Eraser: Dynamic Data Race Detection

15-712

Topics overview

- Concurrency and race detection
  - Framework: dynamic, static
  - Sound vs. unsound
- Tools, generally:
  - Binary rewriting (ATOM, Etch, ...) and analysis (BAP, etc) - see also use in JITs and VMMs.
  - Techniques used for state space reduction (c.f. model checking)
- What are the eval criteria they used? How did they argue?

Debugging Concurrency is Hard

- Few tools beyond per-proc gdb
  - Debugging multi-process systems is harder than single process, even without...
- Threads come with unique problems
  - Deadlock, data races, non-determinism
- High performance typically implies lots of locks
  - For max parallelism, vs. one "big" lock
  - Shows up in modern kernel evolution as SMP grows
  - As #cores grow, parallelism will have to extend further and further into apps/libs to keep getting faster

Eraser: Lint for multi-threading

- Multiple threads in single address space
- Shared memory, one CPU
- Assumes:
  - pthreads lock() is sync, not monitors
  - libc memory allocation
- Doesn't work out causality
  - Costly bookkeeping; requires observing right interleaving
- Instead looks for idiom/style
  - Must hold lock to access shared variable
  - Data race: simultaneous access w/1+ writer
  - Limitation: must be consistent locking, not "either of two" locks
    - e.g., DB pages or multi-page locks

Binary Rewriting

- "Metaprogramming" tool for executables
  - Read & partially understand binary
    - Could also be done in compiler...
  - Write new extended code after adding function
  - (Harder on x86, but it's been done - variable length binary instruction set vs. more RISC-like systems)
- DEC ATOM tool for Alpha
  - Insert counters -- "super gprof"
  - Idea: Add memory restriction for safer code (dynamic bounds checking)
  - Add lock analysis to "lint" the sync code.
- compare to: modifying the source, interpreting the instruction stream, trapping system calls in the kernel

See Savage Slides

- http://www.cs.ucsd.edu/~savage/papers/Sosp97Slides.pdf
- Next bunch of slides taken in very large part, mostly verbatim, from the SOSP talk.
  - Some annotations. Blame dga, not SOSP talk, for bugs

How *happens-before* misses races

Thread 1	Thread 2

`y := y + 1;`
`lock(mu);`
`v := v + 1;`
`unlock(mu);`	

	`lock(mu);`
	`v := v + 1;`
	`unlock(mu);`
	`y := y + 1;`

Not detected as a race by *happens-before*

Lockset algorithm

- Dynamic analysis
- Require programmer to adhere to convention
  - *Locking Discipline:*
    - Consistently hold lock when using resource
  - Automatically infers *which* lock(s) protect resource
- Finds more bugs than "happens-before"
- But can generate many false positives!

Checking simple discipline

C(v): locks that might protect variable v
Initialize C(v) := set of all locks

On each access to v by thread t,
C(v) := C(v) ∩ locks_held(t)

If C(v) is empty, then issue a warning

Refining the candidate set

Program	New value of C(v)
	C(v) = {mu1, mu2}
`lock(mu1);`	
`v := v + 1;`	C(v) = {mu1}
`unlock(mu1);`	
`...`	
`lock(mu2);`	
`v := v + 1;`	C(v) = {}
`unlock(mu2);`	

False Positives

- FPs are *the* defining problem with this type of approach
  - We'll see later some other examples...
  - Really hurt usability. 1000 FPs + 1 bug isn't useful.
- Much of the rest of paper is about avoiding FPs
  - Ideally without reducing true positives (does it?)

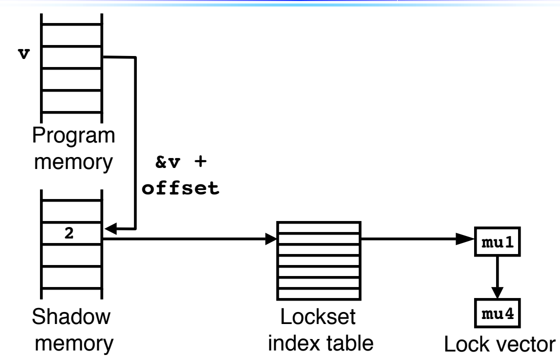
Limitations of simple algorithm

- Initialization
  - Don't need locks until data is shared
- Read-shared data
  - Don't need locks if all accesses are reads
- Reader/writer locks
  - Read locks can't protect writes

