Principles of Concurrency

Lecture 9

Data Races

The Problem

T1	T2
`R(x) //r1`	`R(x) //r2`
`W(x, r1+1)`	`W(x, r2+1)`

- If the value of `x` was initially 0, we would expect that the final value of `x` after both threads have completed would be 2
- But, the read of `x` in T1 (T2) can happen concurrently with the write of x in T2 (T1), leading to a final result of 1
- Not sequentially consistent!

An execution contains a *data race* if it allows two concurrent accesses to the same location, one of which is a write

- this manifests in a trace by having the events corresponding to these accesses be adjacent to one another
- equivalently, all conflicting actions (i.e., R-W or W-W actions) are ordered by a happens-before edge

A data race is a symptom of a potential race condition

Happens-Before Relation

A history H is a trace/interleaving of actions (or events) performed by different threads in a concurrent execution

Event e1 happens-before e2 (hb(e1,e2)) in a history H if:

- e1 and e2 are events from the same thread and e1 occurs before e2 in H
- e1 is a lock.rel() event and e2 is lock.acq() event and e1 occurs before e2 in H
- if hb(e1,e2) and hb(e2,e3) then hb(e1,e3)

Events e1 and e2 are in a *data race* in history H if e1 and e2 are:

- not related by hb
- generated from different threads
- perform accesses to the same memory location, and one of the accesses is a write

Concurrency Problems

Unintended sharing:

```
int x;

void P () {
  x += ...
```

Two threads may call P() concurrently

Atomicity violation:

```
void deposit(int x) {
  int t = balance
  balance = x + t
}
```

```
void withdraw(int x) {
  int t = balance
  balance = t - x
}
```

Two threads may incorrectly interleave their actions

Ordering violation:

```
work = ...;
createThread(2);
work = new Work()
```

```
ConsumeWork(work)
```

Two threads may incorrectly (not) observe desired actions of the other

Preventing Data Races

Use locks

- concurrent accesses separated by lock/unlock pairs
- challenge: using locks consistently

A compiler views a lock/unlock instruction as potentially modifying any location

- no reorderings around them are permitted
- induce happens-before edge on conflicting accesses
- they enforce strong fences to prevent hardware/software reordering

Other approaches:

- monitors, `synchronized`, etc.
- Monitors (Hoare 1974)

  - a group of shared variables along with procedures to access them

  - all accesses protected by the same (anonymous) lock acquired and released upon entry/exit of the monitor

  - shared variables not visible outside monitor

  - But, lots of issues: dynamically allocated data, exceptions, signals, nesting, …

Datarace Freedom (DRF)

A program is data race-free if none of its possible executions contains a data race

T1

```
if (R(x) == 1) {
   W(y,1)
}
```

T2

```
if (R(y) == 1) {
   W(x,1)
}
```

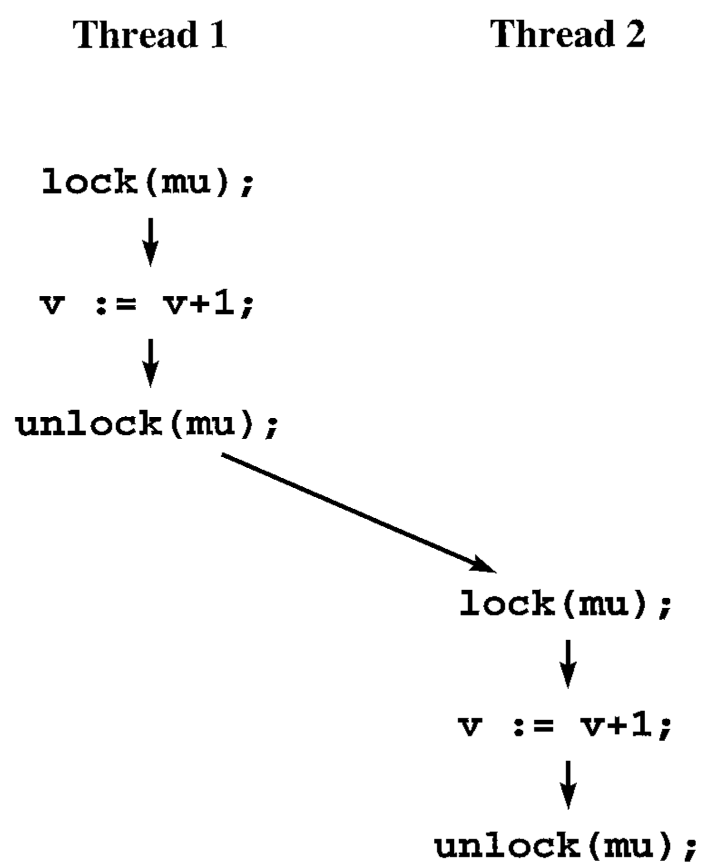
Is this program DRF?

