CONCURRENCY:
SEQUENTIAL CONSISTENCY, DATA RACES, AND DYNAMIC ANALYSES

Lecture by Rohan Padhye

17-355/17-665/17-819: Program Analysis

Material from past lectures by Jonathan Aldrich, based in large part on slides by John Erickson, Stephen Freund, Madan Musuvathi, Mike Bond, and Man Cao

Lecture Goals

- What is sequential consistency and why is it important?
- What is a data race, and what is data-race-free execution?
- Subtleties of data races and memory models
  - Why taking advantage of “harmless races” is almost certainly a bad idea
- Lockset analysis for data race detection
- Happens-before based data race detection
  - And high performance implementations, e.g. as in FastTrack

SEQUENTIAL CONSISTENCY

First things First
Assigning Semantics to Concurrent Programs

int X = F = 0;

```
X = 1;
F = 1;
```

```
t = F;
u = X;
```

- What does this program mean?
- Sequential Consistency [Lamport '79]

  Program behavior = set of its thread interleavings

Recall: Semantics of WHILE$_{||}$ from midterm

$$\frac{\langle E, S_1 \rangle \rightarrow \langle E', S_1' \rangle}{\langle E, S_1; S_2 \rangle \rightarrow \langle E', S_1'; S_2 \rangle} \textit{ small-seq-congruence}$$

$$\frac{}{\langle E, \texttt{skip}; S_2 \rangle \rightarrow \langle E, S_2 \rangle} \textit{ small-seq}$$

$$\frac{\langle E, S_1 \rangle \rightarrow \langle E', S_1' \rangle}{\langle E, S_1 \parallel S_2 \rangle \rightarrow \langle E', S_1' \parallel S_2 \rangle} \textit{ small-par-congruence-1}$$

$$\frac{\langle E, S_2 \rangle \rightarrow \langle E', S_2' \rangle}{\langle E, S_1 \parallel S_2 \rangle \rightarrow \langle E', S_1 \parallel S_2' \rangle} \textit{ small-par-congruence-2}$$

$$\frac{}{\langle E, \texttt{skip} \parallel \texttt{skip} \rangle \rightarrow \langle E, \texttt{skip} \rangle} \textit{ small-par-skip}$$

Exercise 1:

```
int X = F = 0;
```

```
X = 1;
F = 1;
```

```
t = F;
u = X;
```

- What are the possible final values for variables `t` and `u` after running this program, assuming sequential consistency?

Sequential Consistency Explained

int X = F = 0; // F = 1 implies X is initialized

```
X = 1;
F = 1;
```

```
t = F;
u = X;
```

X = 1;	X = 1;	X = 1;	t = F;	t = F;	t = F;
F = 1;	t = F;	t = F;	u = X;	X = 1;	X = 1;
t = F;	F = 1;	u = X;	X = 1;	u = X;	F = 1;
u = X;	u = X;	F = 1;	F = 1;	F = 1;	u = X;
t=1, u=1	t=0, u=1	t=0, u=1	t=0, u=0	t=0, u=1	t=0, u=1

t=1 implies u=1

Naturalness of Sequential Consistency

- Sequential Consistency provides two crucial abstractions
- Program Order Abstraction
  - Instructions execute in the order specified in the program

A ; B

means “Execute A and then B”

- Shared Memory Abstraction
  - Memory behaves as a global array, with reads and writes done immediately
- We implicitly assume these abstractions for sequential programs
  - As we will see, we can only rely on these abstractions under certain conditions in a concurrent context

WHAT IS A DATA RACE ?

- The term “data race” is often overloaded to mean different things

- Precise definition is important in designing a tool

Data Race

- Two accesses *conflict* if
  - they access the same memory location, and
  - at least one of them is a write

Write X – Write X

Write X – Read X

Read X – Write X

Read X – Read X

- A data race is a pair of conflicting accesses that happen concurrently

“Happen Concurrently”

- A and B happen concurrently if they occur in different threads, and
- there exists a sequentially consistent execution in which they occur one after the other

```
X = 1;
F = 1;
```

```
t = F;
u = X;
```

```
X = 1;
F = 1;
t = F;
u = X;
```

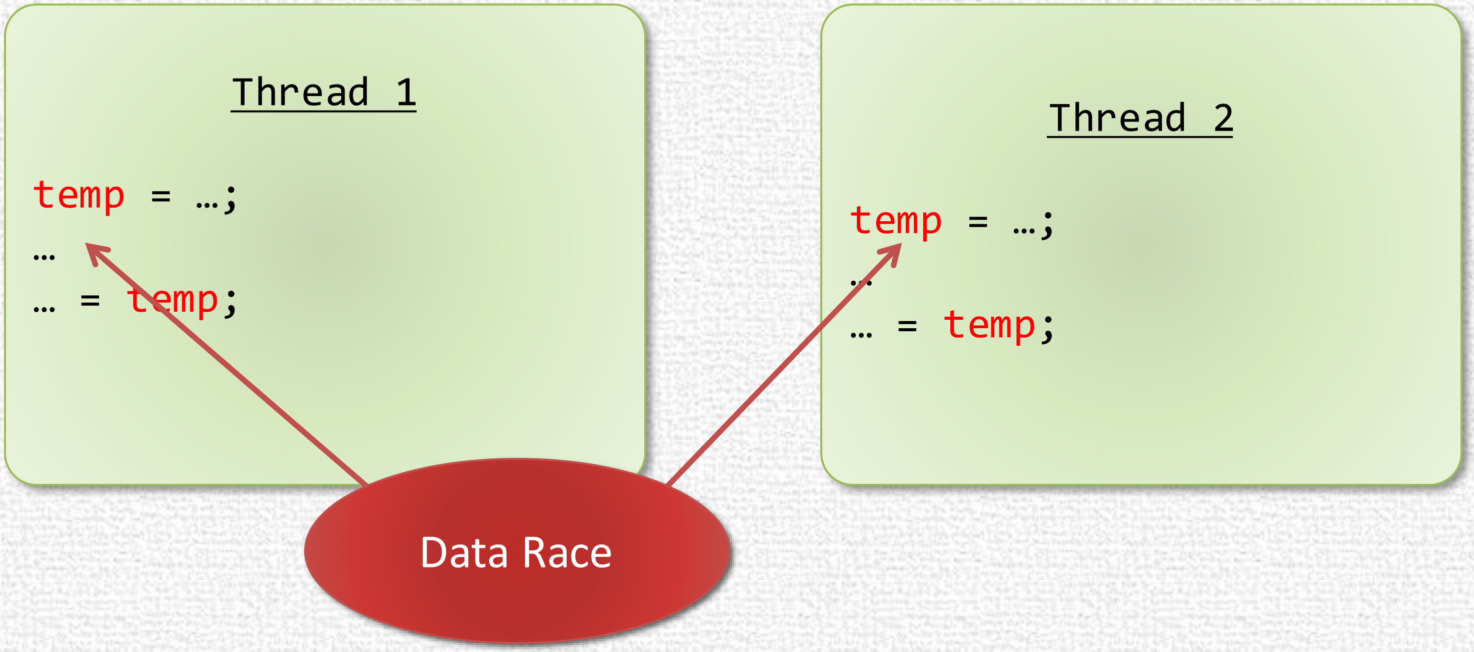
Happen Concurrently

Data races are almost always no good

- What are some consequences of a data race, even when assuming sequential consistency?

Unintended Sharing

- Threads accidentally sharing data that should not be global
- *Solution*: Change allocation (e.g., stack var or static thread-local)



Atomicity Violation

- When code that is meant to execute *atomically* (that is, perform a single undivisible operation) suffers interference from some other thread
- *Solution*: Surround critical sections with locks

Thread 1

```
void Bank::Update(int a)
{
    int t = bal;
    bal = t + a;
}
```

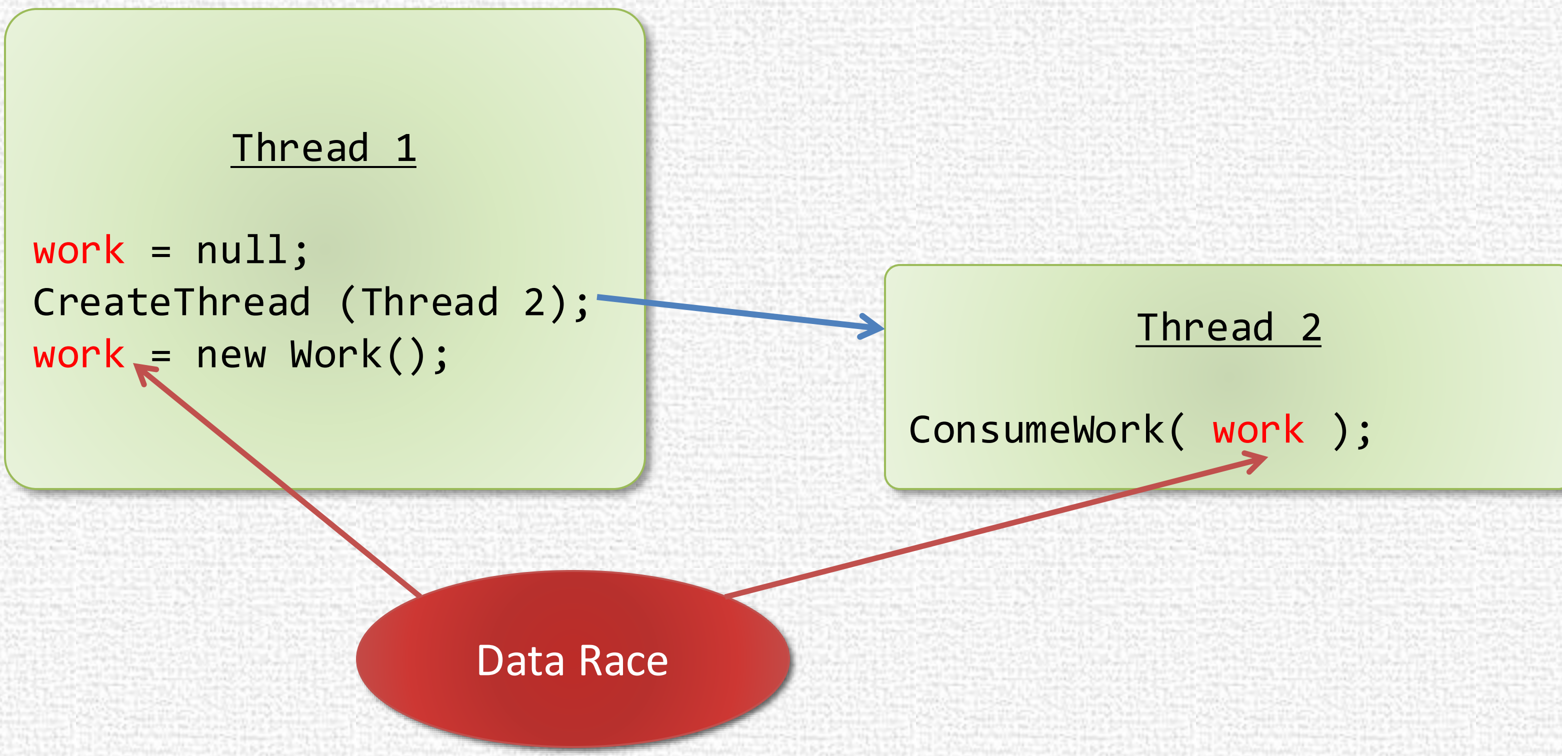
Thread 2

```
void Bank::Withdraw(int a)
{
    int t = bal;
    bal = t - a;
}
```

Data Race

Ordering Violation

- Incorrect signaling between a producer and a consumer
- *Solution*: Reorder operations or use synchronization (e.g., signals)



But,….

- How do you think ”locks” are implemented?
- Atomic compare-and-swap (CAS)

```
AcquireLock(lock){
  while (!CAS (lock, 0, 1)) {}
}
```

```
ReleaseLock(lock) {
    lock = 0;
}
```

Data Race ?

Acceptable Concurrent Conflicting Accesses

- Implementing synchronization (such as locks) usually requires concurrent conflicting accesses to shared memory

- Innovative uses of shared memory
  - Fast reads
  - Double-checked locking
  - Lazy initialization
  - Setting dirty flag
  - …

- Need mechanisms to distinguish these from erroneous conflicts

Solution: Programmer Annotation

- Programmer explicitly annotates variables as “synchronization”
  - Java – volatile keyword
  - C++ – std::atomic<> types

Data Race

- Two accesses *conflict* if
  - they access the same memory location, and
  - at least one of them is a write
- A data race is a pair of concurrent conflicting accesses to locations not annotated as synchronization
  - Recall: “Concurrent” means there exists a sequentially consistent execution in which they happen one after the other
- Equivalent definition: a pair of conflicting accesses where one doesn’t happen before the other
  - Program order
  - Synchronization order
    - Acquire/release, wait-notify, fork-join, volatile read/write

Exercise 2: Is there a data race? If so, on what variable(s)?

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
data = 42;
flag = true;
```

T2:

```
if (flag)
  t = data;
```

Is there a data race?

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
data = 42;
flag = true;
```

T2:

```
if (flag)
   t = data;
```

Consider regular compiler transformations/optimizations

Before:

```
data = 42;
flag = true;
```

After:

```
flag = true;
data = 42;
```

Possible behavior

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
flag = true;
```

T2:

```
if (flag)
  t = data;
```

```
data = 42;
```

Consider regular compiler transformations/optimizations

Before:

```
if (flag)
  t = data;
```

After:

```
t2 = data;
if (flag)
  t = t2;
```

Possible behavior

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
data = 42;
flag = true;
```

T2:

```
t2 = data;

if (flag)
  t = t2;
```

How do we fix this?

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
data = 42;
flag = true;
```

T2:

```
if (flag)
  t = data;
```

Using “synchronized” keyword in Java

Initially:

```
int data = 0;
boolean flag = false;
```

T1:

```
data = ...;
synchronized (m) {
  flag = true;
}
```

T2:

```
boolean f;
synchronized (m) {
  f = flag;
}
if (f)
  ... = data;
```

… Implemented via locks

Initially:

```
int data = 0;
boolean flag = false;
```

<u>T1</u>:

```
data = ...;
acquire(m);
  flag = true;
release(m);
```

Happens-before relationship

<u>T2</u>:

```
boolean f;
acquire(m);
  f = flag;
release(m);
if (f)
  ... = data;
```

Using “volatile” keyword in Java

Initially:

```
int data = 0;
volatile boolean flag = false;
```

<u>T1</u>:

```
data = ...;
flag = true;
```

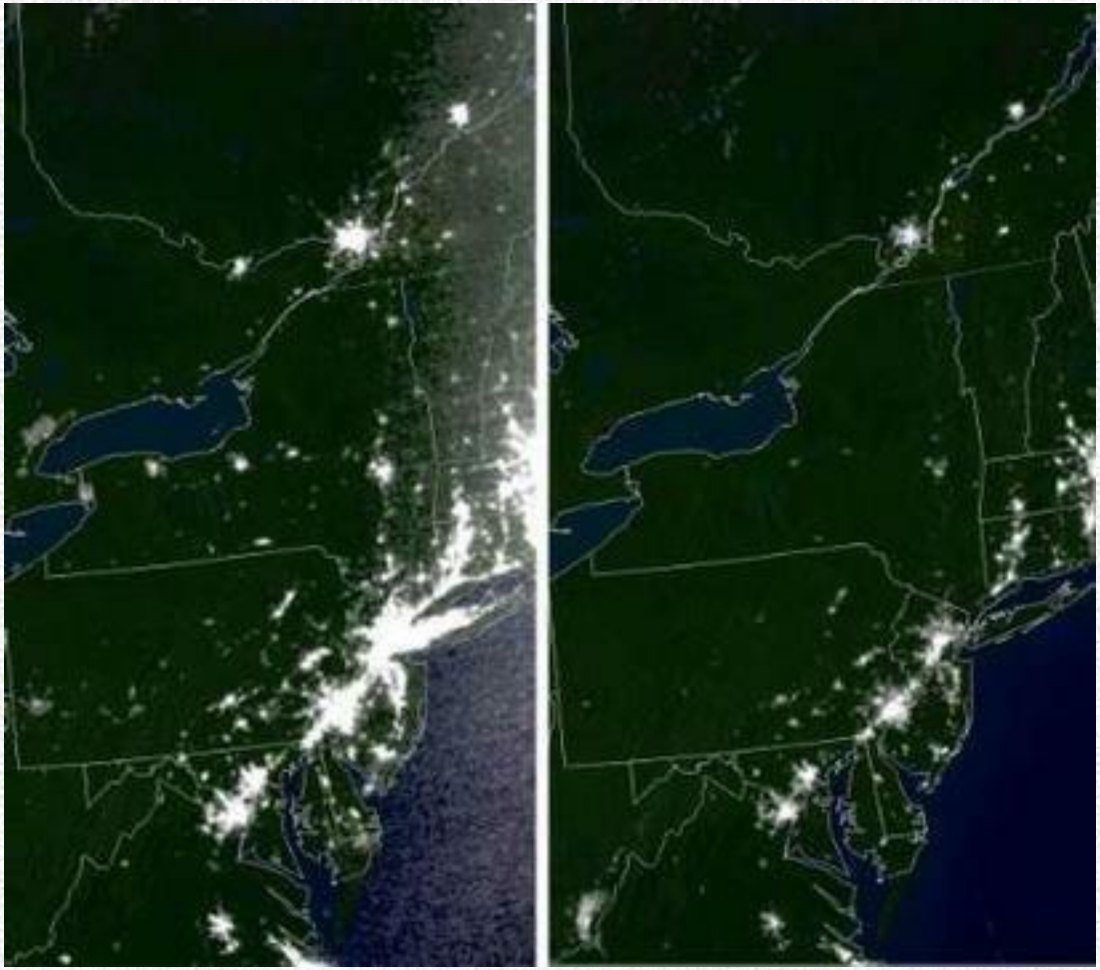
Happens-before relationship

<u>T2</u>:

```
if (flag)
  ... = data;
```

Data Race vs Race Conditions

- Data Races != Race Conditions
  - Confusing terminology
- Race Condition
  - Any timing error in the program
  - Due to events, device interaction, thread interleaving, …
  - Race conditions can be very bad!



Data Race vs Race Conditions

- Data Races != Race Conditions
  - Confusing terminology

- Race Condition
  - Any timing error in the program
  - Due to events, device interaction, thread interleaving, …
  - Race conditions can be very bad!

- Data races are neither sufficient nor necessary for a race condition
  - Data race is a good symptom for a race condition

DATA-RACE-FREEDOM SIMPLIFIES LANGUAGE SEMANTICS

Advantage of Eliminating All Data Races

- Defining semantics for concurrent programs becomes surprisingly easy
- In the presence of compiler and hardware optimizations

Can A Compiler Do This?

```
L1: t = X*5;
L2: u = Y;
L3: v = X*5;
```

```
L1: t = X*5;
L2: u = Y;
L3: v = t;
```

OK for sequential programs
if X is not modified between L1 and L3

t,u,v are local variables
X,Y are possibly shared

Can Break Sequential Consistent Semantics

Init: X = Y = 0;

```
L1: t = X*5;
L2: u = Y;
L3: v = X*5;
```

```
M1: X = 1;
M2: Y = 1;
```

u == 1 ➔ v == 5

Data Race

Init: X = Y = 0;

```
L1: t = X*5;
L2: u = Y;
L3: v = t;
```

```
M1: X = 1;
M2: Y = 1;
```

possibly u == 1 && v == 0

Can A Compiler Do This?

