A Review/Tour of Concurrency & Parallelism

CMPT 886
Automated Software Analysis & Security
Nick Sumner

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

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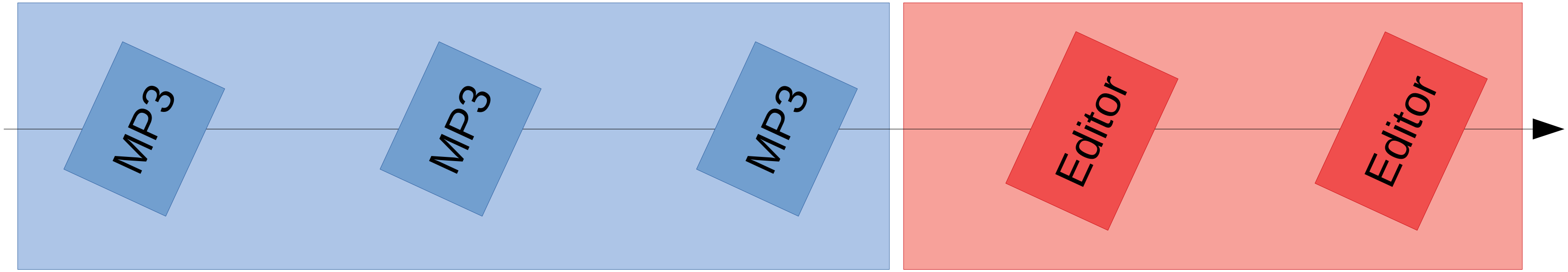

Sequential

Concurrency & Parallelism

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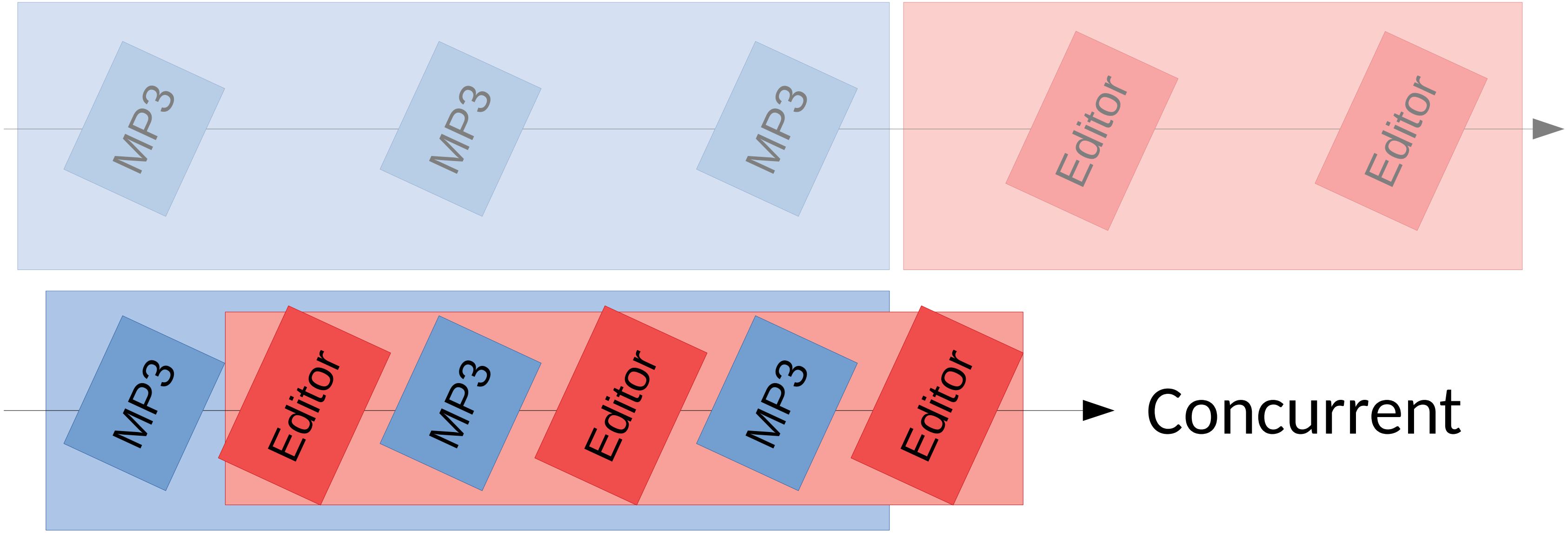

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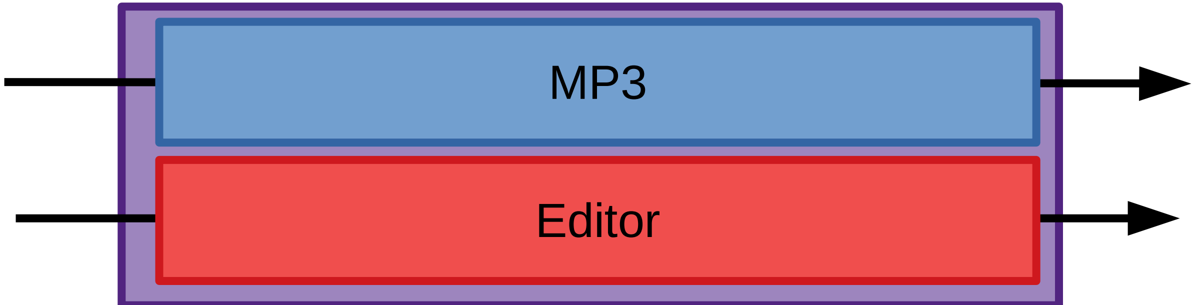
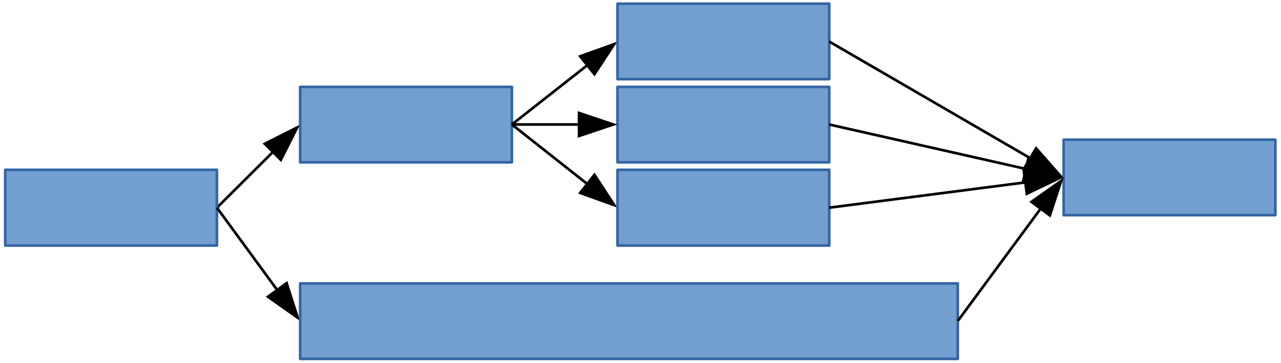


Using Parallelism

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



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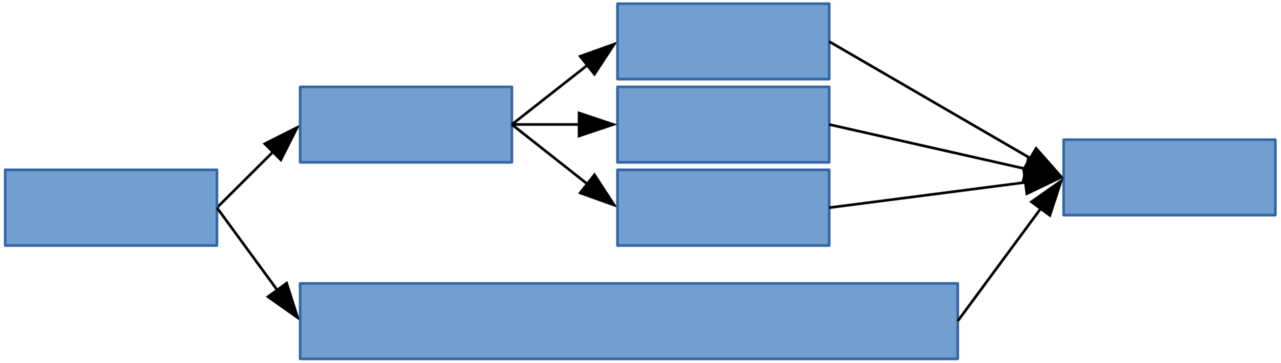

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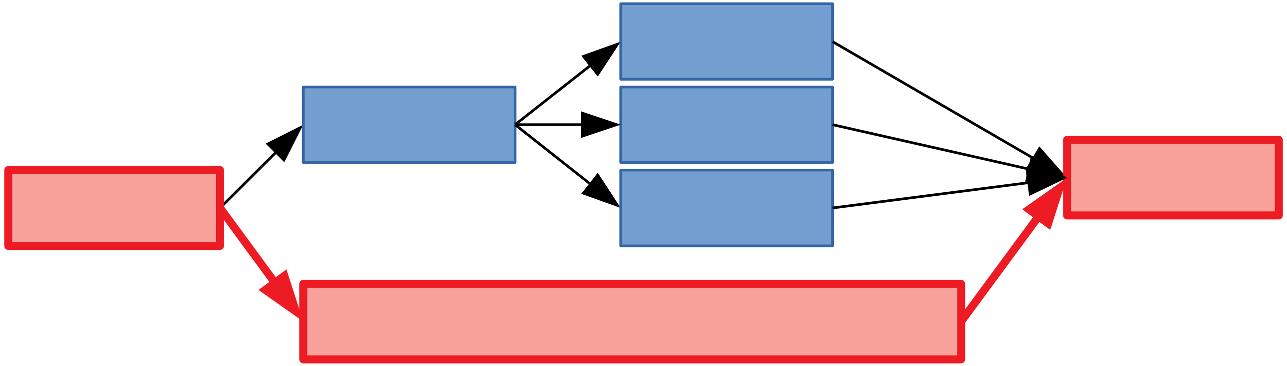

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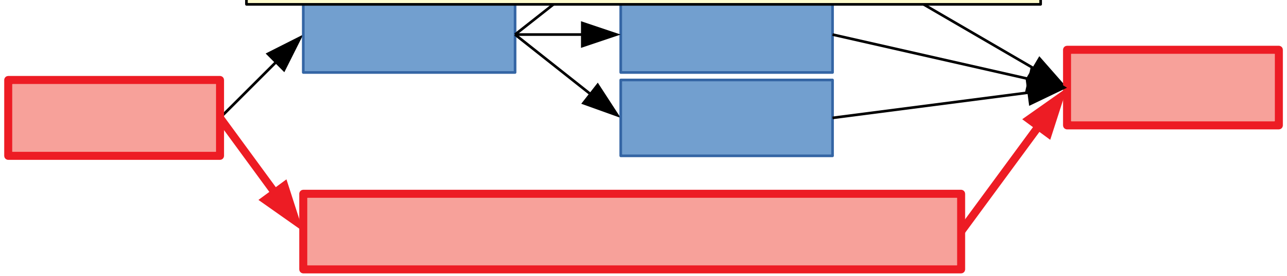
This is too optimistic!
Why?



