Detecting Data Races in Multi-Threaded Programs

Eraser

A Dynamic Data-Race Detector for Multi-Threaded Programs

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Key Points

1. Data races are easy to cause and hard to debug.

2. Data races can be prevented by following a locking discipline.

3. Lockset enforces a locking discipline.

4. Locking discipline violations are located by lockset refinement.

Key Points Cont.

5. Lockset is (mostly) insensitive to the scheduler.
6. Lockset will detect races which do not manifest in a given execution.
7. Lockset is vulnerable to false alarms.

Data Race Review

Two threads access a shared variable

- At least one access is a write,
- Simultaneous access is not prevented.

- Example (variable X is global and shared)

Execution ↓	Thread 1	Thread 2
	X = 2.7	X = 3.1
	Z = 2	T = X

Data Race Demonstration Cont.

```
int[] shared = new int[1];
Thread t1, t2;
public DataRace() {
  // Initialize and start threads (shown below)
}
```

```
t1 = new Thread() {
  public void run() {
    while(t1 != null) {
      ...
      shared[0] = shared[0] + 1;
      ...
    }
  ...
```

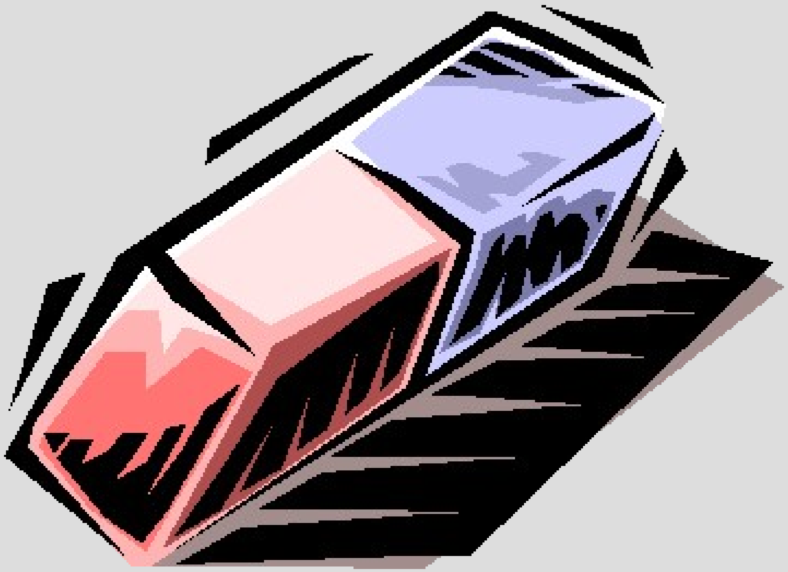
```
t2 = new Thread() {
  public void run() {
    while(t2 != null) {
      ...
      shared[0] = shared[0] + 1;
      ...
    }
  ...
```

Data Race Demonstration

- Data races often lead to unexpected and even nondeterministic behavior
- The outcome may be dependent on specific execution order (threads' interleaving)
- Click image to start

Eraser
[Savage, Burrows, et al., 1997]

- On-the-fly tool.
- Lockset algorithm.
- Code annotations to flag special cases.
- Can be extended to handle other locking mechanisms (IRQs).
- Used in industry.
- Slows applications by a factor of 10 – 30.



The Lockset Algorithm (Simple Form)

- Detects races not manifested in one execution.
- Generates false alarms.

Lockset Refinement

- *Let **locks_held(t)*** be the set of locks held by thread t
- For each shared memory location ***v***, initialize ***C(v)*** to the set of all locks
- On each access to ***v*** by thread ***t***,
  - Set ***C(v)*** := ***C(v)*** ∩ ***locks_held(t)***
  - If ***C(v)*** := {}, then issue a warning

Lockset Refinement Example

Program	***locks_held***	***C(v)***
int v;	{}	{mu1, mu2}
v := 1024;		
lock(mu1);		
	{mu1}	
v := v + 1;		
		{mu1}
unlock(mu1);		
	{}	
lock(mu2);		
	{mu2}	
v := v + 1;		
		{} ← Warning!
unlock(mu2);		
	{}	