```
L1: t = X*5;
L2: u = Y;
L3: v = X*5;
```

```
L1: t = X*5;
L2: u = Y;
L3: v = t;
```

OK for sequential programs
if X is not modified between L1 and L3

OK for concurrent programs
if there is no data race on X or
if there is no data race on Y

t,u,v are local variables
X,Y are possibly shared

Key Observation [Adve& Hill '90]

- Many sequentially valid (compiler & hardware) transformations also preserve sequential consistency
- Provided the program is data-race free

- Forms the basis for modern C++, Java semantics

data-race-free → sequential consistency

otherwise → weak/undefined semantics

DATA RACE DETECTION

Overview of Data Race Detection Techniques

- Static data race detection
- Dynamic data race detection
  - Lock-set
  - Happen-before
  - DataCollider

Static Data Race Detection

- Advantages:
  - Reason about all inputs/interleavings
  - No run-time overhead
  - Adapt well-understood static-analysis techniques
  - Annotations to document concurrency invariants
- Example Tools:
  - RCC/Java type-based
  - ESC/Java "functional verification" (theorem proving-based)

Static Data Race Detection

- Advantages:
  - Reason about all inputs/interleavings
  - No run-time overhead
  - Adapt well-understood static-analysis techniques
  - Annotations to document concurrency invariants
- Disadvantages of static:
  - Undecidable…
  - Tools produce "false positives" or "false negatives"
  - May be slow, require programmer annotations
  - May be hard to interpret results

Dynamic Data Race Detection

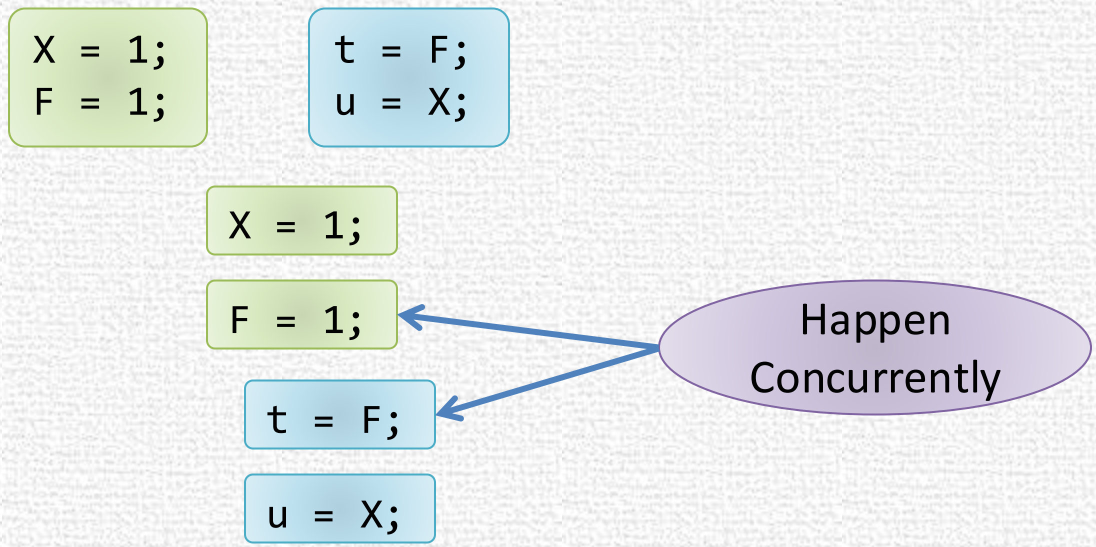
- Advantages
  - Can avoid “false positives”
  - No need for language extensions or sophisticated static analysis
- Disadvantages
  - Run-time overhead (5-20x for best tools)
  - Memory overhead for analysis state
  - Reasons only about observed executions
    - sensitive to test coverage
    - (some generalization possible...)

Tradeoffs: Static vs Dynamic

- Coverage
  - generalize to additional traces?
- Soundness
  - all reported warnings are actually races
- Completeness
  - every actual data race is reported
- Overhead
  - run-time slowdown
  - memory footprint
- Programmer overhead

Definition Refresh

- A data race is a pair of concurrent conflicting accesses to unannotated locations (i.e. not locks or volatile variables)



- Problem for dynamic data race detection
  - Very difficult to catch the two accesses executing concurrently

Solution

- Lockset
  - Infer data races through violation of locking discipline

- Happens-before
  - Infer data races by generalizing a trace to a set of traces with the same happens-before relation

LOCKSET ALGORITHM

Eraser [Savage et.al. ‘97]

Lockset Algorithm Overview

- Checks a sufficient condition for data-race-freedom
- Consistent locking discipline
  - Every data structure is protected by a single lock
  - All accesses to the data structure made while holding the lock
- Example:

```
// Remove a received packet
AcquireLock( RecvQueueLk );
pkt = RecvQueue.RemoveTop();
ReleaseLock( RecvQueueLk );

… // process pkt

// Insert into processed
AcquireLock( ProcQueueLk );
ProcQueue.Insert(pkt);
ReleaseLock( ProcQueueLk );
```

RecvQueue is consistently protected by RecvQueueLk

ProcQueue is consistently protected by ProcQueueLk

Inferring the Locking Discipline

- How do we know which lock protects what?
  - Asking the programmer is cumbersome

- Solution: Infer from the program

```
AcquireLock( A );
AcquireLock( B );
x ++;
ReleaseLock( B );
ReleaseLock( A );
```

```
AcquireLock( B );
AcquireLock( C );
x ++;
ReleaseLock( C );
ReleaseLock( B );
```

X is protected by A, or B, or both

X is protected by B, or C, or both

X is protected by B

LockSet Algorithm

- Two data structures:
  - LocksHeld(t) = set of locks held currently by thread t
    - Initially set to Empty
  - LockSet(x) = set of locks that could potentially be protecting x
    - Initially set to the universal set

- When thread t acquires lock l
  - $LocksHeld(\ t\ ) = LocksHeld(\ t\ ) \cup \{l\}$
- When thread t releases lock l
  - $LocksHeld(\ t\ ) = LocksHeld(\ t\ ) - \{l\}$

- When thread t accesses location x
  - $LockSet(\ x\ ) = LockSet(\ x\ ) \cap LocksHeld(\ t\ )$
  - Report "data race" when LockSet(x) becomes empty

LockSet Algorithm

- No warnings → no data races on the current execution
  - The program followed consistent locking discipline in this execution
- Warnings does not imply a data race
  - Thread-local initialization

```
// Initialize a packet
pkt = new Packet();
pkt.Consumed = 0

AcquireLock( SendQueueLk );
SendQueue.Enqueue(pkt);
ReleaseLock( SendQueueLk );
```

```
// Process a packet
AcquireLock( SendQueueLk );
pkt = SendQueue.Top();
pkt.Consumed = 1;
ReleaseLock( SendQueueLk );
```

LockSet Algorithm

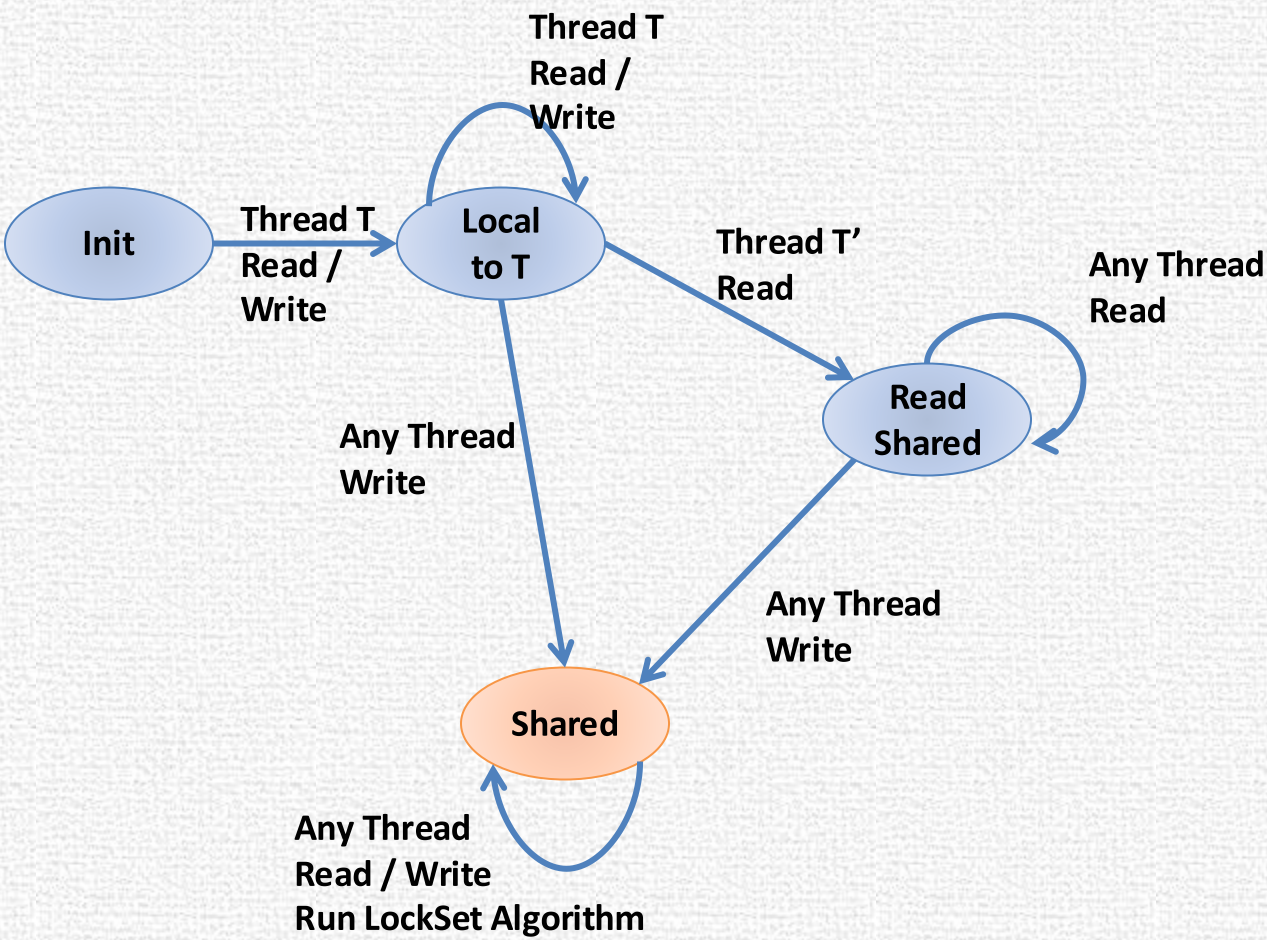
- No warnings → no data races on the current execution
  - The program followed consistent locking discipline in this execution
- Warnings does not imply a data race
  - Object read-shared after thread-local initialization

```
A = new A();
A.f = 0;

// publish A
globalA = A;
```

```
f = globalA.f;
```

Maintain A State Machine Per Location



LockSet Algorithm

- State machine misses some data races

```
// Initialize a packet
pkt = new Packet();
pkt.Consumed = 0;

AcquireLock( WrongLk );
pkt = SendQueue.Top();
pkt.Consumed = 1;
ReleaseLock( WrongLk );
```

```
// Process a packet
AcquireLock( SendQueueLk );
pkt = SendQueue.Top();
pkt.Consumed = 1;
ReleaseLock( SendQueueLk );
```

LockSet Algorithm

- Does not handle locations consistently protected by different locks during a particular execution

```
// Remove a received packet
AcquireLock( RecvQueueLk );
pkt = RecvQueue.RemoveTop();
ReleaseLock( RecvQueueLk );