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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

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  - Deadlock / Livelock
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  - Atomicity violations
  - Order violations
  - …

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} 97% of real world concurrency bugs

[Lu, ASPLOS 2008]

Data Races

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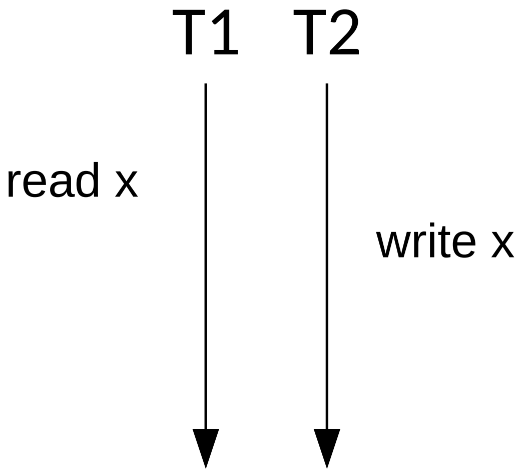

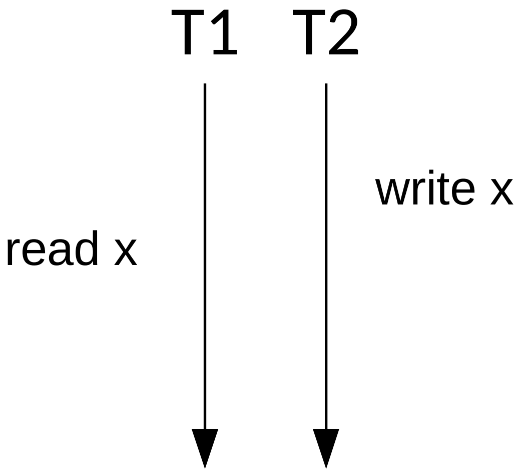

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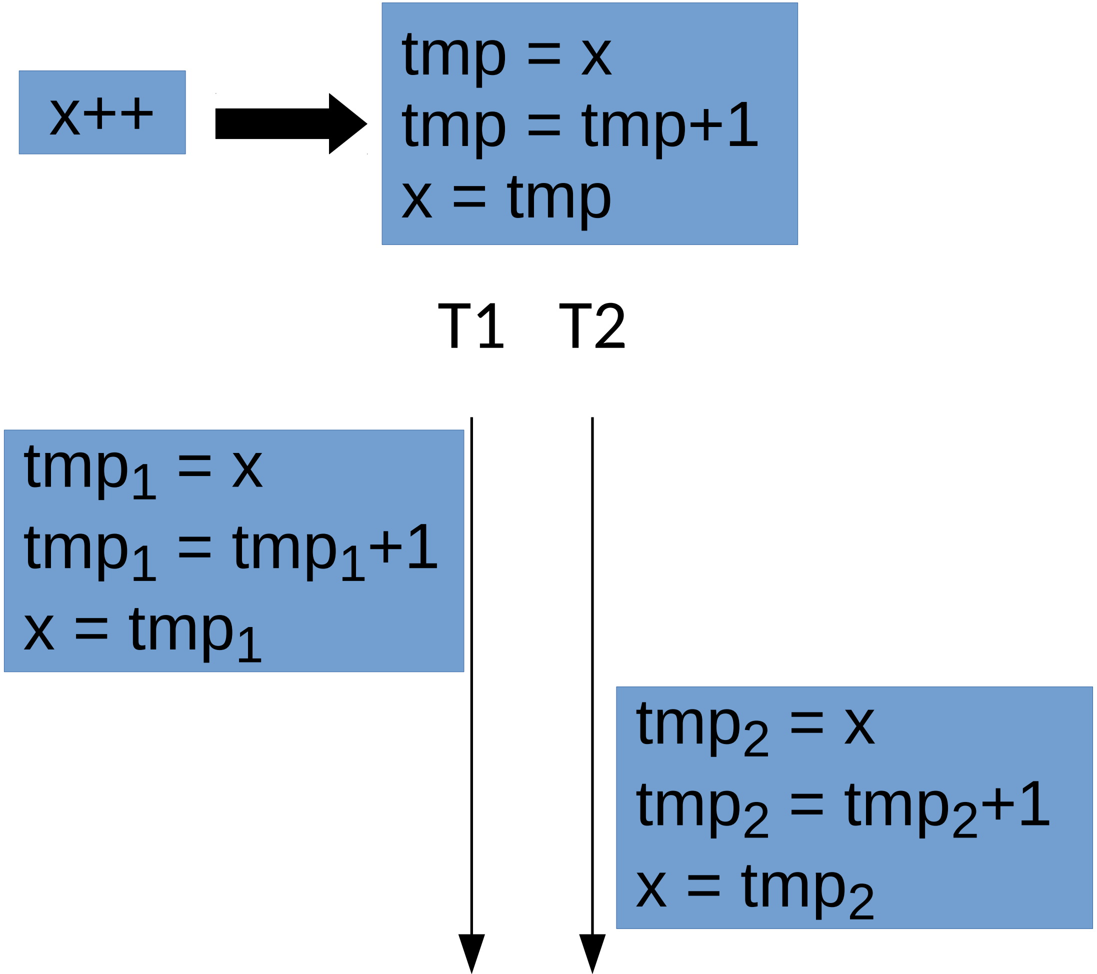

x++

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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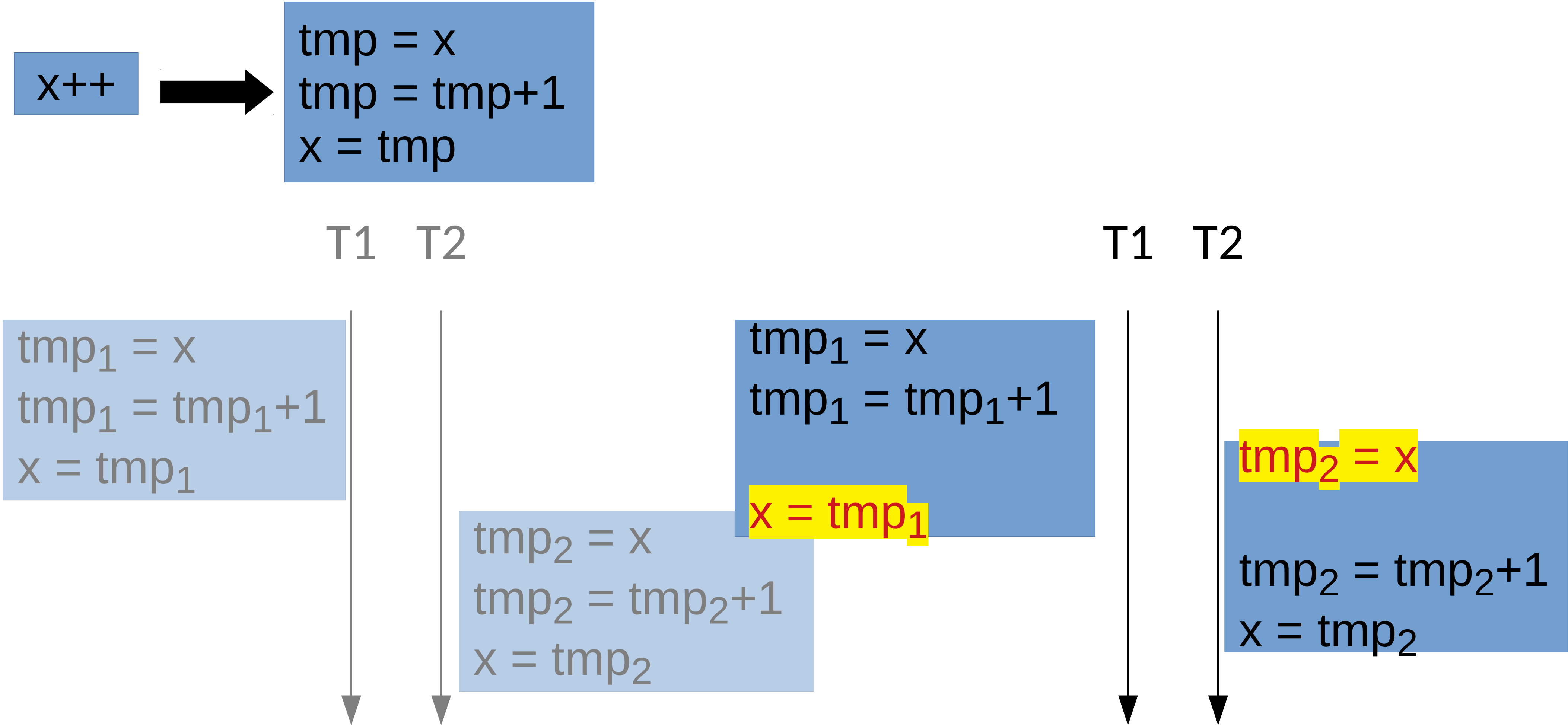

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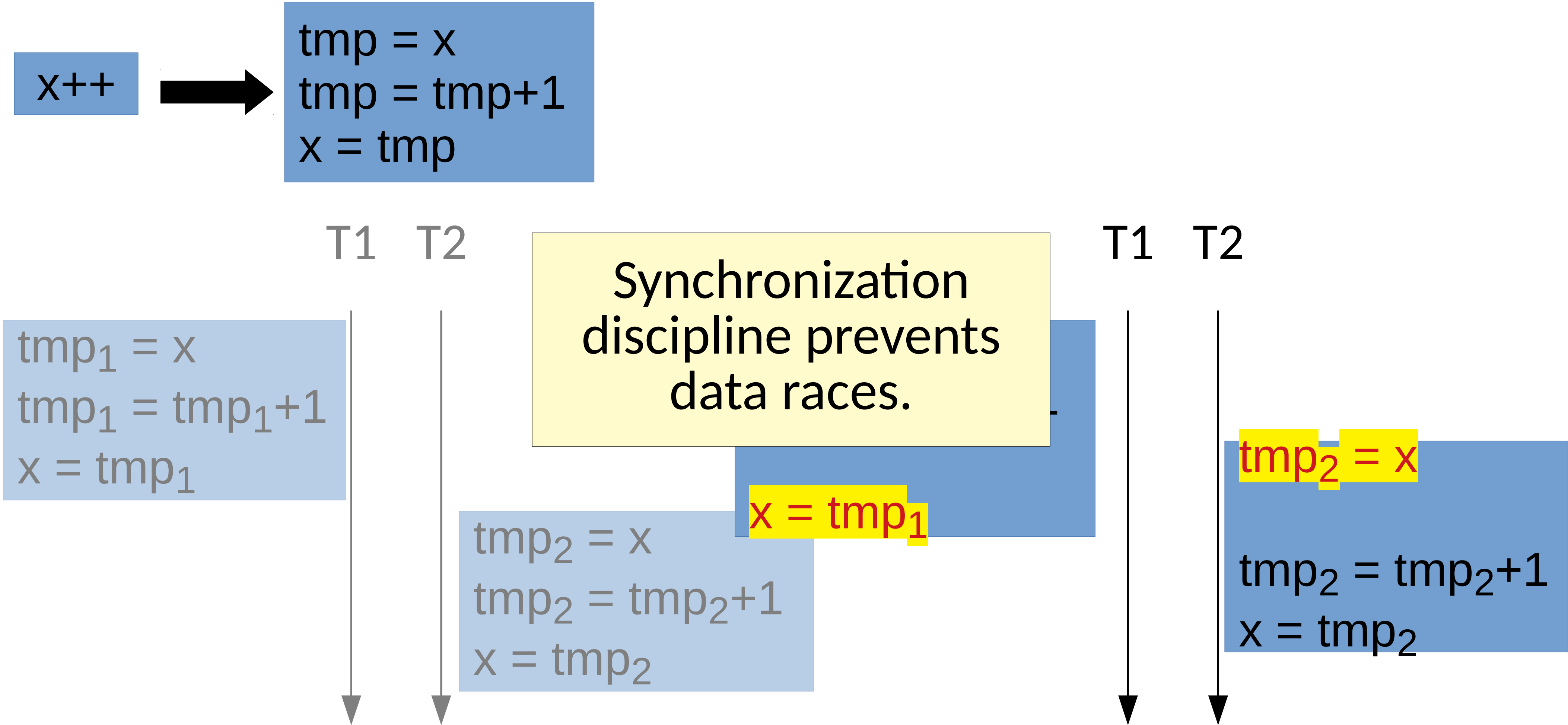

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Synchronization discipline prevents data races.

x = tmp_1

T1 T2

tmp_2 = x

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x = tmp_2

“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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- 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]

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- Threads race on `init`
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“Benign” Data Races

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

[Boehm, Hotpar 2011]

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- Data race freedom allows extra reads.

