RacerX: effective, static detection of race conditions and deadlocks

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The problem.

- Big picture:
  - Races and deadlocks are bad.
  - Hard to get w/ testing: depend on low-probability events.
  - Want to get rid of them.
  - Main games in town have problems.
- Language: Mesa, Java, various type systems.
  - Forced to use language; still have errors
- Tools:
  - Dynamic (Eraser&co): must execute code: no run, no bug.
  - Static (ESC, Warlock): High annotation overhead.
  - Static & dynamic high false positive rates.

RacerX: lightweight checking for big code

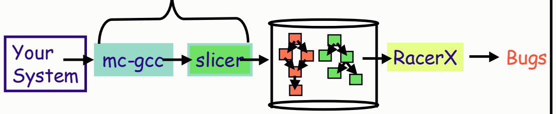
- Goal:
  - As many bugs as possible with as little help as possible

  - Works on real million line systems
  - Low annotation overhead (<100 lines per system)
  - Aggressively infers checking information.

  - Unusual techniques to reduce false positives.

The RacerX experience

- How to use:
  - List locking functions & entry points. Small:
    - Linux: 18 + 31, FreeBSD: 30 + 36, System X: 50 + 52
  - Emit trees from source code (2x cost of compile)



  - Run RacerX over emitted trees
    - Links all trees into global control flow graph (CFG)
    - Checks for deadlocks & races
    - ~2-20 minutes for Linux.
  - Post-process to rank errors (most of IQ spent here)
  - Inspect

Talk Overview

- Context
- RacerX overview

- Context-sensitive, flow-sensitive lockset analysis.

- Deadlock checking
- Race detection.

- Conclusion.

Lockset analysis

- Lockset: set of locks currently held [Eraser]
  - For each root, do a flow-sensitive, inter-procedural DFS traversal computing lockset at each statement

    initial ➔ lockset = { }
    lock(l) ➔ lockset = lockset U { l }
    unlock(l) ➔ lockset = lockset – { l }

  - Speed: If stmt s was visited before with lockset ls, stop.
- Inter-procedural:
  - Routine can exit with multiple locksets: resume DFS w/ each after callsite.
  - Record <in-ls, {out-ls}> in fn summary. If ls in summary, grab cached out-ls's and skip fn body.

Lockset

```
connect() {
  lock(a);        { a }
  open_conn();    { a }
  send();
}                     { a }       summary:
                                    { a } → ?
                        open_conn() {
                          if (x)            { a }
                            lock(b);       { a, b }
                          else              { a }
                            lock(c);       { a, c }

                          }              { a, b }  { a, c }
```

Lockset

```
connect() {
  lock(a);          { a }
  open_conn();      { a }
  send();        { a, b }, {a, c}
}                                  summary:
                                   { a } → { a, b }, {a, c}
                        open_conn() {
                          if (x)              { a }
   { a, b }, {a, c}         lock(b);        { a, b }
                          else                { a }
                            lock(c);        { a, c }

                        }                 { a, b }, {a, c}
```

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Big picture: Deadlock detection

- Pass 1: constraint extraction
  - **emit 1-level locking dependencies during lockset analysis**

```
lock(a);               lock(b);
lock(b); → "a→b"       lock(a); → "b→a"
```

- Pass 2: constraint solving
  - **Compute transitive closure & flag cycles.**
  - **"a→b→a" : T1 acquires a, T2 acquires b, boom.**
- Ranking:
  - **Global locks over local**
  - **Depth of callchain & number of conditionals (less better)**
  - **Number of threads involved (fewer MUCH better)**

Simplest deadlock example

```
// 2.5.62/drivers/char/rtc.c
int rtc_register(rtc_task_t *task) {
  spin_lock_irq(&rtc_lock);
  //...
  spin_lock(&rtc_task_lock);
  if (rtc_callback) {
     spin_unlock(&rtc_task_lock);
     spin_unlock_irq(&rtc_lock);
```

```
//2.5.62/drivers/char/rtc.c
rtc_unregister(rtc_task_t *task)
{
  spin_lock_irq(&rtc_task_lock);
  //...
  spin_lock(&rtc_lock);
```

Constraint extraction emits "rtc_lock→rtc_task_lock" and "rtc_task_lock→rtc_lock"
Constraint solving flags cycle: T1 acquires rtc_lock, T2 acquires rtc_task_lock. Boom.
Ranked high: only two threads, global locks, local error.