… // process pkt

// Insert into processed
AcquireLock( ProcQueueLk );
ProcQueue.Insert(pkt);
ReleaseLock( ProcQueueLk );
```

Pkt is protected by RecvQueueLk

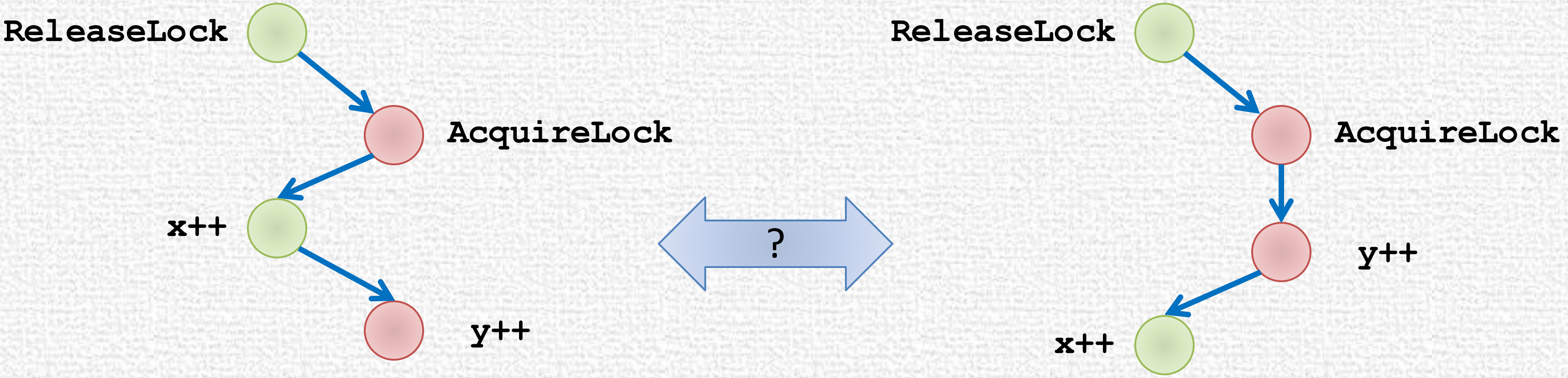
Pkt is thread local

Pkt is protected by ProcQueueLk

HAPPENS-BEFORE

Happens-Before Relation [Lamport '78]

- A concurrent execution is a partial-order determined by communication events
- The program cannot “observe” the order of concurrent non-communicating events



Happens-Before Relation [Lamport '78]

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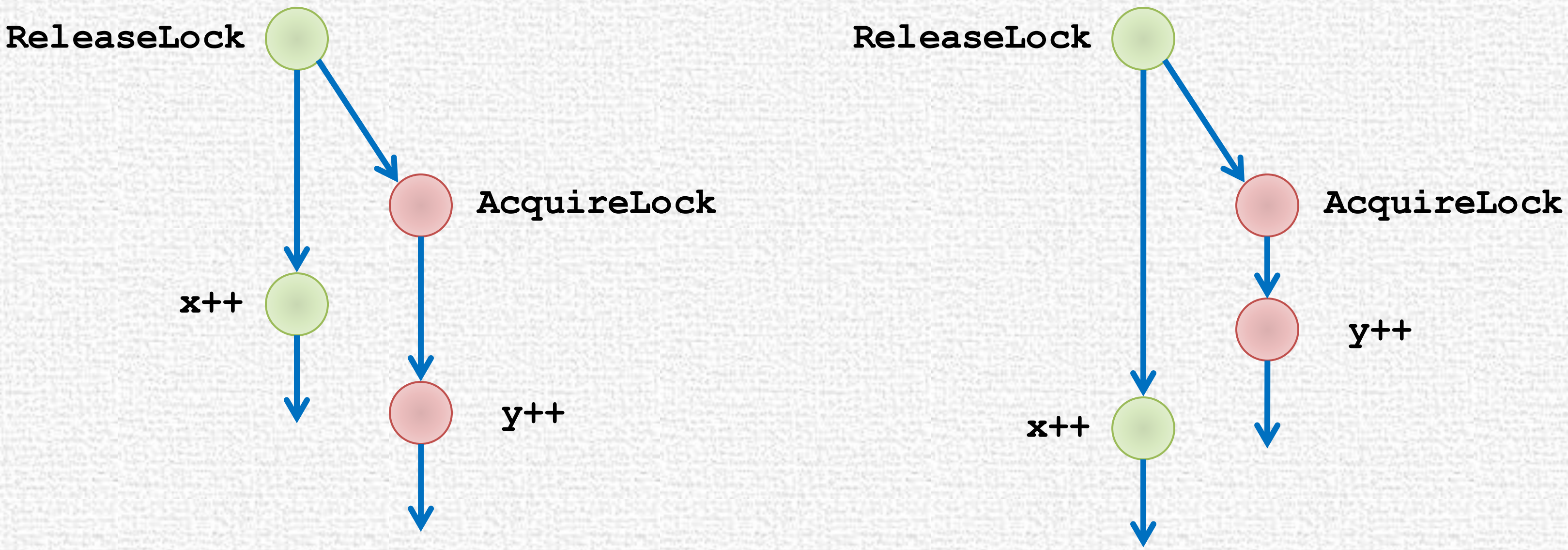
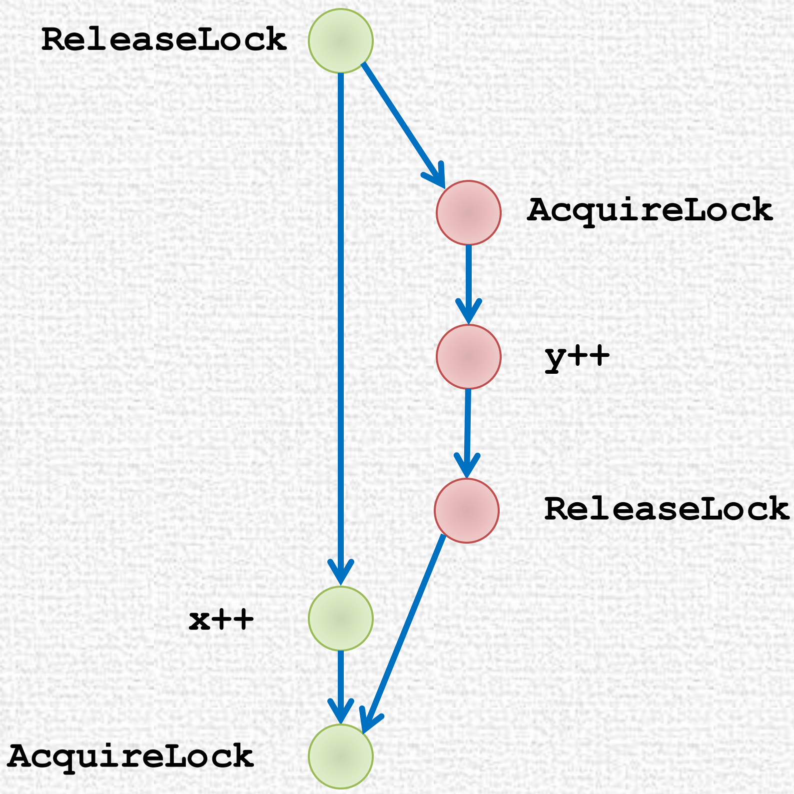


- Both executions form the same happens-before relation

Constructing the Happens-Before Relation

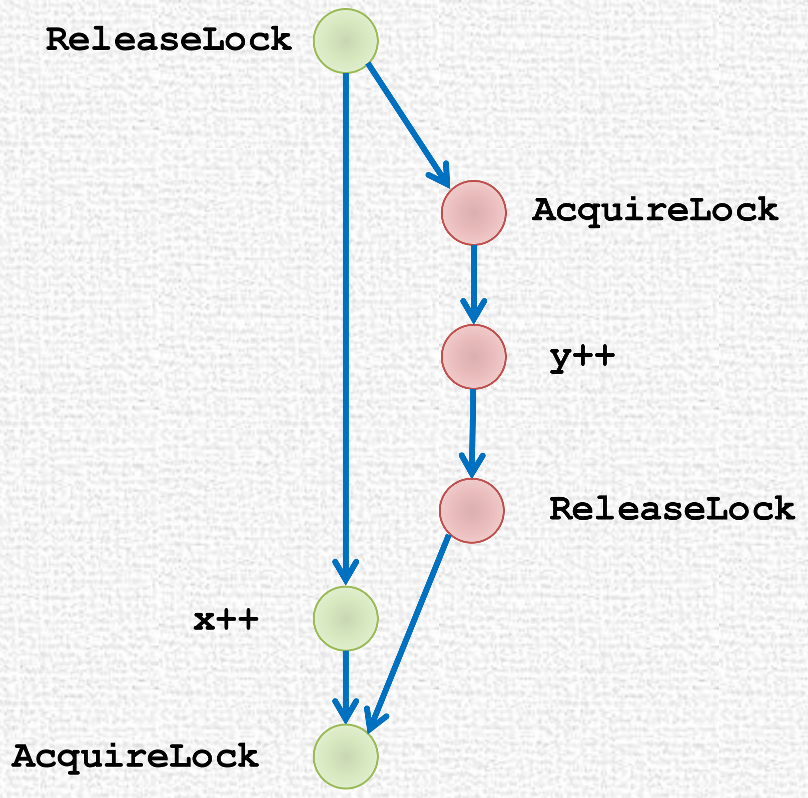
- Program order
  - Total order of thread instructions
- Synchronization order
  - Total order of accesses to the same synchronization



Happens-Before Relation And Data Races

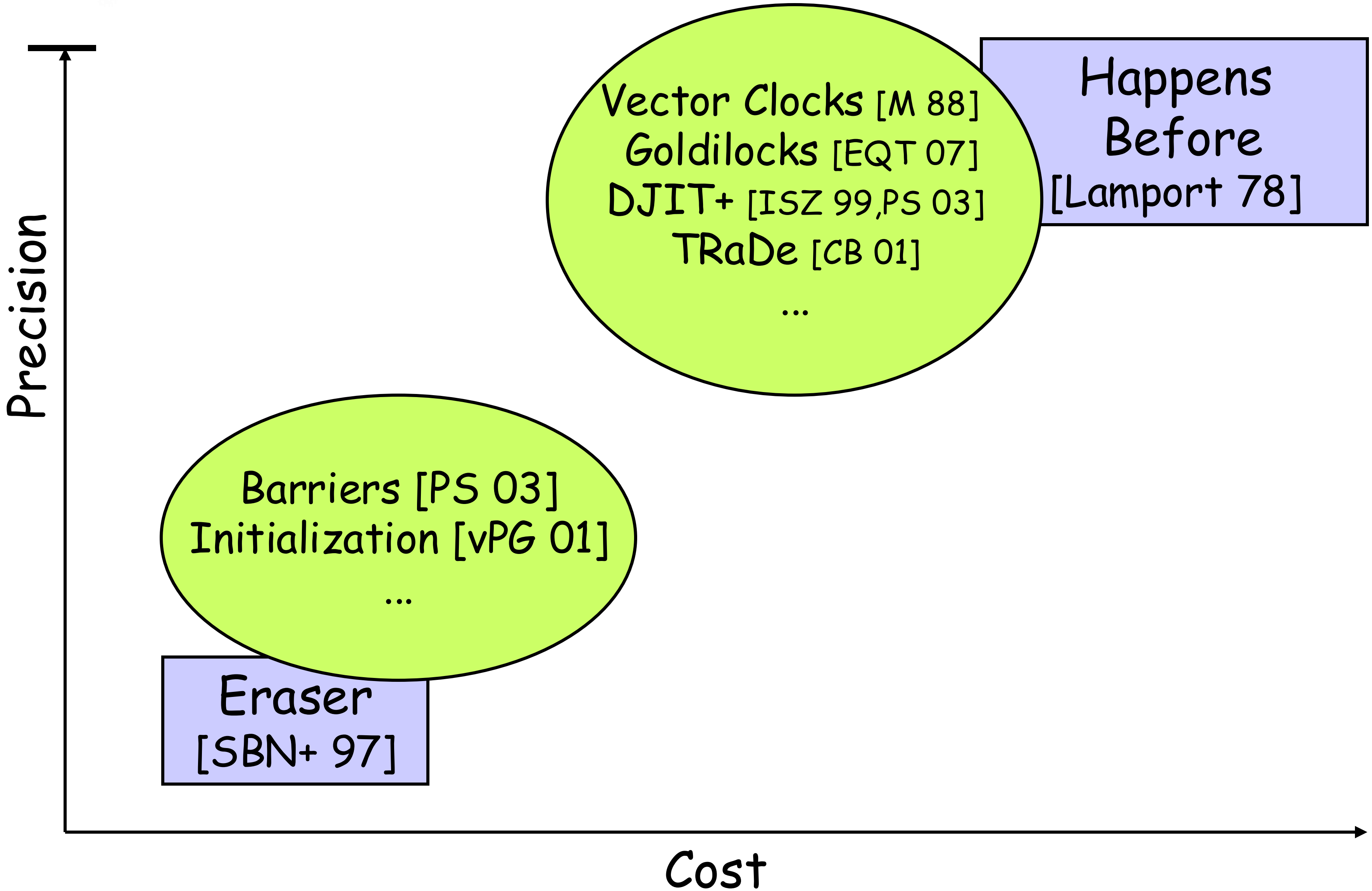
- If all conflicting accesses are ordered by happens-before
- → data-race-free execution
- → All linearizations of partial-order are valid program executions

- If there exists conflicting accesses not ordered
- → a data race

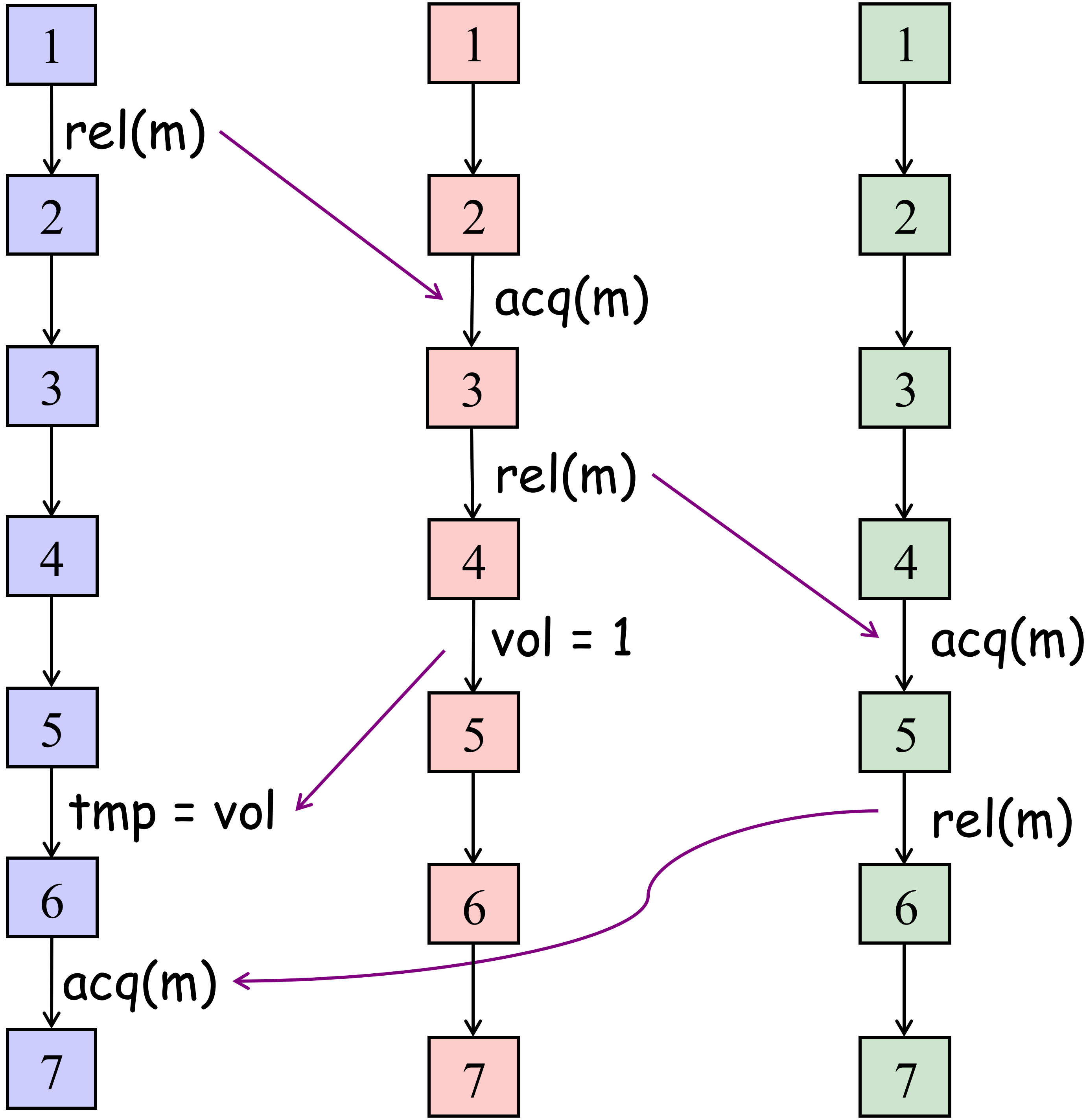


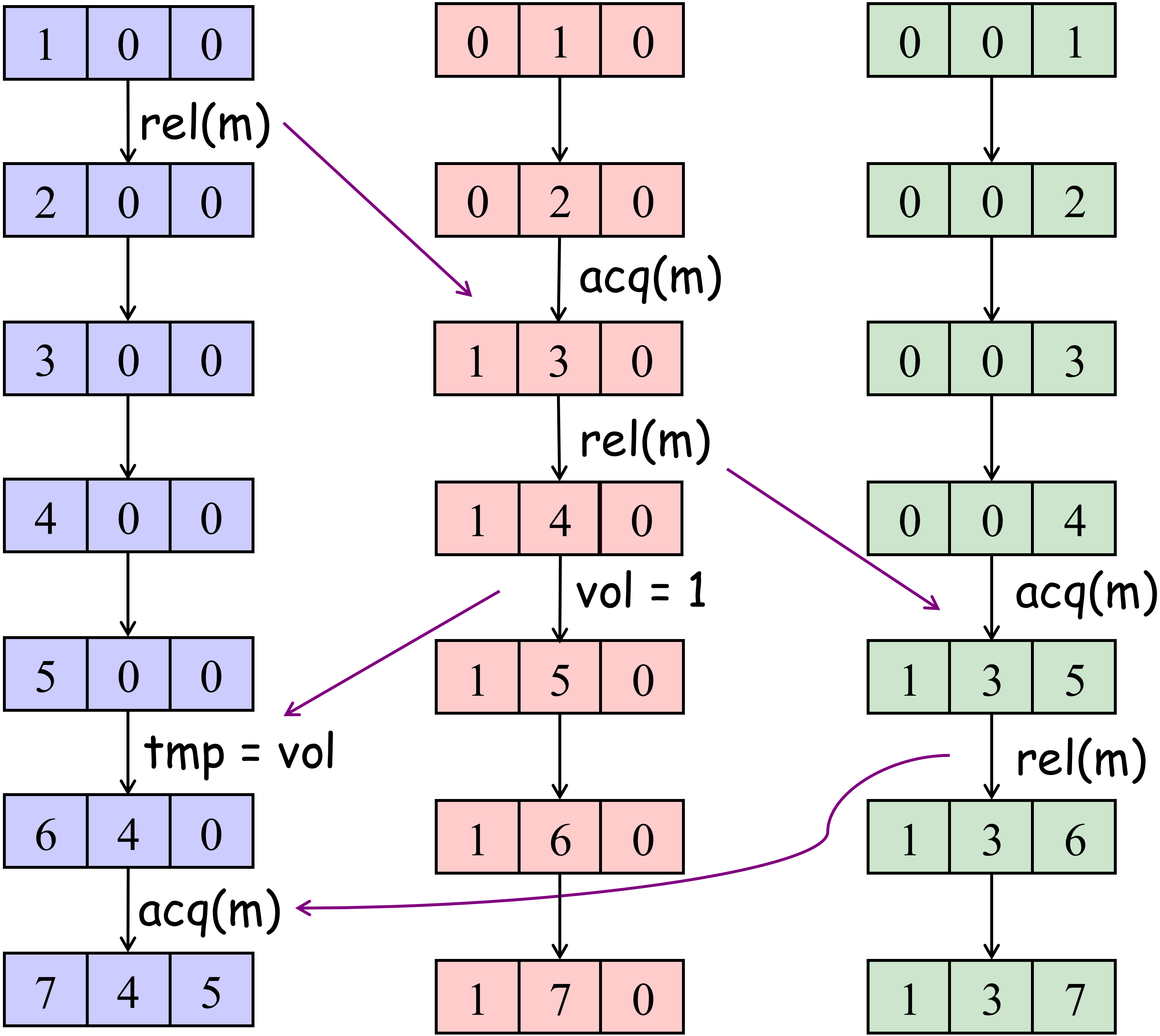
IMPLEMENTING HAPPENS-BEFORE ANALYSES

Dynamic Data-Race Detection

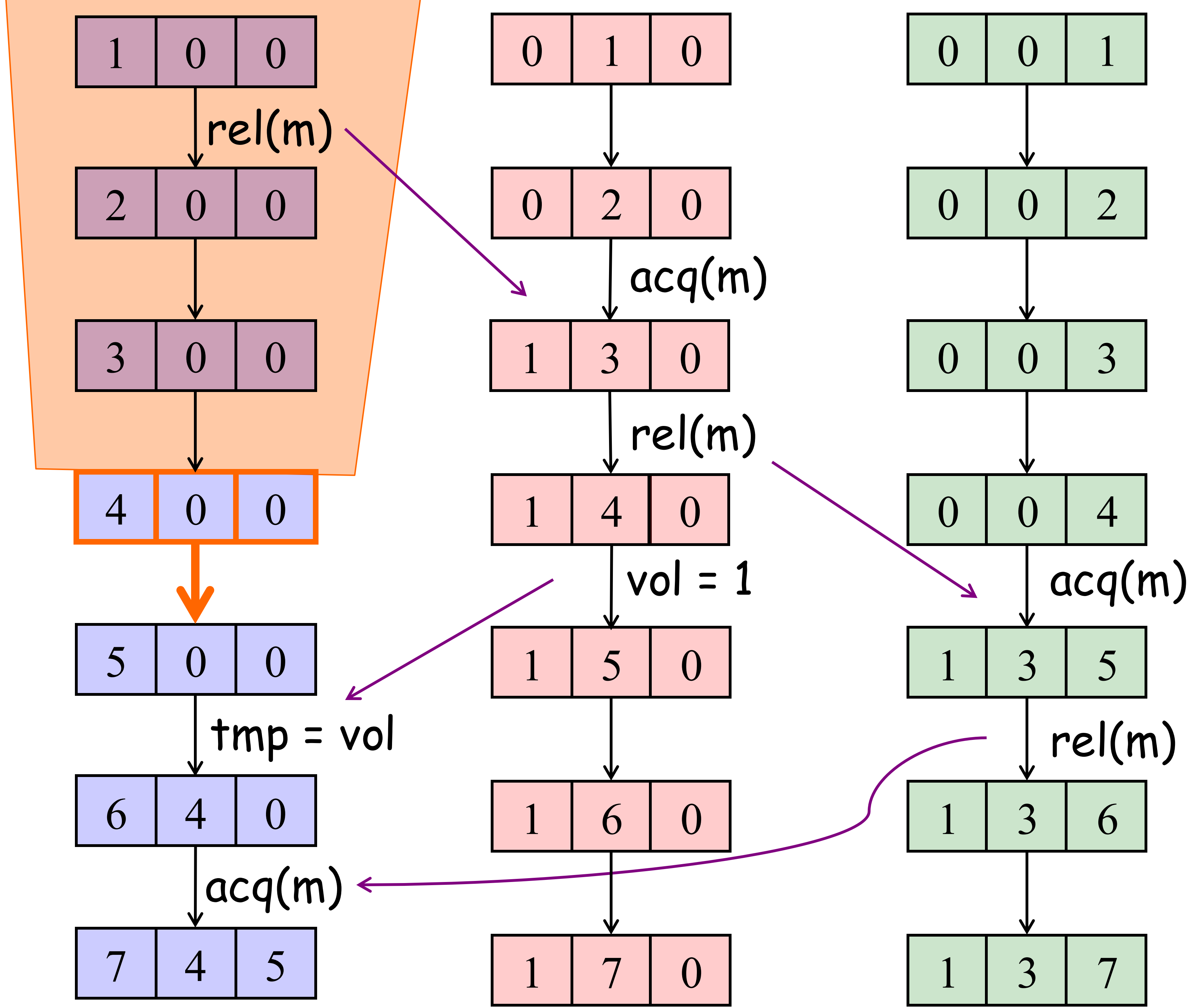


Precise Happens-Before

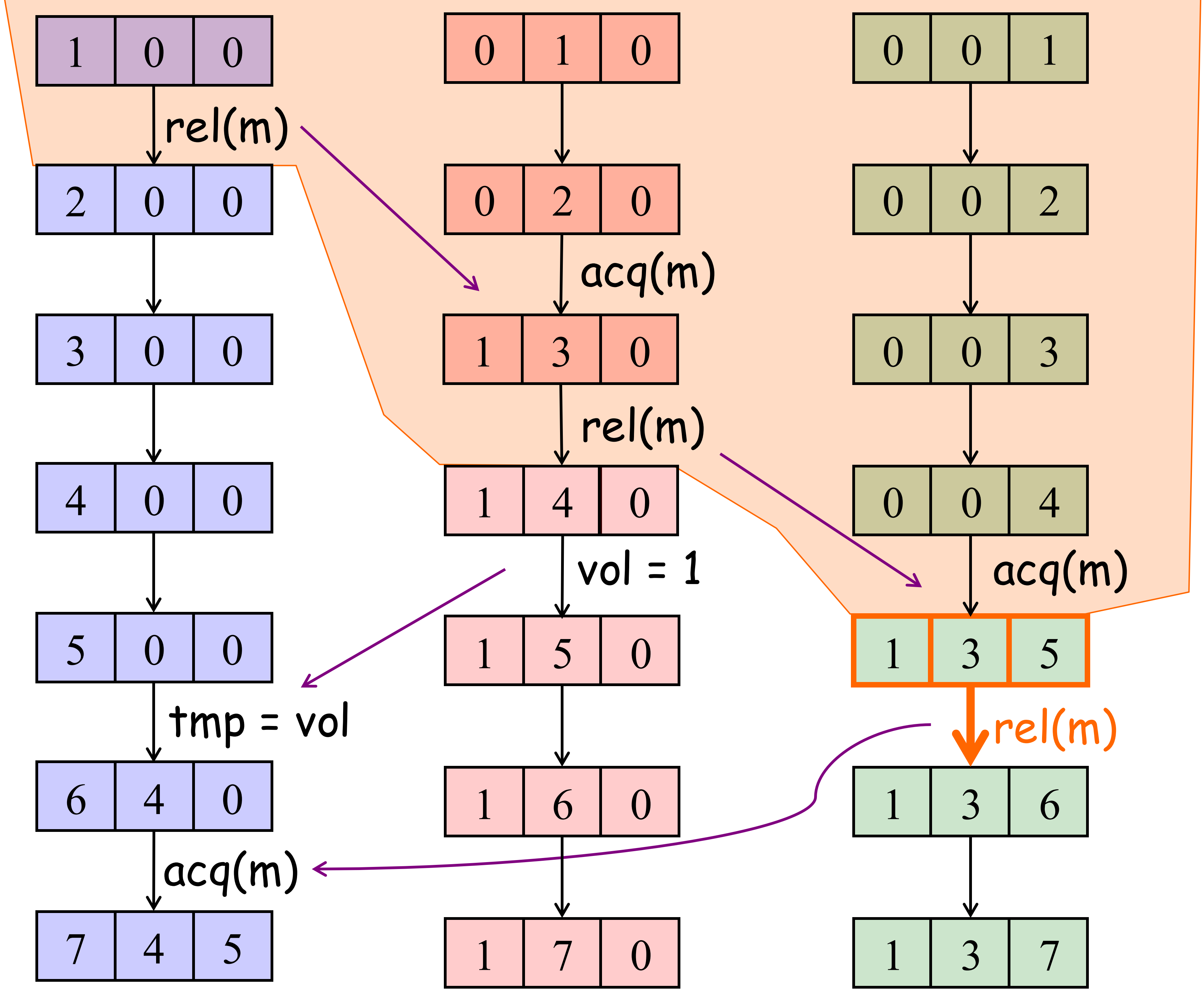


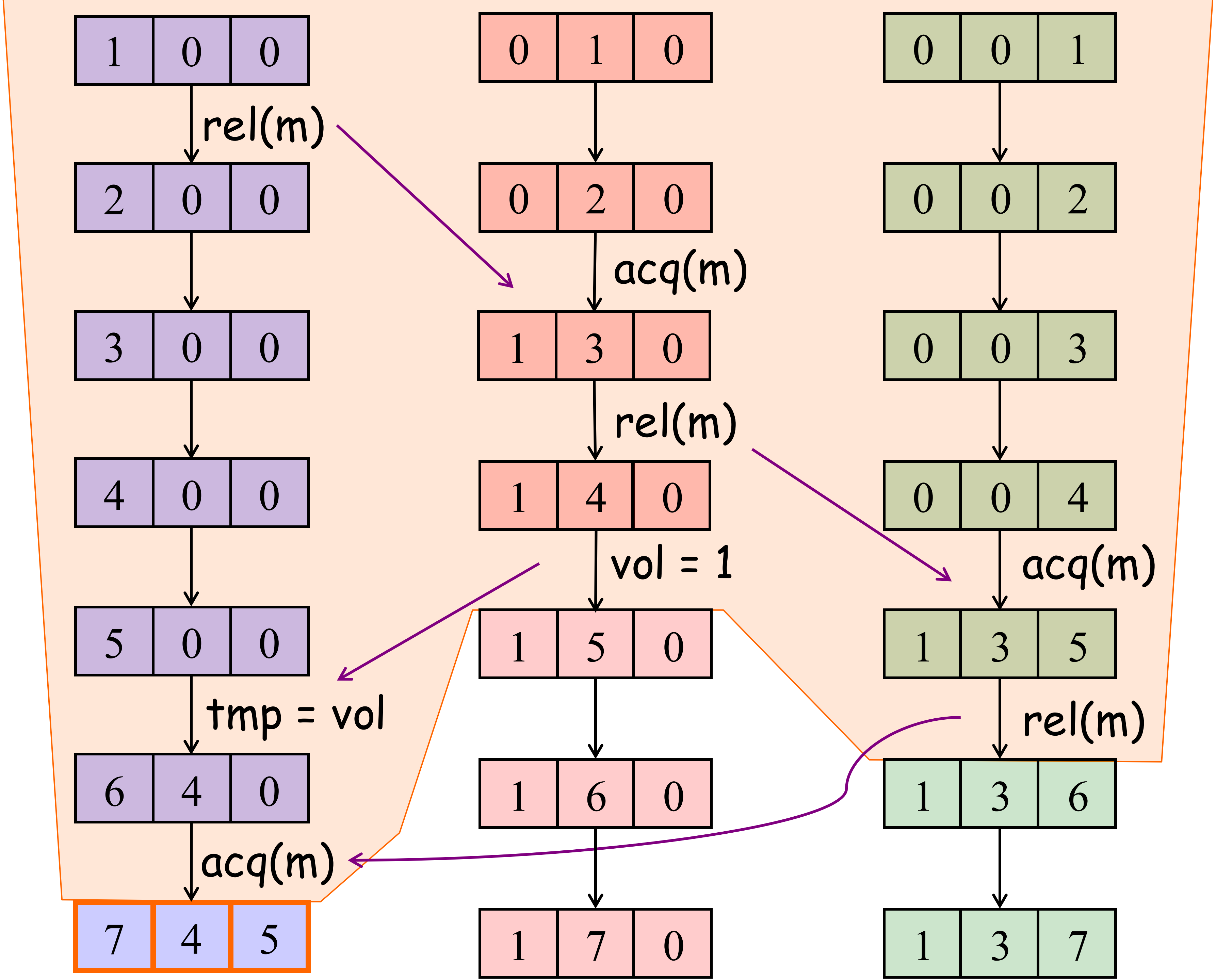


1 0 0
rel(m)
2 0 0
3 0 0
4 0 0
5 0 0
tmp = vol
6 4 0
acq(m)
7 4 5
0 1 0
0 2 0
acq(m)
1 3 0
rel(m)
1 4 0
vol = 1
1 5 0
1 6 0
1 7 0
0 0 1
0 0 2
0 0 3
0 0 4
acq(m)
1 3 5
rel(m)
1 3 6
1 3 7

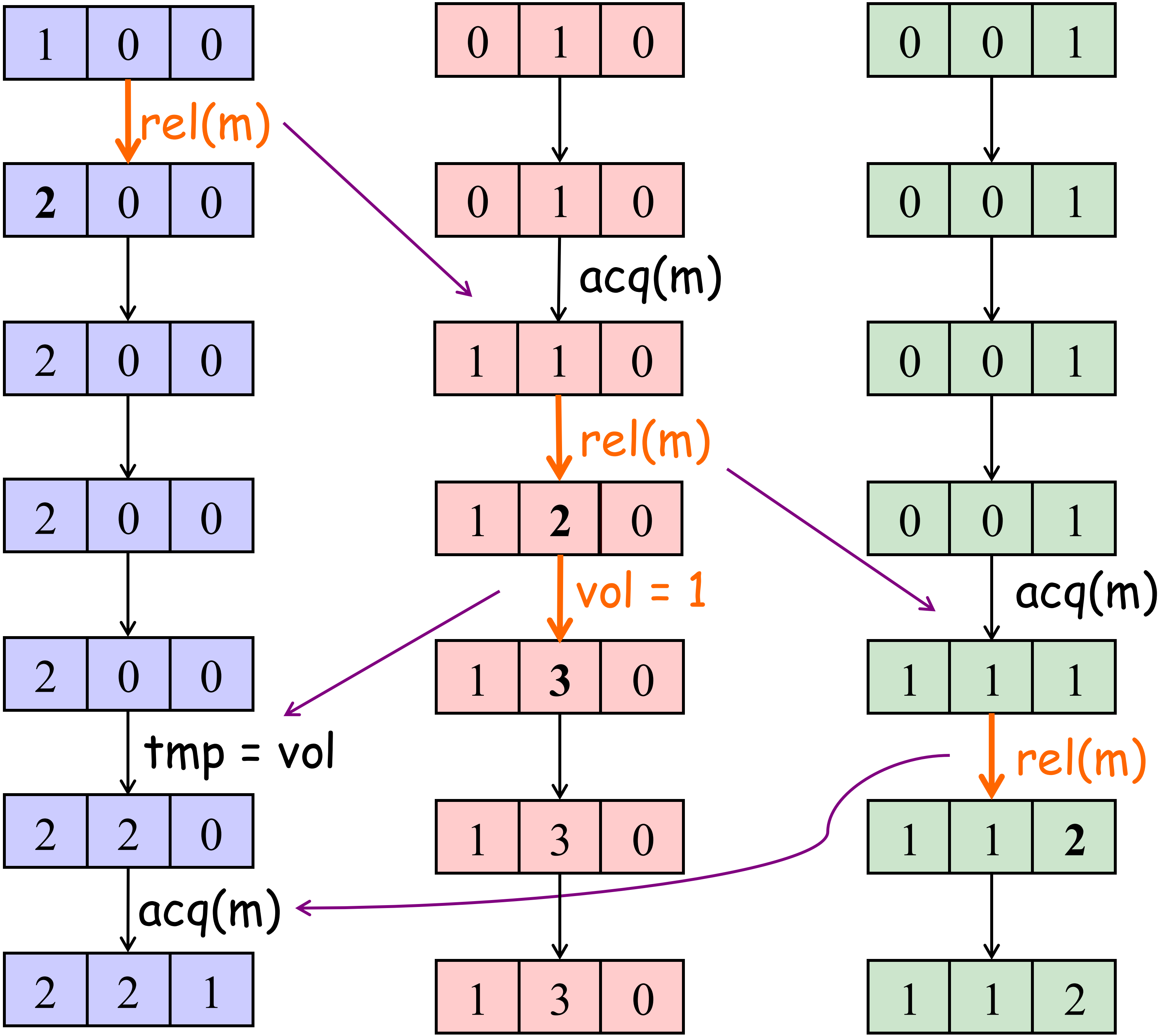


1 0 0
rel(m)
2 0 0
3 0 0
4 0 0
5 0 0
tmp = vol
6 4 0
acq(m)
7 4 5
0 1 0
0 2 0
acq(m)
1 3 0
rel(m)
1 4 0
vol = 1
1 5 0
1 6 0
1 7 0
0 0 1
0 0 2
0 0 3
0 0 4
acq(m)
1 3 5
rel(m)
1 3 6
