ThreadSanitizer
Data race detection in practice

Konstantin Serebryany <kcc@google.com>

Timur Iskhodzhanov <timur.iskhodzhanov@phystech.edu>

Dec 12 2009

Data races are scary

A data race occurs when two or more threads concurrently access a shared memory location and at least one of the accesses is a write.

```
std::map<int,int> my_map;
```

```
void Thread1() {
   my_map[123] = 1;
}
```

```
void Thread2() {
   my_map[345] = 2;
}
```

Our goal: find races in Google code

Dynamic race detectors

- Intercept program events at run-time
  - Memory access: READ, WRITE
  - Synchronization: LOCK, UNLOCK, SIGNAL, WAIT
- Maintain global state
  - Locks, other synchronization events, threads
  - Memory allocations
- Maintain shadow state for each memory location (byte)
  - Remember previous accesses
  - Report race in appropriate state
- Two major approaches:
  - LockSet
  - Happens-before

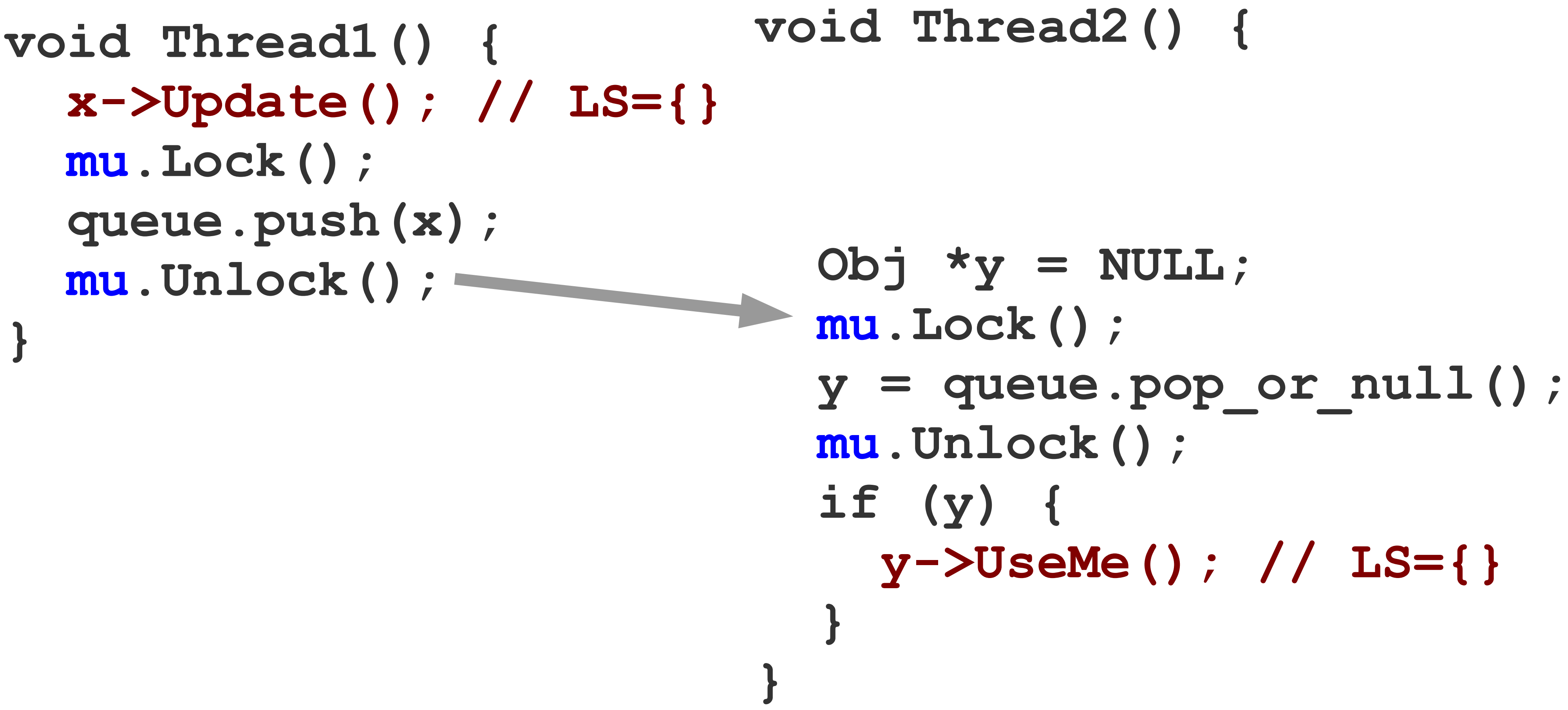
LockSet

```
void Thread1() {
  mu1.Lock();
  mu2.Lock();
  *X = 1;
  mu2.Unlock();
  mu1.Unlock(); ...
```

```
void Thread2() {
  mu1.Lock();
  mu3.Lock();
  *X = 2;
  mu3.Unlock();
  mu1.Unlock(); ...
```