Some crucial improvements

- Unlockset analysis to counter lockset mistakes.
- Automatic elimination of rendezvous semaphores
- Release-on-block semantics.
  - **Release lock when thread blocks. No dependency.**
- Handling lockset mistakes with
  - **Summary selection heuristics**
  - **Computing the same result more than one way.**
  - **Pruning false paths based on locking errors**

False positive trouble.

- Most FPs from bogus locks in lockset
  - Typically caused by mishandled data dependencies
- Oversimplified typical example
  - Naïve analysis will think four paths rather than two, including false one that holds lock a at line 5.

```
1: if(x)              {}
2:      lock(a);      {a}
3: if(x)              {a}
4:      unlock(a);
5: lock(b);           {a}    "a➔b"
```

Inter-procedural analysis makes this much worse.

Could add path-sensitivity, but undecidable in general

Unlockset analysis

- Observations:
  - In practice, all false positives due to the A in "A➔B", most because A goes "too far"
  - We had unconsciously adopted pattern of inspecting errors where there was an explicit unlock of "A" after "A➔B" since that strongly suggested "A" was held.

```
// 2.5.62/drivers/char/rtc.c
rtc_register(rtc_task_t *task) {
  spin_lock_irq(&rtc_lock);
  //...
  spin_lock(&rtc_task_lock);        ➔rtc_lock➔rtc_task_lock
  if (rtc_callback) {
     spin_unlock(&rtc_task_lock);
     spin_unlock_irq(&rtc_lock);
```

Unlockset analysis

At statement S remove any lock L from lockset if there exists no successor statement S' reachable from S that contains an unlock of L.

```
1: if(x)              {}
2:      lock(a);      {a}
3: if(x)              {a}
4:      unlock(a);
5: lock(b);           ~~{a}~~ ➔  {}
```

Key: lockset holds exactly those locks the analysis can handle. Scales with analysis sophistication.

Without this we just can't check FreeBSD.

Unlockset implementation sketch

- Essentially compute reaching definitions
  - Run lockset analysis in reverse from leaves to roots
  - Unlockset holds all locks that will be released
    - initial ➔ unlockset = { }
    - lock(l) ➔ unlockset = unlockset - { l }
    - unlock(l) ➔ unlockset = unlockset U { l }
    - s.unlockset = s.unlockset U unlockset
  - During lockset analysis:
    - lockset = intersect(s.unlockset, lockset);
- Main complication: function calls.
  - Different locks released after different callsites. Don't want to mix these up (context sensitivity)

Deadlock results

System	Confirmed	Unconfirmed	False
System X	2	3	7
Linux 2.5.62	4	8	6
FreeBSD	2	3	6
Total	8	14	19

- A bit surprised at the low bug counts
  - Main reason seems to be not that many locks held simultaneously
  - < 1000 unique constraints, only so many chances for error.

The most surprising error

```
// Entered holding scsiLock
int FindHandle(int handleID) {
   prevIRQL = SP_LockIRQ(&handleArrayLock, …);
   Validate(handle);
   ...
int Validate(handle) {
    ASSERT(SP_IsLocked(&scsiLock));
    while (adapter->openInProgress) {
       CpuSched_Wait(&adapter->openInProgress,
                  CPUSCHED_WAIT_SCSI, &scsiLock);
      SP_Lock(&scsiLock);
```

T1 enters FindHandle with scsiLock, calls Validate, calls CpuSched_wait (rel scsiLock, sleep w/ handleArrayLock)

T2 acquires scsiLock and calls FindHandle. Boom.

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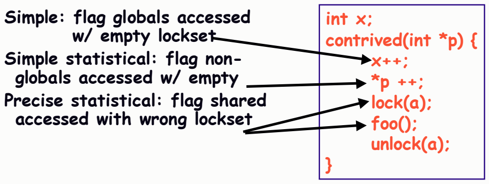
The big picture: race detection

- Three modes



Simple: flag globals accessed w/ empty lockset

Simple statistical: flag non-globals accessed w/ empty

Precise statistical: flag shared accessed with wrong lockset

```
int x;
contrived(int *p) {
    x++;
    *p ++;
    lock(a);
    foo();
    unlock(a);
}
```

- Ranking
  - Bulk of effort devising heuristics for probable races
  - Each error message falls under several. Need to order.
  - The usual trick: use a scoring function to map non-numeric attributes to a numeric value. Sort by value.