1 3 7


rel(m)
acq(m)
rel(m)
vol = 1
acq(m)
rel(m)
tmp = vol
acq(m)



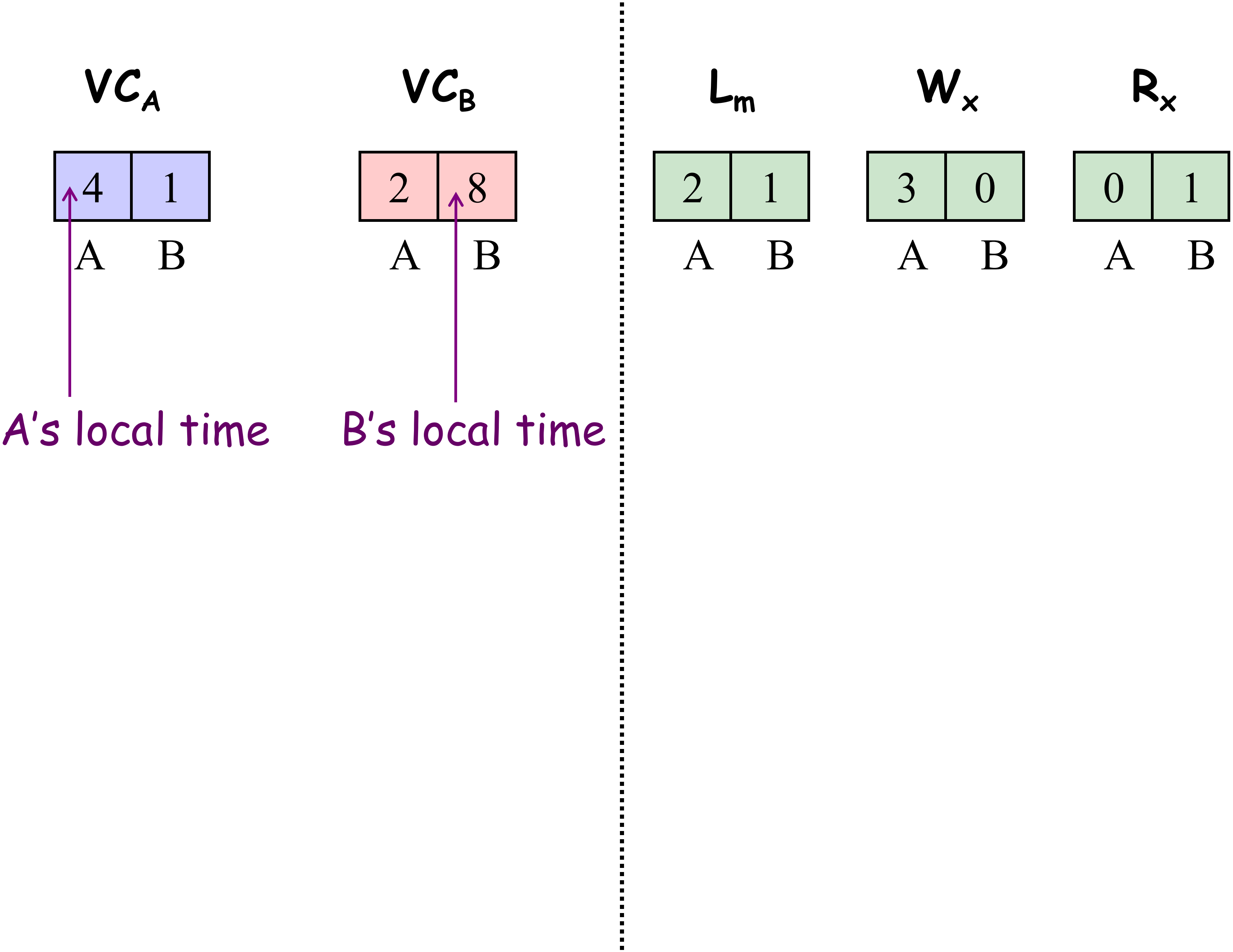
1 0 0
rel(m)
2 0 0
3 0 0
4 0 0
5 0 0
tmp = vol
6 4 0
acq(m)
7 4 5
0 1 0
0 2 0
acq(m)
1 3 0
rel(m)
1 4 0
vol = 1
1 5 0
1 6 0
1 7 0
0 0 1
0 0 2
0 0 3
0 0 4
acq(m)
1 3 5
rel(m)
1 3 6
1 3 7



1 0 0
rel(m)
2 0 0
2 0 0
2 0 0
2 0 0
tmp = vol
2 2 0
acq(m)
2 2 1
0 1 0
0 1 0
acq(m)
1 1 0
rel(m)
1 2 0
vol = 1
1 3 0
1 3 0
1 3 0
0 0 1
0 0 1
0 0 1
0 0 1
acq(m)
1 1 1
rel(m)
1 1 2
1 1 2

Exercise on vector clocks and partial ordering

- $VC = [t_1, t_2, \ldots t_N]$
- What is $VC_a \sqsubseteq VC_b$?
- What is $VC_a \sqcup VC_b$?
- What are sufficient and necessary conditions for there to be a data race between two accesses having vector clocks VC_a and VC_b?



VC_A
4 1
A B
A's local time
VC_B
2 8
A B
B's local time
L_m
2 1
A B
W_x
3 0
A B
R_x
0 1
A B

VC_A

4	1
A	B

VC_B

2	8
A	B

L_m

2	1
A	B

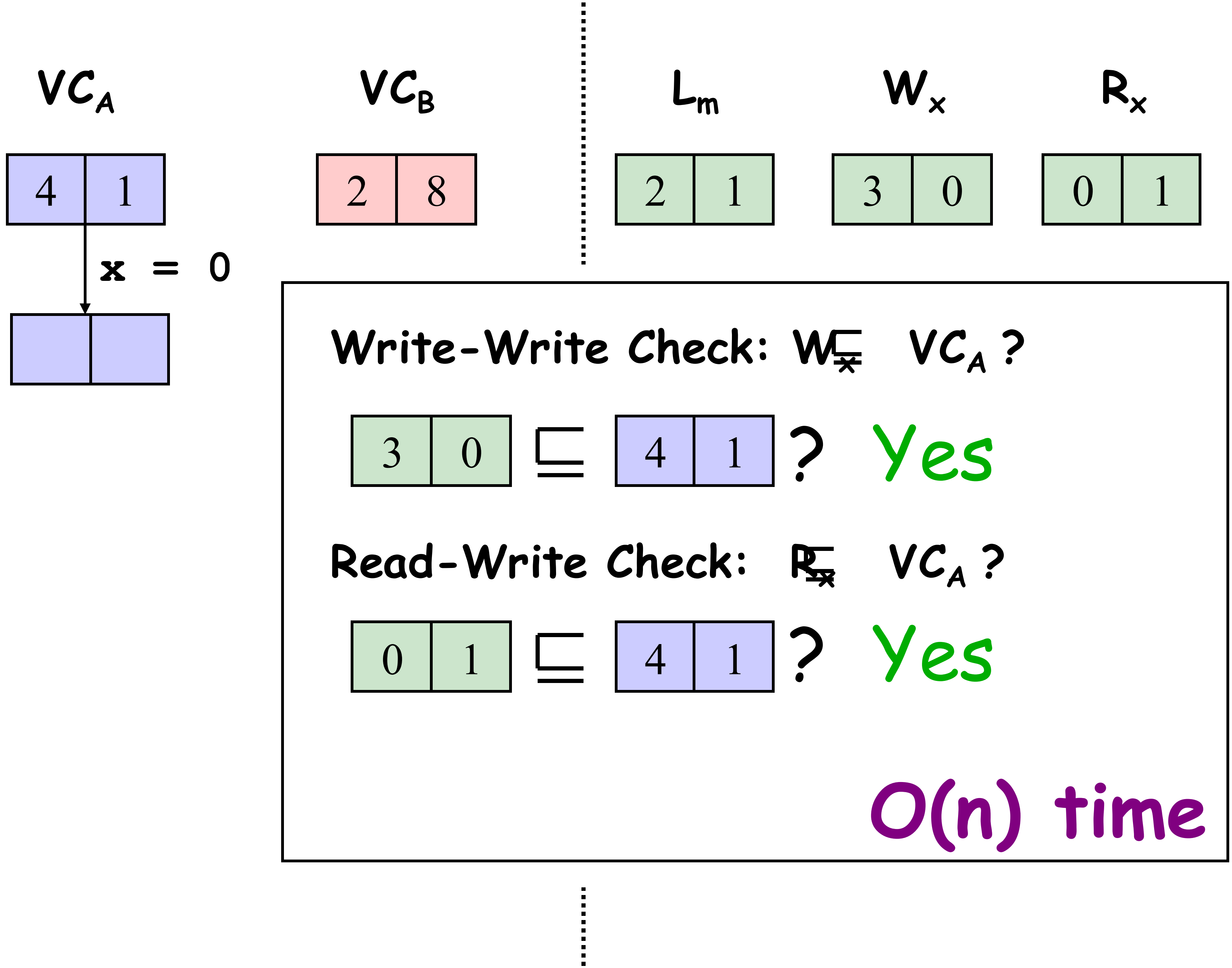
W_x

3	0
A	B

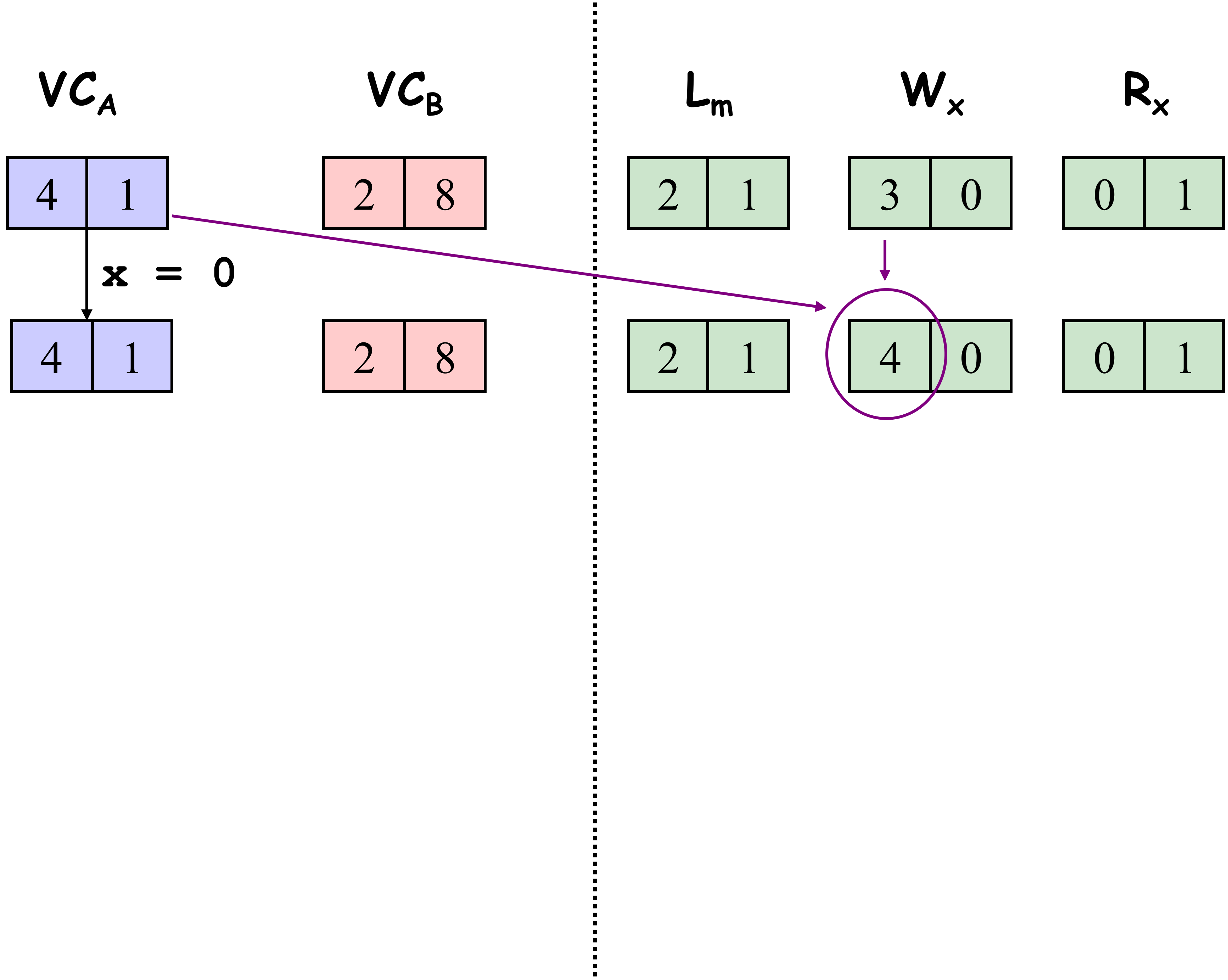
R_x

0	1
A	B

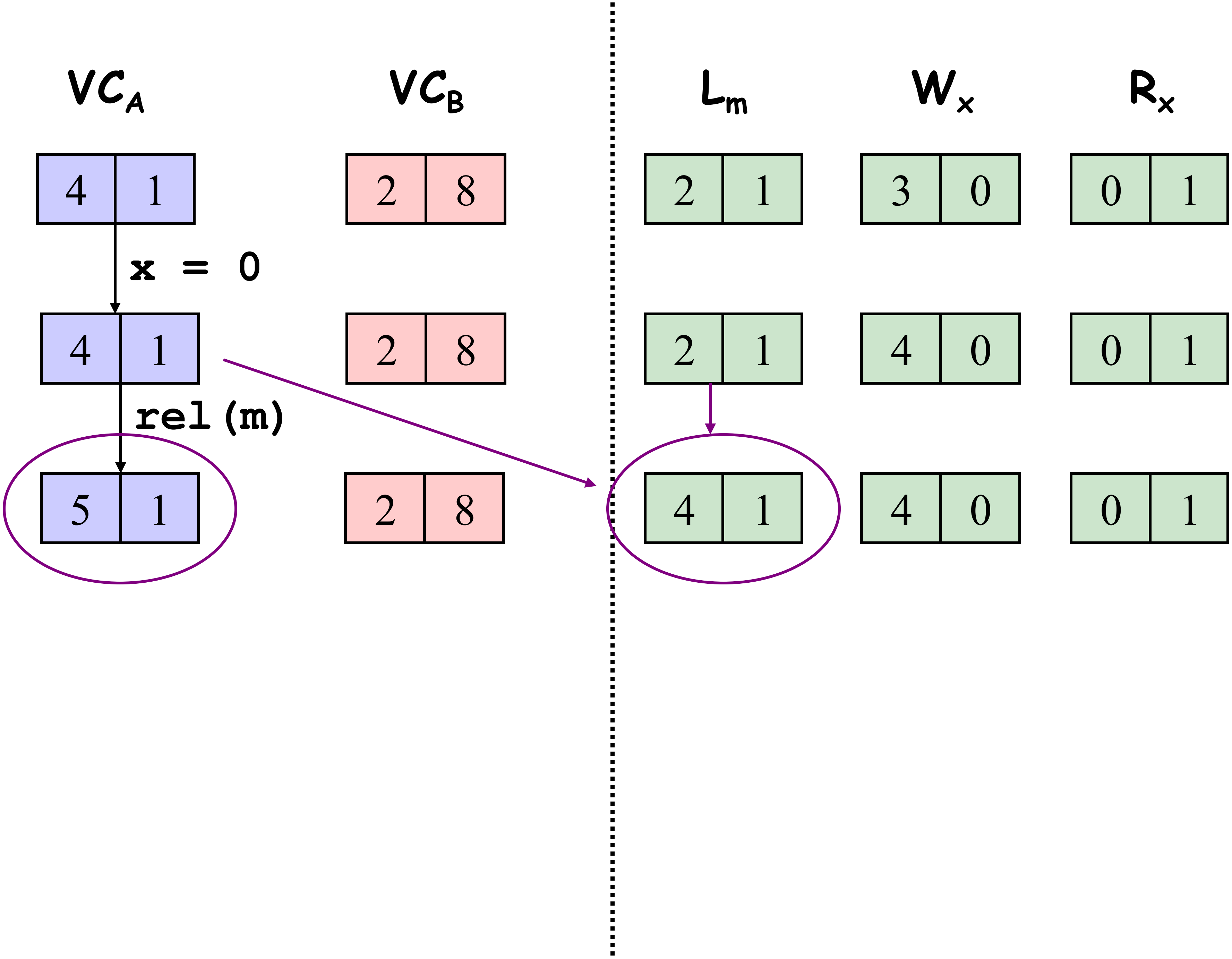
B-steps with B-time ≤ 1
happen before
A's next step



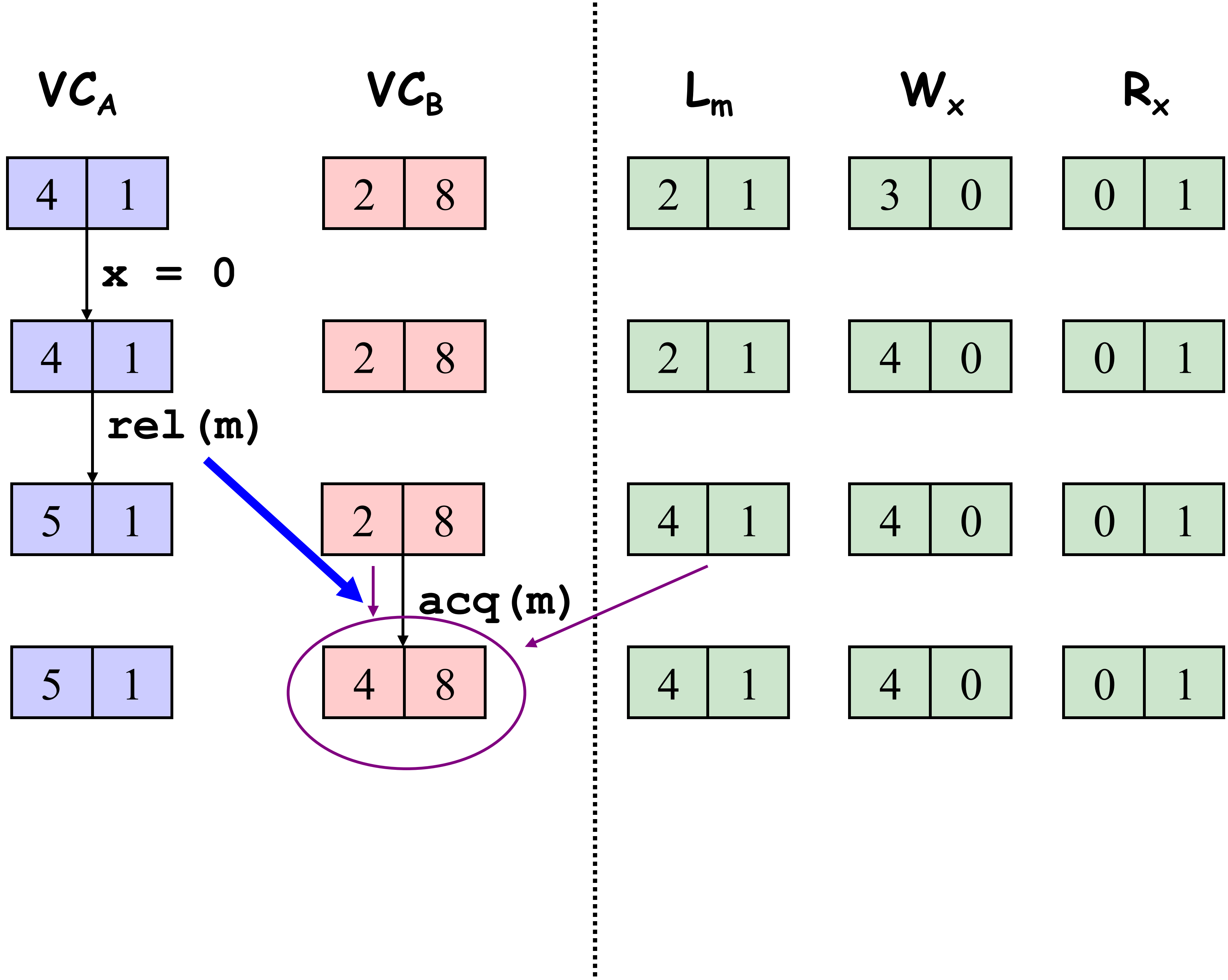
VC_A
VC_B
L_m
W_x
R_x
4 1
2 8
2 1
3 0
0 1
x = 0
Write-Write Check: W_x ⊑ VC_A ?
3 0 ⊑ 4 1 ? Yes
Read-Write Check: R_x ⊑ VC_A ?
0 1 ⊑ 4 1 ? Yes
O(n) time



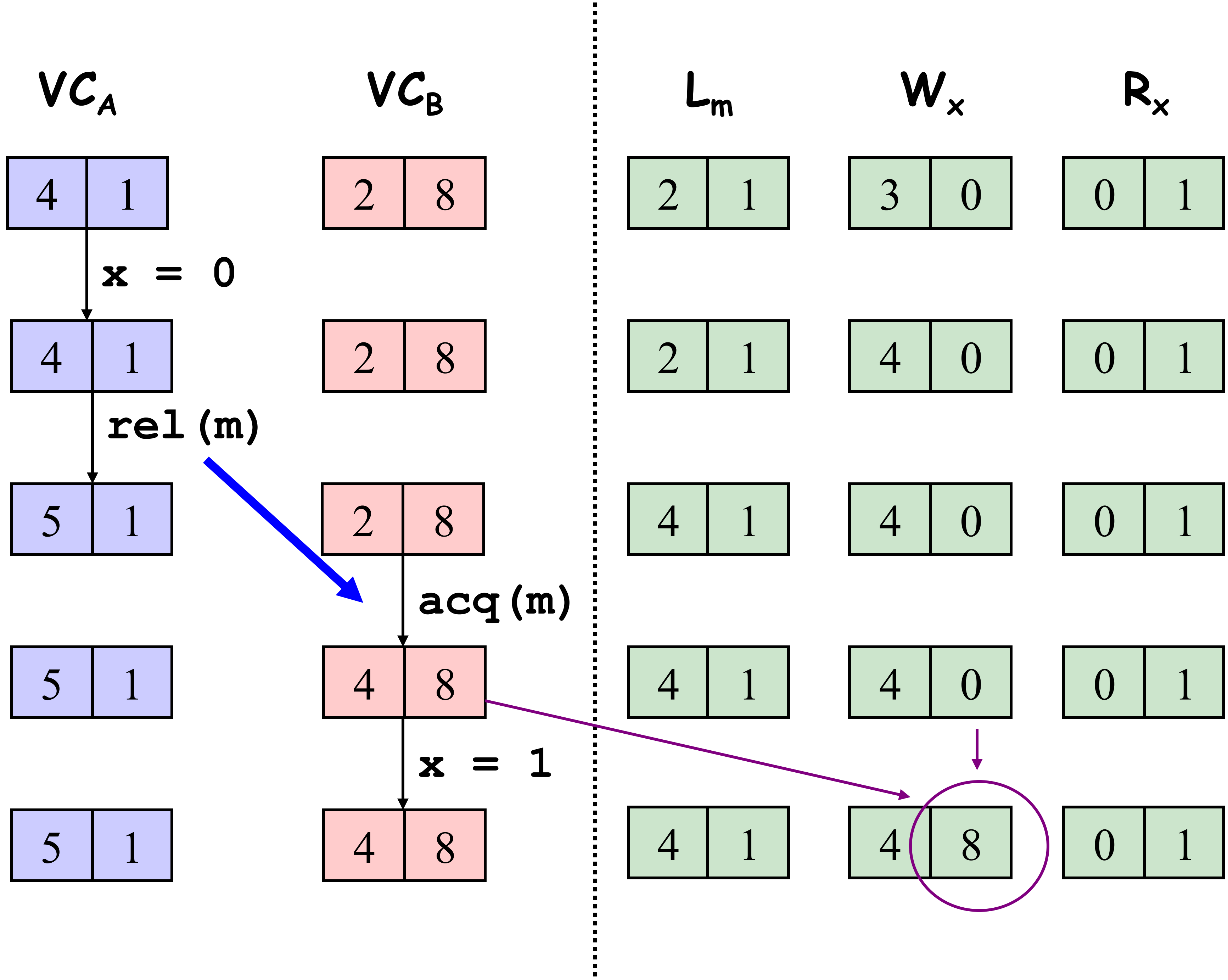
VC_A
VC_B
L_m
W_x
R_x
4 1
2 8
2 1
3 0
0 1
x = 0
4 1
2 8
2 1
4 0
0 1



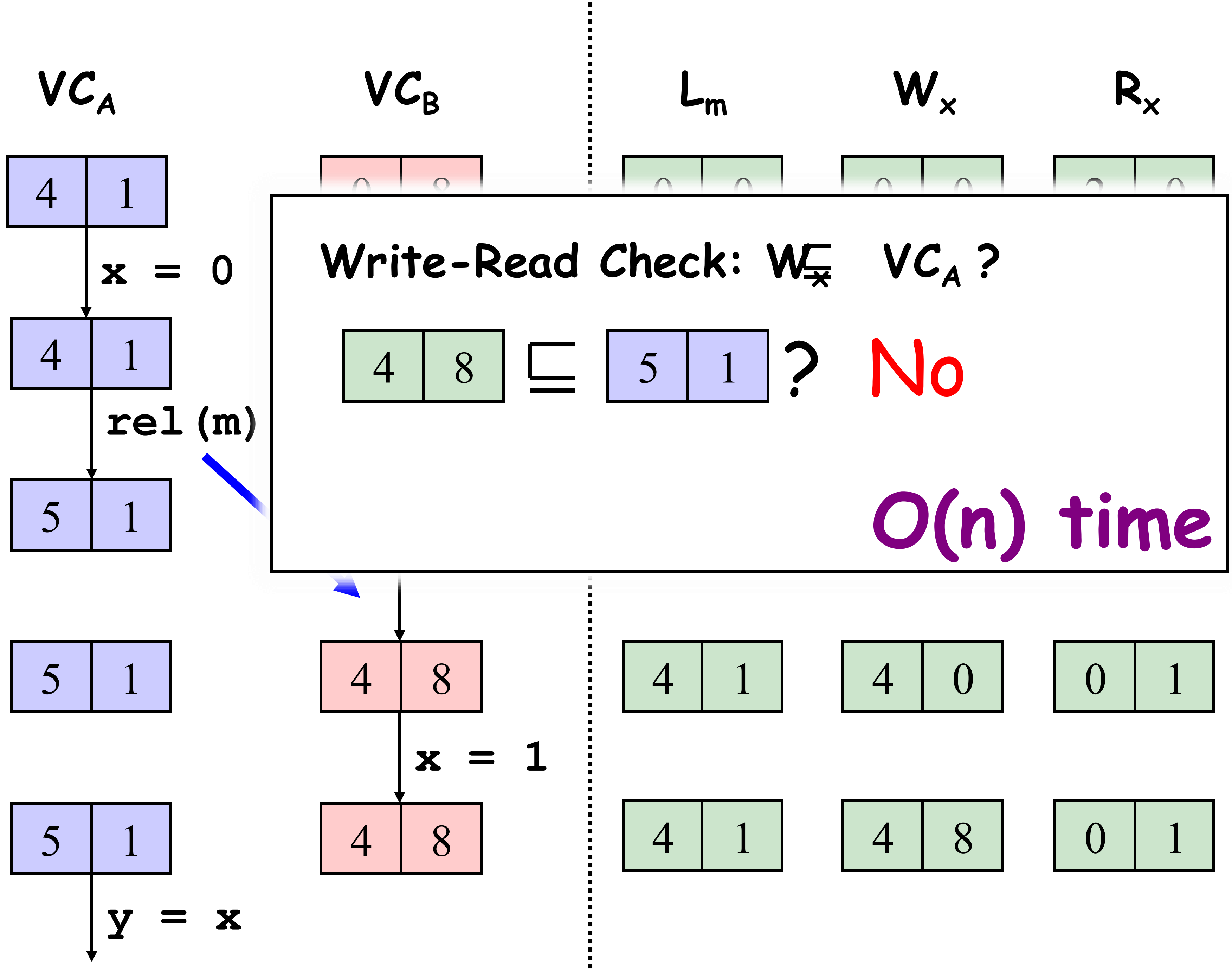
VC_A
VC_B
L_m
W_x
R_x
4 1
2 8
2 1
3 0
0 1
x = 0
4 1
2 8
2 1
4 0
0 1
rel(m)
5 1
2 8
4 1
4 0
0 1



VC_A
VC_B
L_m
W_x
R_x
4 1
2 8
2 1
3 0
0 1
x = 0
4 1
2 8
2 1
4 0
0 1
rel(m)
5 1
2 8
4 1
4 0
0 1
acq(m)
5 1
4 8
4 1
4 0
0 1



VC_A
VC_B
L_m
W_x
R_x
x = 0
rel(m)
acq(m)
x = 1



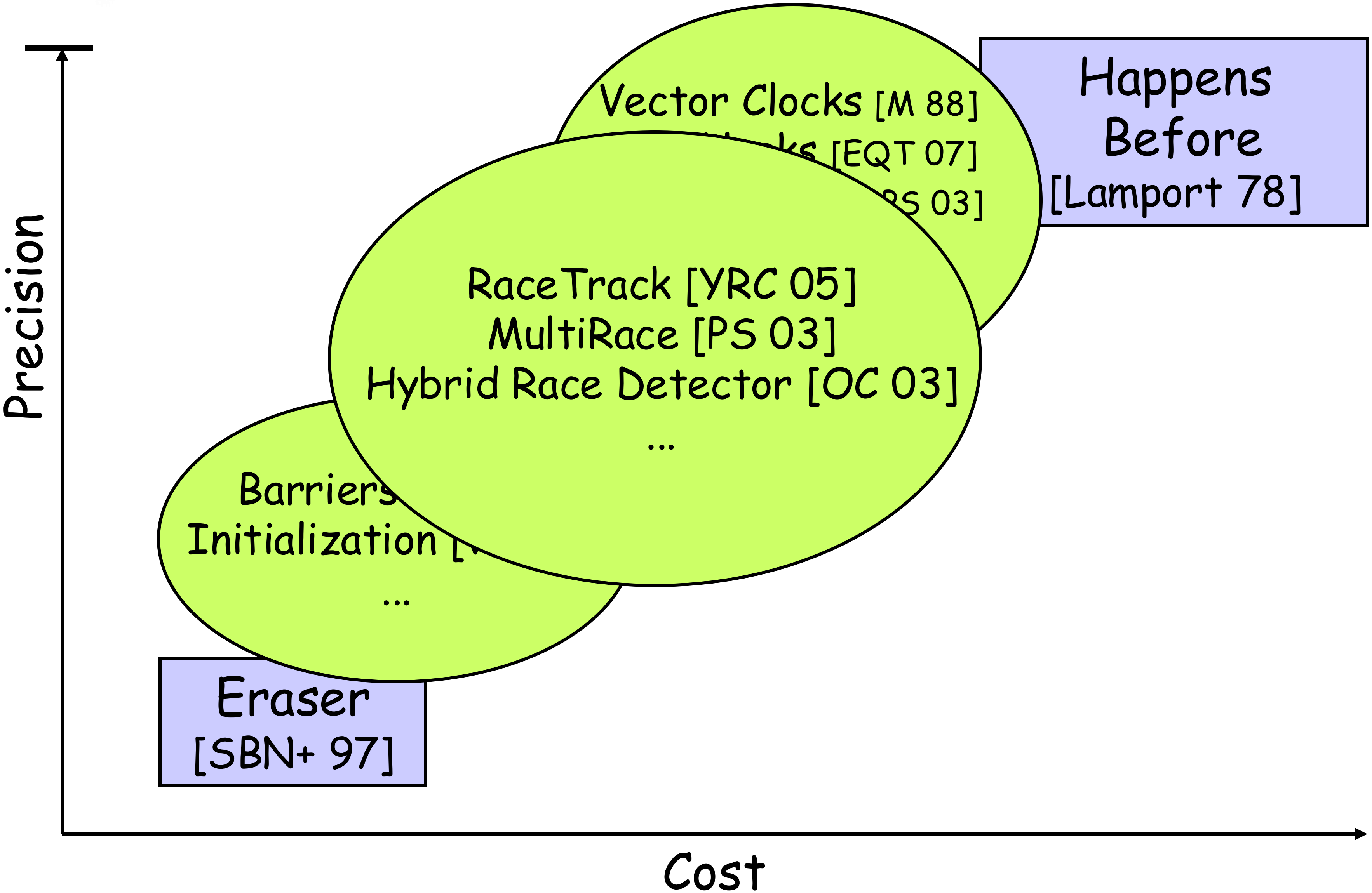
VC_A
VC_B
L_m
W_x
R_x
x = 0
rel(m)
x = 1
y = x
Write-Read Check: W_x ⊑ VC_A ?
4 8 ⊑ 5 1 ? No
O(n) time

VectorClocks for Data-Race Detection

- Sound
  - Warning ➔ data-race exists
