Parallel & Concurrent Programming:

Dynamic Race Detection

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CMPSCI 691W

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Outline

- Last time:
  - Performance + ease of programming
    - Capriccio, Flux
- Today:
  - Race detection

Problem with Races

- Many programs contain **races**
  - Inadvertent programming errors
  - Failure to observe **locking discipline**
- **Race conditions** – insidious bugs
  - Non-deterministic, timing dependent
  - Cause data corruption, crashes
  - Difficult to detect, reproduce, eliminate

Data Races

- A **data race** happens when two threads access a variable simultaneously, and one access is a *write*

```
int t1;
t1= hits;
hits= t1+1;
```

```
int t2;
t2=hits;
hits=t2+1;
```

Data Races

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t1= hits;
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```
int t2;
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int t2;
t2=hits;

hits=t2+1;
```

Data Races

- Problem with data races: **non-determinism**
  - Depends on interleaving of threads
- Usual way to avoid data races: **mutual exclusion**
  - Ensures **serialized** access

Data Races

- Using mutual exclusion:

```
acquire
t1= hits;
hits= t1+1;
release
```

```
acquire
t2=hits;
hits=t2+1;
release
```

Data Races

- Data race types:
  - **Read-write conflict**
  - **Write-write conflict**

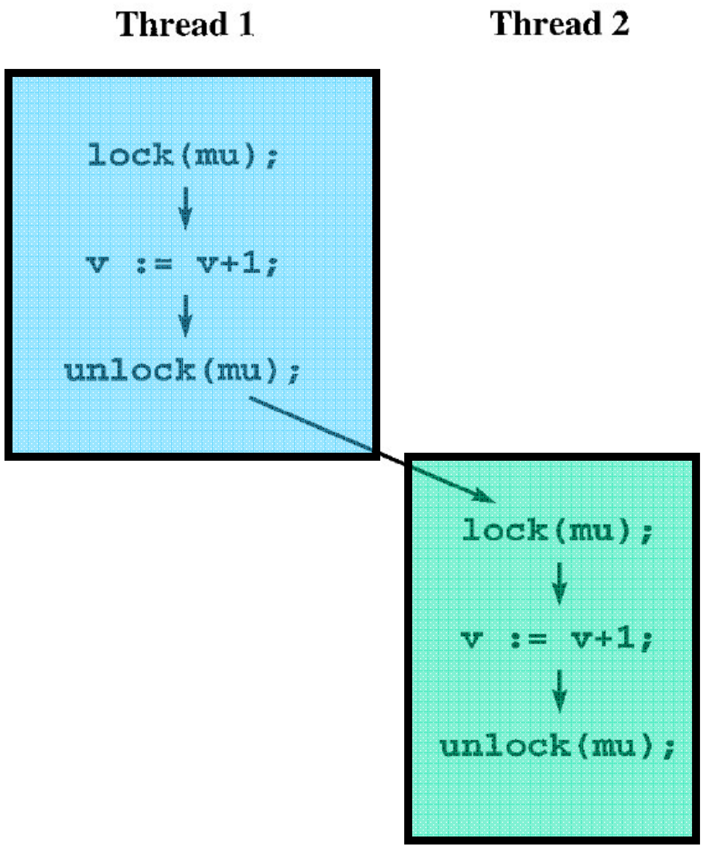
x = 2;	x = 3;
	a = x;

Detecting Races

- Tools to detect data races:
  - **Static** (not today)
  - **Dynamic**
    - **Happens-before** [Lamport]
    - **Locksets** [Savage et al.]

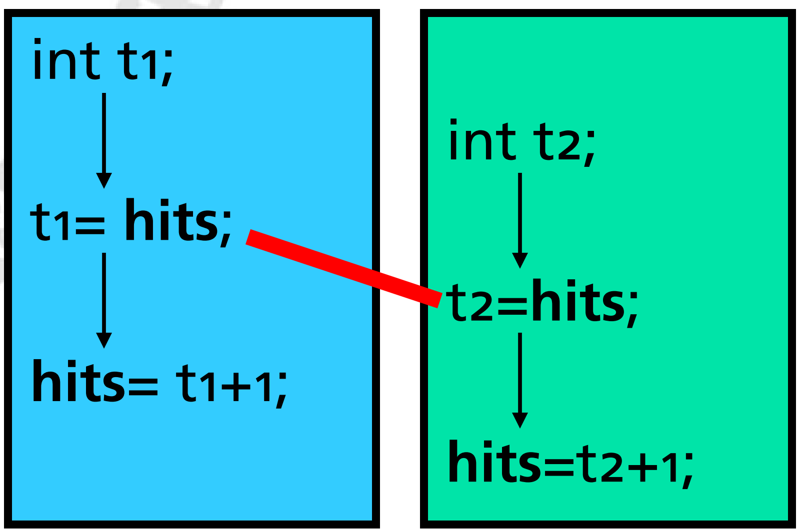
Happens-Before

- **happens-before (a,b):**
