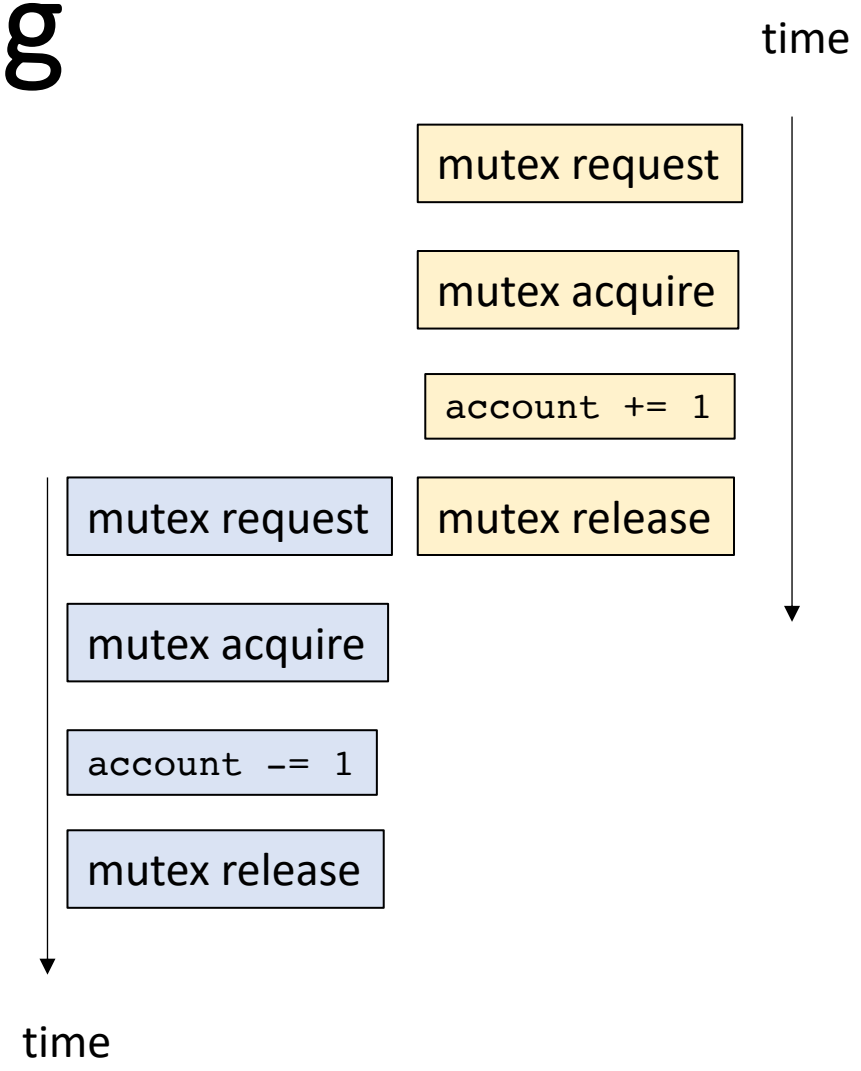
CSE113: Parallel Programming

Jan. 23, 2023

- **Topics**:
  - Review SPMD programming model
  - Intro to mutual exclusion
    - Different types of parallelism
    - Data conflicts
    - Protecting shared data



Announcements

- Starting module 2

- Homework 1
  - We have covered everything you need in class
  - Due on Thursday
  - 4 free late days (until next Monday)
  - No late assignments accepted after that.

- Office hours/mentoring hours/piazza
  - lots of support available

Announcements

- Homework 1 notes:
  - No assigned speedup required. You should get a noticeable speedup from ILP
  - You can start to share results on your personal machines. Everyone's results will be slightly different
  - Sometimes you cannot account for small differences
    - Run your code for more iterations and take an average

Announcements

- Jessica and Devon will give the lecture on Friday
  - I am out for an NSF meeting
  - Should be the only disruption this quarter

Previous quiz

C++ threads are initialized with a function argument where they will start execution, but they must be explicitly started with the "launch" command.

Previous quiz

The "join" function for a C++ thread causes the thread to immediately exit.

Previous quiz

A thread that is launched will eventually exit by itself and there is no need for the main thread to keep track of the threads it launches.

Previous quiz

Which of the following operators is associative?

- ◯ Addition
- ◯ Subtraction
- ◯ modulo
- ◯ boolean AND

Previous quiz

In 2 or 3 sentences, explain the difference between instruction level parallelism and thread parallelism

Review

SPMD programming model

- Same program, multiple data
- Main idea: many threads execute the same function, but they operate on different data.
- How do they get different data?
  - each thread can access their own thread id, a contiguous integer starting at 0 up to the number of threads

SPMD programming model

```
void increment_array(int *a, int a_size) {
    for (int i = 0; i < a_size; i++) {
        a[i]++;
    }
}
```

lets do this in parallel!

each thread increments different elements in the array

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads) {
    for (int i = 0; i < a_size; i++) {
        a[i]++;
    }
}
```

The function gets a thread id and the number of threads

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads) {
    for (int i = 0; i < a_size; i++) {
        a[i]++;
    }
}
```

A few options on how to split up the work

lets do round robin

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads) {
    for (int i = tid; i < a_size; i+=num_threads) {
        a[i]++;
    }
}
```

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads) {
    for (int i = tid; i < a_size; i+=num_threads) {
        a[i]++;
    }
}
```

indices computed by thread 0

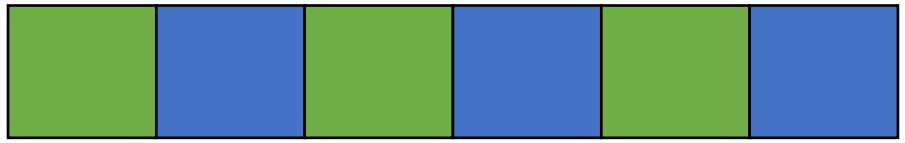
array a

Assume 2 threads
lets step through thread 0
i.e.
tid = 0
num_threads = 2

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads) {
    for (int i = tid; i < a_size; i+=num_threads) {
        a[i]++;
    }
}
```

iterations computed by thread 1



array a

switch to thread 1

Assume 2 threads
lets step through thread 1
i.e.
tid = 1
num_threads = 2

SPMD programming model

```
void increment_array(int *a, int a_size, int tid, int num_threads);


