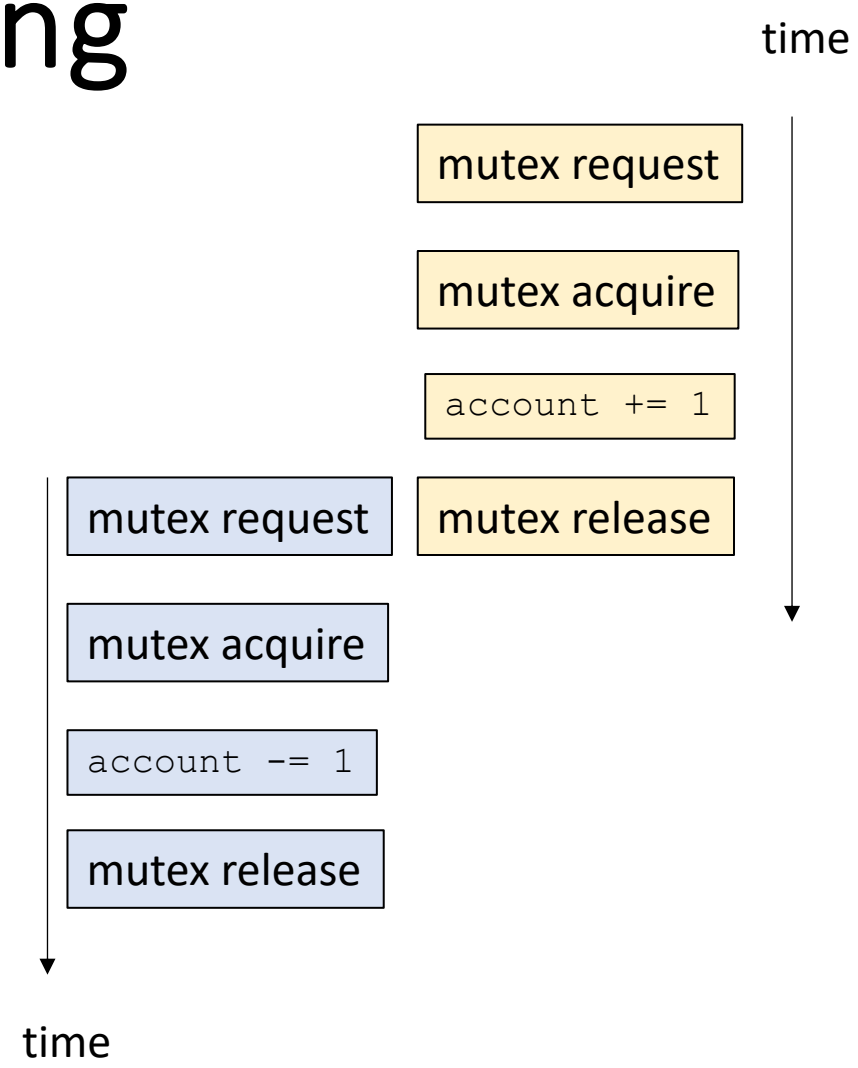
CSE113: Parallel Programming

Jan. 31, 2024

- **Topics**:
  - RMW mutex implementations



Announcements

- Third lecture in Module 2
- HW 1 should be in
- HW 2 was released yesterday at midnight. You can start on part 1, probably part 2 by end of today.
- Office hours available. Start early!

Announcements

- Office hour etiquette
  - If you sign up for a slot, please attend
  - It’s okay to take your name off
    - Even if it is 1 minute before.
  - Some people are going without help because of this
  - Please make an effort, otherwise we’ll have to implement different protocols

Announcements

- Midterm is in 1.5 weeks (Feb 12)
  - In-person test
  - 3 pages of notes front and back (but no memorization questions)
  - 10% of your grade
  - 5 or 6 short answer questions (e.g., how to reverse a linked list)

Previous quiz + review

Previous quiz

Which one of the answers is NOT a property of mutexes?

- ◯ Deadlock Freedom
- ◯ Mutual Exclusion
- ◯ Deterministic Execution
- ◯ Starvation Freedom

Properties of mutexes

Recap: three properties

- **Mutual Exclusion**: Two threads cannot be in the critical section at the same time
- **Deadlock Freedom**: If a thread has requested the mutex, and no thread currently holds the mutex, the mutex must be acquired by one of the requesting threads
- **Starvation Freedom** (*optional*): A thread that requests the mutex must eventually obtain the mutex.

Previous quiz

We should aim to make mutual exclusion regions as short as possible because of the caching overhead of locks.

- ◯ True
- ◯ False

Mutex Performance

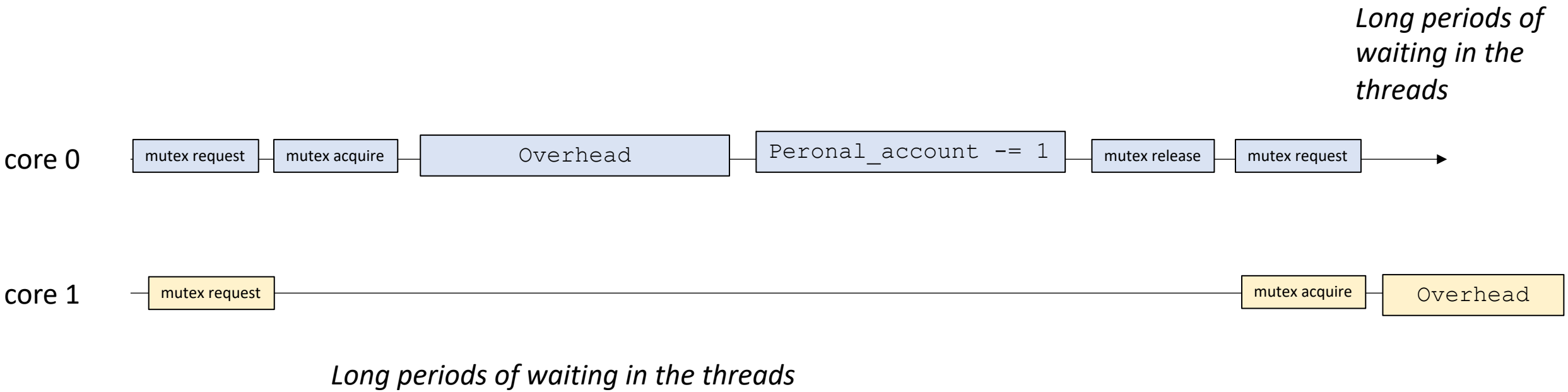
Try to keep mutual exclusion sections small!

Code example with overhead

Mutex Performance

Try to keep mutual exclusion sections small! Protect only data conflicts!

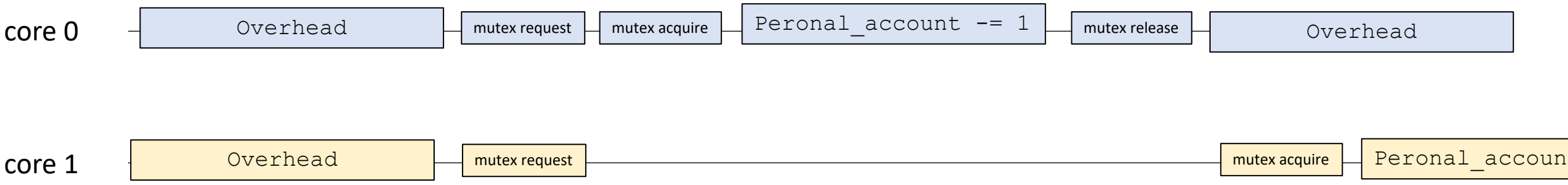
Code example with overhead



Mutex Performance

Try to keep mutual exclusion sections small! Protect only data conflicts!

Code example with overhead



overlap the overhead (i.e. computation without any data conflicts)

Previous quiz

If you run your code with the thread sanitizer and if it doesn't report any issues, then your code is guaranteed to be free from data-conflicts

- ◯ True
- ◯ False

Previous quiz

It is required to use atomic types inside of critical sections

- ◯ True
- ◯ False

Our primitive instructions

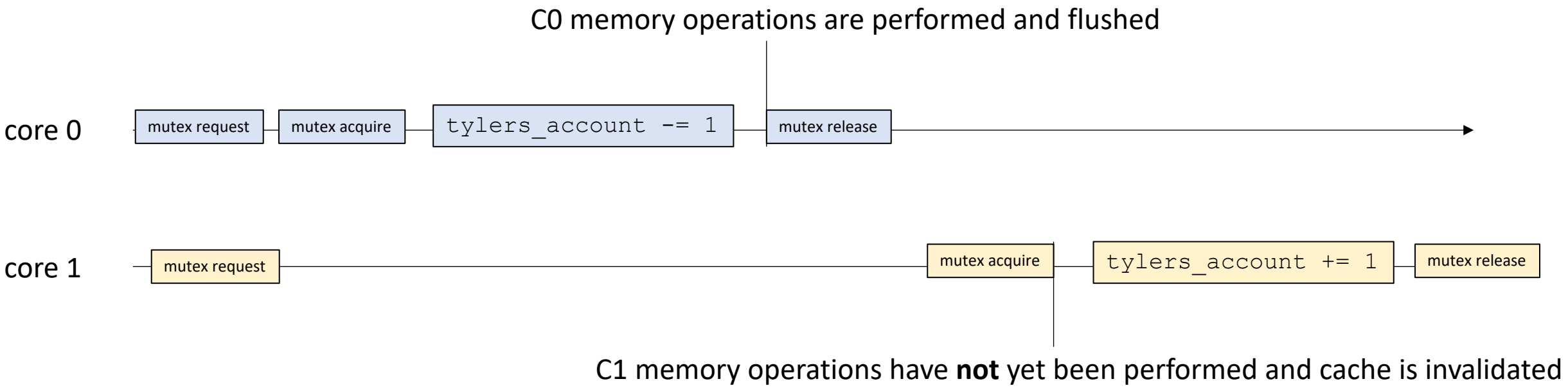
- Types: atomic_int

- Interface (C++ provides overloaded operators):
  - load
  - store

- Properties:
  - loads and stores will always go to memory.
  - compiler memory fence
  - hardware memory fence

Atomics

- What do those fences (compiler and memory) give us?
- Atomics were designed so that we can implement things like mutexes!



Previous quiz

Write 1 or 2 sentences about whether you agree or disagree with the following sentence and why:

"Because atomic data types can safely be accessed concurrently, we should mark all our variables as atomic just to be safe."

Atomic properties

- loads and stores will always go to memory
- Compiler example, performance difference

```
int foo(int x) {
  x = 0;
  for (int i = 0; i < 2048; i++) {
    x++;
  }
  return x;
}
```

```
int foo(atomic x) {
  x.store(0);
  for (int i = 0; i < 2048; i++) {
    int tmp = x.load();
    tmp++;
    x.store(tmp);
  }
  return x.load();
}
```

Previous quiz

Write a few sentences about how you can reason about the correctness of a mutex implementation.

Mutex Implementations

Finally, we can can make a mutex that works:

Use flags to mark interest

Use victim to break ties

Called the **Peterson Lock**

Mutex Implementations

```
class Mutex {
public:
  Mutex() {
    victim = -1;
    flag[0] = flag[1] = 0;
  }

  void lock();
  void unlock();


private:
  atomic_int victim;
  atomic_bool flag[2];
};
```

Initially:
No victim and no threads are interested in the critical section

flags and victim

Mutex Implementations

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
```

j is the other thread

Mark ourself as interested

volunteer to be the victim in case of a tie

Spin only if:
there was a tie in wanting the lock,
and I won the volunteer raffle to spin

Mutex Implementations

```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
}
```

mark ourselves as uninterested

previous flag issue

```
void lock() {
  int i = thread_id;
  flag[i].store(1);
  int j = i == 0 ? 1 : 0;
  while (flag[j].load() == 1);
}
```

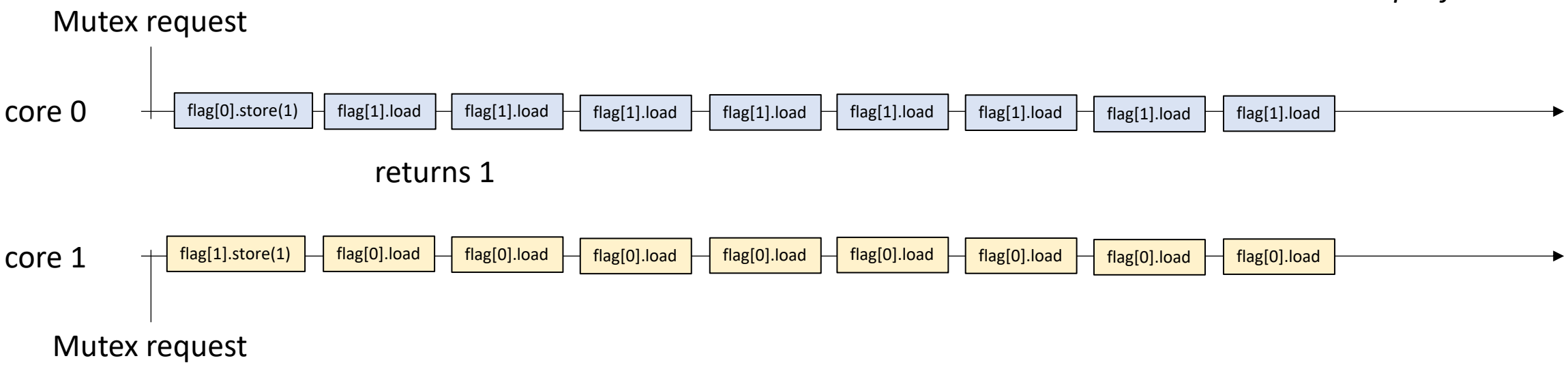
```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
}
```

Thread 0:
`m.lock();`
`m.unlock();`

Thread 1:
`m.lock();`
`m.unlock();`

how does petersons solve this?

Both will spin forever!



Tie breaking with victim

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
```

```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
}
```

