Eraser: A Dynamic Data Race Detector for Multithreaded Programs

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Concurrency

- Multithreaded programs are complicated
- Difficult to avoid or detect concurrency-related bugs (data races, deadlocks, …)
- Different synchronization mechanisms used (semaphores, locks, monitors, …)

➢ Eraser dynamically detects data races in multithreaded, lock-based programs

Data race

- Definition:
  A situation when two (or more) concurrent threads access a shared memory location and:
  - at least one access is a write
  - no explicit mechanism to prevent the accesses from being simultaneous

A solution: locks

- Simple synchronization object used for mutual exclusion
- Either *available* or *owned* by one thread
- But: no explicit relation between locks and shared variables

Thread 1:

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

Thread 2:

```
lock(mu)
x := v
unlock(mu)
```

Eraser: Lockset algorithm

- Eraser tries to infer this protection relation through dynamic analysis

- Idea: Look for a lock that is held whenever a shared variable is accessed. If at least one such lock exists, the variable is race-free.

- Eraser maintains a candidate lockset C(v) for each shared variable v, that contains the locks that consistently protect v so far

Lockset Algorithm (simple version)

- For each shared variable v create a candidate lockset C(v) that initially contains all locks
- In each access of v by thread t, refine C(v):
  C(v) := C(v) ∩ locks_held(t);
- If C(v) = { }, then issue a warning.

Example

Program	locks_held	C(v)
	`{}`	`{mu1, mu2}`
`lock(mu1);`		
	`{mu1}`	`{mu1, mu2}`
`v := v+1;`		
	`{mu1}`	`{mu1}`
`unlock(mu1);`		
	`{}`	`{mu1}`
`lock(mu2);`		
	`{mu2}`	`{mu1}`
`v := v+1;`		
	`{mu2}`	`{}`
`unlock(mu2);`		

warning!

Limitations of simple version

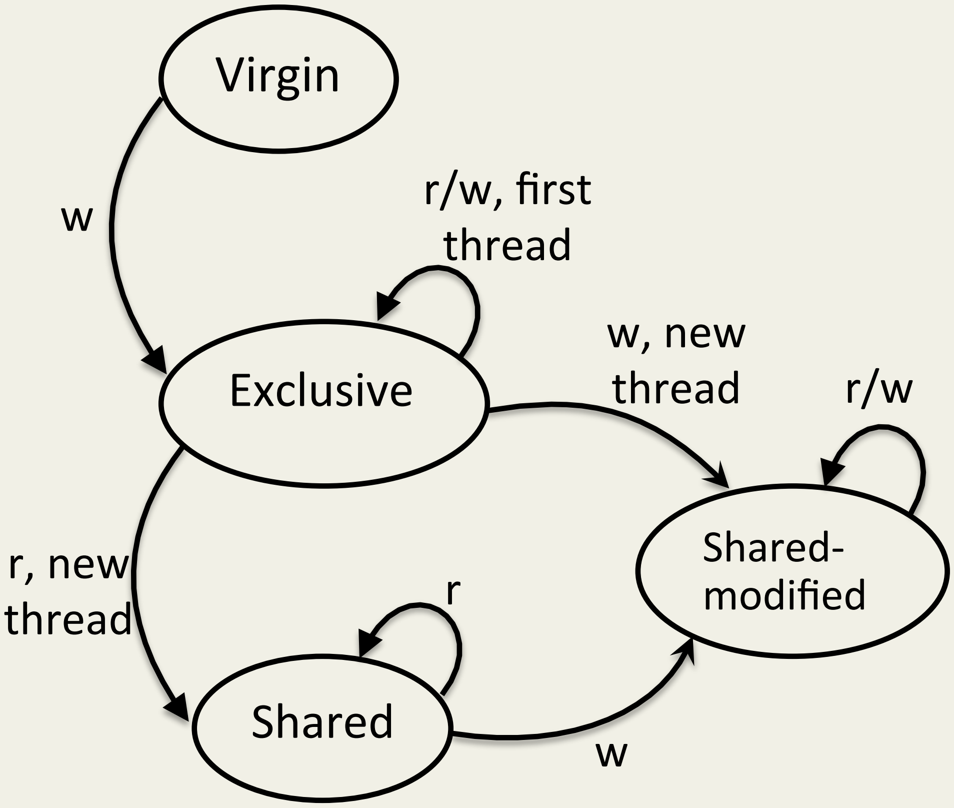
- Simple algorithm is too restrictive:
  - Initialization: thread-local data is always race-free
  - Read-shared data: no data race if after initialization all accesses are reads
  - Read-write locks: no support for locks that can be held in: - read mode (multiple reader) or
    - write mode (single writer)