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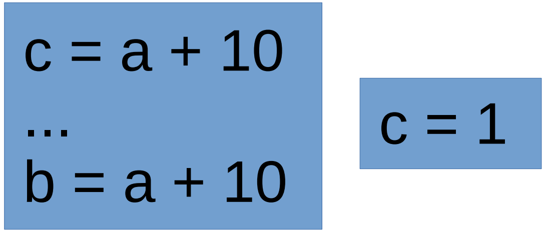

False

True

“Benign” Data Races



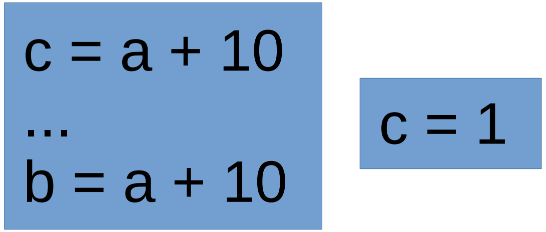
```
c = a + 10
...
b = a + 10
```

```
c = 1
```

[Dolan, PLDI 2018]

- Races can introduce bugs on non-racy variables

“Benign” Data Races



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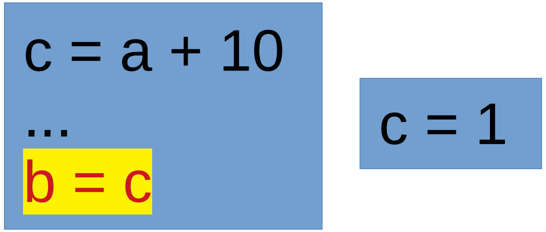

```
c = a + 10
...
b = c
```

```
c = 1
```

“Benign” Data Races

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

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

[Dolan, PLDI 2018]

- Races can jump forward and backward in time

“Benign” Data Races

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a = 1          a = 2
flag = true    f = flag
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- Races can jump forward and backward in time

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

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

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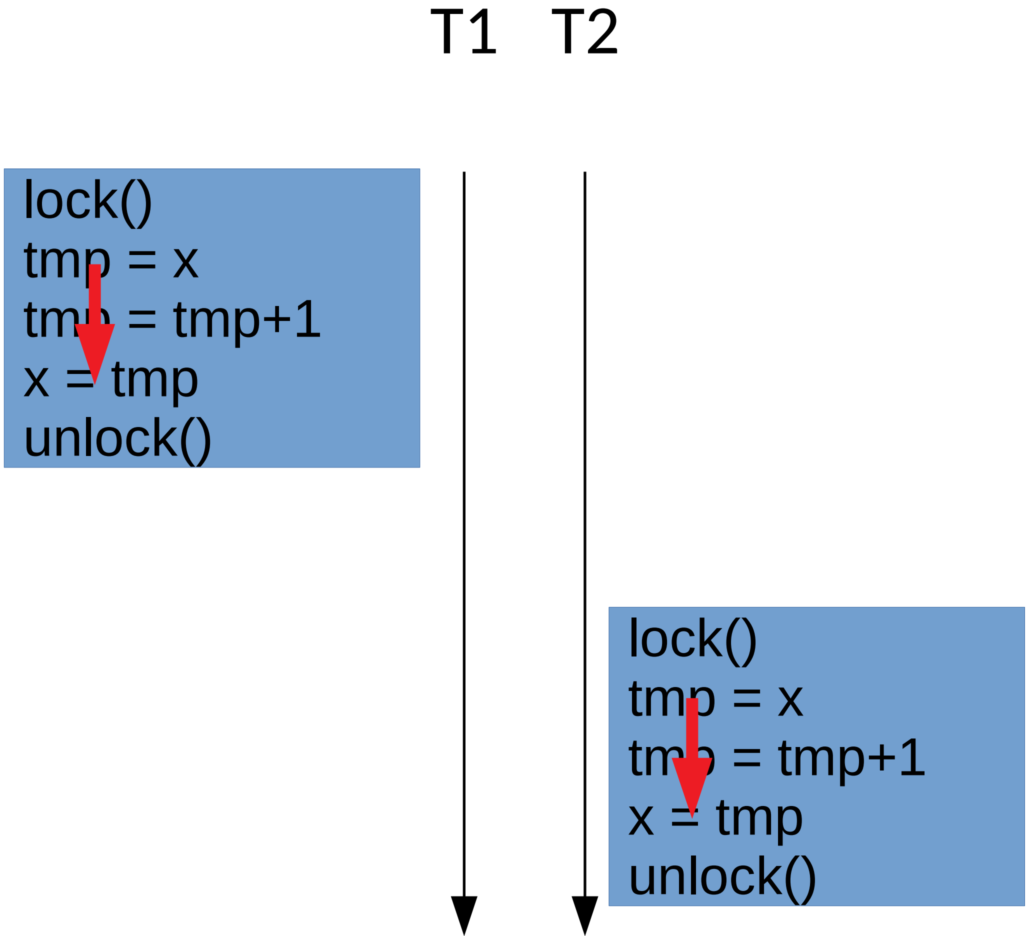
- Happens-Before ordering of a specific execution can be tracked to identify bugs

Happens-Before Ordering



T1 T2

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lock()
tmp = x
tmp = tmp+1
x = tmp
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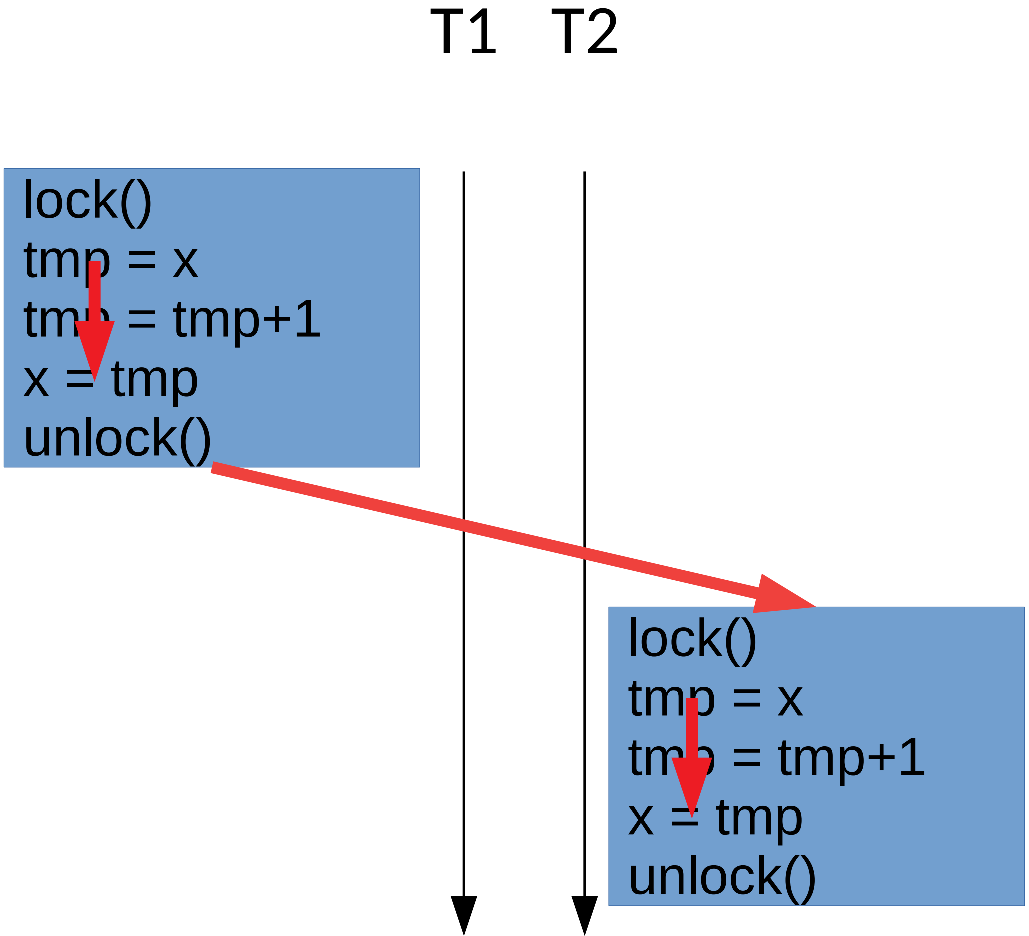

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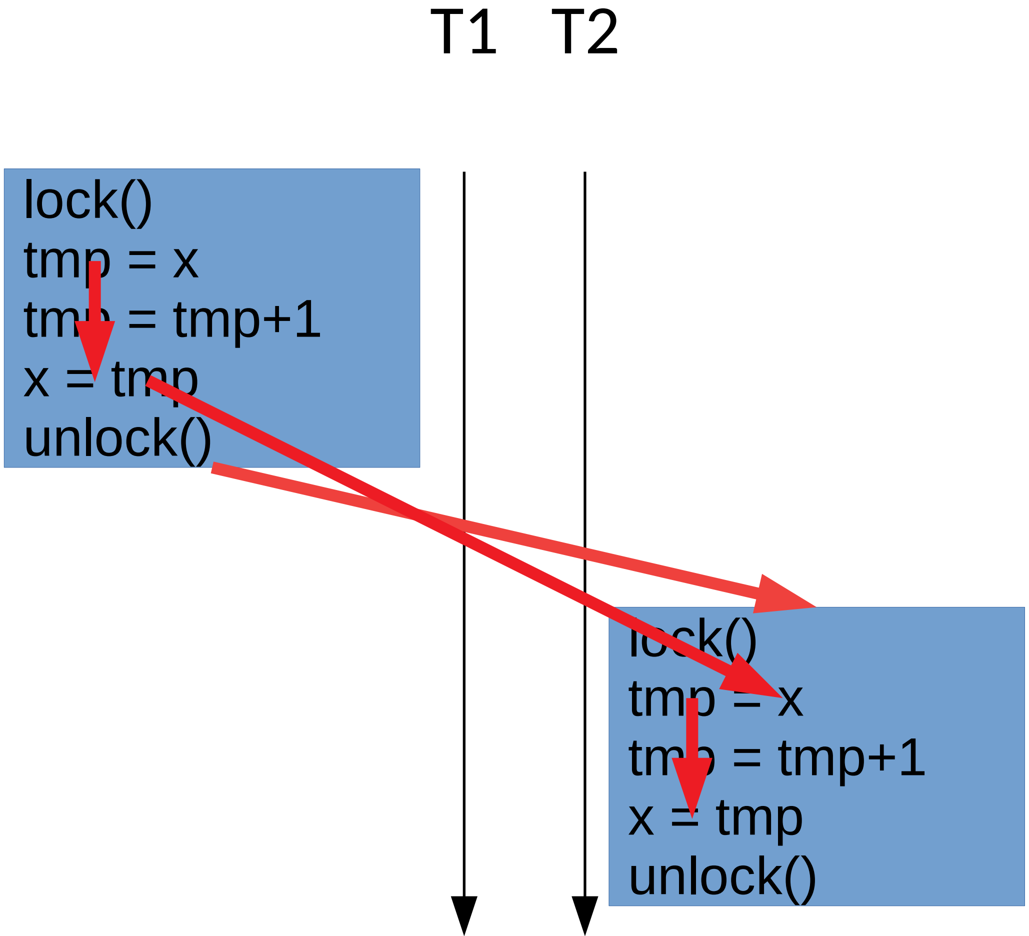