What should the semantics of a program that contains a data race be?

- In C11, Java, Posix, etc. only programs that are DRF are given a semantics. Racy programs have undefined behavior.
- DRF programs, on the other hand, always exhibit SC behavior.

Detecting Data Races

- Dynamically compute the happens-before relation
  - a partial order on events of all threads in a concurrent execution
  - Between threads, events are ordered according to the synchronization objects they access



Detecting Data Races

If two threads access a shared variable, and the accesses are not ordered under a happens-before relation, then there is a potential data race

- But, dynamic detection of happens-before is difficult
  - Requires per-thread information about concurrent accesses to shared memory
  - Highly dependent upon interleavings induced by the scheduler
- To construct the happens-before relation, we need:
  - program order: the total order of thread instructions
  - synchronization order: the total order of accesses to the same synchronization variable

Example

T1 T2

```
W(x,1)        if (R(y) == 1) {
W(y,1)           W(x,2)
              }
```

Both `x` and `y` have unordered conflicting accesses

But, there is no data race on `x`, although there is one on `y`

Lockset algorithm (Eraser)

Rather than computing a precise happens-before relation, we can approximate its structure

- To avoid data races, every shared variable must be protected by some lock
- To infer what these locks are:

  For each shared variable, maintain a set C(v) of candidate locks for v.

  - This set contains those locks that have protected v for the computation so far
  - Initially, the set holds all possible locks
  - When v is accessed, compute the intersection of C(v) with the current set of locks held by the thread
  - If the set is empty, there is no lock that consistently protects v
    - signal a data race

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);`		
	`{}`	

Eraser Algorithm

- Assume a database D storing a set of tuples (m, L) where
  - m is a memory location
  - L is a set of locks that protect m
  - Initially, assume L is the set of all locks in the program
- For a memory event (R, W), generate the tuple (m, L(t)) where L(t) is the set of locks held by t at the time the event is generated
- Let (m, L′) be in D. Then
  - report a race if $L(t) \cap L' = \phi$
  - otherwise, replace (m, L′) with (m, $L(t) \cap L'$) in D

Improvements

Common programming practices often violate locking discipline, but are still race free:

- Initialization
- Reading shared data
- Read-write locks:

