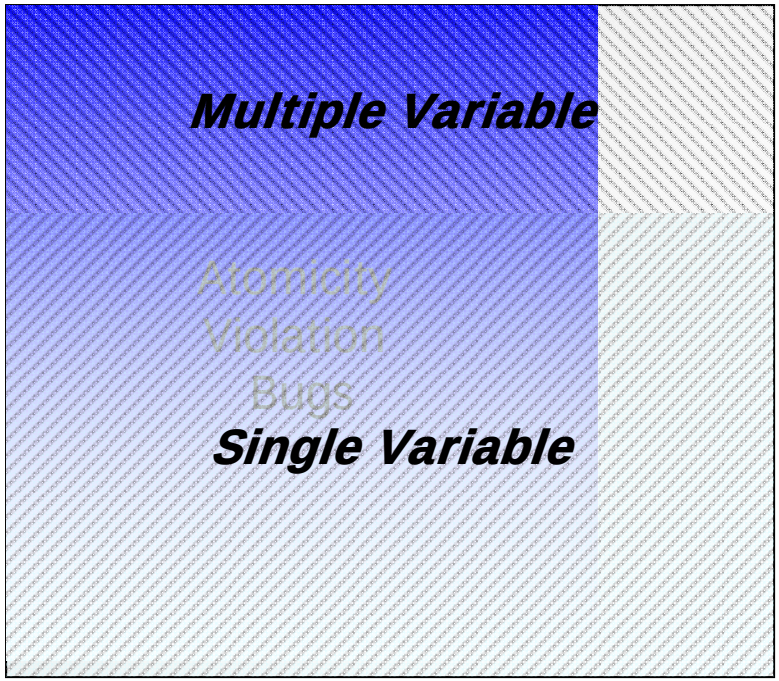
- A study of 105 real-world concurrency bugs

Learning from Mistakes --- A Comprehensive Study on Real World Concurrency Bug Characteristics, ASPLOS08

Root-cause patterns



Root-cause patterns



Why did I do this study?

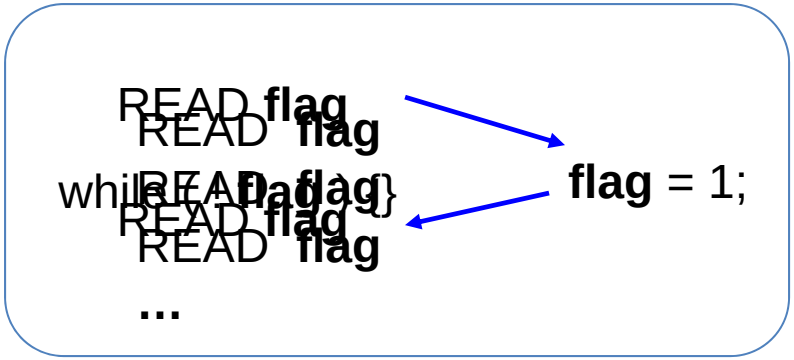
How to detect atomicity-violations?

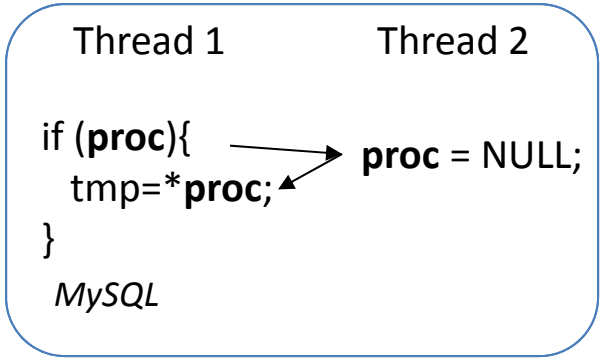
- Problem 1
  - Know which code region should maintain atomicity

- Problem 2
  - Judge whether a code region's atomicity is violated

How to detect atomicity-violations?

- Problem 1
  - Know which code region should maintain atomicity

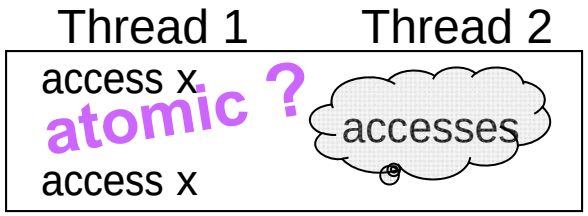




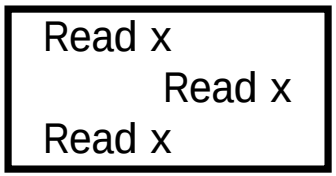
- Problem 2
  - Judge whether a code region's atomicity is violated

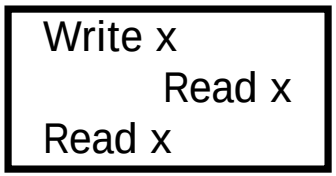
Solution to problem 2

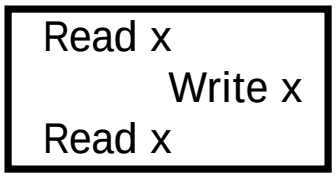
- Atomicity violation = unserializable interleaving

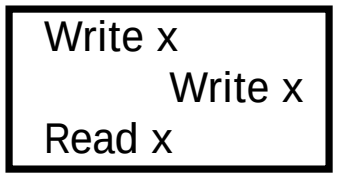


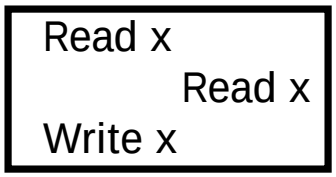
- Totally 8 cases of interleaving

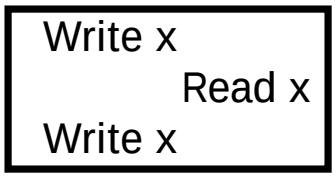


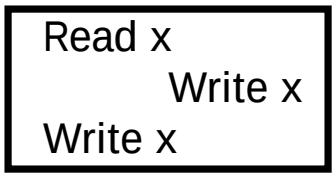


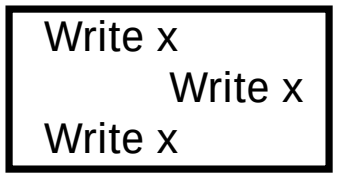










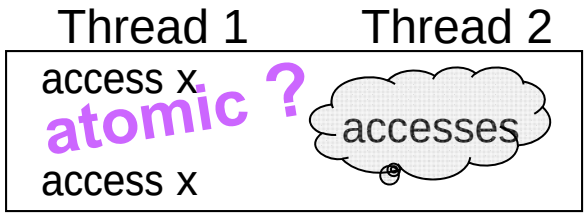


AVIO: Detecting Atomicity Violations via Access-Interleaving Invariants, ASPLOS'06

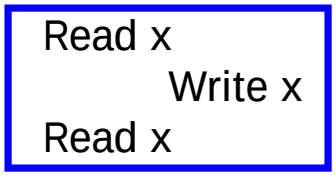
Associating synchronization constraints with data in an object-oriented language, POPL'06

Solution to problem 2

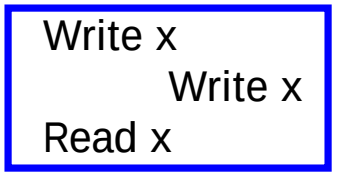
- Atomicity violation = unserializable interleaving