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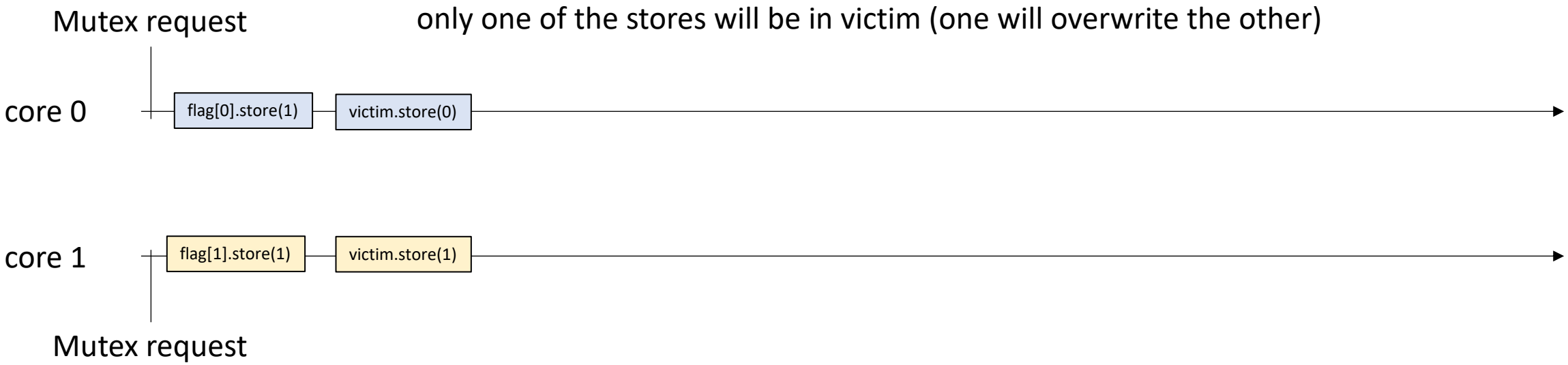

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  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
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}
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void unlock() {
  int i = thread_id;
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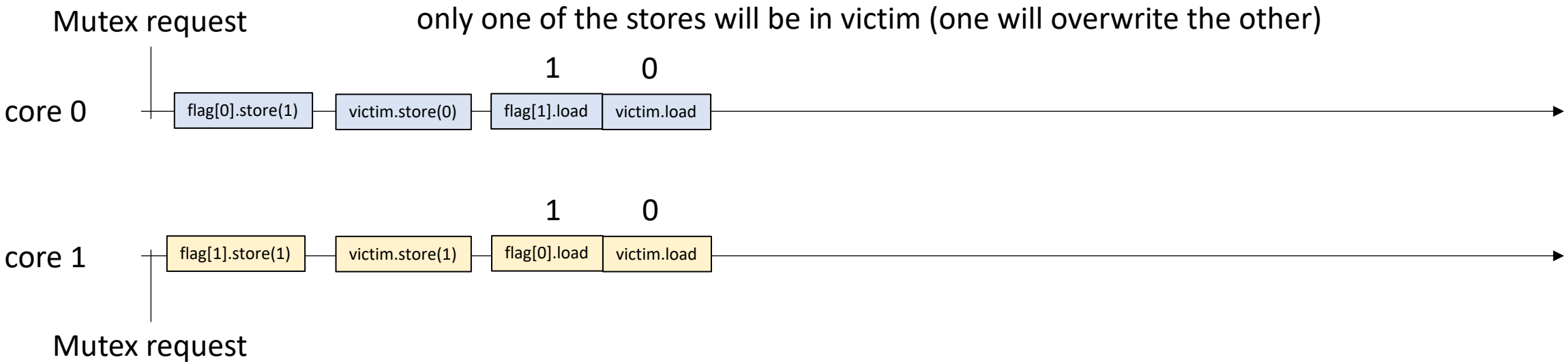

Tie breaking with victim

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  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
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  while (victim.load() == thread_id
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void unlock() {
  int i = thread_id;
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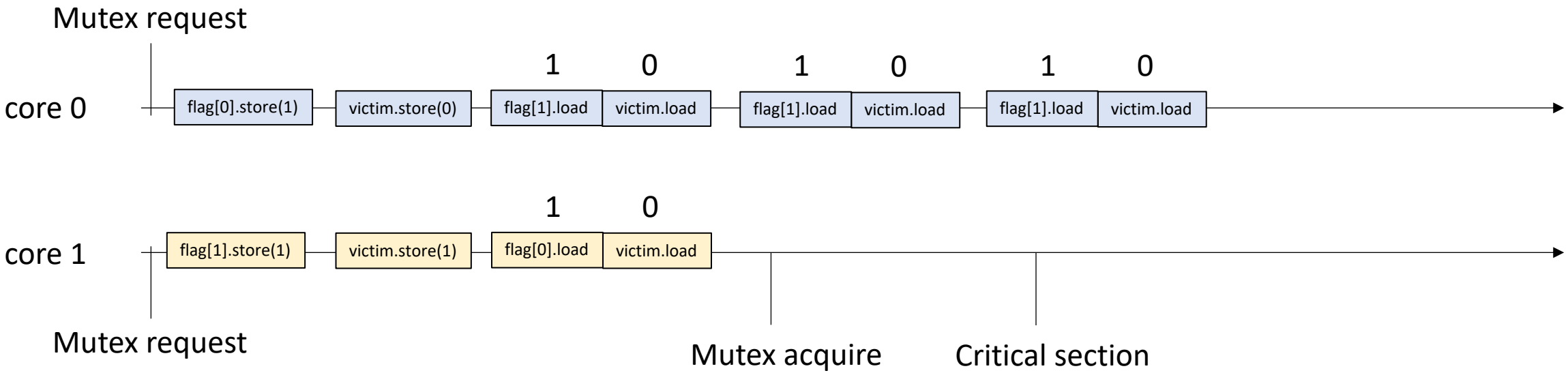

Tie breaking with victim

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
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```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
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Thread 0:
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m.lock();
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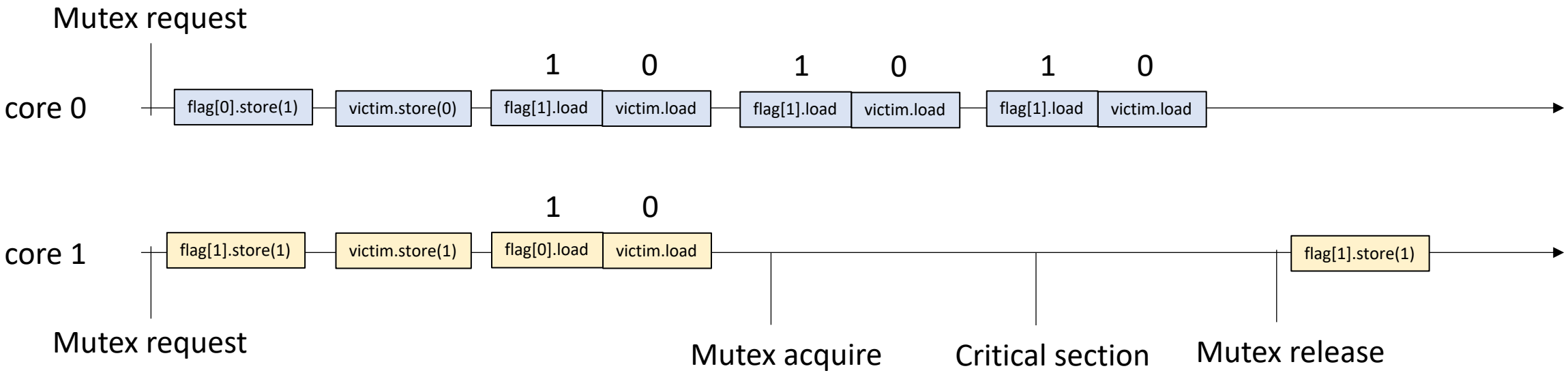

Tie breaking with victim

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
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```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
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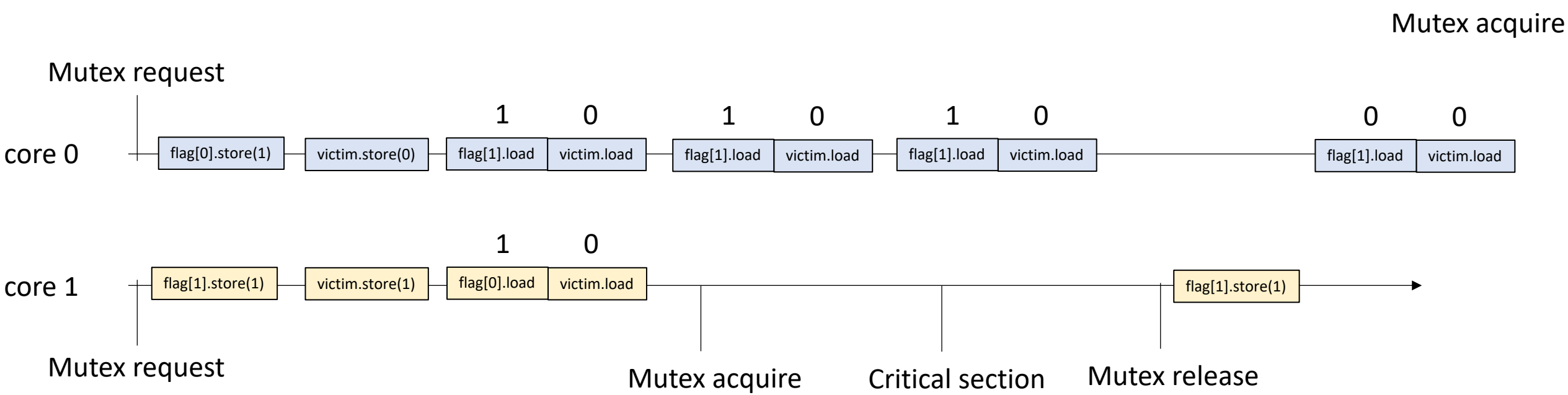


previous victim issue

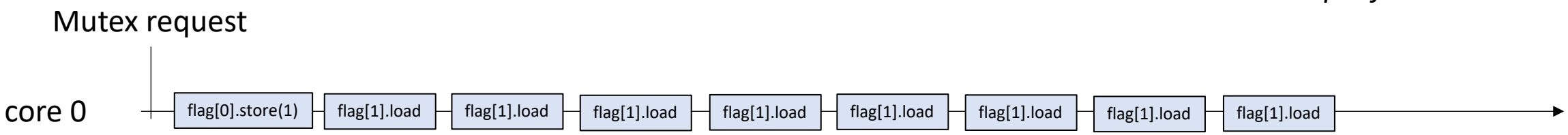
```
void lock() {
  victim.store(thread_id);
  while (victim.load() == thread_id);
}
```

```
void unlock() {}
```

Thread 0:

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

will spin forever!



previous flag issue

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
```

```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
}
```

Thread 0:

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

previous flag issue

```
void lock() {
  int j = thread_id == 0 ? 1 : 0;
  flag[thread_id].store(1);
  victim.store(thread_id);
  while (victim.load() == thread_id
         && flag[j] == 1);
}
```

```
void unlock() {
  int i = thread_id;
  flag[i].store(0);
}
```

Thread 0:

```
m.lock();
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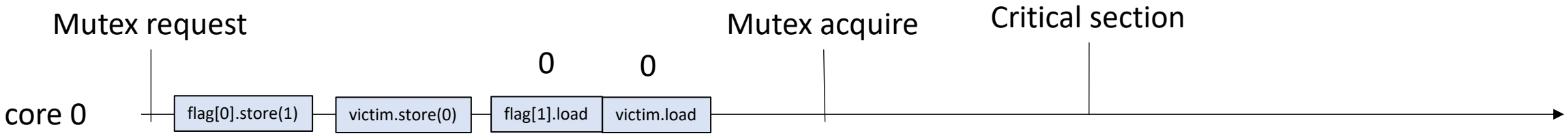


we can enter critical section because the other thread isn't interested

New material

Back to Mutex Implementations

Peterson only works with 2 threads.

Generalizes to the Filter Lock (Read chapter 2 in the book, part 1 of your homework!)