#define THREADS 8
#define A_SIZE 1024
int main() {
  int *a = new int[A_SIZE];
  // initialize a
  thread thread_ar[THREADS];
  for (int i = 0; i < THREADS; i++) {
    thread_ar[i] = thread(increment_array, a, A_SIZE, i, THREADS);
  }
  for (int i = 0; i < THREADS; i++) {
    thread_ar[i].join();
  }
  delete[] a;
  return 0;
}
```

On to the lecture!

Lecture Schedule

- Introduction to thread-level parallelism
- Data conflicts
- Mutual exclusion

Lecture Schedule

- **Introduction to thread-level parallelism**
- Data conflicts
- Mutual exclusion

Embarrassingly parallel

Embarrassingly parallel

Embarrassingly parallel

From Wikipedia, the free encyclopedia

In parallel computing, an **embarrassingly parallel** workload or problem (also called **embarrassingly parallelizable**, **perfectly parallel**, **delightfully parallel** or **pleasingly parallel**) is one where little or no effort is needed to separate the problem into a number of parallel tasks.[1] This is often the case where there is little or no dependency or need for communication between those parallel tasks, or for results between them.[2]

For this class: A multithreaded program is ***embarrassingly parallel*** if there are no ***data-conflicts.***

A ***data conflict*** is where one thread writes to a memory location that another thread reads or writes to concurrently and without sufficient ***synchronization***.

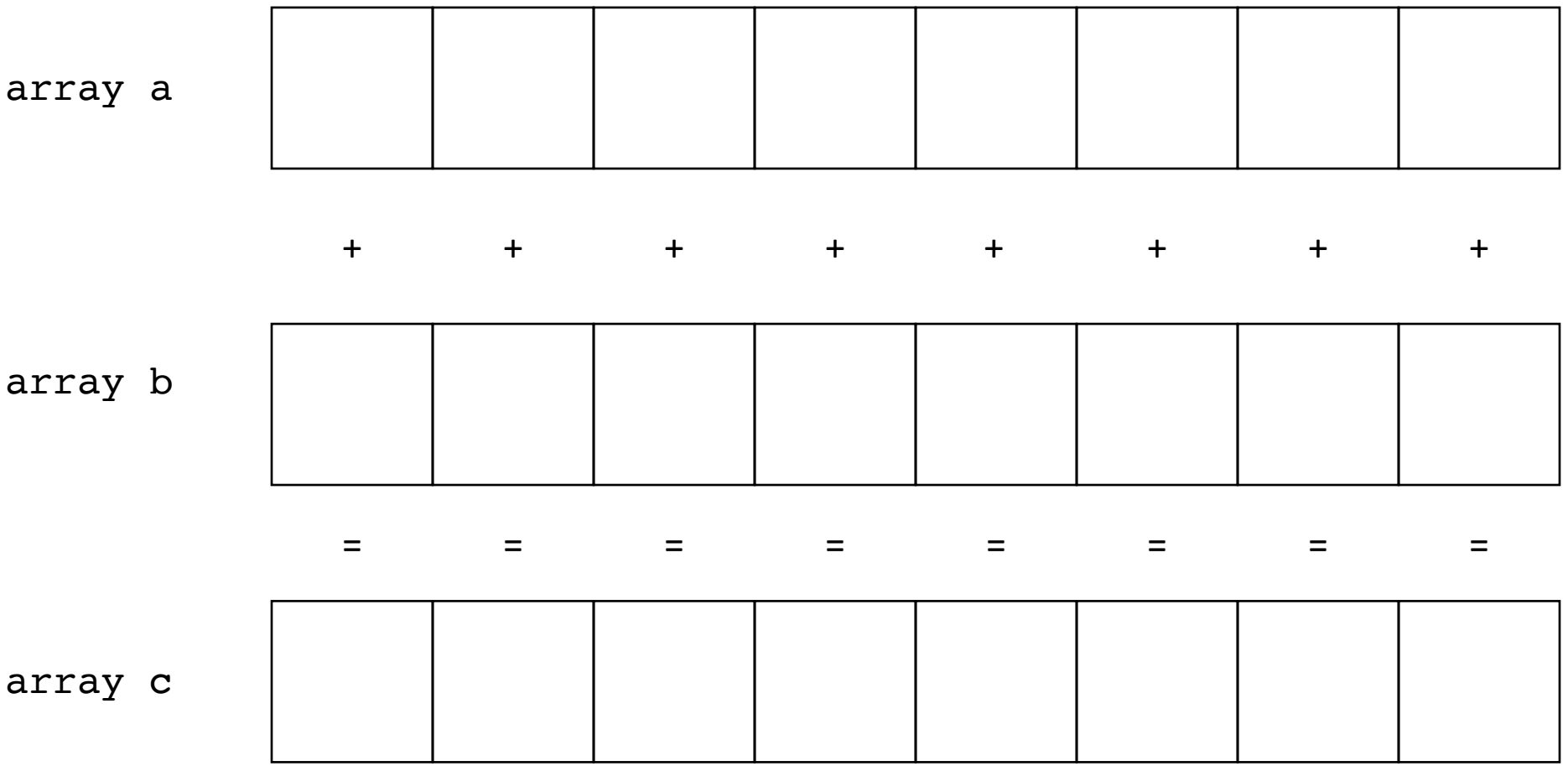
Embarrassingly parallel

- Consider the following program:

There are 3 arrays: `a, b, c.`

We want to compute `c[i] = a[i] + b[i]`

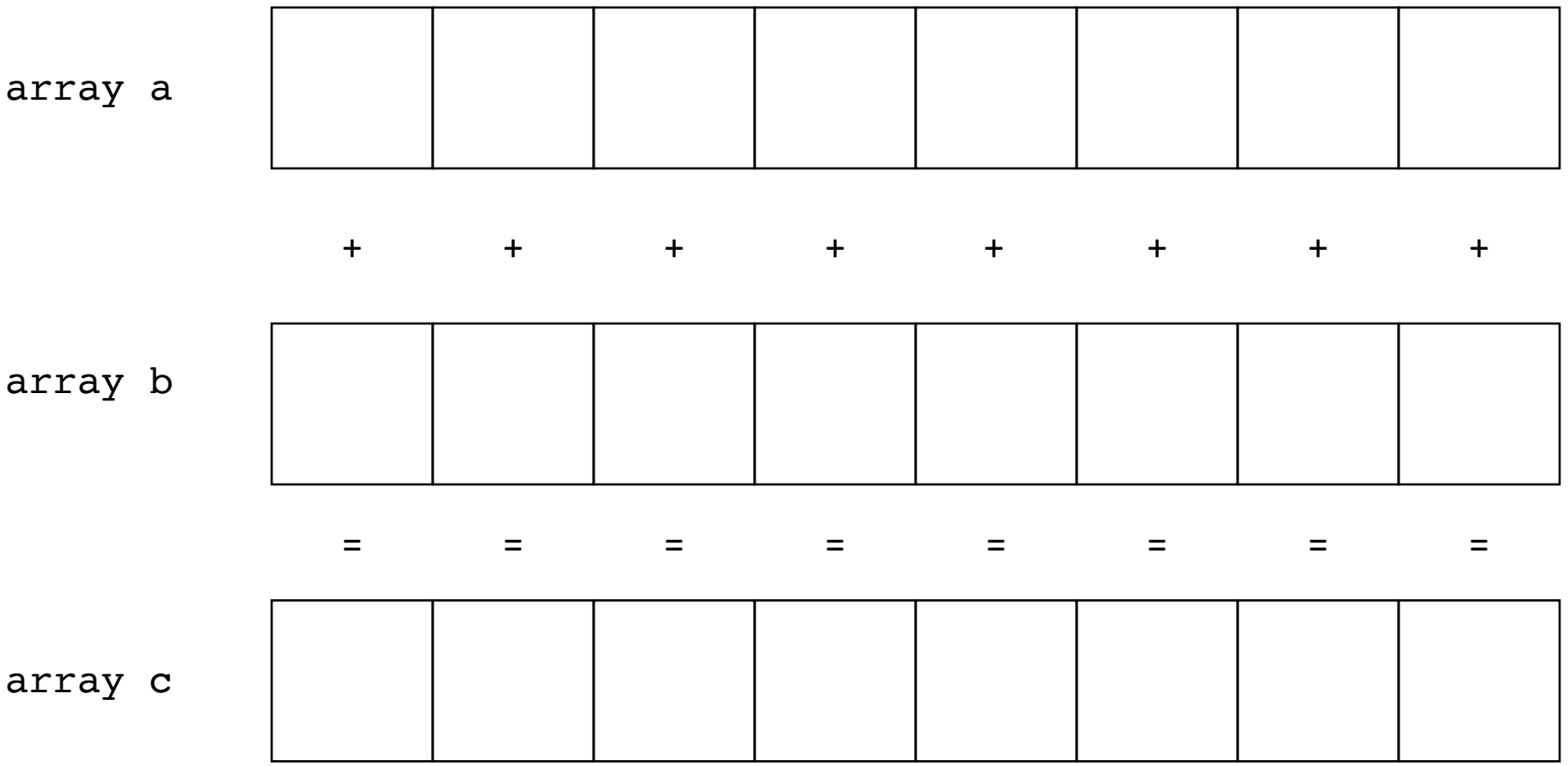
Embarrassingly parallel



Embarrassingly parallel

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange



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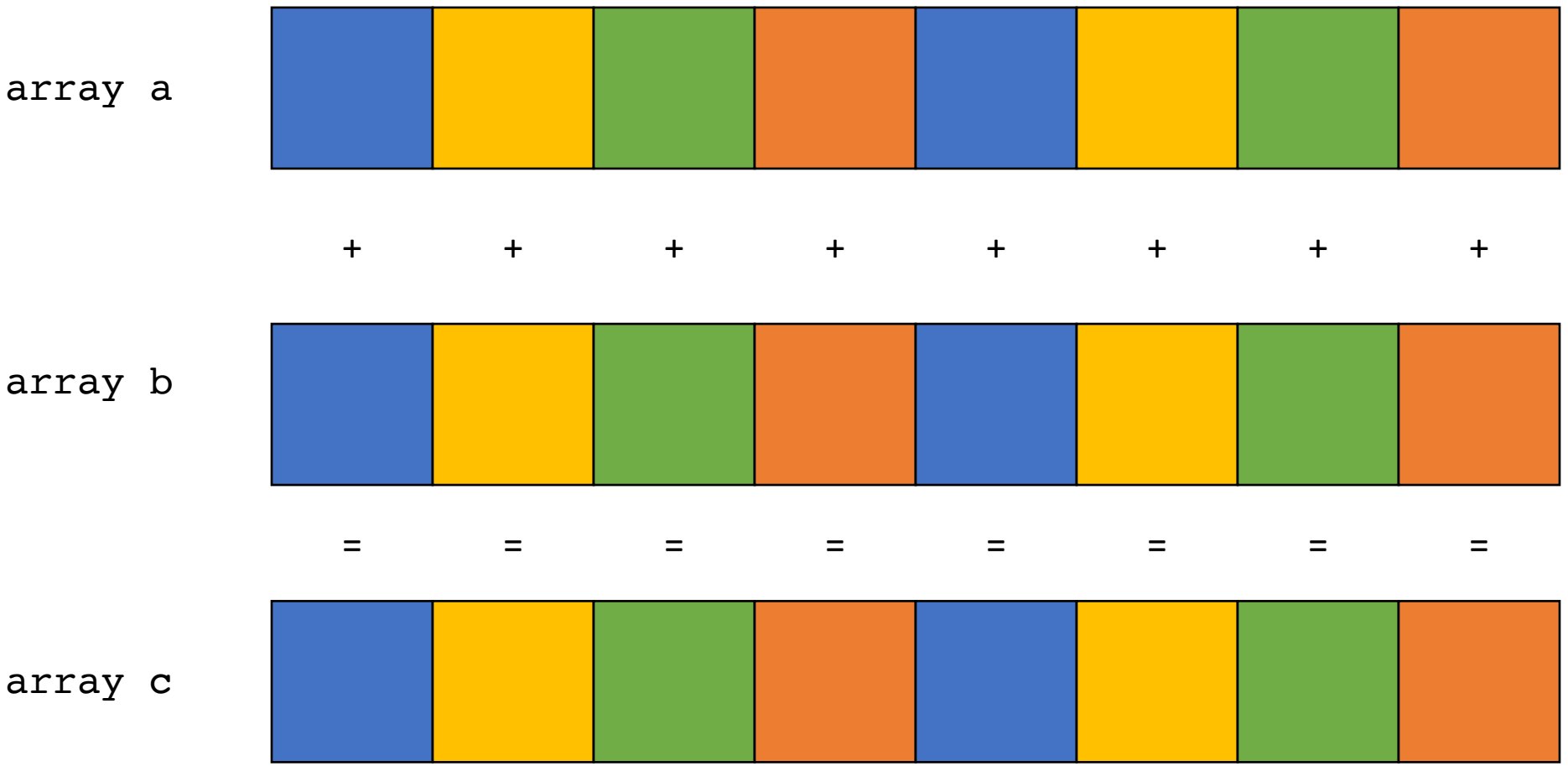

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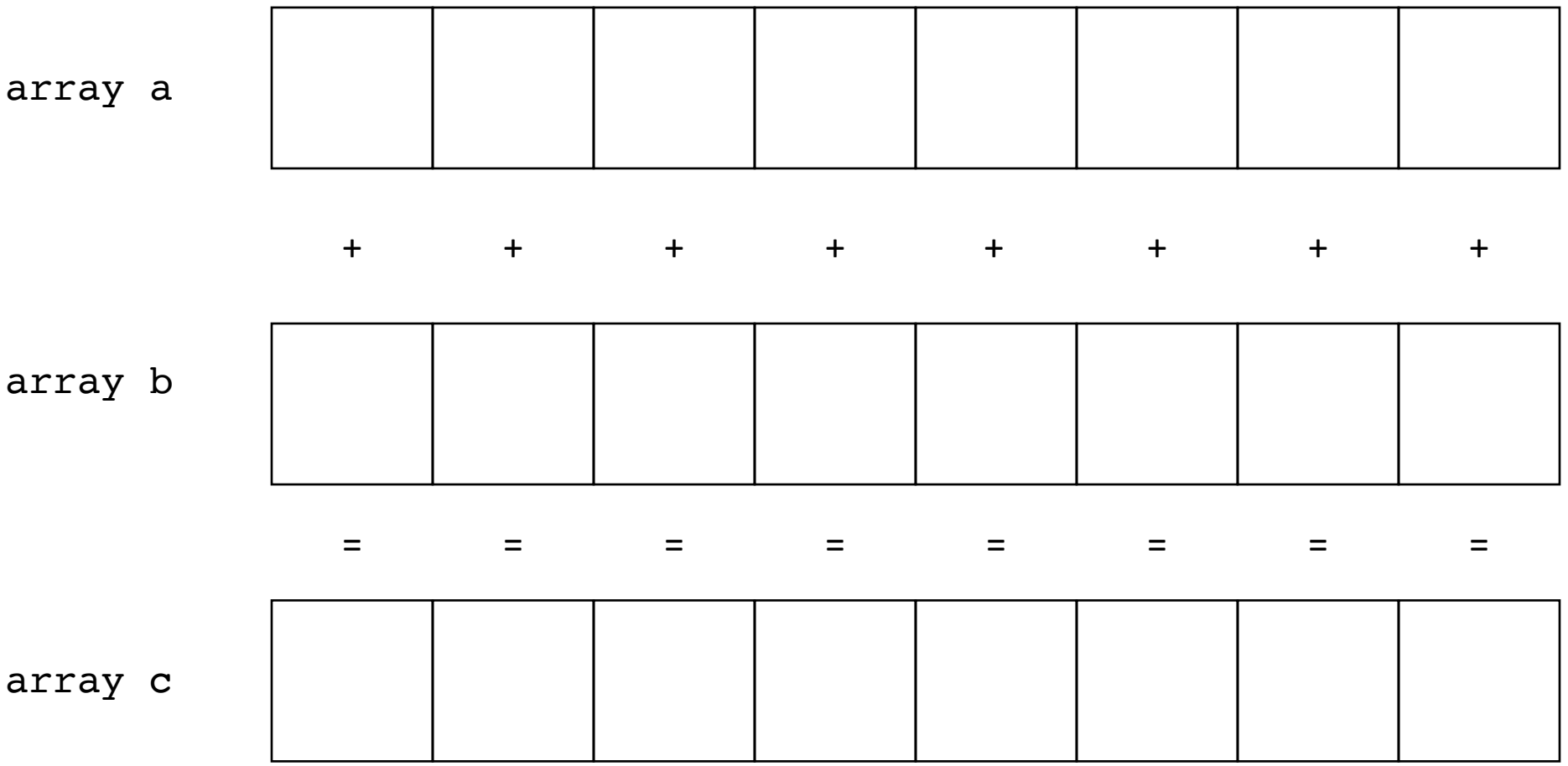

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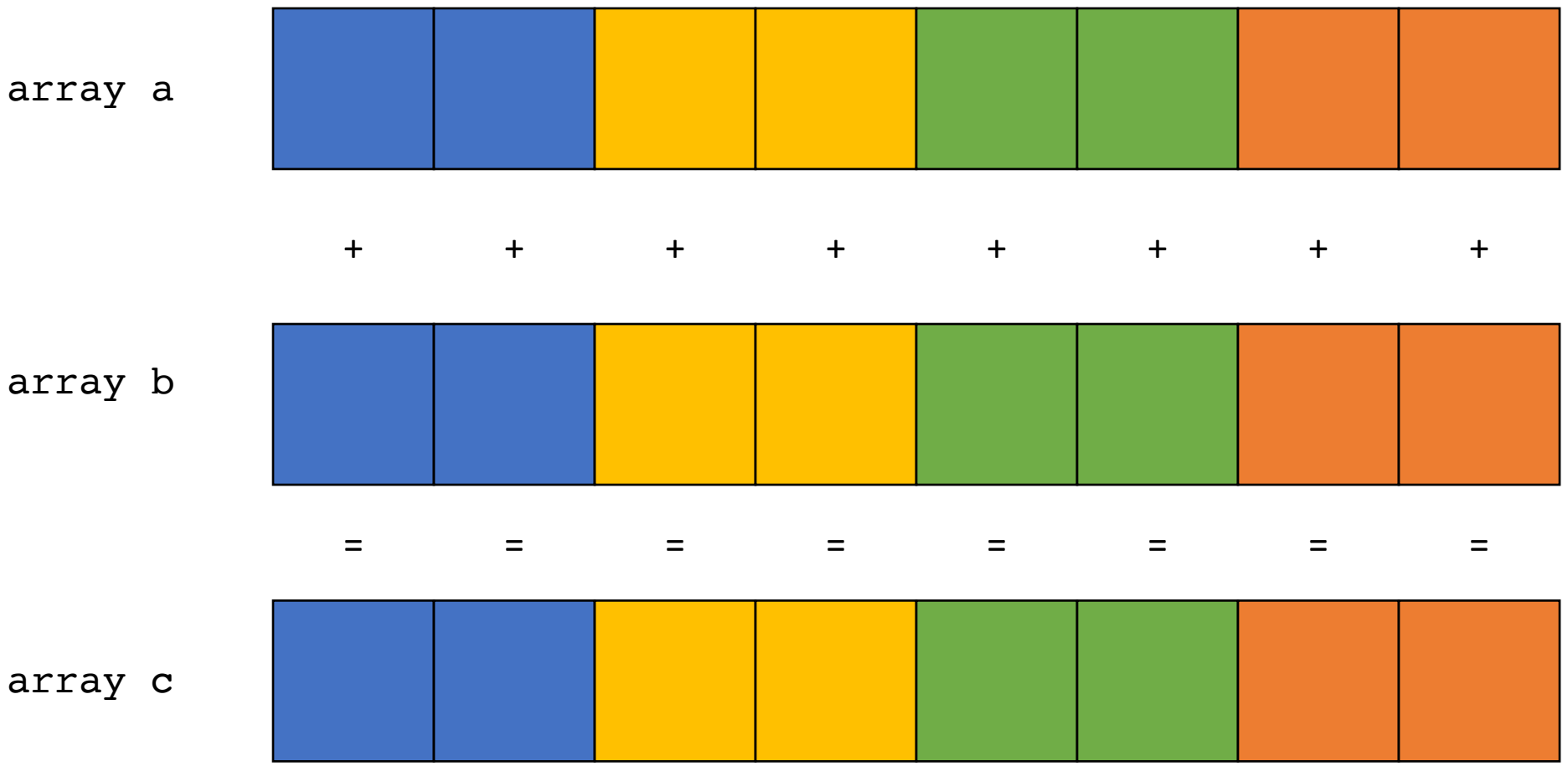


Embarrassingly parallel

- The different parallelization strategies will probably have different performance behaviors.
- But they are both embarrassingly parallel solutions to the problem
- There is lots of research into making these types of programs go fast!
  - but this module will focus on programs that require synchronization