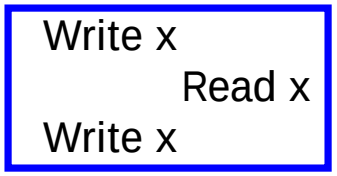
- 4 out of 8 cases are violations



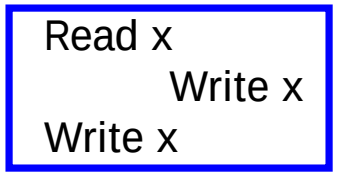
Inconsistent views



Too early overwritten



Leaking intermediate value

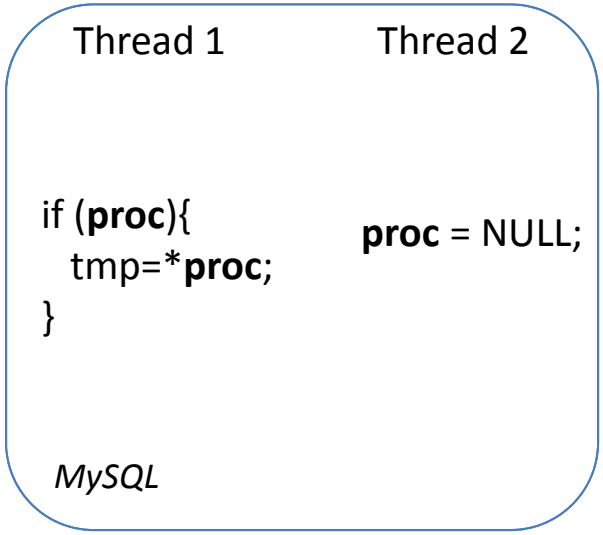


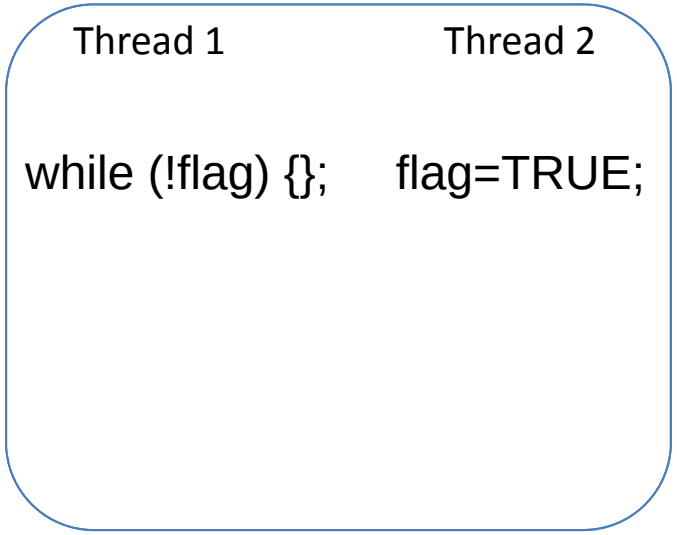
Using stale value

Both hardware and software solutions exist

Solution to problem 1

- Which code regions are expected to be atomic?
  - Manual annotation
  - ??





AVIO: Detecting Atomicity Violations via Access-Interleaving Invariants, ASPLOS'06

Inference based bug detection

Infer likely program invariants

- What is the typical value of x?
- What is the …?

- How to use it to detect general semantic bugs?

- How to use it to detect memory bugs?

- How to use it to detect concurrency bugs?

Solution to problem 1

- Which code regions are expected to be atomic?
  - Manual annotation
  - Training/Learning
  - Testing validation

Thread 1	Thread 2

if (**proc**){
  tmp=***proc**;
}
	proc = NULL;

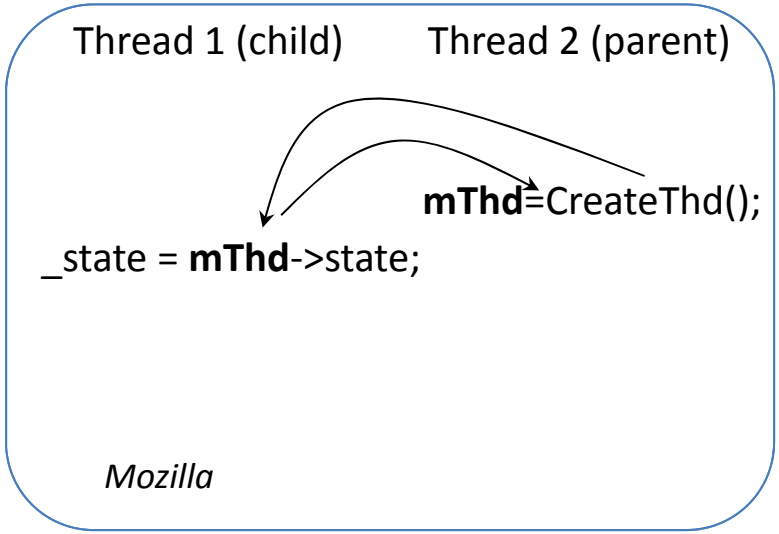
MySQL

Thread 1	Thread 2
while (!flag) {};	flag=TRUE;

AVIO: Detecting Atomicity Violations via Access-Interleaving Invariants, ASPLOS'06

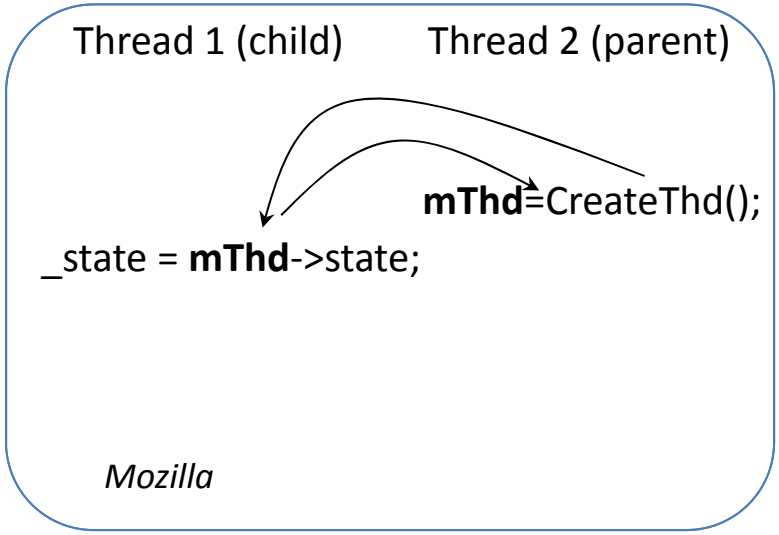
What are order violations?

- Expected order between two operations are flipped
- Can it be detected by atom. vio. detectors?
- Can it be detected by race detectors?



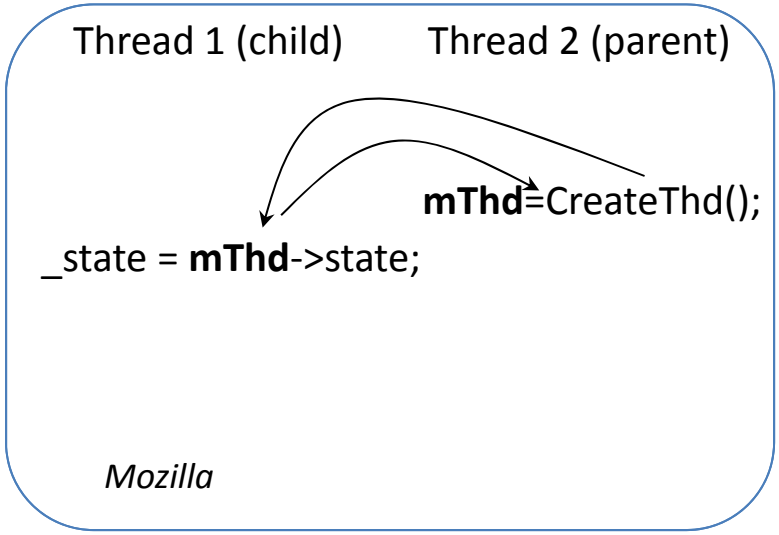
How to detect order violation?

- Problem 1
  - How to judge which is the correct order?
- Problem 2
  - How to detect the order violation?



