CMPT 745
Software Engineering

Concurrency & Parallelism

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Concurrency & Parallelism

Seeking out performance

- Improving performance can come from tuning
  - Algorithmic complexity
  - Memory access patterns
  - Concurrency
  - Parallelism

Seeking out performance

- Improving performance can come from tuning
  - Algorithmic complexity
  - Memory access patterns
  - Concurrency
  - Parallelism
- As processor speeds have slowed increasing, much focus has been placed on the last two

Concurrency & Parallelism

- ***Concurrency*** is the management of multiple tasks at the same time.
  - e.g. Sharing a CPU across multiple processes.

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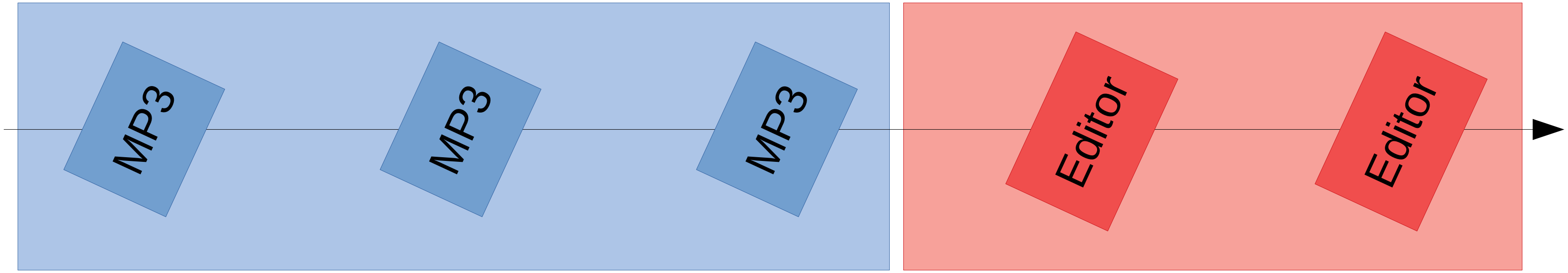

Sequential

Concurrency & Parallelism

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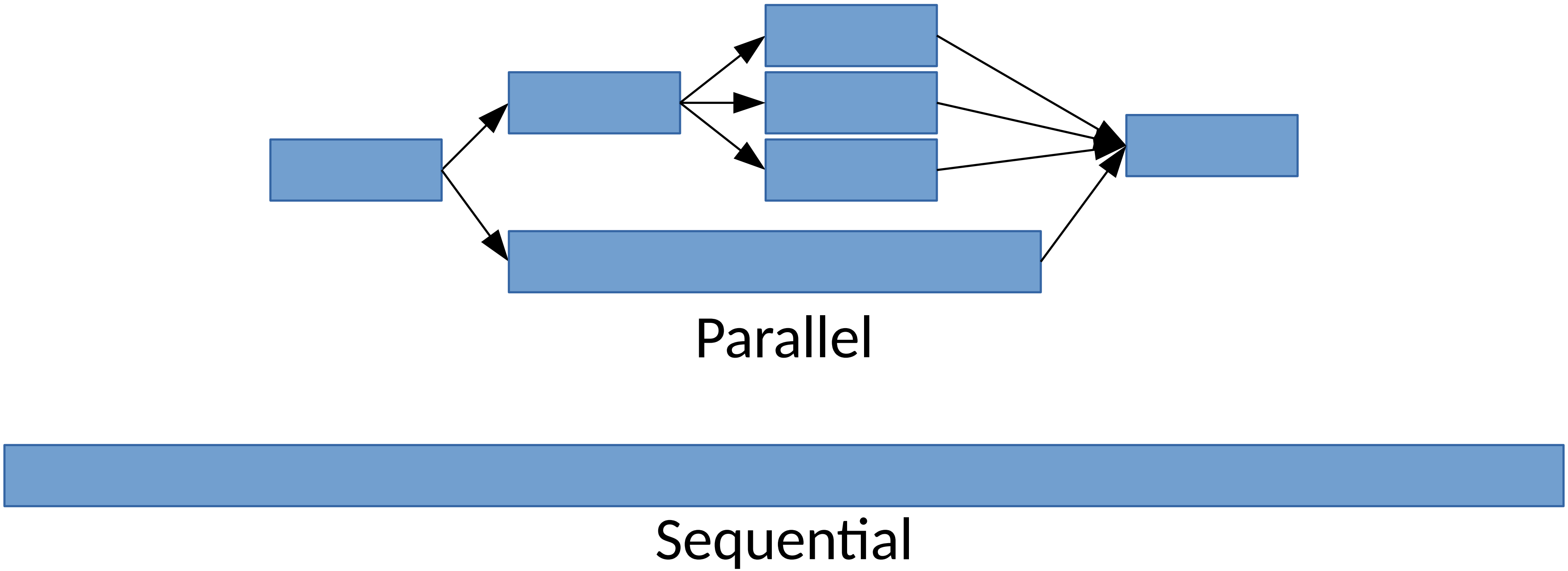
Using Parallelism

- Large problems can sometimes be split into parallel tasks, and the effects of the parallel tasks combined



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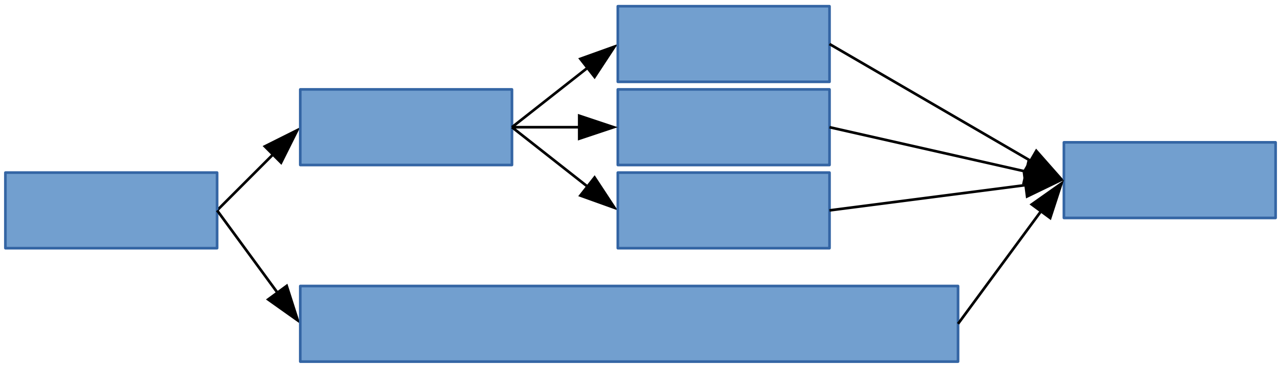

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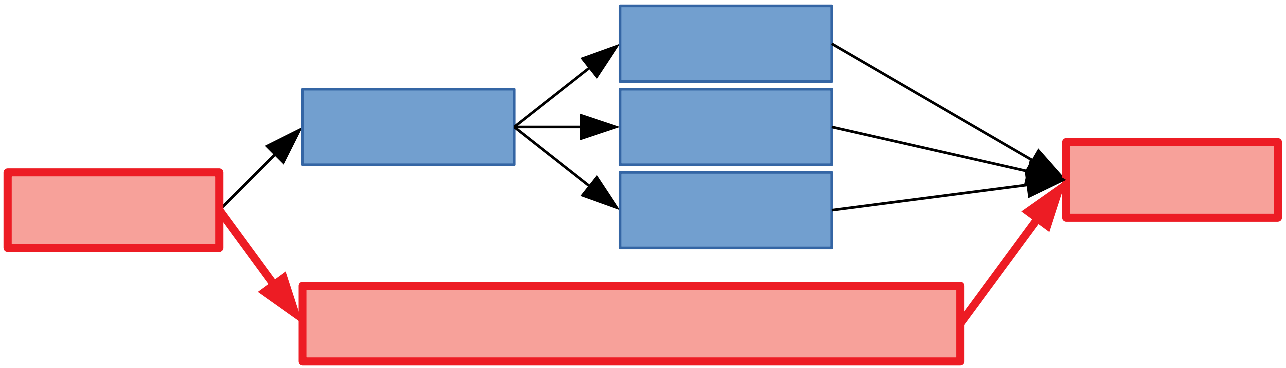

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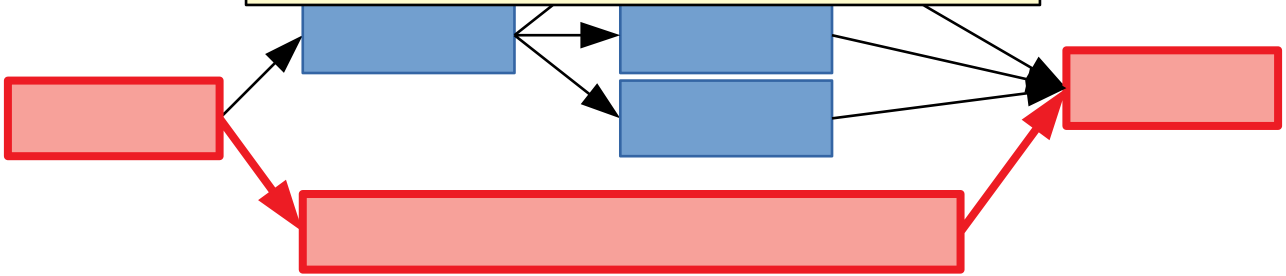
This is too optimistic!
Why?



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- Identifying good opportunities for effective parallelism is open to research
  - Profiling for tasks to extract
  - Understanding the effect of speeding specific tasks
  - …

Correctness issues

- Parallel & concurrent code is challenging to write
  - Nondeterministic timing
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- Specifically
  - Deadlock / Livelock
  - Starvation
  - Data races
  - Atomicity violations
  - Order violations
  - …

Correctness issues

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  - Atomicity violations
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  - …

} 97% of real world concurrency bugs

[Lu, ASPLOS 2008]

Data Races

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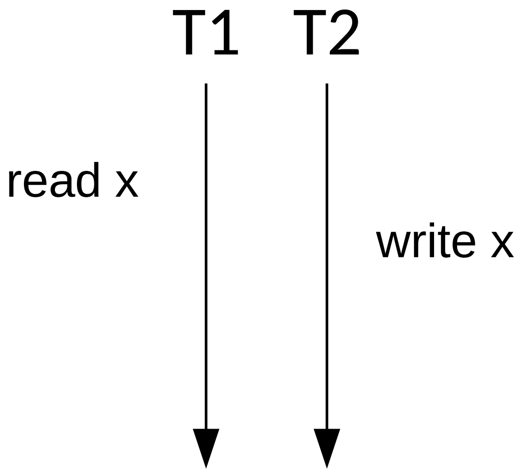

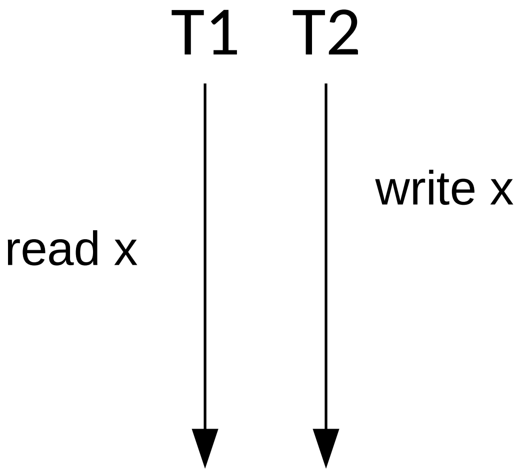

Data Races

x++ →

tmp = x
tmp = tmp+1
x = tmp

T1 T2

tmp_1 = x
tmp_1 = tmp_1+1
x = tmp_1

tmp_2 = x
tmp_2 = tmp_2+1
x = tmp_2

Data Races

x++ →

```
tmp = x
tmp = tmp+1
x = tmp
```

T1 T2

$x \mapsto 0$

T1:

$tmp_1 = x$
$tmp_1 = tmp_1+1$
$x = tmp_1$

T2:

$tmp_2 = x$
$tmp_2 = tmp_2+1$
$x = tmp_2$

Data Races

```
x++
```

→

```
tmp = x
tmp = tmp+1
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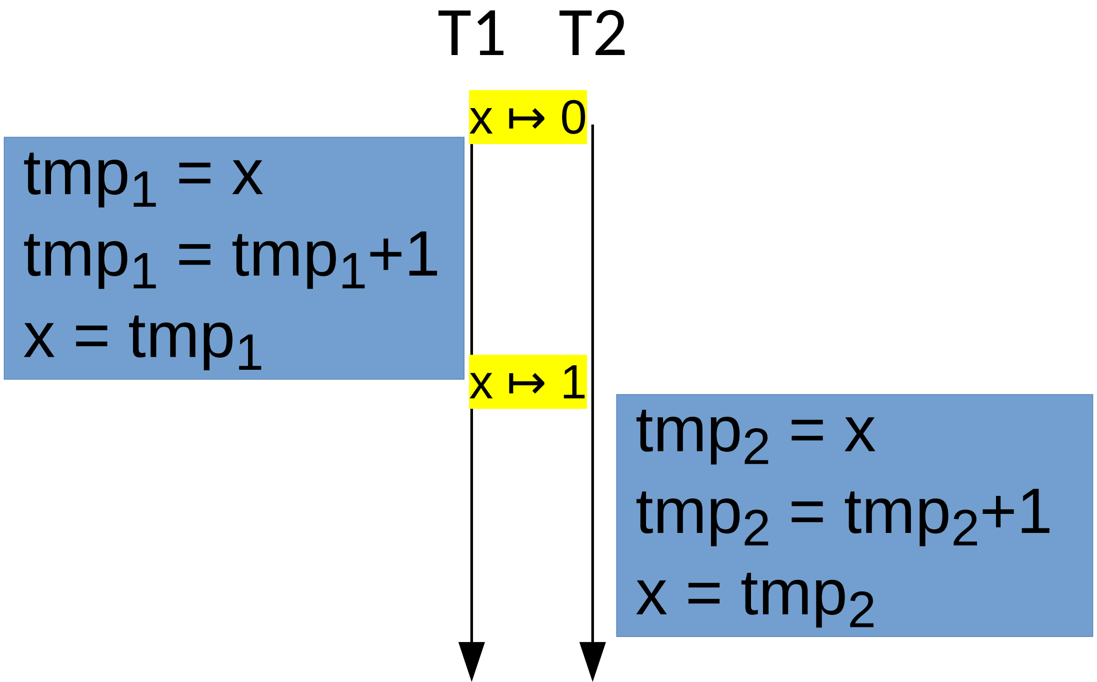

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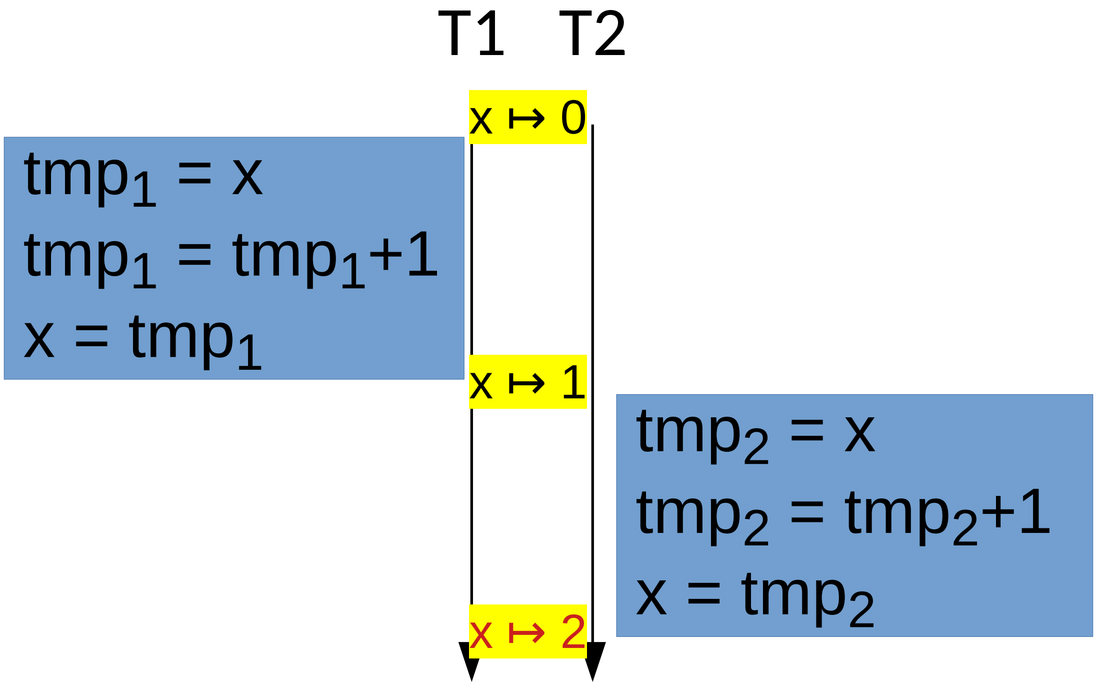

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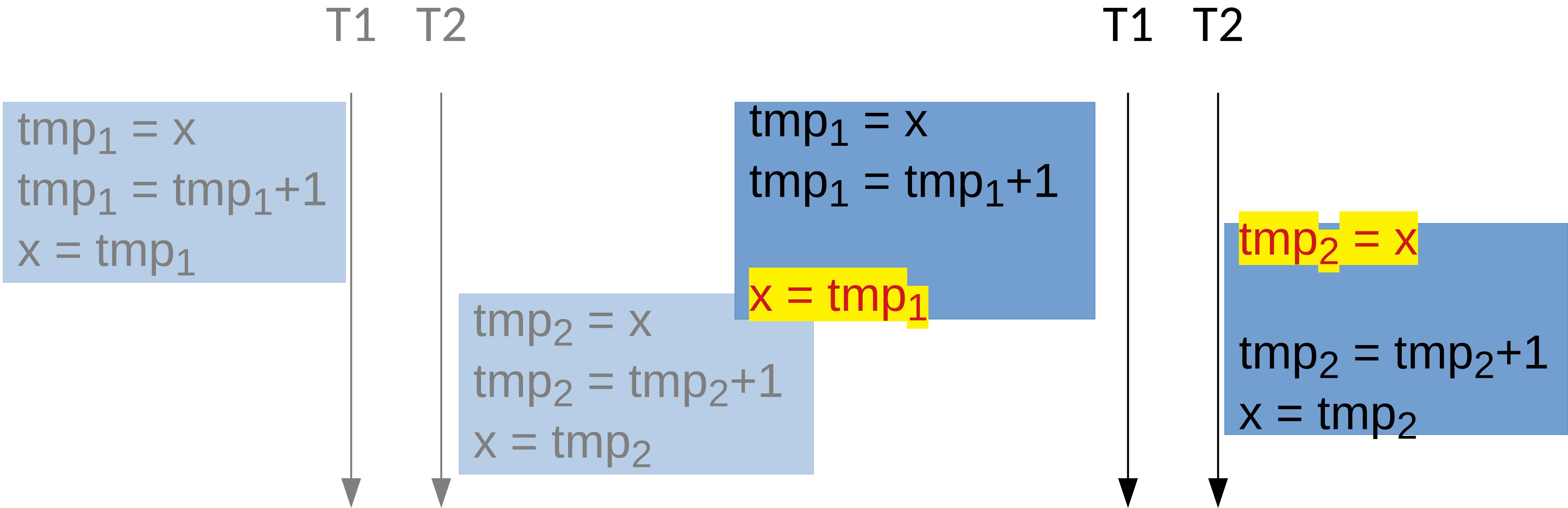

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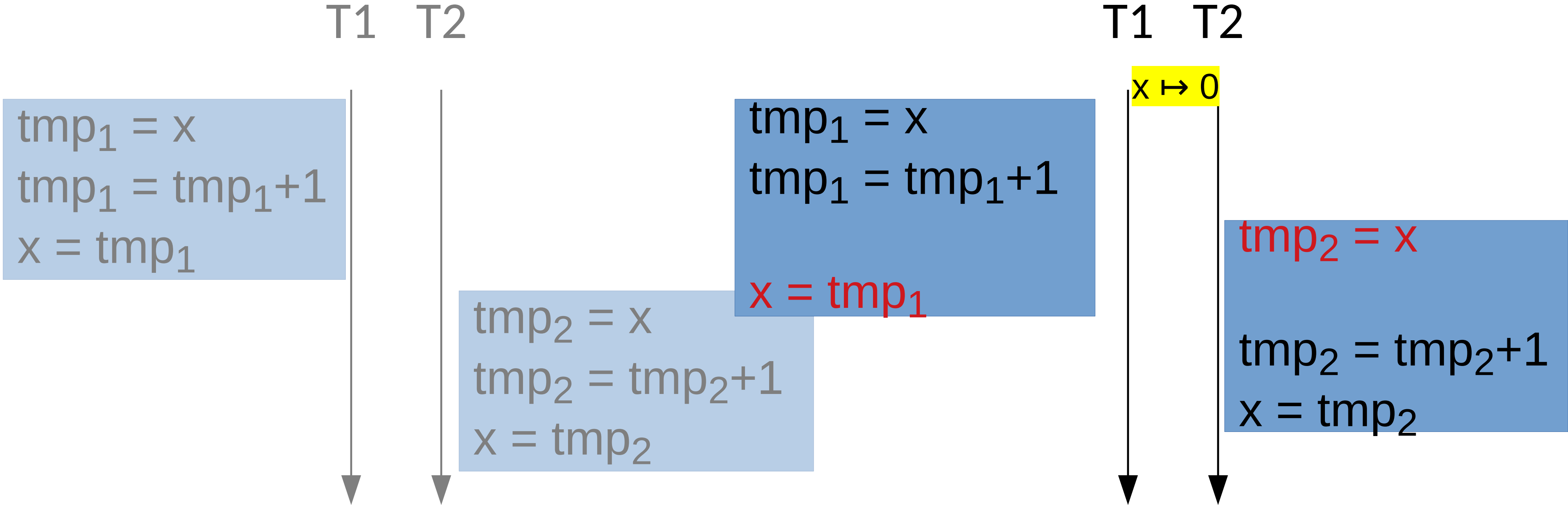

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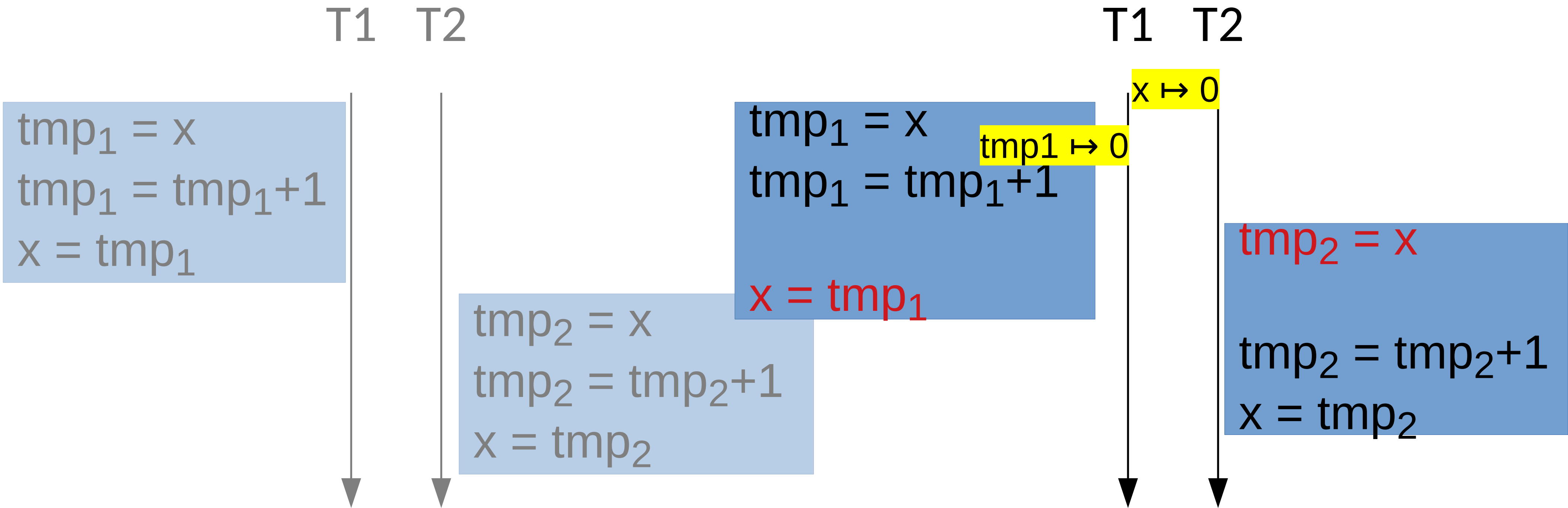

Data Races

x++ →