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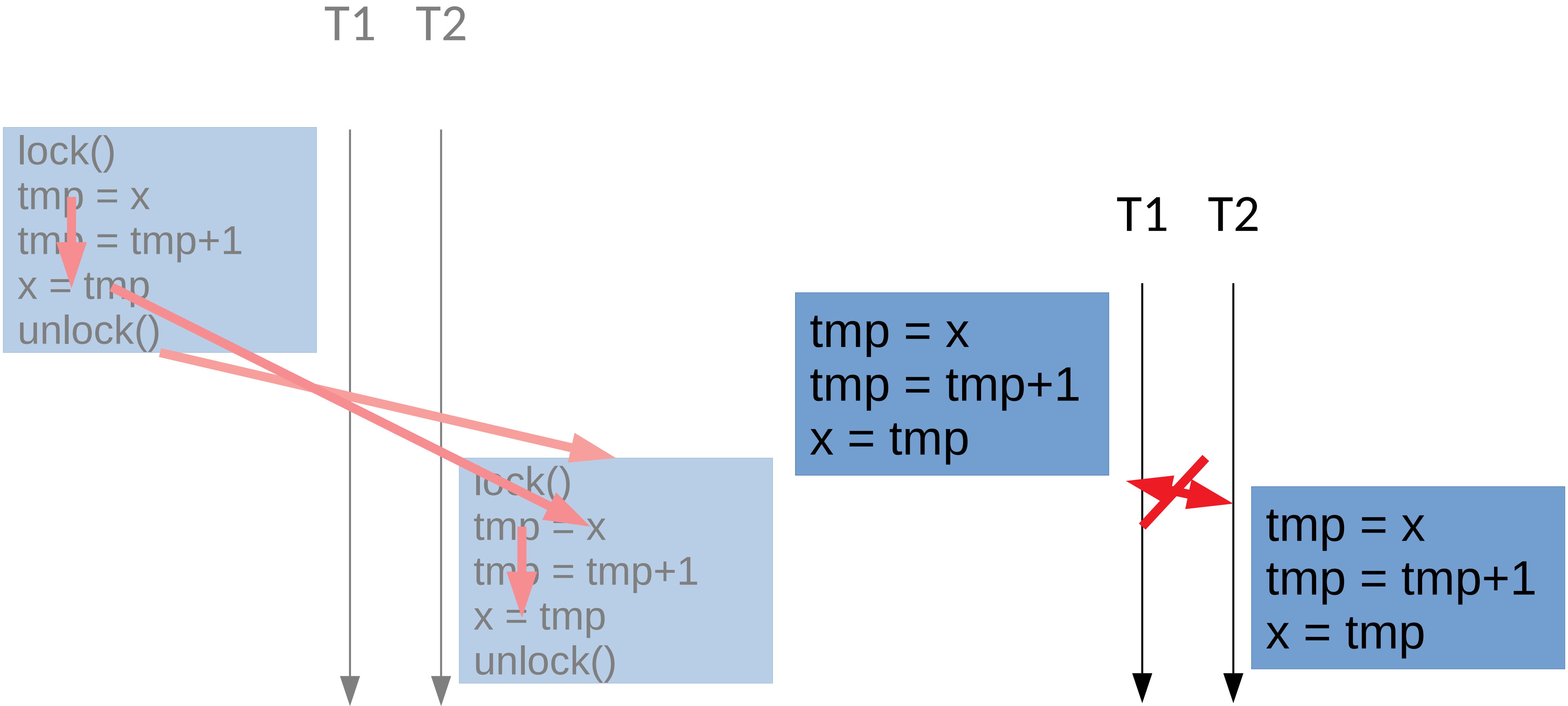

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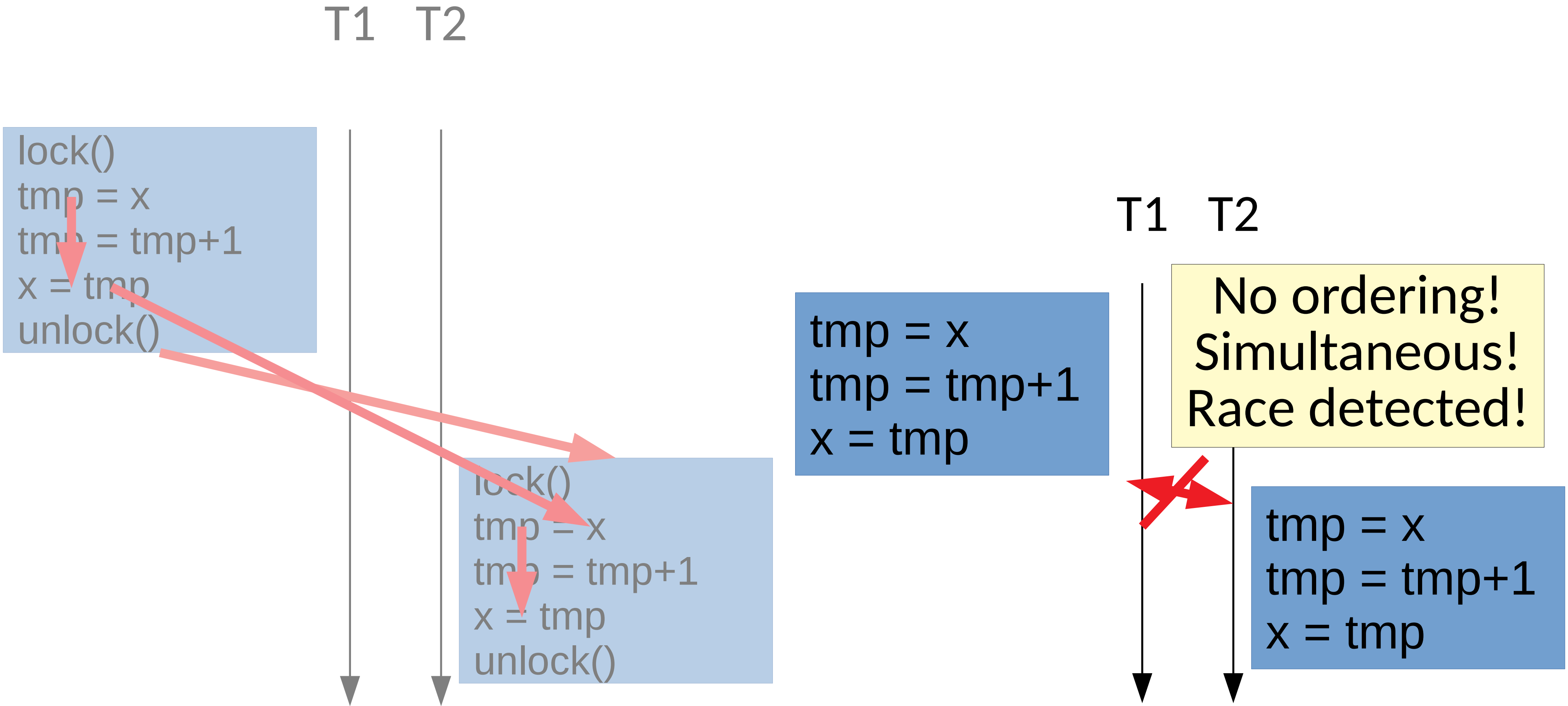

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T1 T2

```
tmp = x
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```

No ordering!
Simultaneous!
Race detected!

```
tmp = x
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Happens-Before Ordering

- Note, this only detects races in the current execution!
    - *Sound predictive* data race detection can extend it across other executions **[PLDI 2017/2018]**

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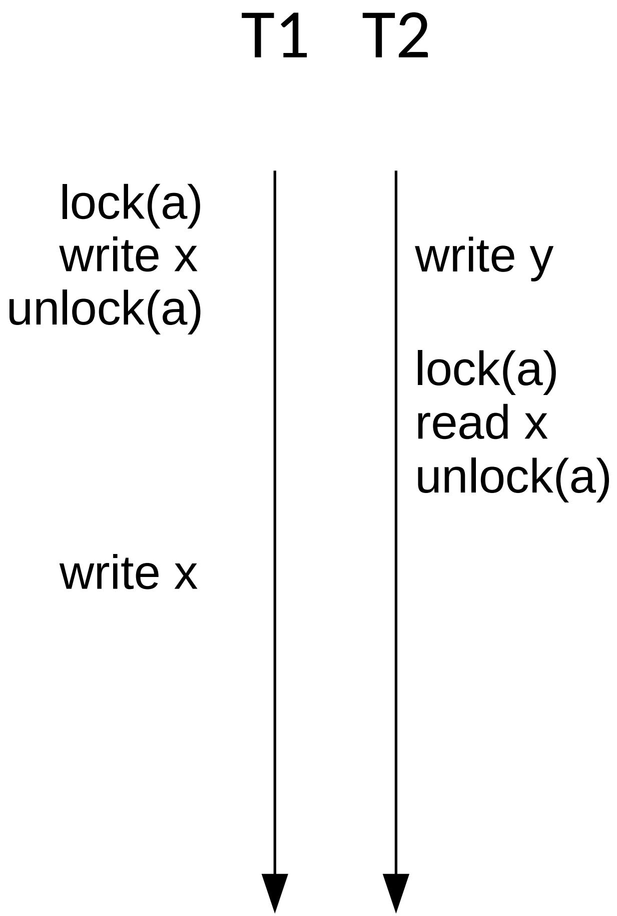
- Note, this only detects races in the current execution!
  - *Sound predictive* data race detection can extend it across other executions **[PLDI 2017/2018]**
- Requires careful tracking of dependences
  - Careful construction of logical time using ***vector clocks*** **[JVM 2001, PLDI 2009]**

Logical Time & Vector Clocks



T1 T2

T1: lock(a)
write x
unlock(a)

T2: write y

T2: lock(a)
read x
unlock(a)

T1: 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]
```

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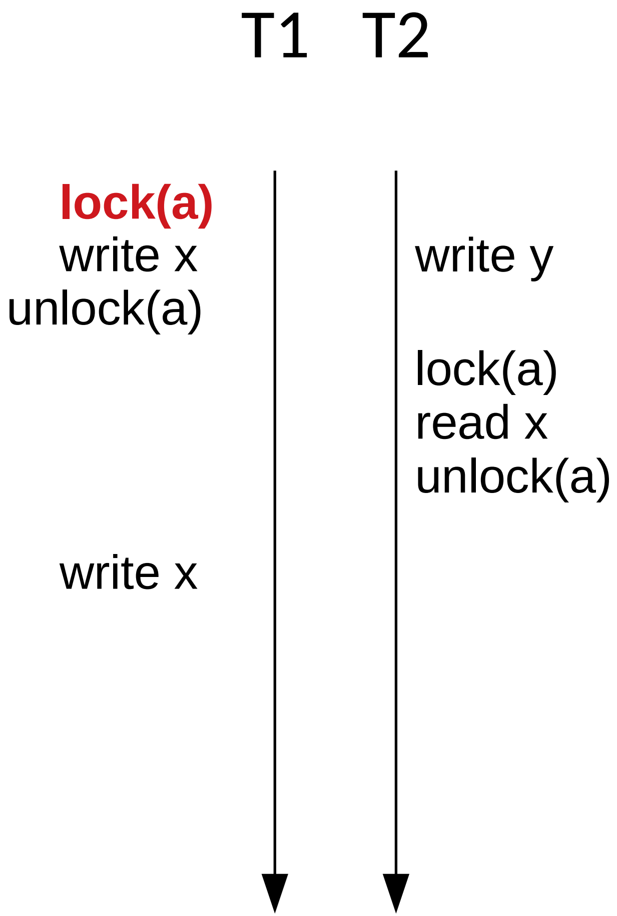

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Clocks