- LockSet: a set of locks held during a memory access
  - Thread1: {`mu1, mu2`}
  - Thread2: {`mu1, mu3`}
- Common LockSet: intersection of LockSets
  - {`mu1`}

LockSet: false positives

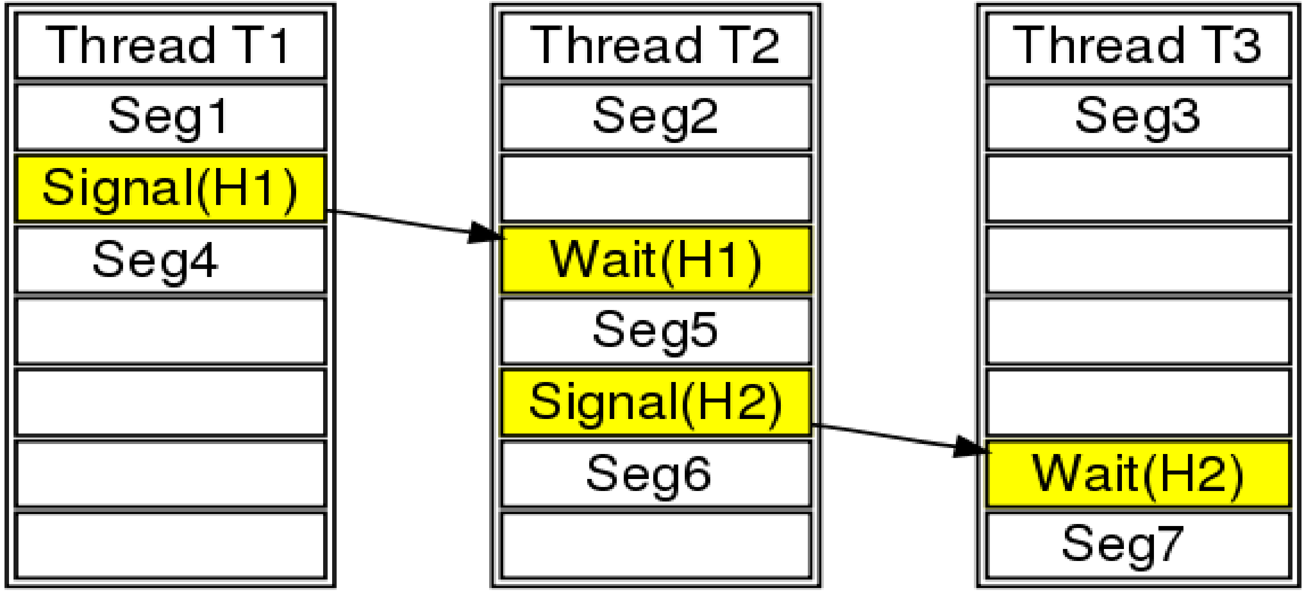


```
void Thread1() {
  x->Update(); // LS={}
  mu.Lock();
  queue.push(x);
  mu.Unlock();
}
```

```
void Thread2() {



  Obj *y = NULL;
  mu.Lock();
  y = queue.pop_or_null();
  mu.Unlock();
  if (y) {
    y->UseMe(); // LS={}
  }
}
```