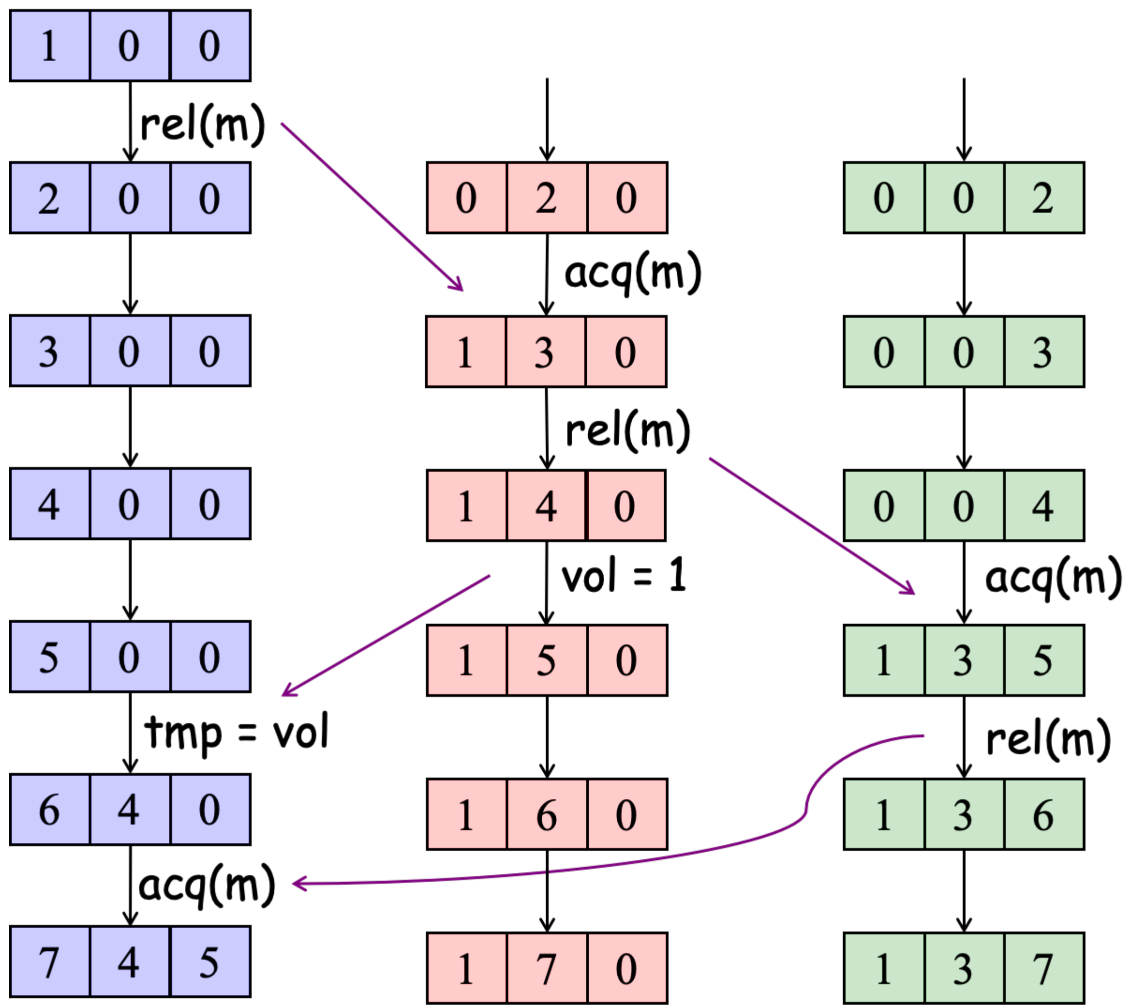
  multiple readers, single writer
- multiple locks for an object:

```
T1:          T2:          T3:
l1.acq()     l2.acq()     l1.acq()
  …            …            …
l2.acq()     l3.acq()     l3.acq()
 comp1()      comp2()      comp3()
l1.rel()     l2.rel()     l1.rel()
  …            …            …
l2.rel()     l3.rel()     l3.rel()
```