- Many false positives

Lockset Algorithm (improved version)

- ➢ Improved version supports initialization and read-shared data:

- Introduce states for each shared variable:
  - <u>Virgin/Exclusive</u>: no candidate lockset refinement (data is local)
  - <u>Shared</u>: refinement is done, but no warnings are reported (read-shared data)
  - <u>Shared-Modified</u>: refinement is done and warnings are reported (write-shared data)



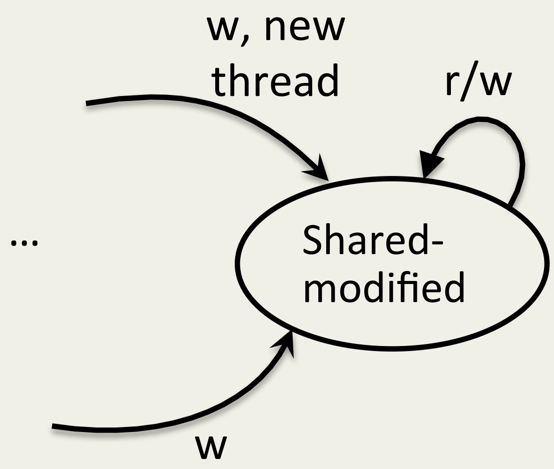
Lockset Algorithm (improved version)

- Improved version supports read/write locks

- Improved refinement:

On each **read** of *v* by thread *t*,
    set *C(v)* := *C(v)* ∩ *locks_held(t);*
    if *C(v)* = { }, then issue a warning

On each **write** of *v* by thread *t*,
    set *C(v)* := *C(v)* ∩ *write_locks_held(t);*
    if C(v) = { }, then issue a warning



locks_held(t) : set of locks held in any mode by thread t.
write_locks_held(t) : set of locks held in write mode by thread *t*.

Implementation

- Instrumentation of binary program by embedding calls to Eraser runtime for every:
  - load/store
  - lock/unlock
  - thread initialization/finalization
  - call to storage allocator
- 10 – 30 times slowdown: Important for time-sensitive applications

Program annotations

- Still many false alarms because of:
  - memory reuse
  - private locks
  - benign races

➢ Use of explicit annotations to communicate this information to Eraser and reduce the false alarms

Experiments

- Eraser was used to test:
  - Two modules of Altavista web indexing service (25K loc)
  - Vesta cache server (30K loc)
  - Petal distributed storage system (25K loc)
  - Undergraduate student projects

- <u>Results:</u>
  - Some serious data races detected in 3 out of 4 servers (e.g. unprotected reads and writes in Vesta)
  - Several false alarms (almost all of them disappeared after a few annotations were added)

Aftermath

- Influence: 299 citations (ACM DL)
- Many improvements/extensions of lockset algorithm
  - ***Hybrid Dynamic Data Race Detection*[1] (2003)**: combines lockset and happens-before algorithms, fewer false positives, better performance
  - ***MultiRace*[2] (2007)**: source code instrumentation, better performance
  - **Locksmith[3] (2011)**: static implementation of lockset algorithm for C programs

[1] R. O'Callahan and J. Choi. 2003. Hybrid dynamic data race detection. *SIGPLAN Not.* 38, 10 (June 2003), 167-178

[2] E. Pozniansky and A. Schuster. 2007. MultiRace: efficient on-the-fly data race detection in multithreaded C++ programs: Research Articles. *Concurr. Comput. : Pract. Exper.* 19, 3 (March 2007), 327-340.

[3] P. Pratikakis, J. Foster and M. Hicks. 2011. LOCKSMITH: Practical static race detection for C. *ACM Trans. Program. Lang. Syst.* 33, 1, Article 3 (January 2011)

Conclusion

- Eraser dynamically detects data-races in lock-based programs
  - cannot prove that a program is race-free
  - only produces warnings that can be possible false alarms
- Nevertheless, it finds more bugs than previous approaches
- Tested real-world multithreaded systems for data-races with significant success
- Lockset algorithm has been widely used in further research on this field

Discussion