```
tmp = x
tmp = tmp+1
x = tmp
```

T1 T2

$tmp_1 = x$
$tmp_1 = tmp_1+1$
$x = tmp_1$

$tmp_2 = x$
$tmp_2 = tmp_2+1$
$x = tmp_2$

T1 T2

x ↦ 0

$tmp_1 = x$
tmp1 ↦ 0
$tmp_1 = tmp_1+1$

$x = tmp_1$

$tmp_2 = x$
tmp2 ↦ 0
$tmp_2 = tmp_2+1$
$x = tmp_2$

Data Races

x++ →

```
tmp = x
tmp = tmp+1
x = tmp
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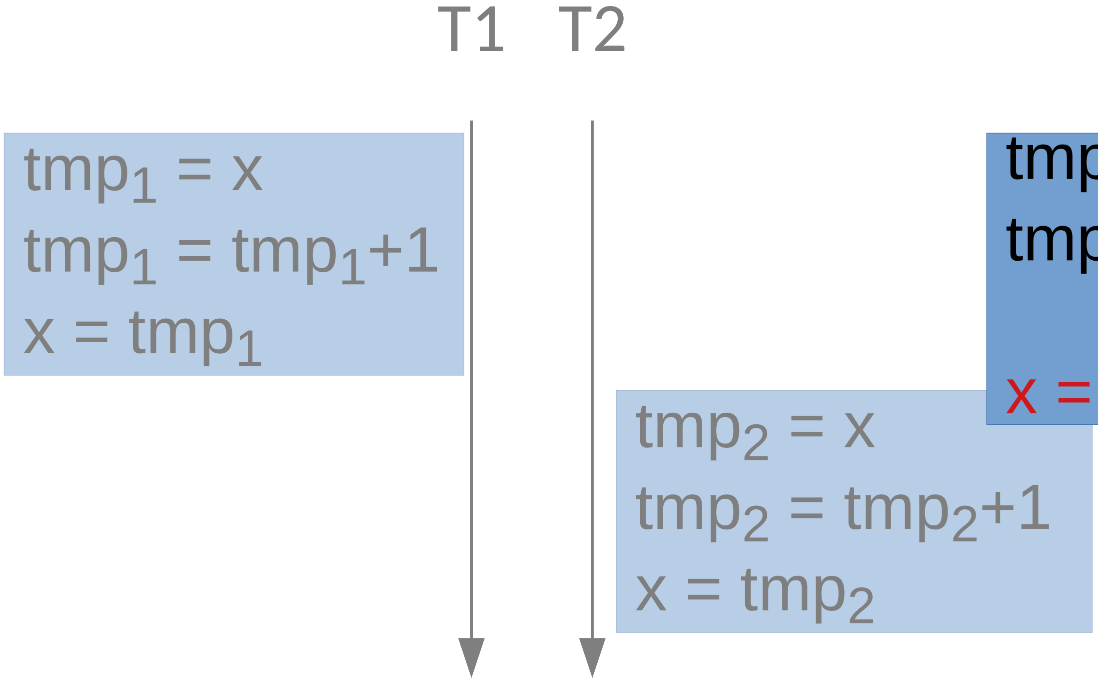

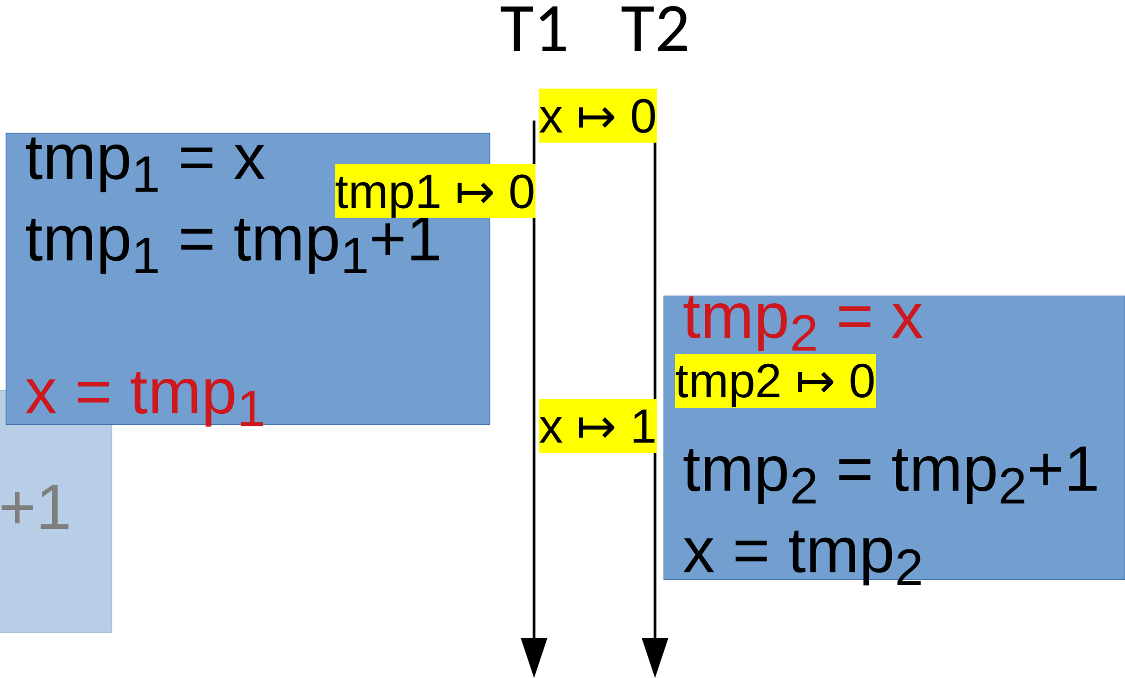

Data Races

x++ →

```
tmp = x
tmp = tmp+1
x = tmp
```

T1 T2

tmp_1 = x
tmp_1 = tmp_1+1
x = tmp_1

tmp_2 = x
tmp_2 = tmp_2+1
x = tmp_2

T1 T2

x ↦ 0

tmp_1 = x
tmp1 ↦ 0
tmp_1 = tmp_1+1

tmp_2 = x
tmp2 ↦ 0

x = tmp_1

x ↦ 1

tmp_2 = tmp_2+1
x = tmp_2

x ↦ 1

Data Races

x++ →

$tmp = x$
$tmp = tmp+1$
$x = tmp$

T1 T2

$tmp_1 = x$
$tmp_1 = tmp_1+1$
$x = tmp_1$

$tmp_2 = x$
$tmp_2 = tmp_2+1$
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Synchronization discipline prevents data races.

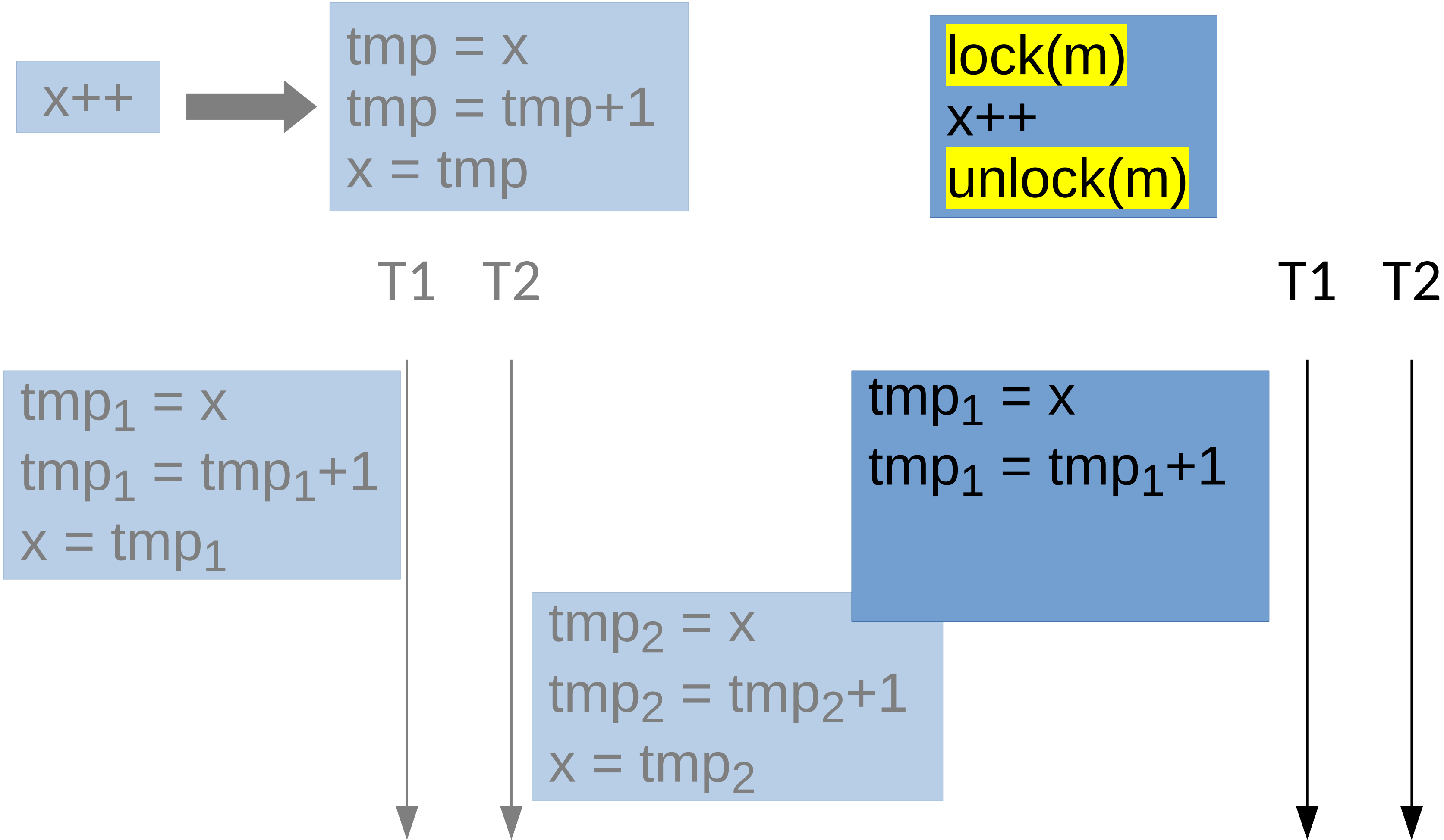
$x = tmp_1$

T1 T2

$tmp_2 = x$

$tmp_2 = tmp_2+1$
$x = tmp_2$

Data Races


x++
tmp = x
tmp = tmp+1
x = tmp
lock(m)
x++
unlock(m)
T1 T2
T1 T2
tmp_1 = x
tmp_1 = tmp_1+1
x = tmp_1
tmp_2 = x
tmp_2 = tmp_2+1
x = tmp_2
tmp_1 = x
tmp_1 = tmp_1+1

Data Races

```
x++  →  tmp = x
        tmp = tmp+1
        x = tmp
```

```
lock(m)
x++
unlock(m)
```

T1 T2

```
tmp1 = x
tmp1 = tmp1+1
x = tmp1
```

```
tmp2 = x
tmp2 = tmp2+1
x = tmp2
```

T1 T2

```
lock(m)
tmp1 = x
tmp1 = tmp1+1
```

Data Races

x++ →

tmp = x
tmp = tmp+1
x = tmp

lock(m)
x++
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T1 T2

tmp_1 = x
tmp_1 = tmp_1+1
x = tmp_1

tmp_2 = x
tmp_2 = tmp_2+1
x = tmp_2

T1 T2

lock(m)
tmp_1 = x
tmp_1 = tmp_1+1

The second task must wait.

Data Races

x++ →

tmp = x
tmp = tmp+1
x = tmp

lock(m)
x++
unlock(m)

T1 T2

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tmp_1 = tmp_1+1
x = tmp_1

tmp_2 = x
tmp_2 = tmp_2+1
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lock(m)
tmp_1 = x
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Data Races

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T1 T2

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$tmp_2 = x$
$tmp_2 = tmp_2+1$
$x = tmp_2$

T1 T2

lock(m)
$tmp_1 = x$
$tmp_1 = tmp_1+1$
$x = tmp_1$
unlock(m)

lock(m)
$tmp_2 = x$
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“Benign” Data Races

- Sometimes a developer will make use of a data race
  - Avoid expensive synchronization
  - The race looks “benign” or harmless

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- Sometimes a developer will make use of a data race
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  - The race looks “benign” or harmless
- Both programming languages and hardware have memory models that determine what is really okay
  - A ***memory model*** determines what values may be read by a given memory access, esp. w.r.t. previous writes
    [CACM 2010, PLDI 2018]

“Benign” Data Races

```
if (!init) {
    lock();
    if (!init) {
        data = create();
        init = true;
    }
    unlock();
}
tmp = data;
```

[Boehm, Hotpar 2011]

Sometimes developers want to lazily initialize data

even with multiple threads.

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- Threads race on `init`
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Accesses can be reordered

"Benign" Data Races

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    lock();
    if (!init) {
        init = true;
    unlock();
}
tmp = data;
```

Data can even be loaded early.

This can even be done just by hardware!