Can refine lockset algorithm to handle these cases

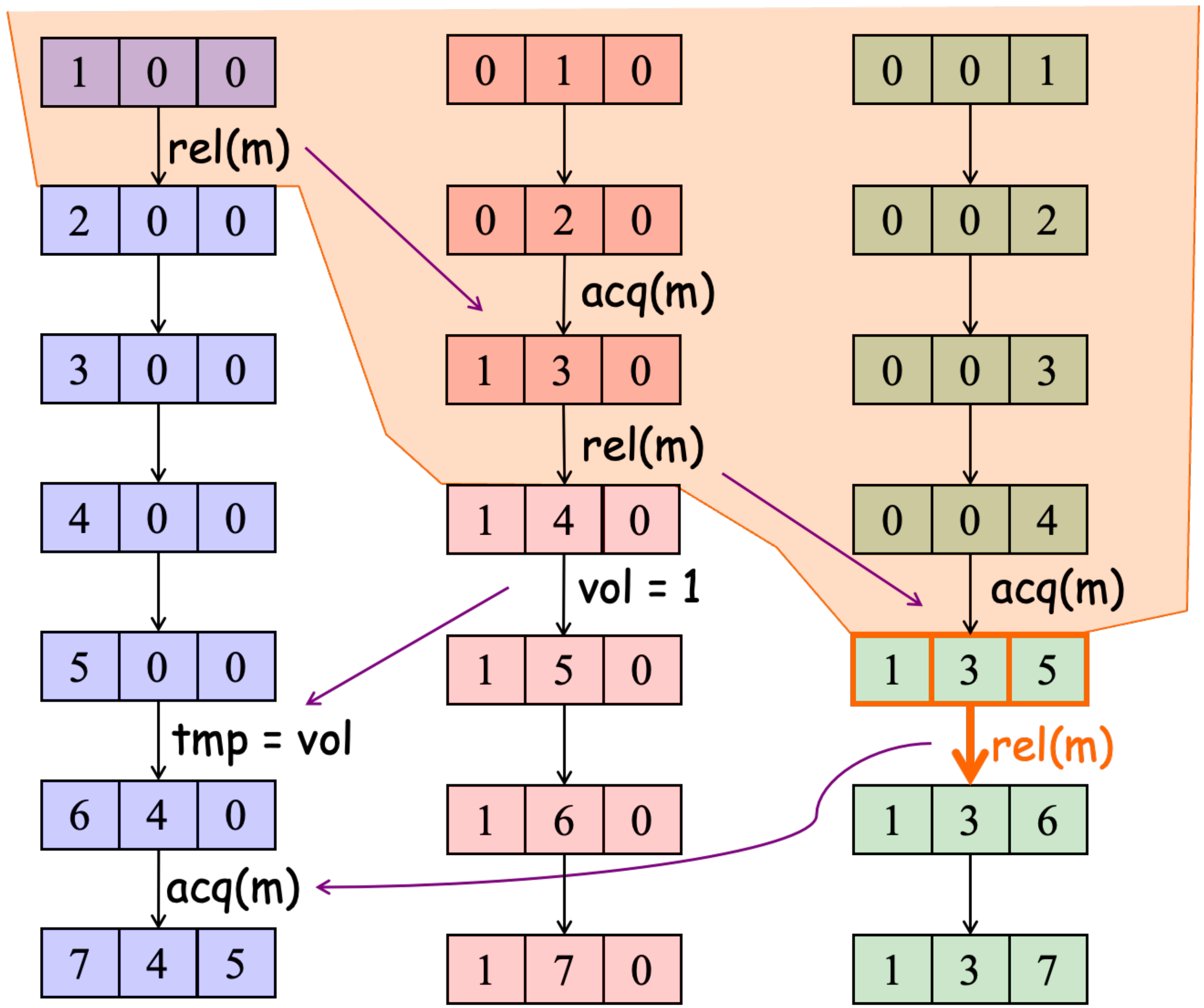
Tracking Happens-Before

A vector clock is an array of logical clocks maintained by each thread that records its view of the global state of an execution