What's important to know

- Is lockset valid?
  - Roughly same as for deadlock.
- Is code multithreaded?
- Does X have to be protected (by lock L)?

Does X have to be protected?

- Naïve: flag any access to shared state w/o lock held.
  - Way too strong: 1000s of unprotected accesses. Only a few errors.
- The right definition:
  - Race = concurrent access that violates app invariant.
- Problem:
  - No one tells us invariants
  - Diagnosing race requires understanding app…
- General approach: belief analysis [sosp'01]
  - Analyze if programmer seems to *believe* X must be protected.

Infer if coder believes X needs locking

- If X "often" protected, flag when not.

```
lock(l);    lock(l);    lock(l);    lock(l);    lock(l);    // error!
foo();      foo();      foo();      foo();      foo();      foo();
unlock(l);  unlock(l);  unlock(l);  unlock(l);  unlock(l);
```

- Two modes:
  - Simple: count how often protected (S) versus not (F)
  - More precise: count how often protected by "most common" lock L (S) versus not (F).
  - Use "z-test statistic" to rank based on S and F counts
  - Intuition: the more protected (S/(S+F)), and the more samples (S+F), the higher the score.

Infer if coder believes X needs locking

- Coders generally don't do spurious concurrency ops
- If X is only object in critical section
  - Almost certainly protected (by L)

```
lock(l);            // error!
foo();              foo();
unlock(l);
```

  - Similar (but weaker) if first or last.

```
lock(l);
bar();
foo();
unlock(l);
```

- Most important ranking feature
  - Almost always look at these errors first.

Combined belief analysis example

- serial_out-info pair:
  - First statement in csection 11 times & last 17 times.

```
//Ex1: drivers/char/esp.c
cli();
serial_out(info, ...);
serial_out(info, ...);
restore_flags(flags);
```

```
// Ex 2:drivers/char/esp.c
cli();
info->IER &= ~UART_IER_RDI;
serial_out(info, ...);
serial_out(info, ...);
sti();
```

Obvious bug, trivial to diagnose.

```
restore_flags(flags); // re-enable interrupts
...
//ERR: calling <serial_out-info> w/o cli!
serial_out(info,...);
```

Race results

System	Confirmed	Unconfirmed	Minor	False
System X	7	4	13	14
Linux 2.5.62	3	2	2	6
Total	10	6	15	20

Many more uninspected results. Races *very* hard to inspect: 10 minutes+ rather than 10 seconds.

Summary

- RacerX
  - Few annotations: 100 or less for > million lines of code
  - Takes an hour to setup for new system
  - Finds bugs
  - Reasonable false positive rate
- Main tricks
  - Belief analysis is a big win.
  - Unlockset analysis kills many false positives.
  - Ranking heuristics: other tools should be able to use.
  - Much more in paper…
- Lots of work left to do.

Some high-probability unsafe operations

- Non-atomic writes (> 32-bits, bitfields):
  - easy to diagnose, almost certainly bad.

```
st r1, 0(r3)
st r2, 4(r3)
```

Read here = bizarre value

- Many vars modified in "non-critical section"
  - > 1 variable on unprotected path, almost certainly going to result in an inconsistent world-view.

```
shared int x, y;
x = i;
y = j;
```

Read x,y here = bizarre values

- Data shared with interrupt handler.
  - Bug on uniprocessor.
- Many others…

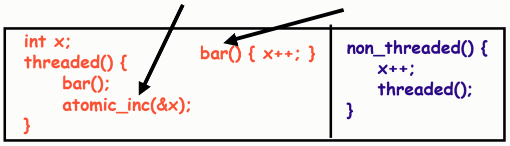
An illustrative race

```
/* ERROR:RACE: unprotected access to
    [logLevelPtr, _loglevel_offset_vmm,
        (*theIOSpace).enabledPassthroughPorts,
        (*theIOSpace).enabledPassthroughWords]
   [nvars=4] [modified=1] [has_locked=1] */
    LOG(2,("IOSpaceEnablePassthrough 0x%x count=%d\n",
          port, theIOSpace->resumeCount));
    theIOSpace->enabledPassthroughPorts = TRUE;
    theIOSpace->enabledPassthroughWords |= (1<<word);
```