Embarrassingly parallel

- Next Program

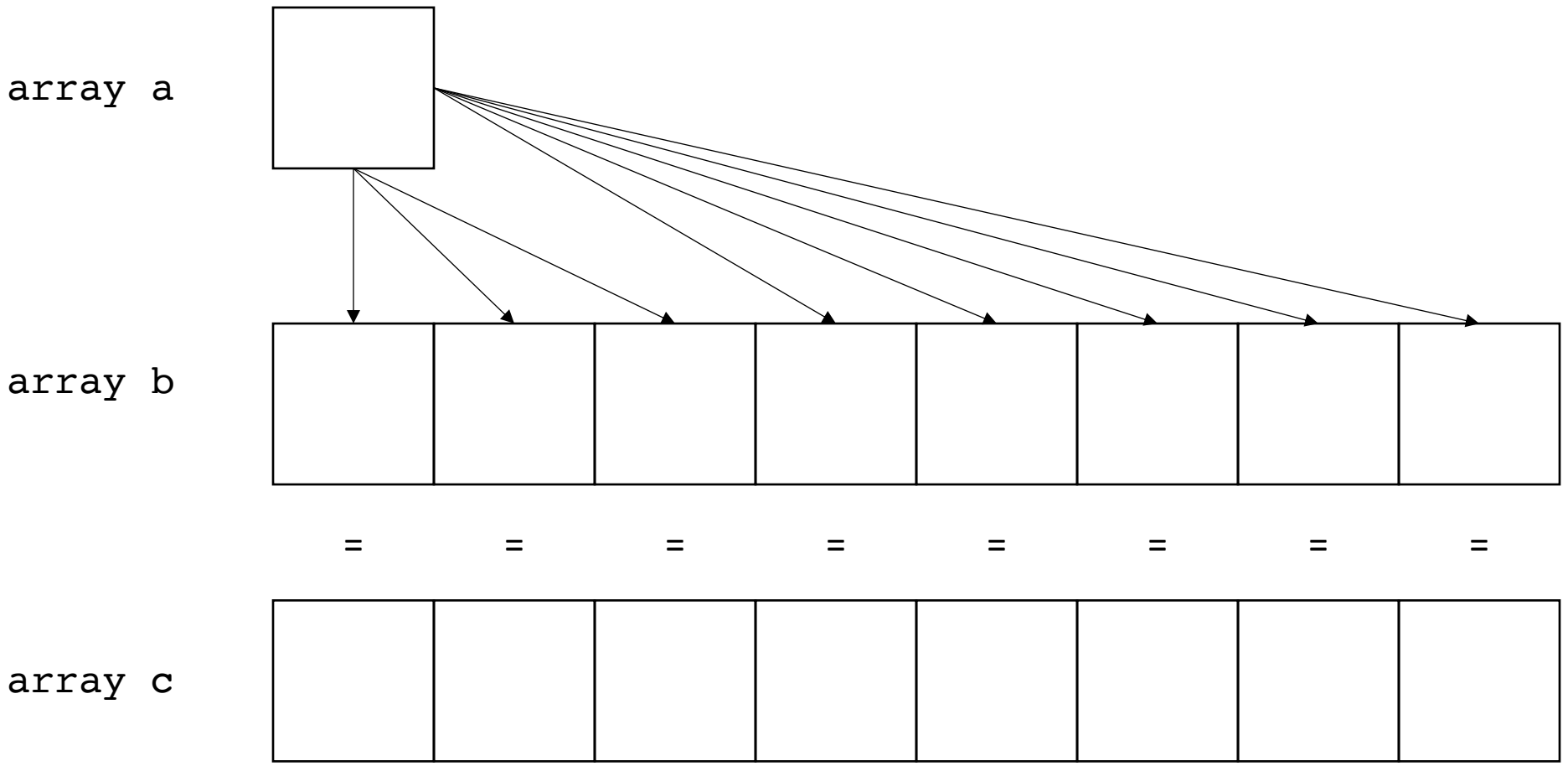
There are 3 arrays: `a, b, c.`

We want to compute `c[i] = a[0] + b[i]`

Embarrassingly parallel

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

is this problem embarrassingly parallel?



Embarrassingly parallel

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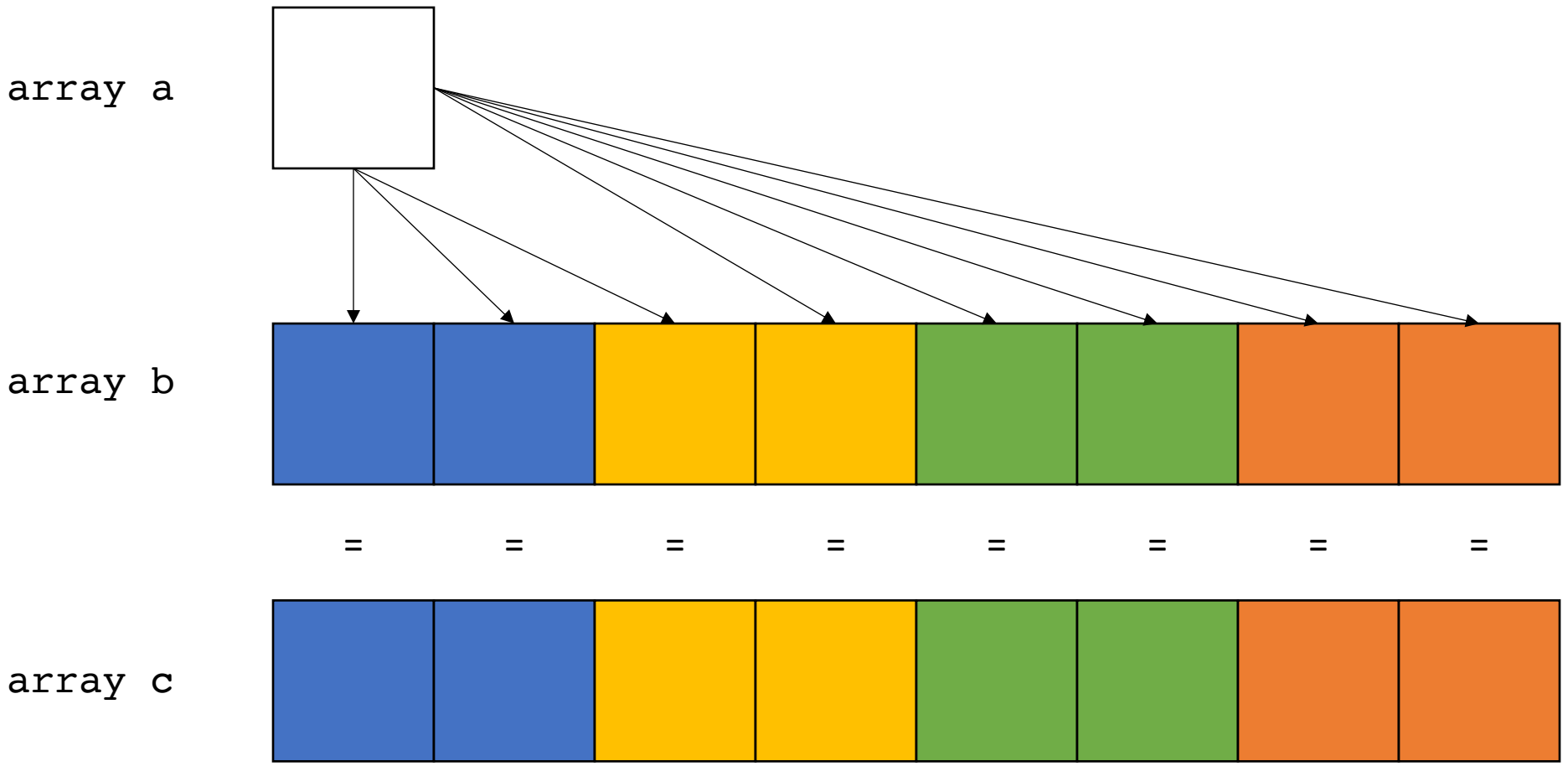
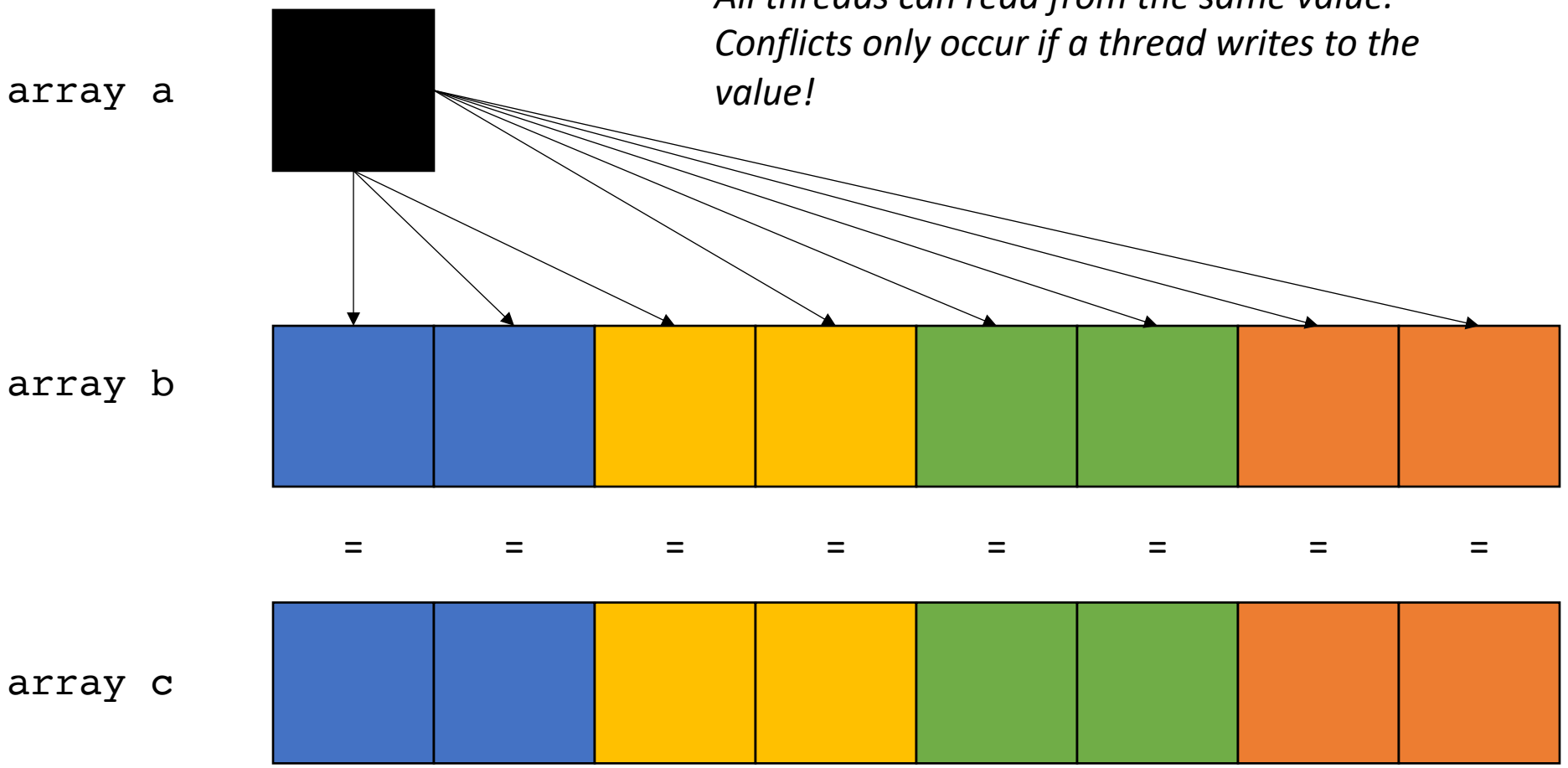


Embarrassingly parallel

All threads can read from the same value. Conflicts only occur if a thread writes to the value!

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange



is this problem embarrassingly parallel?

Embarrassingly parallel

- Next Program

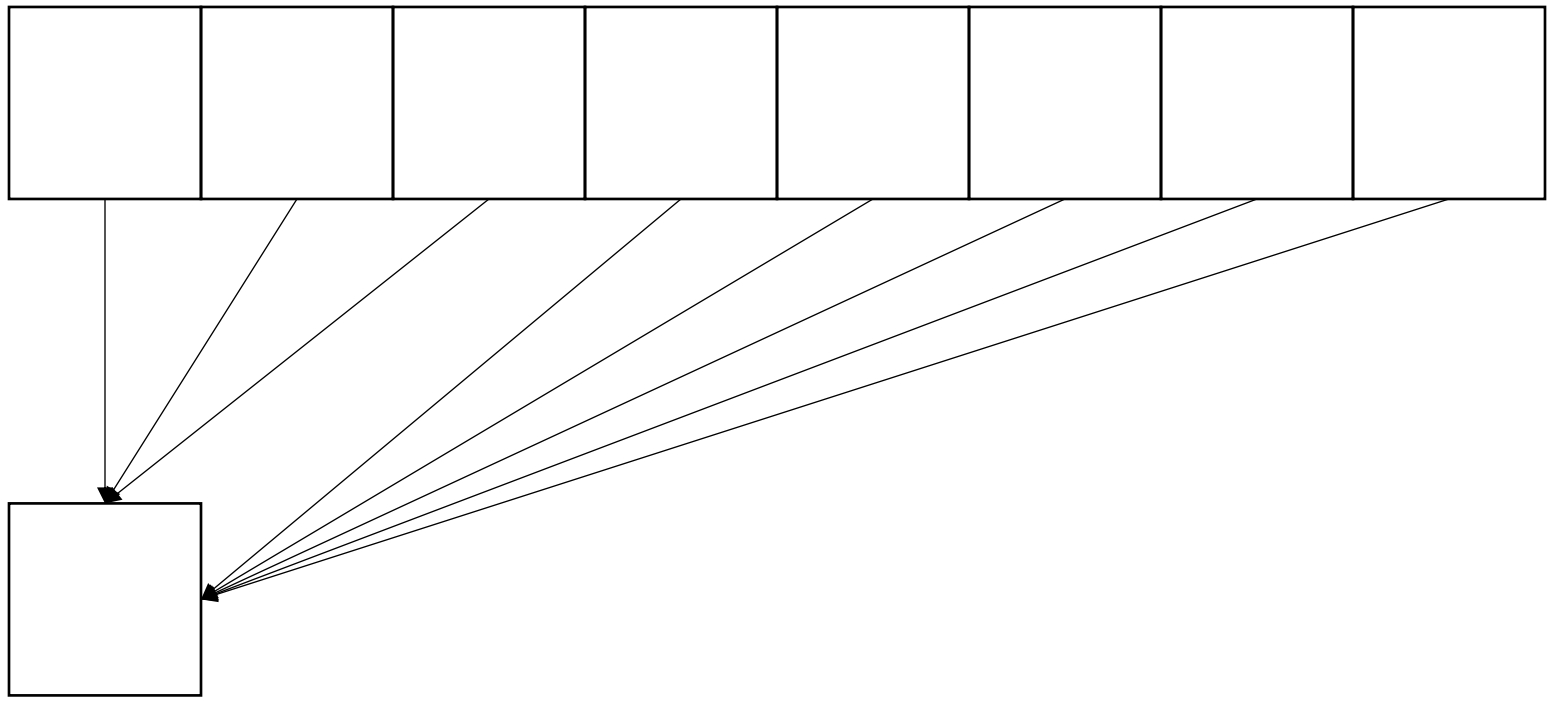
There are 2 arrays: `b, c`

We want to compute `c[0] = b[0] + b[1] + b[2] ...`

Embarrassingly parallel

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

is this problem embarrassingly parallel?



Embarrassingly parallel

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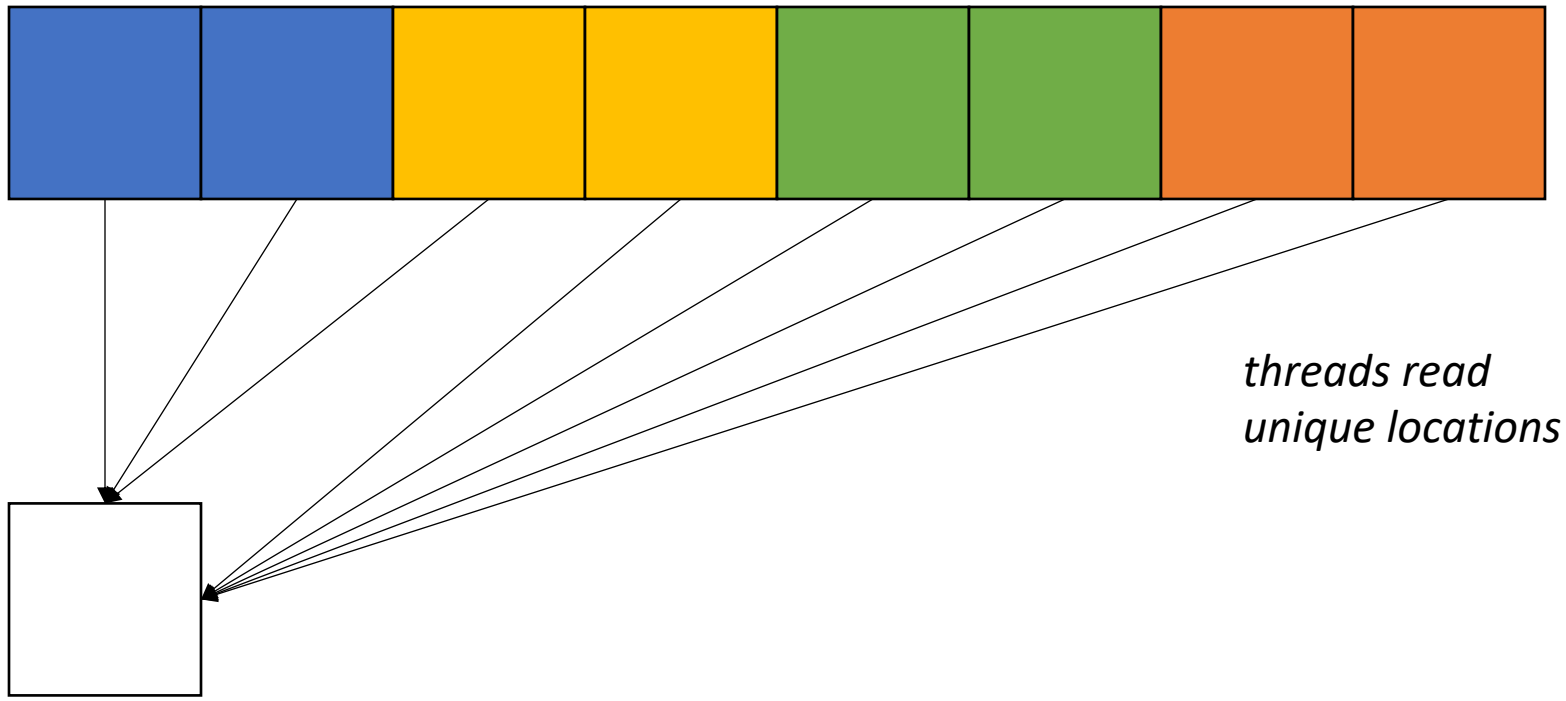
`array b`



threads read unique locations

is this problem embarrassingly parallel?

`array c`

Embarrassingly parallel

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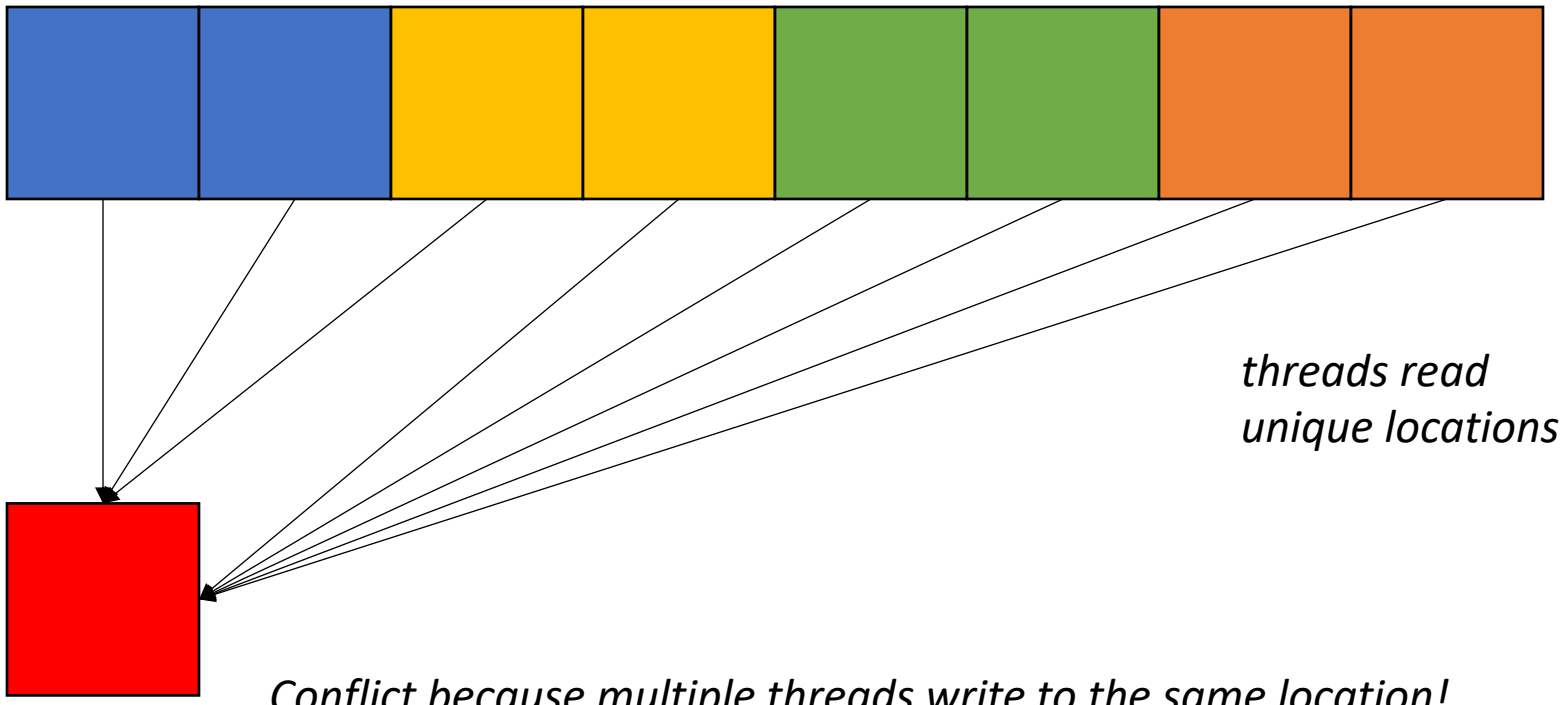
`array b`



threads read unique locations

is this problem embarrassingly parallel?

`array c`

Conflict because multiple threads write to the same location!

Embarrassingly parallel

Note: Reductions have some parallelism in them, as seen in your homework.

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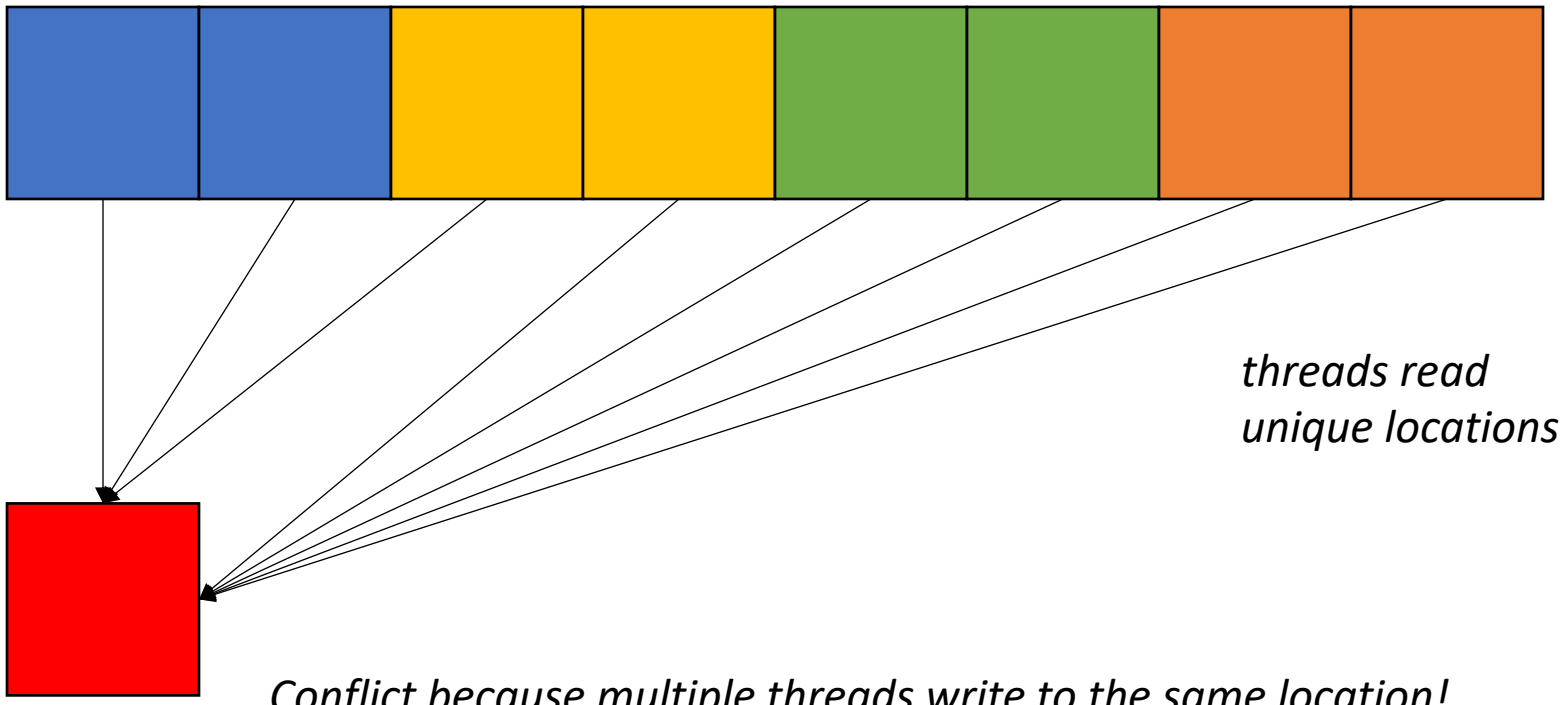
Thread 3 - Orange

`array b`



threads read unique locations

is this problem embarrassingly parallel?

`array c`

Conflict because multiple threads write to the same location!

We need a way how to safely share memory

- *Many applications are not embarrassingly parallel*

We need a way how to safely share memory

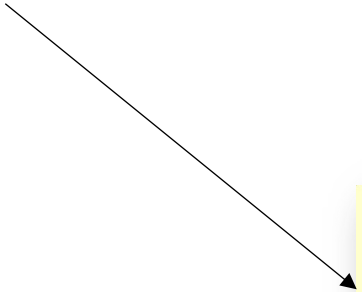
- Bank

My account: $$

We need a way how to safely share memory

- Bank

My account: $$



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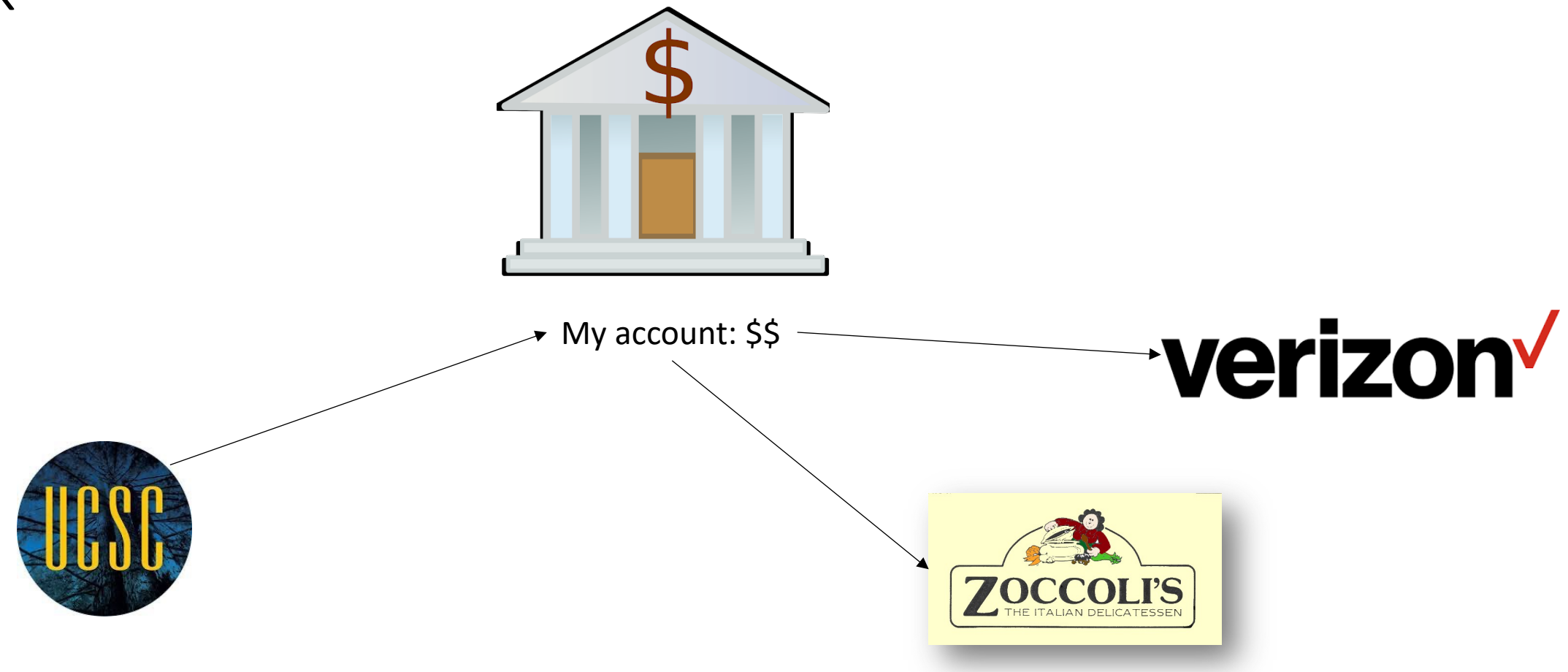

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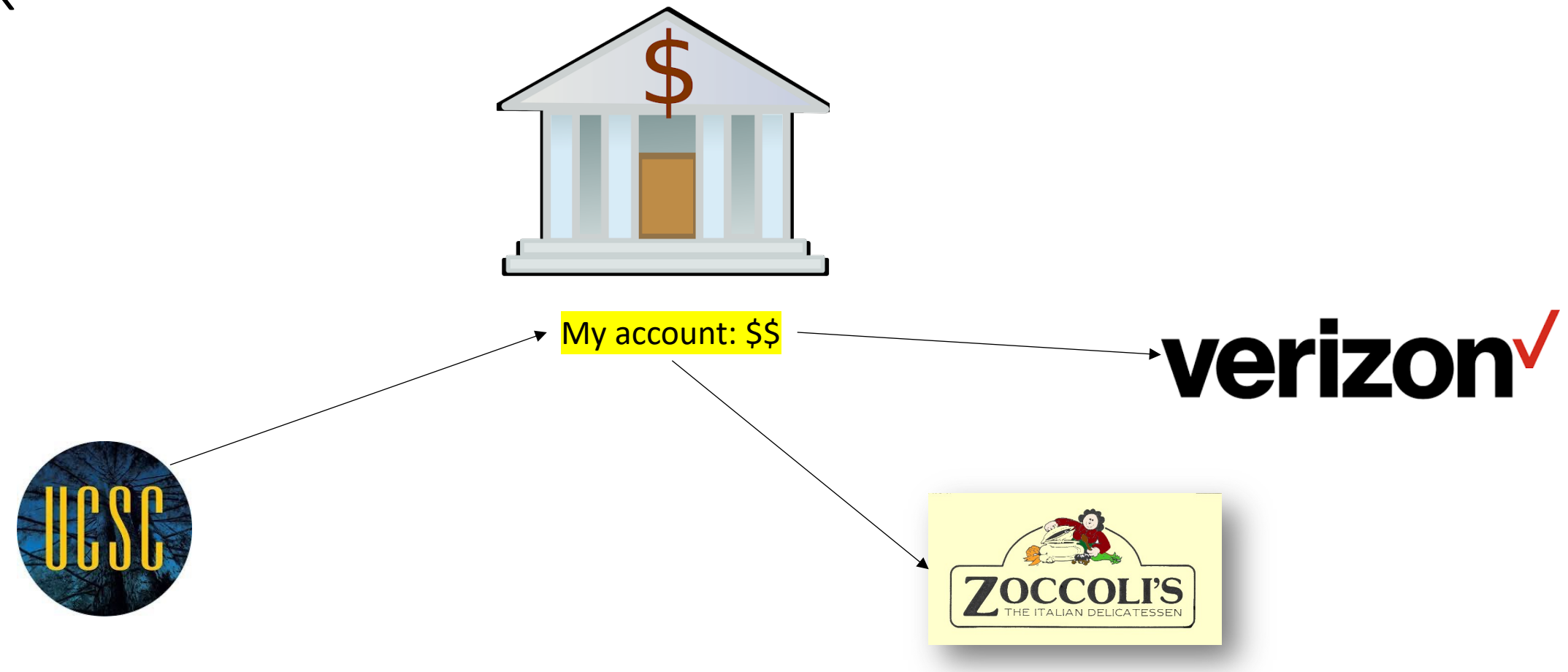
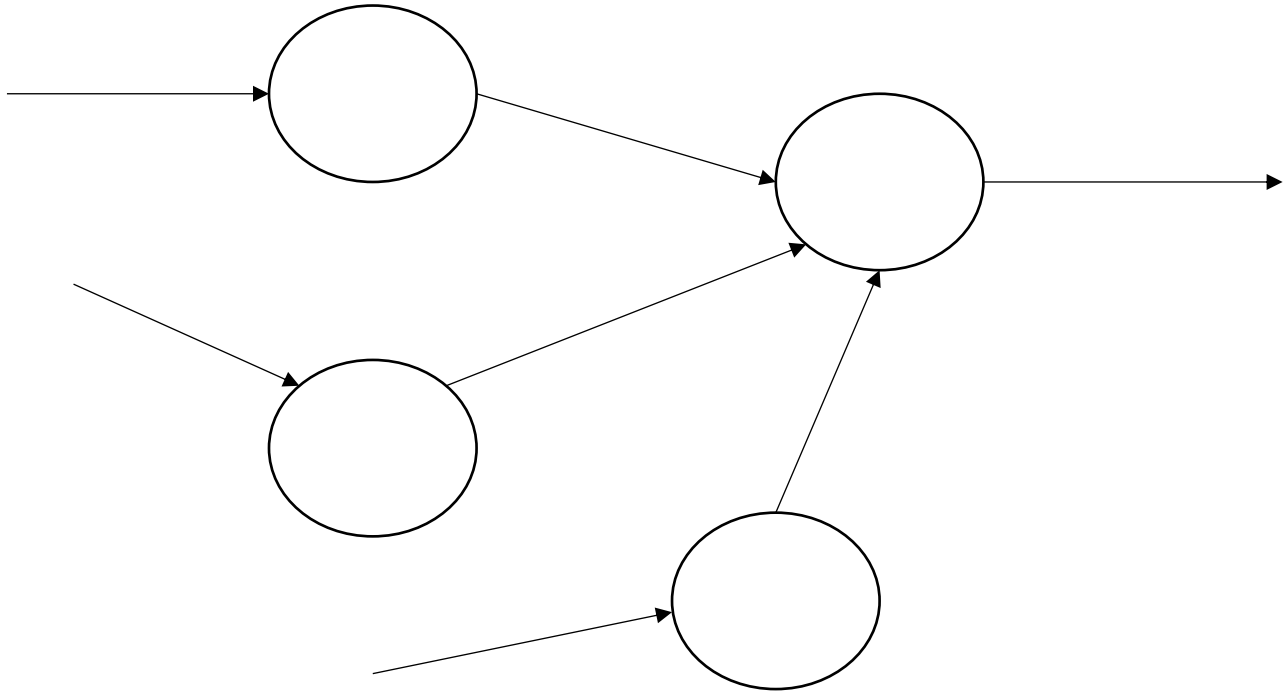