Modified algorithm

- Assume first thread is initializer
  - Only update C(v) after two threads touch v
- Only report races after data is known to be write-shared
- Track read and write locks separately
  - Remove read locks from C(v) on a write

Mapping variables to sets of locks



Performance

- Fast enough to be useful
  - 10-30x user-time slowdown
- Lots of opportunities for optimization
  - Half of overhead due to ATOM

Experiences

- Tested real programs
  - AltaVista web server and index library
  - Vesta cache server
  - Petal distributed disk server
  - Undergrad coursework from intro OS class
- Most programs found to contain races
- False alarms easy to manage

Program characterization

Program	*Lines of code*	*Threads*	*Locks*	*Lock sets*
AltaVista				
Ni2	20,000	10	900	3600
mhttpd	5,000	10	100	250
Vesta	30,000	10	26	70
Petal	25,000	64		

Case study: AltaVista

- Double blind experiment
  - Two old races reintroduced
  - Previously undetected for several months
  - Found and fixed in 30 minutes
- Several additional (minor) races found
- Several benign races
  - Tricky optimizations

- Re-introducing bugs is a useful and now common technique

Benign race example

```
if (p->fp == 0) {
   lock(p->lock);
   if (p->fp == 0) {
        p->fp = open_file();
   }
   unlock(p->lock);
}
```

- Advanced programmers make automatic inference hard...
  - Subtle optimization, hard to reason about its correctness

Serious race (subtle)

```
if (p->fp == 0) {
   lock(p->lock);
   if (p->fp == 0) {
        p->fp = open_file();
   }
   unlock(p->lock);
}
pos = p->fp->pos;
```

Case study: Undergraduate OS

- Four simple synchronization problems
  - e.g. producer consumer
- ~180 homeworks tested
- Found data races in more than 10%

Overall races detected

Program	*Serious races*	*Minor races*	*Benign races*
AltaVista		✓	✓
Vesta	✓	✓	
Petal		✓	
Undergrad assignments	✓		

Kinds of false alarms

- Private memory allocators
  - e.g. free list
  - Need to reinitialize C(v)
- Private lock implementations
  - e.g. reader/writer locks
  - Need to know when locks are held
- Benign races

Removing false alarms

- Simple program annotations
- Number of annotations needed to remove all false alarms:
  - AltaVista (19)
  - Vesta (10)
  - Petal (4)

end SOSP talk slides

Eval

- Modern systems eval
  - Real impl (distributable; recently rediscovered value for research code)
    - Injected faults by sticking old bugs back into code
      - This technique used in many subsequent evals
      - cvs/svn/git/etc. history
  - Applied to large, real applications and multiple mostly independent tests (students)
- Would have been nice to see more quantitative comparison between systems, but that's another paper... :)

Eval 2

- Not perfect tool:
  - 10x slowdown
  - Processor specific for dead processor
  - No guarantee to catch all races
    - In particular: Engler papers suggest many bugs lurk in infrequently hit code -- error handling, etc.
    - Dynamic detection has hard time catching those
      - Just like testing does.
- But useful for an otherwise hard problem

Design Space

- Static vs. Dynamic analysis
  - Dynamic: Depends on execution order
  - Static: Intractable (but can work well, today)
- Sound vs. Unsound
  - Note tension between pragmatists and correct-ists
- Existing languages (C...) vs. "Better" languages
  - Actual code? Annotations? Model?
  - Type systems; correct by construction?
  - Code generation: prove correct, then generate code.
- Eval questions:
  - False positives? False negatives? Coverage?
  - Running time?
  - Run in tests vs. in production system?

Follow-on

- Want more?
  - "Bugs as Deviant Behavior: A General Approach to Inferring Errors in Systems Code"
    - SOSP 2001. Dawson Engler, David Yu Chen, Seth Hallem, Andy Chou, and Benjamin Chelf
  - "The Daikon system for dynamic detection of likely invariants"
    - Science of Computer Programming 2007. Michael D. Ernst, Jeff H. Perkins, Philip J. Guo, Stephen McCamant, Carlos Pacheco, Matthew S. Tschantz, Chen Xiao.
  - Both examine more general invariants
    - Daikon examines more invariants;
    - Engler et al. is static
    - Both use machine-learning/statistical techniques to infer invariants