- High rank:
  - Modified (modified=1)
  - Four variables in non-critical section (nvars=4)
  - Concurrency operations in callchain (has_locked)

Multithreaded inference

- Infer if coder *believes* code is multithreaded.
  - Programmers generally don't do spurious concurrency ops
  - Any such op implies belief code is multithreaded.
  - RacerX marks function F as multithreaded if concurrency ops occur (1) in F's body or (2) above it in callchain.



```
int x;                          bar() { x++; }
threaded() {
     bar();
     atomic_inc(&x);
}
```

```
non_threaded() {
     x++;
     threaded();
}
```

Note: concurrency ops in callee do not nec imply caller multithreaded

Programmer-written annotators

- Use coder knowledge to automatically mark code as:
  - Multithreaded or interrupt handlers (errors promoted)
  - Ignore or single-threaded (elided)

```
// mark all system calls as multithreaded
for(struct fn *f = fn_list; f; f = fn_next(f))
     if(strncmp(f->name, "sys_", 4) == 0)
            f->multithreaded_p = 1;
```

Big win: small fixed cost ➔ many annotations (100-1000)

- Function pointer equivalence
  - Functions assigned to same fptr ~ have same interface
  - If one annotated, automatically annotate others

Main limitations

- Very weak alias analysis:
  - Pointers to locals and parameters named by type.
    - "struct foo *f" ➔ <struct:foo:local>
- Limited function pointer analysis
  - Record all functions assigned to fptr (static or explicitly)
  - Assume call using that fptr type can call any of them.
  - Miss: functions passed as arguments and then assigned.
- Main speed problem:
  - Deep fns called in many places with different locksets.
  - Will cause RacerX to re-analyze each time. Expensive.
  - Skips any fn when more than > 100 different locksets.

The problem with rendevous semaphores

- Two conflated semaphore uses

Sometimes as locks (dep)

```
down(a);
lock(b);
up(a);
```

→ "a➔b"

Sometimes for signaling (no dependency)

```
// Producer
up(a);  // signal
```

```
// Consumer
down(a); // wait
lock(b);
```

→ ~~"a➔b"~~

If not separated cause lots of false positives. Many.
Use behavioral analysis to automatically eliminate!

Behavioral analysis

- Does s behave more like lock or more like semaphore?
  - Lock: (1) many down-up pairings, (2) few spurious ups

```
down(a);  down(a);  down(a);  down(a);  down(a);
up(b);    up(b);    up(b);    up(b);    up(b);
```

Scheduling: (1) few down-up pairs, (2) many spurious ups

```
down(s);  up(s)    down(s);  down(s);  up(s  up(s)
```

- Use statistical analysis to calculate which s behaves like

Statistical classification sketch

- Foreach semaphore s, compute:
  - Ratio of paired down(s)/up(s)
  - Ratio of spurious up(s)'s to total down(s) calls
  - Baseline ratios using known spin-lock functions
  - Compare s's ratio against baseline using "z-test statistic"
  - "Very improbable"? classify s as scheduling sem.

name	down	up	spurious up
PQFCH BA.complete	5	0	5
event_exit	2	0	9
thread_exit	2	0	1
us_data.sem	8	28	2
mm_struct.sem	141	208	2

Example scoring

- X first, last, or only object in critical section.
  - +4 if only object > 1 times, +2 if 1 time.
  - +1 if first, last object > 0 times
- Count protected vs unprotected, rank using z-test
  - +2 if z > 2; -2 if non-global and z < -2.
- Writes:
  - Unprotected vars in non-csection: +2 n > 2, +1 if n > 1
  - Non-atomic write: +1
  - Written by interrupt handler: +2, in general: +1.
  - Modified by > 2 roots: +2
- Rank
  - Cases with concurrency op in callchain above not.
  - Order same score by callchain depth and conditionals