```
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```

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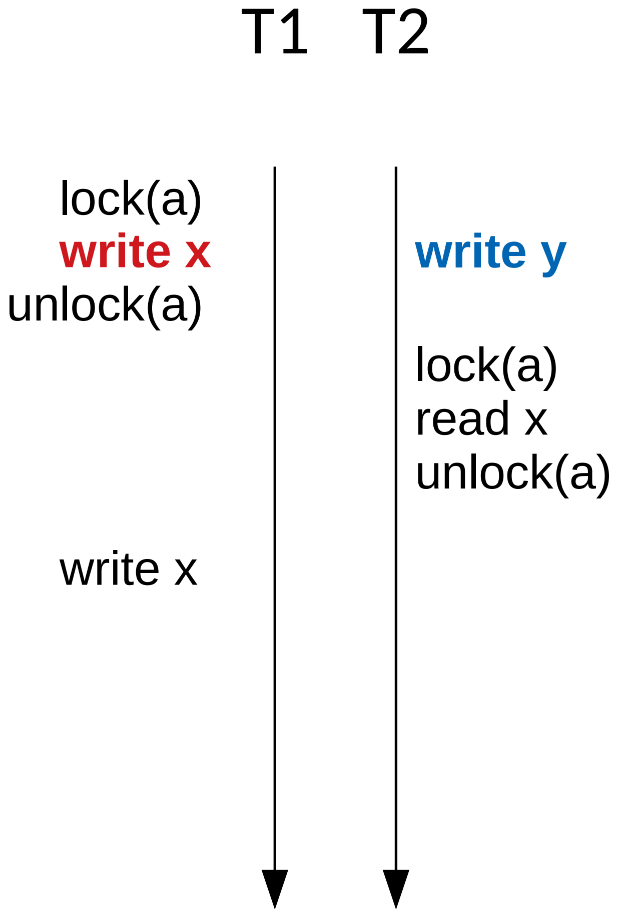

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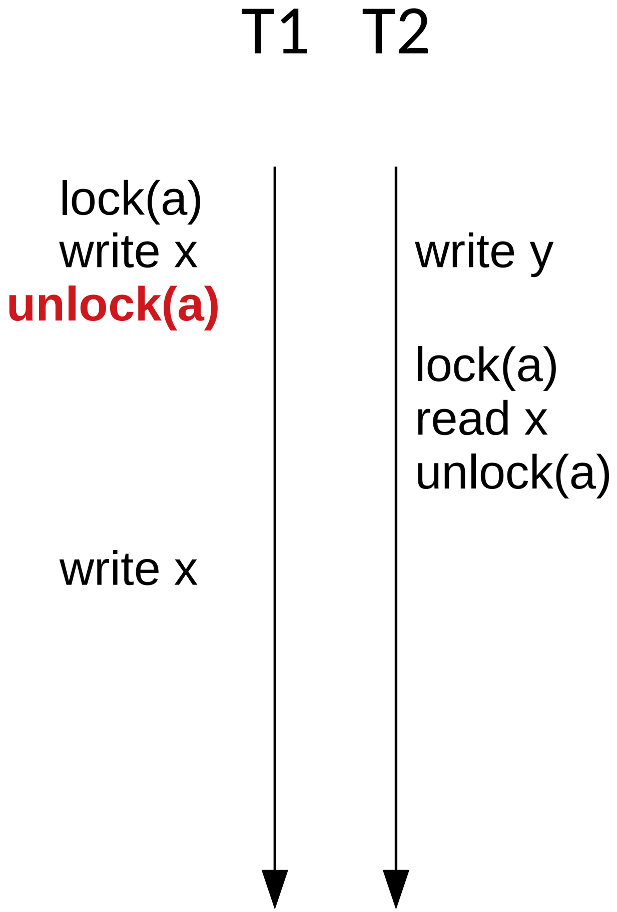

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Clocks

```
T1↦[2,0]
T2↦[0,0]
```

Shadow Memory

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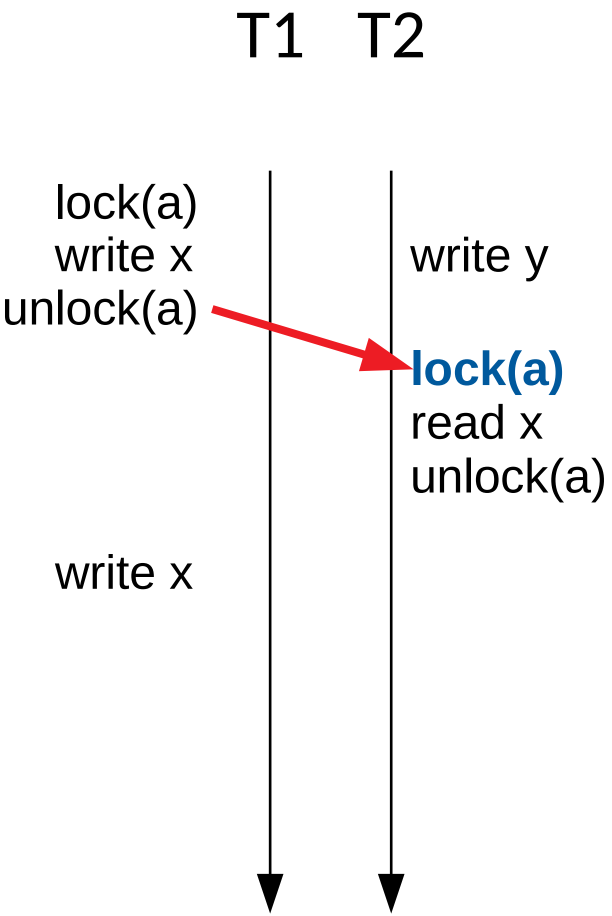
Logical Time & Vector Clocks



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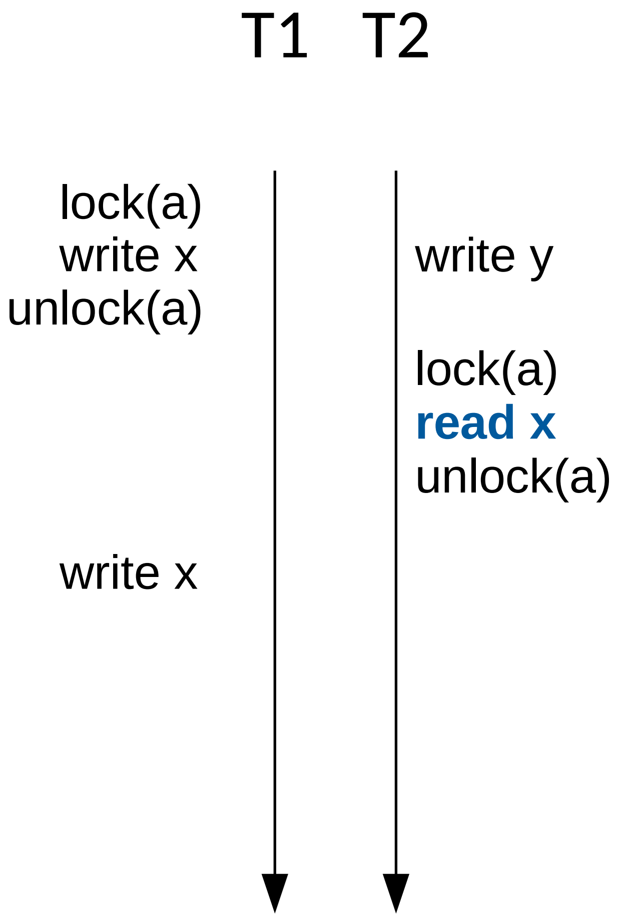

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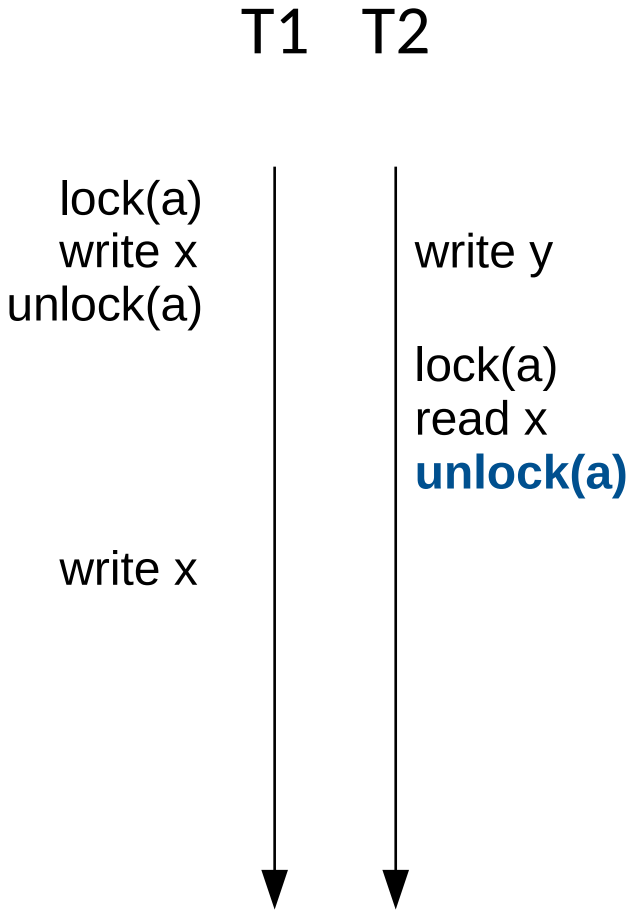

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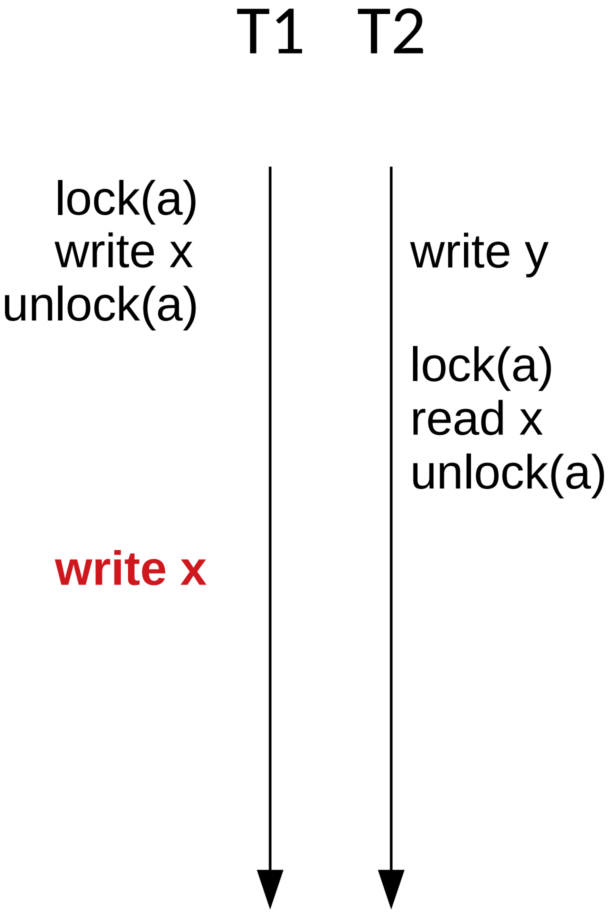