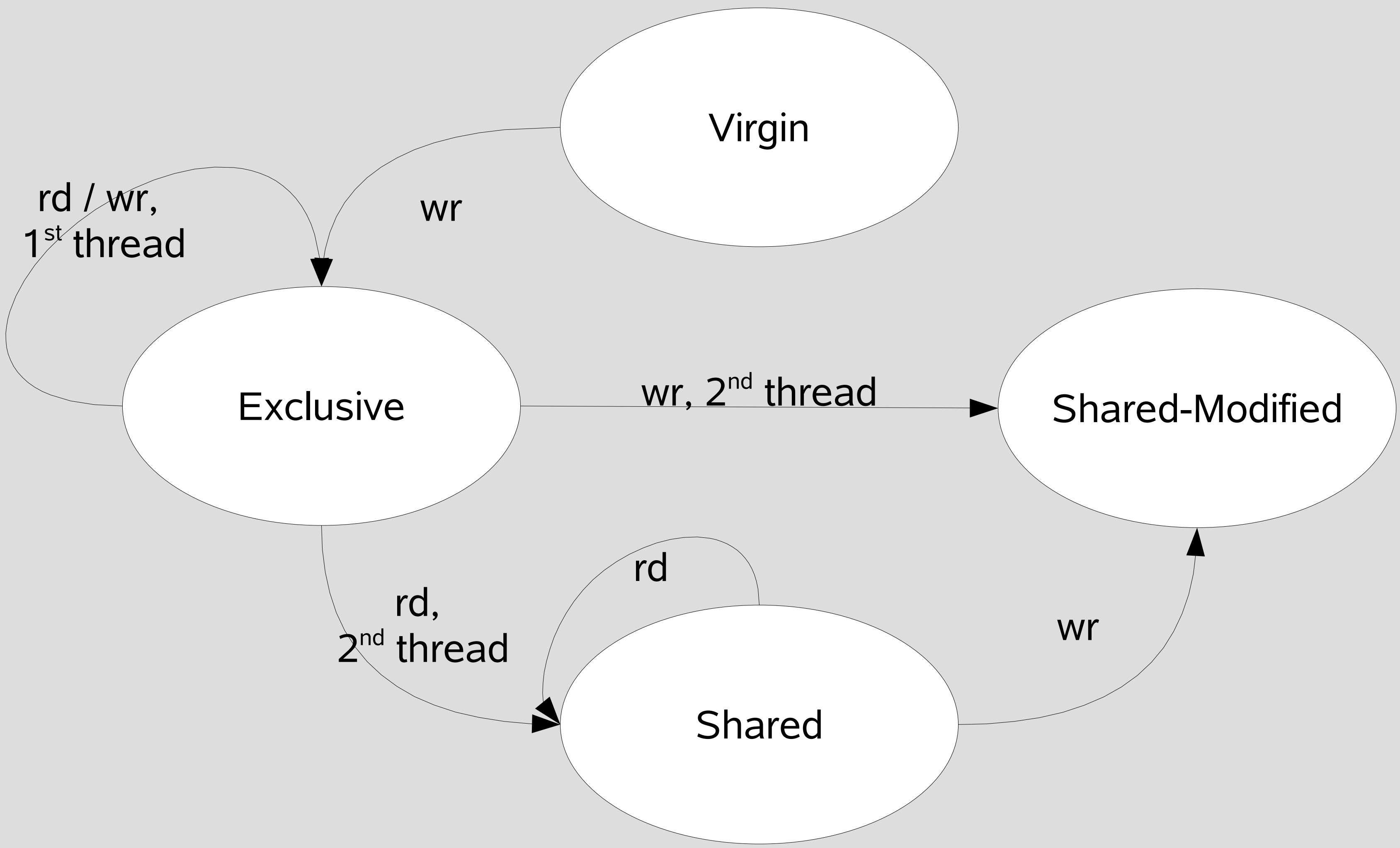
Simple Lockset is too Strict

Lockset will produce false-positives for:

- Variables initialized without locks held.
- Read-shared data read without locks held.
- Read-write locking mechanisms (producer / consumer).