Historical perspective

- These locks are not very performant compared to modern solutions
  - Your HW will show this
- However, they are academically interesting: they can be implemented with plain loads and stores
- We will now turn our attention to more performant implementations that use RMWs

Start by revisiting our first mutex implementation

- A first attempt:
  - A mutex contains a boolean.
  - The mutex value set to 0 means that it is free. 1 means that some thread is holding it.
  - To lock the mutex, you wait until it is set to 0, then you store 1 in the flag.
  - To unlock the mutex, you set the mutex back to 0.
- Let’s remember why it was buggy

Buggy Mutex implementation: Analysis

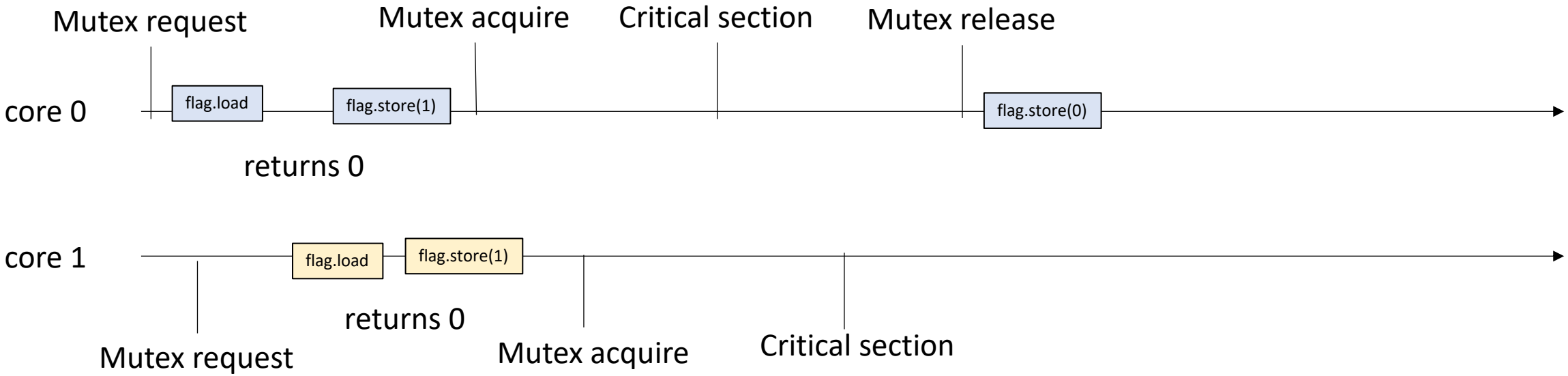
```
void lock() {
  while (flag.load() == 1);
  flag.store(1);
}
```

```
void unlock() {
  flag.store(0);
}
```

Thread 0:
```
m.lock();
m.unlock();
```

Thread 1:
```
m.lock();
m.unlock();
```

Critical sections overlap! This mutex implementation is not correct!



What went wrong?

- The load and stores from two threads interleaved
  - What if there was a way to prevent this?

What went wrong?

- The load and stores from two threads interleaved
  - What if there was a way to prevent this?

- Atomic RMWs
  - operate on atomic types (we already have atomic types)
  - recall the non-locking bank accounts:

```
atomic_fetch_add(atomic *a, value v);
```

What is a RMW

A read-modify-write consists of:

- ***read***
- ***modify***
- ***write***

done atomically, i.e. they cannot interleave.

Typically returns the value (in some way) from the read.

atomic_fetch_add

Recall the lock free account

Atomic Read-modify-write (RMWs): primitive instructions that implement a read event, modify event, and write event indivisibly, i.e. it cannot be interleaved.

```
atomic_fetch_add(atomic_int * addr, int value) {
   int tmp = *addr; // read
   tmp += value;    // modify
   *addr = tmp;     // write
}
```

atomic_fetch_add

Recall the lock free account

Atomic Read-modify-write (RMWs): primitive instructions that implement a read event, modify event, and write event indivisibly, i.e. it cannot be interleaved.

```
int atomic_fetch_add(atomic_int * addr, int value) {
    int stash = *addr; // read
    int new_value = value + stash;     // modify
    *addr = new_value;      // write
    return stash;       // return previous value in the memory location
}
```

lock-free accounts

Tyler's coffee addiction:

```
atomic_fetch_add(&tylers_account, -1);
```

Tyler's employer

```
atomic_fetch_add(&tylers_account, 1);
```

lock-free accounts

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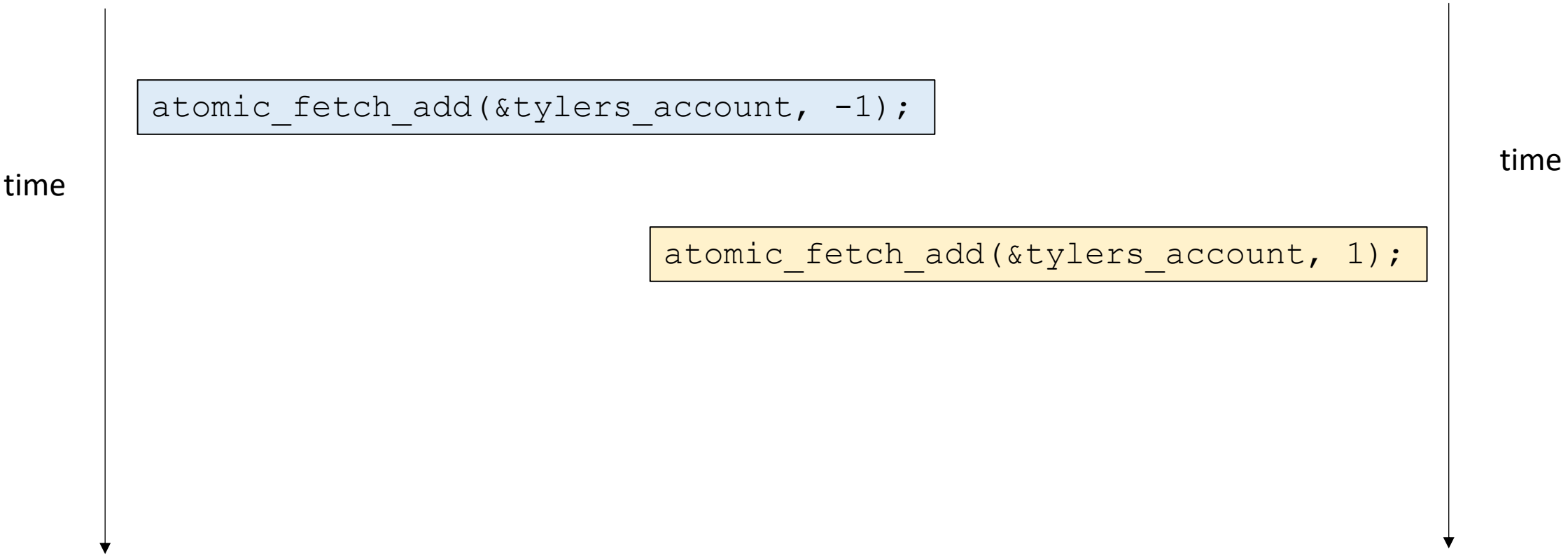

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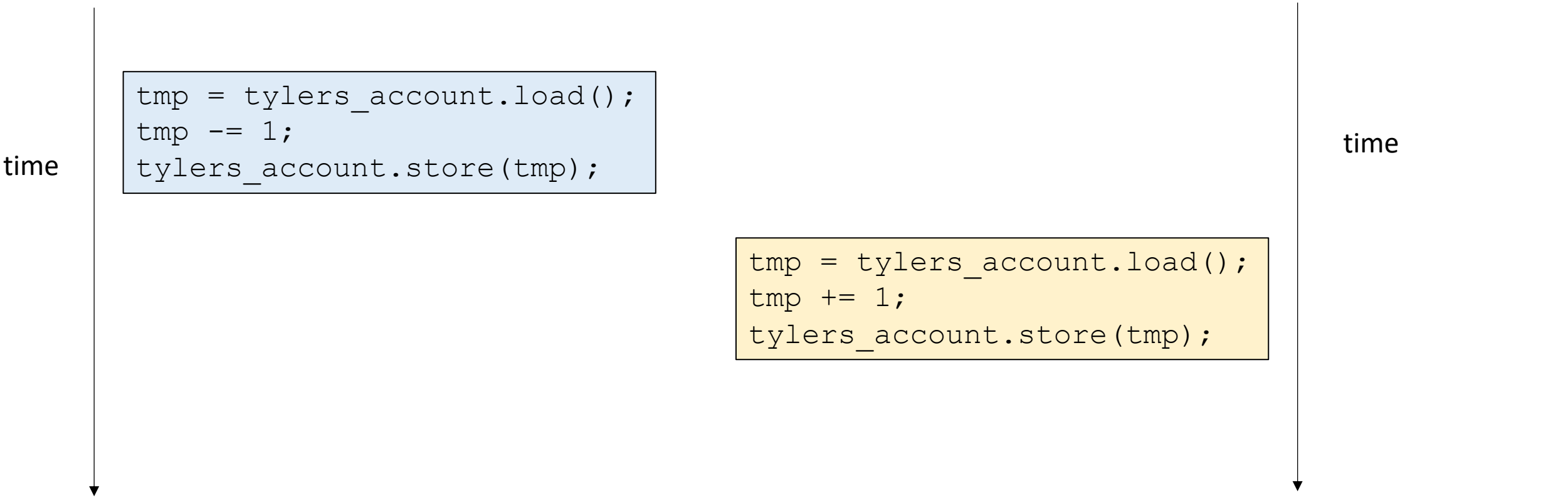

lock-free accounts

Tyler's coffee addiction:

```
atomic_fetch_add(&tylers_account, -1);
```

Tyler's employer

```
atomic_fetch_add(&tylers_account, 1);
```

time

```
tmp = tylers_account.load();
tmp -= 1;
tylers_account.store(tmp);
```

cannot interleave!

```
tmp = tylers_account.load();
tmp += 1;
tylers_account.store(tmp);
```

time

lock-free accounts

Tyler's coffee addiction:

```
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Tyler's employer

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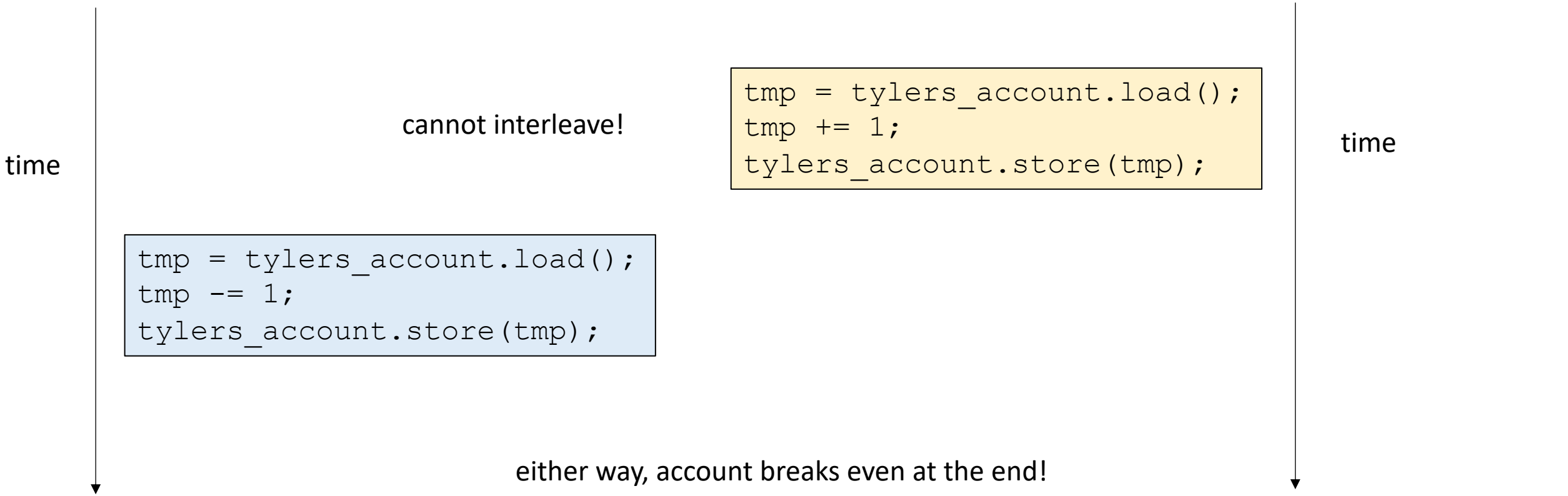

RMW-based locks

- A few simple RMWs enable lots of interesting mutex implementations
- When we have simpler implementations, we can focus on performance

First example: Exchange Lock

- Simplest atomic RMW will allow us to implement an:

- N-threaded mutex with 1 bit!

First example: Exchange Lock

```
value atomic_exchange(atomic *a, value v);
```

Loads the value at `a` and stores the value in `v` at `a`. Returns the value that was loaded.

First example: Exchange Lock

```
value atomic_exchange(atomic *a, value v);
```

Loads the value at `a` and stores the value in `v` at `a`. Returns the value that was loaded.

```
value atomic_exchange(atomic *a, value v) {
  value tmp = a.load();
  a.store(v);
  return tmp;
}
```

First example: Exchange Lock

```
#include <atomic>
using namespace std;

class Mutex {
public:
  Mutex() {
    flag = false;
  }

  void lock();
  void unlock();

private:
  atomic_bool flag;
};
```

Lets make a mutex with just one atomic bool!

First example: Exchange Lock

```
#include <atomic>
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class Mutex {
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initialized to `false`

one atomic flag

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Lets make a mutex with just one atomic bool!

initialized to `false`

one atomic flag

main idea:

The flag is false when the mutex is free.

The flag is true when some thread has the mutex.