We need a way how to safely share memory

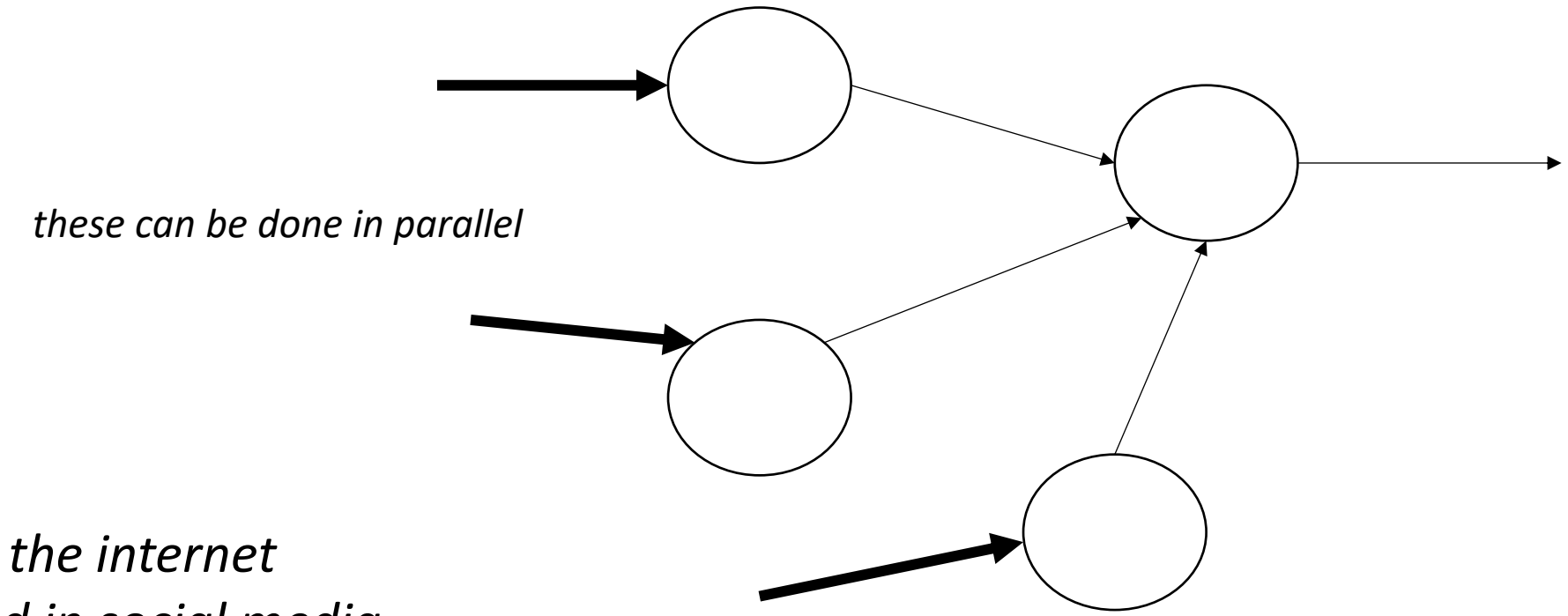
- Graph algorithms



Examples:
Ranking pages on the internet
information spread in social media

We need a way how to safely share memory

- Graph algorithms



Examples:
Ranking pages on the internet
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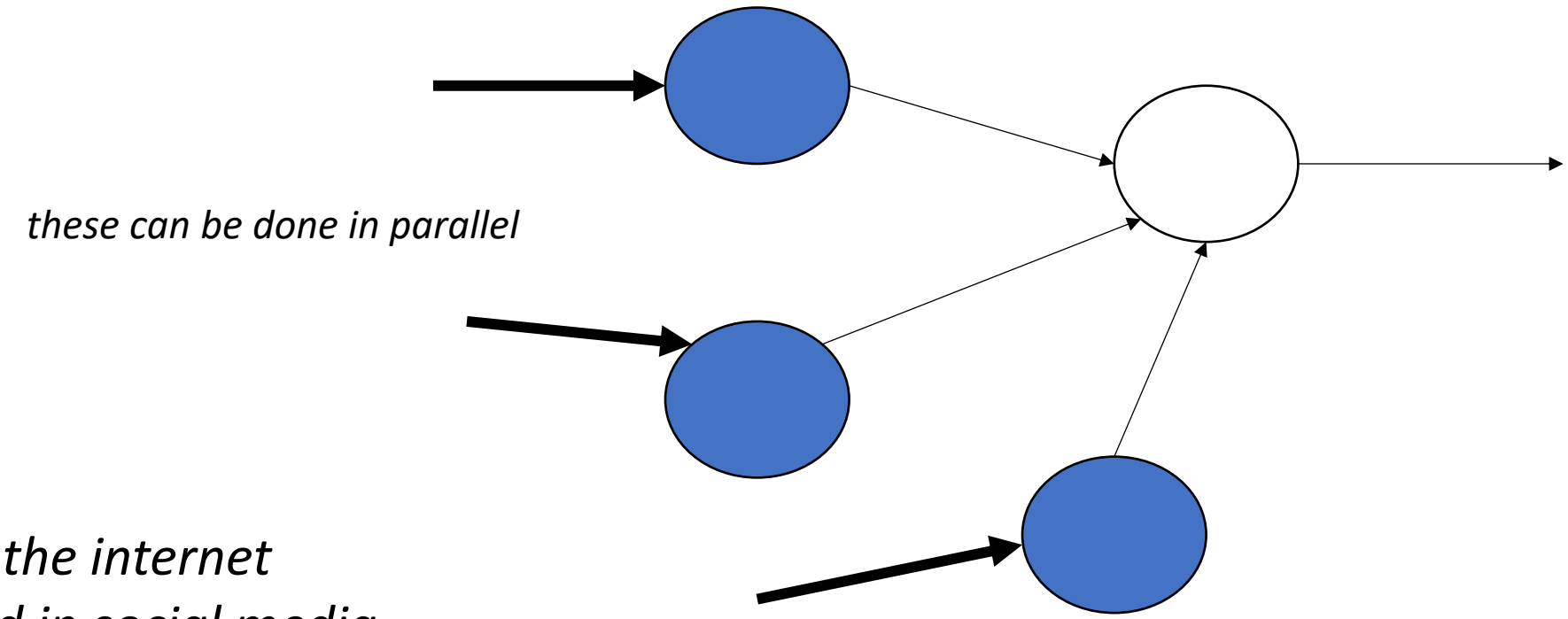
We need a way how to safely share memory

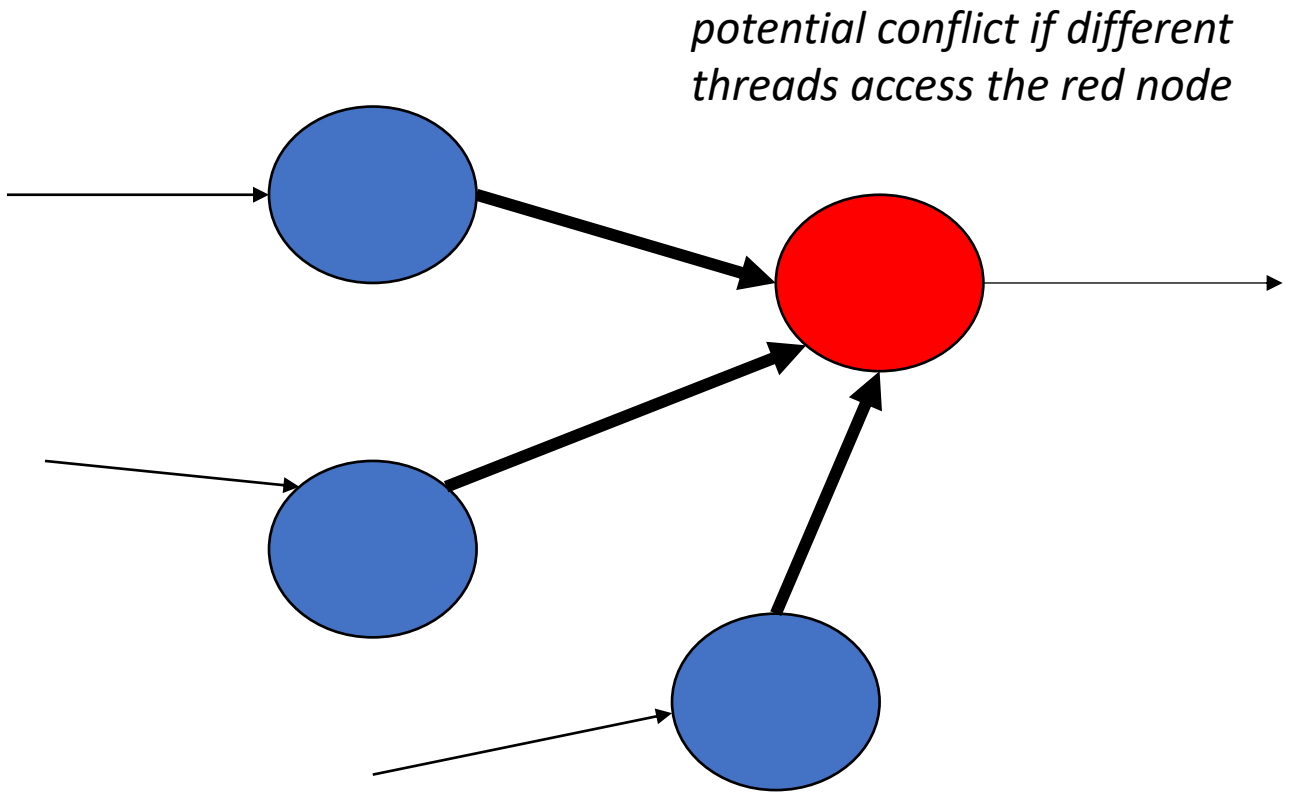
- Graph algorithms



Examples:
Ranking pages on the internet
information spread in social media

We need a way how to safely share memory

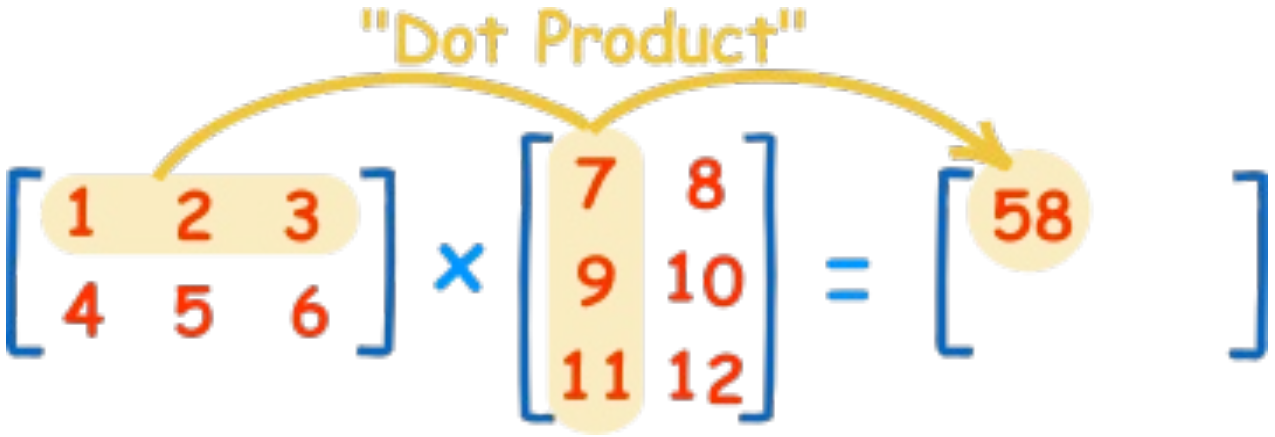
- Graph algorithms



Examples:
Ranking pages on the internet
information spread in social media

We need a way how to safely share memory

- Machine Learning



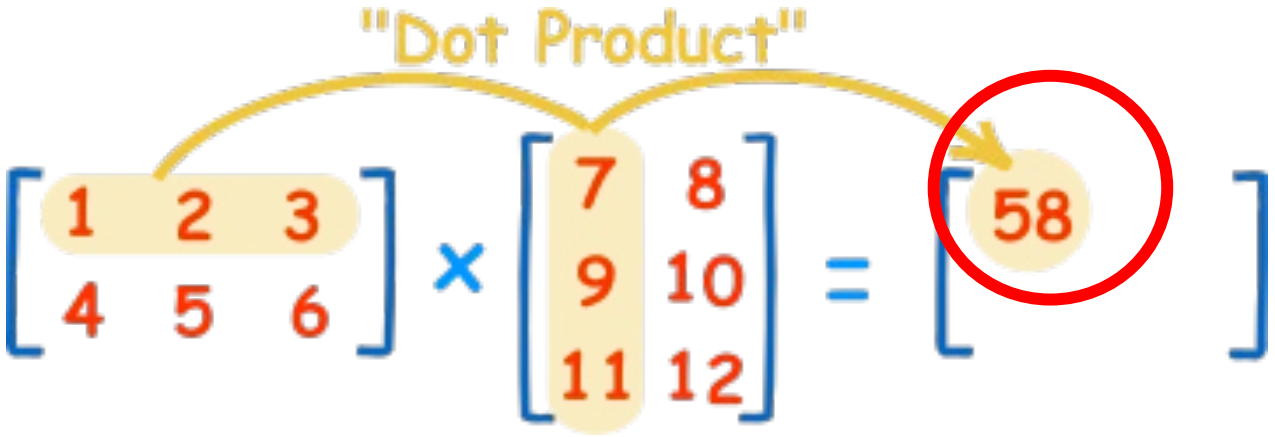
Lots of machine learning is some form of matrix multiplication

image from: https://www.mathsisfun.com/

We need a way how to safely share memory

- Machine Learning

conflict!



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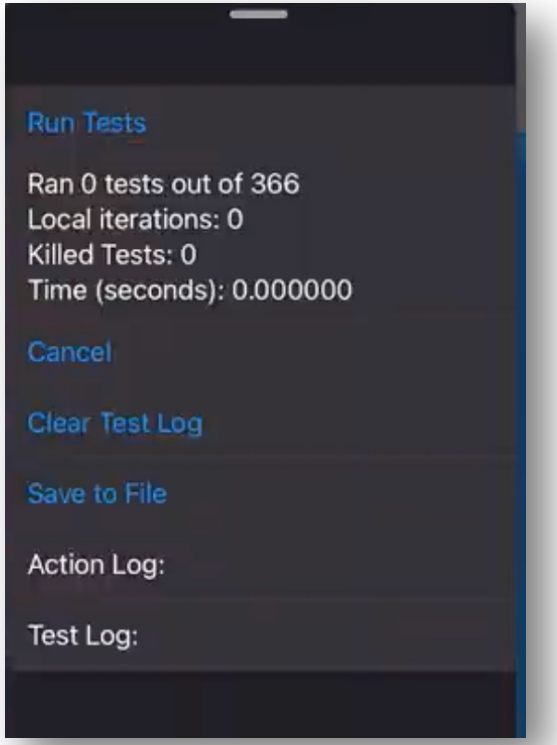
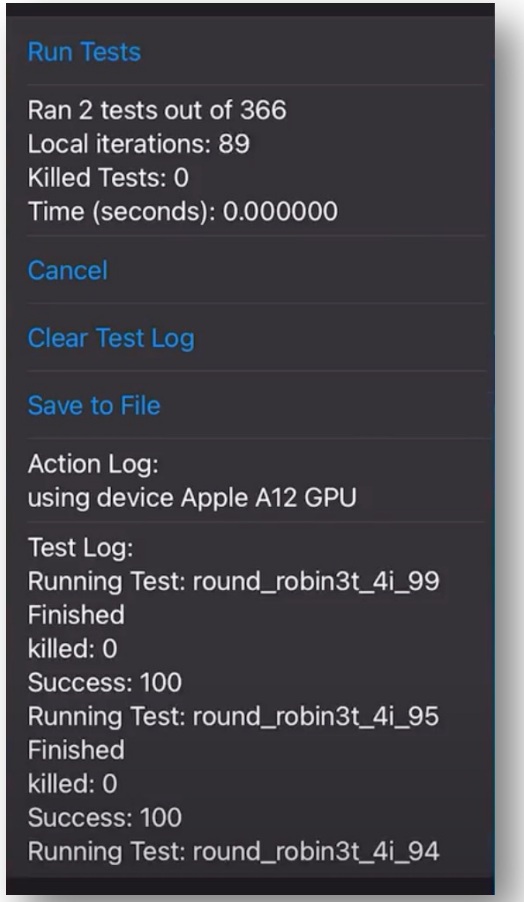
We need a way how to safely share memory

- User interfaces



background process that provides progress updates to the UI.

UI updates must be synchronized!!



Lecture Schedule

- Introduction to thread-level parallelism
- **Data conflicts**
- Mutual exclusion

Dangers of conflicts

- We will illustrate using a running bank account example

Sequential bank scenario

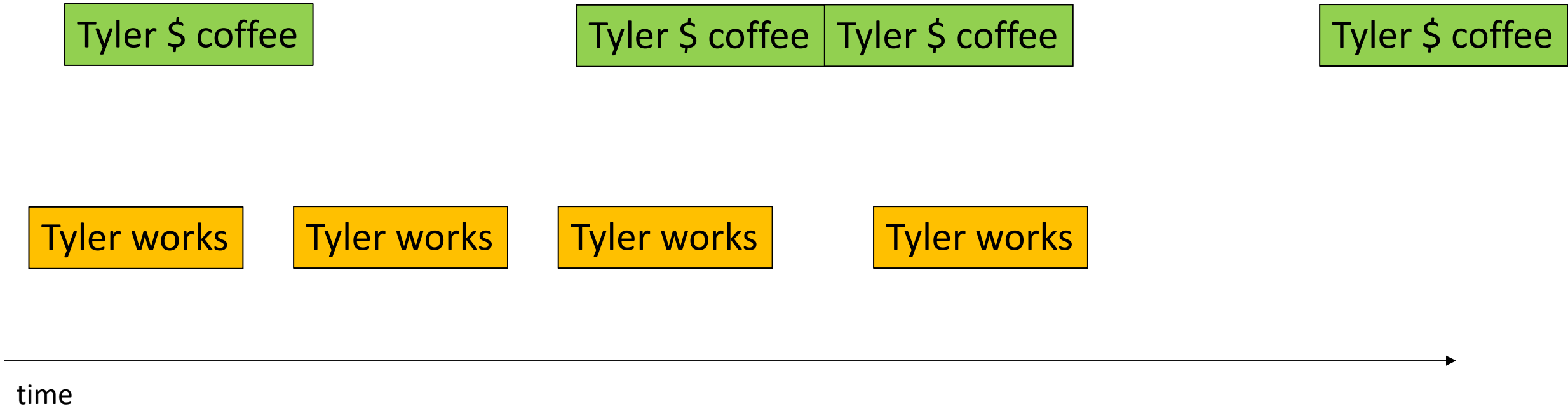
- UCSC deposits $1 in my bank account after every hour I work.
- I buy a cup of coffee ($1) after each hour I work.
- I work 1M hours (which is actually true).
- *I should break even*
- C++ code

Concurrent bank scenario

- UCSC contracts me to work 1M hours.
- My bank is so impressed with my contract that they give me a line of credit. i.e. I can overdraw as long as I pay it back.
- UCSC deposits $1 in my bank account **after** every hour I work.
- I budget $1M to spend on coffee **during** work.

Concurrent bank scenario

This sets up a scheme where I buy coffee concurrently with working



Reasoning about concurrency

- What is going on?
- We need to be able to reason more rigorously about concurrent programs

Code demo

A thread is a sequential program

Tyler's coffee addiction:

```
for (int i = 0; i < HOURS; i++) {
   tylers_account -= 1;
}
```

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account += 1;
}
```

A thread is a sequential program

Tyler's coffee addiction:

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}
```

The execution of a program gives rise to events

Important distinction between program and events

A thread is a sequential program

Tyler's coffee addiction:

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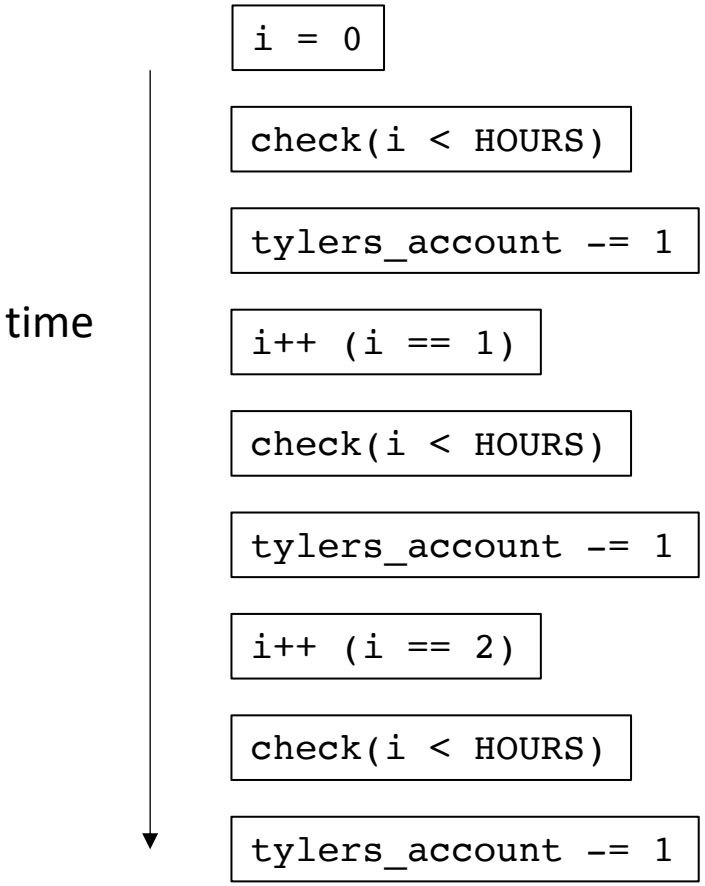

A thread is a sequential program

Tyler's coffee addiction:

```
for (int i = 0; i < HOURS; i++) {
   tylers_account -= 1;
}
```

time

```
i = 0
check(i < HOURS)
tylers_account -= 1
i++ (i == 1)
check(i < HOURS)
tylers_account -= 1
i++ (i == 2)
check(i < HOURS)
tylers_account -= 1
```

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account += 1;
}
```

time

```
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```

A thread is a sequential program

Tyler's coffee addiction:

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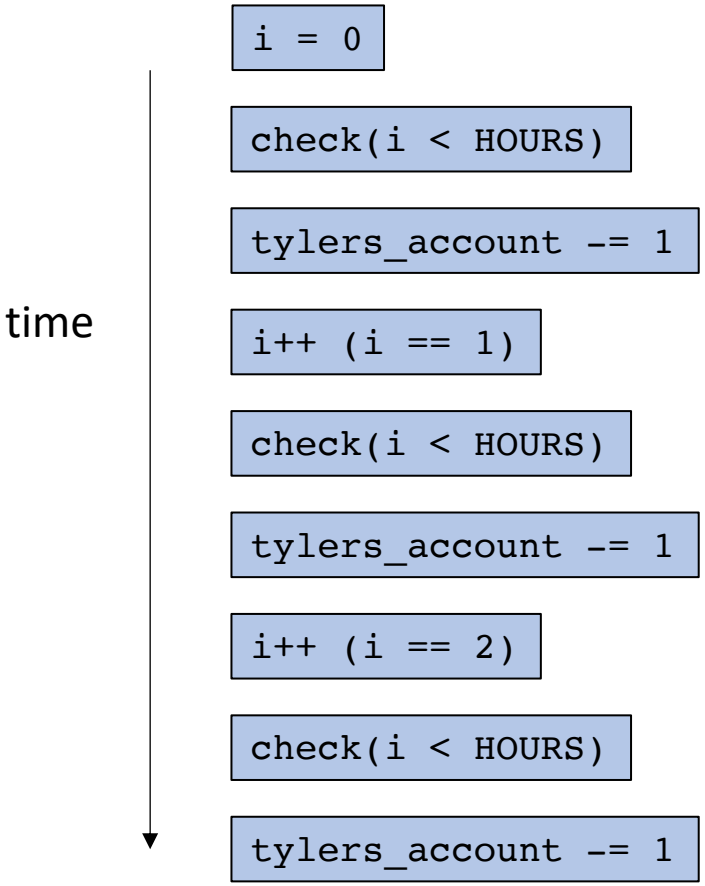
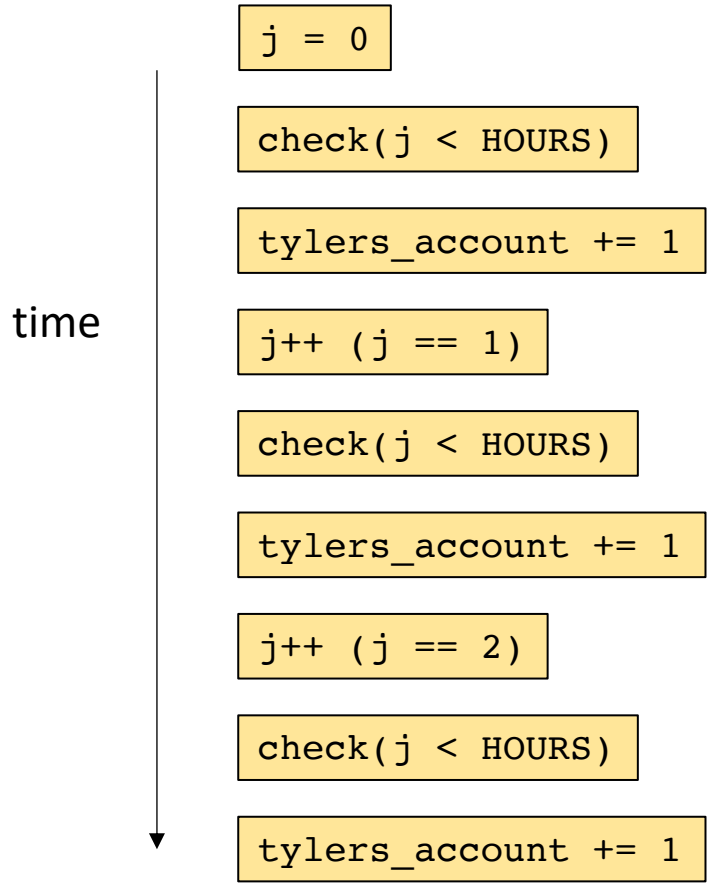


color code events.
coffee thread is blue
payment thread is yellow

Tyler's employer