Tracking Happens-Before

Can be used to propagate a global ordering from local views

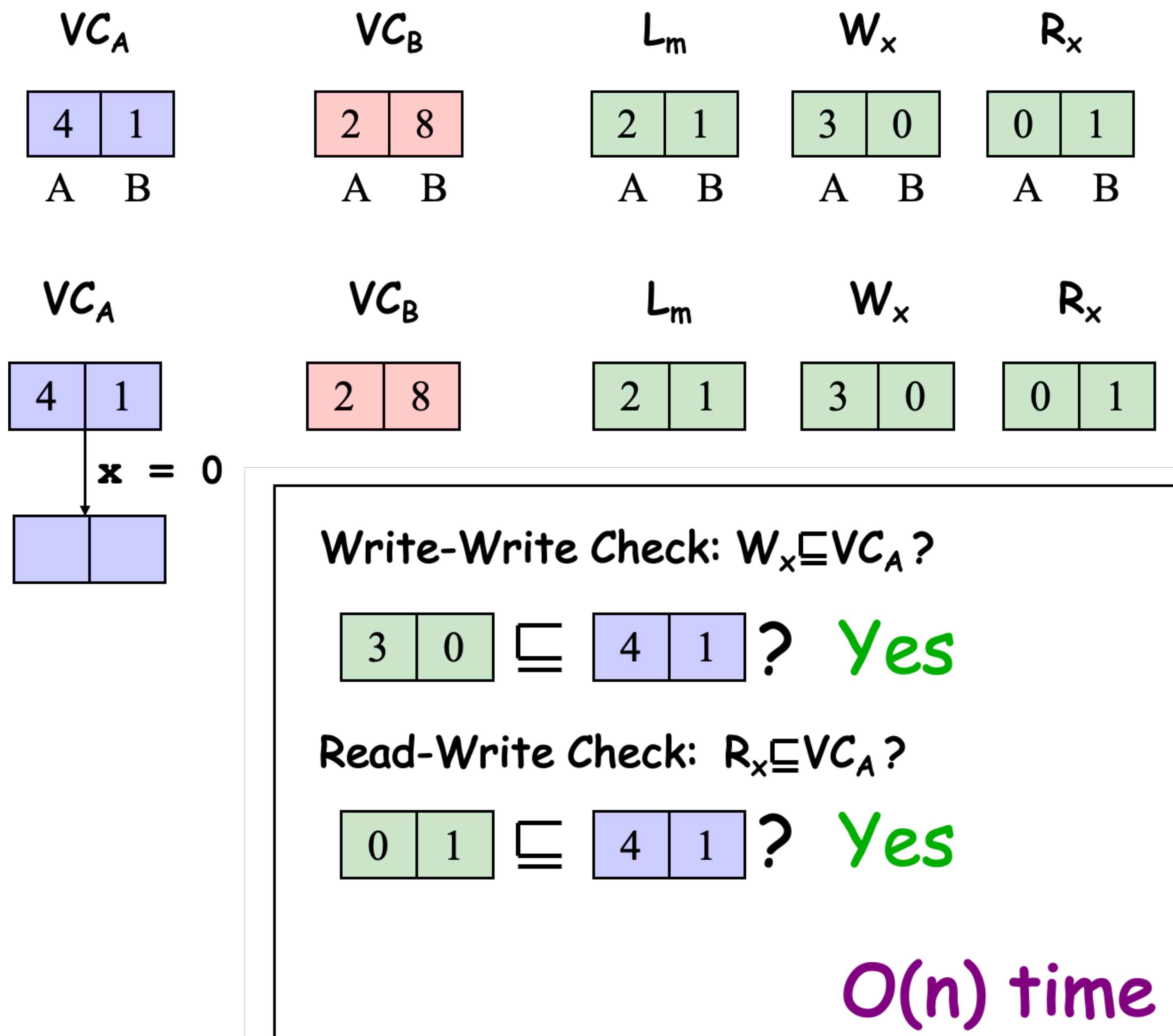


Application to Data Race Detection

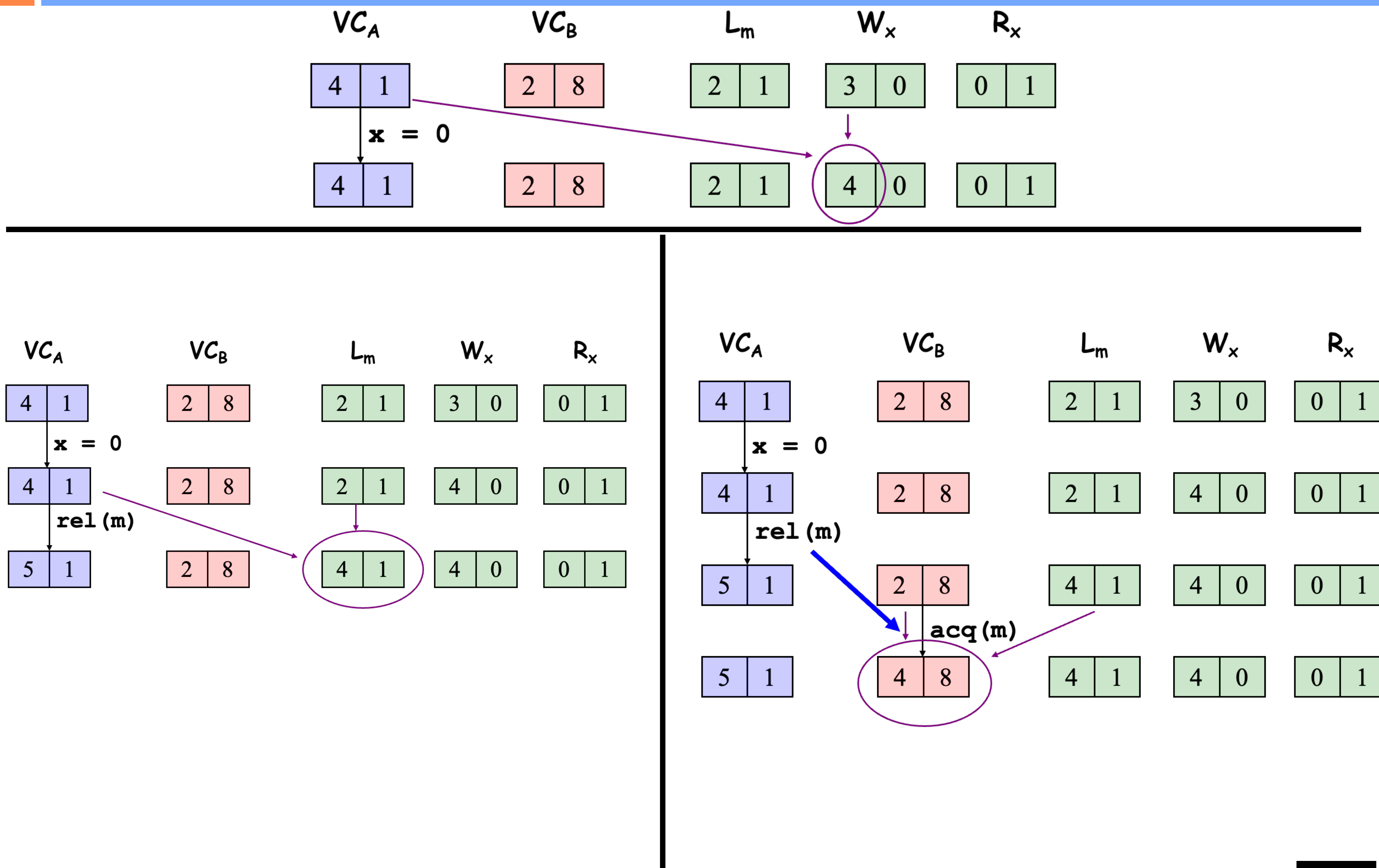
- Each thread maintains a clock C incremented at each lock release operation, as well as a vector clock $C_t(t')$ that records the clock for the last operation performed by t′ that happens-before the current operation of t
- A global vector clock L is also maintained for every lock m
  - When thread t′ releases lock m, $L(m) = C_{t'}$
  - When t subsequently acquires m, $C_t = \max(L(m), C_t)$
- Two vector clocks (R_x and W_x) are also maintained that records the clock of the last read and write to x by a thread t.
  - A read from x by thread t′ is race-free if $W_x \sqsubseteq C_{t'}$
  - A write to x by thread t′ is race-free if the write happens after all previous access to the variable, $W_x \sqsubseteq C_{t'}$ and $R_x \sqsubseteq C_{t'}$