First example: Exchange Lock

```
void lock() {
  while (atomic_exchange(&flag, true) == true);
}
```

First example: Exchange Lock

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void lock() {
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}
```

So what's going on?

First example: Exchange Lock

```
void lock() {
  while (atomic_exchange(&flag, true) == true);
}
```

So what's going on?

Two cases:

mutex is free: the value loaded is false. We store true. The value returned is False, so we don't spin

mutex is taken: the value loaded is true, we put the SAME value back (true). The returned value is true, so we spin.

First example: Exchange Lock

```
void unlock() {
  flag.store(false);
}
```

Unlock is simple: just store false to the flag, marking the mutex as available.

Analysis

```
void lock() {
  while (atomic_exchange(&flag, true) == true);
}
```

```
void unlock() {
  flag.store(false);
}
```

Thread 0:
```
m.lock();
m.unlock();
```

Thread 1:
```
m.lock();
m.unlock();
```

Analysis

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void lock() {
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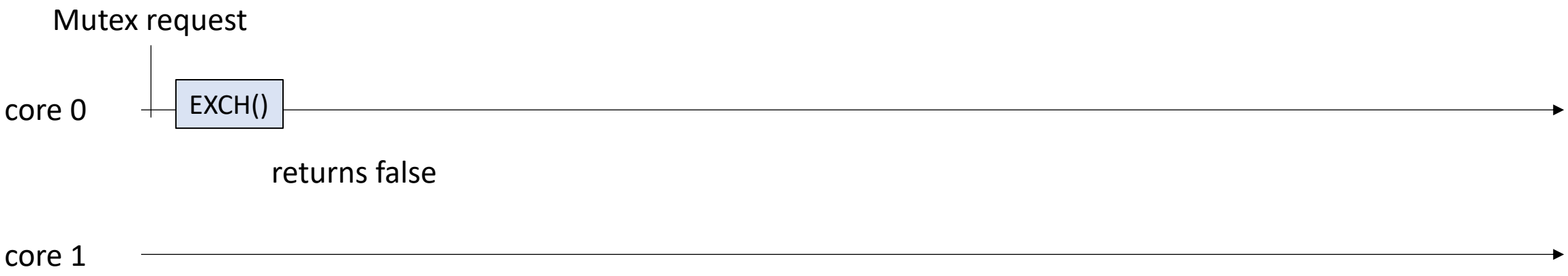

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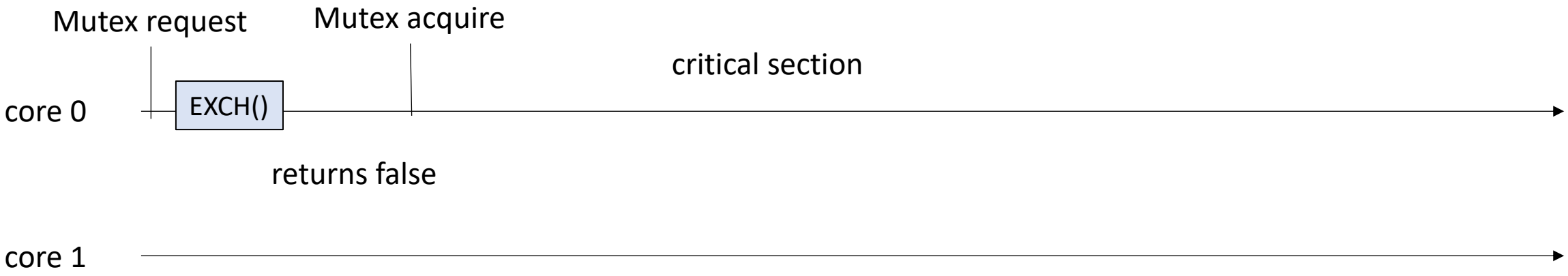

Analysis

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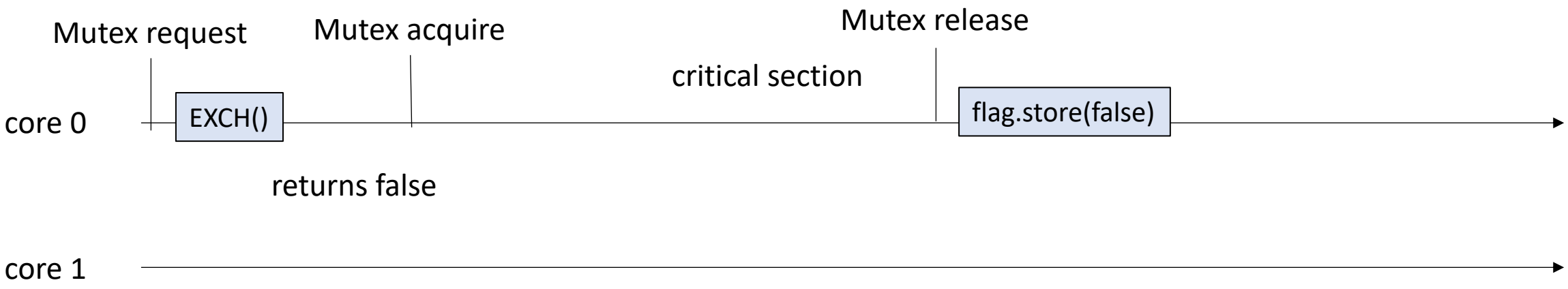

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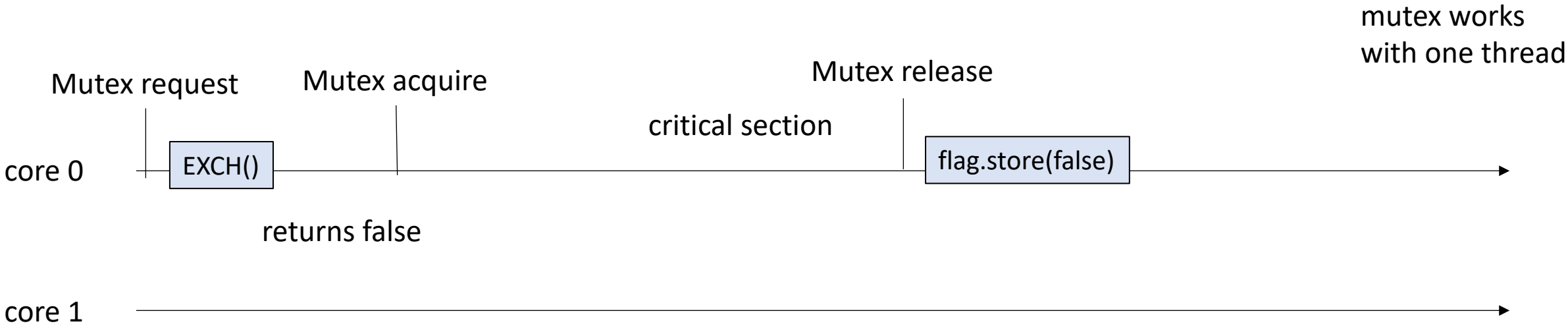

Analysis