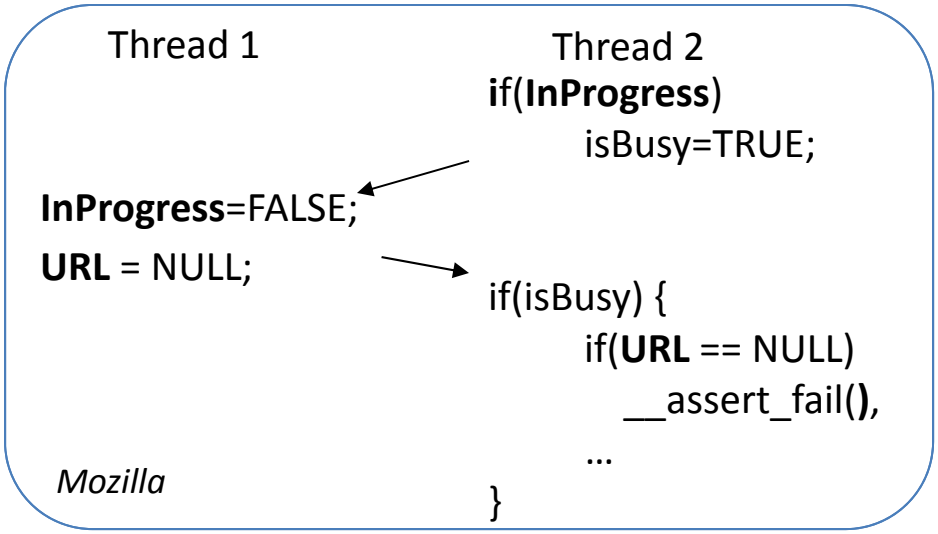
Solutions

- How to judge which is the correct order?
  - Learning based techniques [Micro'09, OOPSLA'10]
  - Semantic guided techniques [ASPLOS'11]
- How to detect the order violation
  - Easy



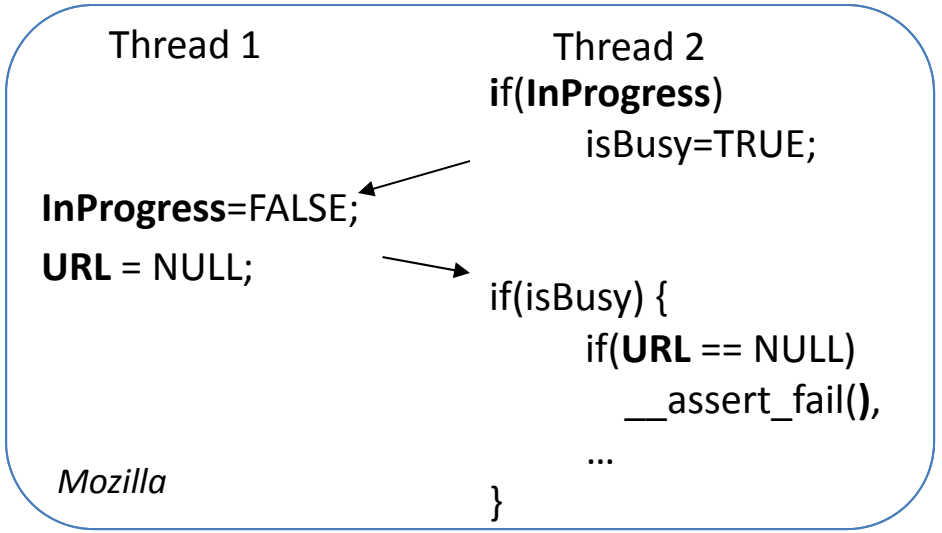
What are multi-var conc. bugs?

- Multi-variable bugs
  - Untimely accesses to correlated variables
- Can it be detected by race detectors?
- Can it be detected by AVIO?



How to detect multi-variable bugs?

- Problem 1
  - How to judge which variables are correlated?
- Problem 2
  - How to detect untimely accesses



Solutions

- Which variables are correlated?
  - Variables that are frequently accessed together
- How to detect the violation?
  - Extend existing single-variable bug detectors

```
struct JSCache {
  ...
  JSEntry table[SIZE];
  bool empty;
  ..
}
```
Mozilla

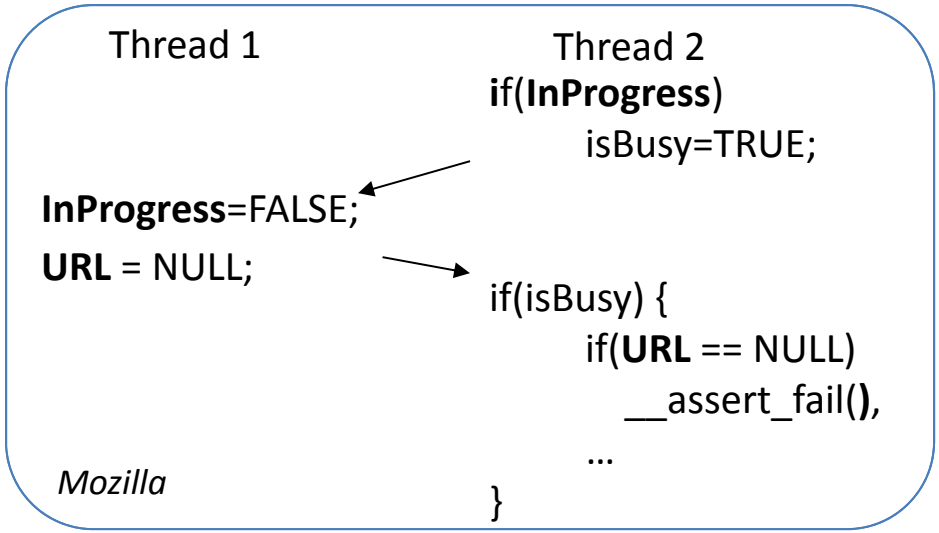
```
struct JSRuntime {
  ...
  int totalString;
  double lengthSum;
  ..
}
```
Mozilla

```
struct fb_var_screeninfo
{  ...
    int red_msb;
    int blue_msb;
    int green_msb;
    int transp_msb;
}
```

Linux

Solutions

- Which variables are correlated?
  - Variables that are frequently accessed together
- How to detect the violation?
  - Extend existing single-variable bug detectors



Are we done?

- Are these “learning”-based techniques perfect?

Are we done?

- False positives
  - Still a problem!
- False negatives
  - Still a problem!

Break

How to do better?

Thread 1 Thread 2

```
if (proc){
  tmp=*proc;
}
```

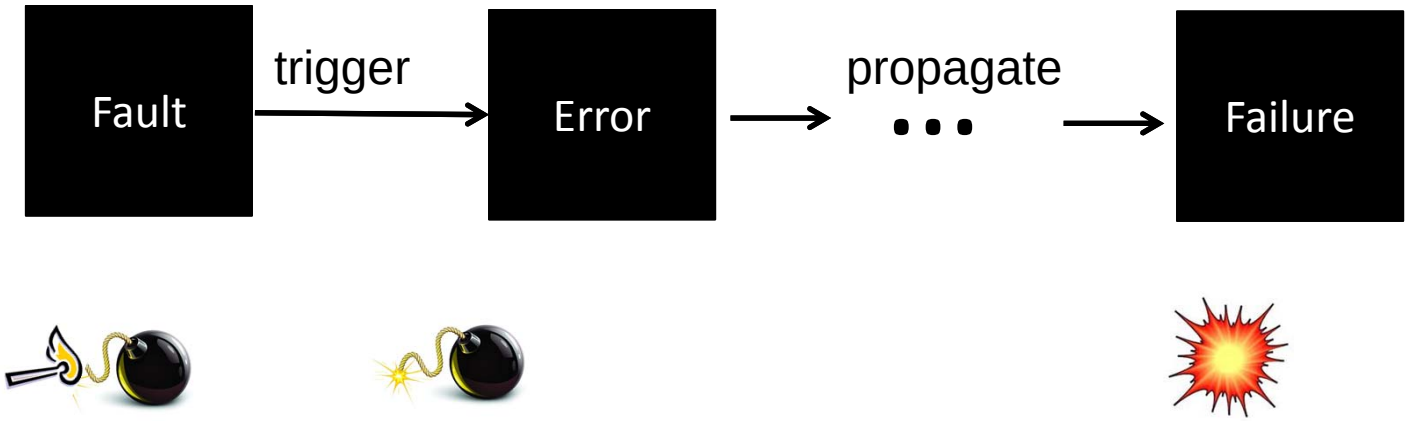
proc = NULL;

MySQL

How to do better?

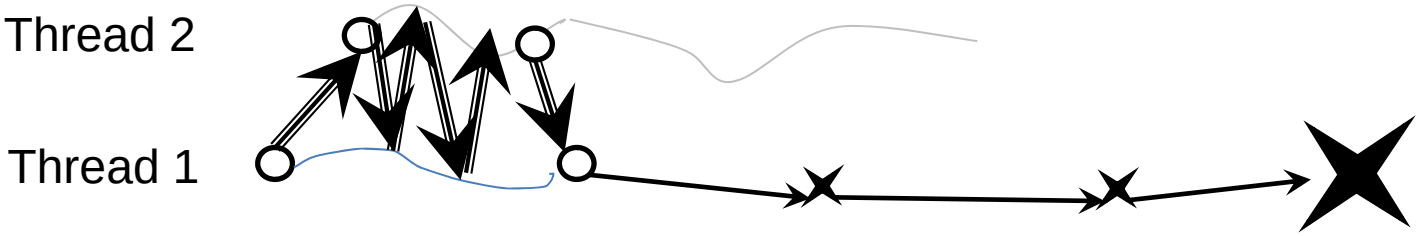
If we cannot find a more accurate root-cause pattern,
let's look at the effect patterns of concurrency bugs!