$$VC_1 \sqsubseteq VC_2 \text{ iff } \forall t.\ VC_1(t) \leq VC_2(t)$$

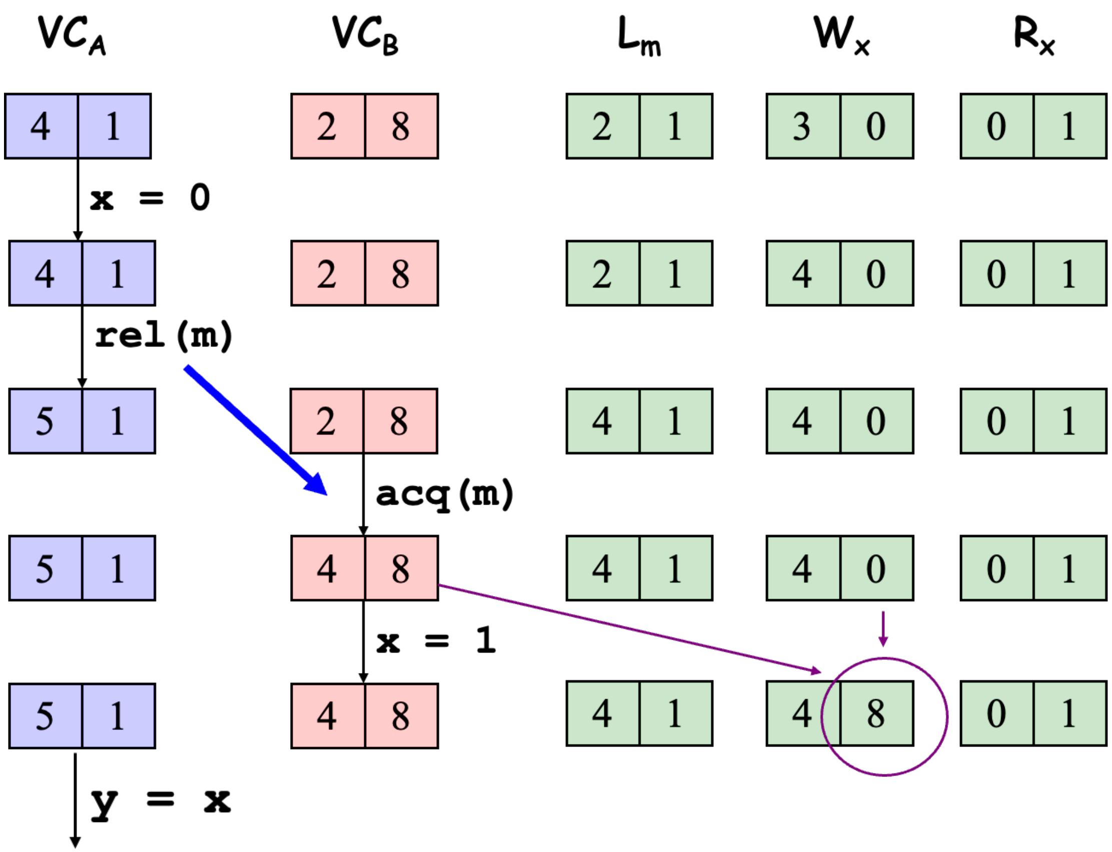
Application to Data Race Detection



Application to Data Race Detection



Application to Data Race Detection



Write-Read Check: $W_x \sqsubseteq VC_A$?

4	8	$\sqsubseteq$	5	1	? No

Application to Data Race Detection

- Sound: if the algorithm does not raise a warning, the execution is DRF

- Complete: if the algorithm does raise a warning, then there is an actual data race

As described, the implementation is expensive

- in space overheads (vector clocks for every read and write operation for every location)
- performance - every vector clock operation requires O(n) time where n is the number of threads
- It's possible to reduce these costs by having a lighter-weight representation (FastTrack algorithm)