Lockset State Diagram

Warnings are issued only in the Shared-Modified state



Lockset State Example

Thread	Program	locks_held	C(v)	State(v)
	int v;	{}	{mu1, mu2}	Virgin
T1	v := 1024;			Exclusive
T2	lock(mu1);	{mu1}		
T2	v := v + 1;			Shared Shared-Modified
T2	unlock(mu1);	{}	{mu1}	
T1	lock(mu2);	{mu2}		
T1	v := v + 1;		{}	
T1	unlock(mu2);	{}		

Race detected correctly

The Lockset Algorithm (Extended)

- Let ***locks_held(t)*** be the set of locks held in any mode by thread ***t***
- Let ***write_locks_held(t)*** be the set of locks held in write mode by thread ***t***
- For each shared memory location ***v***, initialize ***C(v)*** to the set of all locks
- 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

Unhandled Cases in Eraser

- Memory reuse
- Unrecognized thread API
- Initialization in different thread
- Benign races

```
if(fptr == NULL) {
   lock(fptr_mu);
   if(fptr == NULL) {
         fptr = open(filename);
   }
   unlock(fptr_mu);
}
```

Unhandled Cases in Eraser Cont.

- Race on ★ and ★★ will be missed if ★★ executes first

```
     int[] shared = new int[1];
     Thread t = new Thread() {
       public void run() {
★          shared = shared + 1;
           ...
     };
     ...
     shared = 512;
     t.start();
★★   shared = shared + 256;
     ...
```

[Seragiotto, 2005]

Unhandled Cases in Eraser Cont.

Program	*locks_held*	*C(v)*	*State(shared)*
int[] shared = new int[1];	{}	{mu1}	Virgin
shared = 512;			
			Exclusive
t.start();			
shared = shared + 256;			
Thread t = new Thread() {			
public void run() {			
shared = shared + 1;			Shared
...			Shared-Modified
};		{}	
...			

Data race is not detected!

Unhandled Cases in Eraser Cont.

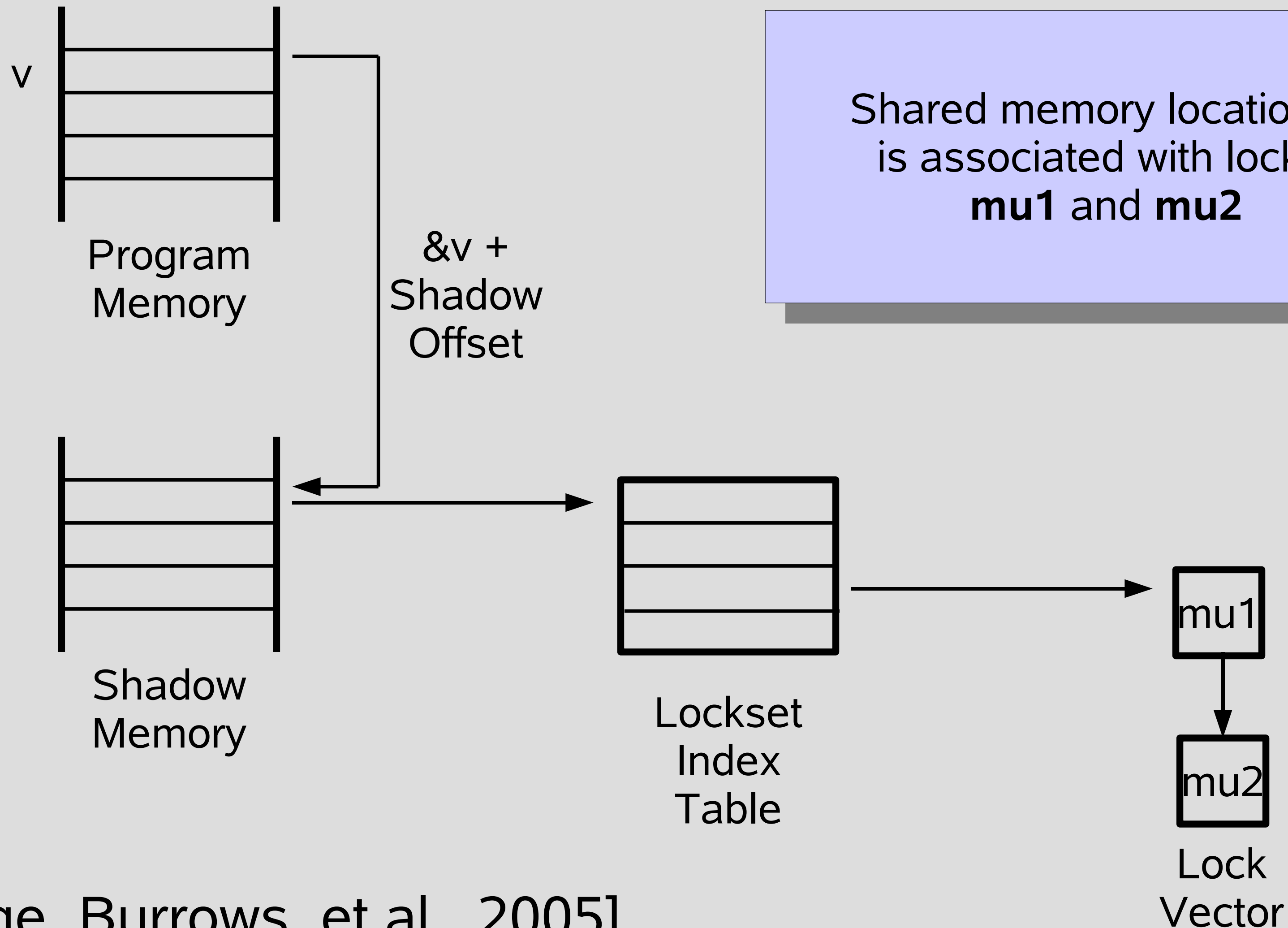
Program	*locks_held*	*C(v)*	*State(shared)*
int[] shared = new int[1];	{}	{mu1}	Virgin
shared = 512;			
			Exclusive
t.start();			
Thread t = new Thread() {			
public void run() {			
shared = shared + 1;			Shared
...			Shared-Modified
};		{}	
shared = shared + 256;			