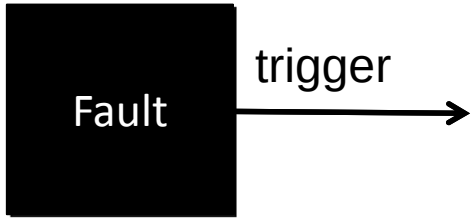
The lifecycle of bugs



The lifecycle of (most) concurrency bugs

based on 70 real-world bugs

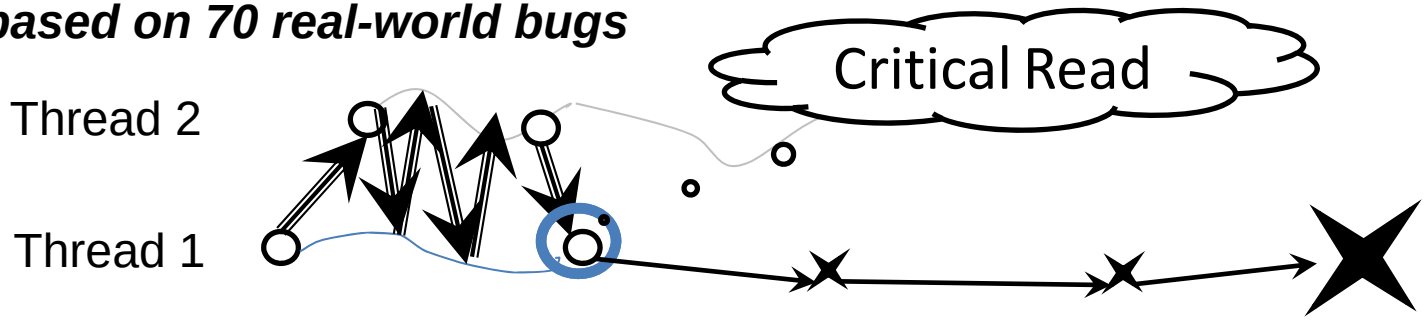


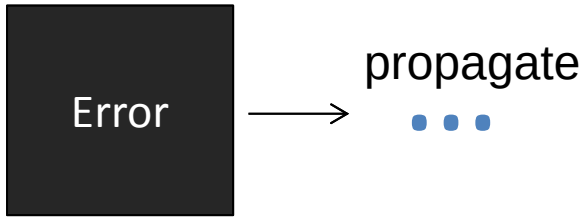


Data races
Atomicity violations
    single variable
    multiple variables
Order violations
…

The lifecycle of (most) concurrency bugs

based on 70 real-world bugs





- Memory errors
  - NULL ptr
  - Dangling ptr
  - Uninitialized read
  - Buffer overflow
- Semantic errors

The lifecycle of (most) concurrency bugs

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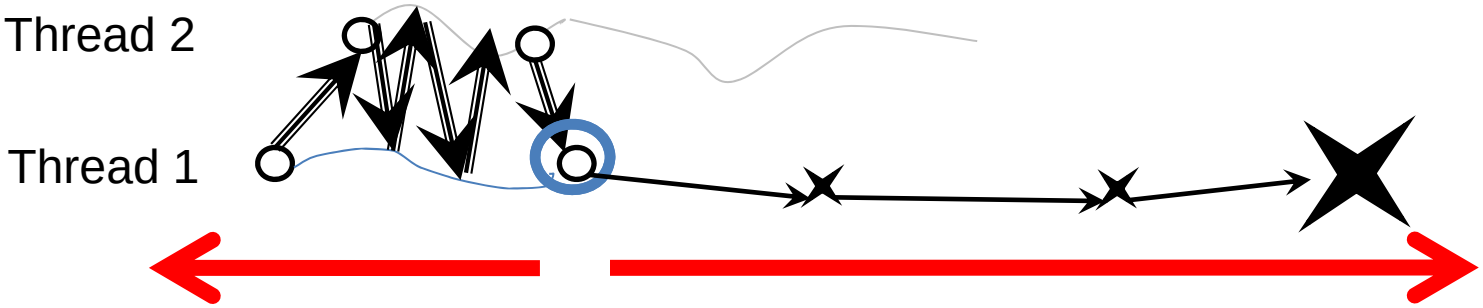
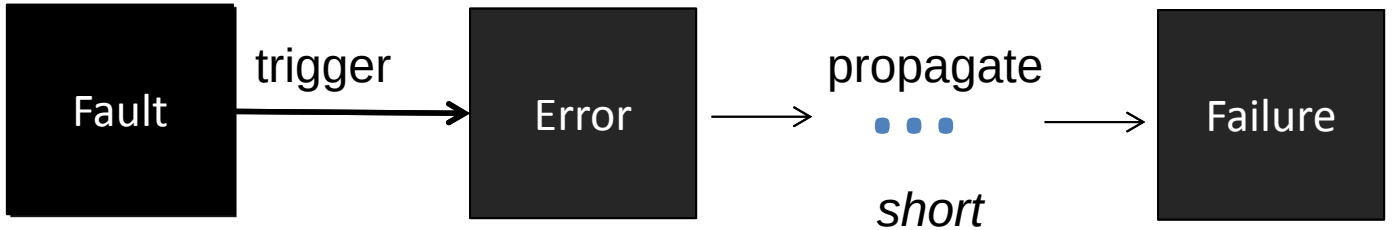




short
single-threaded

- Crash @ invalid memory
- Crash @ assertion
- Infinite loops
- Incorrect outputs
- Error messages

Examples

Thread 1	Thread 2

if (**proc**){
  tmp=* **proc**;
}
	proc = NULL;

MySQL

atomicity violation → null-ptr deref. → crash

Thread 1	Thread 2
	mThd=CreateThd();
_state = **mThd**->state;	