  - *a* immediately precedes *b* in same thread
    - E.g.: *a; b*
  - *a* releases a lock, *b* acquires it



Using Happens-Before

- Two accesses to shared object without being ordered by *happens-before*: **possible data race**

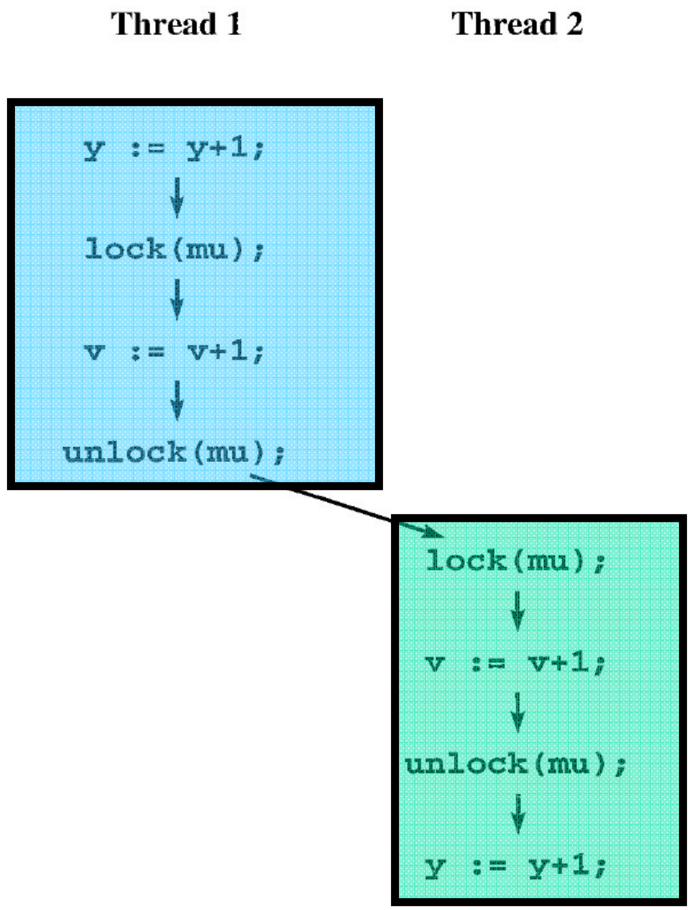


Drawbacks

- Happens-before – numerous drawbacks
  - Must track per-thread info about concurrent accesses to **every** shared location
  - Depends on scheduler interleaving: can miss races (**false negative**)

Drawback Example

- Missed race condition by luck



Eraser

- Another approach: track **locksets**
  - Discover which locks are held for every shared object
  - If at any time *no* locks are held while accessing shared object: **data race**
- Finds more races than happens-before

Lockset Algorithm

- Each shared variable *v*
  - *C(v)* – **candidate locks** – initially set of all locks
- Every access to *v*
  - *C(v)* = *C(v)* ∩ locks currently held
  - **lock refinement**
- If *C(v)* = *{}*, **data race warning**

Lockset Example

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

Lockset Limitations

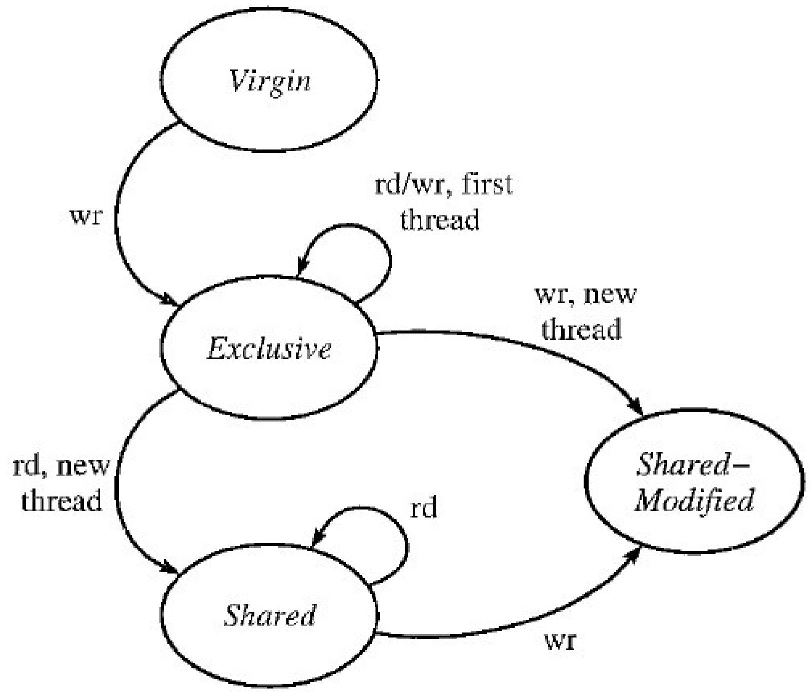
- Too strict for common synch operations
  - **Initialization**
    - Usually no lock held
  - **Read-shared data**
    - Some written during initialization, but only read from then on
    - Safe without locks
  - **Reader-writer locks**

Refined Algorithm

- How do you know when data is completely initialized?
  - Assume initialized when accessed by other thread than creator
- Read-sharing
  - Assume safe until first written

Updated Algorithm

- Initially *Virgin*
- *Exclusive*
  - Initialization
- *Shared*
  - *C(v)* updated but no race reports
- *Shared-Modified*