```
tmp = data;
if (!init) {
    lock();
    if (!init) {
        data = create();
        tmp = data;
        init = true;
    }
    unlock();
}
```

“Benign” Data Races

```
local = counter;
if (local > localMax) {
    handler = ...;
}
update = work();
if (local > localMax) {
    handler(update);
}
```

[Boehm, Hotpar 2011]

Sometimes developers want to interleave conditional behavior.

“Benign” Data Races

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- Data race freedom allows extra reads.

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```

Other Thread

```
counter = ...;
```

“Benign” Data Races

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- Data race freedom allows extra reads.

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local = counter;
if (local > localMax) {
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update = work();
if (counter > localMax) {
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}
```

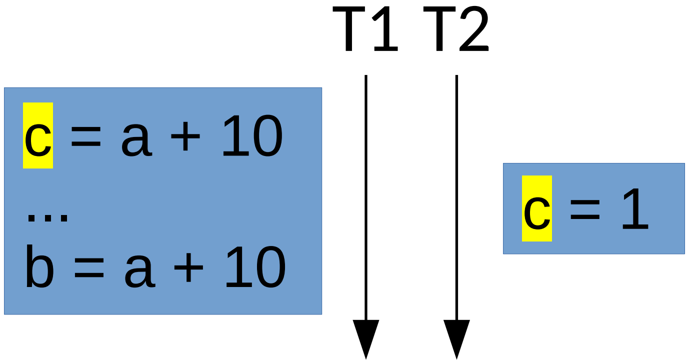
False

True

Other Thread

counter = ...;

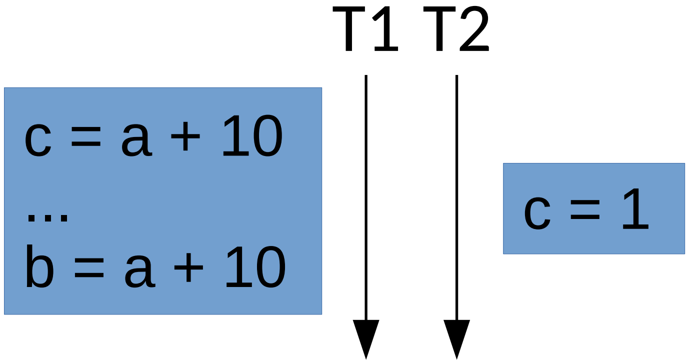
“Benign” Data Races



[Dolan, PLDI 2018]

- Races can introduce bugs on *non-racy variables*

“Benign” Data Races



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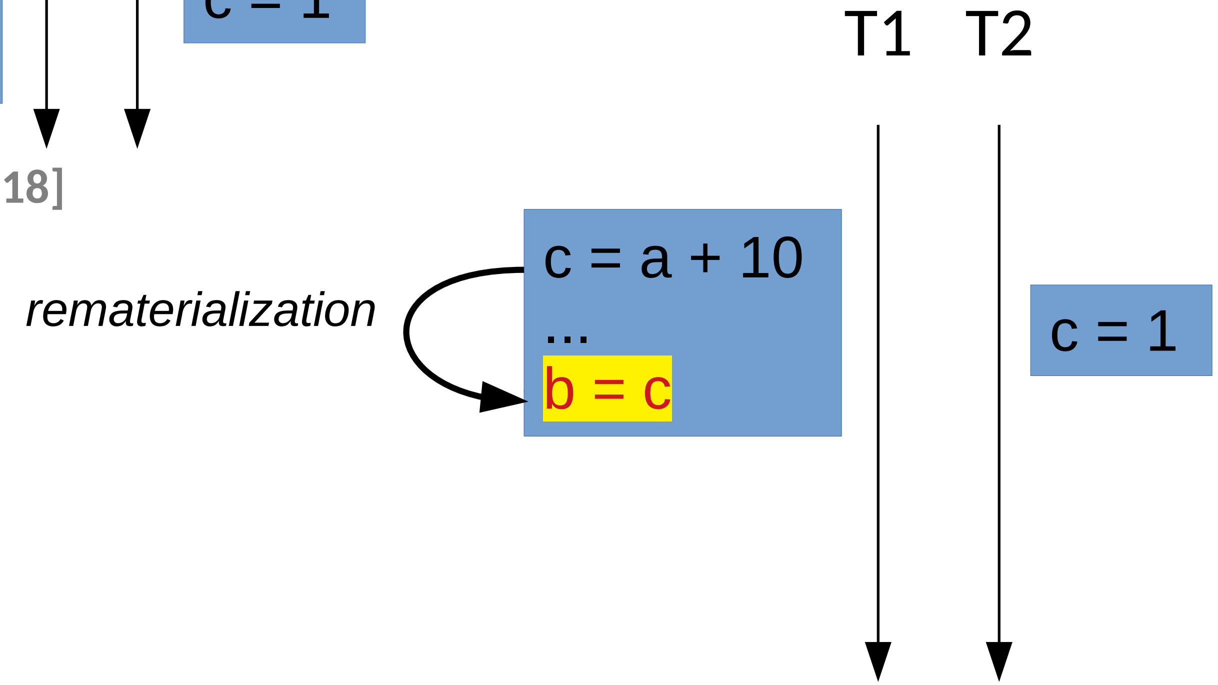

“Benign” Data Races

T1 T2

```
a = 1
flag = true
```

```
a = 2
f = flag
b = a
c = a
```

- Races can jump forward and backward in time

[Dolan, PLDI 2018]

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This can happen in Java when flag is volatile
& b is a complex reference

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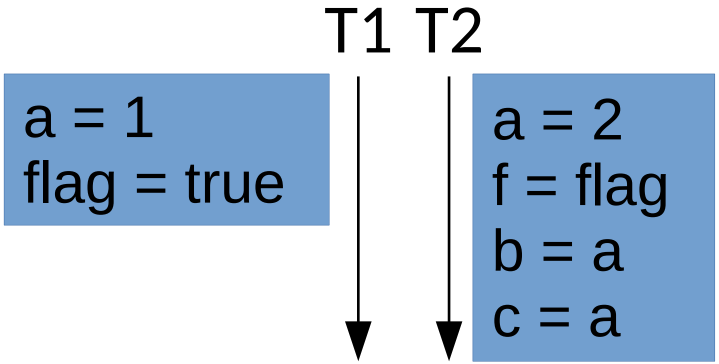

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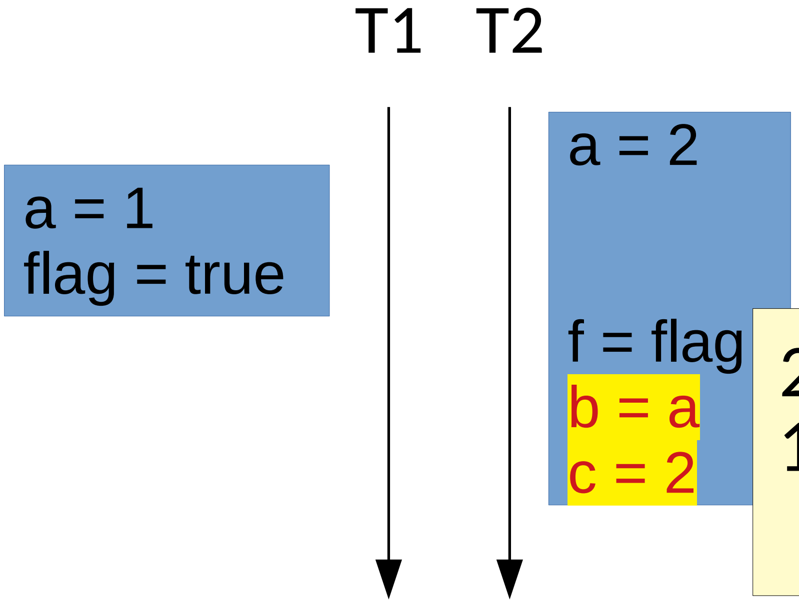

2 can be read after 1 even in the same thread!

Happens-Before Ordering

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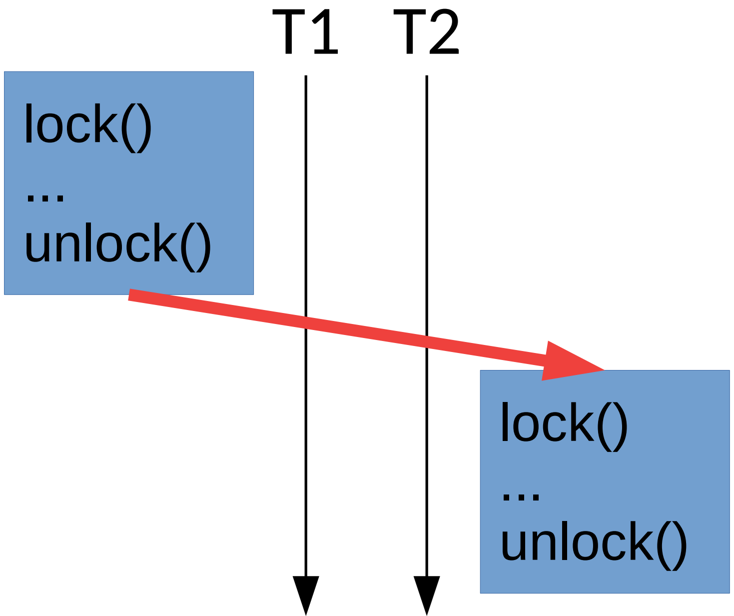

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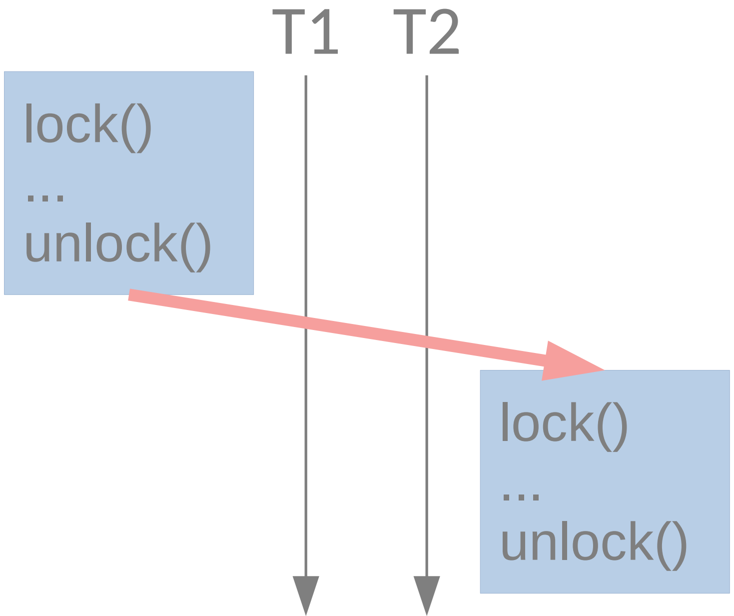

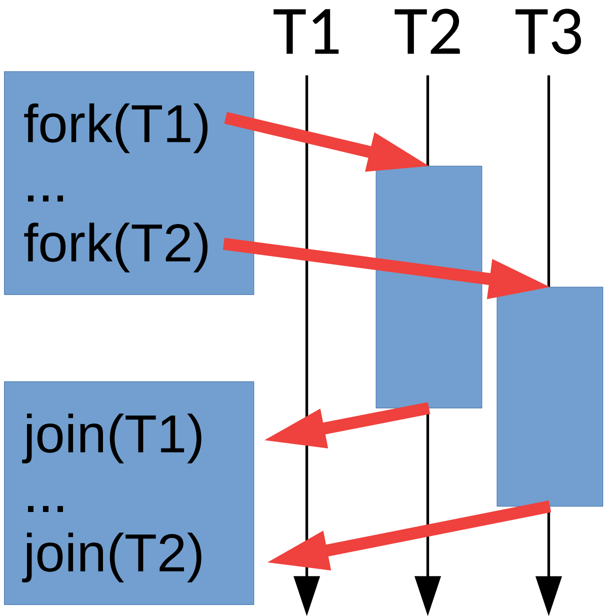

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  - a partial order over logical time (recall: *simultaneously*)
  - defined behavior occurs when writes & reads are ordered
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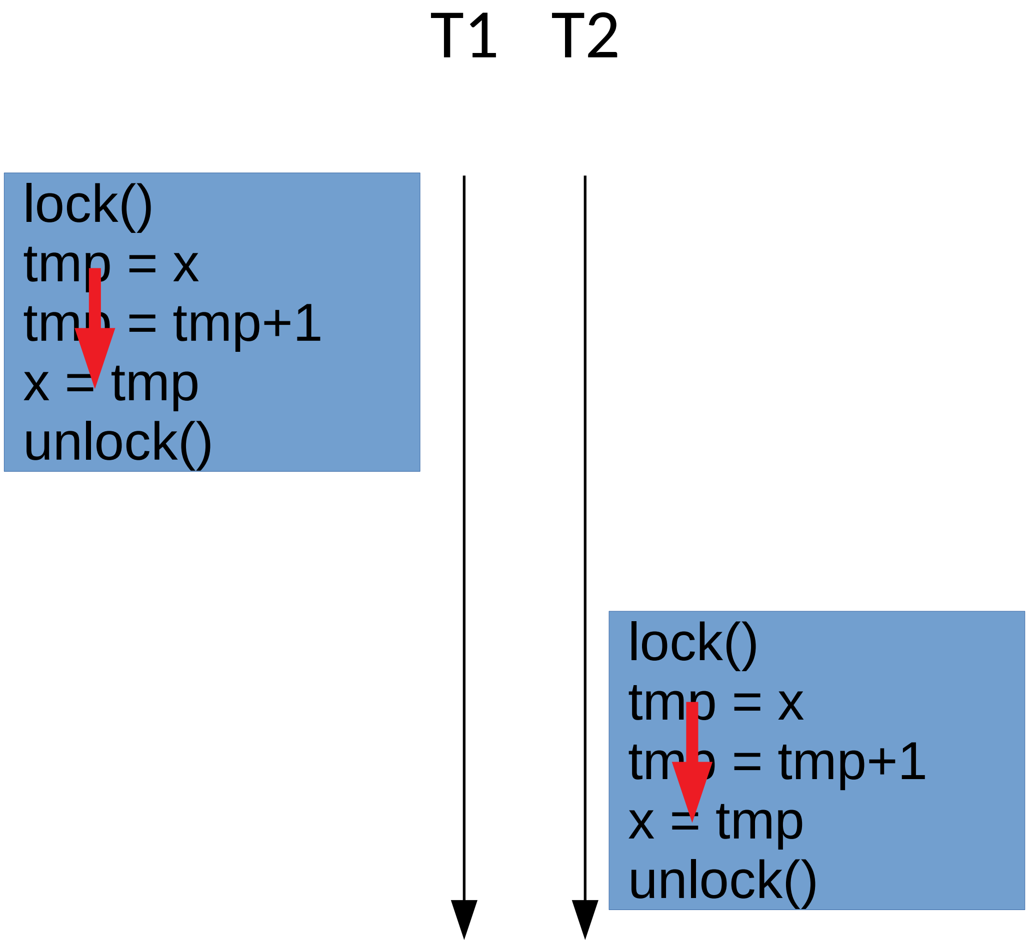
  - access to volatile variables keeps per individual variable order
- Happens-Before ordering of a specific execution can be tracked to identify bugs

Happens-Before Ordering



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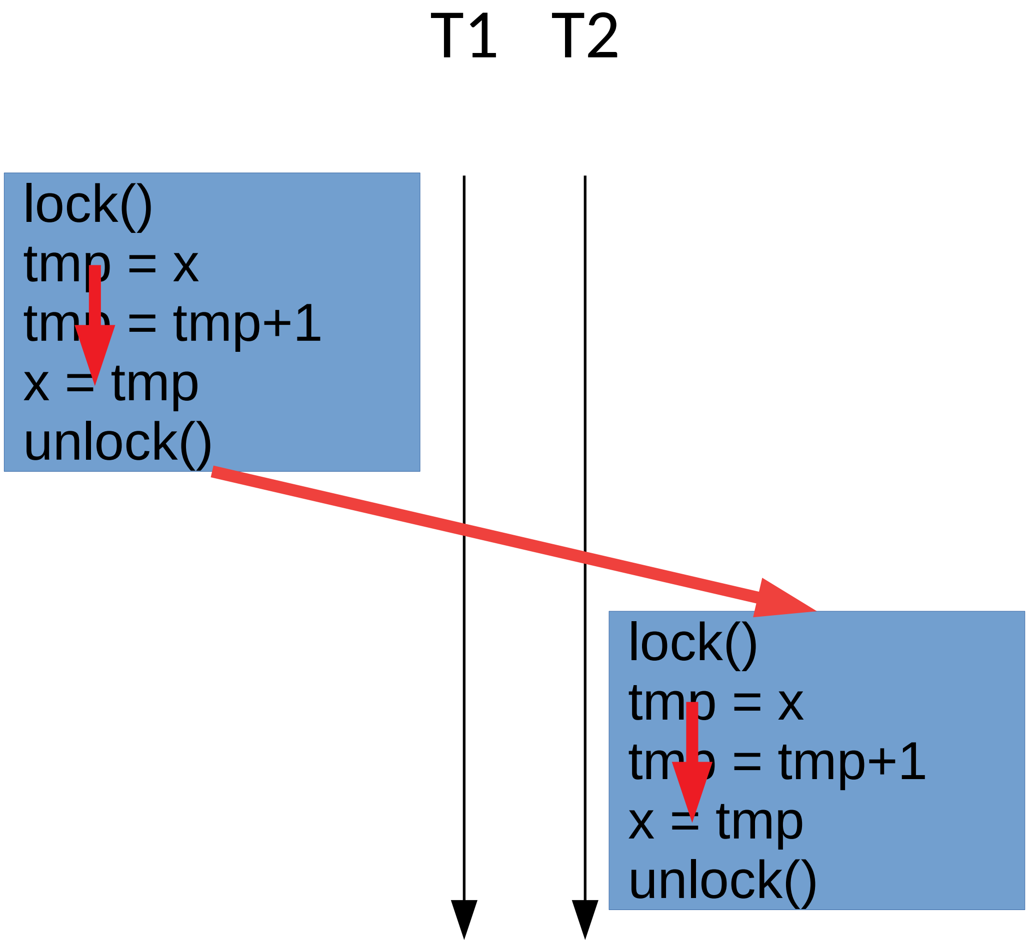

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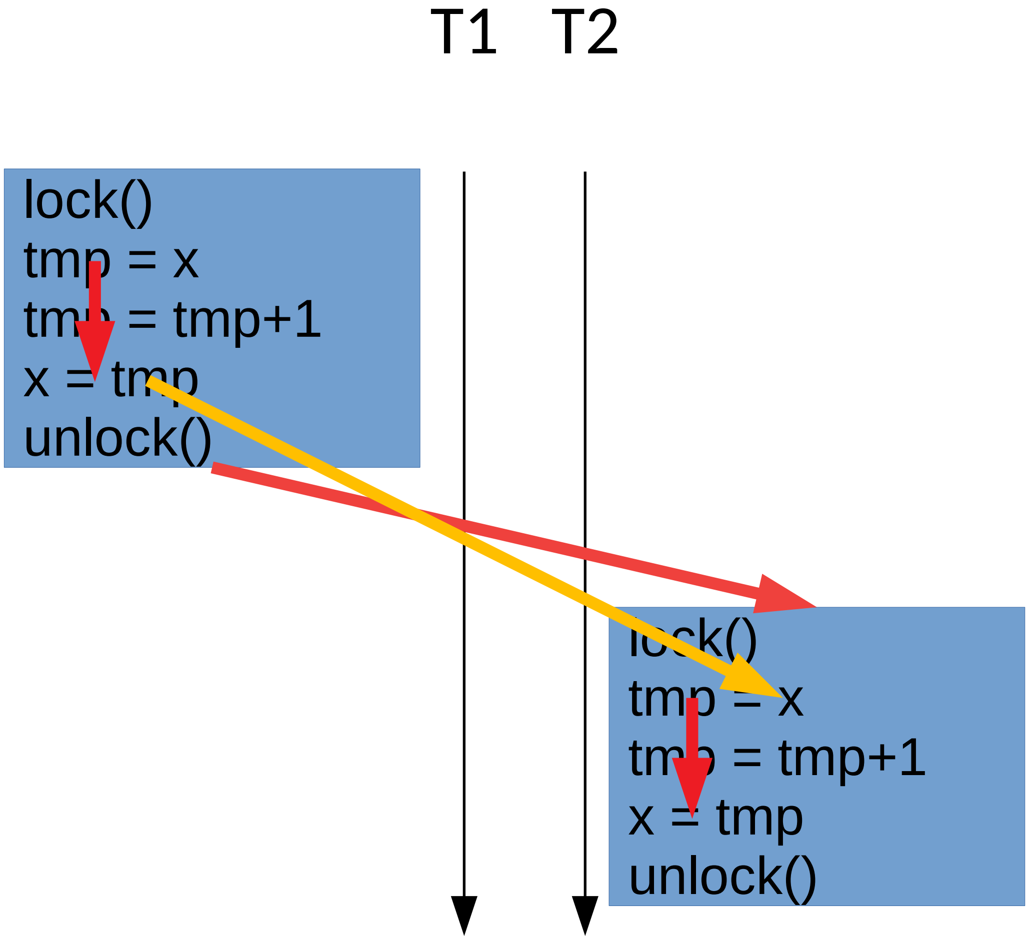