Happens-before

partial order on all events



Thread T1

Seg1

Signal(H1)

Seg4

Thread T2

Seg2

Wait(H1)

Seg5

Signal(H2)

Seg6

Thread T3

Seg3

Wait(H2)

Seg7

Segment: a sequence of READ/WRITE events of one thread

Signal(obj) ⟹ Wait(obj) is a happens-before arc

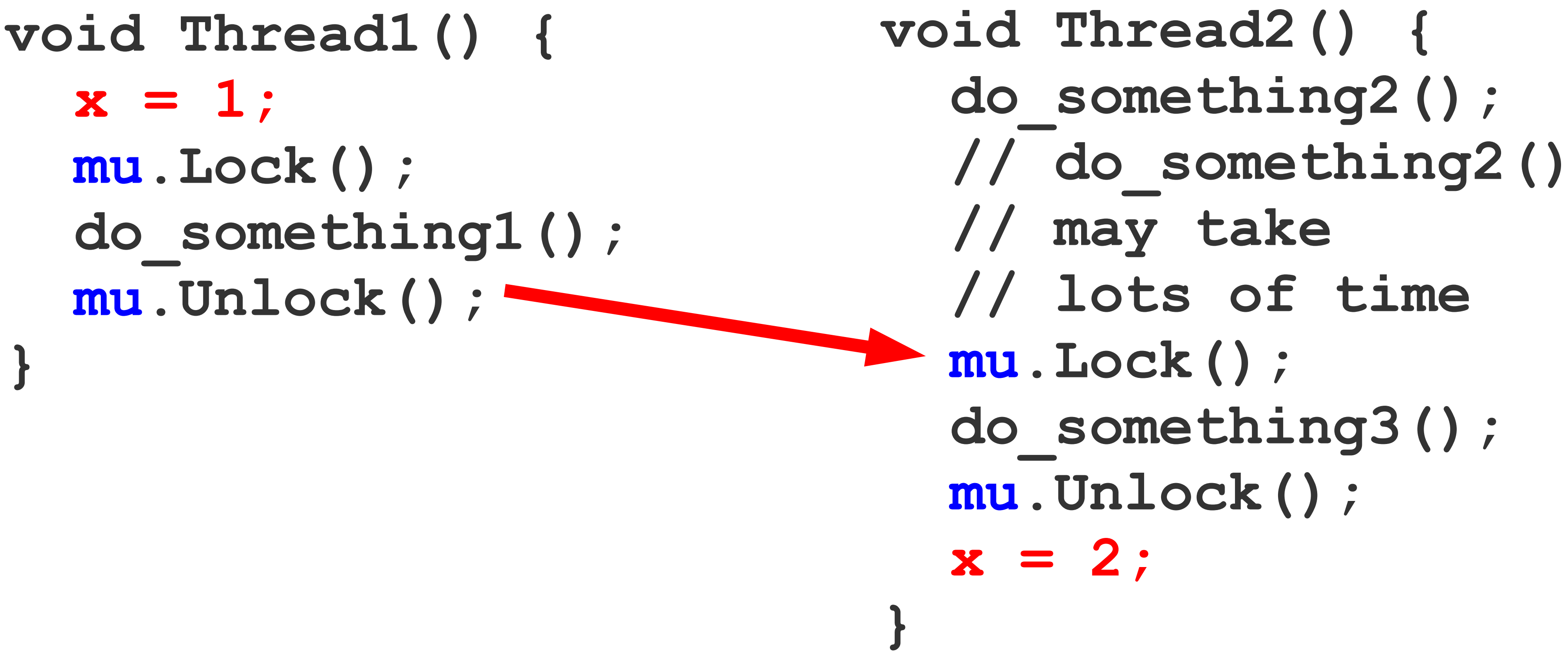
Seg1 $\prec$ Seg4 -- segments belong to the same thread.

Seg1 $\prec$ Seg5 -- due to Signal/Wait pair with a macthing object.

Seg1 $\prec$ Seg7 -- happens-before is transitive.