Data race is detected!

Implementations: Eraser

- Maintains hash table of sets of locks.
- Represents each set of locks with an index.
- Every shared memory location has shadow memory containing lockset index and state.
- Shadow memory is located by adding offset to shared memory location address.

Implementations: Eraser



Shared memory location **v** is associated with locks **mu1** and **mu2**

[Savage, Burrows, et al., 2005]

Ladybug Demonstration

- Rewrite class file
  - `java -cp Ladybug.jar br.ime.usp.ladybug.LadybugClassRewriter DataRace.class`
- Run modified class
  - `java -cp Ladybug.jar:. DataRace`
- Races reported as exceptions

```
br.ime.usp.ladybug.RCException: [line 9]
Race condition detected: t2 of DataRace (hash code = 1b67f74) with Thread-0
        at br.ime.usp.ladybug.StaticLadybug.warn(StaticLadybug.java:1014)
        at br.ime.usp.ladybug.eraser.EraserGC.writeField(EraserGC.java:47)
        ...
        at DataRace.access$202(DataRace.java:9)
        at DataRace$1.run(DataRace.java:37)
```

- Can also use GUI

Conclusion

1. Data races are easy to cause and hard to debug.
2. Data races can be prevented by following a locking discipline.
3. Lockset enforces a locking discipline.
4. Locking discipline violations are located by lockset refinement.
5. Lockset is vulnerable to false alarms.

References

- S. Savage, M. Burrows, G. Nelson, P. Sobalvarro, and T.E. Anderson. Eraser: A Dynamic Data Race Detector for Multithreaded Programs. In *ACM Transactions on Computer Systems*, 15(4): pp. 391-411, 1997.
- E. Pozniansky and A. Schuster. Dynamic Data-Race Detection in Lock-Based Multi-Threaded Programs. In *Principles and Practice of Parallel Programming*, pp. 170-190, 2003.
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- C. Seragiotto. *Ladybug: Race Condition Detection in Java. 2005*. http://www.par.univie.ac.at/~clovis/ladybug/