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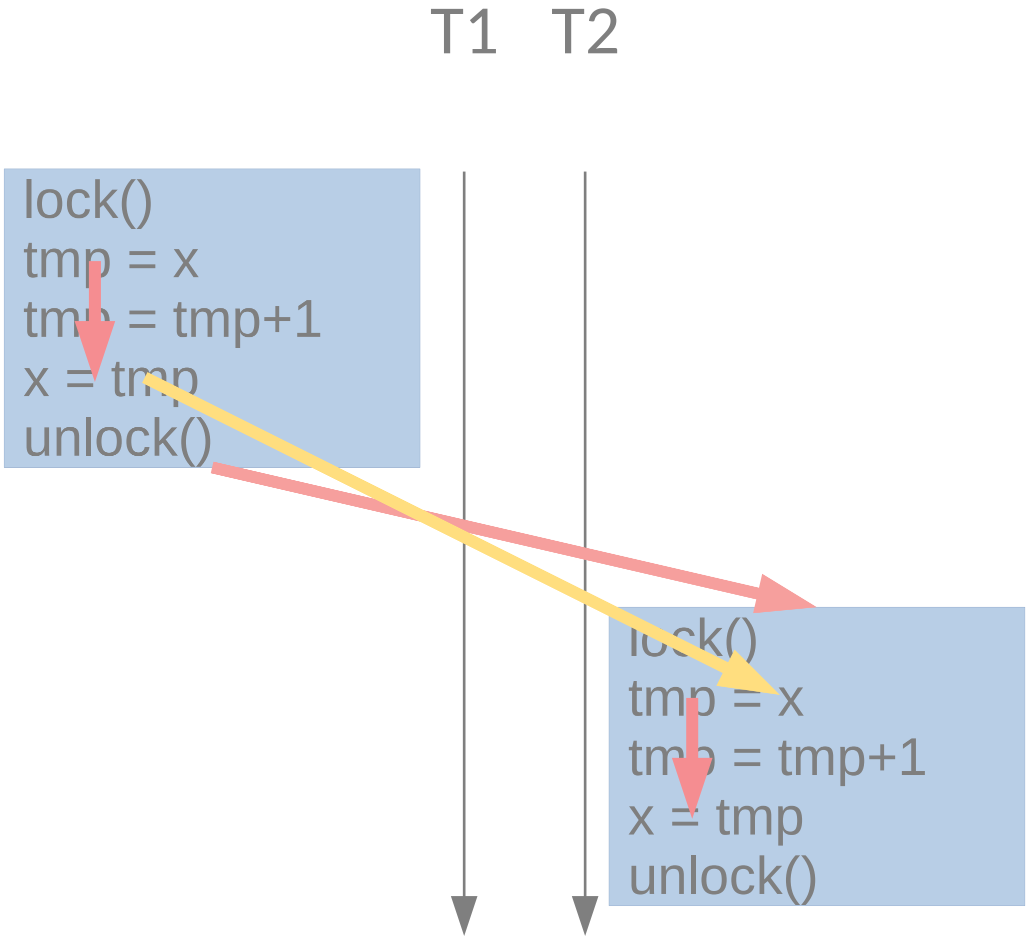
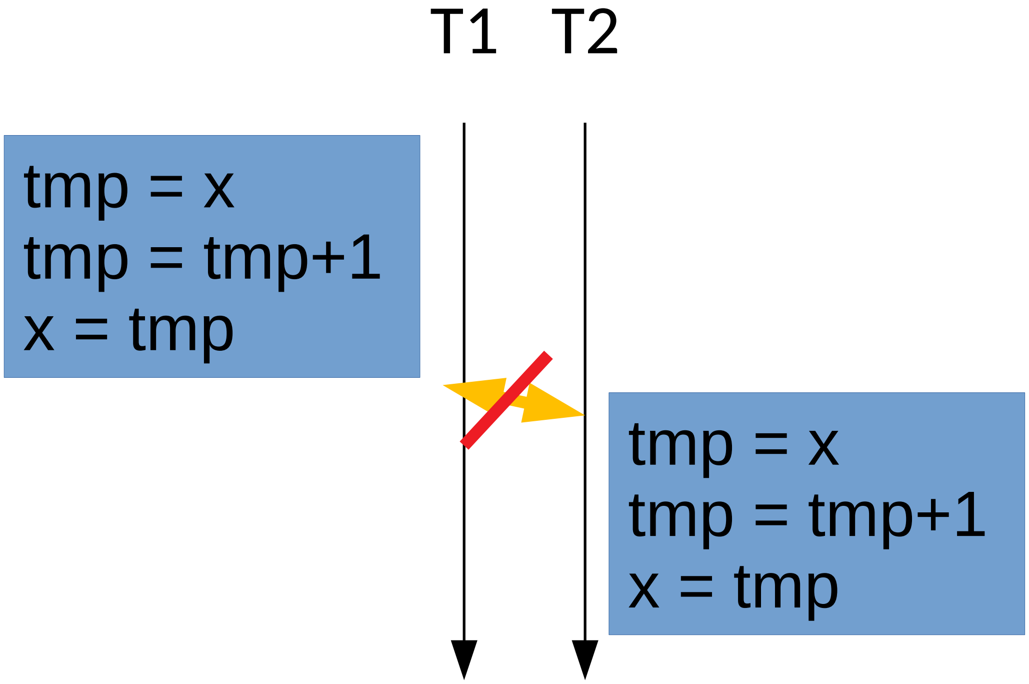
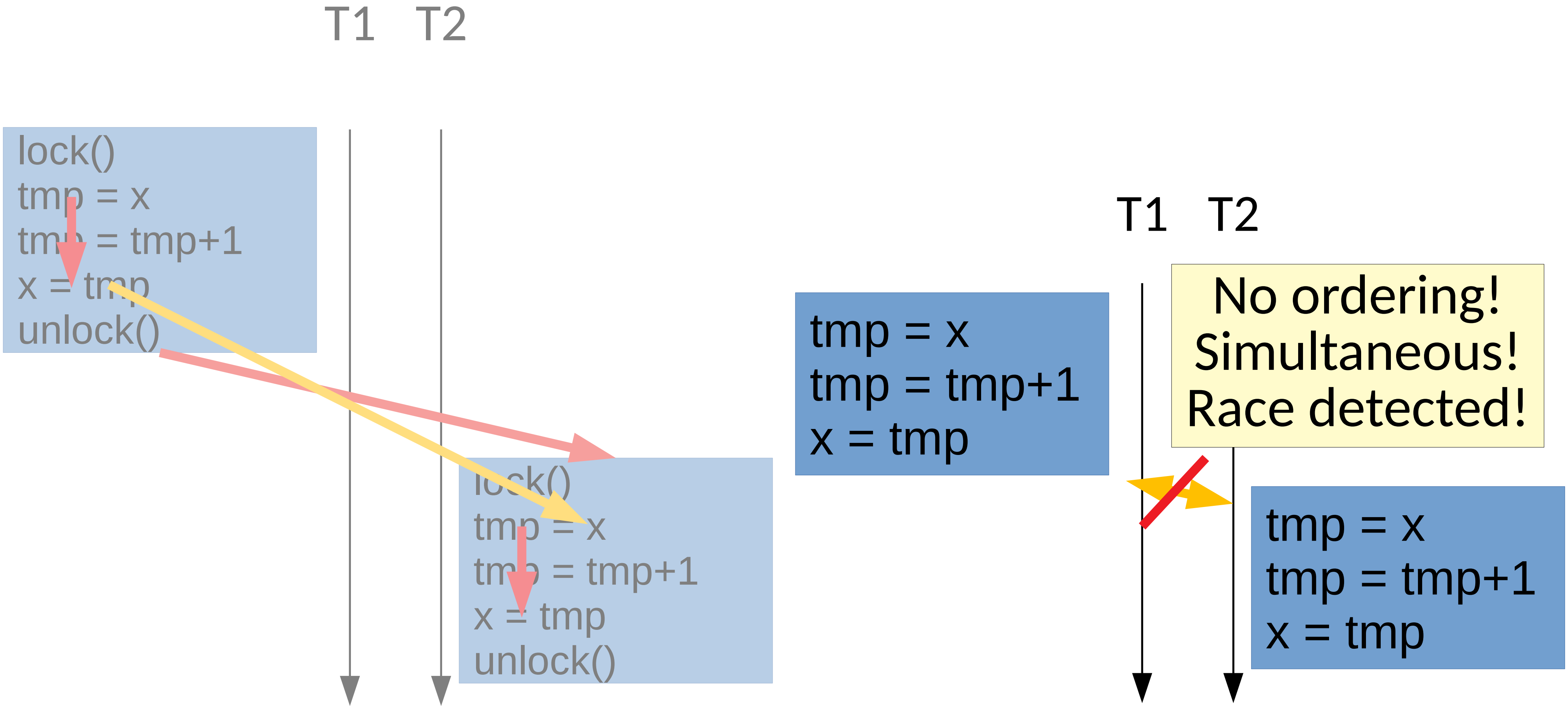




Happens-Before Ordering



Happens-Before Ordering

- Note, this only detects races in the current execution & schedule!

Why?

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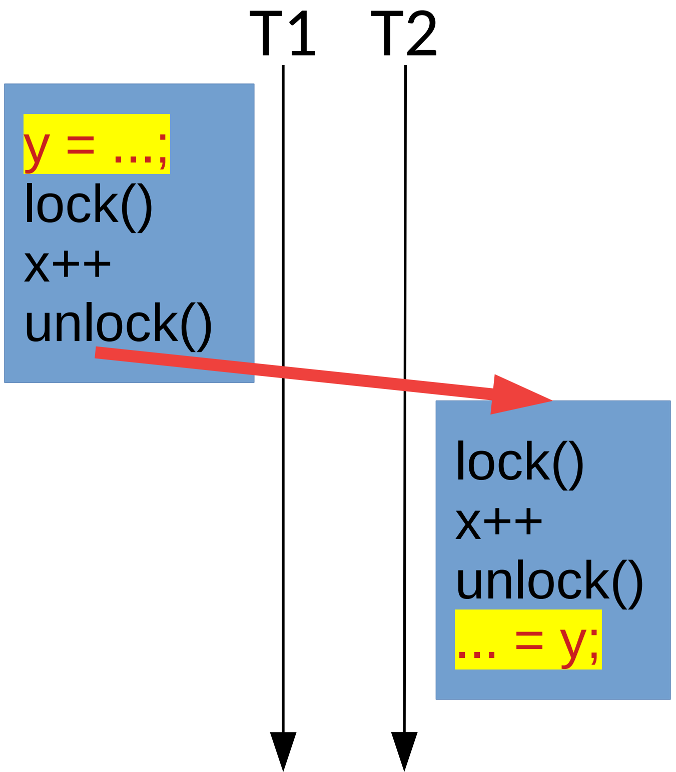
Why?



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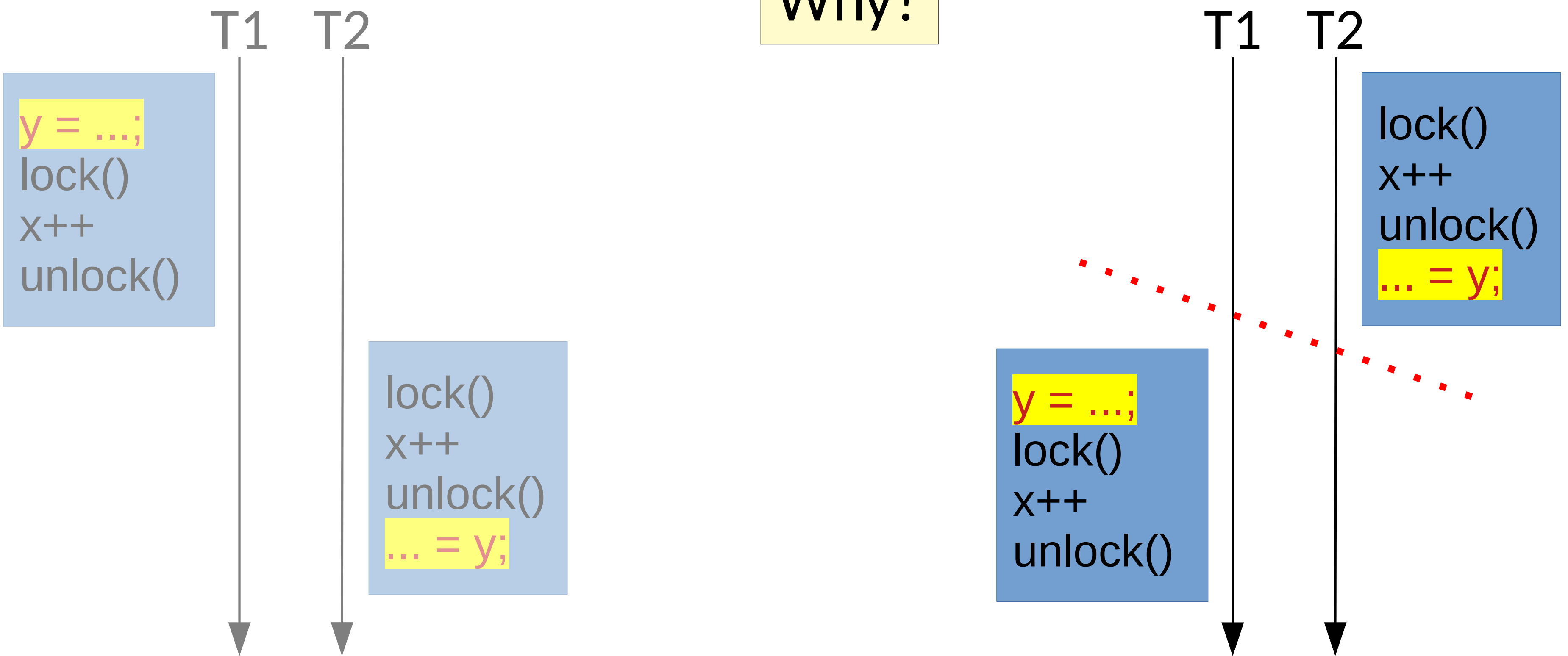
Why?



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  - *Sound predictive* data race detection can extend it *across other executions* **[PLDI 2017/2018, 2020]**

Happens-Before Ordering

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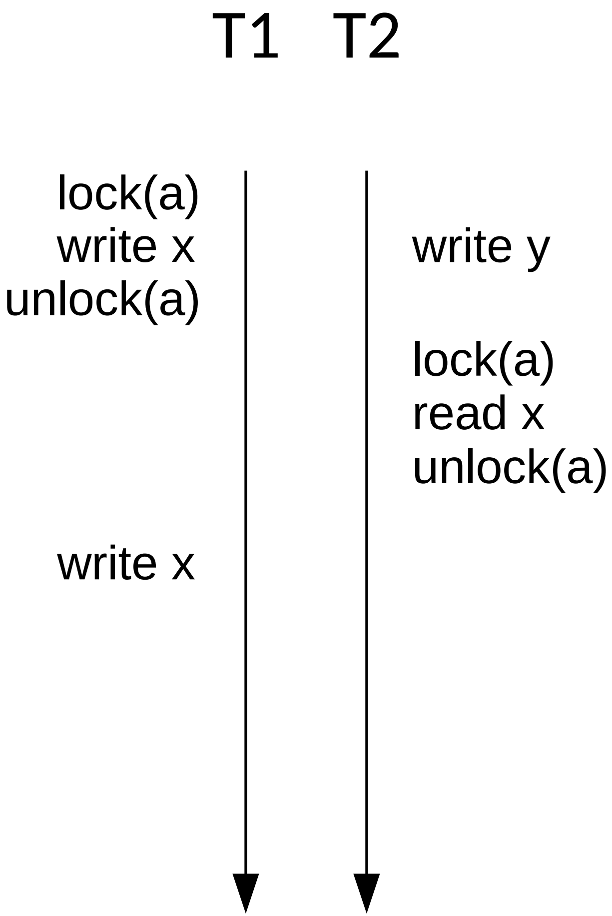
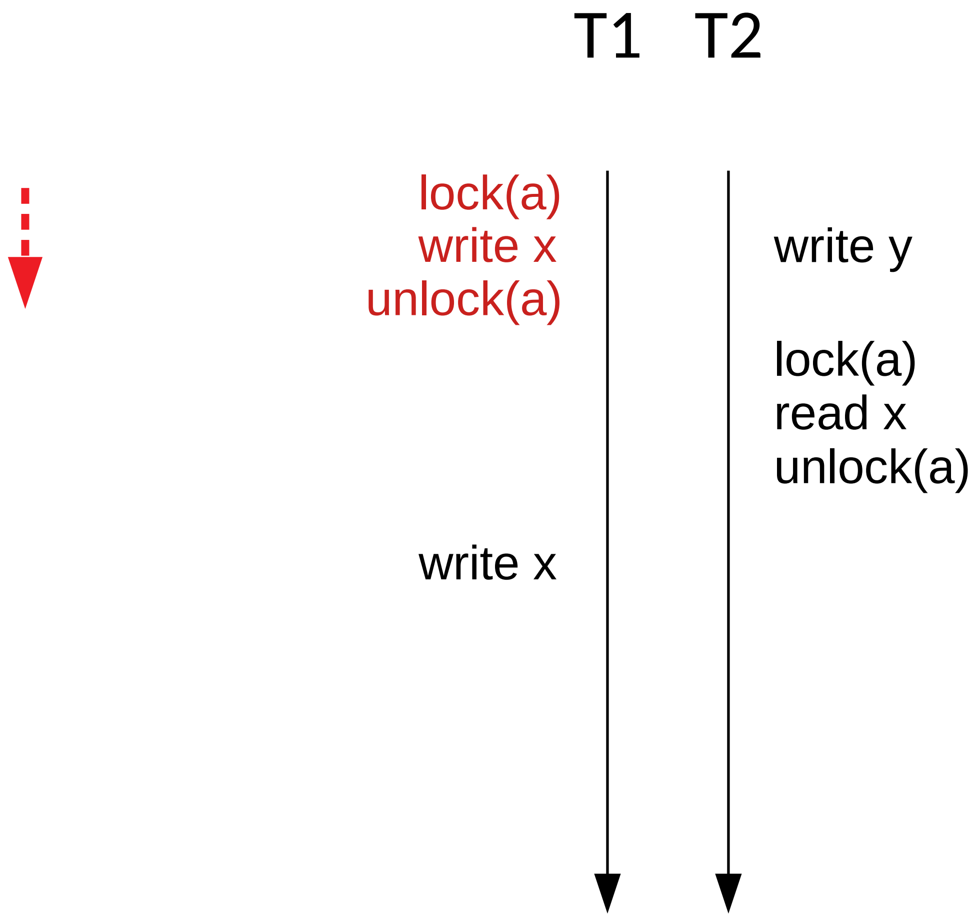
  - *Sound predictive* data race detection can extend it across other executions **[PLDI 2017/2018, 2020]**
- Requires careful tracking of dependences
  - Careful construction of logical time using ***vector clocks*** **[JVM 2001, PLDI 2009]**

Logical Time & Vector Clocks



What is the happens-before relation?