```
void lock() {
  while (atomic_exchange(&flag, true) == true);
}
```

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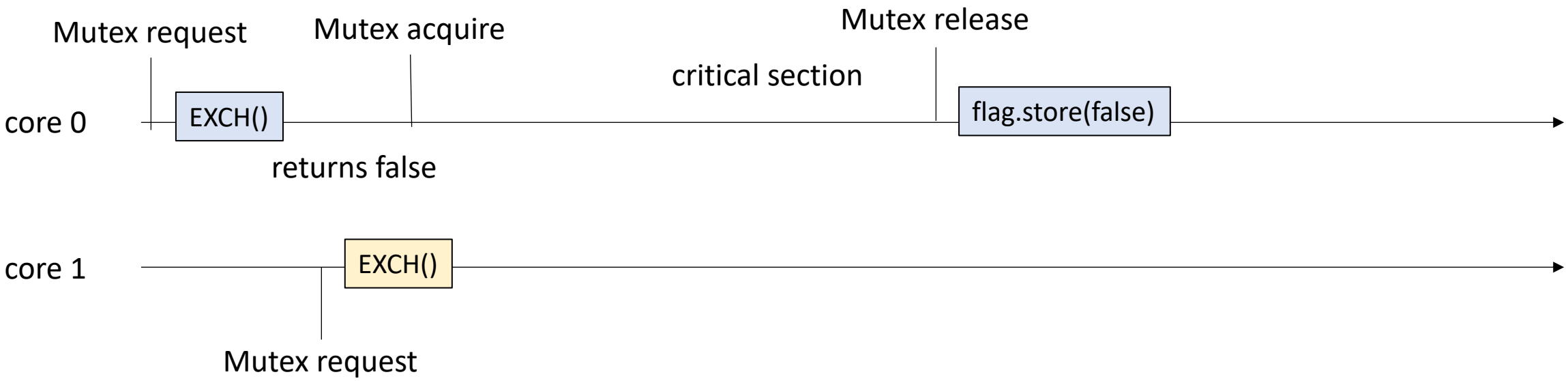

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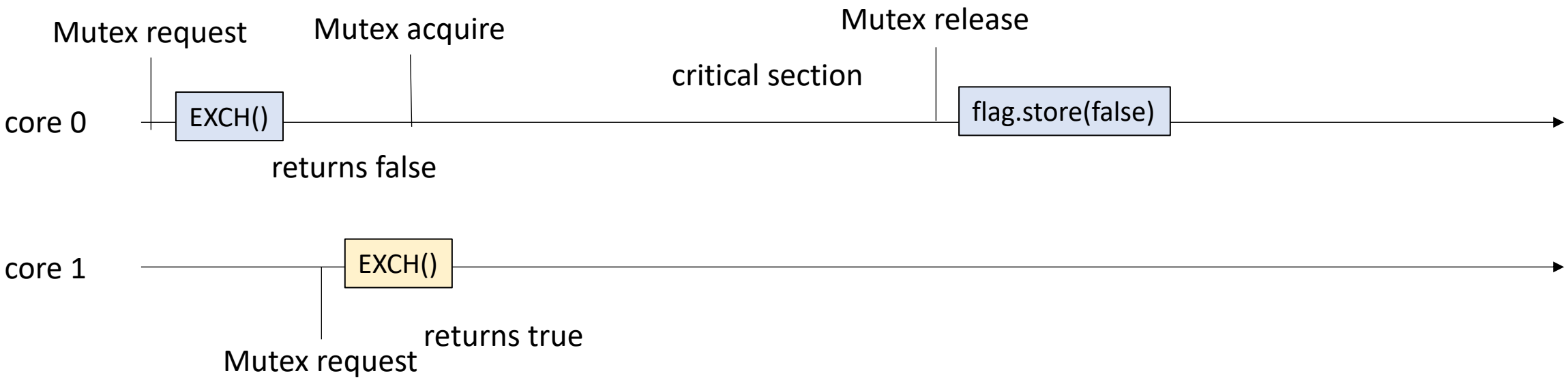

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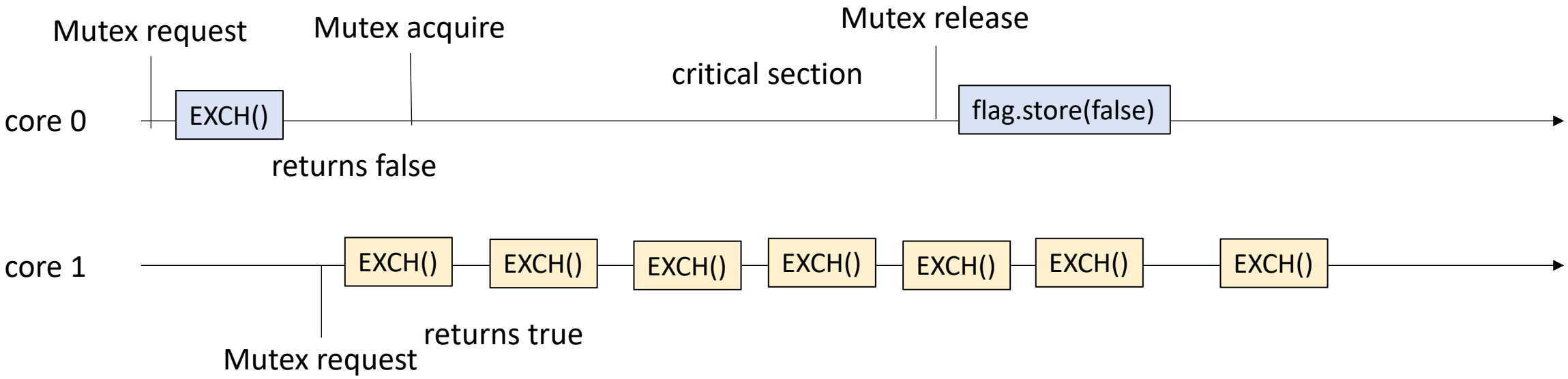

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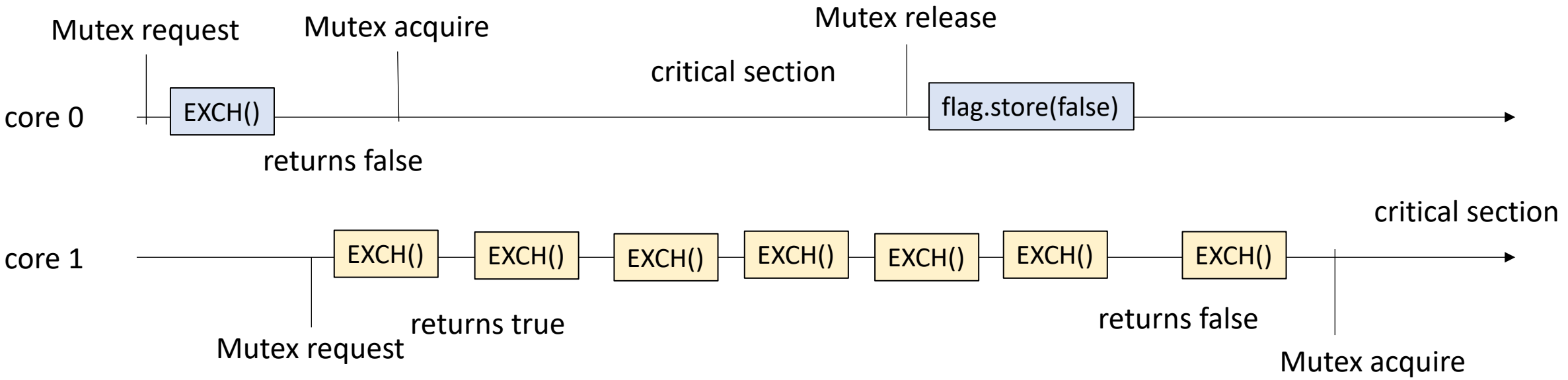

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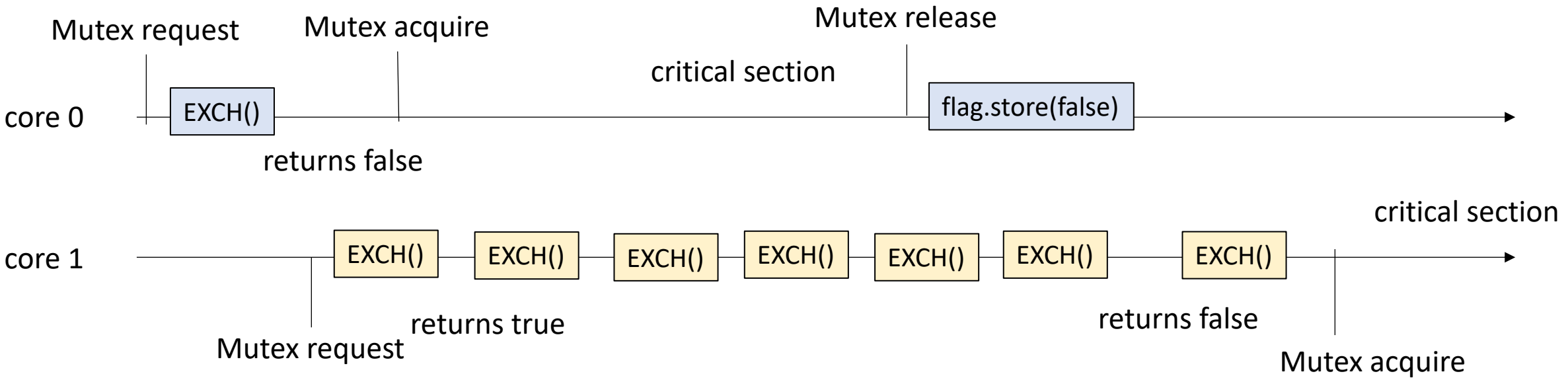
what about interleavings?



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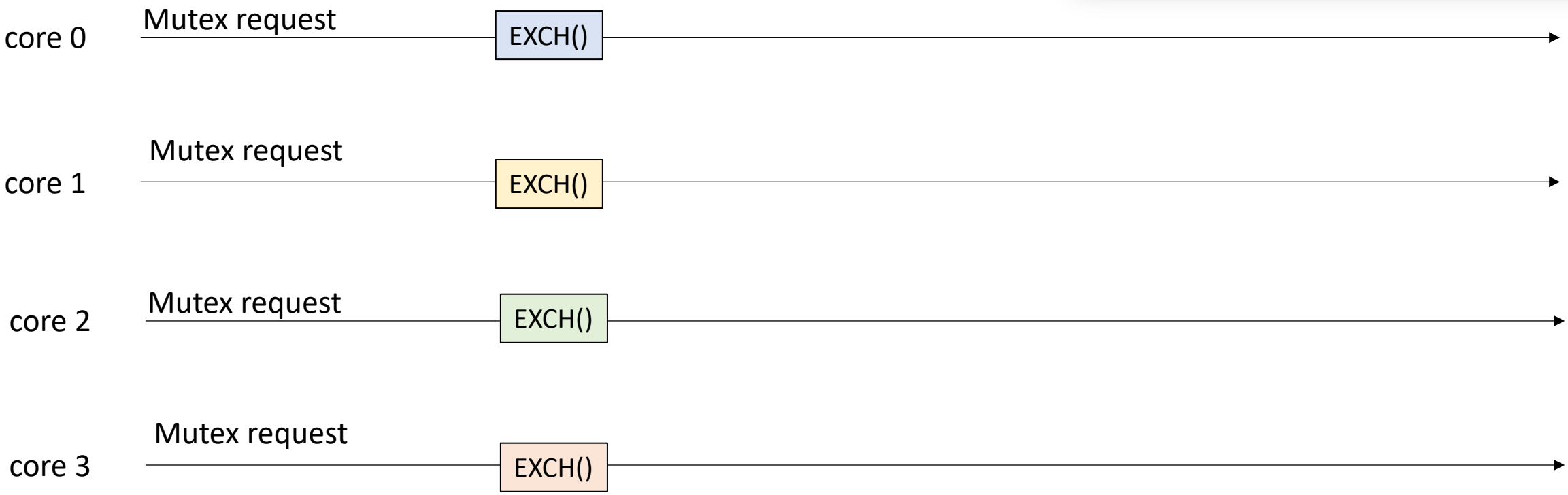
what about 4 threads?



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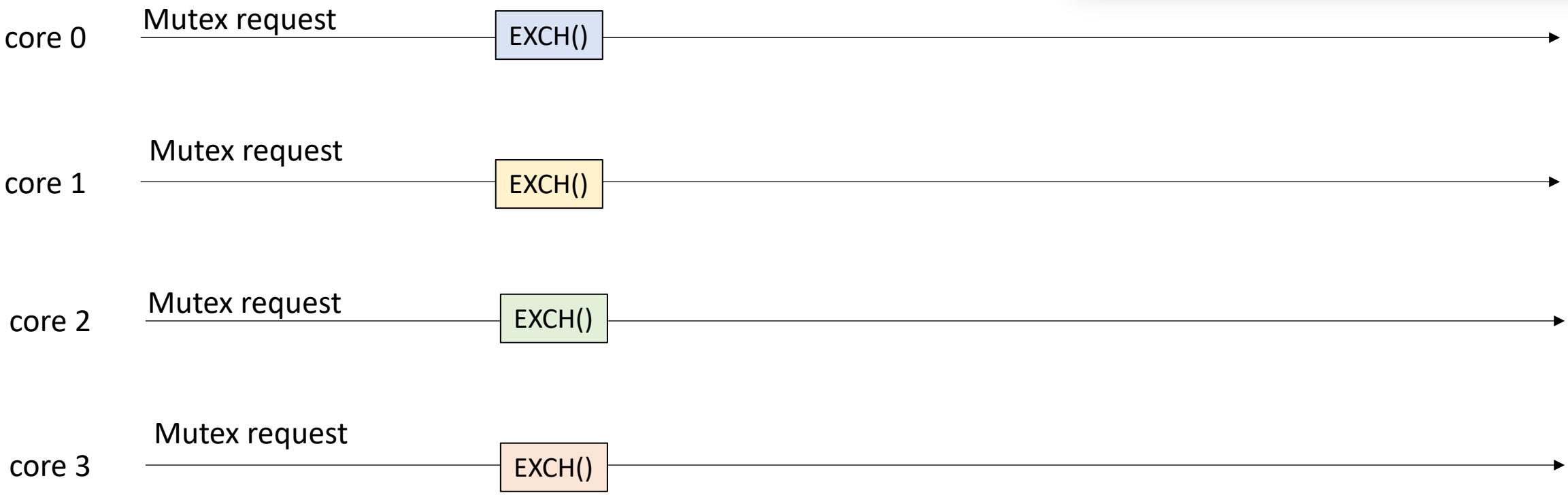
atomic operations can't overlap



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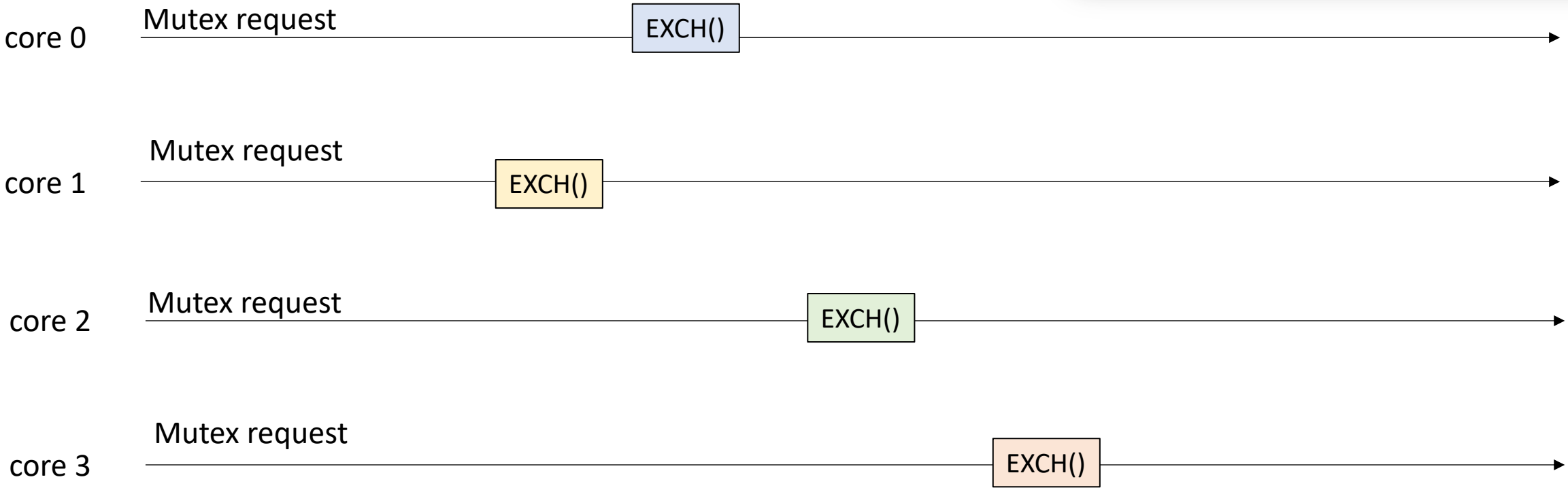

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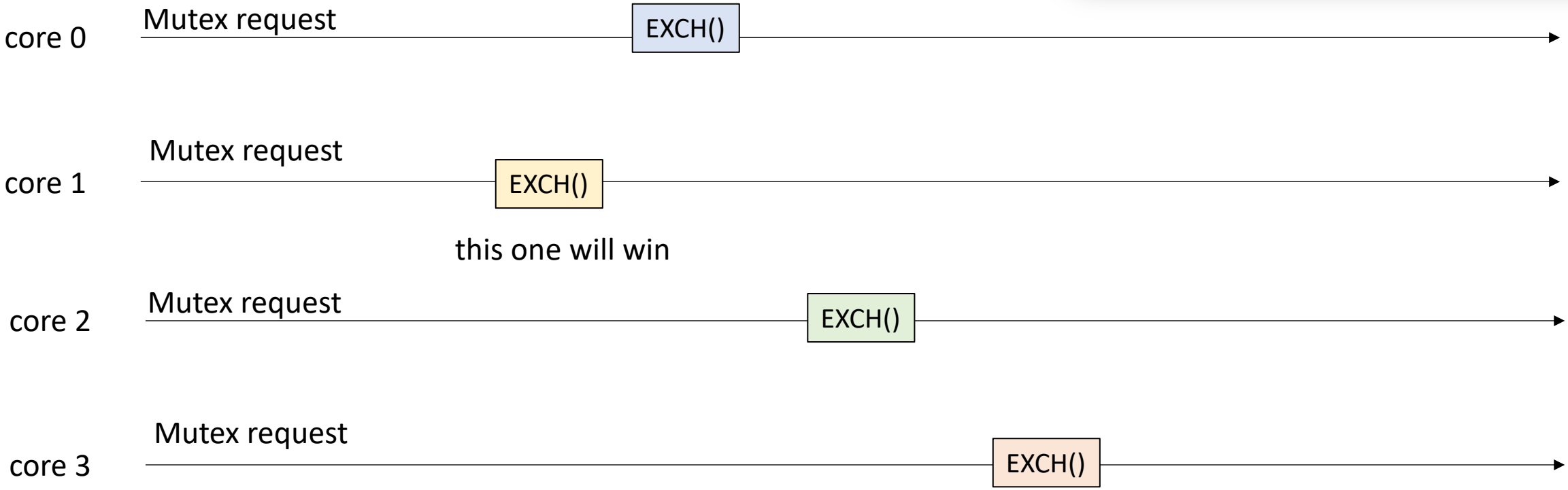

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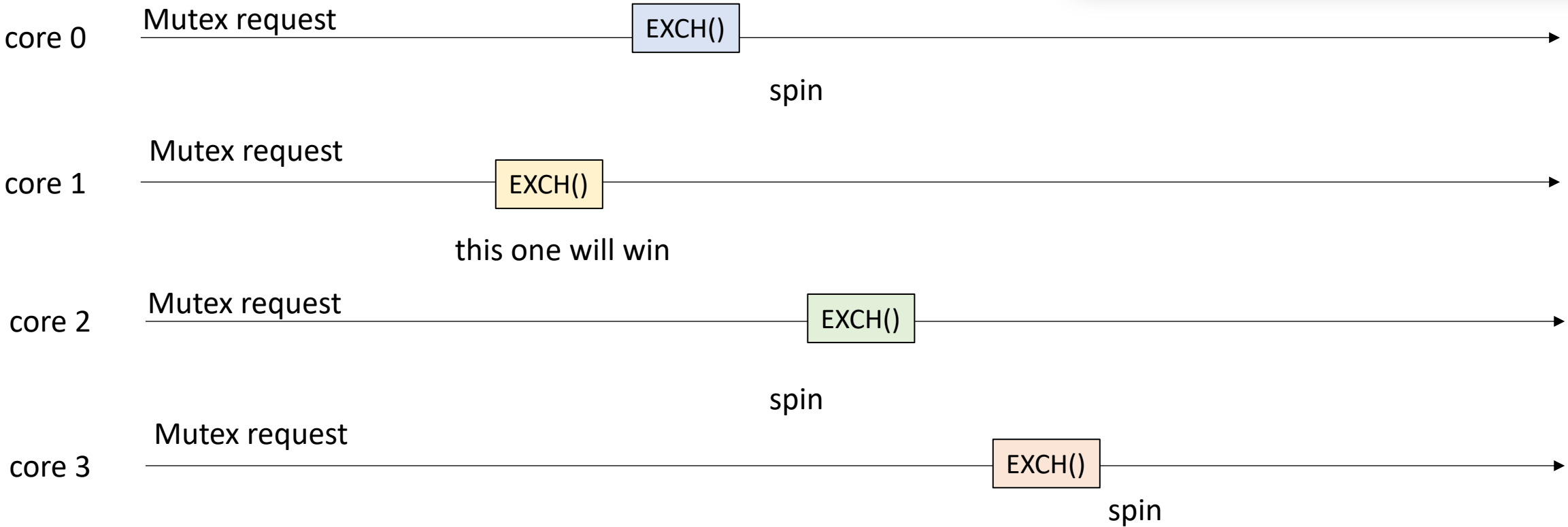

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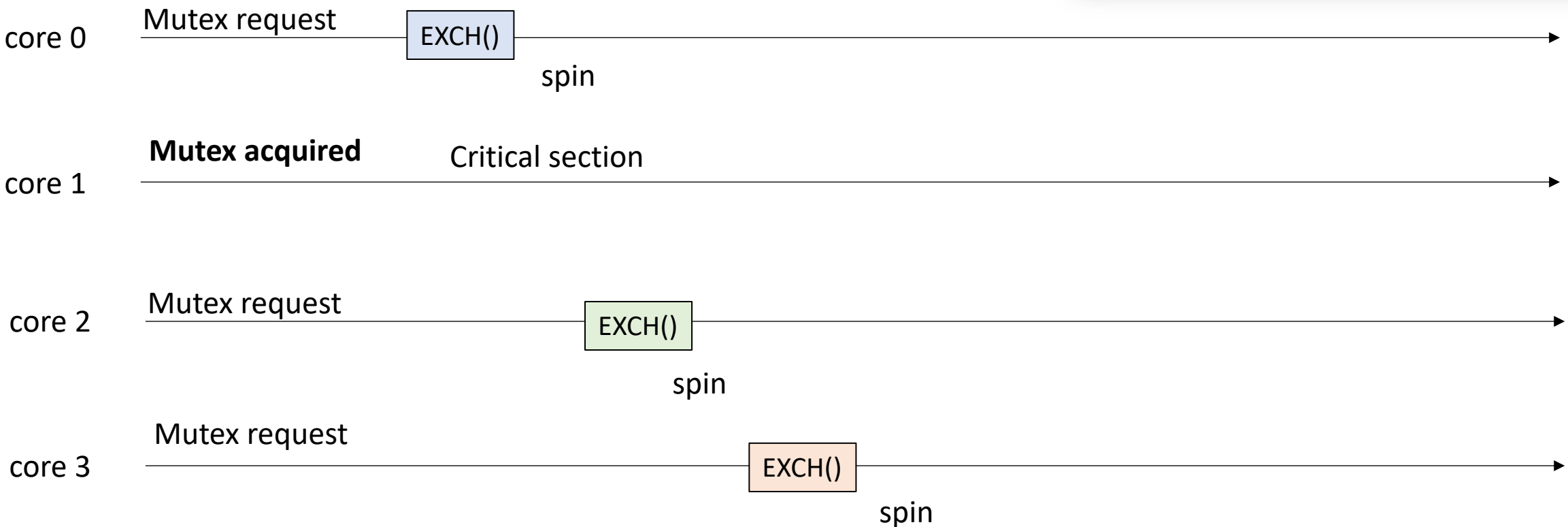

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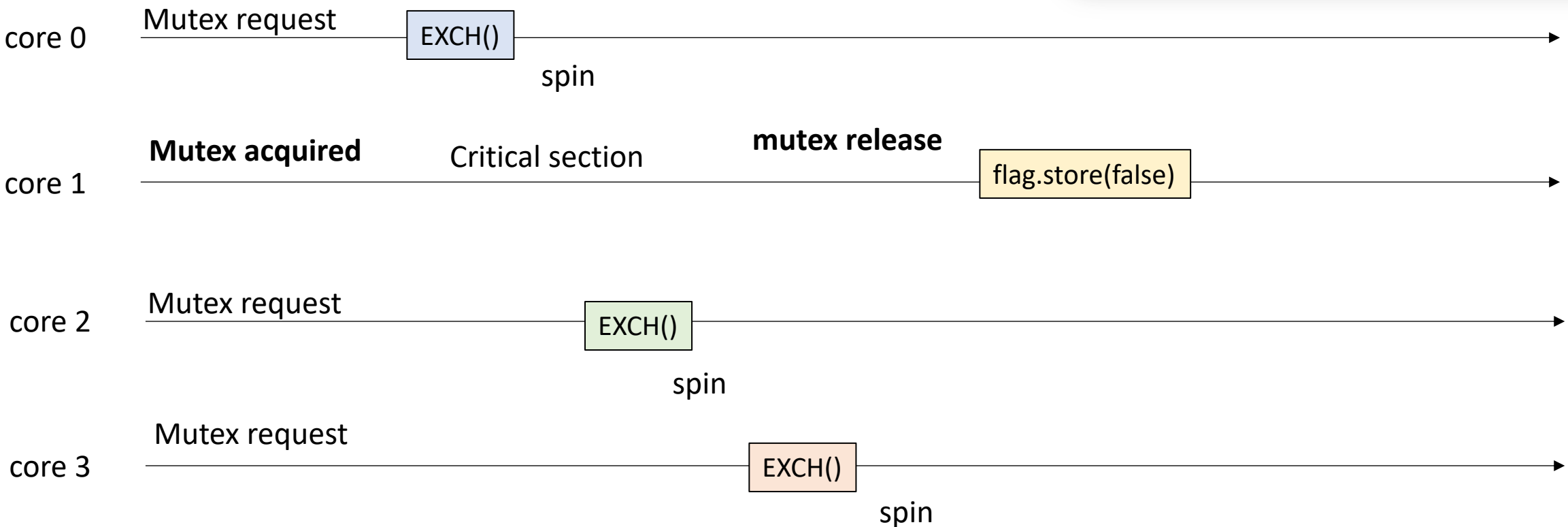

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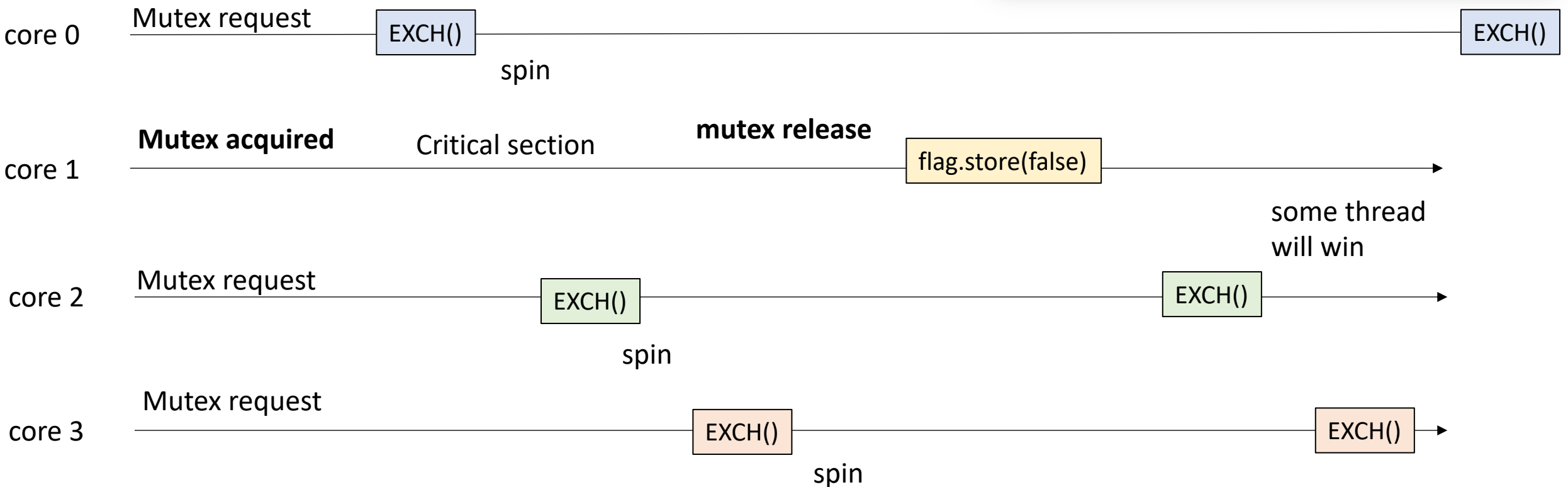

First example: Exchange Mutex

- Questions?

Most versatile RMW: Compare-and-swap

- Exchange was the simplest RMW (no modify)
- Most versatile RMW: Compare-and-swap (CAS)