Seg3 $\nprec$ Seg6 -- no ordering constraint.

Pure happens-before: misses races



```
void Thread1() {
  x = 1;
  mu.Lock();
  do_something1();
  mu.Unlock();
}
```

```
void Thread2() {
  do_something2();
  // do_something2()
  // may take
  // lots of time
  mu.Lock();
  do_something3();
  mu.Unlock();
  x = 2;
}
```

Happens-before vs LockSet

- Pure LockSet
  - Many false warnings (impractical in most cases)
  - Does not miss races, fast
- Pure happens-before detectors:
  - Unlock → Lock is a happens-before arc
  - No false positives
    - unless you use lock-free synchronization
  - Less predictable (bad for continuos build)
  - Misses many races (30% - 50%)
- Hybrid (LockSet for locks, happens-before for the rest):
  - No happens-before arc on Unlock/Lock
  - Has false positives (easy to annotate)
  - More predictable
  - Finds more races

Dynamic annotations

```
void Thread1() {
  x->Update(); // LS={}
  mu.Lock();
  queue.push(x);
  ANNOTATE_HAPPENS_BEFORE(x);
  mu.Unlock();
}
```

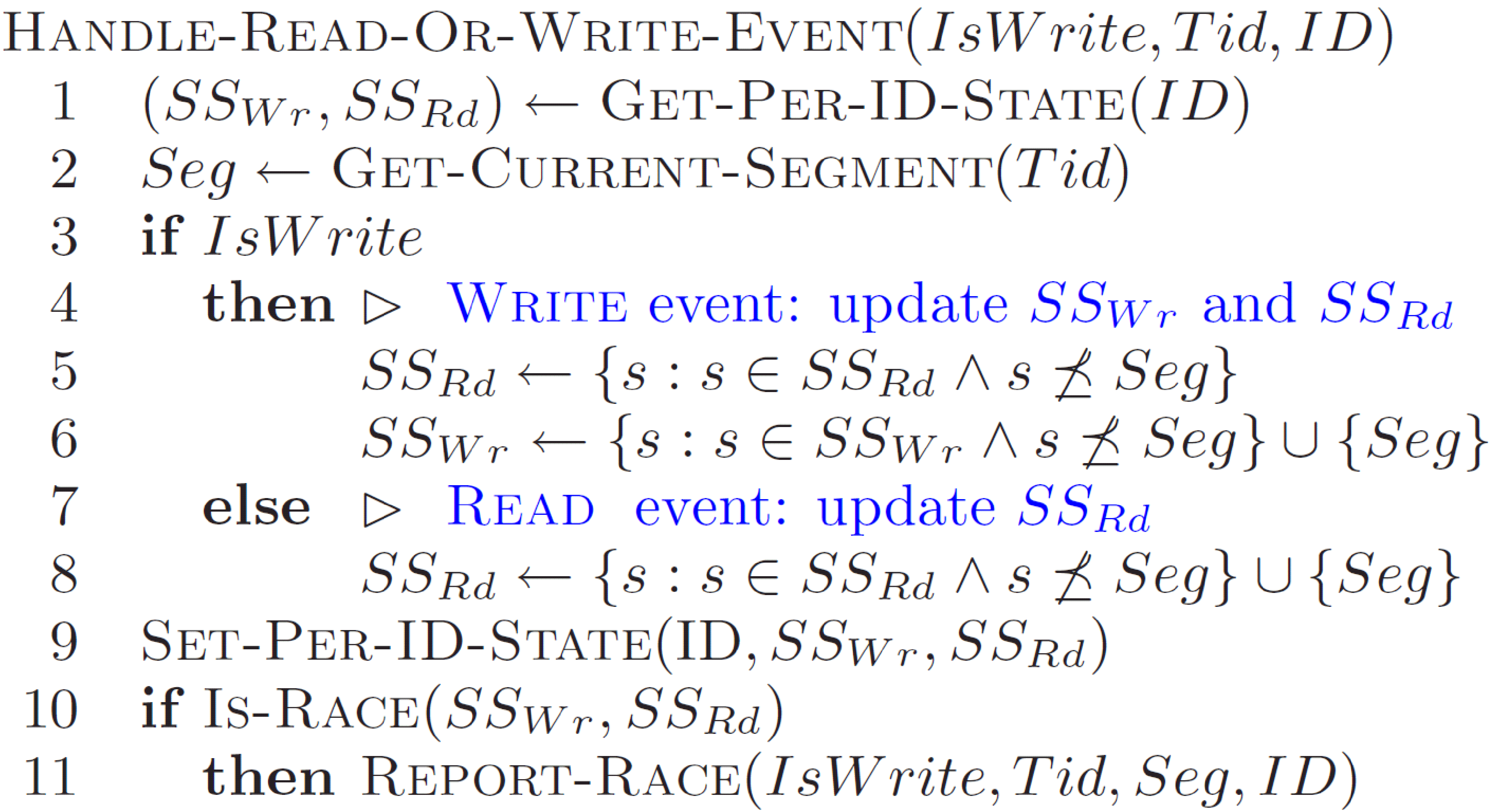
```
void Thread2() {



  Obj *y = NULL;
  mu.Lock();
  y = queue.pop_or_null();
  ANNOTATE_HAPPENS_AFTER(y);
  mu.Unlock();
  if (y) {
    y->UseMe(); // LS={}
  }
}
```