Logical Time & Vector Clocks



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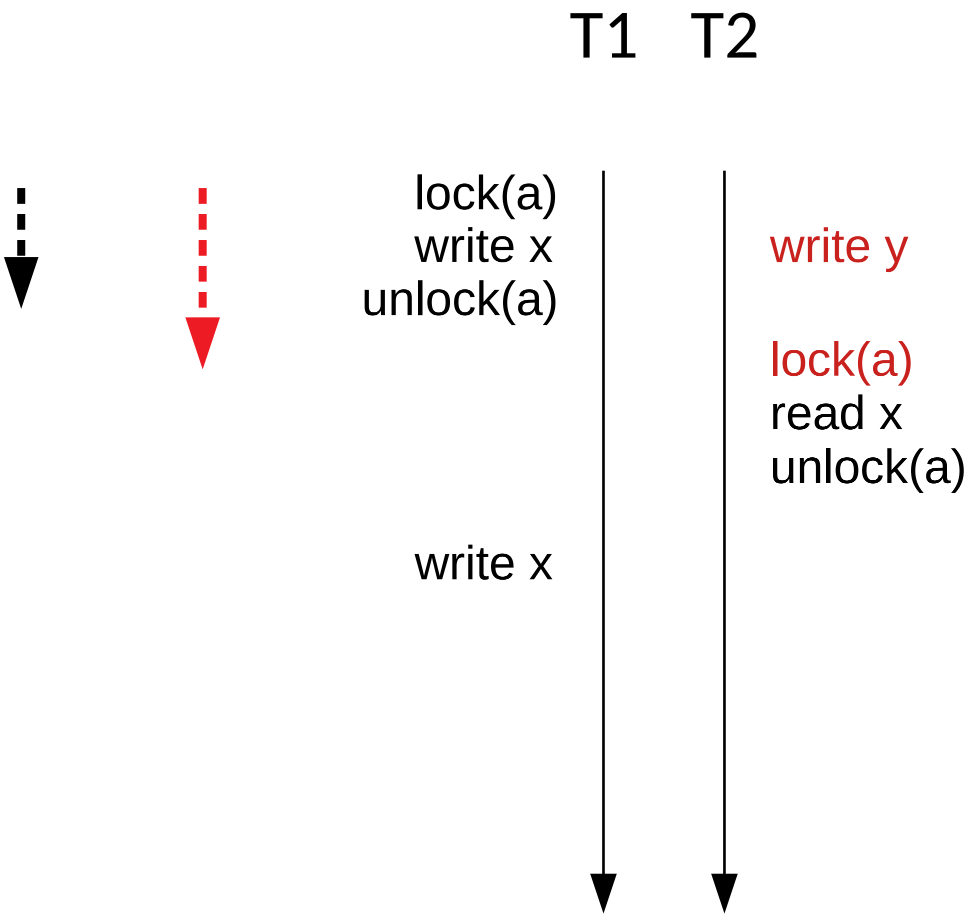

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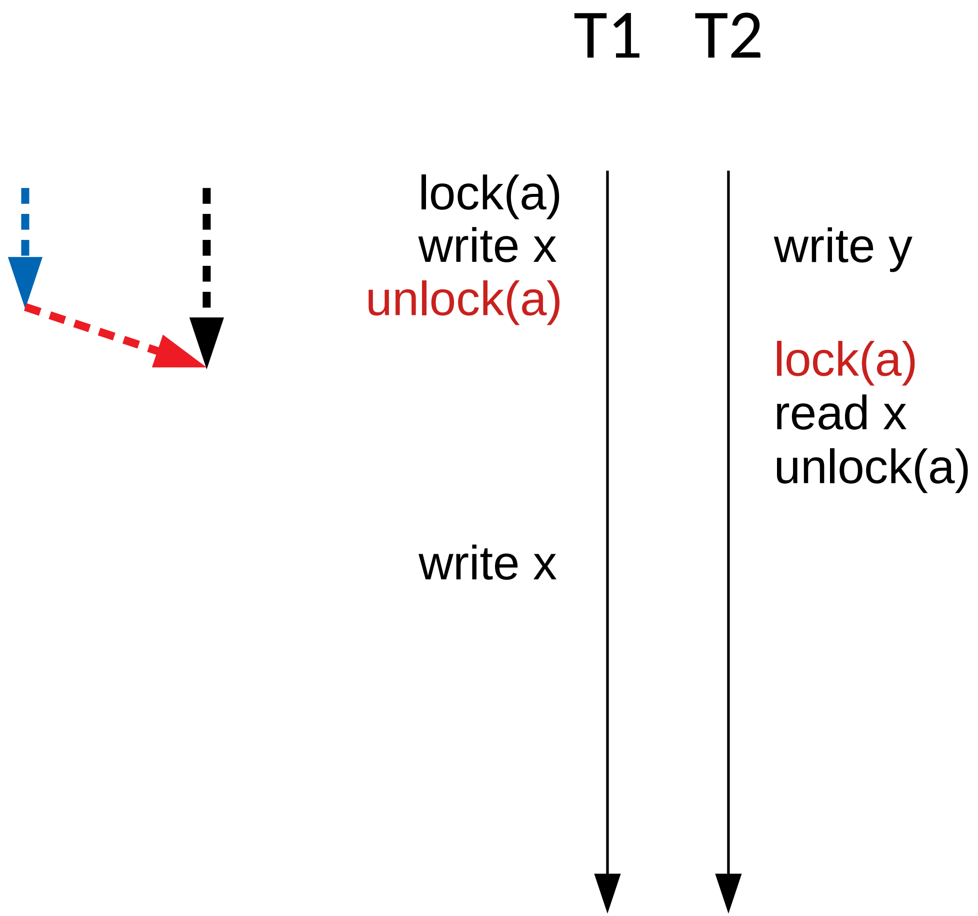
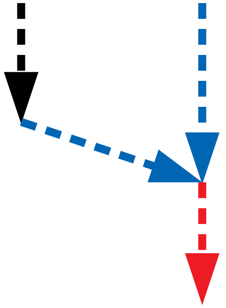
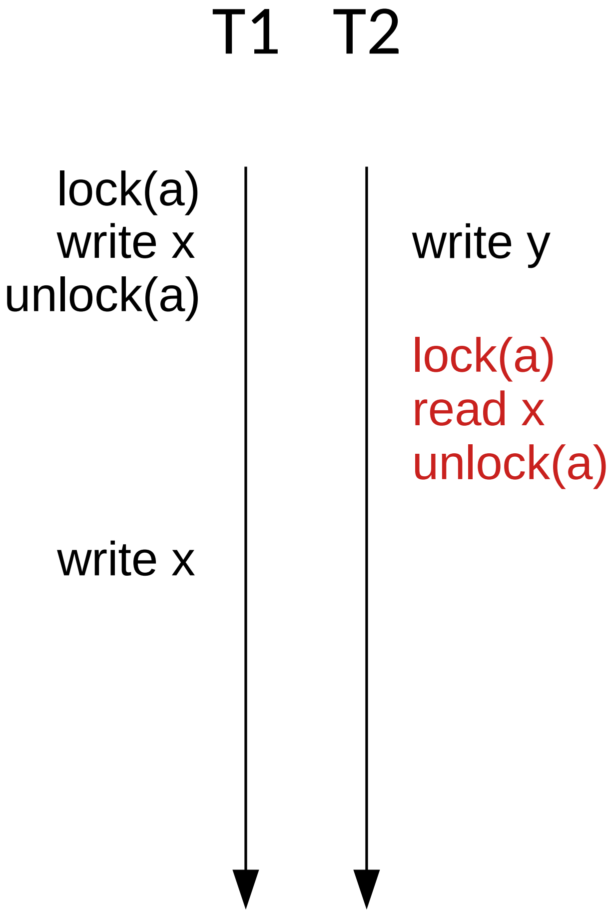


What is the happens-before relation?

Logical Time & Vector Clocks





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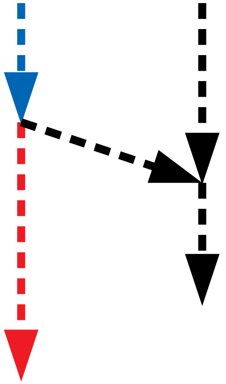

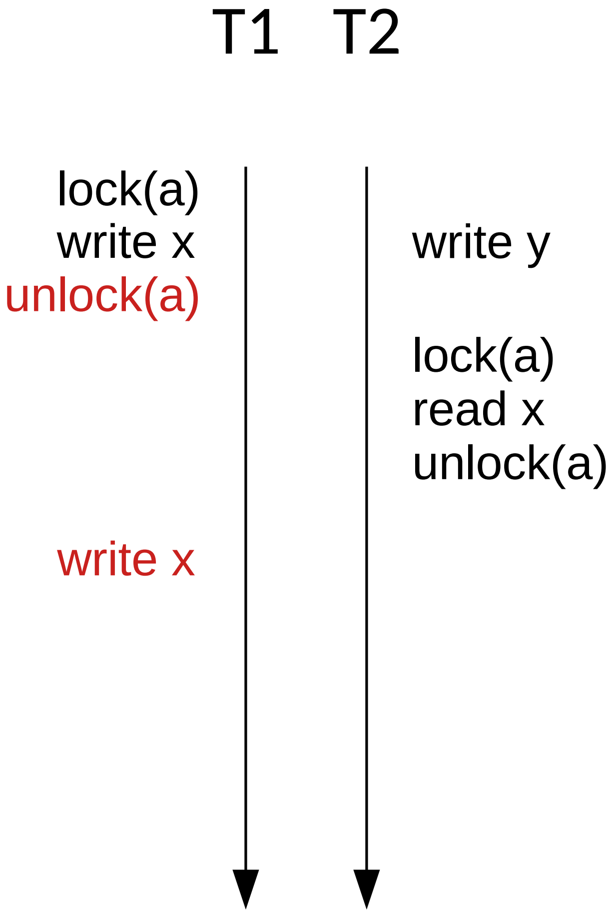

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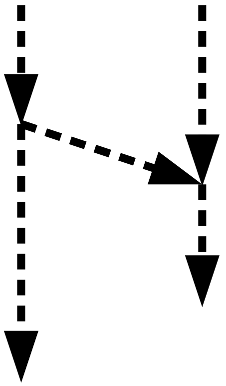
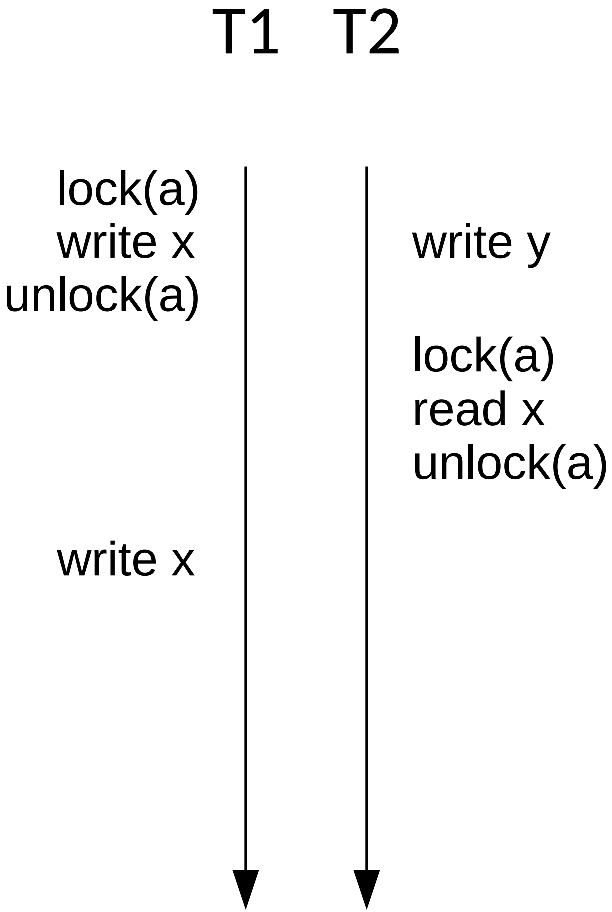




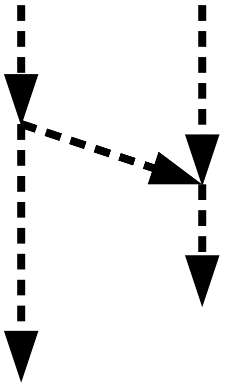
Clocks

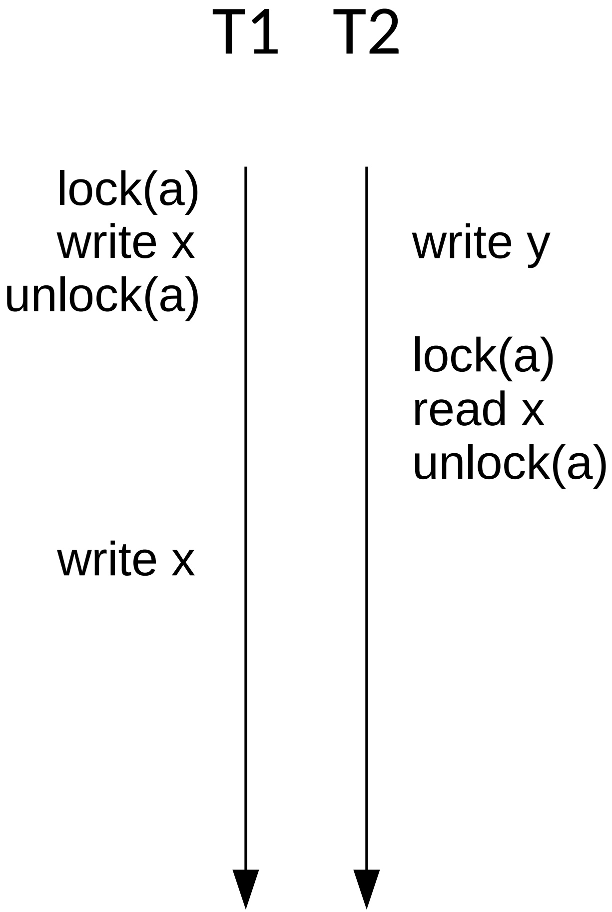
T1↦[0,0]
T2↦[0,0]

Shadow Memory

x↦ R[0,0]
W[0,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks





Clocks

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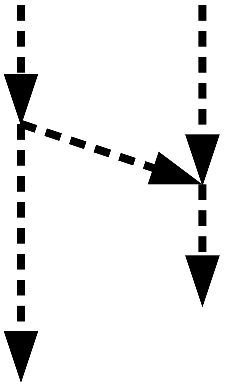
Logical Time & Vector Clocks



	T1	T2
lock(a) write x unlock(a)		
		write y
		lock(a) read x unlock(a)
write x		

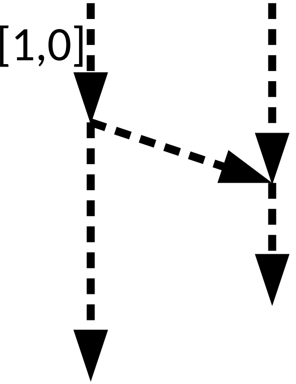
Clocks

```
T1↦[0,0]
T2↦[0,0]
```

Shadow Memory

```
x↦ R[0,0]
   W[0,0]
y↦ R[0,0]
   W[0,0]
```

Logical Time & Vector Clocks



	T1	T2
lock(a)		
write x		write y
unlock(a)		
		lock(a)
		read x
		unlock(a)
write x		

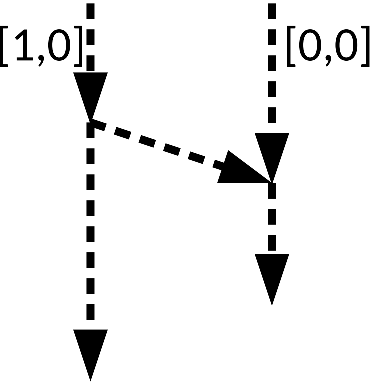
Clocks

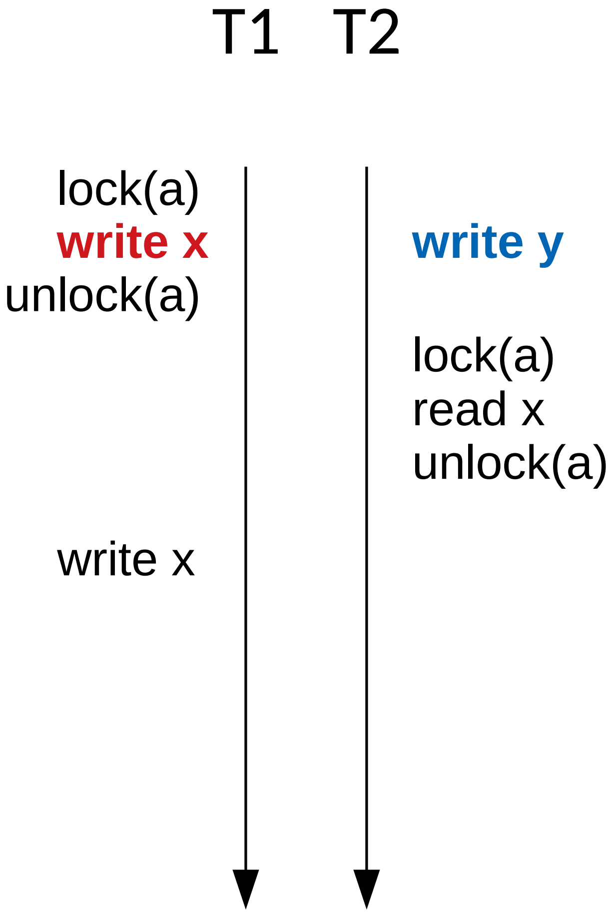
T1↦[**1**,0]
T2↦[0,0]

Shadow Memory

x↦ R[0,0]
 W[0,0]
y↦ R[0,0]
 W[0,0]