- Complete
  - No warnings ➔ data-race-free execution

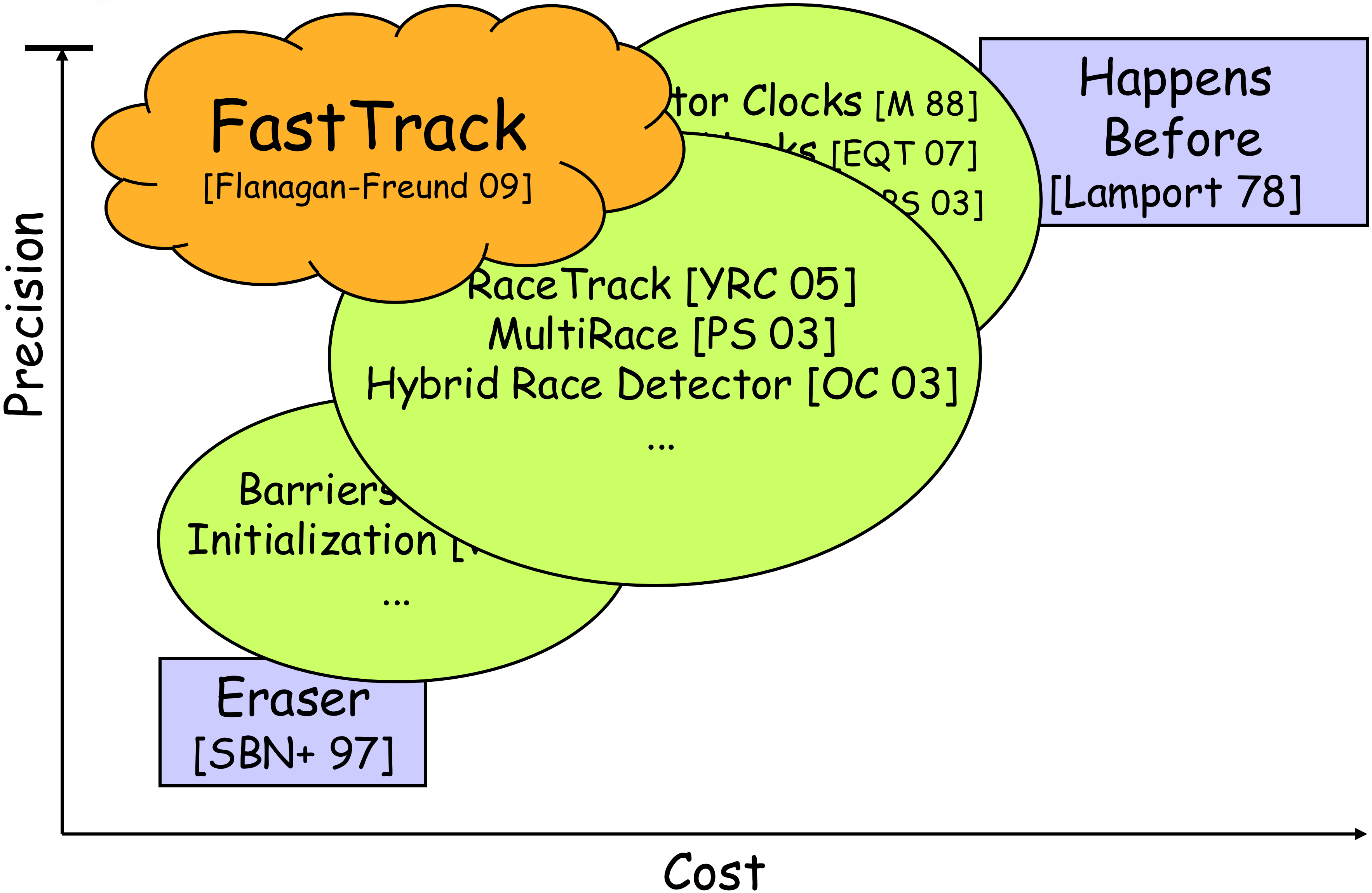
- Performance
  - slowdowns > 50x
  - memory overhead

Dynamic Data-Race Detection

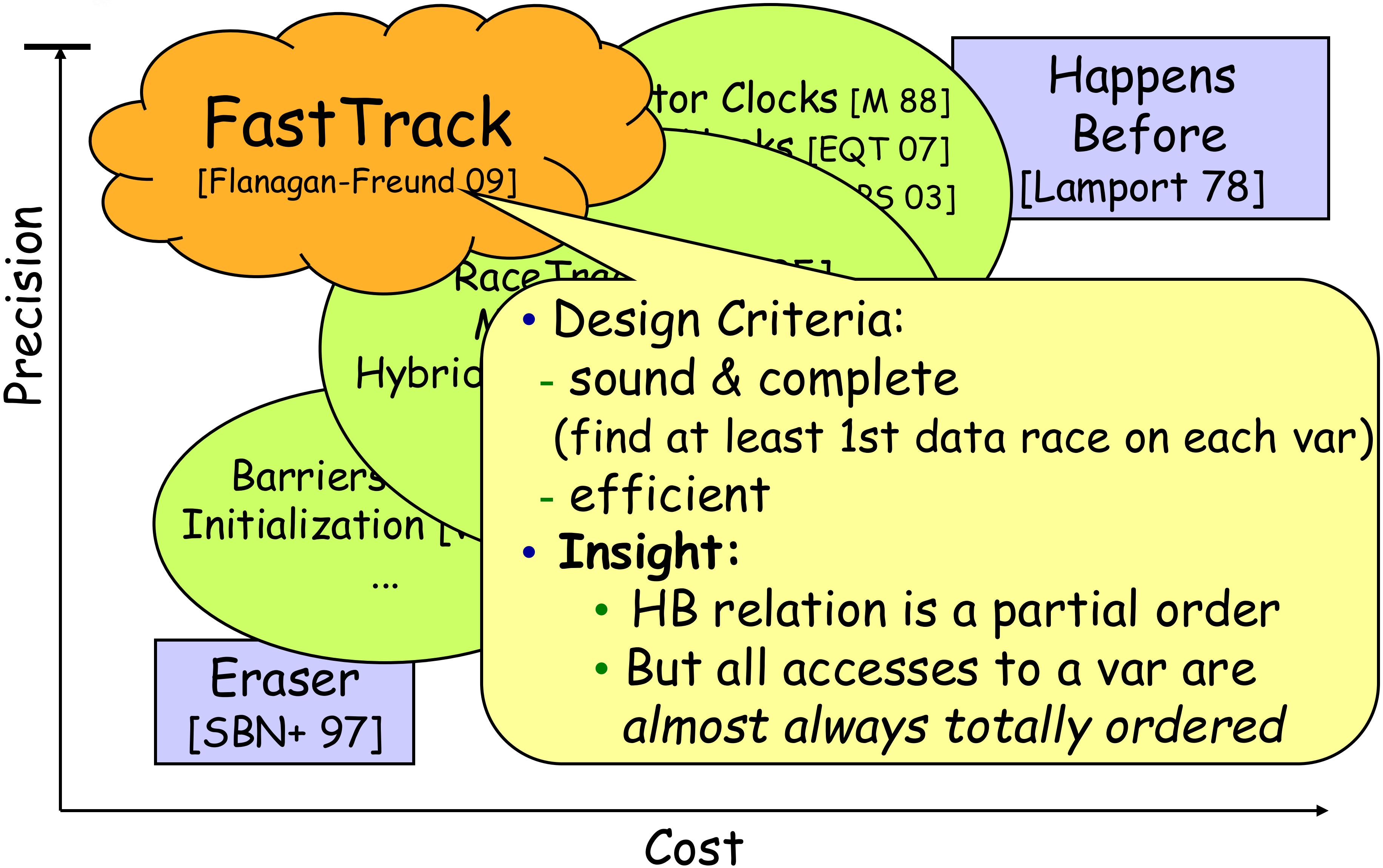


FASTTRACK

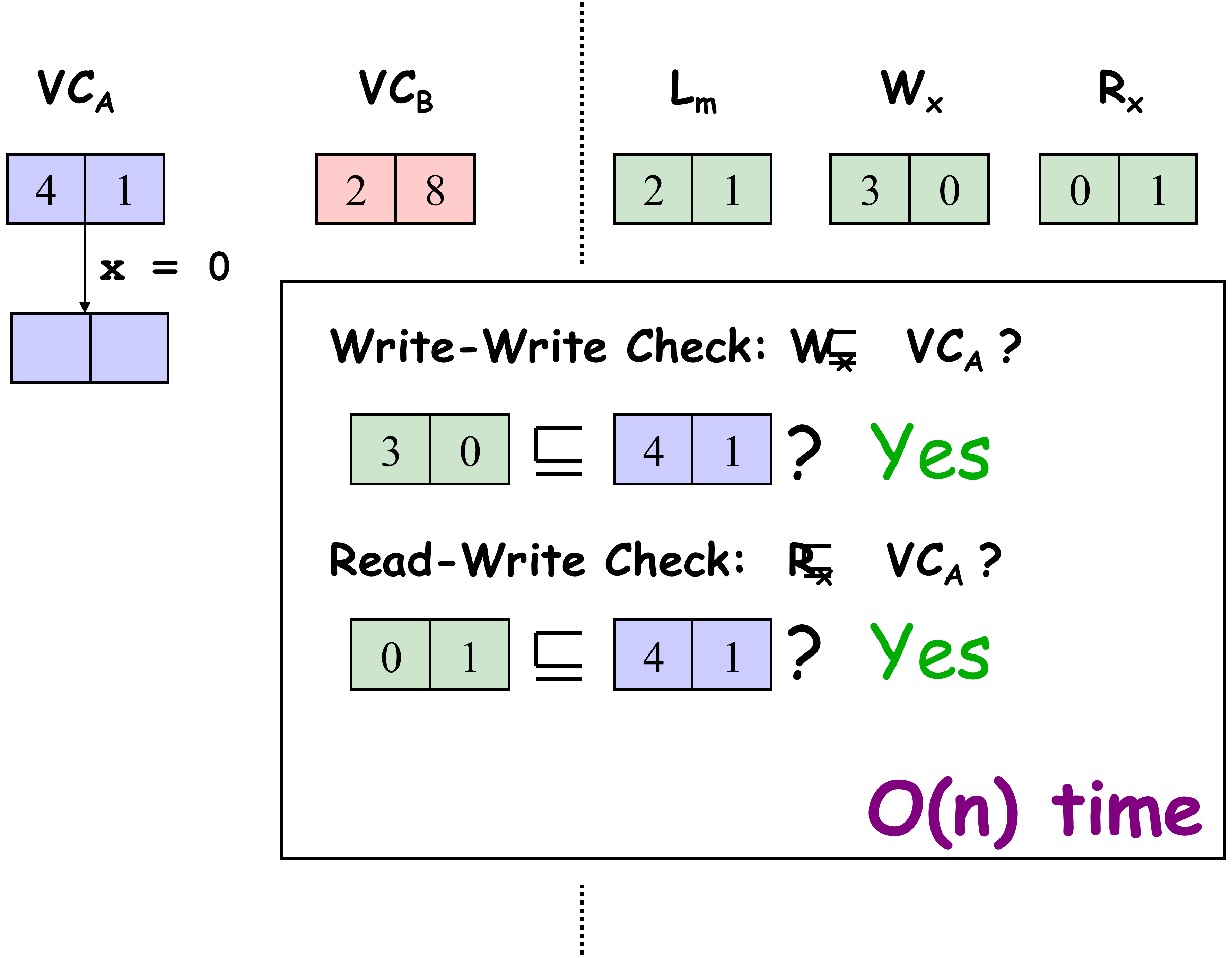
Dynamic Data-Race Detection



Dynamic Data-Race Detection

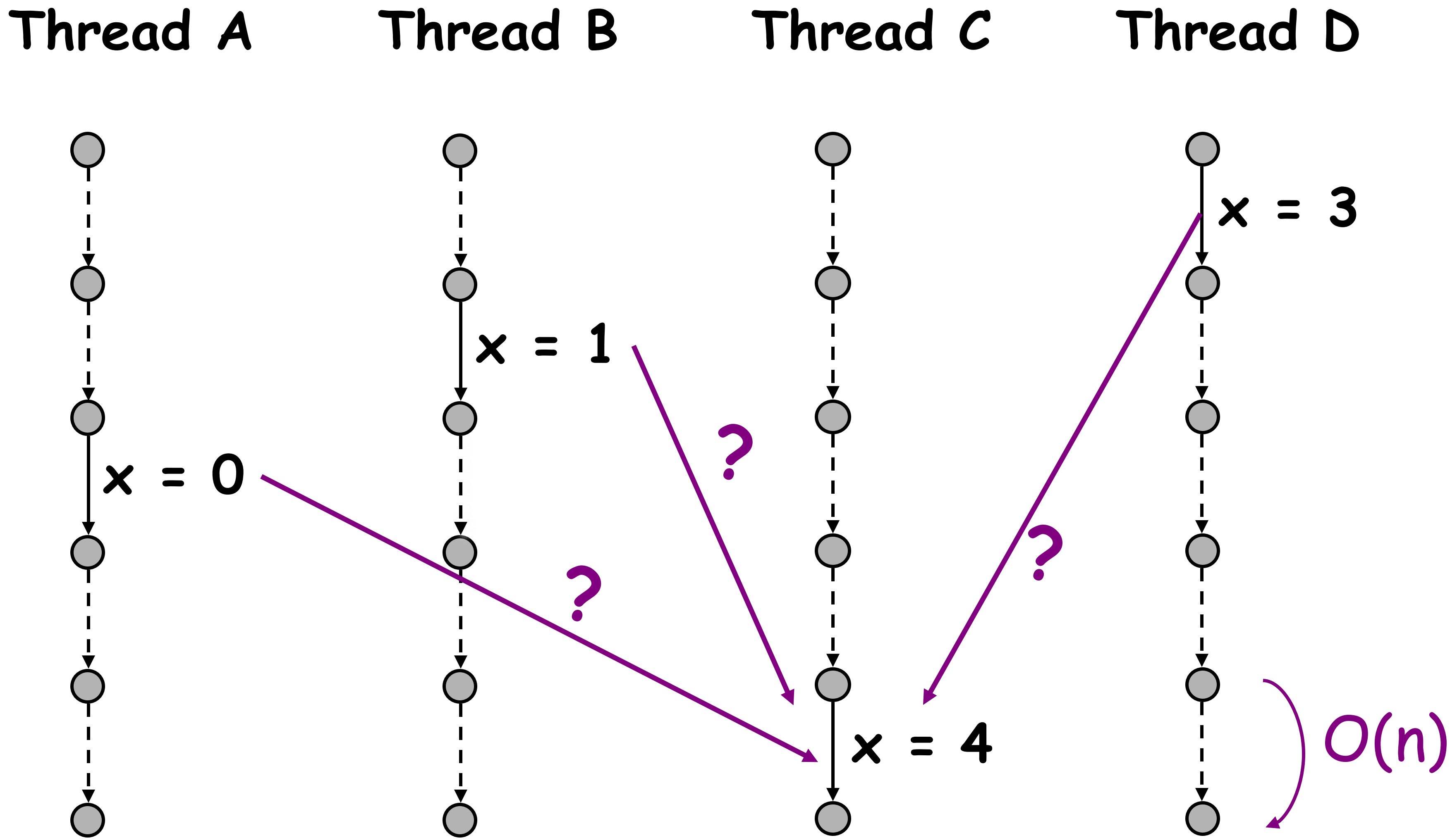


- Design Criteria:
  - sound & complete
    (find at least 1st data race on each var)
  - efficient
- **Insight:**
  - HB relation is a partial order
  - But all accesses to a var are *almost always totally ordered*

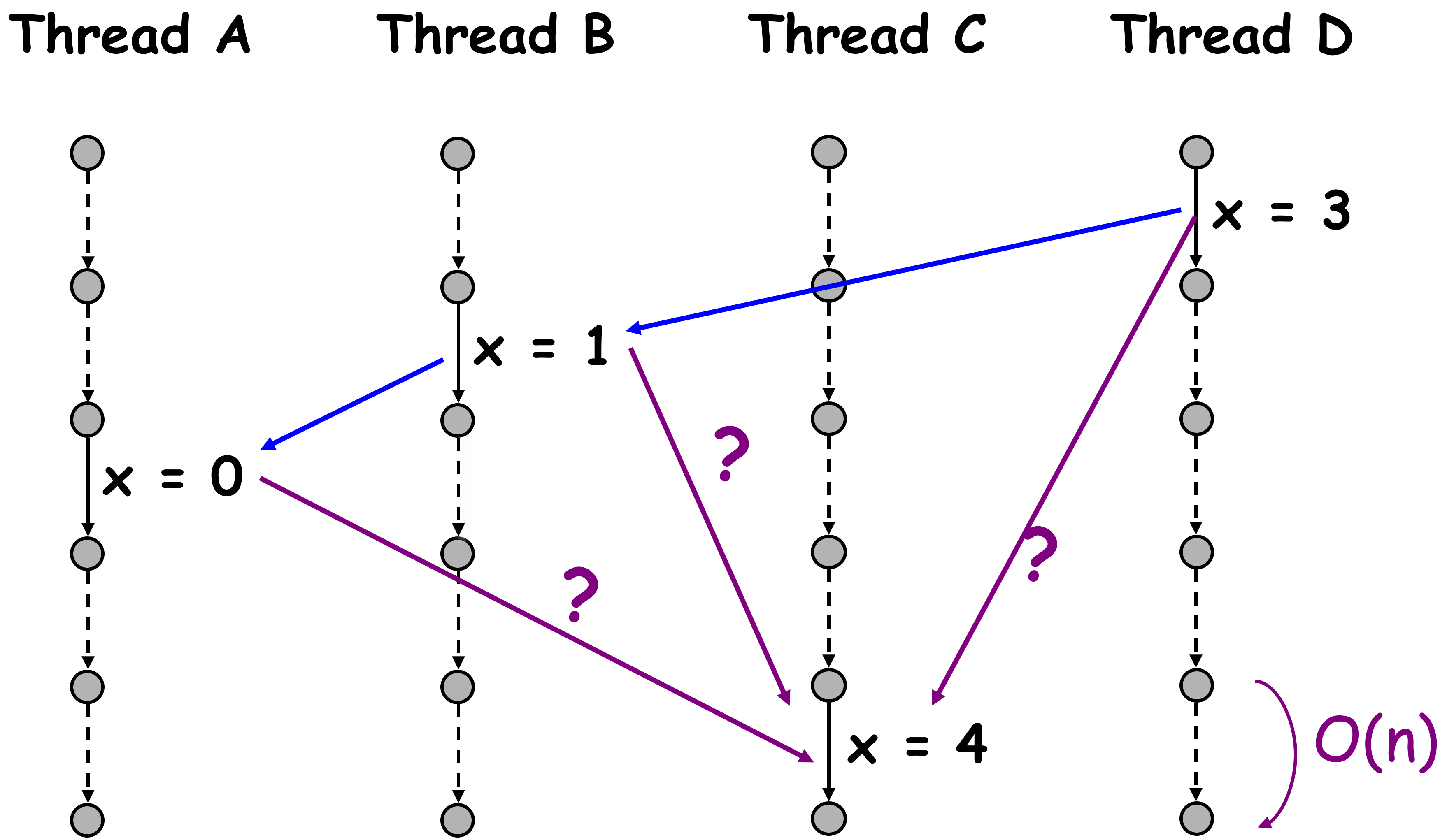


VC_A
VC_B
L_m
W_x
R_x
4 1
2 8
2 1
3 0
0 1
x = 0
Write-Write Check: $W_x \sqsubseteq VC_A$?
3 0 $\sqsubseteq$ 4 1 ? Yes
Read-Write Check: $R_x \sqsubseteq VC_A$?
0 1 $\sqsubseteq$ 4 1 ? Yes
O(n) time

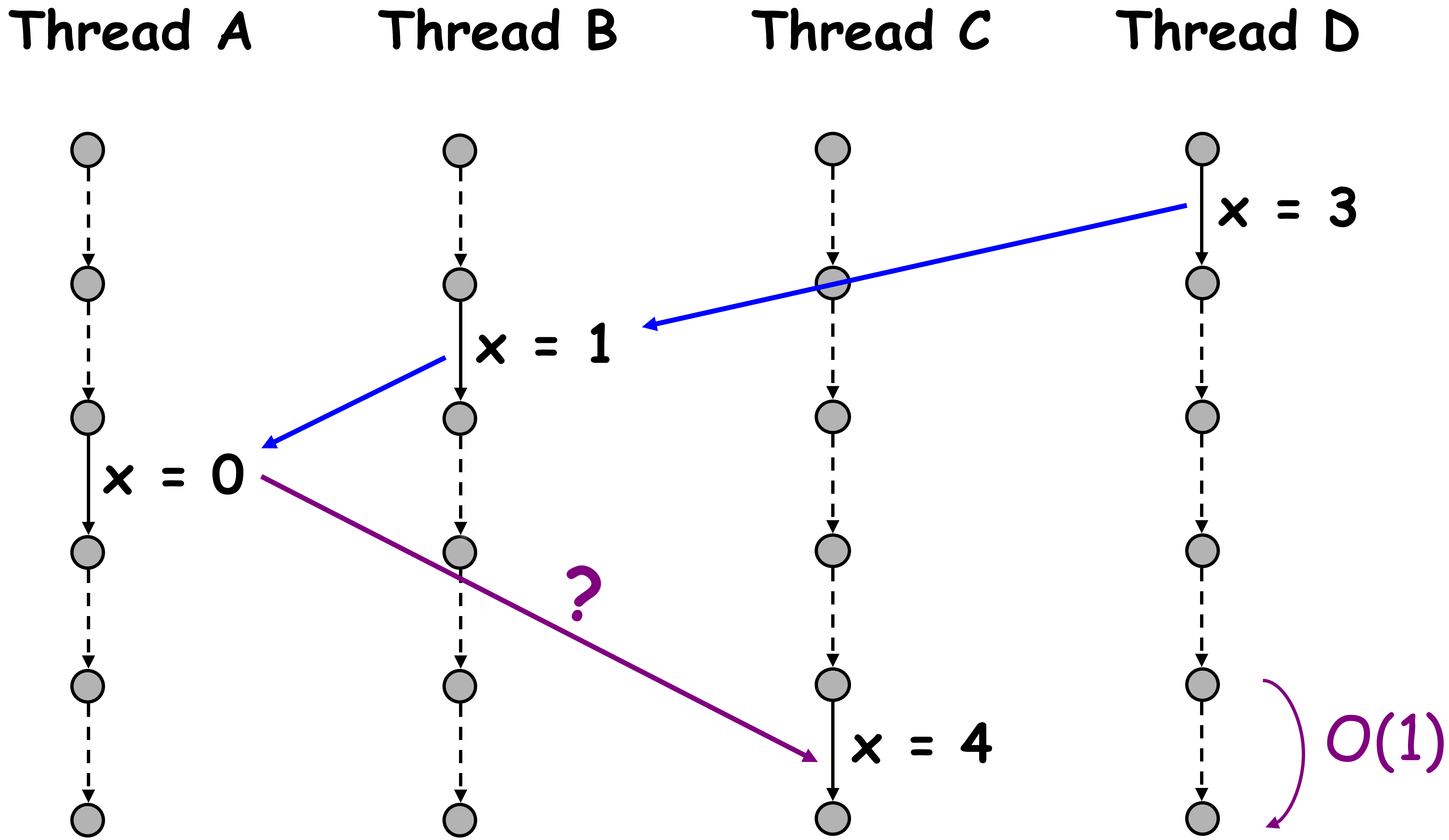
Write-Write and Write-Read Data Races

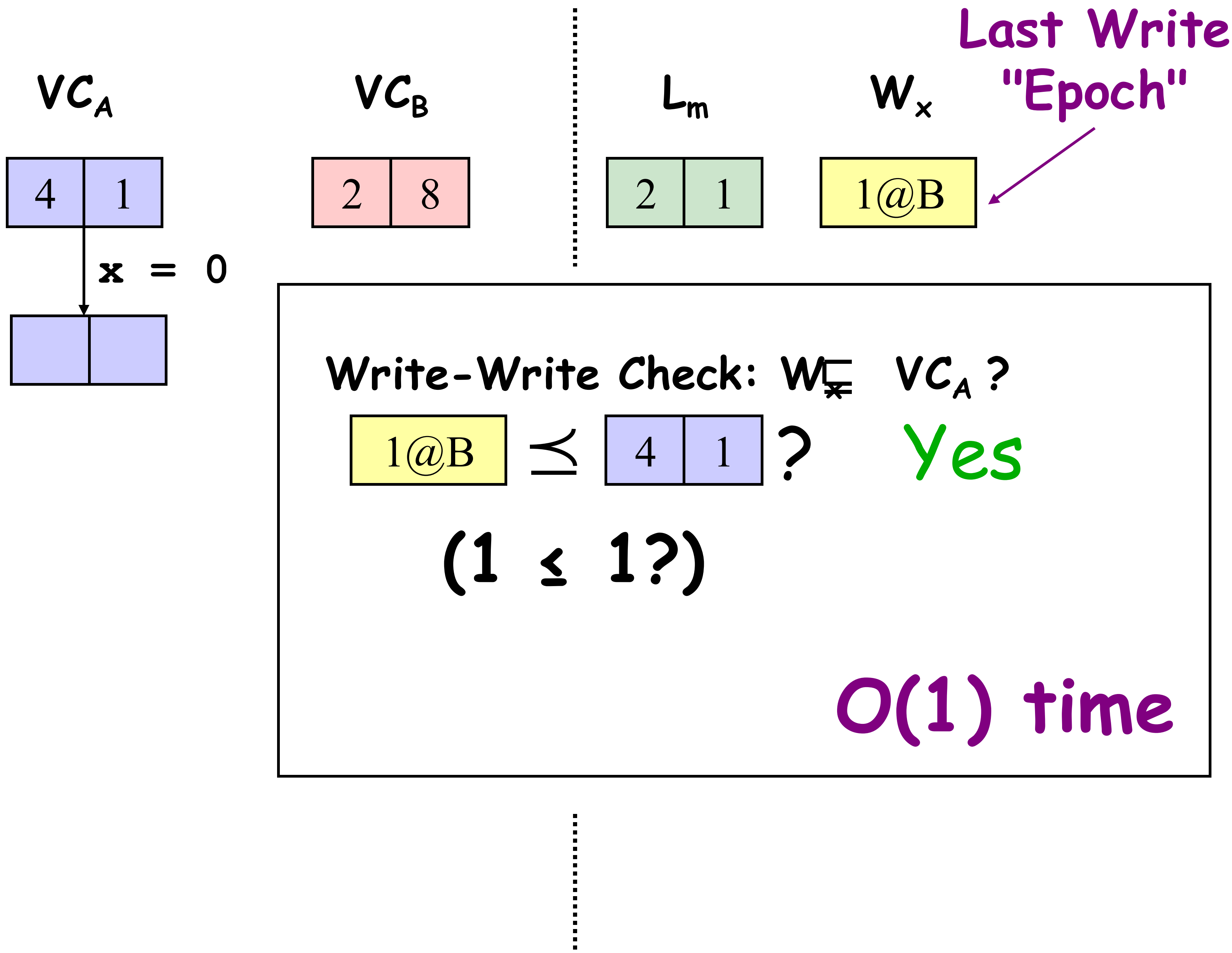


No Data Races Yet: Writes Totally Ordered

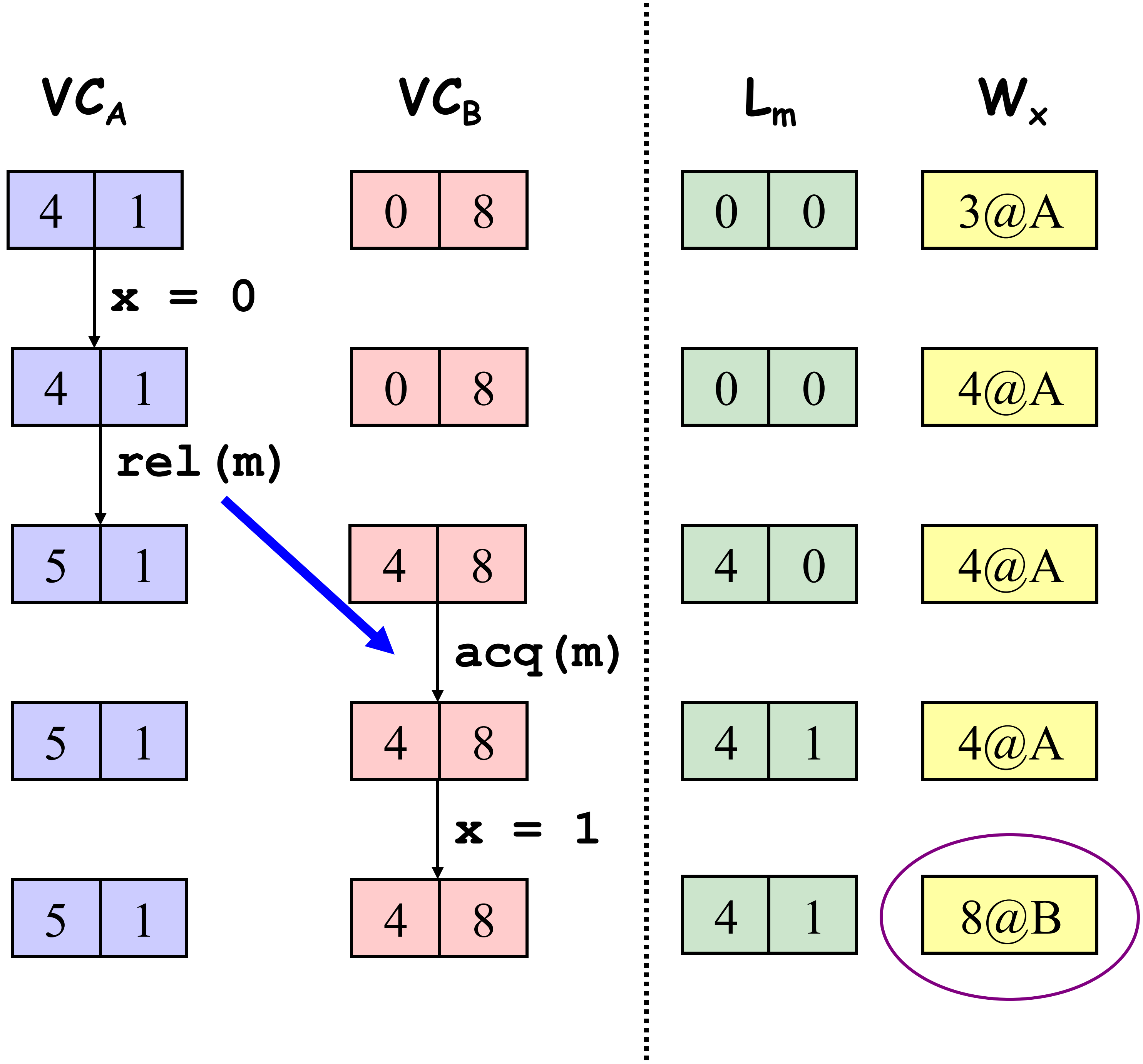


No Data Races Yet: Writes Totally Ordered

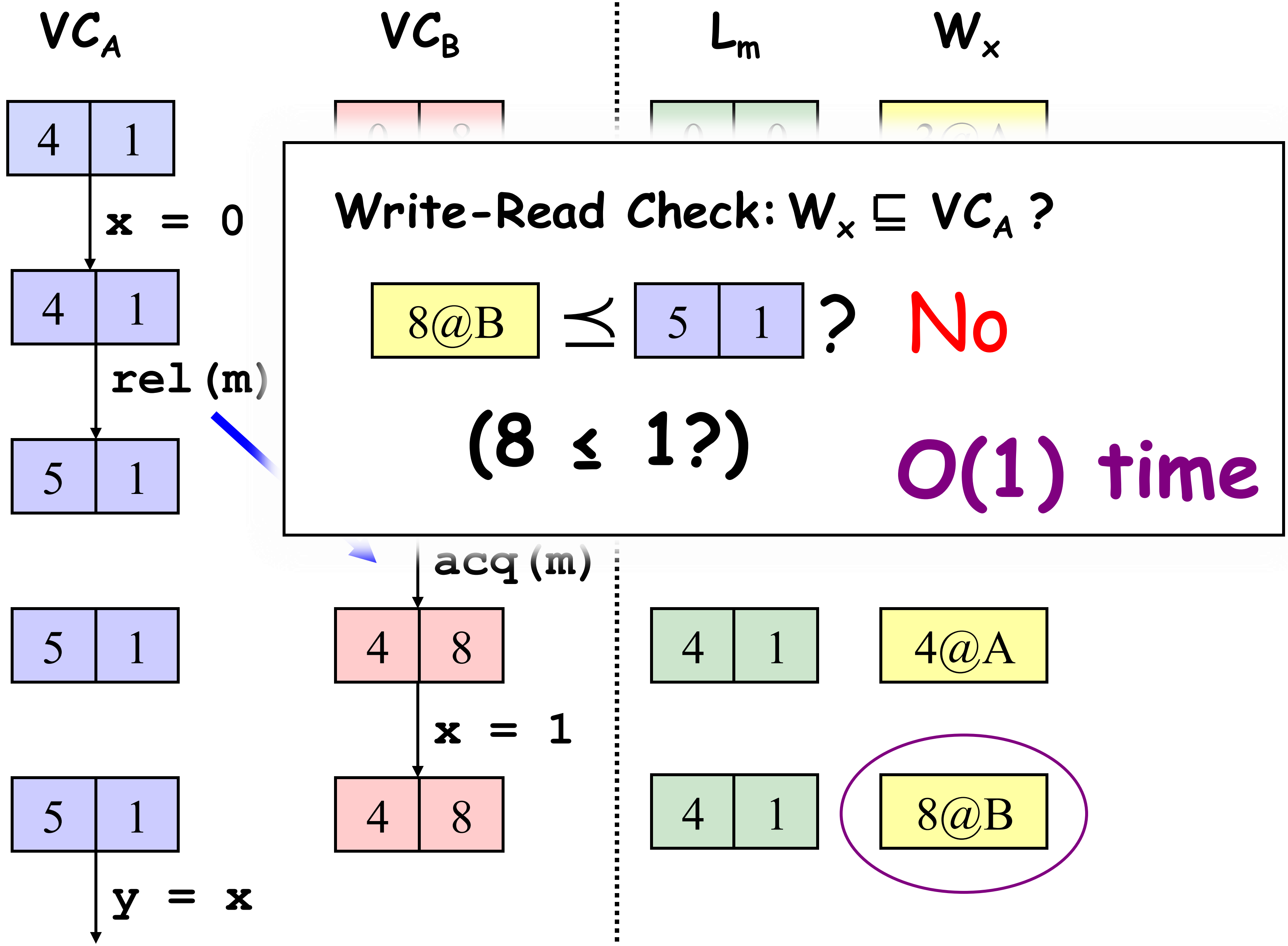




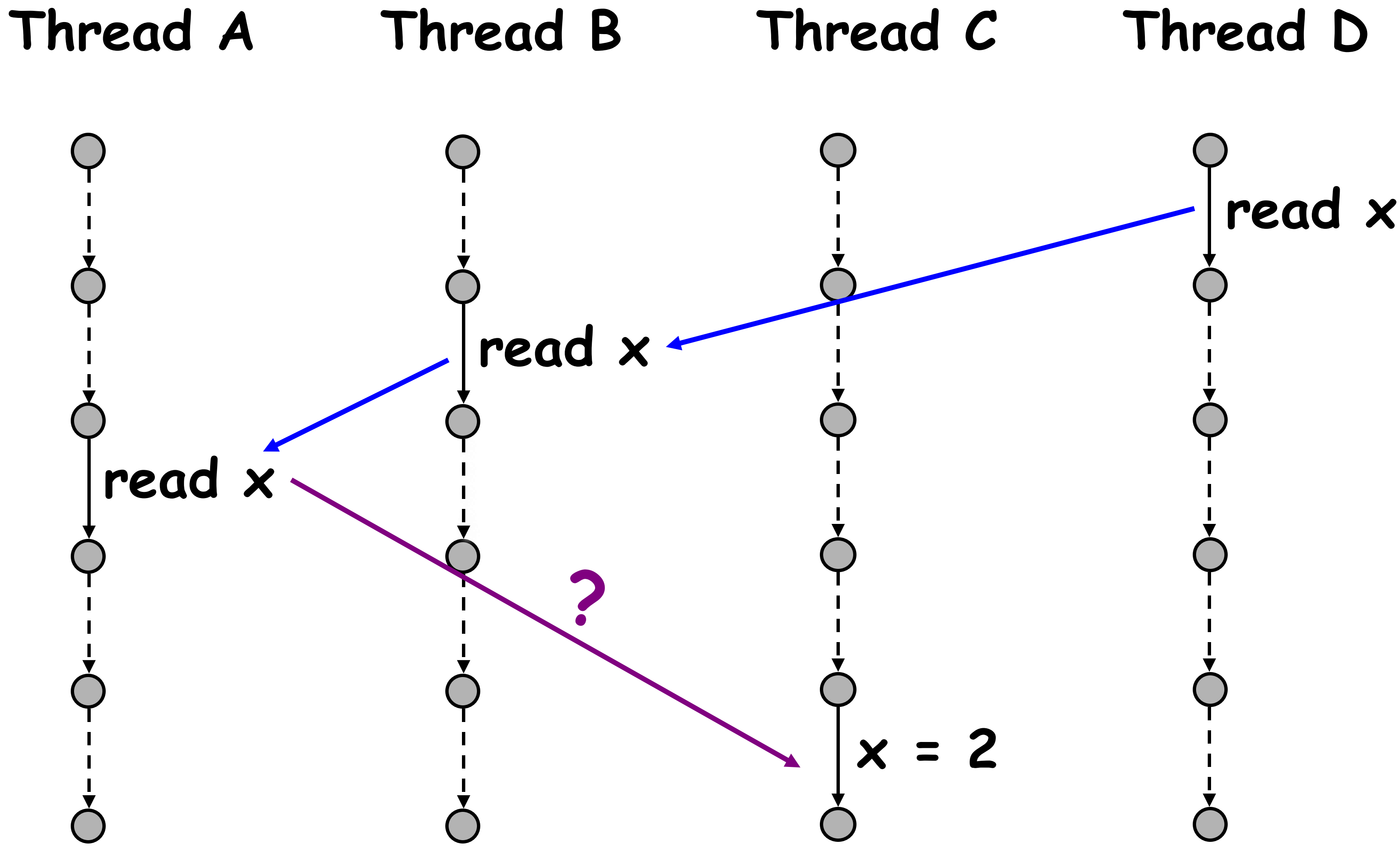
Last Write "Epoch"
VC_A
4 1
x = 0
VC_B
2 8
L_m
2 1
W_x
1@B
Write-Write Check: $W_x \sqsubseteq VC_A$?
1@B $\preceq$ 4 1 ?
Yes
(1 ≤ 1?)
O(1) time



VC_A
VC_B
L_m
W_x
4 1
0 8
0 0
3@A
x = 0
4 1
0 8
0 0
4@A
rel(m)
5 1
4 8
4 0
4@A
acq(m)
5 1
4 8
4 1
4@A
x = 1
5 1
4 8
4 1
8@B

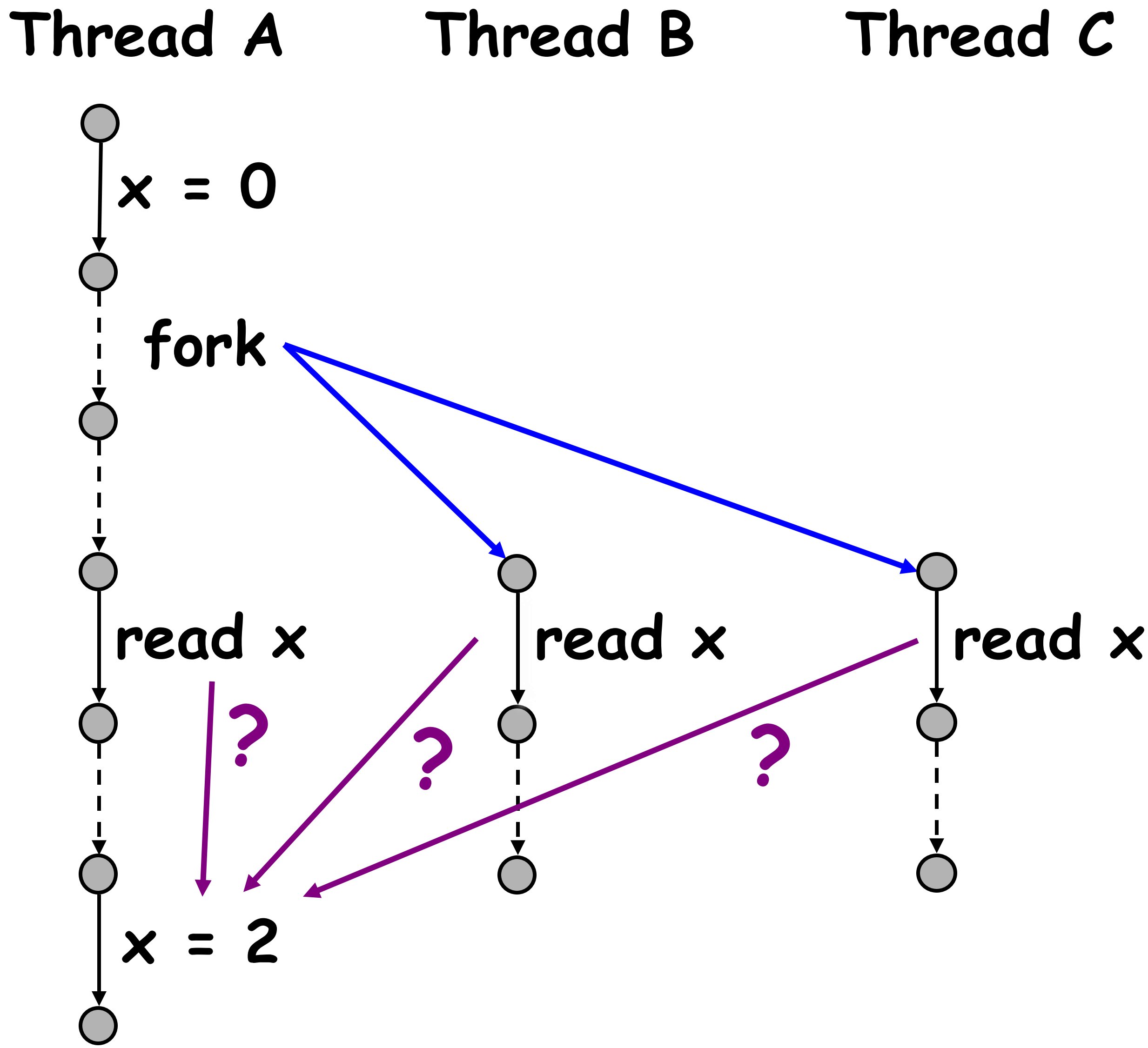

VC_A
VC_B
L_m
W_x
4 1
x = 0
4 1
rel(m)
5 1
acq(m)
5 1
4 8
4 1
4@A
x = 1
5 1
4 8
4 1
8@B
y = x
Write-Read Check: W_x ⊑ VC_A ?
8@B ≼ 5 1 ? No
(8 ≤ 1?)
O(1) time

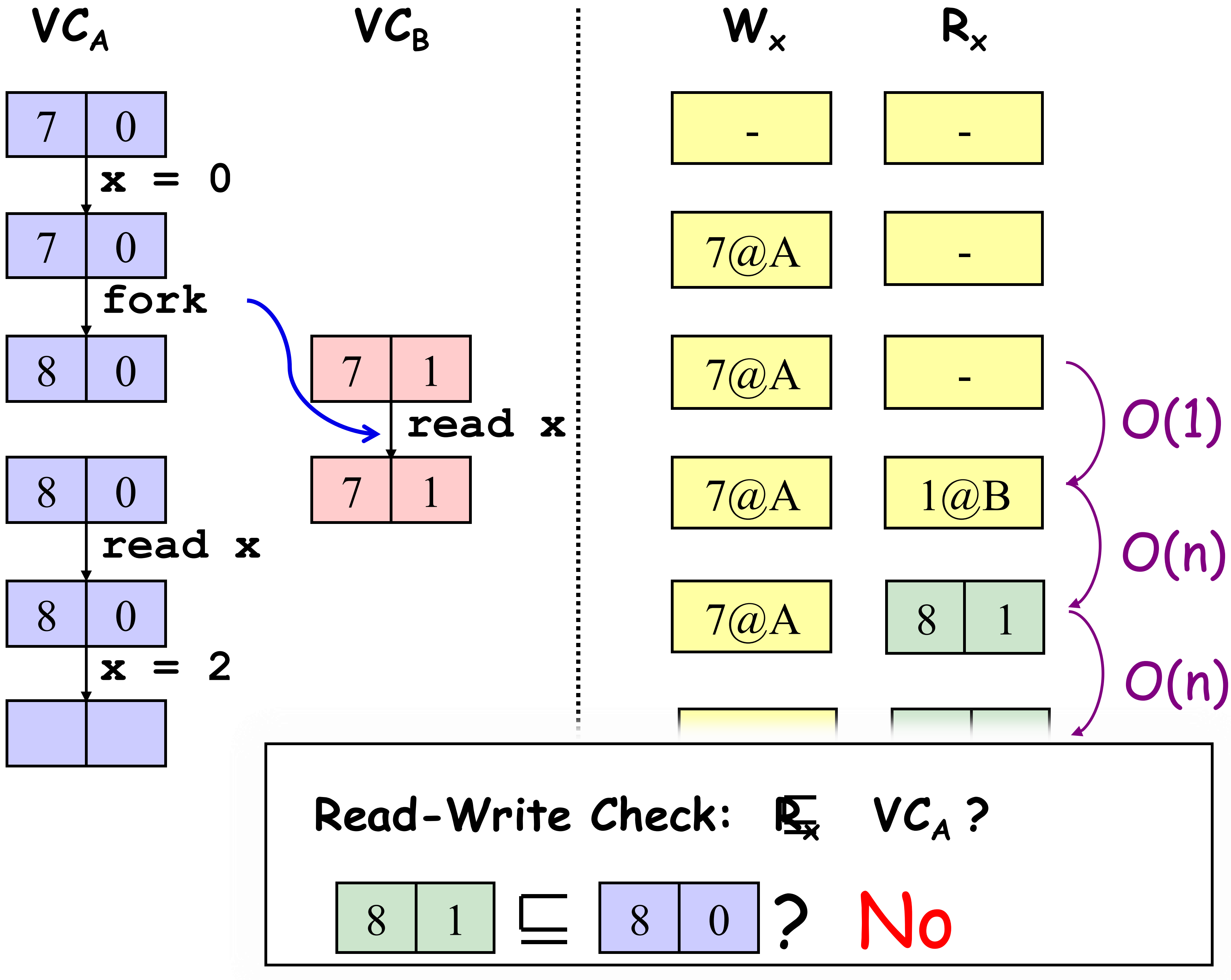
Read-Write Data Races -- Ordered Reads

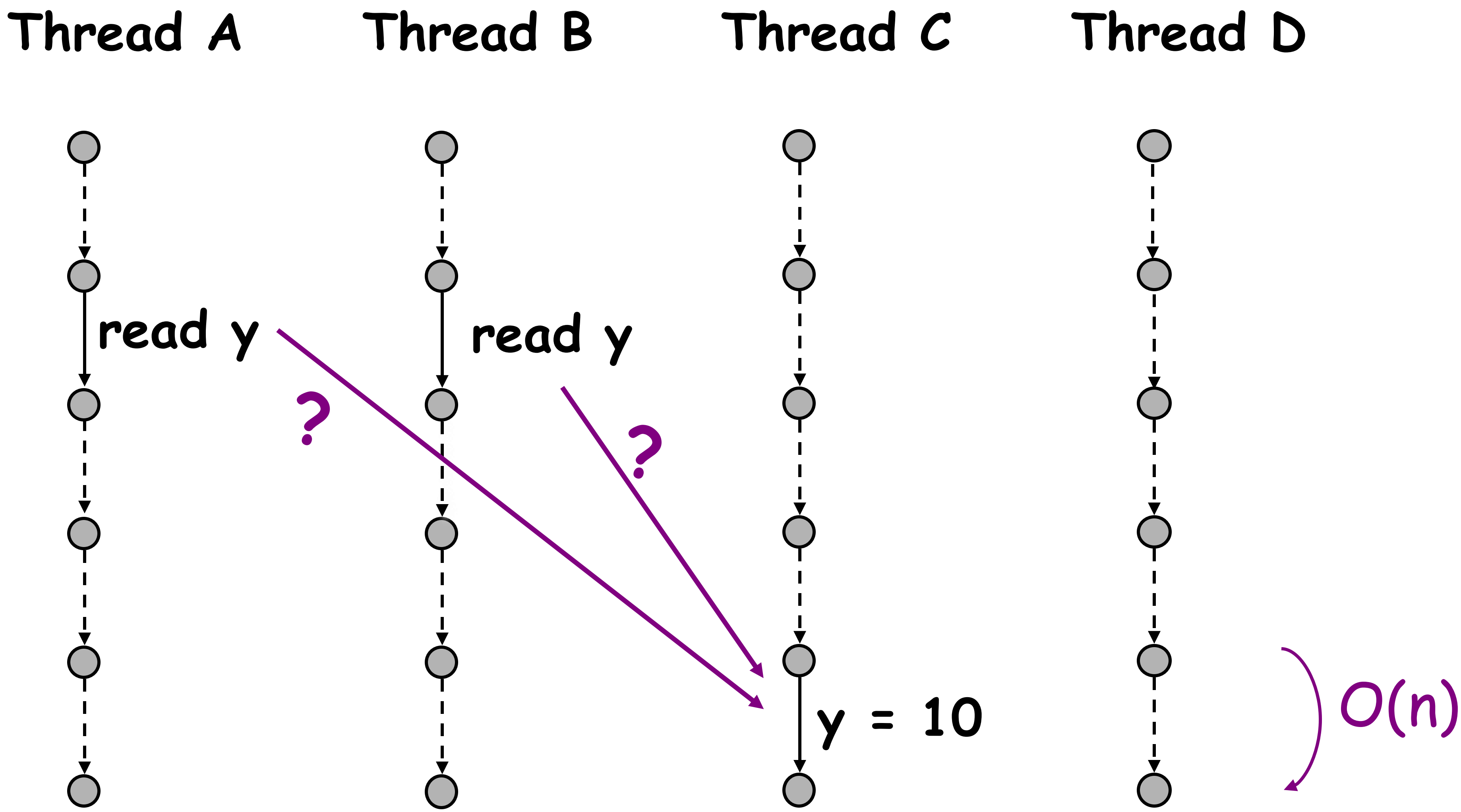


Most common case: thread-local, lock-protected, ...

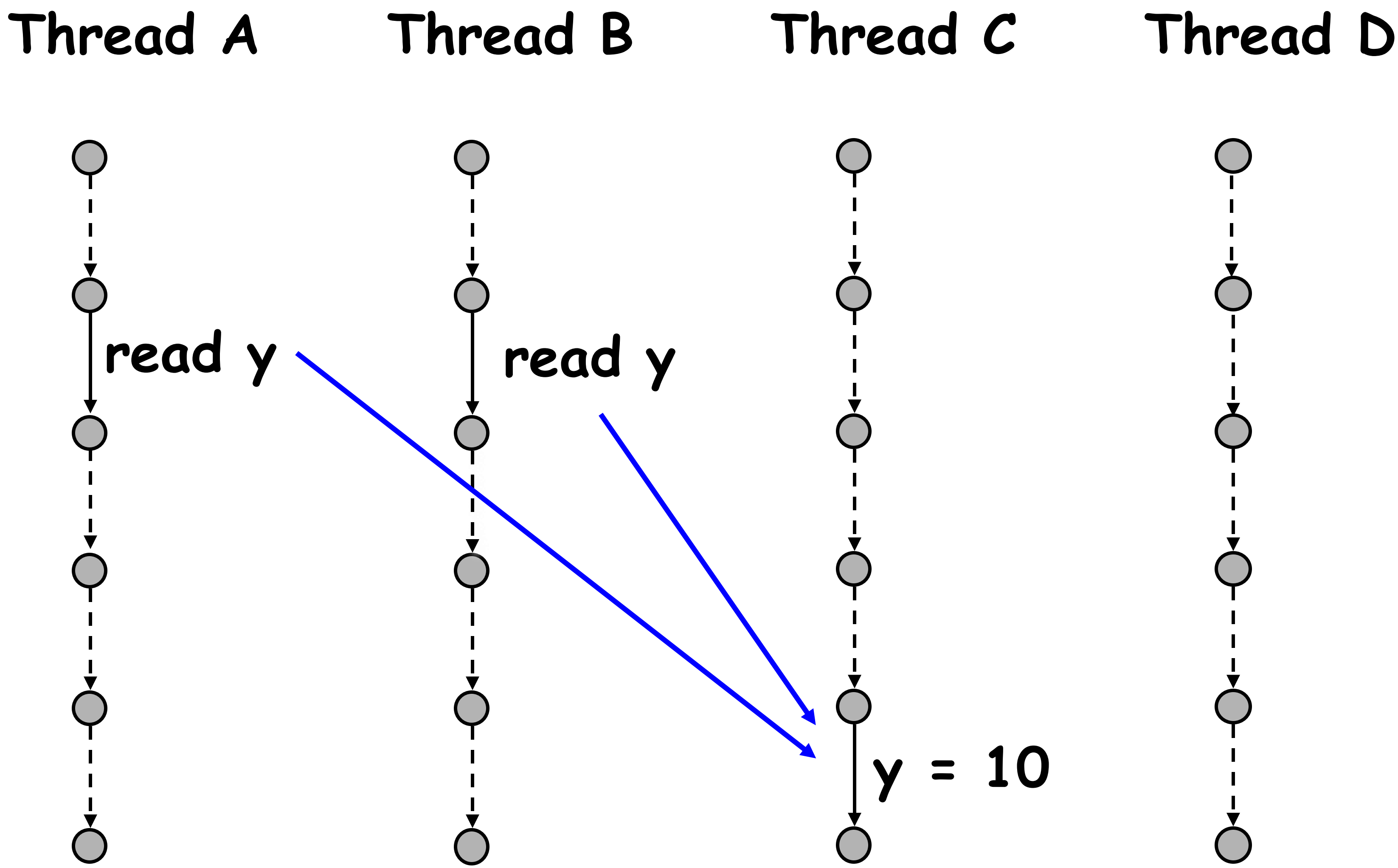
Read-Write Data Races -- Unordered Reads