- Annotate lock-free synchronization
- Annotate false positives of hybrid mode
- Annotate benign races

ThreadSanitizer: Algorithm

- Segment: a sequence of READ/WRITE events of one thread
  - All events in a segment have the same LockSet
- Segment Set: a set of segments none of which happen-before any other
- Shadow state:
  - Writer Segment Set: all recent writes
  - Reader Segment Set: all recent reads, unordered with or happened-after writes
- State machine: on each READ/WRITE event
  - update the Segment Sets
  - check accesses for race

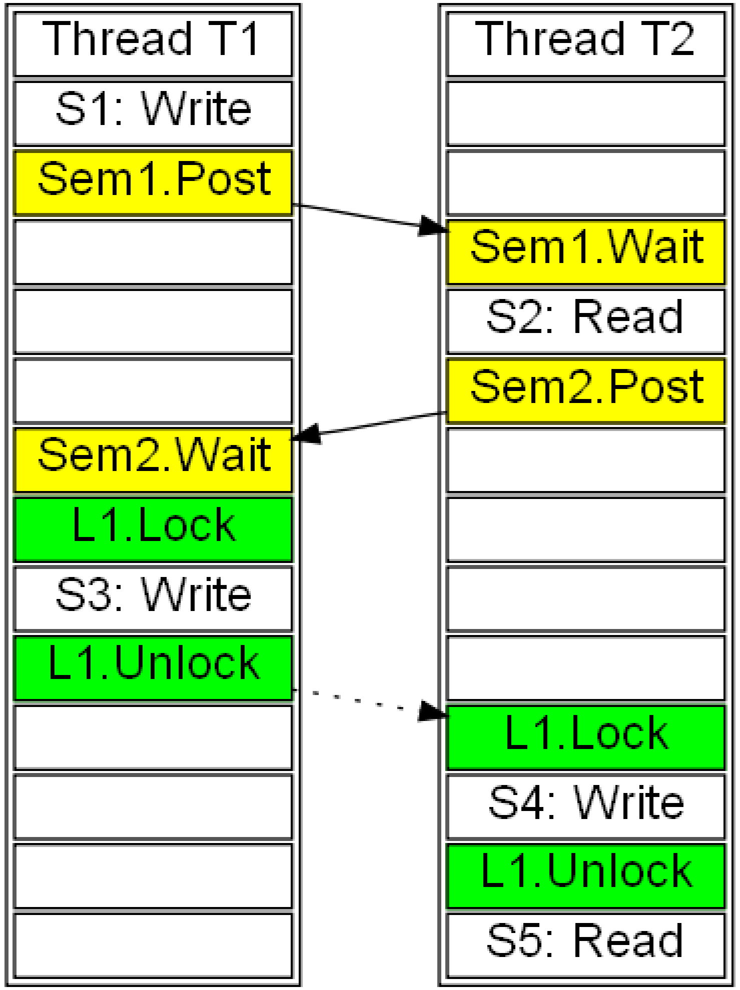
ThreadSanitizer: Algorithm



```
HANDLE-READ-OR-WRITE-EVENT($IsWrite, Tid, ID$)
    $(SS_{Wr}, SS_{Rd})$ ← GET-PER-ID-STATE($ID$)
    $Seg$ ← GET-CURRENT-SEGMENT($Tid$)
    if $IsWrite$
        then ▷ WRITE event: update $SS_{Wr}$ and $SS_{Rd}$
                $SS_{Rd} \leftarrow \{s : s \in SS_{Rd} \wedge s \not\preceq Seg\}$
                $SS_{Wr} \leftarrow \{s : s \in SS_{Wr} \wedge s \not\preceq Seg\} \cup \{Seg\}$
        else ▷ READ event: update $SS_{Rd}$
                $SS_{Rd} \leftarrow \{s : s \in SS_{Rd} \wedge s \not\preceq Seg\} \cup \{Seg\}$
    SET-PER-ID-STATE(ID, $SS_{Wr}, SS_{Rd}$)
    if IS-RACE($SS_{Wr}, SS_{Rd}$)
        then REPORT-RACE($IsWrite, Tid, Seg, ID$)
```