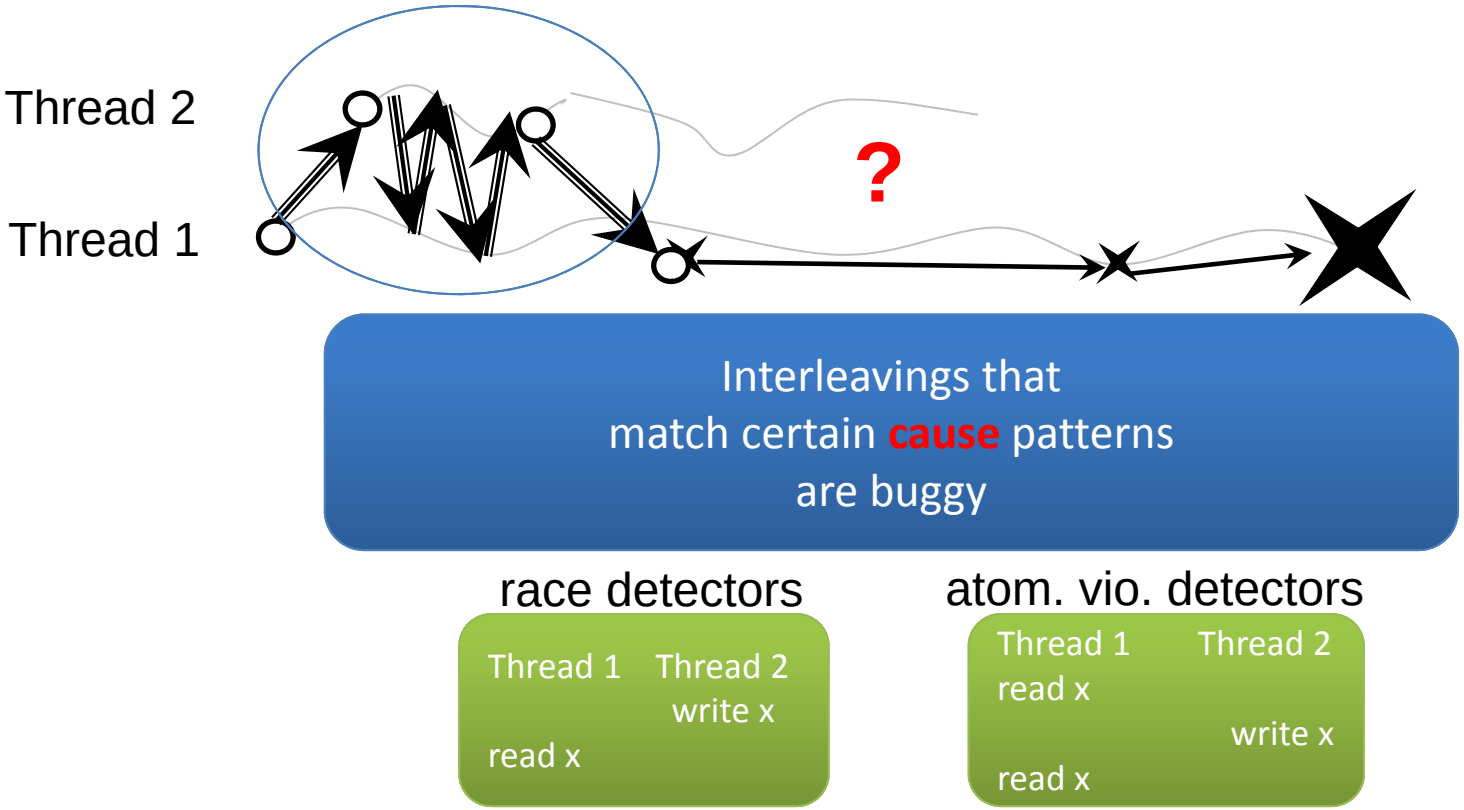
Mozilla

order violation → uninitialized read → crash

Summary of effect characteristics

- Simple error/failure patterns
- Single-threaded error propagation
- Short error propagation

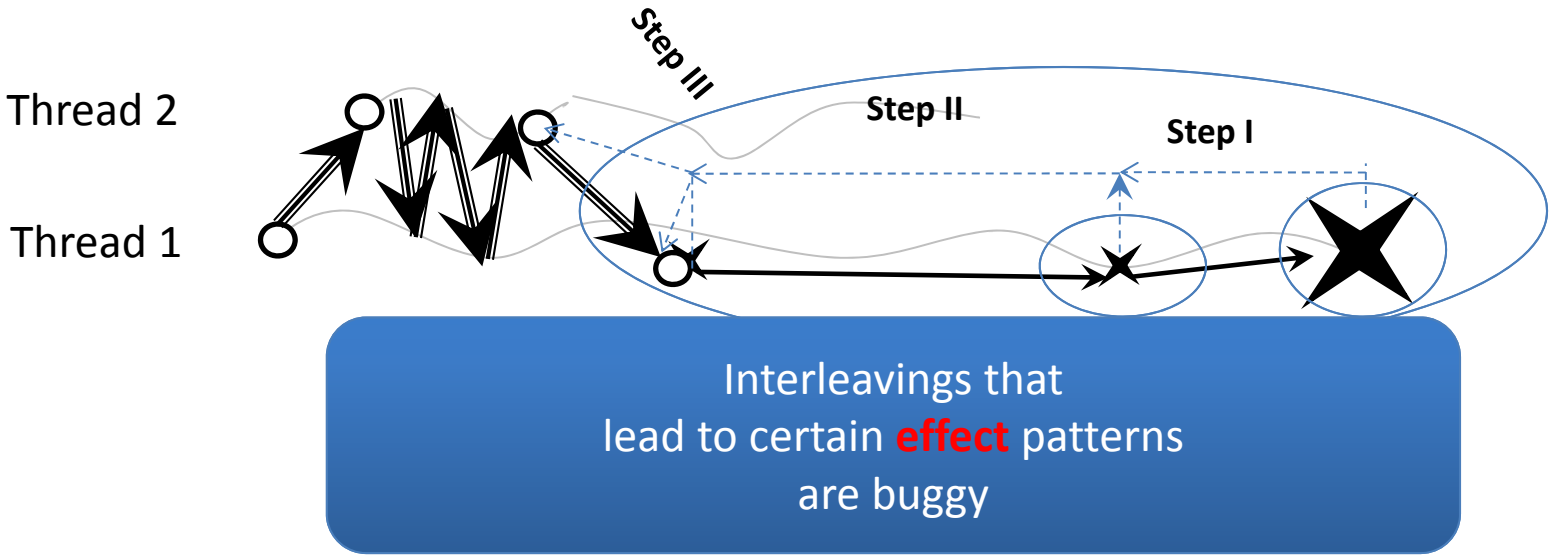
Cause-oriented approach



- Limitations
  - False positives
  - False negatives

SL29
SL31
SL30

Effect-oriented approach



- Step 1: *Statically* identify potential failure/error site
- Step 2: *Statically* look for critical reads
- Step 3: *Dynamically* identify buggy interleaving

Fewer false positive

Fewer* false negative

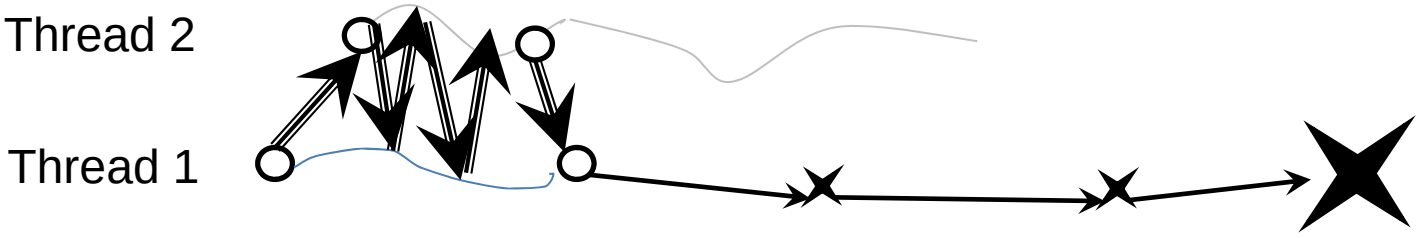
Slide 70

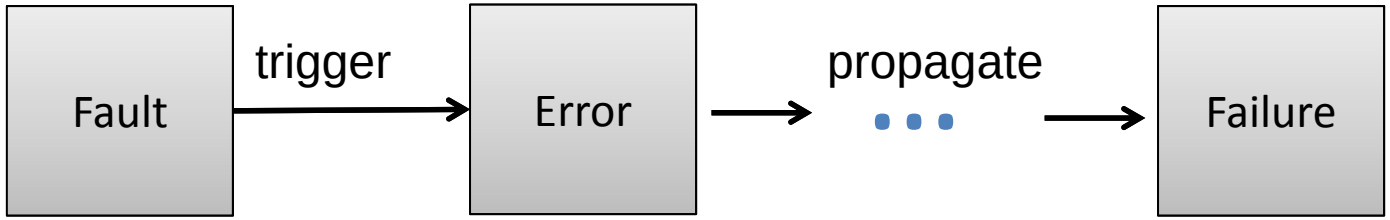
SL29 Shan Lu, 2014-1-7

SL30 i like the mapping in paper: cause maps to xxx effects; effect map back to xxx.
Shan Lu, 2014-1-7

SL31 if i refer to interleaving here, we need to define interleaving earlier
Shan Lu, 2014-1-8

Our tools





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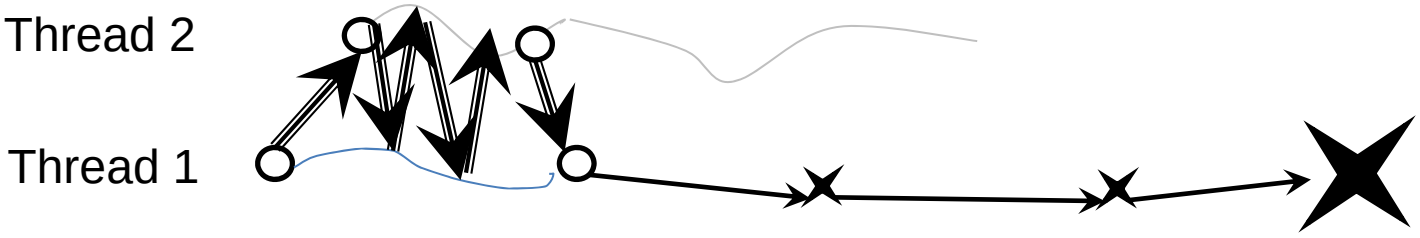