  - As in original algorithm



R/W Locks

- Track locks held only when writing, separately from usual lock checking

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 v, initialize $C(v)$ to the set of all locks.
On each read of v by thread t,
  set $C(v) := C(v) \cap locks\_held(t)$;
  if $C(v) := \{ \}$, then issue a warning.
On each write of v by thread t,
  set $C(v) := C(v) \cap write\_locks\_held(t)$;
  if $C(v) = \{ \}$, then issue a warning.

Implementation

- Eraser implemented using **ATOM**
  - Binary rewriting tool (Alpha only)
  - Now would be in **Pin**
- Locks represented by *lockset index* into table
  - Locksets = sorted vectors
- *Shadow word* (lockset index + state) for every word in DS & heap
- Instruments every direct memory access
  - 10-30x performance hit

Races Not Enough

```
class Account {
  private int balance = 0;


  public read() {
    int r;
    synchronized(this) {
      r = balance;
    }
    return r;
  }

}
```

```
 public void deposit(int n) {
    int r = read();
other threads can update balance
    synchronized(this) {
      balance = r + n;
    }
}
```

Fixed

```
class Account {
  private int balance = 0;


  public read() {
    int r;
    synchronized(this) {
      r = balance;
    }
    return r;
  }

}
```

```
public void deposit(int n) {
  synchronized(this) {
    int r = balance;
    balance = r + n;
  }
}
```

Race-Freedom Needed?

```
class Account {
  private int balance = 0;


  public read() {
    return balance;
  }

}
```

```
public void deposit(int n) {
  synchronized(this) {
    int r = balance;
    balance = r + n;
  }
}
```

- Race-freedom neither **sufficient** nor **necessary!**

The End

- Next time:
  - **Atomicity**