Logical Time & Vector Clocks





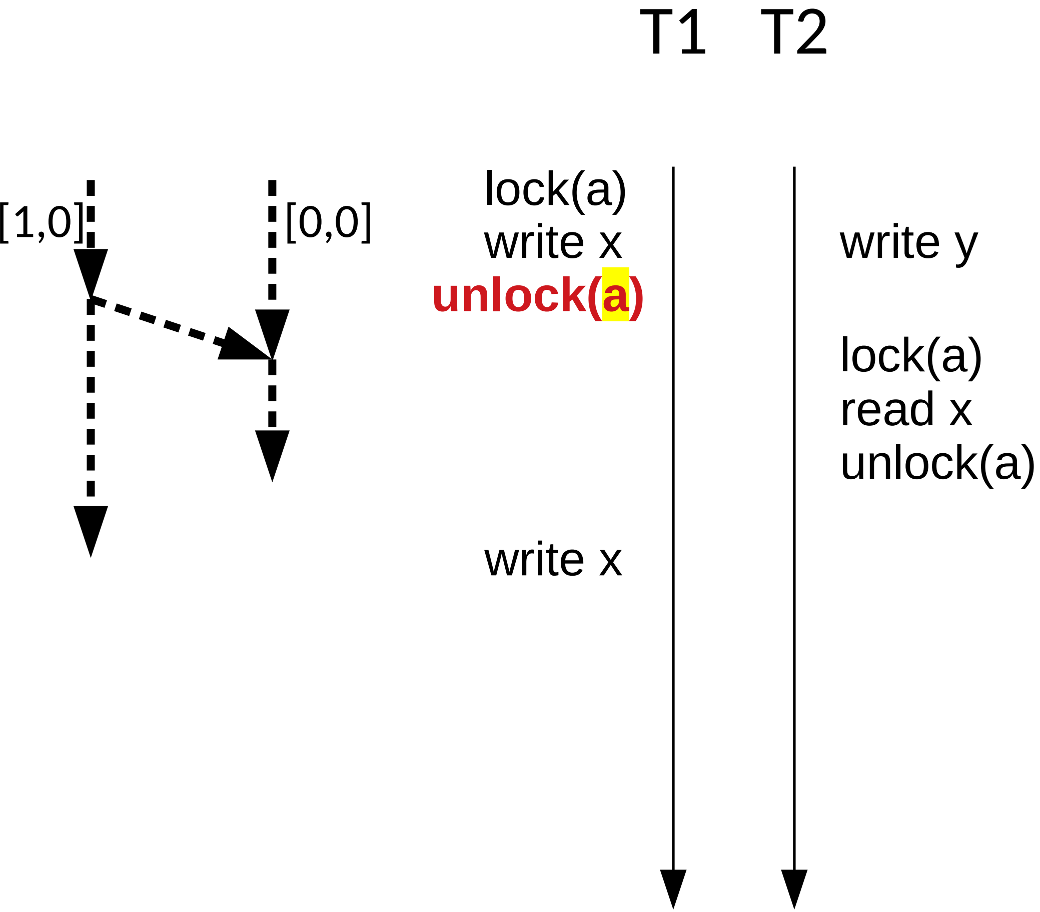
Clocks

T1↦[1,0]
T2↦[0,0]

Shadow Memory

x↦ R[0,0]
W[1,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks



Clocks

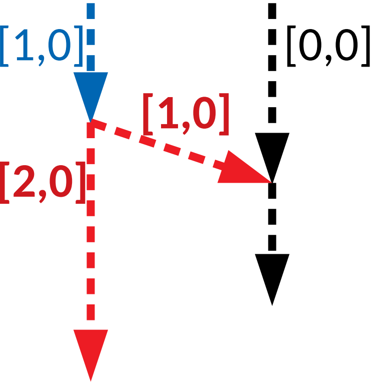
T1↦[2,0]
T2↦[0,0]

a↦[1,0]

Shadow Memory

x↦ R[0,0]
W[1,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks



T1	T2
lock(a)	
write x	write y
unlock(a)	
	lock(a)
	read x
	unlock(a)
write x	

Clocks

```
T1↦[2,0]
T2↦[0,0]
```

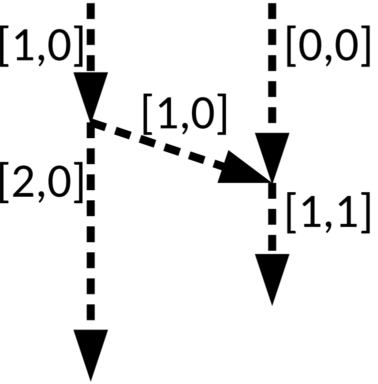
```
a↦[1,0]
```

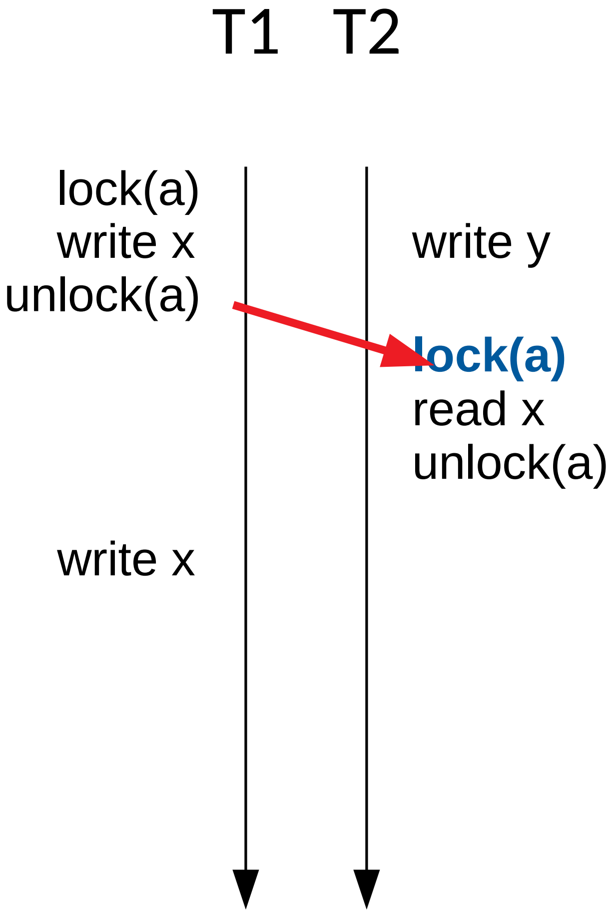
Shadow Memory

```
x↦ R[0,0]
   W[1,0]
y↦ R[0,0]
   W[0,0]
```

```
sendProgress(T1, a)
advanceLocal(T1)
```

Logical Time & Vector Clocks





Clocks

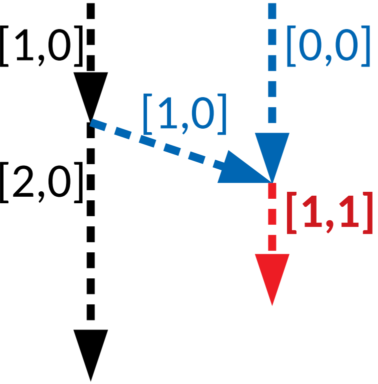
T1↦[2,0]
T2↦[1,1]

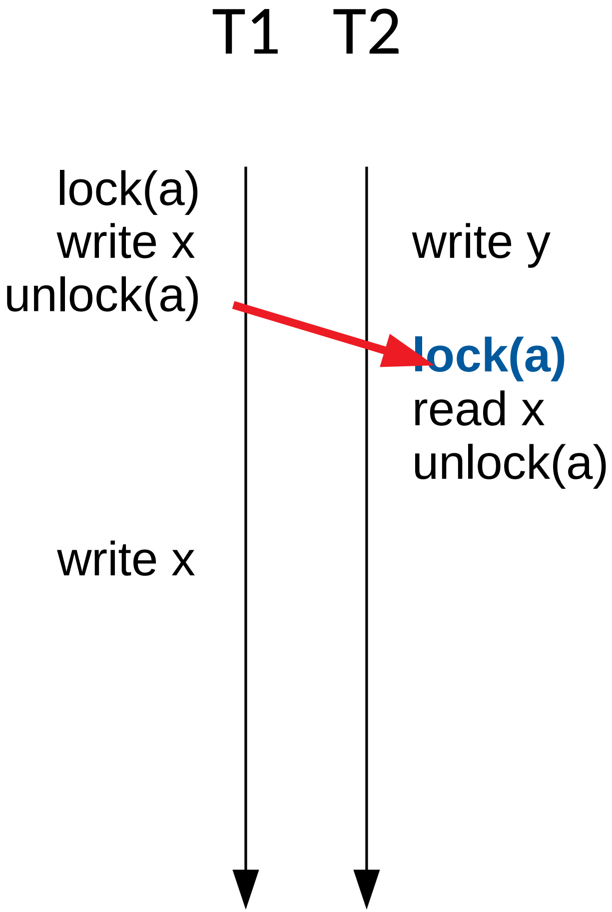
a↦[1,0]

Shadow Memory

x↦ R[0,0]
W[1,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks





Clocks

T1↦[2,0]
T2↦[1,1]

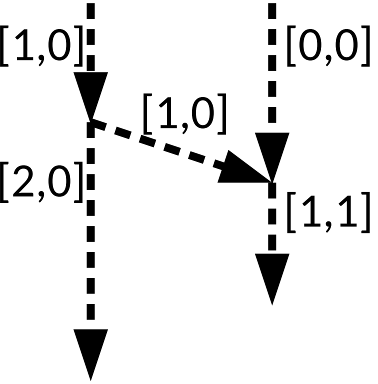
a↦[1,0]

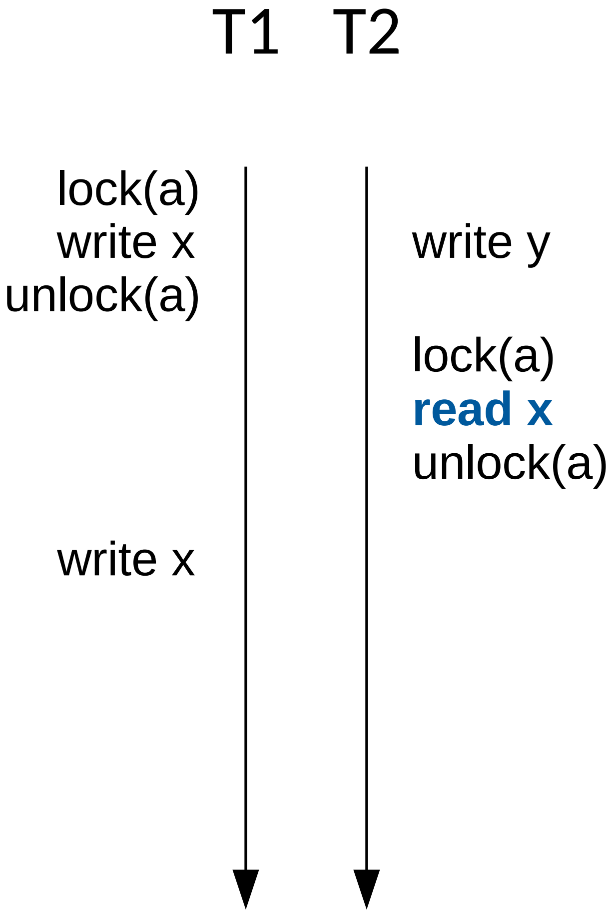
Shadow Memory

x↦ R[0,0]
W[1,0]
y↦ R[0,0]
W[0,0]

```
receiveProgress(T2, a)
advanceLocal(T2)
```

Logical Time & Vector Clocks





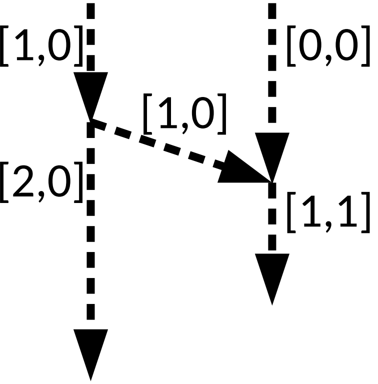
Clocks

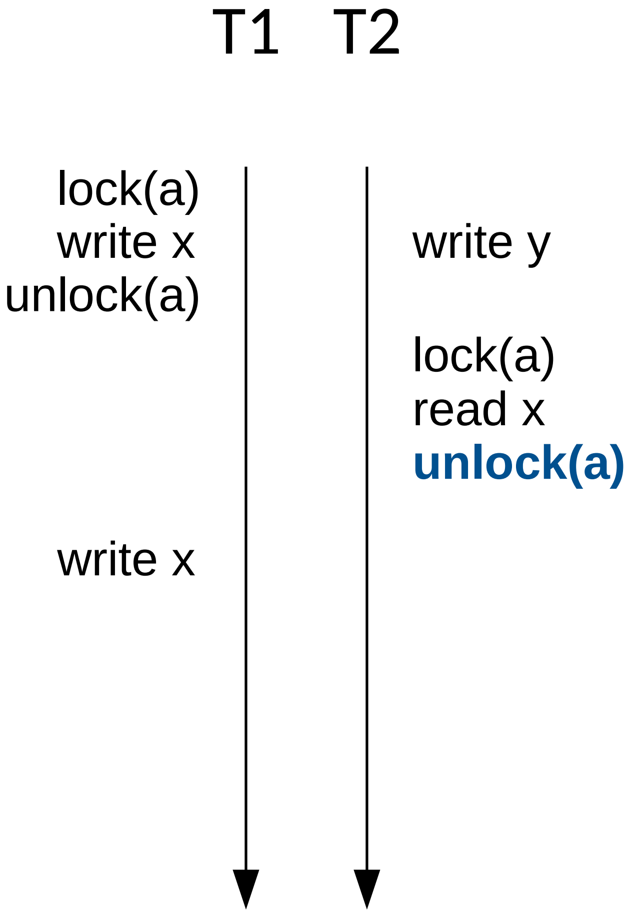
```
T1↦[2,0]
T2↦[1,1]
```

Shadow Memory

```
x↦ R[1,1]
   W[1,0]
y↦ R[0,0]
   W[0,0]
```

Logical Time & Vector Clocks





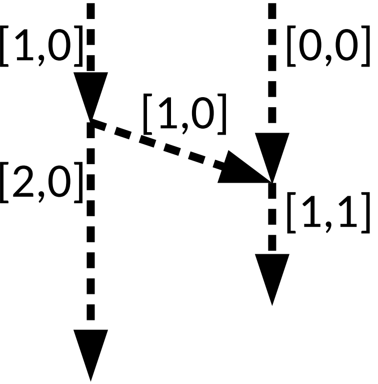
Clocks

T1↦[2,0]
T2↦[1,2]

Shadow Memory

x↦ R[1,1]
W[1,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks



T1	T2
lock(a) write x unlock(a)	
	write y
	lock(a) read x unlock(a)
write x	

Clocks

T1↦[2,0]
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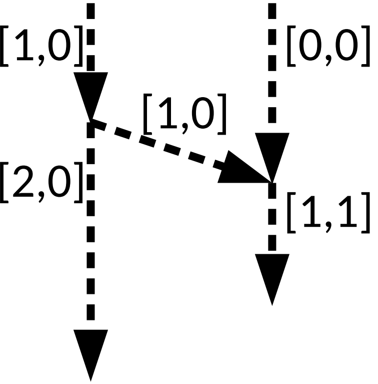
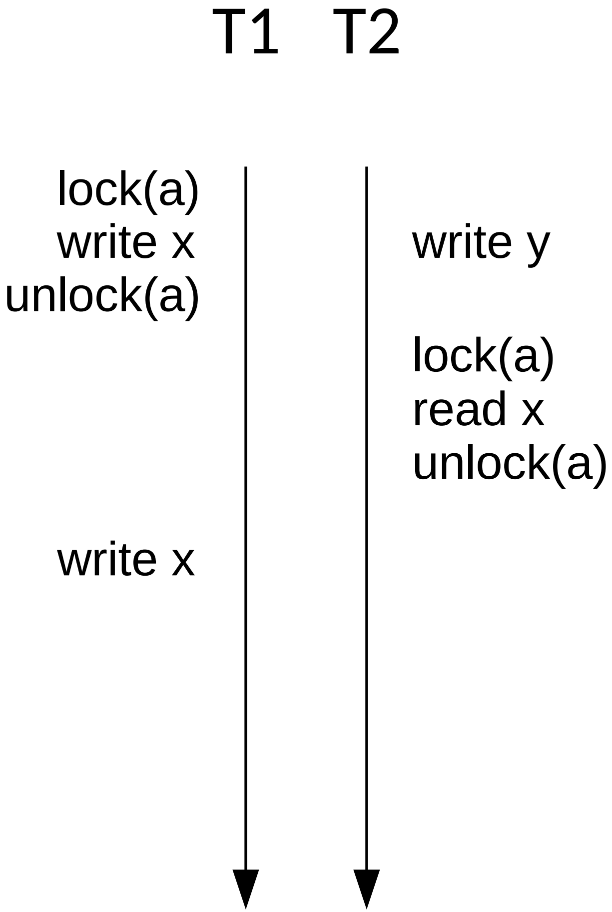
Shadow Memory

x↦ R[1,1]
W[2,0]
y↦ R[0,0]
W[0,0]

Logical Time & Vector Clocks





Clocks

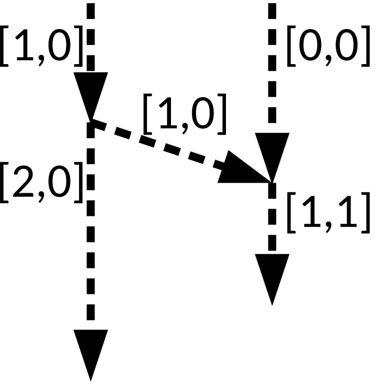
T1↦[2,0]
T2↦[1,2]

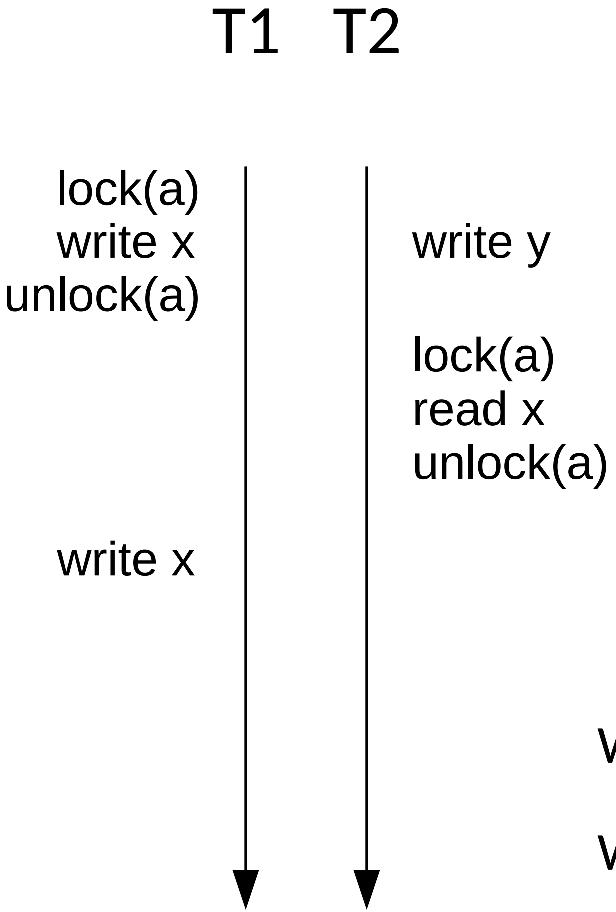
Shadow Memory

x↦ R[1,1]
W[2,0]
y↦ R[0,0]
W[0,0]

C(R,X) ⋢ C(W,X)
& C(W,X) ⋢ C(R,X) → race!

Logical Time & Vector Clocks





Clocks

T1↦[2,0]
T2↦[1,2]

Shadow Memory

x↦ R[1,1]
W[2,0]
y↦ R[0,0]
W[0,0]

$C(R,X) \not\sqsubseteq C(W,X)$
$\& \; C(W,X) \not\sqsubseteq C(R,X) \rightarrow$ race!

When reading:
check against the last write
When writing:
check against the last read and write

Vector Clocks

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- Vector clocks have a long history in reasoning about distributed systems and concurrency
- With many threads/parallel tasks, clock overheads increase
  - With effort, newer approaches optimize and replace vector clocks [Mathur 2021]

Data Race Detection - Locksets

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- We can dynamically track the locks guarding an address!