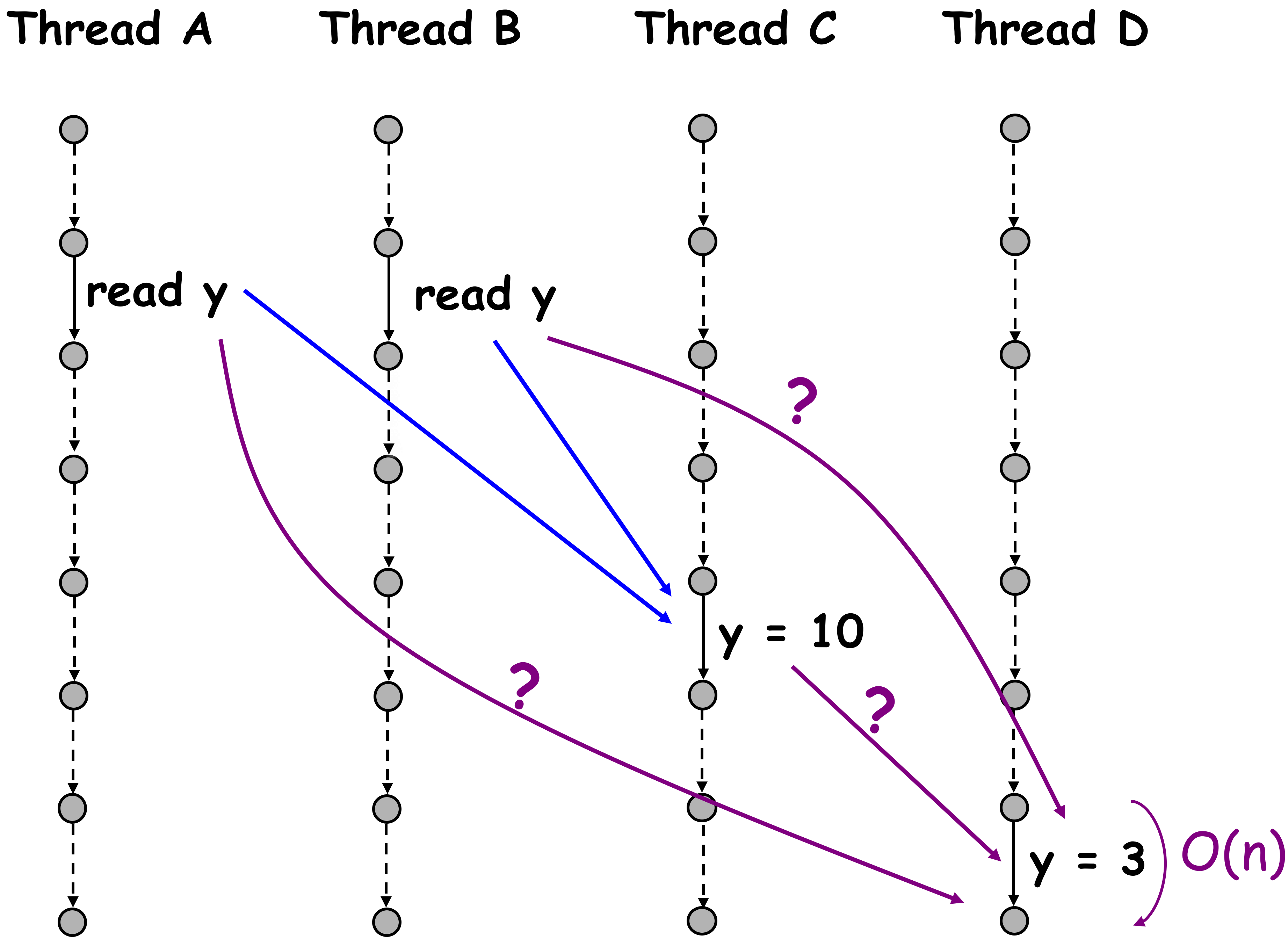


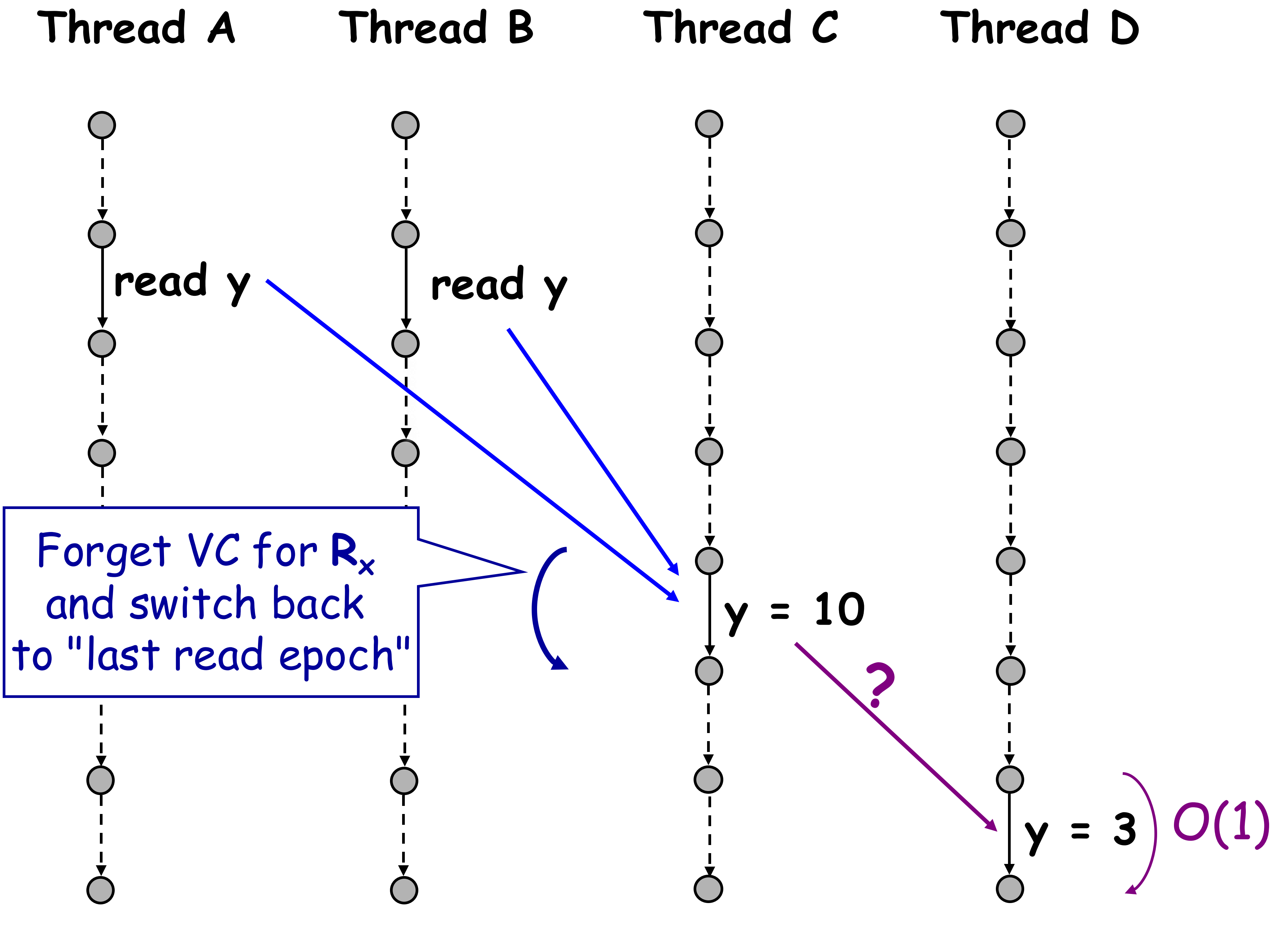

VC_A
VC_B
W_x
R_x
7 0
x = 0
7 0
fork
8 0
7 1
read x
7 1
8 0
read x
8 0
x = 2
-
-
7@A
-
7@A
-
7@A
1@B
7@A
8 1
O(1)
O(n)
O(n)
Read-Write Check: R_x ⊑ VC_A ?
8 1 ⊑ 8 0 ? No



Thread A
Thread B
Thread C
Thread D
read y
read y
?
?
y = 10
O(n)

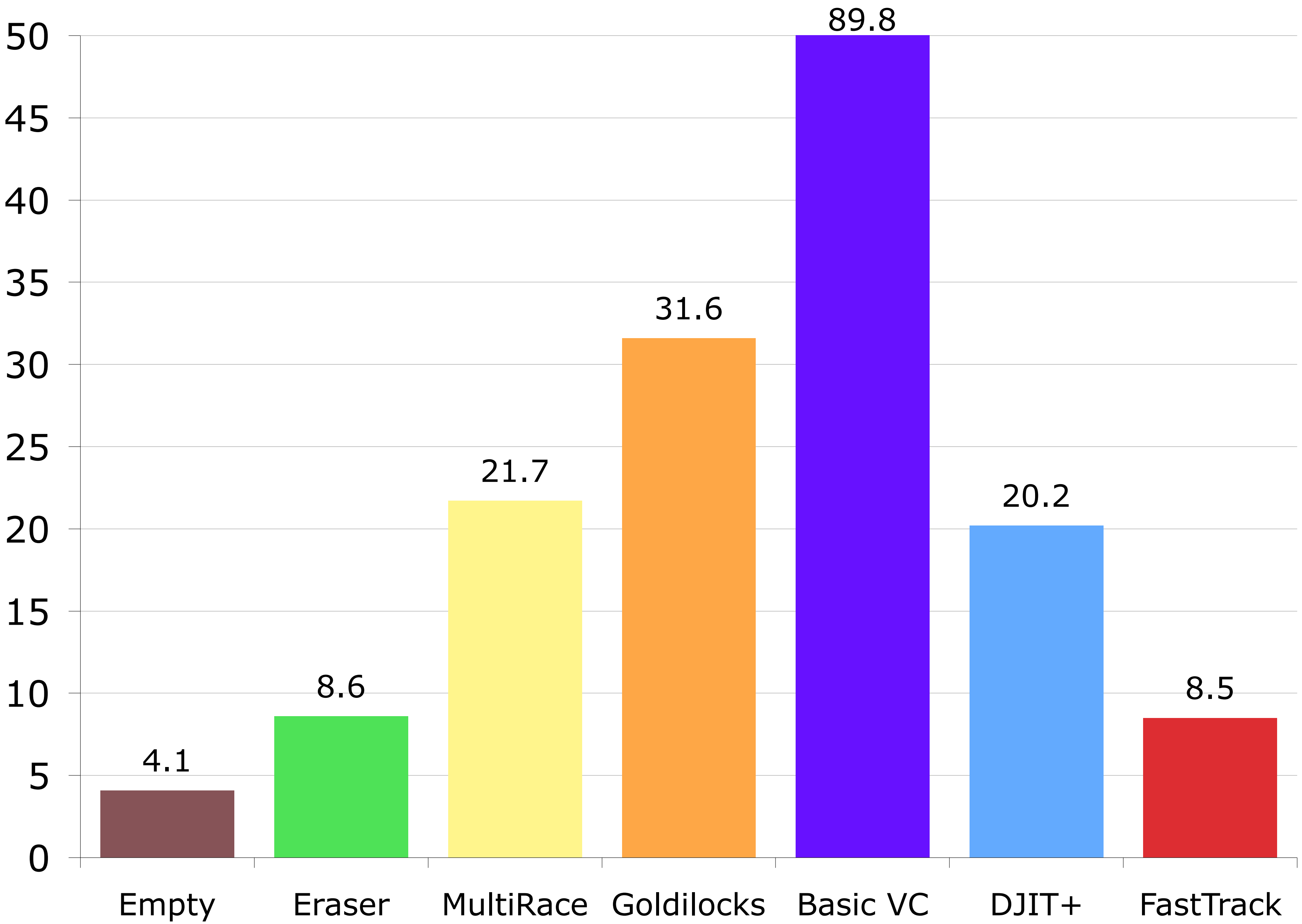

Thread A
Thread B
Thread C
Thread D
read y
read y
y = 10


Thread A
Thread B
Thread C
Thread D
read y
read y
?
y = 10
?
?
y = 3
O(n)



Thread A
Thread B
Thread C
Thread D
read y
read y
Forget VC for R_x and switch back to "last read epoch"
y = 10
?
y = 3
O(1)

Slowdown (x Base Time)



Memory Usage

- FastTrack allocated ~200x fewer VCs

Checker	Memory Overhead
Basic VC, DJIT+	7.9x
FastTrack	2.8x
Empty	2.0x

(Note: VCs for dead objects are garbage collected)

- Improvements
  - accordion clocks [CB 01]
  - analysis granularity [PS 03, YRC 05]

Eclipse 3.4

- Scale
  - > 6,000 classes
  - 24 threads
  - custom sync. idioms
- Precision (tested 5 common tasks)
  - Eraser: ~1000 warnings
  - FastTrack: ~30 warnings
- Performance on compute-bound tasks
  - > 2x speed of other precise checkers
  - same as Eraser

FUZZING TECHNIQUES

Fuzzing can also find data races

- Idea: Catch races “red handed”. Loosely,
  - Pause thread execution when writing to X
  - If another thread reaches a statement that reads or writes X then we have observed concurrent conflicting accesses!
- Analysis does not care about locks or other synchronization primitives.
  - Consistent locking will make the above condition impossible to trigger.

Race Fuzzer

- Run-time Overhead
  - No overhead of tracking synchronization, locks, or vector clocks (hey, that rhymes!)
  - But pausing threads forever can lead to deadlocks
  - Pausing threads for a short while (e.g. sleep(1000)) adds overhead for every write access, though this approach is very effective.
- Solution idea:
  - Instead of "pausing" thread, just deprioritize it in the OS scheduler