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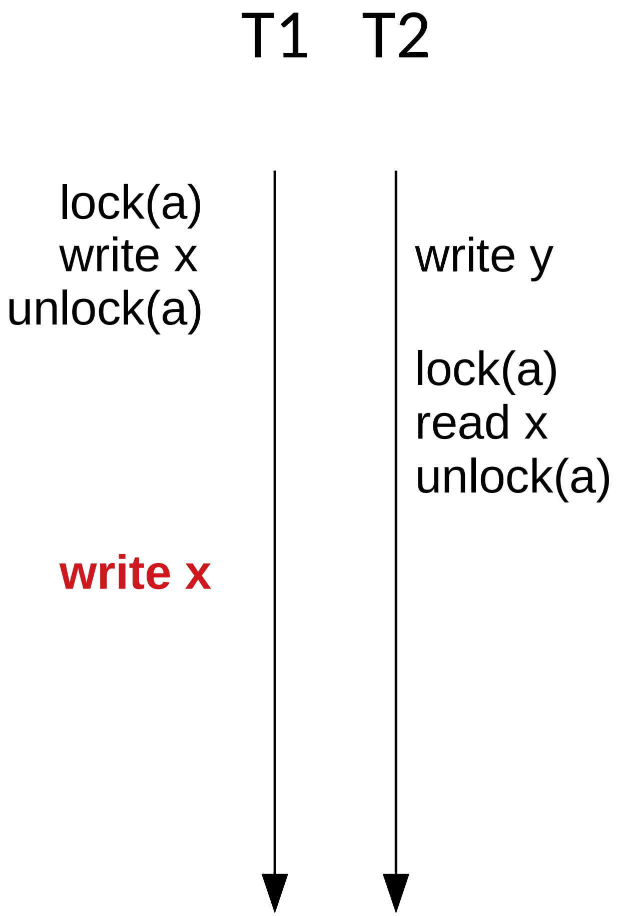
```

Logical Time & Vector Clocks



T1 T2

lock(a)
write x
unlock(a)

write y

lock(a)
read x
unlock(a)

write x

Clocks