Example

```
// Thread1          // Thread2
X = ...;
Sem1.Post();        Sem1.Wait();
                    ... = X;
                    Sem2.Post();
Sem2.Wait();
L1.Lock();
X = ...;
L1.Unlock();        L1.Lock();
                    X = ...;
                    L1.Unlock();
                    ... = X;
```

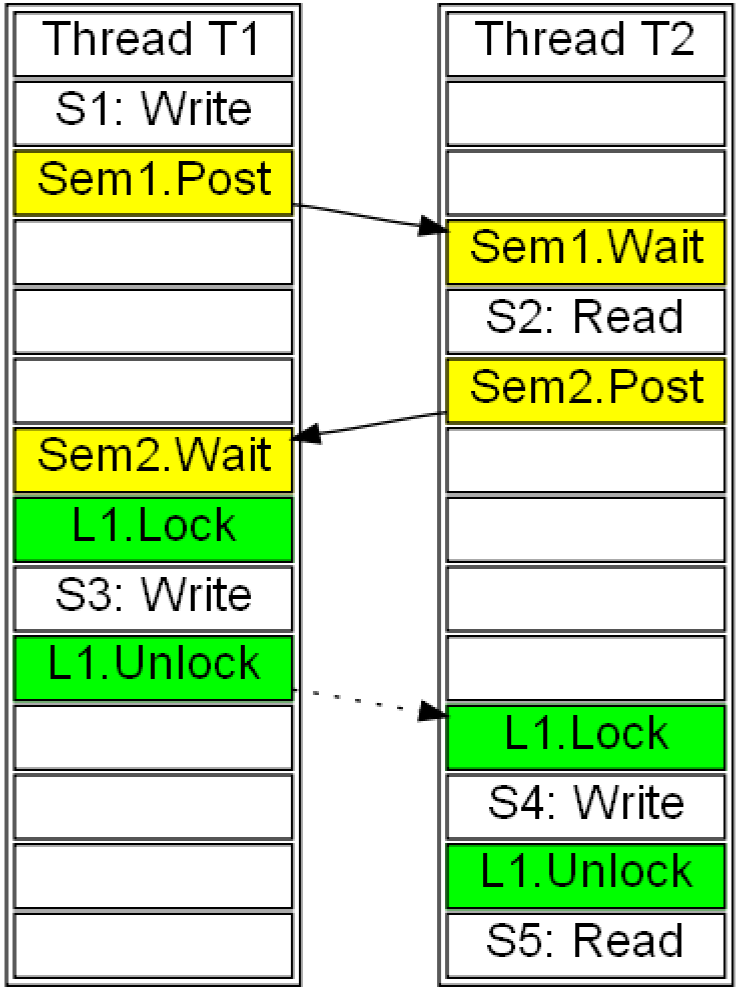


Thread T1	Thread T2
S1: Write	
Sem1.Post	
	Sem1.Wait
	S2: Read
	Sem2.Post
Sem2.Wait	
L1.Lock	
S3: Write	
L1.Unlock	
	L1.Lock
	S4: Write
	L1.Unlock
	S5: Read