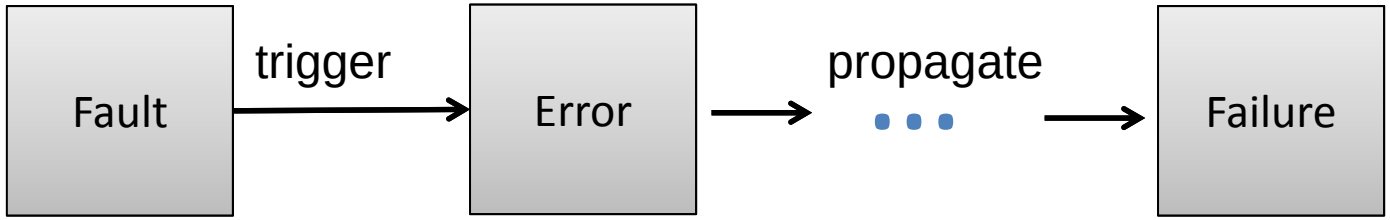

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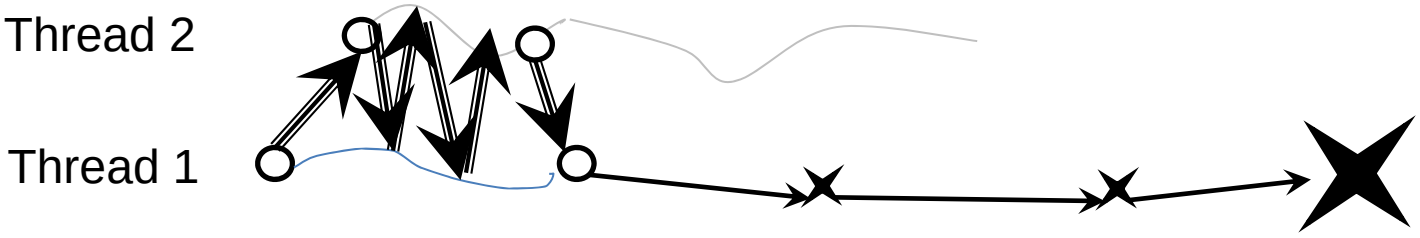

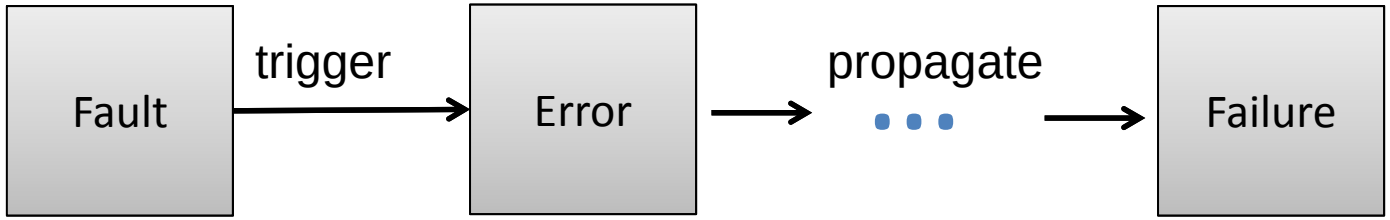

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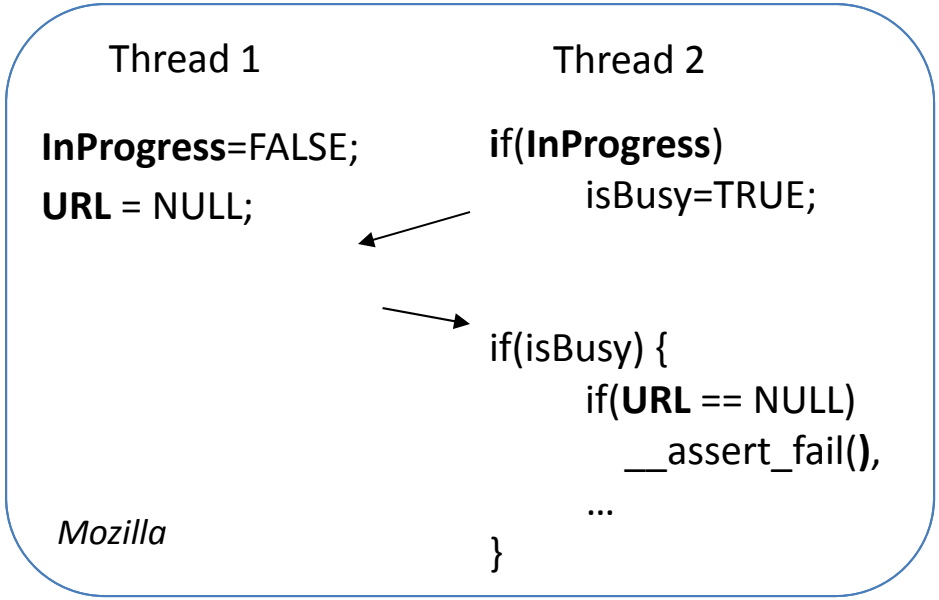
  - Error messages

ConSeq bug example



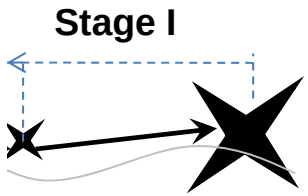
MUVI: Automatically Inferring Multi-Variable Access Correlations and Detecting Related Semantic and Concurrency Bugs.
Shan Lu, et. al., SOSP'09

Slide 74

SL32 the sosp, muvi reference should be put earlier

Shan Lu, 2014-1-8

Step 1: Identify potential failure sites

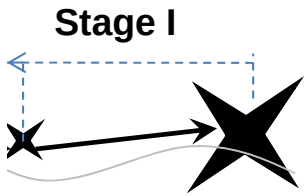


Statically look for places where failures could happen

Failure Type
Assertion Failure
Error Message
Incorrect output
Infinite loop

Number of failure sites in MySQL: ~1000

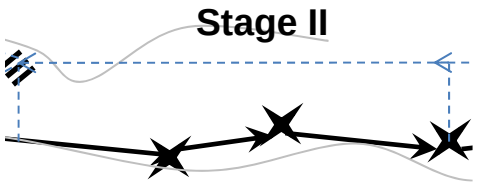
Step 1: Identify potential failure sites



Statically look for places where failures could happen

```
if(InProgress)
        isBusy=TRUE;
if(isBusy){
        if(URL ==NULL){
                __assert_fail();
        }
}
```

Step 2: Look for critical reads



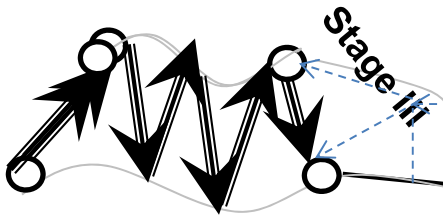
Statically find shared mem. reads that impact failure sites

```
if(InProgress)
        isBusy=TRUE;
if(isBusy){
    if(URL ==NULL){
            _assert_fail();
        }
}
```