Race Fuzzing

- Randomized scheduling still depends on luck
- Can do systematic schedule exploration with a bounded number of context switches
- Sophisticated randomized algorithms like PCT can give probabilistic guarantees of uncovering concurrency bugs with a bounded number of "ordering constraints".
- Or use heuristics, e.g. TSVD uses an initial run to infer "likely" happens-before relationships based on wall-clock timestamps to select candidate "racing pairs".

Lecture Takeaways

- Data race: two accesses, one of which is a write, with no happens-before relation
- Data races are subtle
  - Compiler optimizations, hardware reordering make racy program behavior hard to predict
  - Better to synchronize consistently
- Lockset analysis: intuitive, fast
  - But many false warnings
- Happens-before data race detection
  - Sound; OK speed if carefully implemented
- Stress testing
  - Sound and fast; Can catch data races red handed
  - Needs assumptions to prune the space of possible races

Key References

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Key References

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- Madanlal Musuvathi, Sebastian Burckhardt, Pravesh Kothari, and Santosh Nagarakatte, "A Randomized Scheduler with Probabilistic Guarantees of Finding Bugs", ASPLOS 2010.
- Michael D. Bond, Katherine E. Coons, Kathryn S. McKinley, "PACER: proportional detection of data races", PLDI 2010.
- Cormac Flanagan and Stephen N. Freund, "Adversarial memory for detecting destructive races", PLDI 2010.
- Koushik Sen. "Race directed random testing of concurrent programs". PLDI 2010.
- Guangpu Li, Shan Lu, Madanlal Musuvathi, Suman Nath, and Rohan Padhye. "Efficient scalable thread-safety-violation detection: finding thousands of concurrency bugs during testing", SOSP 2019.

Bonus slides on the Java Memory Model (JMM)

Behaviors Allowed in JMM

int data = flag = 0;

T1