Example: shadow state

Hybrid	
Writer SS	Reader SS
S1	-
S1	S2
S3/L1	-
S3/L1, S4/L1	-
S3/L1, S4/L1	**S5 {Race!}**

Pure Happens-before	
Writer SS	Reader SS
S1	-
S1	S2
S3/L1	-
S4/L1	-
S4/L1	S5



Thread T1	Thread T2
S1: Write	
Sem1.Post	
	Sem1.Wait
	S2: Read
	Sem2.Post
Sem2.Wait	
L1.Lock	
S3: Write	
L1.Unlock	
	L1.Lock
	S4: Write
	L1.Unlock
	S5: Read

Report example

```
WARNING: Possible data race during write of size 4 at 0x633AA0: {{{
   T2 (test-thread-2) (locks held: {L122}):
    #0  test301::Thread2() racecheck_unittest.cc:5956
    #1  MyThread::ThreadBody(MyThread*) thread_wrappers_pthread.h:320
    #2  ThreadSanitizerStartThread ts_valgrind_intercepts.c:387
  Concurrent write(s) happened at (OR AFTER) these points:
   T1 (test-thread-1) (locks held: {L121}):
    #0  test301::Thread1() racecheck_unittest.cc:5951
    #1  MyThread::ThreadBody(MyThread*) thread_wrappers_pthread.h:320
    #2  ThreadSanitizerStartThread ts_valgrind_intercepts.c:387
  Address 0x633AA0 is 0 bytes inside data symbol "_ZN7test3013varE"
  Locks involved in this report (reporting last lock sites): {L121, L122}
   L121 (0x633A10)
    #0  pthread_mutex_lock ts_valgrind_intercepts.c:602
    #1  Mutex::Lock() thread_wrappers_pthread.h:162
    #2  MutexLock::MutexLock(Mutex*) thread_wrappers_pthread.h:225
    #3  test301::Thread1() racecheck_unittest.cc:5950
    #4  MyThread::ThreadBody(MyThread*) thread_wrappers_pthread.h:320
    #5  ThreadSanitizerStartThread ts_valgrind_intercepts.c:387
   L122 (0x633A70)
    #0  pthread_mutex_lock ts_valgrind_intercepts.c:602
    #1  Mutex::Lock() thread_wrappers_pthread.h:162
    #2  MutexLock::MutexLock(Mutex*) thread_wrappers_pthread.h:225
    #3  test301::Thread2() racecheck_unittest.cc:5955
    #4  MyThread::ThreadBody(MyThread*) thread_wrappers_pthread.h:320
    #5  ThreadSanitizerStartThread ts_valgrind_intercepts.c:387
```

Conclusions

- Valgrind-based dynamic detector of data races for C/C++
- Works on Linux x86/x86_64 and Mac
- Has several modes of operation:
  - most conservative (pure happens-before):
    - few false reports, misses some races
  - most aggressive (hybrid):
    - more false positives, more real races
- Supports "Dynamic Annotations", a race detector API:
  - describe custom (e.g. lock-less) synchronization
  - hide benign races
  - zero noise level even in the most aggressive mode
- Opensource

Conclusions (cont)

- Overhead is comparable to Valgrind/Memcheck
  - Slowdown: 5x-50x
  - Memory overhead: 3x-6x
- Detailed output
  - Contains all locks involved in a race
- Runs regularly on thousands Google tests
  - Including all Chromium tests
- Found thousands of races
  - Several 'critical' (aka 'top crashers')
  - Dozens of potentially harmful
  - Tons of benign or test-only

Q&A

http://www.google.com/search?q=ThreadSanitizer&btnI