```
T1↦[2,0]
T2↦[2,2]
```

Shadow Memory

```
x↦ R[2,1]
   W[2,0]
y↦ R[0,0]
   W[0,0]
```

C(R,X) ⋢ C(W,X) → race!
(simplified for this case)

Data Race Detection - Locksets

- Lack of synchronization arises with complex locking
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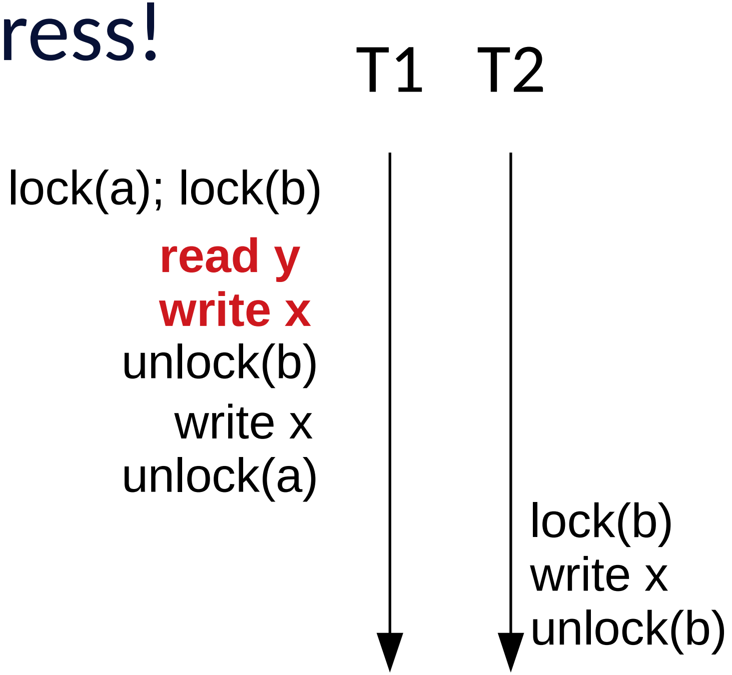

T1 T2

lock(a); lock(b)

read y

write x

unlock(b)

write x

unlock(a)

lock(b)

write x

unlock(b)

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y↦a,b
x↦a,b

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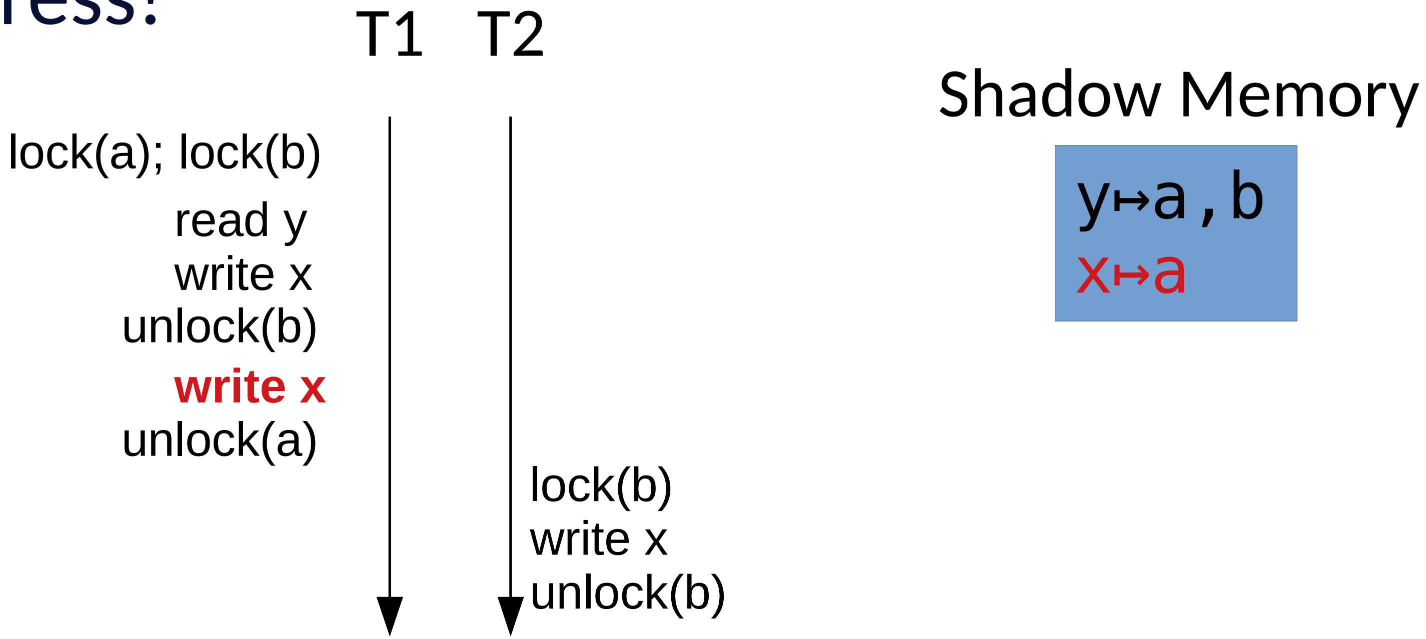

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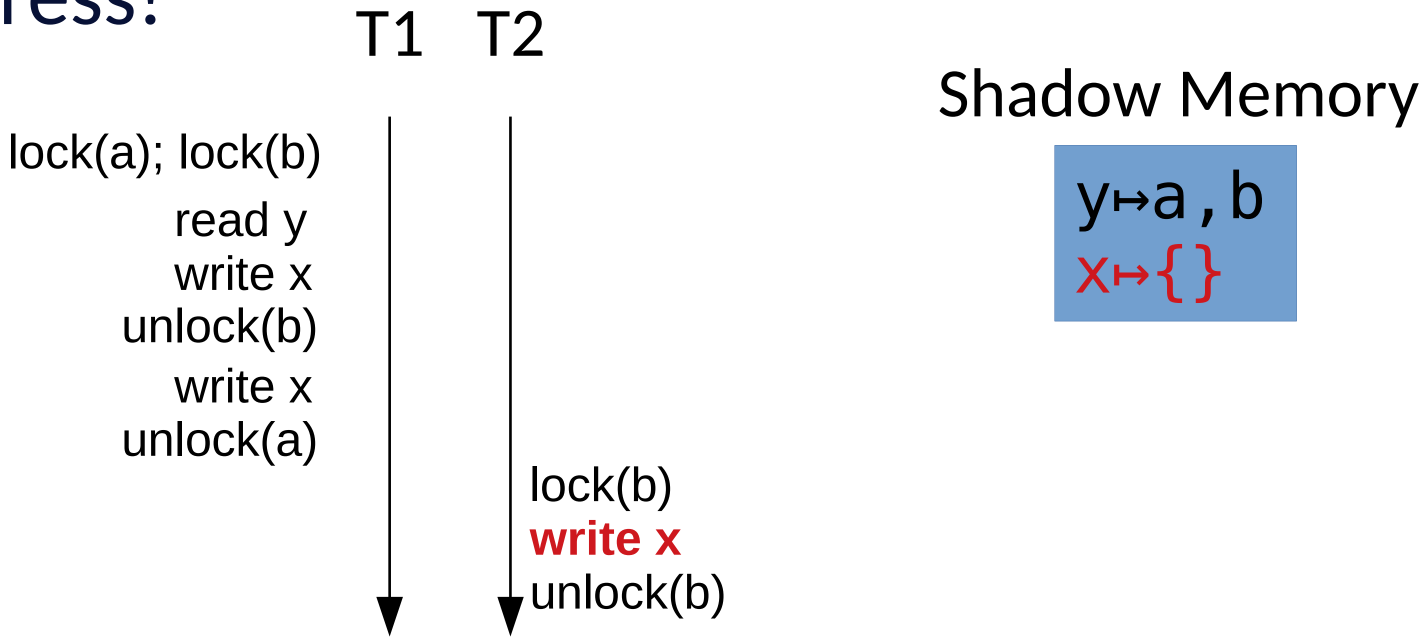

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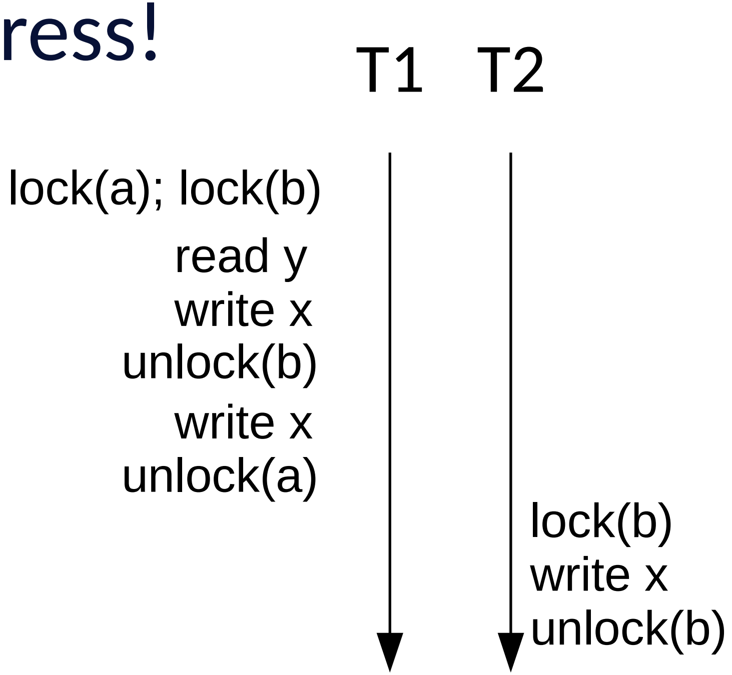


T1 T2

lock(a); lock(b)
read y
write x
unlock(b)
write x
unlock(a)

lock(b)
write x
unlock(b)

Shadow Memory

y↦a,b
x↦{}

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

Data Race Detection - Locksets

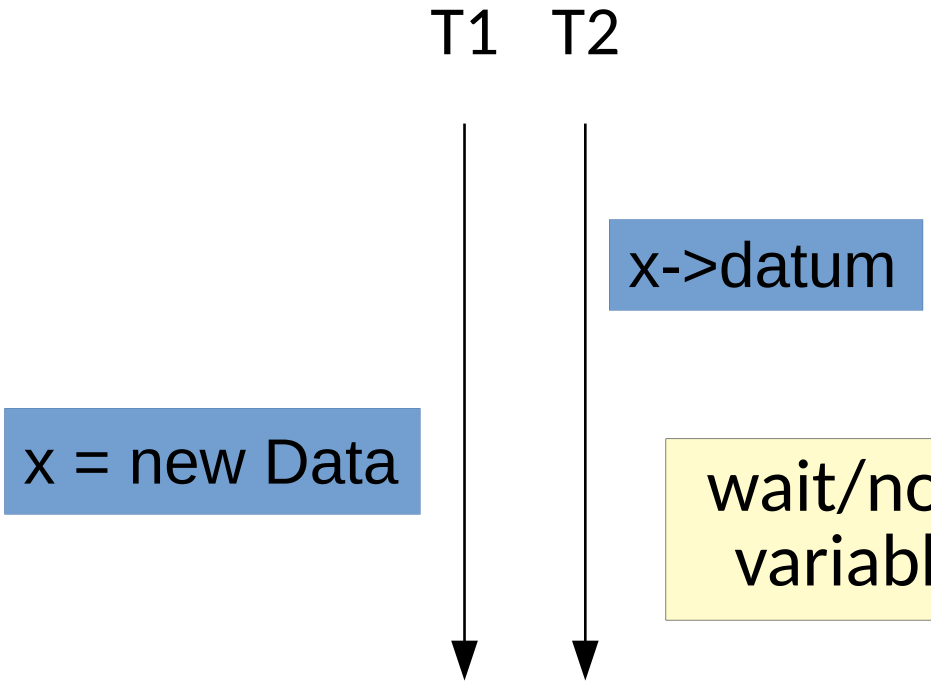
- Lockset based data race detection has many issues
  - Synchronization may be fork/join, wait/notify based
  - Initialization --> Process in Parallel --> Combine
  - Richer parallel designs

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
- Tends to have many false positives

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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```
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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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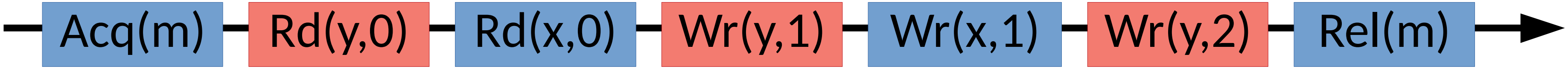

Acq(m) Rd(y,0) Rd(x,0) Wr(y,1) Wr(x,1) Wr(y,2) Rel(m)

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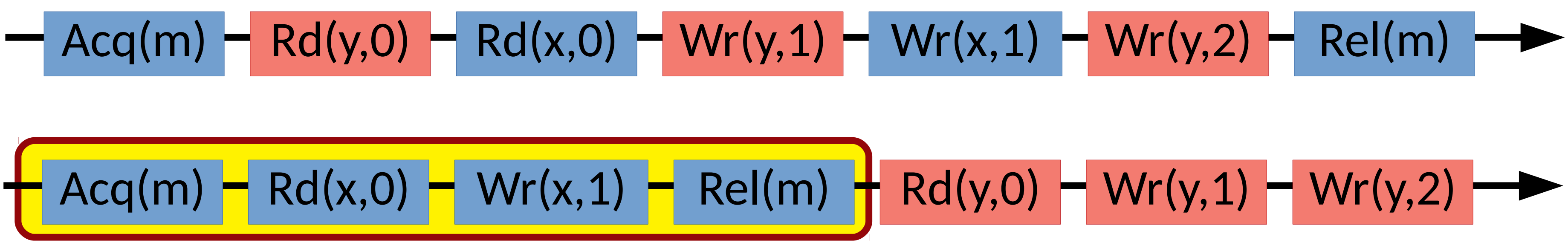

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Atomicity Violations