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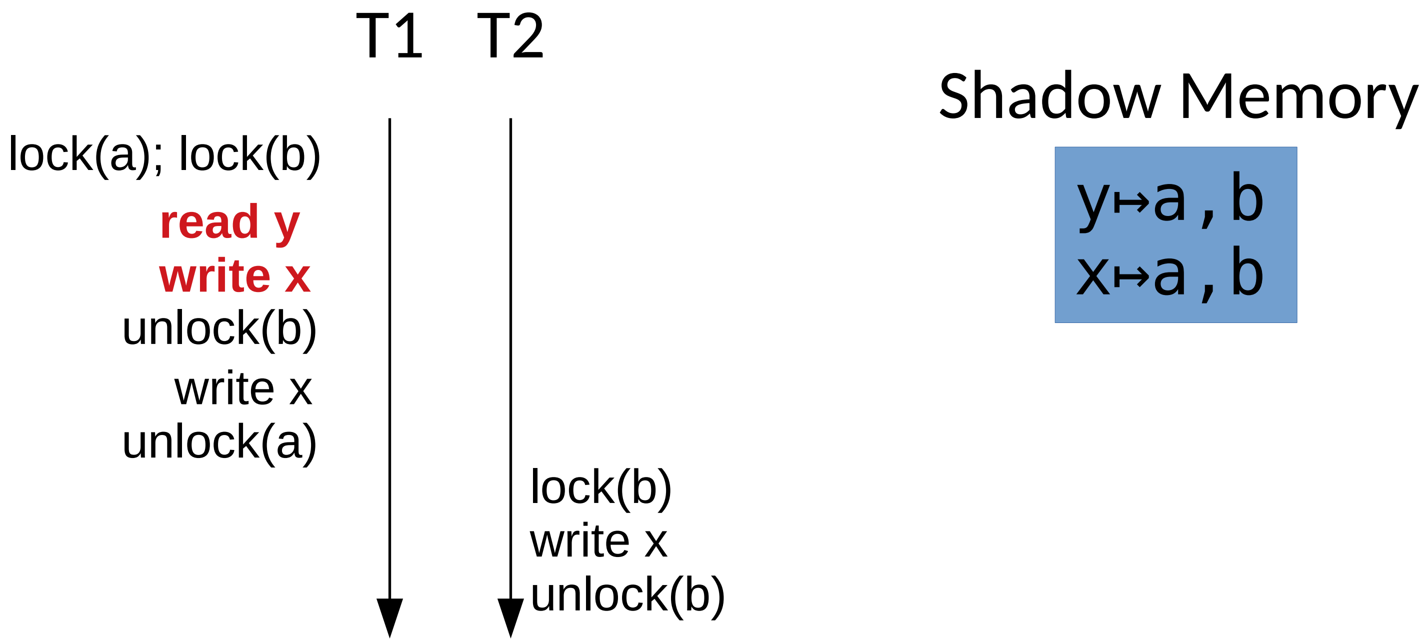

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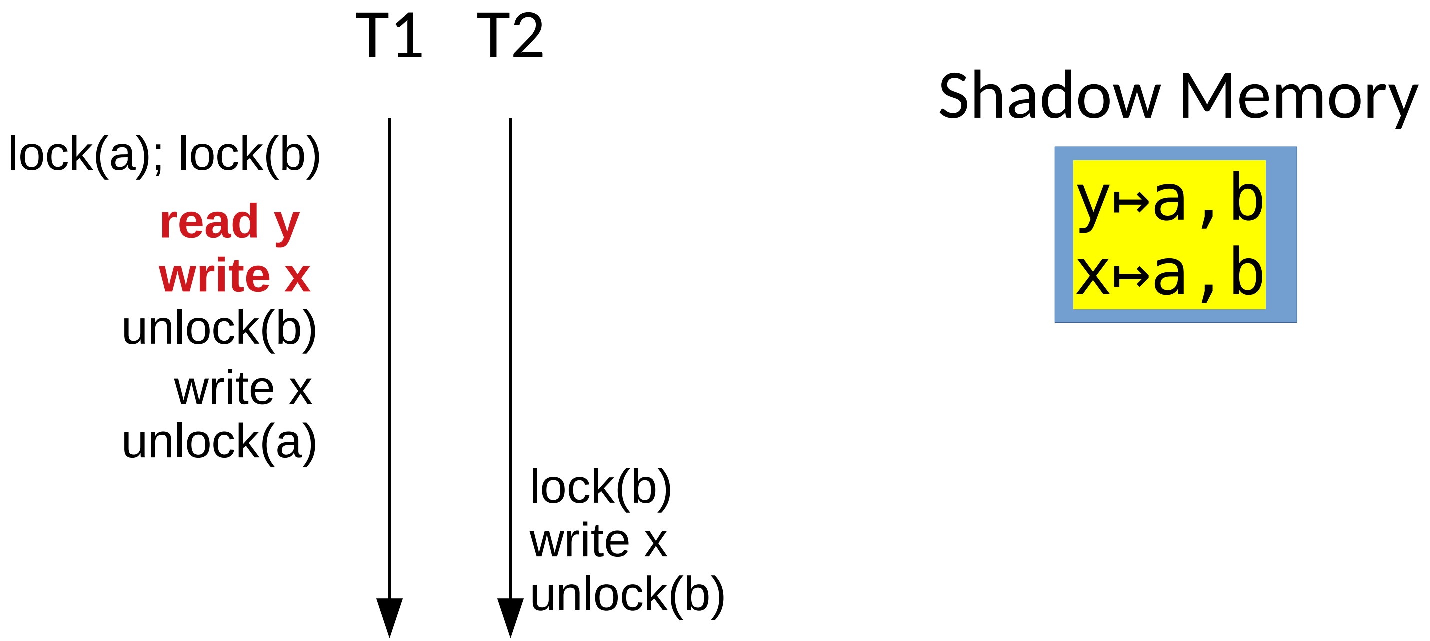

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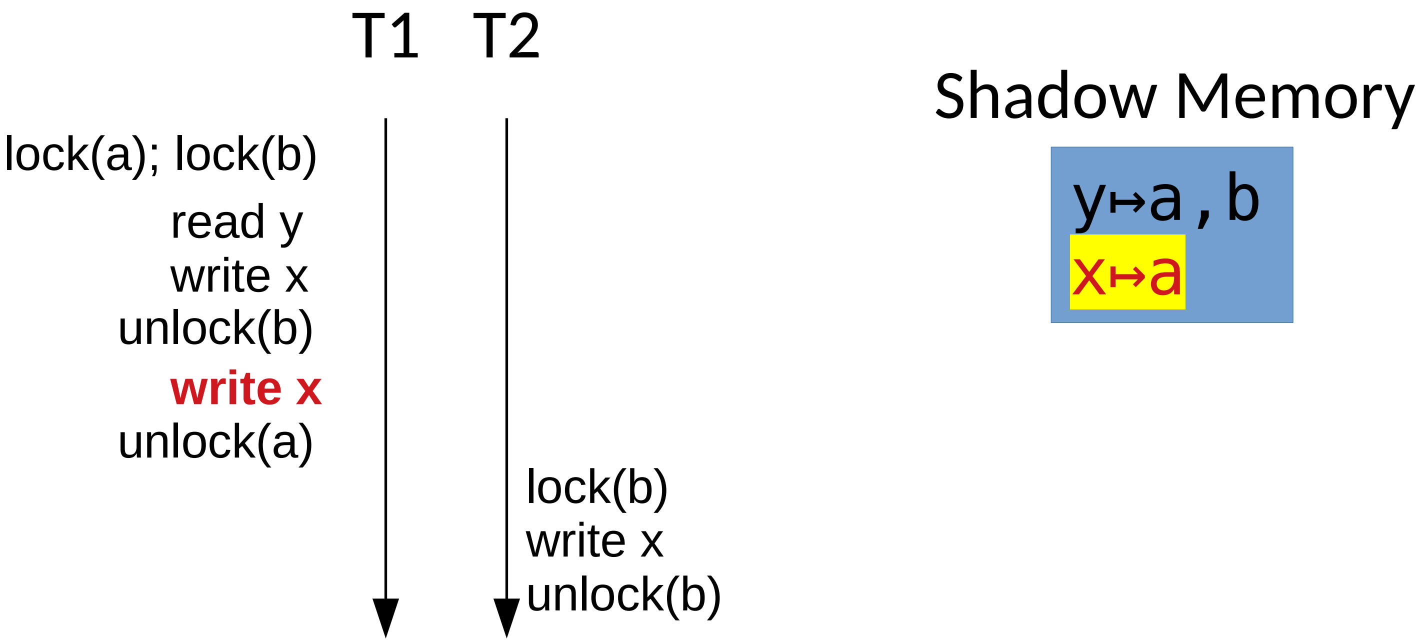

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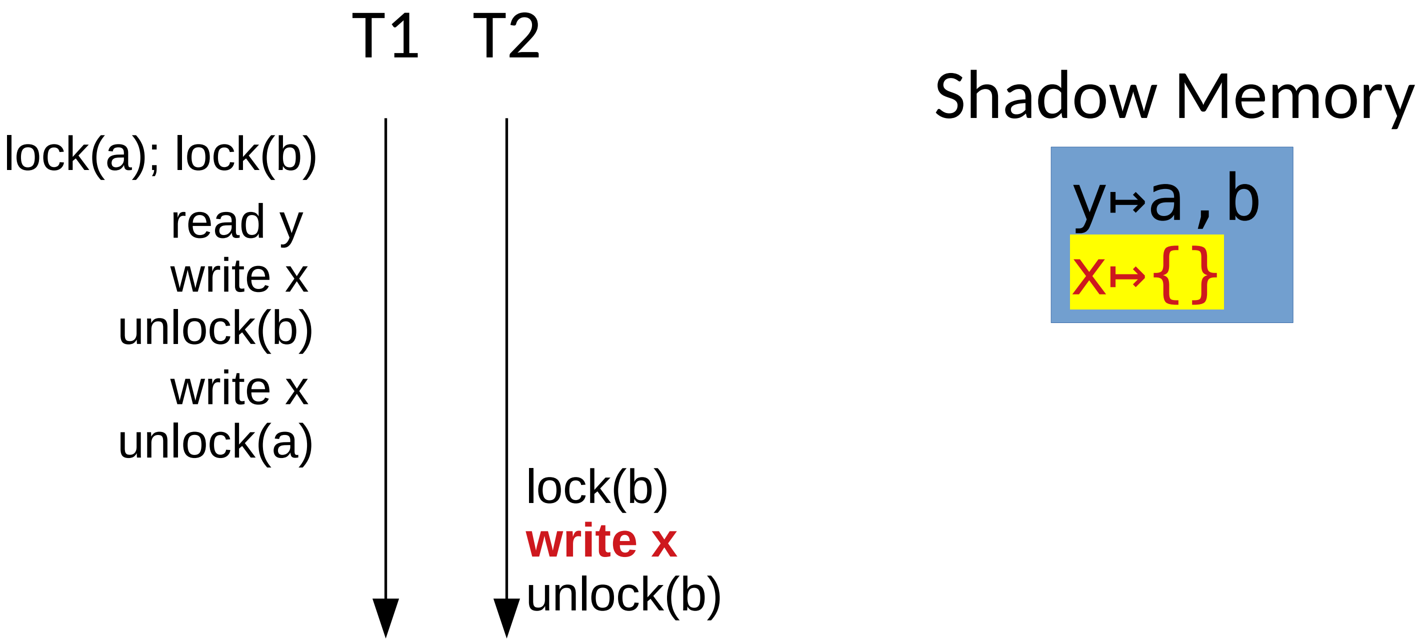

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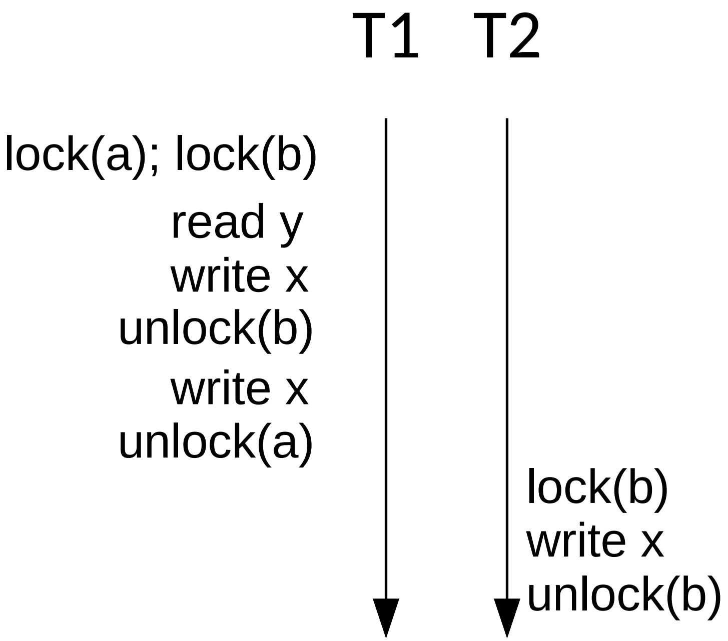

Shadow Memory

y↦a,b
x↦{}

Note: Both x and y are always protected by locks. x *still* races.

Data Race Detection - Locksets

- Lockset based data race detection has many issues
  - Synchronization may be fork/join, wait/notify based
  - Initialization --> Process in Parallel --> Combine
  - Richer parallel designs

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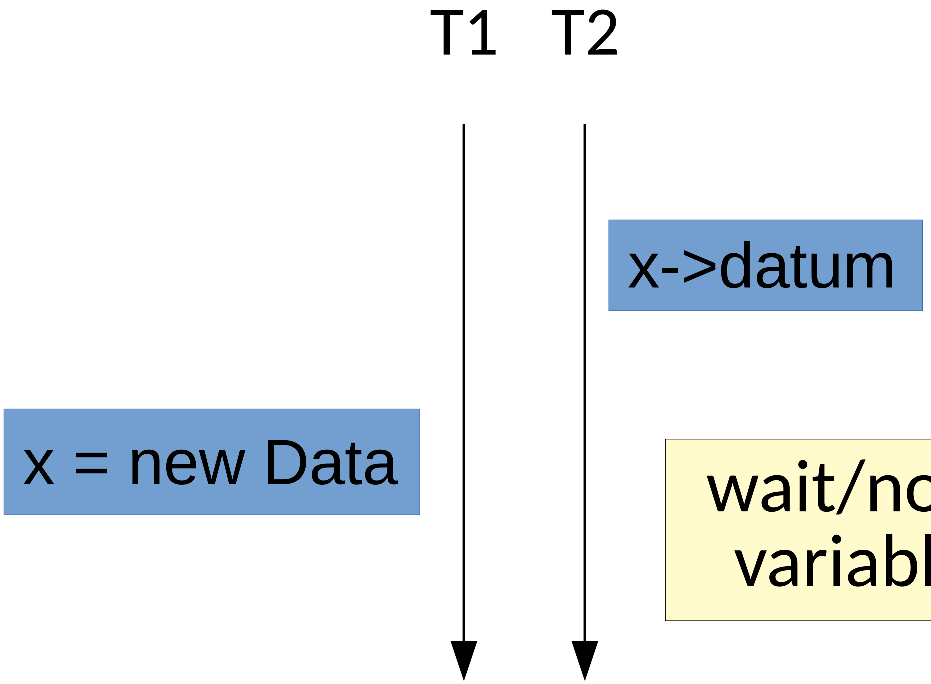
Can you think of concurrency bugs it will miss, too?

Order Violations

- Some accesses are wrongly assumed to occur before others



wait/notify or condition variables can fix these

Atomicity Violations

- Data races are a matter of perspective
  - Fine grained locking doesn't solve much.

```
tmp = x
tmp = tmp+1
x = tmp
```

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```

vs

```
lock()
tmp = x
unlock()

tmp = tmp+1

lock()
x = tmp
unlock()
```

No race,
similar effect!

Atomicity Violations

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  - Fine grained locking doesn't solve much.

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tmp = x
tmp = tmp+1
x = tmp
```

vs

```
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tmp = x
unlock()

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x = tmp
unlock()
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What do we really want?

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- An execution (or fragment thereof) is ***atomic*** if it is equivalent to a sequentially executed one.

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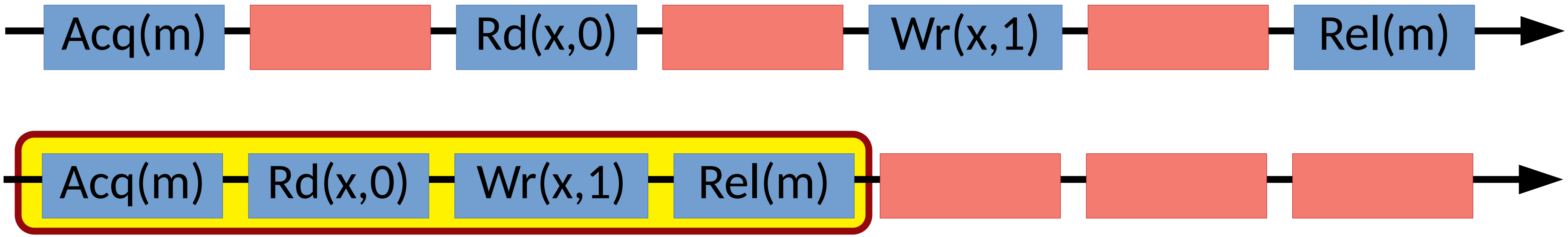

Atomicity Violations

- Data races are a matter of perspective
  - Fine grained locking doesn't solve much.
- An execution (or fragment thereof) is ***atomic*** if it is equivalent to a sequentially executed one.
  - This also takes care of data races
  - Similar to notions from databases (serializability & linearizability)

Atomicity Violations

- How can we find atomicity violations (or correctness)?