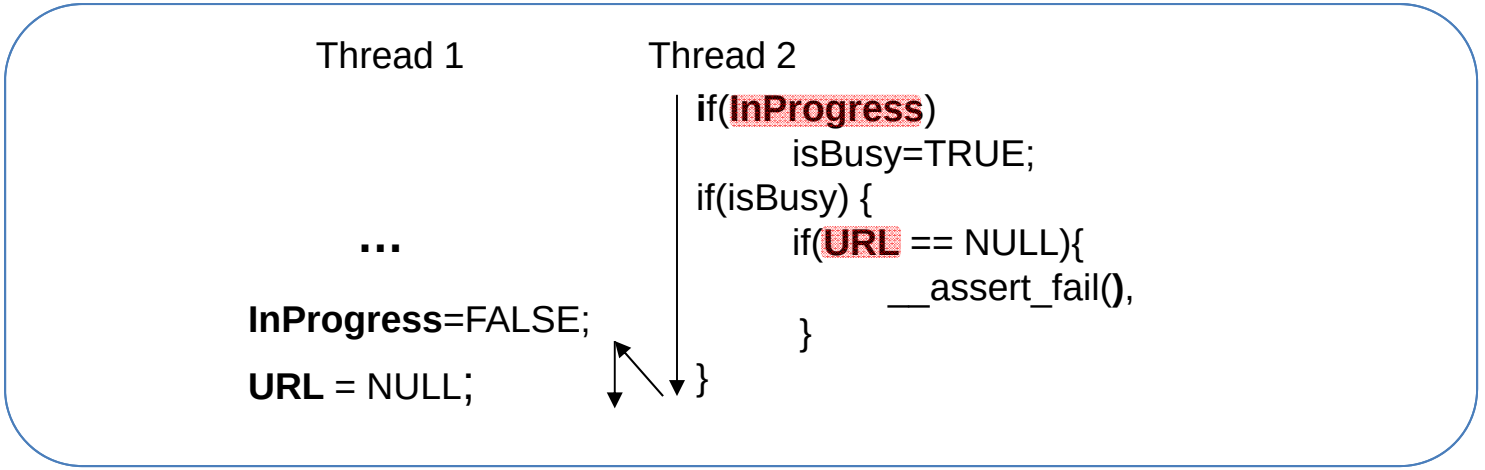
4 3 2 1

Static slicing

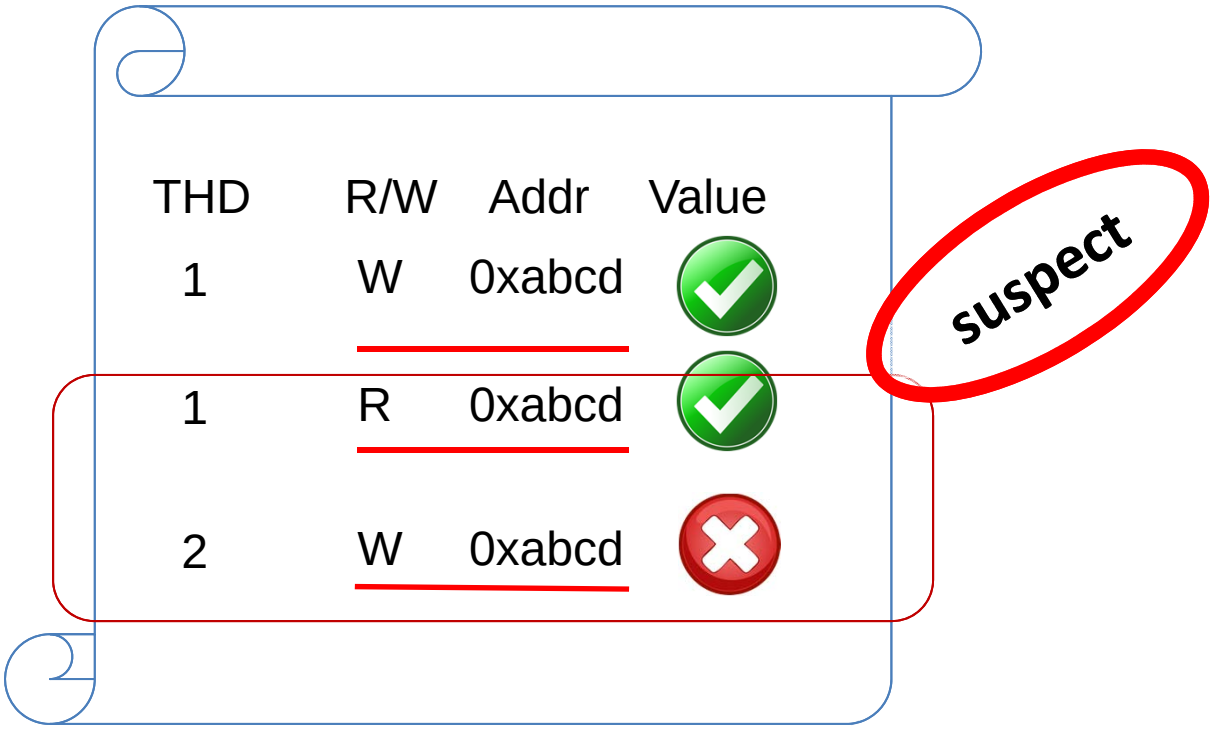
Stage 3: Look for buggy interleavings



Dynamic analysis looks for interleavings that provide critical reads with bad values



Look for alternative data dependence



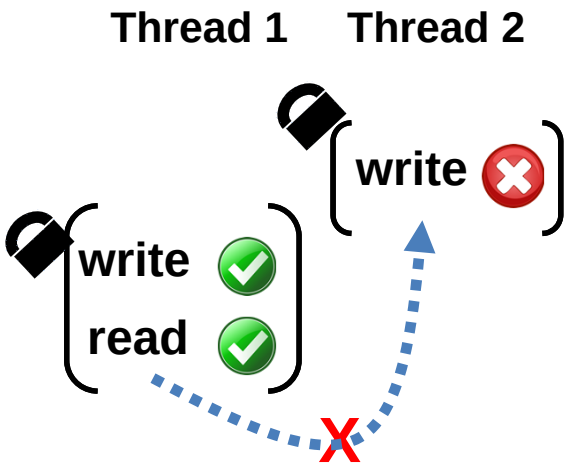
Is the alternative data dependence feasible in future runs?

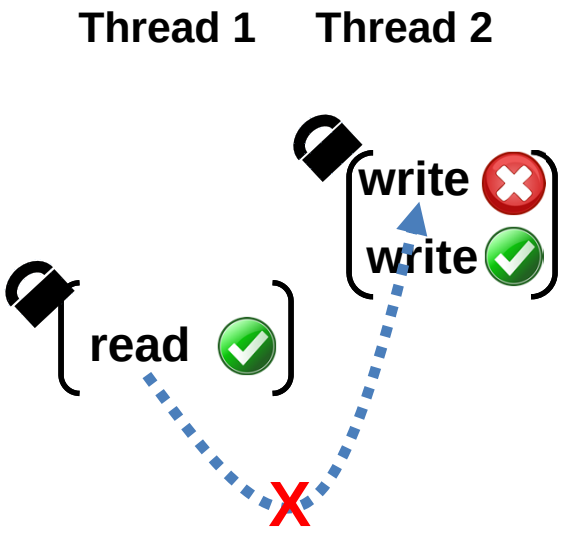
Dependence feasibility analysis

- Can synchronization prevent a data dependence?

Dependence feasibility analysis

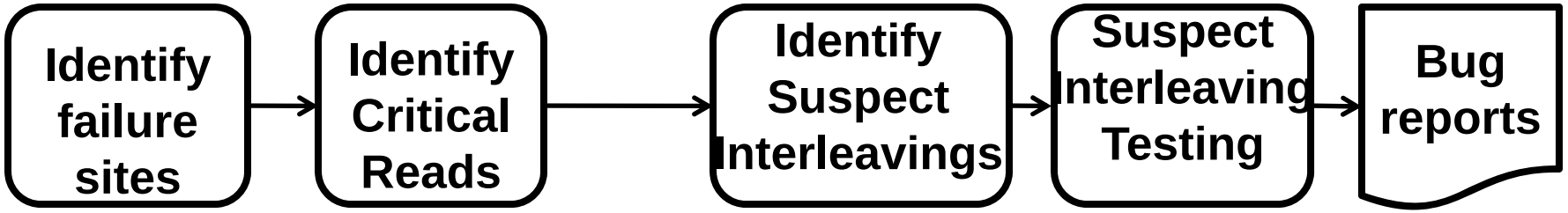
- Locks could make a data-dependence infeasible