```
for (int j = 0; j < HOURS; j++) {
   tylers_account += 1;
}
```



A thread is a sequential program

Tyler's coffee addiction:

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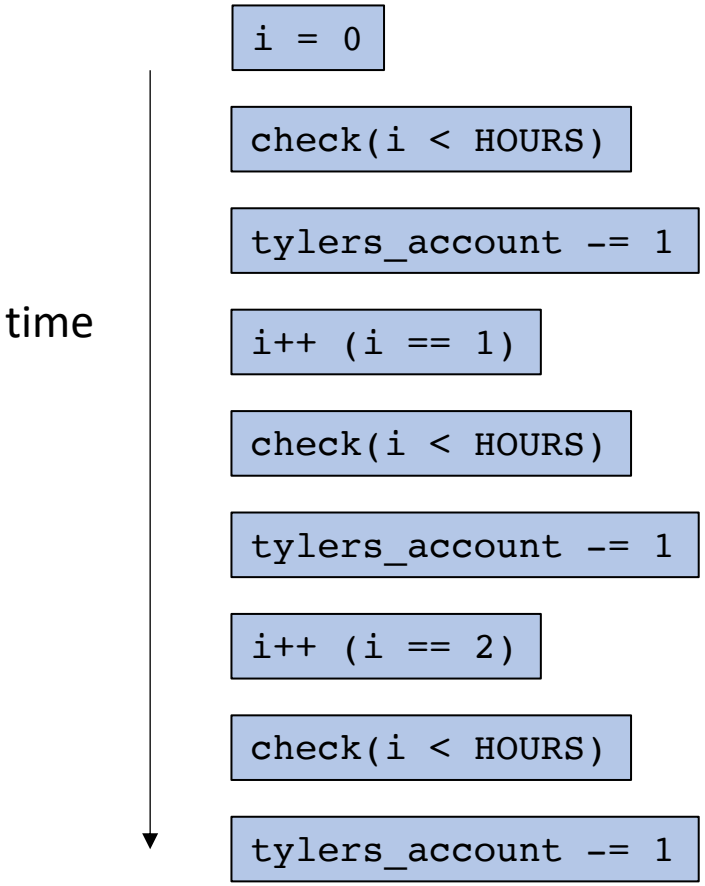
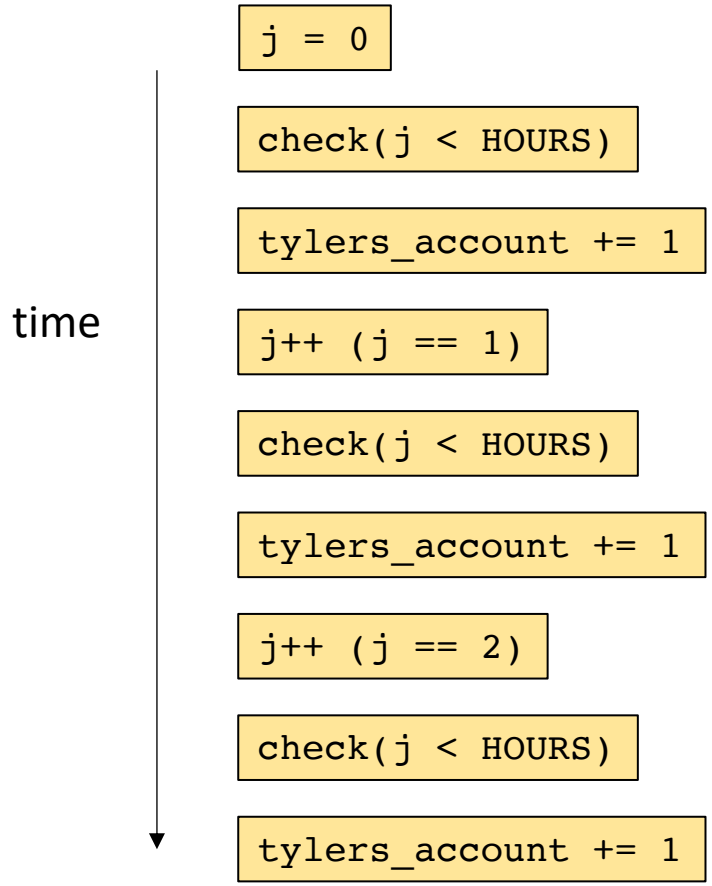
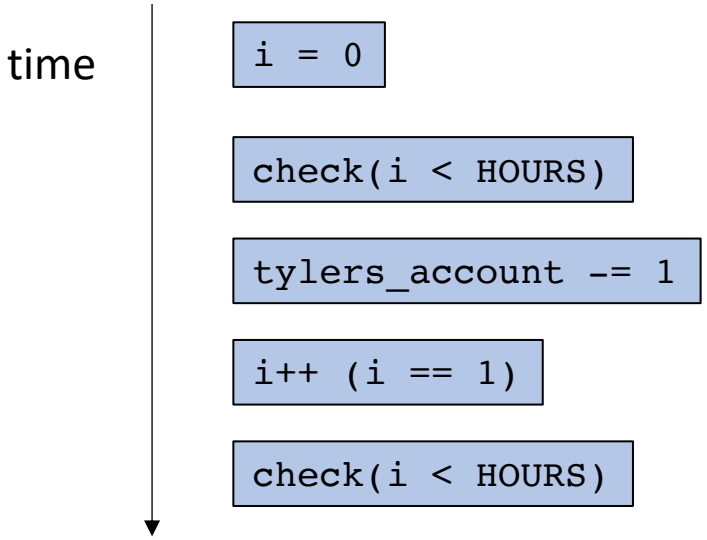


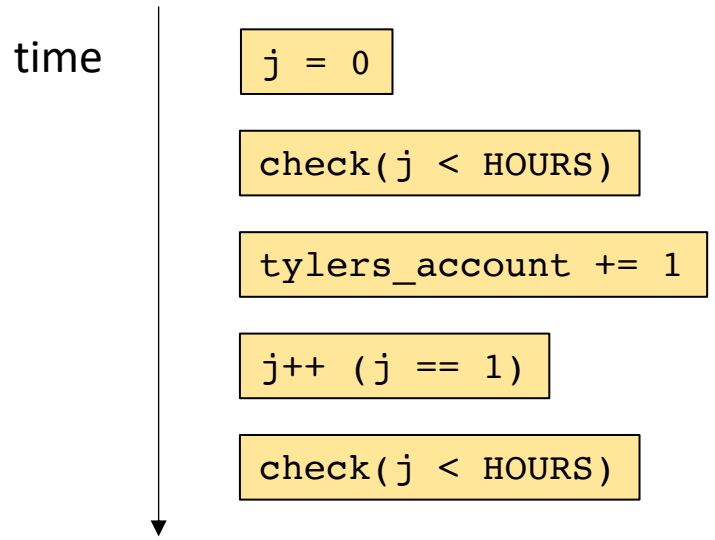
Any interleaving of the events is a valid execution of the concurrent program!

Tyler's employer

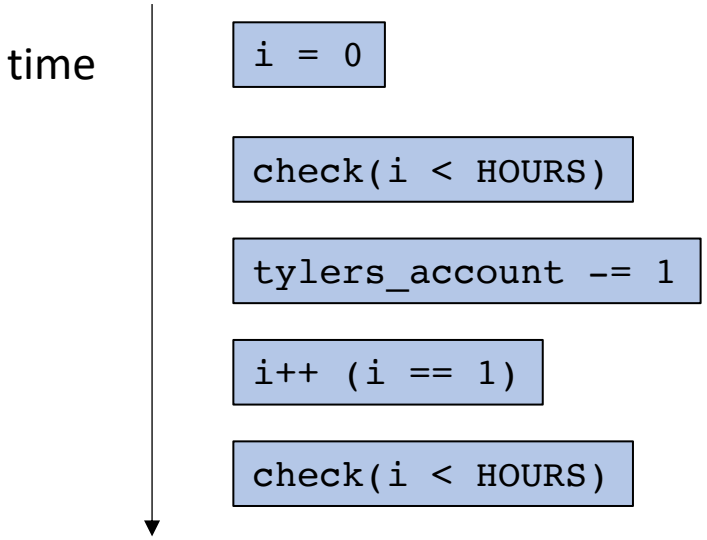
```
for (int j = 0; j < HOURS; j++) {
   tylers_account += 1;
}
```

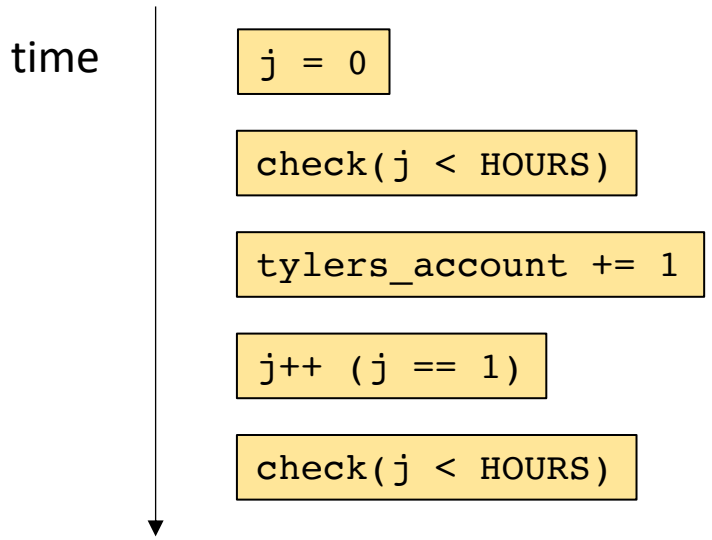




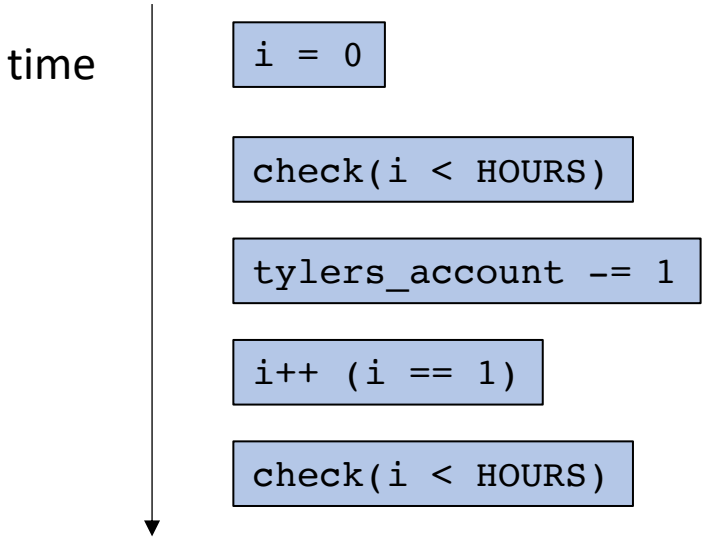


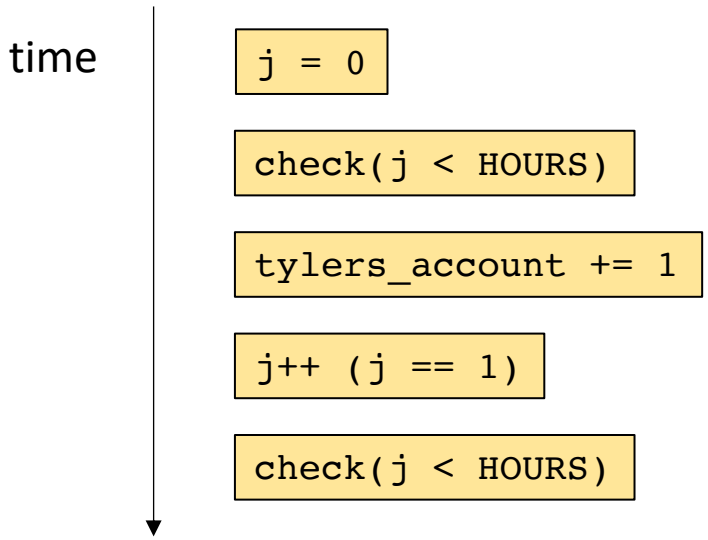
consider just one loop iteration





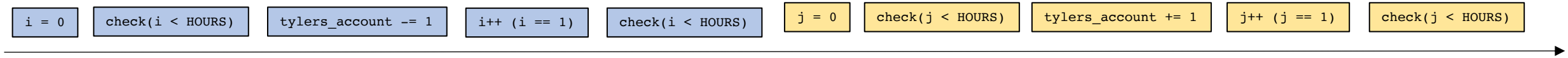
Concurrent execution





one possible execution

Concurrent execution



time

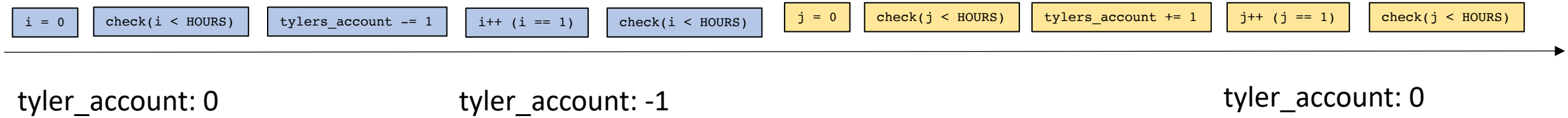
```
i = 0
check(i < HOURS)
tylers_account -= 1
i++ (i == 1)
check(i < HOURS)
```

time

```
j = 0
check(j < HOURS)
tylers_account += 1
j++ (j == 1)
check(j < HOURS)
```

one possible execution

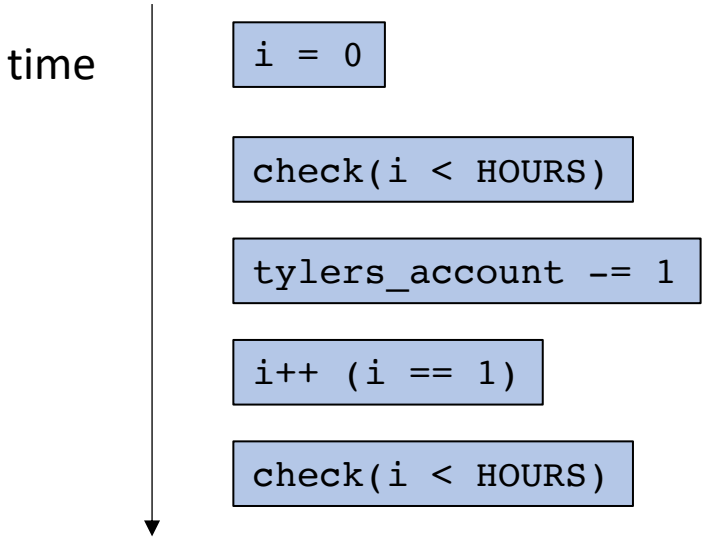
Concurrent execution

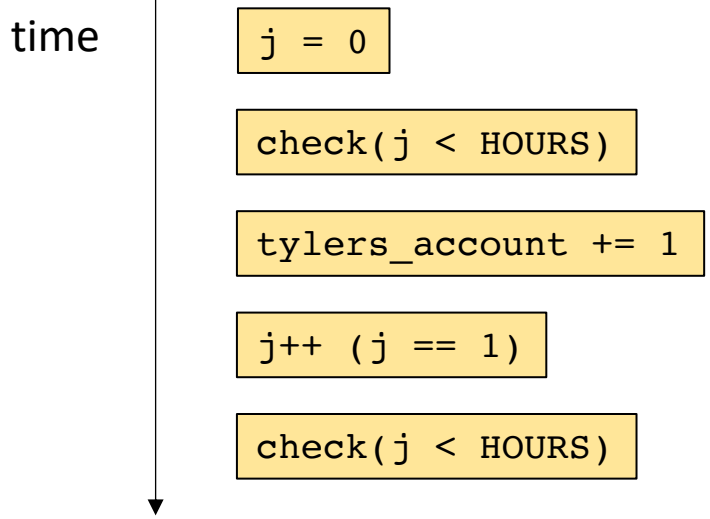


tyler_account: 0

tyler_account: -1

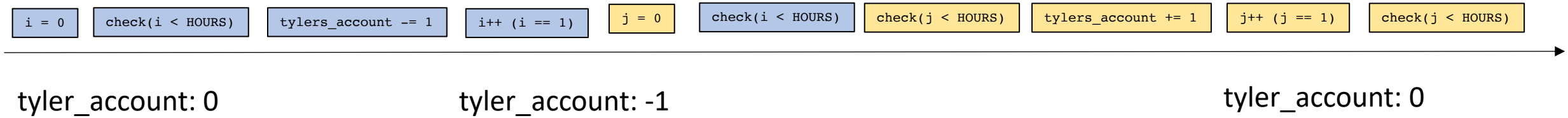
tyler_account: 0





Another possible execution

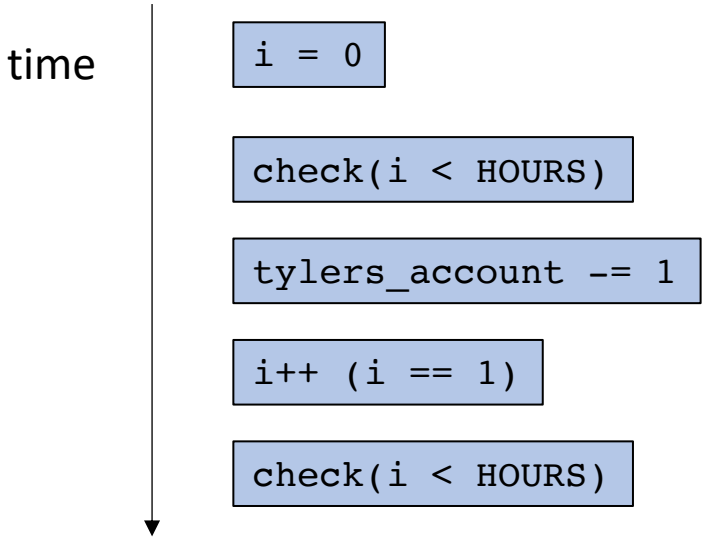
Concurrent execution

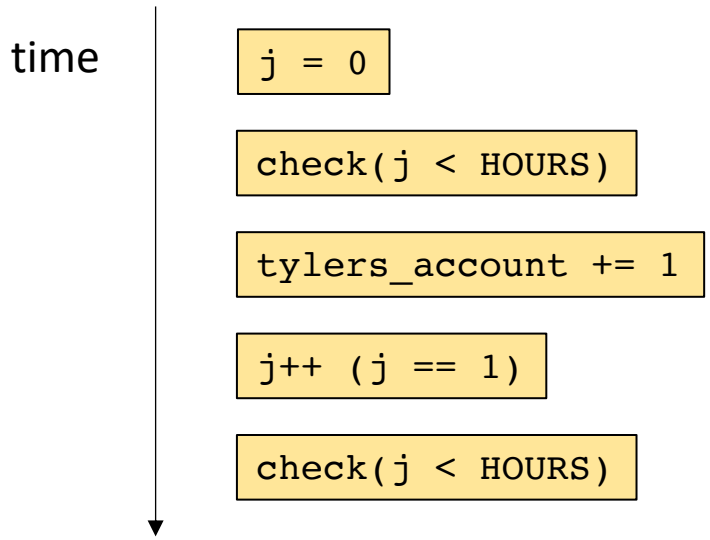


tyler_account: 0

tyler_account: -1

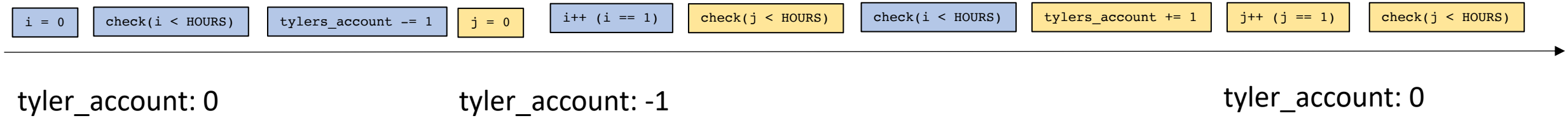
tyler_account: 0





Another possible execution

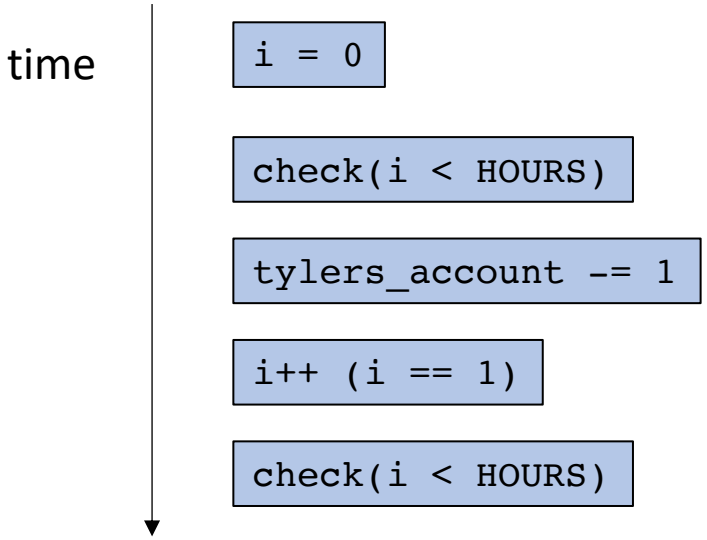
Concurrent execution

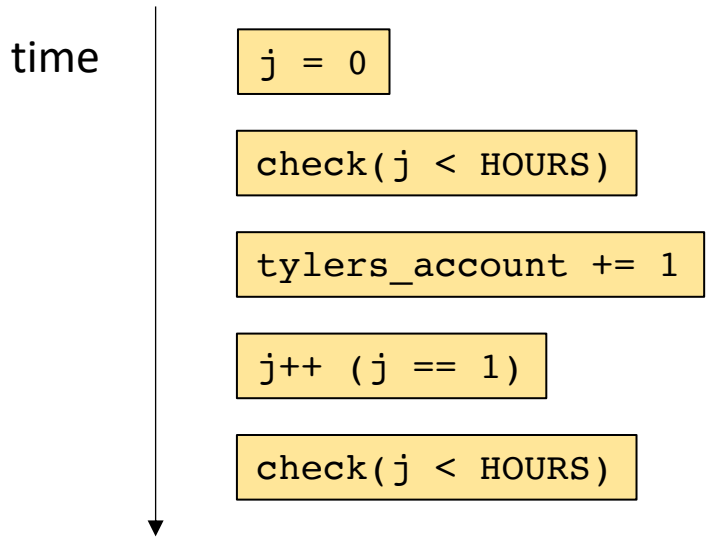


tyler_account: 0

tyler_account: -1

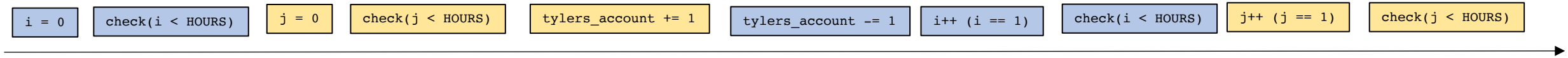
tyler_account: 0





Another possible execution

Concurrent execution



time