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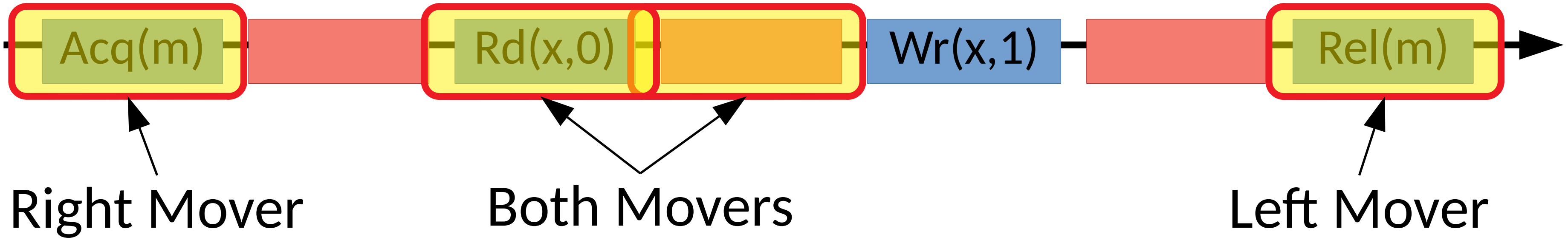

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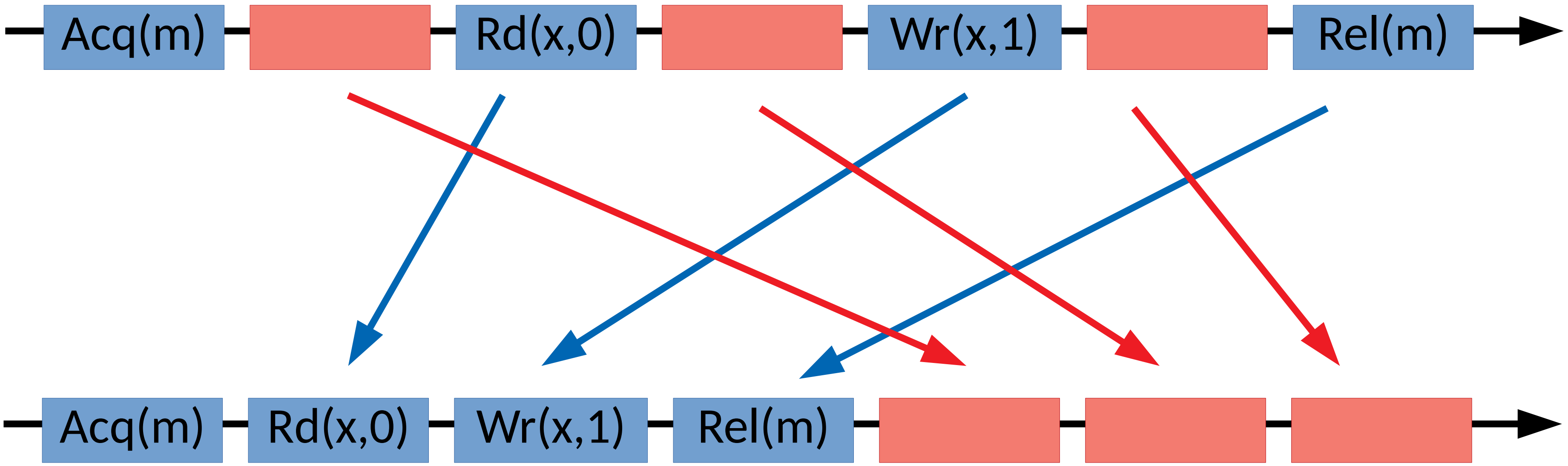

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Time →

T1	T2	T1
R	R	R
W	R	R
R	W	R
W	W	R
R	R	W
W	R	W
R	W	W
W	W	W

Only some patterns are unserializable.
Detect unlikely issues via training.

Atomicity Violations

- How can we find atomicity violations (or correctness)?
  - Lipton’s Theory of Reduction **[CACM ‘75, POPL ‘04]**
  - 2 thread atomicity patterns **[Lu ASPLOS ‘06]**
  - Conflict graphs **[PLDI ‘08, RV ‘11]**

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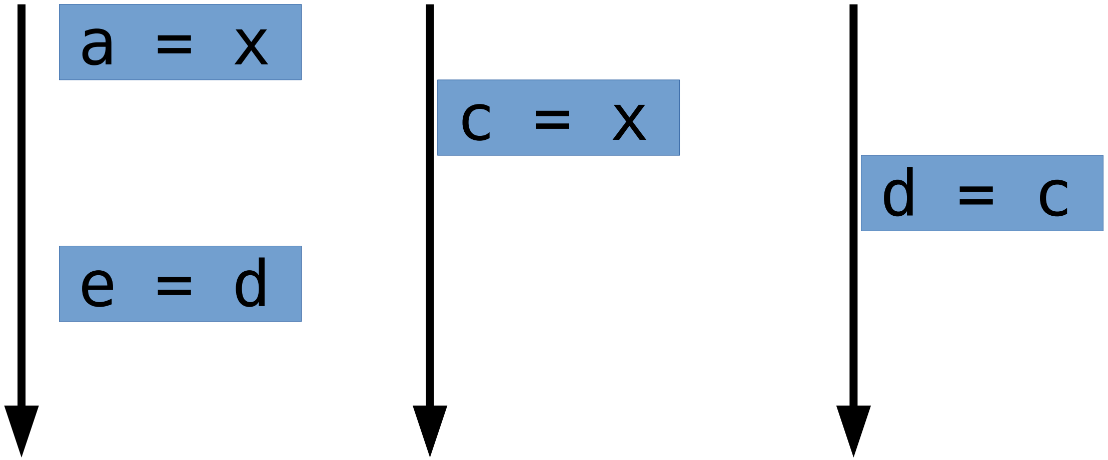

Atomicity Violations

- How can we find atomicity violations (or correctness)?
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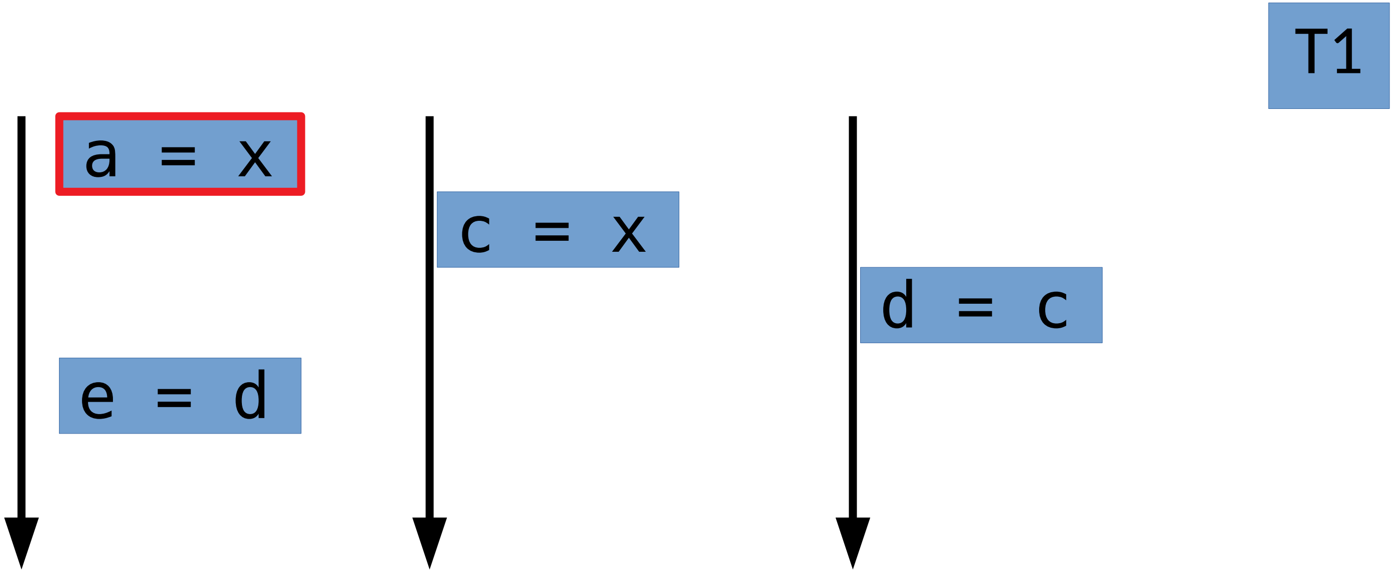

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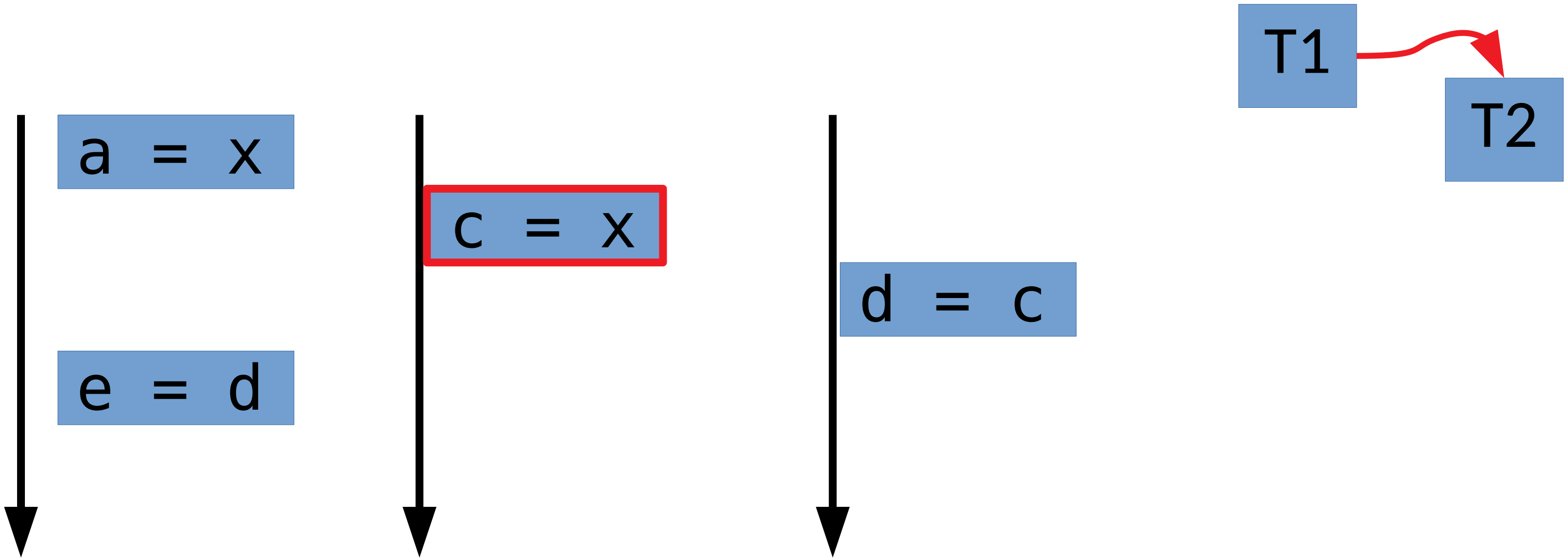

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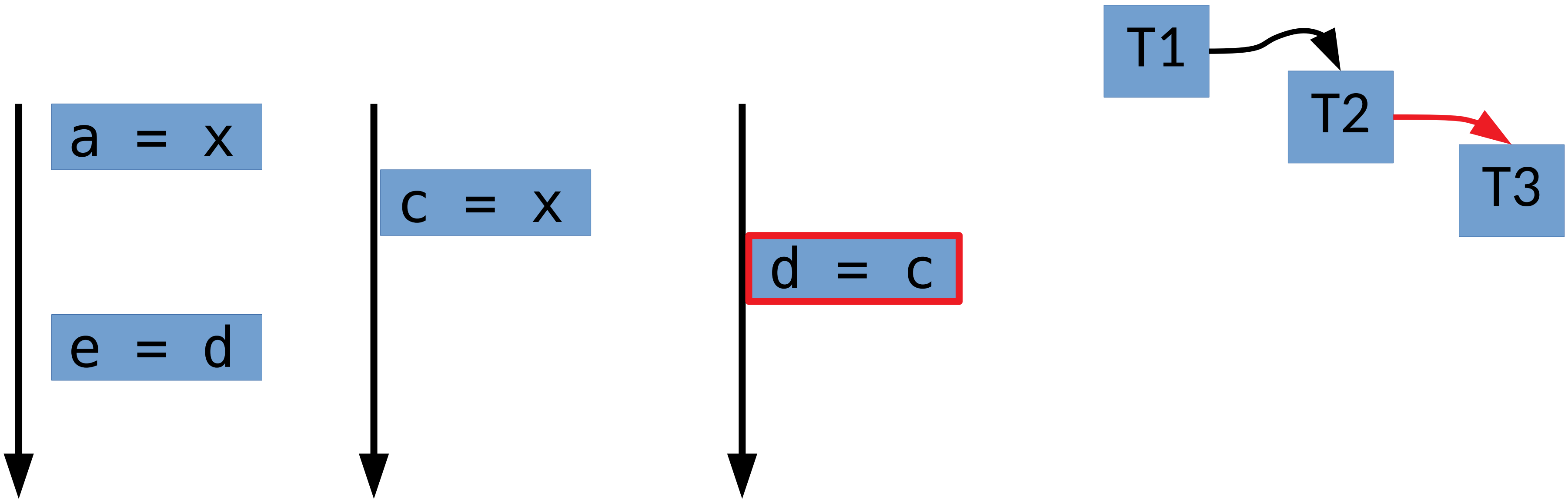

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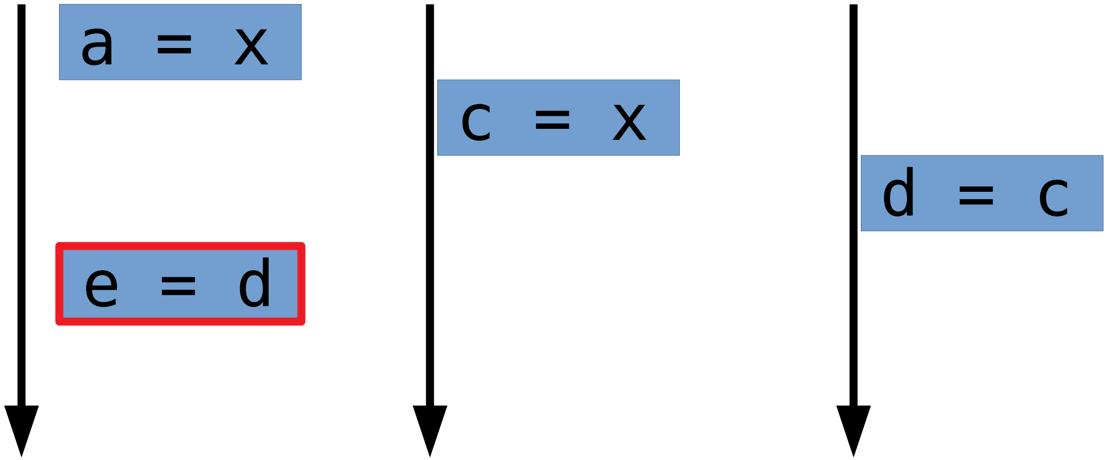

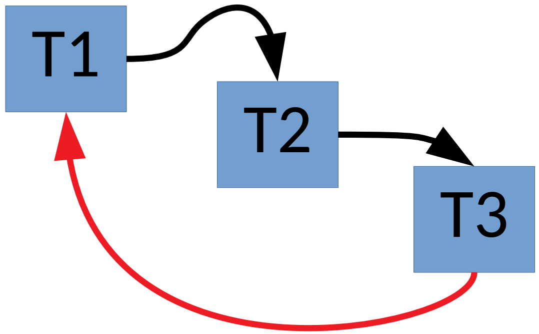

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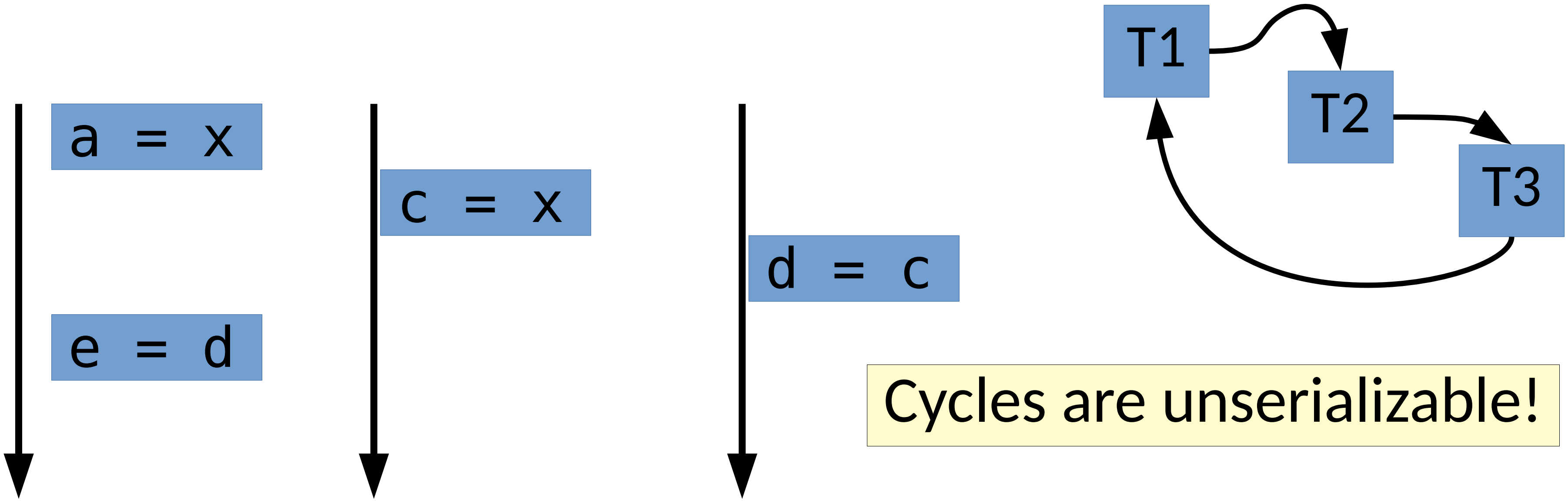

Cycles are unserializable!

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- How do we know what regions should be atomic?

Concurrency in the land of Single Threads

- Even programs without threads face concurrency bugs
  - Does your program have events?
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[Hong 2014]

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<html><body>
  <button id="b1"onclick="fn()">b1</button>
  <script>
    function fn(){
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  </script>

  <script src="lib.js"></script>
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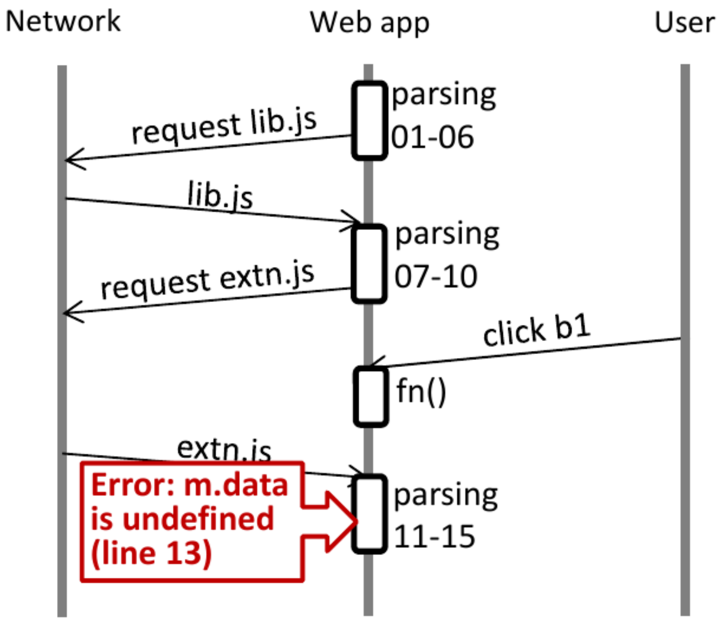


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A user can click “here”

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  - Both in client side & server side [Raychev 2013, Hong 2014, Endo 2020]

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var doneTasks = 0;
var entries = 0;

function processFile(filePath) {
  entries++;
  fs.lstat(filePath, function stat(err, stats) {
    if (err) {
      entries--;
      return;
    }
    useStatData(stats);
    fs.readFile(filePath, function read(err, data) {
      performTask(data);
      doneTasks++;
      if (doneTasks === entries)
        finalize();
    });
  });
}
```

[Endo 2020]

it can be unexpected & confusing.

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When the missing file stats last,
finalize is not called,
and Node hangs.

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- In practice, semantic concurrency bugs exist in Javascript!
  - Both in client side & server side [Raychev 2013, Hong 2014, Endo 2020]
  - In fact, locks are simulated to control interleavings
- Careful (1) monitoring, (2) happens-before analysis, & (3) test generation can automatically find these issues

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- Careful schedule generation & selection
- Generate API unit tests targeting concurrency
  - Small enough for exhaustive schedule exploration

Other Directions

- Shepherding toward good behaviors
- Tolerating & avoiding on the fly
- Static analysis

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- Parallelism is important for modern performance
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And the hard problems
are interesting to study.