```
bool atomic_compare_exchange_strong(atomic *a, value *expected, value replace);
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Checks if value at `a` is equal to the value at `expected`. If it is equal, swap with `replace`. returns `True` if the values were equal. `False` otherwise.

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```

Checks if value at `a` is equal to the value at `expected`. If it is equal, swap with `replace`. returns `True` if the values were equal. `False` otherwise.
`expected` is passed by reference: the previous value at `a` is returned

Most versatile RMW: Compare-and-swap

- Exchange was the simplest RMW (no modify)
- Most versatile RMW: Compare-and-swap (CAS)

```
bool atomic_compare_exchange_strong(atomic *a, value *expected, value replace) {
    value tmp = a.load();
    if (tmp == *expected) {
      a.store(replace);
      return true;
    }
    *expected = tmp;
    return false;
}
```

Most versatile RMW: Compare-and-swap

- Exchange was the simplest RMW (no modify)
- Most versatile RMW: Compare-and-swap (CAS)

we will discuss this soon!

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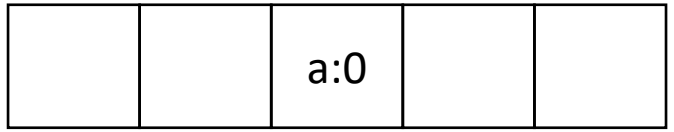
```

thread 0:

```
// some atomic int address a
int e = 0;
bool s = atomic_CAS(a,&e,6);
```



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next example

thread 0:

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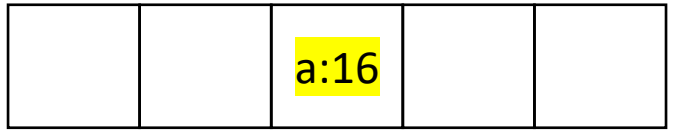

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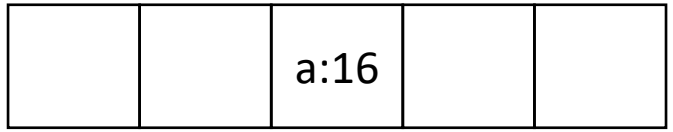
false



CAS lock

```
#include <atomic>
using namespace std;

class Mutex {
public:
  Mutex() {
    flag = false;
  }

  void lock();
  void unlock();

private:
  atomic_bool flag;
};
```

Pretty intuitive: only 1 bit required again:

CAS lock

```
void lock() {
  bool e = false;
  int acquired = false;
  while (acquired == false) {
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
    e = false;
  }
}
```

Check if the mutex is free, if so, take it.

compare the mutex to free (false), if so, replace it with taken (true). Spin while the thread isn't able to take the mutex.

CAS lock

```
void unlock() {
  flag.store(false);
}
```

Unlock is simple! Just store false back

Starvation

- Are these RMW locks fair?

Analysis

Is this mutex starvation Free?

```
void lock() {
  while (atomic_exchange(&flag, true) == true);
}
```

```
void unlock() {
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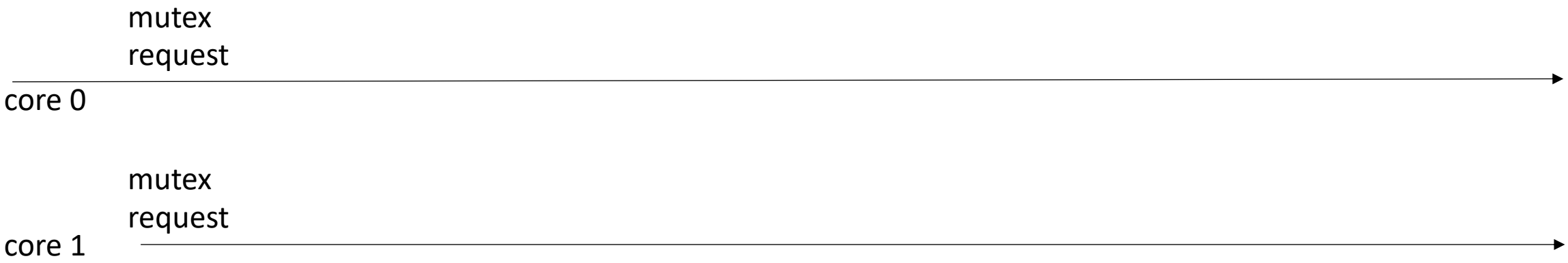