- 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?

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  - Lipton’s Theory of Reduction **[CACM ‘75, POPL ‘04]**

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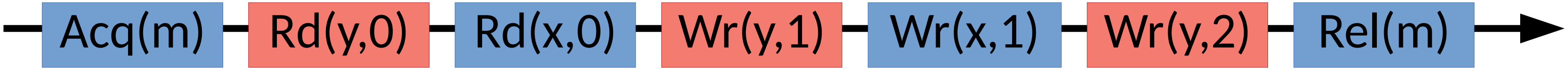

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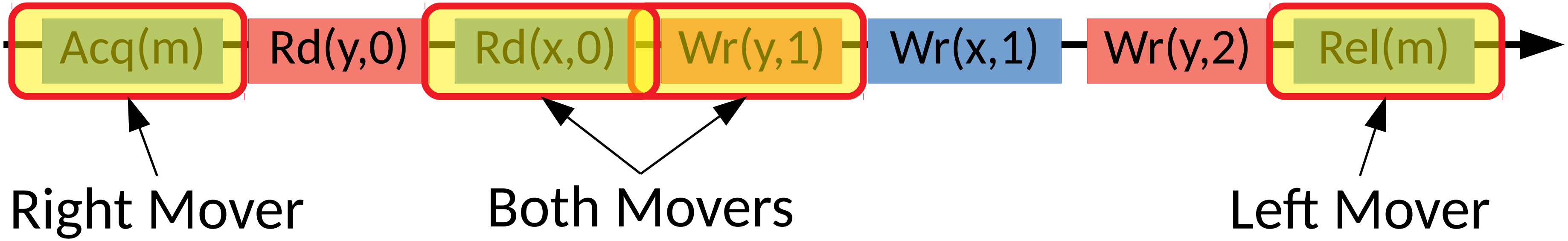

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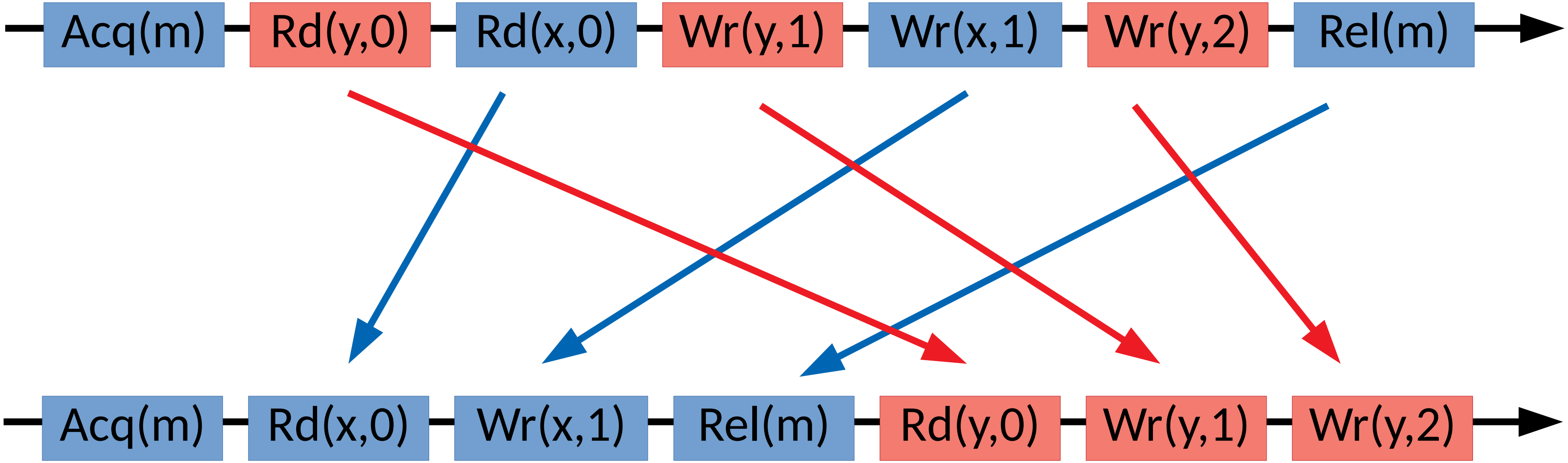

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Time →

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.

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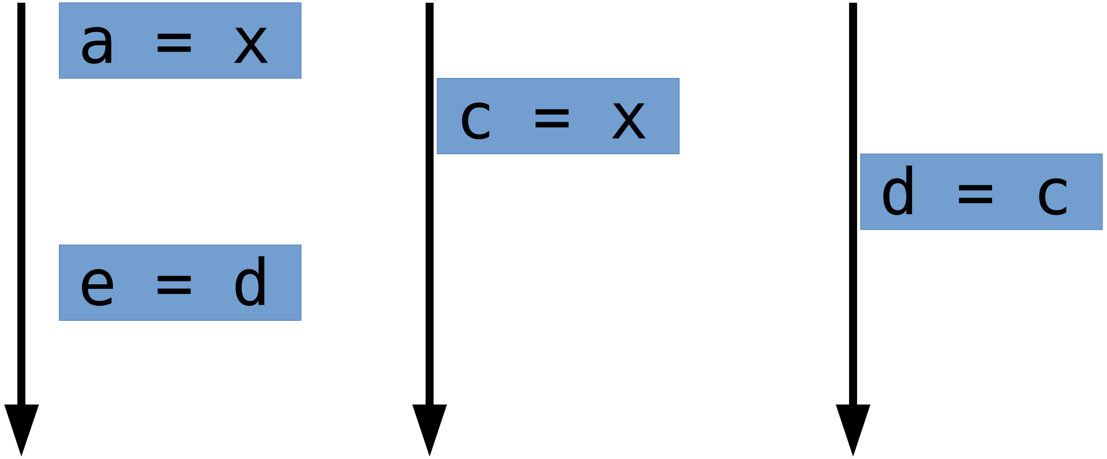

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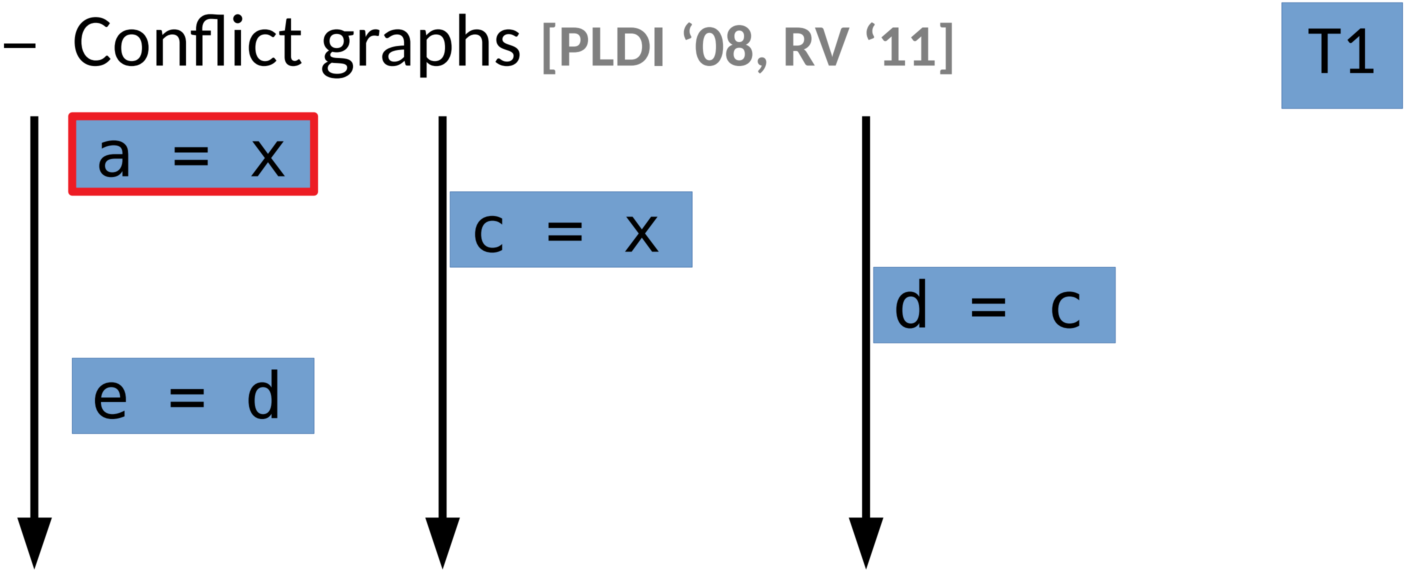

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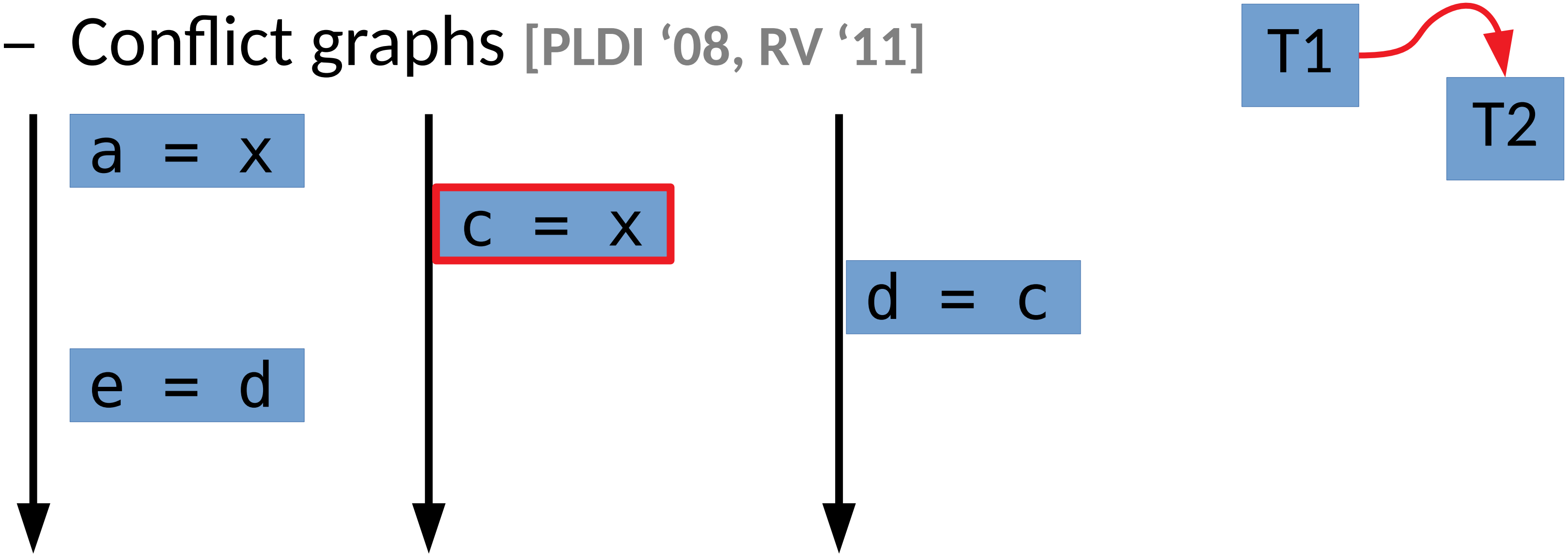

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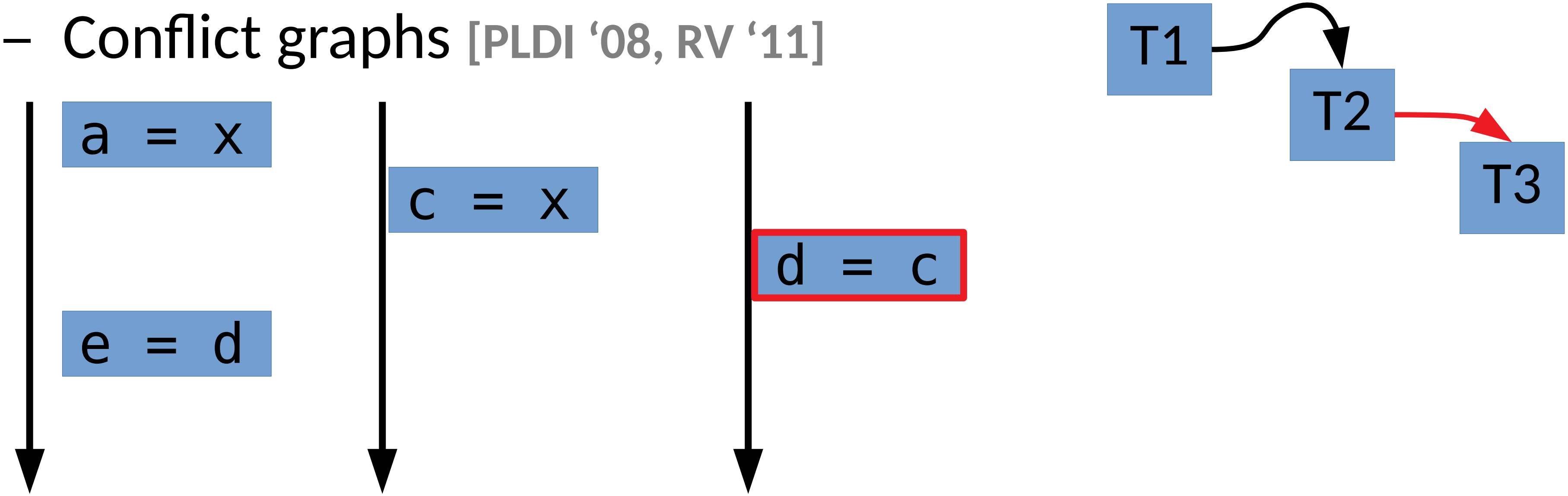

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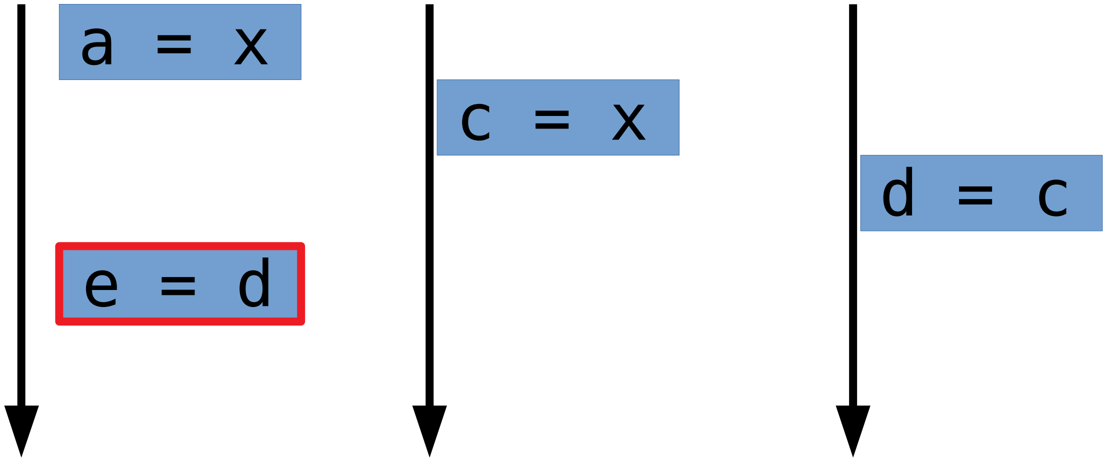
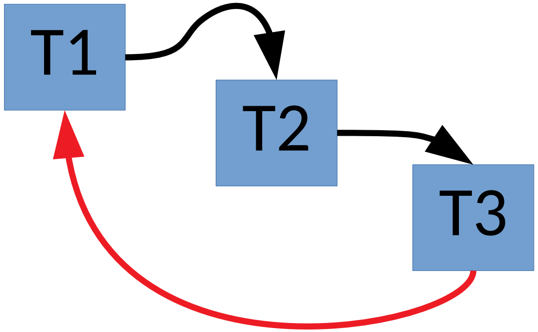


a = x

c = x

d = c

e = d



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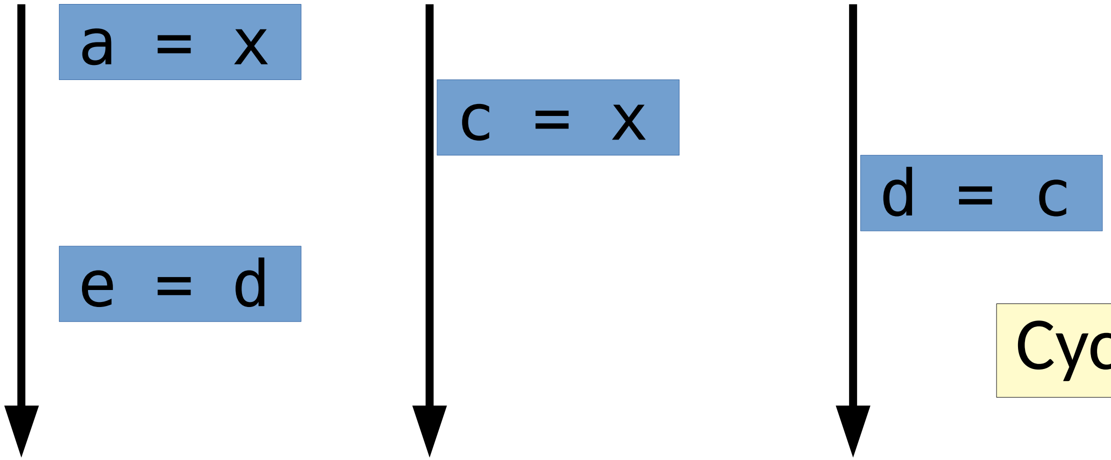

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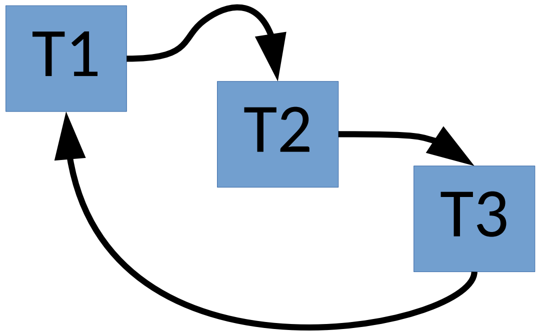

T1

T2

T3

Cycles are unserializable!

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- How do we know what regions should be atomic?

Concurrent Test Generation

- What if we don’t already have a buggy execution?

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- Explore bounded schedules
  - 2 threads and few pre-emptions finds most bugs
- 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

Summary

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