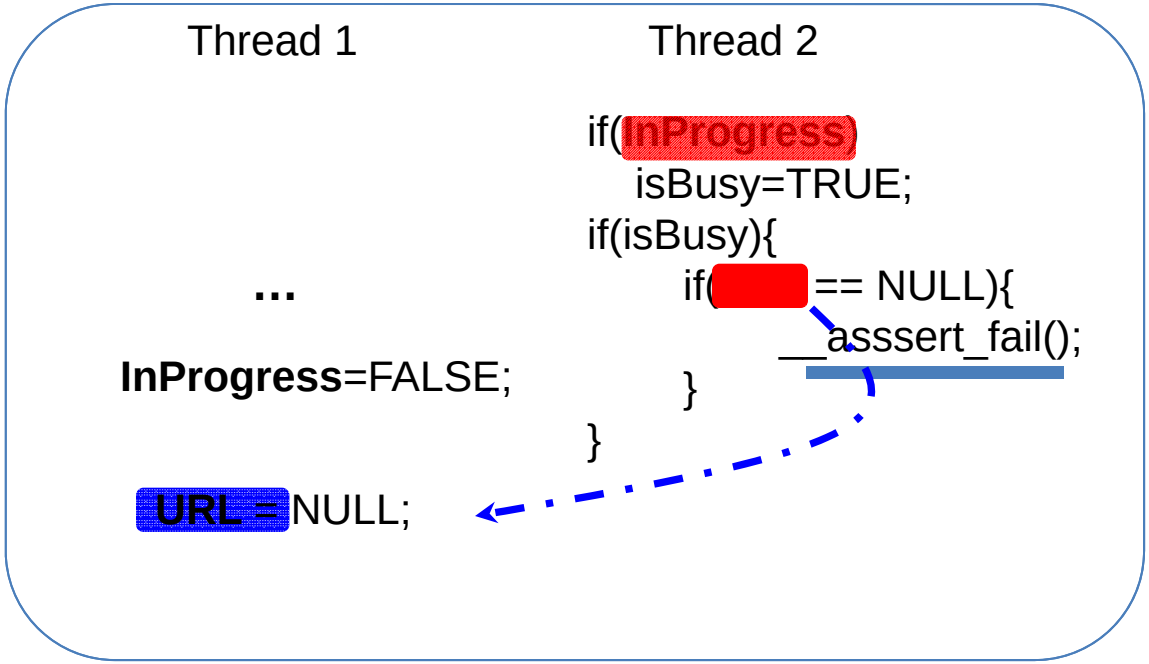




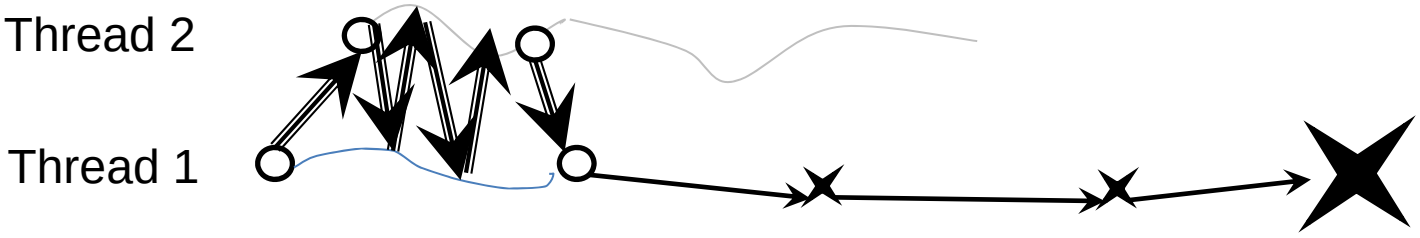
- Barriers could make a data-dependence infeasible

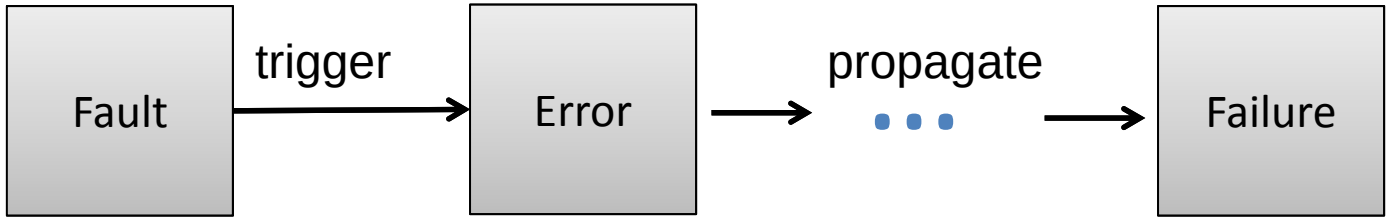
Put everything together





ConMem





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- Semantic errors

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- Error messages

ConMem bug example

- What are the errors?
- How to detect them using dynamic analysis?

Thread 1	Thread 2

if (**proc**){
tmp=* **proc**;
}
	proc = NULL;

MySQL

Thread 1	Thread 2
_state = **mThd**->state;	**mThd**=CreateThd();

Mozilla

5-min Break?

Summary of conc. bug detection

- How to detect them?
  - Find patterns
    - Cause patterns
    - Effect patterns
- What are the remaining challenges?
  - Performance
  - False negatives [ReEnact.ISCA03, ParaLog.ASPLOS10, RaceMob.SOSP13, LiteRace, …]
  - False positives
    - Customized synchronization
- The state of practice
  - Race detection; Atom. detection; …

Outline

- What are concurrency bugs
- Concurrency bug detection
- Concurrency bug exposing
- Concurrency bug failure recovery
- Concurrency bug fixing
- Others
- Conclusion

Exposing Concurrency Bugs

Background --- Software Testing

- Testing space
- Coverage criteria
  - Testing property
- Test suite
- Software testing is extremely important!

The challenges

- Huge state space

- What is the coverage criteria?
- How to cover a testing property?

Background in testing

- Coverage criteria
  - Examples
  - Complexity vs. Capability

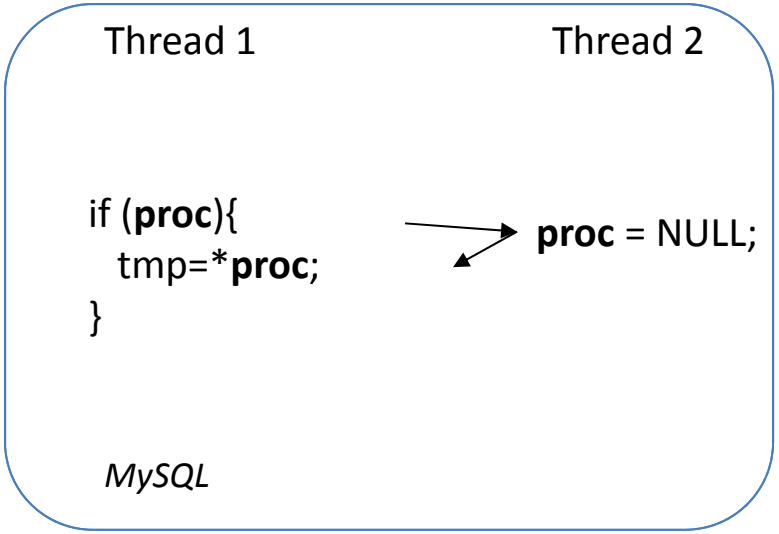
- Test input design

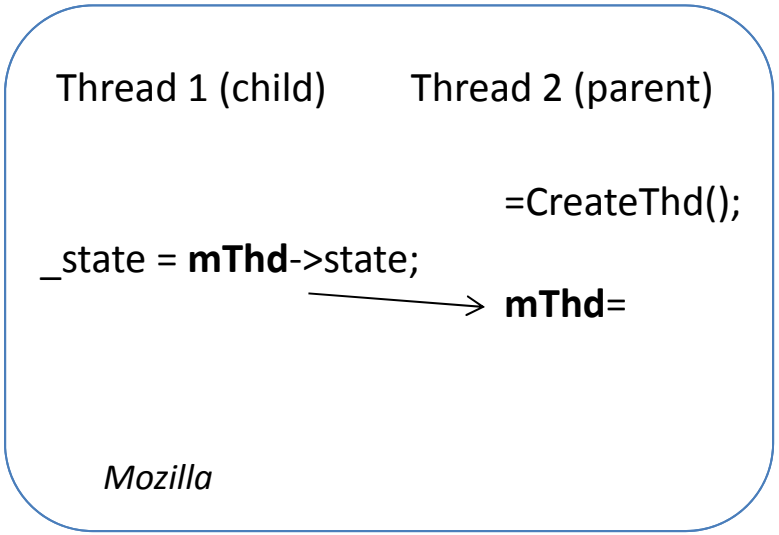
What are the coverage criteria?

- Total-order [TSE92]
- ALL-DU [ICSM92,ISSTA98]
- Synchronization [PPoPP05]
- Function [SoQua07]

- Bug-pattern based

  [Chess, RaceFuzzer, CTrigger…]





How to cover a testing property?

How can I make A execute before B?

- Ad-hoc solution
  - Single-core based
  - Multi-core based
- Constraint-solving based solution [Madhu Viswanathan, NEC]

- How many properties can be covered in one run?

[Madan Musuvathi]

Summary of exposing con. bugs

- Key challenges
- Key solutions
- What are the remaining challenges?
  - Better coverage criteria
  - Input generation
  - Regression testing
  - Unit testing

Summary of the day

- Concurrency bug detection
  - Cause based detection
    - Data race; atomicity violation; order violation; single variable; multi-variable
  - Effect based detection
  - Bug exposing (testing)
- Detection mechanisms
  - Run-time analysis
  - Static analysis
  - Learning-based technique