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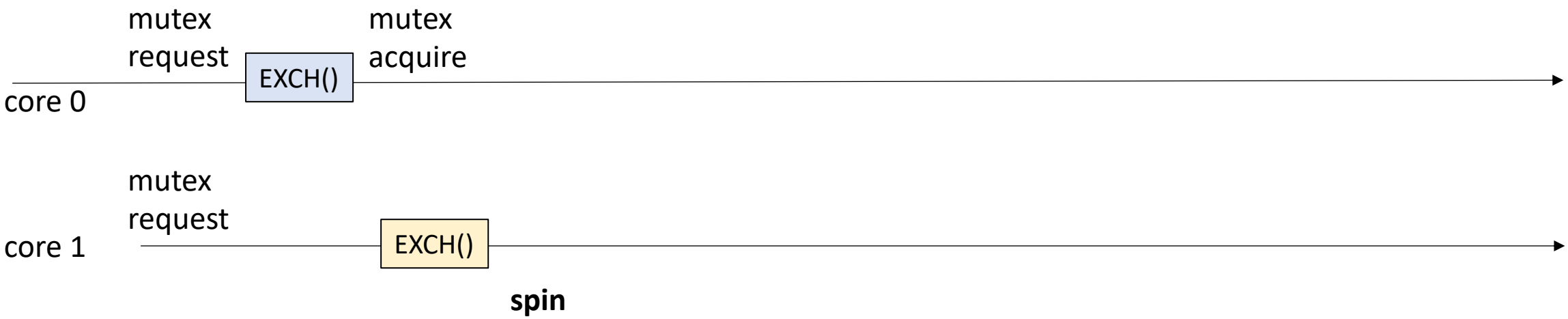

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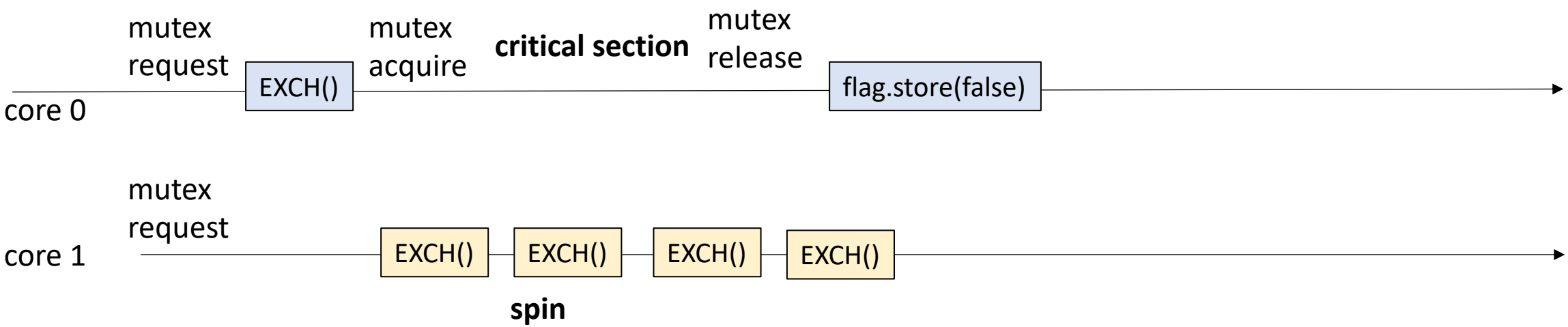

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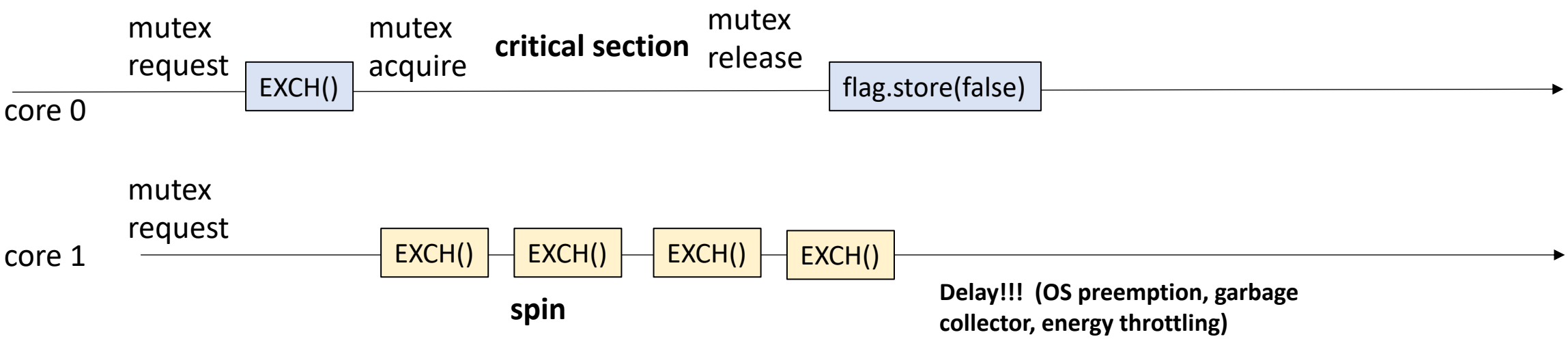

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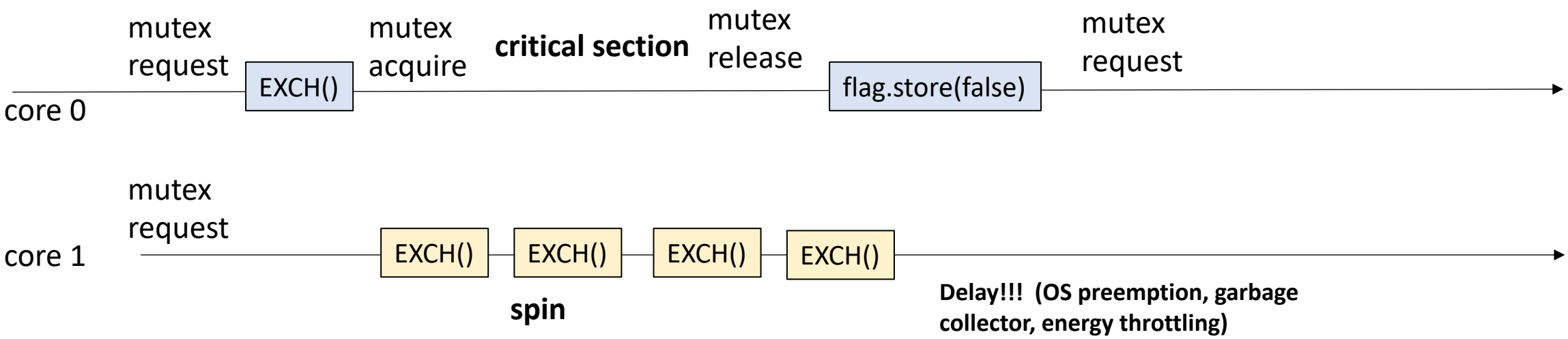

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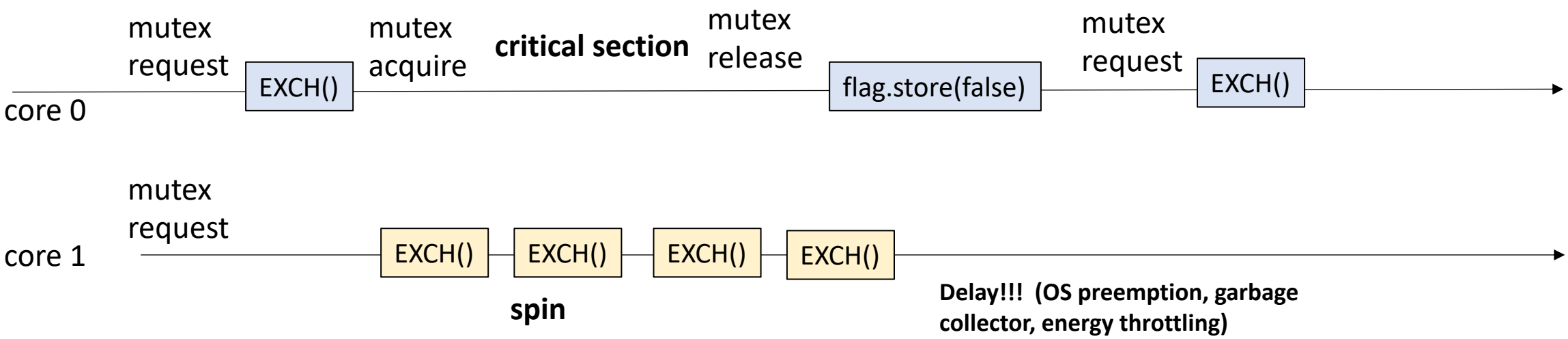

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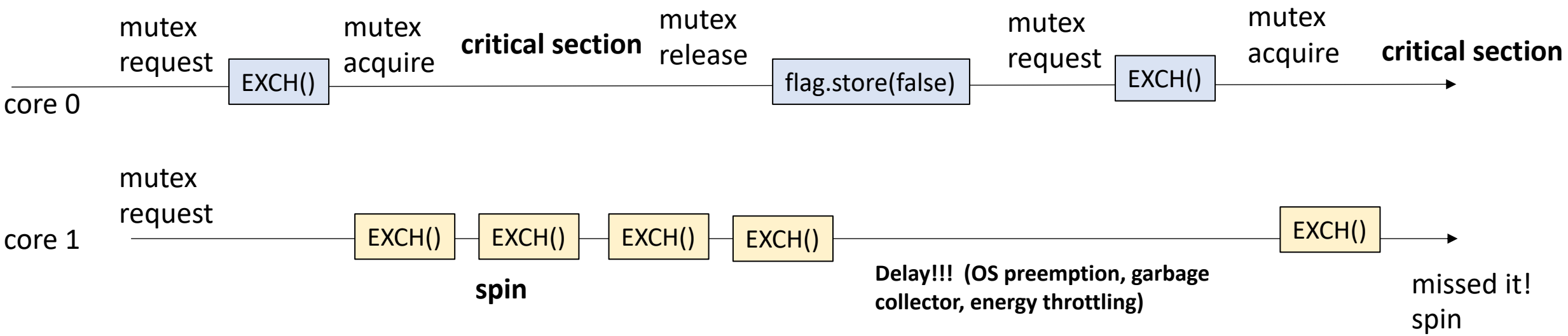

How about in practice?

- Code demo

How can we make this more fair?

- Use a different atomic instruction:
  - `int atomic_fetch_add(atomic_int *a, int v);`

We've seen this one before!

How can we make this more fair?

- Use a different atomic instruction:
  - `int atomic_fetch_add(atomic_int *a, int v);`

We've seen this one before!
intuition: take a ticket

like at Zoccoli's!

Ticket lock

```
class Mutex {
public:
  Mutex() {
    counter = 0;
    currently_serving = 0;
  }

  void lock() {
    int my_number = atomic_fetch_add(&counter, 1);
    while (currently_serving.load() != my_number);
  }

  void unlock() {
    int tmp = currently_serving.load();
    tmp += 1;
    currently_serving.store(tmp);
  }

private:
  atomic_int counter;
  atomic_int currently_serving;
};
```

- Ticket lock: instead of 1 bit, we need an integer for the counter.
- The mutex also needs to track of which ticket is currently being served

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- Ticket lock: instead of 1 bit, we need an integer for the counter.
- The mutex also needs to track of which ticket is currently being served

Get a unique number

Spin while your number isn't being served

To release, increment the number that's currently being served.

Analysis

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  int my_number = atomic_fetch_add(&counter, 1);
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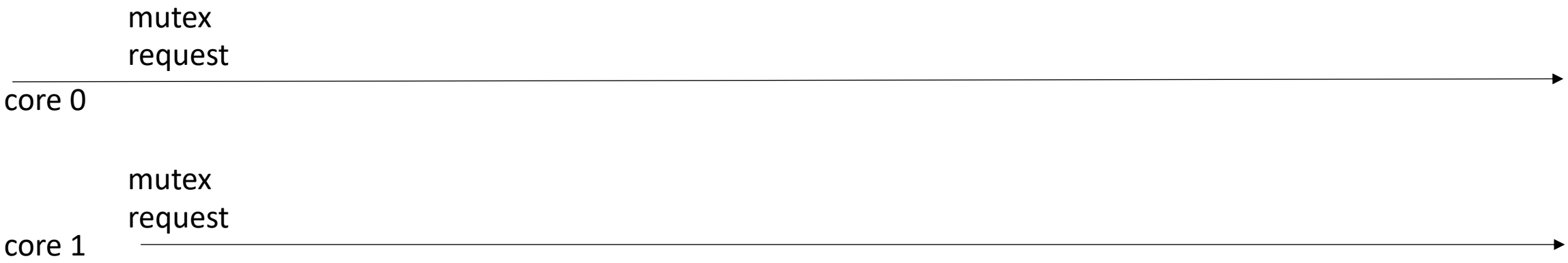

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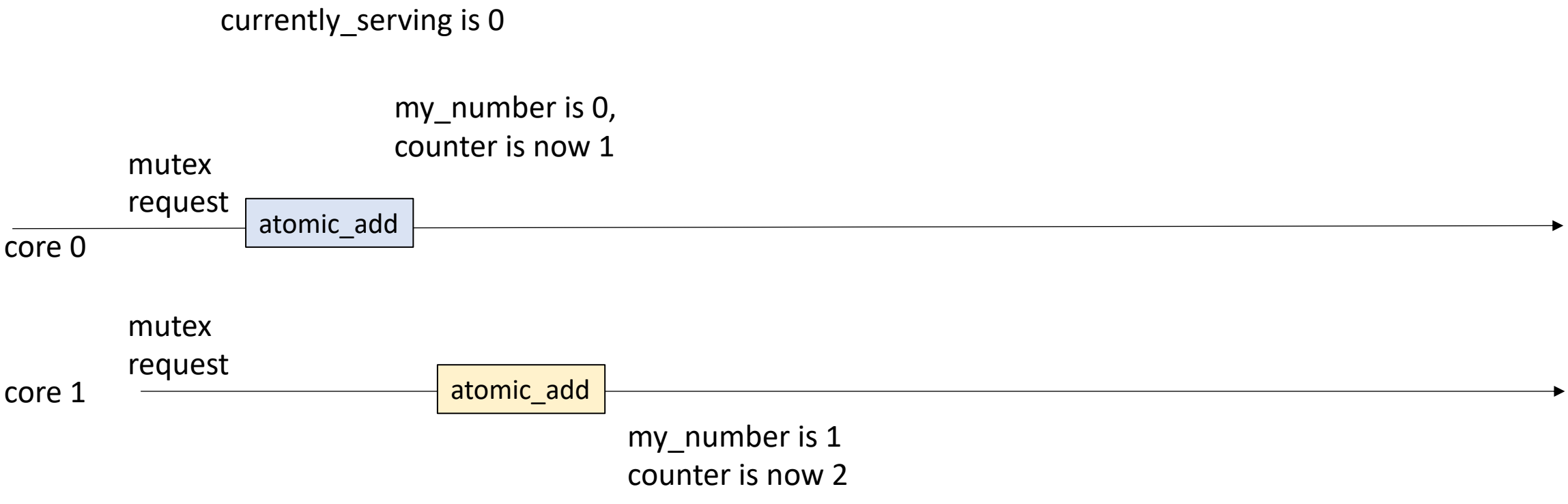