```
i = 0
check(i < HOURS)
tylers_account -= 1
i++ (i == 1)
check(i < HOURS)
```

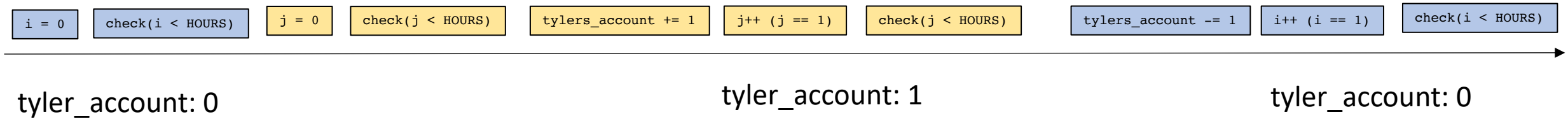
time

```
j = 0
check(j < HOURS)
tylers_account += 1
j++ (j == 1)
check(j < HOURS)
```

Another possible execution

This time my account isn't ever negative

Concurrent execution



tyler_account: 0

tyler_account: 1

tyler_account: 0

time

```
i = 0
check(i < HOURS)
tylers_account -= 1
i++ (i == 1)
check(i < HOURS)
```

time

```
j = 0
check(j < HOURS)
tylers_account += 1
j++ (j == 1)
check(j < HOURS)
```

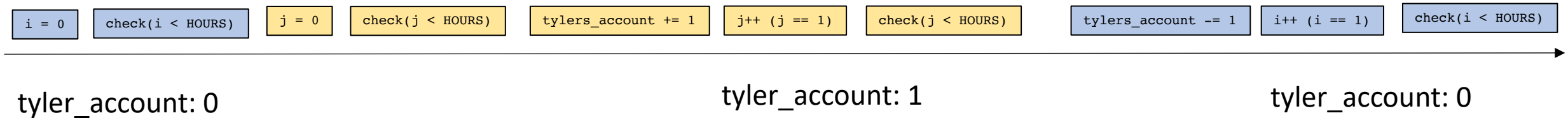
How many possible interleavings?
Combinatorics question:

if Thread 0 has N events
if Thread 1 has M events

$$\frac{(N+M)!}{N!\,M!}$$

Concurrent execution

in our example there are 252 possible interleavings!



tyler_account: 0

tyler_account: 1

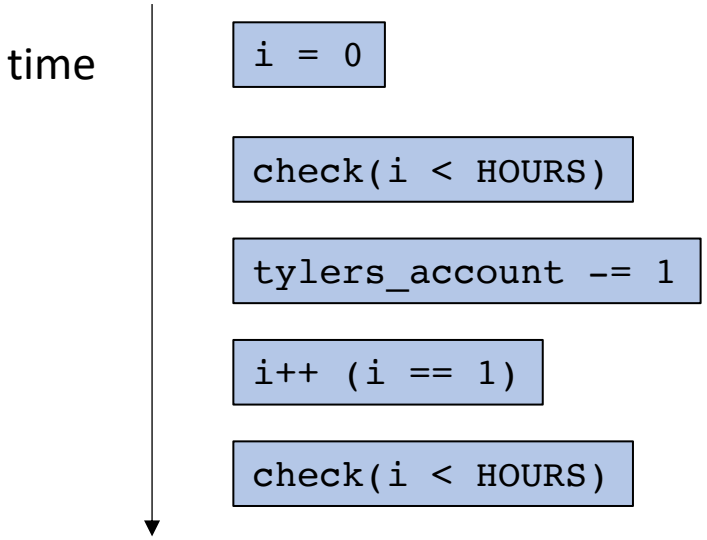
tyler_account: 0

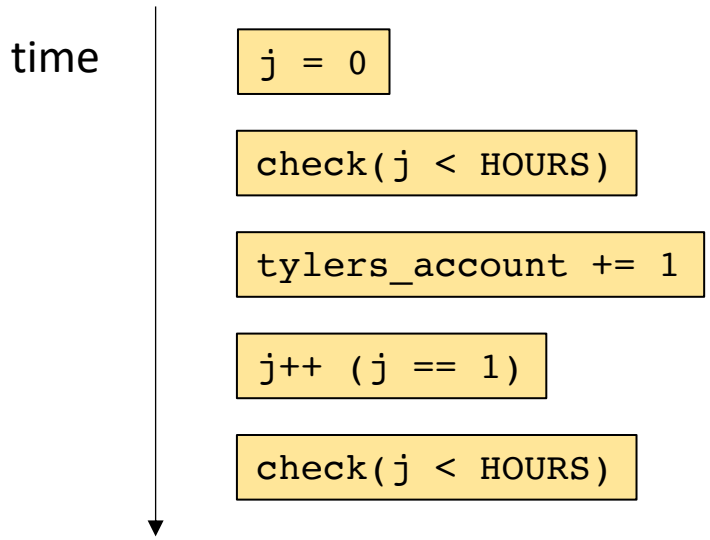
Reasoning about concurrency

- Not feasible to think about all interleavings!
  - Lots of interesting research in pruning, testing interleavings (Professor Flanigan)
  - Very difficult to debug

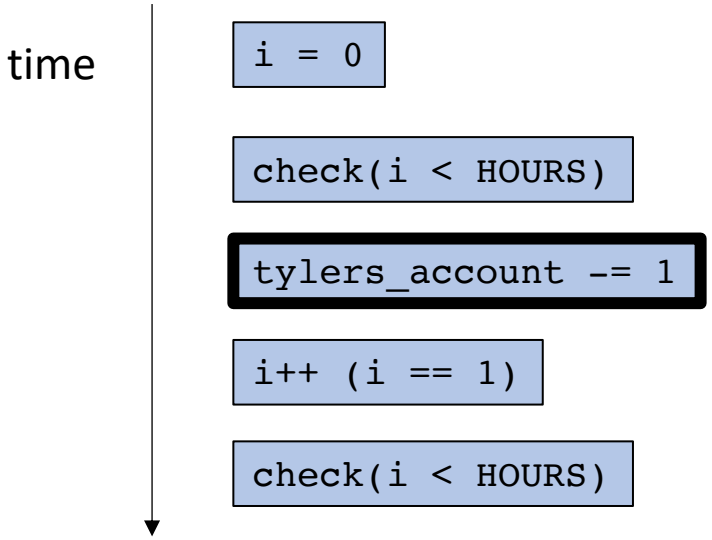
- Think about smaller instances of the problem, reason about the problem as a whole.
  - Tyler spends a total of $1M on coffee
  - Tyler gets paid a total of $1M
  - The balance should be 0!

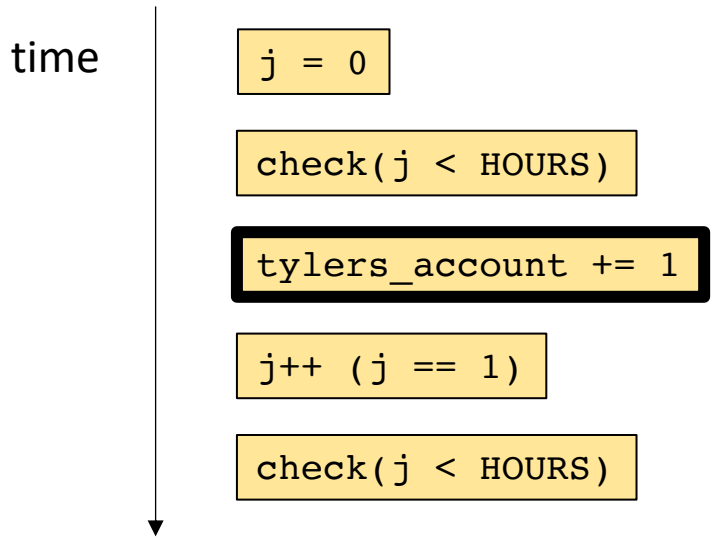
- **Reduce the problem**: *If there's a problem we should be able to see it in a single loop iteration.*



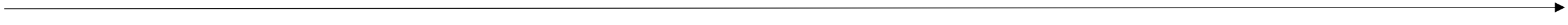


Lets get to the bottom of our money troubles:
For any interleaving, both of the increase and decrease must happen in some order.
So there isn't an interleaving that will explain the issue.





concurrent execution



time

time

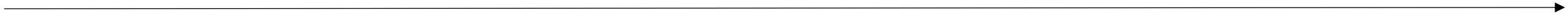
```
tylers_account -= 1
```

time

```
tylers_account += 1
```

Remember 3 address code...

concurrent execution



time

time

```
T0_load = *tylers_account
T0_load -= 1
*tylers_account = T0_load
```

```
tylers_account -= 1
```

time

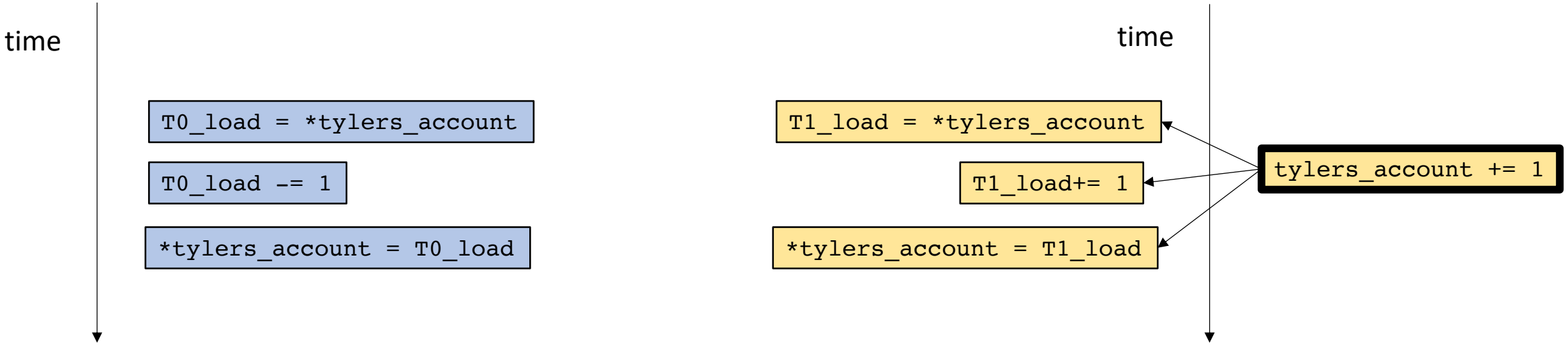
```
tylers_account += 1
```

this line of code needs to be expanded

Remember 3 address code...

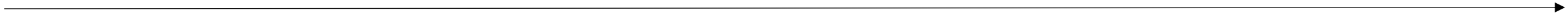
concurrent execution

time



Remember 3 address code...

concurrent execution



time

time

```
T0_load = *tylers_account
```

```
T0_load -= 1
```

```
*tylers_account = T0_load
```

time

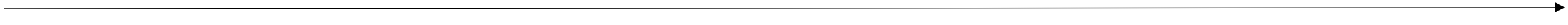
```
T1_load = *tylers_account
```

```
T1_load+= 1
```

```
*tylers_account = T1_load
```

What if we interleave these instructions?

concurrent execution



time

time

```
T0_load = *tylers_account
```

```
T0_load -= 1
```

```
*tylers_account = T0_load
```

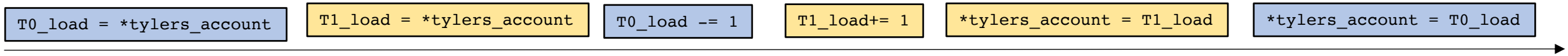
time

```
T1_load = *tylers_account
```

```
T1_load+= 1
```

```
*tylers_account = T1_load
```

concurrent execution



time

time

```
T0_load = *tylers_account
```

```
T0_load -= 1
```

```
*tylers_account = T0_load
```

time

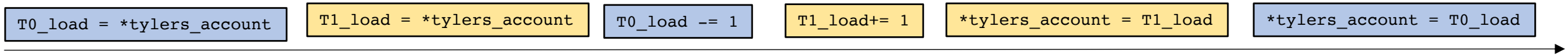
```
T1_load = *tylers_account
```

```
T1_load+= 1
```

```
*tylers_account = T1_load
```

tylers_account has -1 at the end of this interleaving!

concurrent execution



time

What now?

- Data conflicts lead to many different types of issues, not just strange interleavings.
  - Data tearing
  - Instruction reorderings
  - Compiler optimizations

- Rather than reasoning about data conflicts, we will protect against them using ***synchronization***.

Lecture Schedule

- Introduction to thread-level parallelism
- Data conflicts
- **Mutual exclusion**

Synchronization

- A scheme where several actors agree on how to safely share a resource during concurrent access.

- Must define what “safely” means.

- Example:
  - Two neighbors sharing a yard between a dog and cat
  - Sharing refrigerator with roommates
  - An account balance that is written to and read from
  - Chapter 1 in text book

Mutexes

- A synchronization object to protect against data conflicts

Simple API:

```
lock()
unlock()
```

- Before a thread accesses the shared memory, it should call `lock()`
- When a thread is finished accessing the shared data, it should call `unlock()`

A thread is a sequential program

Tyler's coffee addiction:

```
tylers_account -= 1;
```

Tyler's employer

```
tylers_account += 1;
```

assume a global mutex object `m`
protect the account access with the mutex

A thread is a sequential program

Tyler's coffee addiction:

```
m.lock();
tylers_account -= 1;
m.unlock();
```

Tyler's employer

```
m.lock();
tylers_account += 1;
m.unlock();
```

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A thread is a sequential program

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tylers_account += 1;
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```

time

A thread is a sequential program

Tyler's coffee addiction:

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Tyler's employer

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m.lock();
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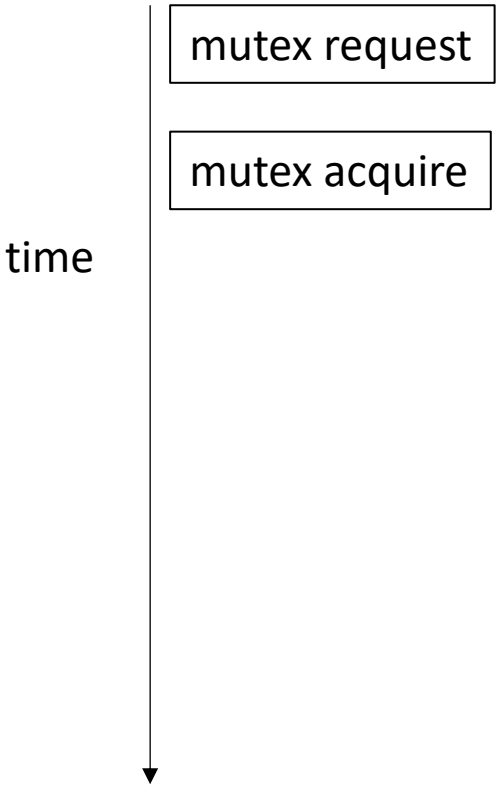

A thread is a sequential program

Tyler's coffee addiction:

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tylers_account -= 1;
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Tyler's employer