```
r = data;
flag = 1;



assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Behaviors Allowed in JMM

```
int data = flag = 0;
```

T1

```
r = data;
flag = 1;
```

T2

```
while (flag == 0) {}
data = 1;
```

```
assert r == 0;
```

Behaviors Allowed in JMM

int data = flag = 0;

latest value

T1

T2

r = data;
flag = 1;

future value

while (flag == 0) {}
data = 1;

assert r == 0;

Behaviors Allowed in JMM

int data = flag = 0;

latest value

T1

T2

r = data;
flag = 1;

future value

while (flag == 0) {}
data = 1;

assert r == 0;

Valid due to lack of happens-before ordering

Behaviors Allowed in JMM

```
int data = flag = 0;
```

latest value

T1	T2
r = data;	
flag = 1;	
	while (flag == 0) {}
	data = 1;
assert r == 0;	

future value

Assertion failure!

Behaviors Allowed in JMM

```
int data = flag = 0;
```

T1

```
r = data;
flag = 1;
```

T2

```
while (flag == 0) {}
data = 1;
```

```
assert r == 0;
```

Assertion failure!

Behaviors Allowed in JMM

int data = flag = 0;

T1

```
r = data;
flag = 1;
assert r == 0;
```

T2

```
while (flag == 0) {}
data = 1;
```

Requires returning future value or reordering to trigger the assertion failure

Can this assert trigger in JVMs? Do you think the JMM allows it?

```
int x = y = 0;
```

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;


assert r2 == 0;
```

The JVM and the JMM

```
int x = y = 0;
```

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = y;
  x = r3;
} else x = 1;

assert r2 == 0;
```

JMM disallows r2 == 1 because of causality requirements

– Ševčík and Aspinall, ECOOP, 2008

The JVM and the JMM

However, in a JVM, after redundant read elimination

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;


assert r2 == 0;
```

The JVM and the JM

However, in a JVM, after redundant read elimination

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

assert r2 == 0;

The JVM and the JM

However, in a JVM, after redundant read elimination

int x = y = 0;

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

```
r2 = y;
x = 1;
```

assert r2 == 0;

The JVM and the JM

However, in a JVM, after redundant read elimination

```
int x = y = 0;
```

T1

```
r1 = x;
y = r1;
```

T2

```
r2 = y;
if (r2 == 1) {
  r3 = r2;
  x = r3;
} else x = 1;

assert r2 == 0;
```

```
r2 = y;
If (r2 == 1)
  x = r2;
else x = 1;
```

```
r2 = y;
x = 1;
```

Assertion failure possible!

Moral: Just say no to data races

Don’t try hacks based on the memory model

- Unless you are as good as Doug Lea

Author of java.util.concurrent

- Or you have formalized the memory model rules in a tool
  - And even then, are the rules right?