Effective Data-Race Detection for the Kernel

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Motivation

- Finding data races is hard
- Analysing them is even harder
- Races often indicate problems
- Kernel code “operates at a lower concurrency abstraction” than user code

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```
struct{
  int status:4;
  int pktRcvd:28;
} st;
```

Thread 1

```
st.status = 1;
```

Thread 2

```
st.pktRcvd ++;
```

Data Races

- *Two operations that access main memory are called conflicting if*
  - *the physical memory they access is not disjoint,*
  - *at least one of them is a write, and*
  - *they are not both synchronization accesses.*
- *A program has a data race if it can be executed on a multiprocessor in such a way that two conflicting memory accesses are performed simultaneously (by processors or any other device).*

Race Detection

Precision

Missed race	No warning from detector
Benign race	Race without negative effects on program behaviour
False race	Error reported even though there is no race

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Detection Techniques

Static

Analyse source or byte code

Dynamic

Instrument program and monitor execution

Race Detection

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Analyse source or byte code

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Happens-Before-Tracking

Record ordering of events and synchronisation operations

Lock Sets

Examine lock set (held locks) during each data access

Data Collider

- Detects data races in existing Windows kernel code (x86)
- Independent of synchronisation protocols
- Extra debugging information about the race (stack trace, “context information”)
- Runtime overhead below $5\,\%$ due to sampling
- Post-processing to prune and prioritise found races

Sampling Algorithm

1. Identify instructions that access data
2. Prune synchronisation instructions (`volatile`, hardware synchronisation instructions)
3. Choose breakpoints uniformly from sampling set initially and after race detection
4. Periodically readjust according to number of fired breakpoints per second

$\Rightarrow$ Effective at low sampling rates

Algorithm

```
AtPeriodicIntervals() {
  // determine k based on desired
  // memory access sampling rate
  repeat k times {
    pc = RandomlyChosenMemoryAccess();
    SetCodeBreakpoint(pc);
  }
}
```

```
OnCodeBreakpoint(pc) {
  // disassemble the instruction at pc
  (loc, size, isWrite) = disasm(pc);

  DetectConflicts(loc, size, isWrite);

  // set another code break point
  pc = RandomlyChosenMemoryAccess();
  SetCodeBreakpoint(pc);
}
```

Algorithm

```
DetectConflicts(loc, size, isWrite) {
  temp = read(loc, size);

  if (isWrite) {
    SetDataBreakpointRW(loc, size);
  } else {
    SetDataBreakpointW(loc, size);
  }

  delay();

  ClearDataBreakpoint(loc, size);
  temp' = read(loc, size);

  if (temp != temp' || data breakpoint fired) {
    ReportDataRace( );
  }
}
```

Data Race Detection

Hardware Data Breakpoints (of x86)

- Based on virtual addresses
- IPI to update atomically on all cores
- Write $\rightarrow$ Trap on read/write
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Repeated Reads

- No detection of conflicting reads or writes with same last value
- Detect concurrent DMA writes
- Fallback when out of hardware data breakpoint
- Workaround for different virtual addresses mapping to same physical address

Pruning Benign Races

Statistics Counters	Counters that maintain low-fidelity statistical data
Safe Flag Updates	Read a bit while a different bit is updated
Special Variables	Races are expected, e.g. current time

$\Rightarrow$ $\sim$90 % of detected data races are benign

$\Rightarrow$ Still reported but deprioritised

Evaluation — Effectiveness

- *[A]pplied DataCollider on several modules in the Windows operating system [...] class drivers, various PnP drivers, local and remote file system drivers, storage drivers, and the core kernel executive itself*
- *[B]enign data races pruned heuristically and manually*

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Data Races Reported	Count
Fixed	12
Confirmed and Being Fixed	13
Under Investigation	8
Harmless	5
Total	38

Evaluation — Overhead

[W]e repeatedly measured the time taken for the boot–shutdown sequence for different sampling rates and compared against a baseline Windows kernel running without DataCollider. These experiments where done on the x86 version of Windows 7 running on a virtual machine with 2 processors and 512 MB memory. The host machine is an Intel Core2-Quad 2.4 GHz machine with 4 GB memory running Windows Server 2008.

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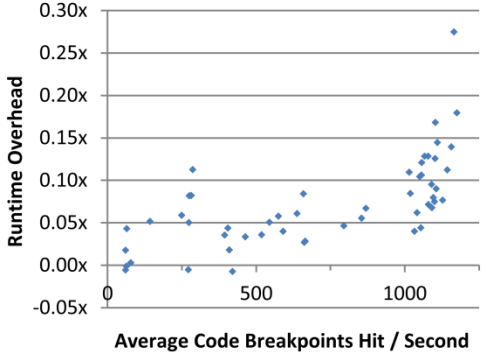

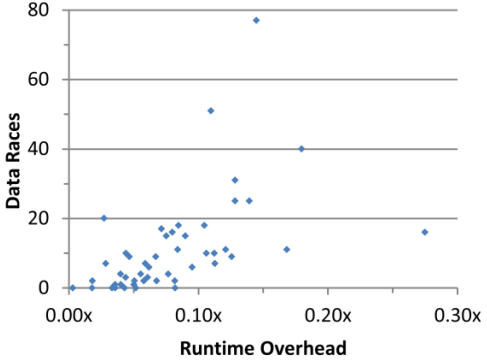

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We enabled DataCollider while running kernel stress tests for 2 hours sampling at approximately 1000 code breakpoints per second.

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Data Race Category		Count
Benign — Heuristically Pruned	Statistic Counter	52
	Safe Flag Update	29
	Special Variable	5
Benign — Manually Pruned	Double-check locking	8
	Volatile	8
	Write Same Value	1
	Other	1
Real	Confirmed	5
	Investigating	4
Total		113

Conclusion

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- DataCollider detects and reports data races on x86
- Use of hardware breakpoints and sampling for low overhead
- Automatic pruning of most false positives
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Discussion

- Astonishingly simple approach
- Evaluation of overhead using a virtual machine!?
- `volatile` vs. synchronisation