```
m.lock();
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```
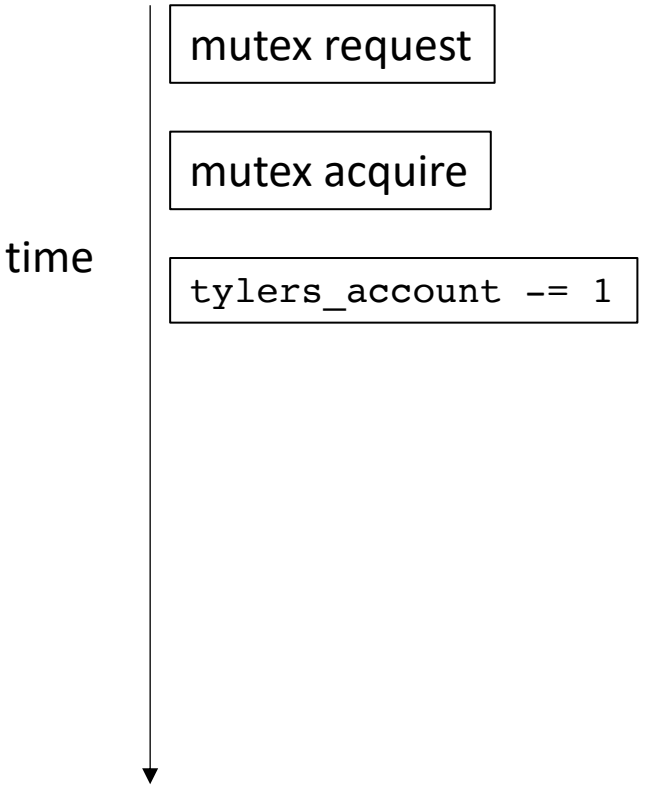
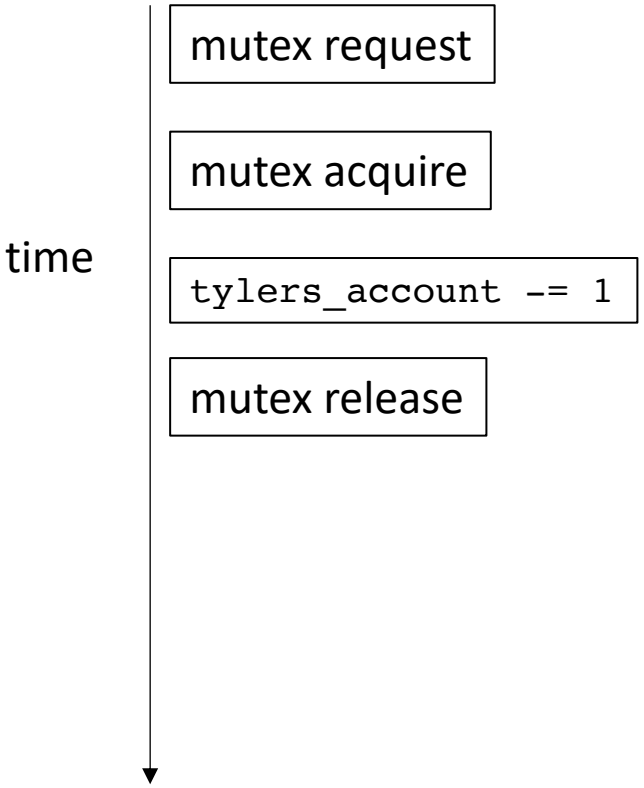



A thread is a sequential program

Tyler's coffee addiction:

```
m.lock();
tylers_account -= 1;
m.unlock();
```



Tyler's employer

```
m.lock();
tylers_account += 1;
m.unlock();
```

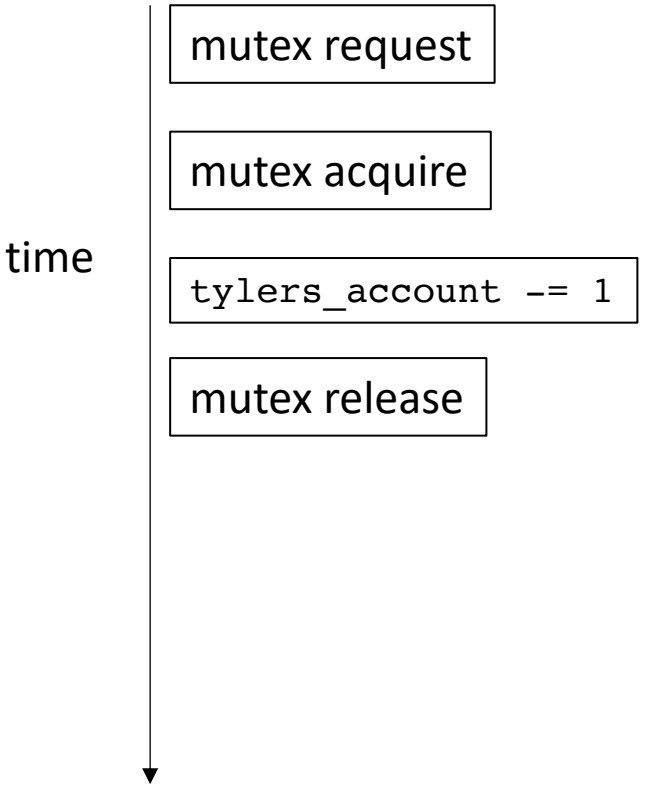
A thread is a sequential program

Tyler's coffee addiction:

```
m.lock();
tylers_account -= 1;
m.unlock();
```

Tyler's employer

```
m.lock();
tylers_account += 1;
m.unlock();
```



A thread is a sequential program

Tyler's coffee addiction:

```
m.lock();
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m.unlock();
```
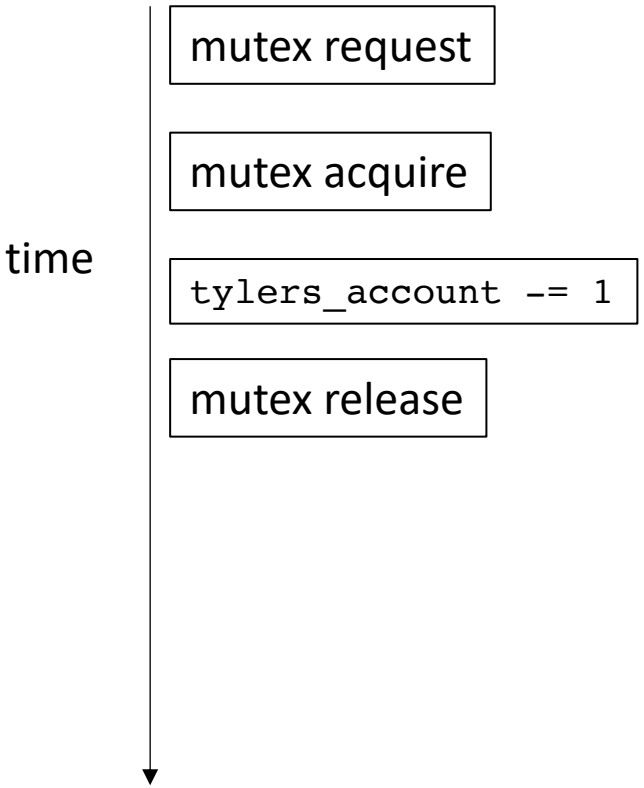
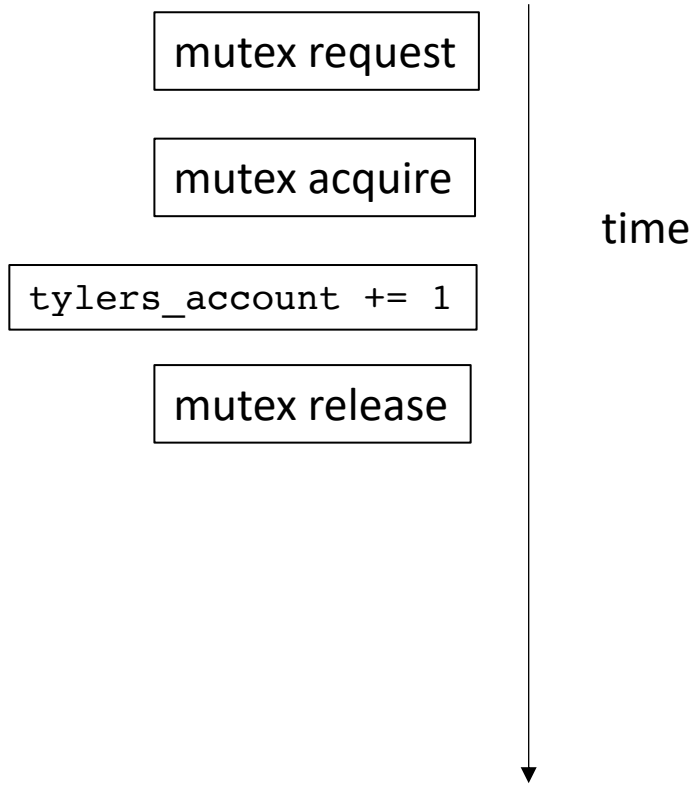



Tyler's employer

```
m.lock();
tylers_account += 1;
m.unlock();
```



concurrent execution

time

concurrent execution

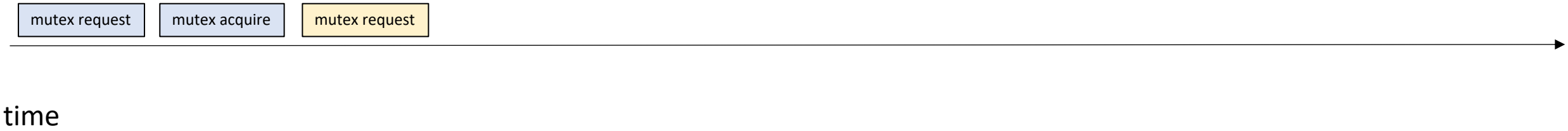
time

at this point, thread 0 holds the mutex.
another thread cannot acquire the mutex until thread 0 releases the mutex
*also called the **critical section.***

concurrent execution

Allowed to request

concurrent execution



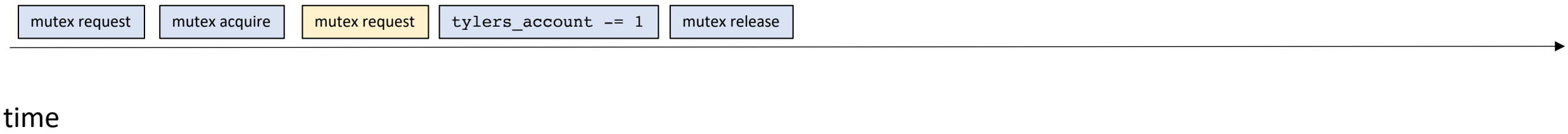
Allowed to request

concurrent execution

disallowed!

Thread 0 has released the mutex

concurrent execution



time

mutex request

mutex acquire

`tylers_account -= 1`

mutex release

mutex request

mutex acquire

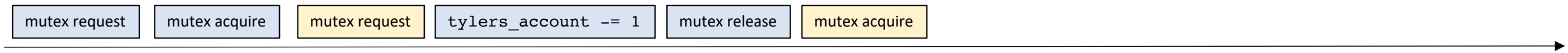
`tylers_account += 1`

mutex release

time

Thread 1 can take the mutex and enter the critical section

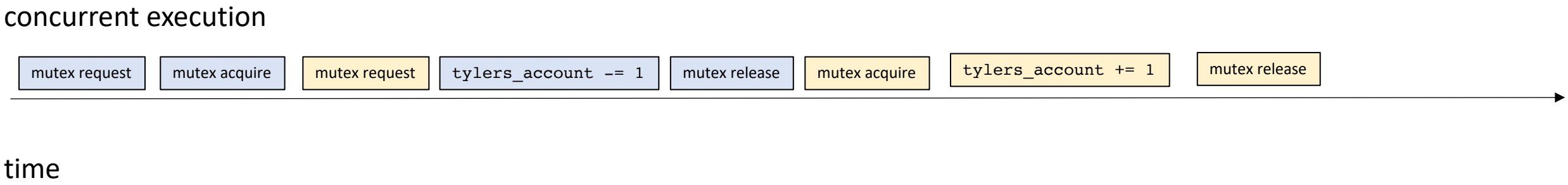
concurrent execution



time

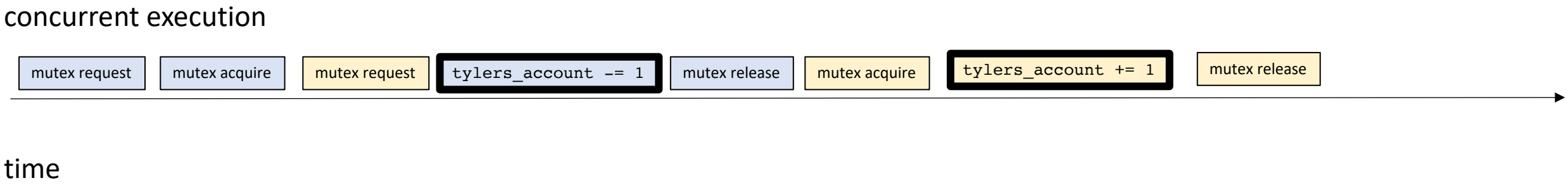
A mutex restricts the number of allowed interleavings
Critical section are mutually exclusive: i.e. they cannot interleave

Thread 1 can take the mutex
and enter the critical section



It means we don't have to think about 3 address code

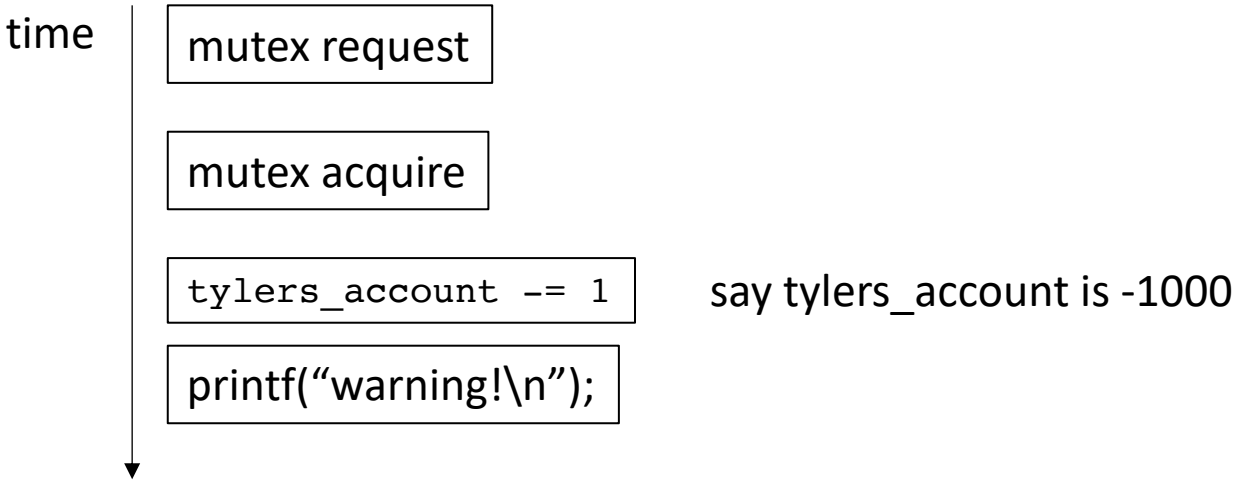
Thread 1 can take the mutex and enter the critical section



Make sure to unlock your mutex!

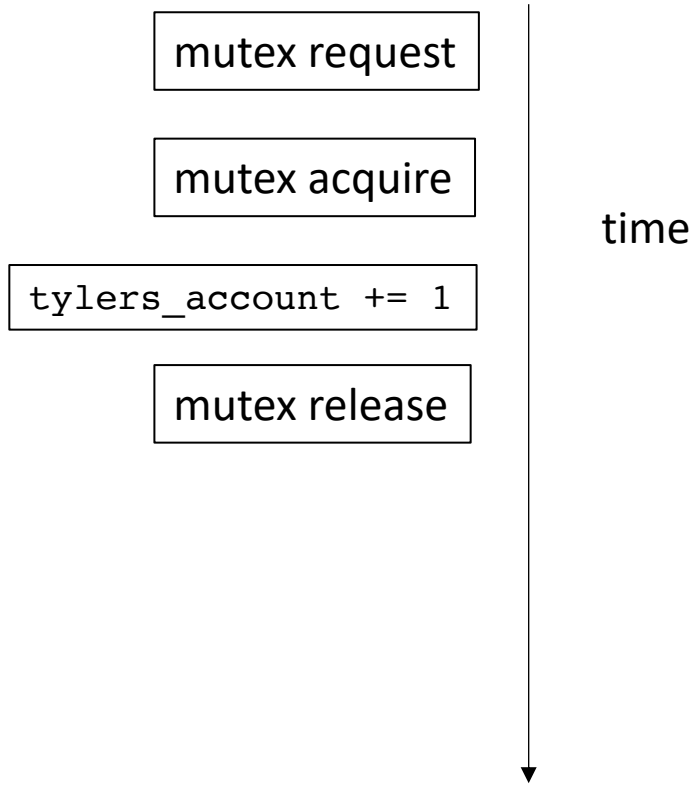
Tyler's coffee addiction:

```
m.lock();
tylers_account -= 1;
if (tylers_account < -100) {
  printf("warning!\n");
  return;
}
m.unlock();
return;
```



Tyler's employer

```
m.lock();
tylers_account += 1;
m.unlock();
```



time

mutex request

mutex acquire

```
tylers_account -= 1
```

printf(“warning!\n”);

mutex request

mutex acquire

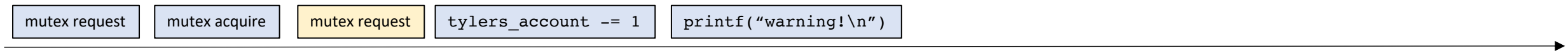
```
tylers_account += 1
```

mutex release

time

Thread 1 is stuck!

concurrent execution



Thanks!

- Next time:
  - Formal properties of mutual exclusion
  - Using multiple mutexes
  - Atomic RMWs

- Keep in mind HW 1 is due on Thursday

- Remember to do the quiz