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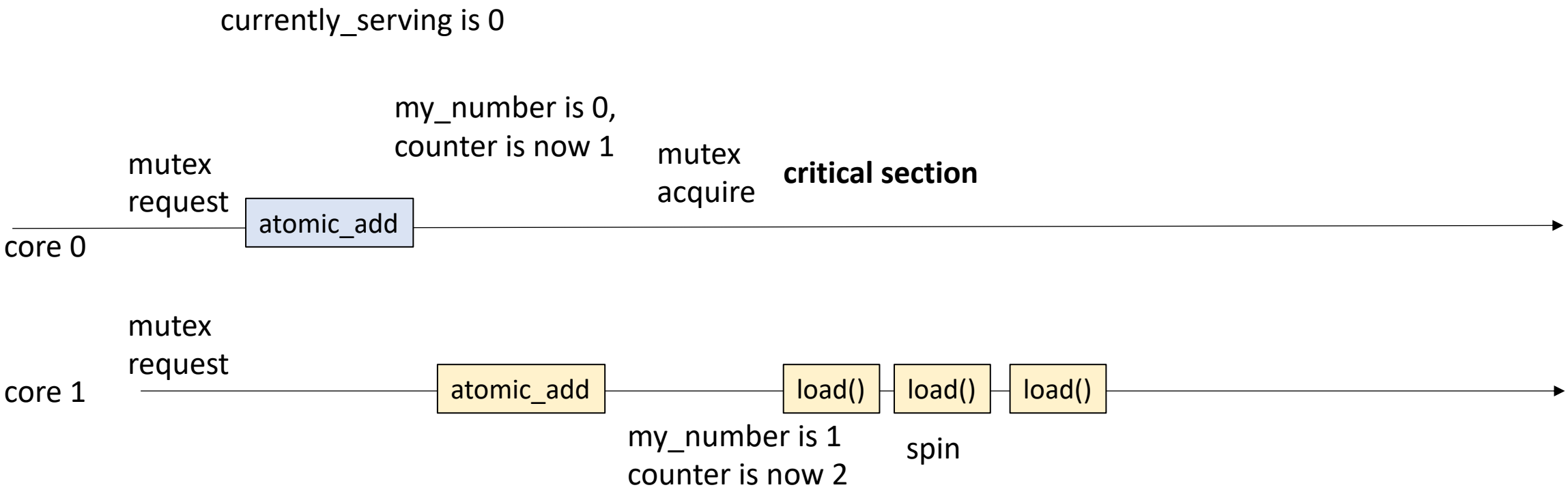

Analysis

Is this mutex starvation Free?

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  while (currently_serving.load() != my_number);
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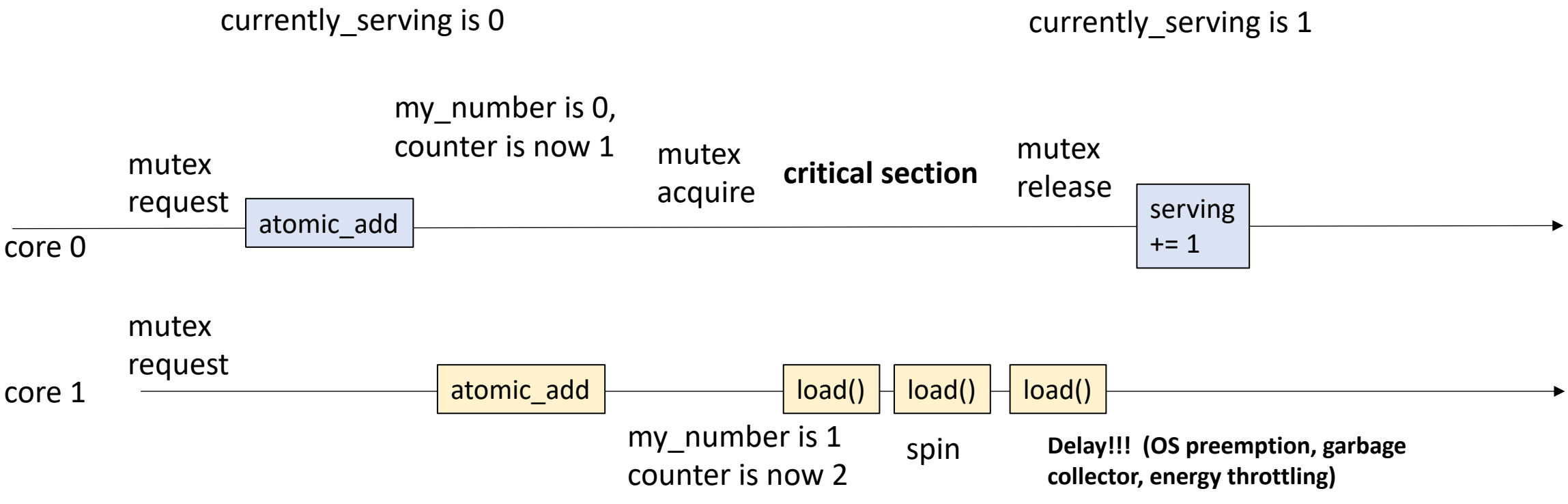

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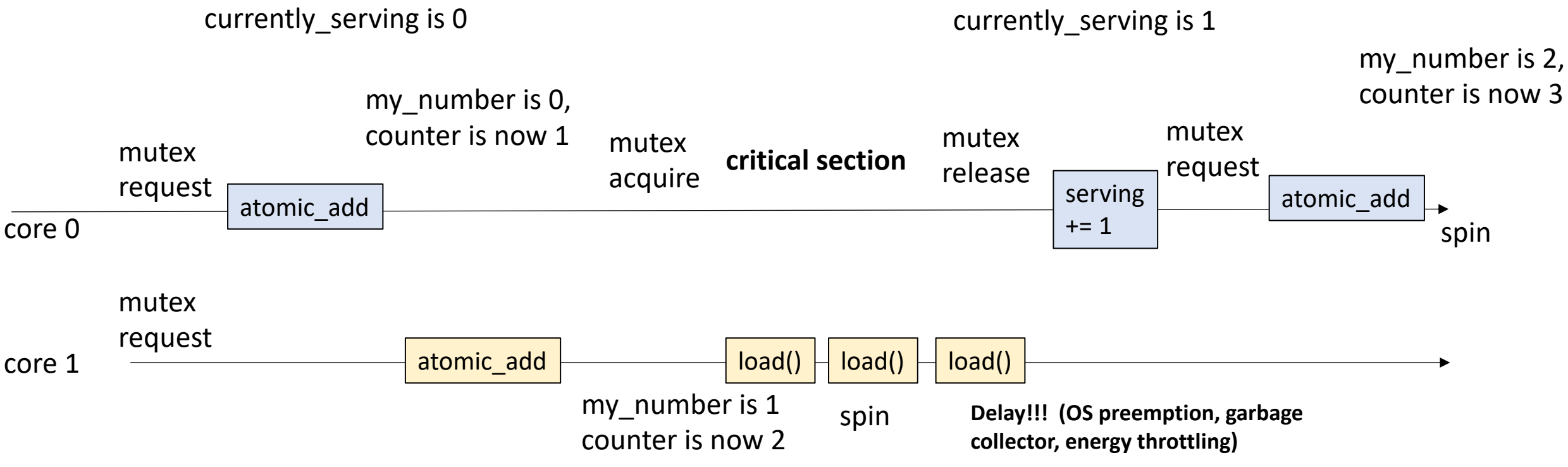

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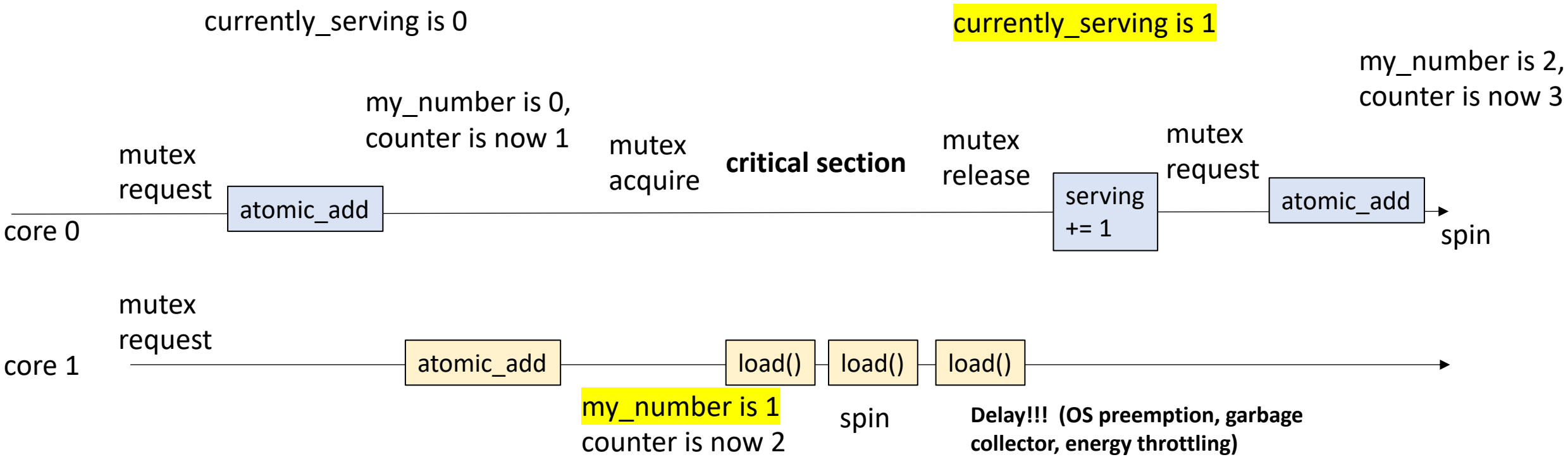

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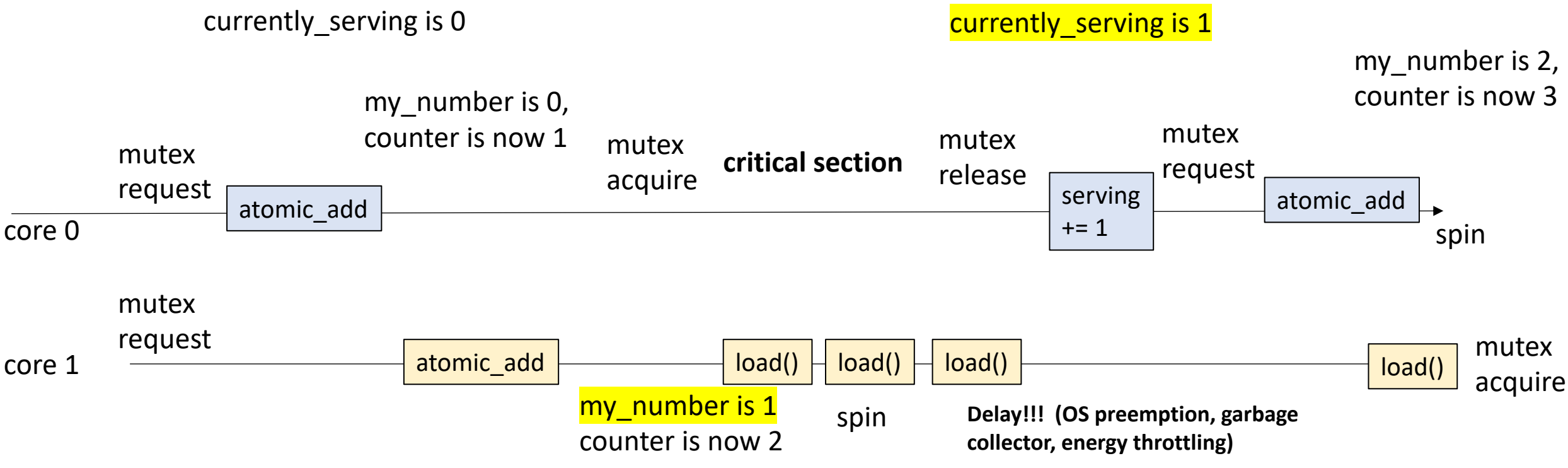


Fair but at what cost?

- Example

Optimizations

How is CAS (and others) implemented?

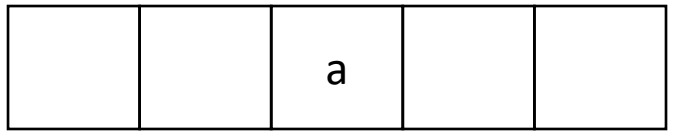
- X86 has an actual instruction
- ARM and POWER are load linked store conditional

Pessimistic Concurrency

- X86 has an actual instruction: lock the memory location
- Known as **Pessimistic Concurrency**
- Assume conflicts will happen and defend against them from the start

thread 0:

```
atomic_CAS(a,...);
```



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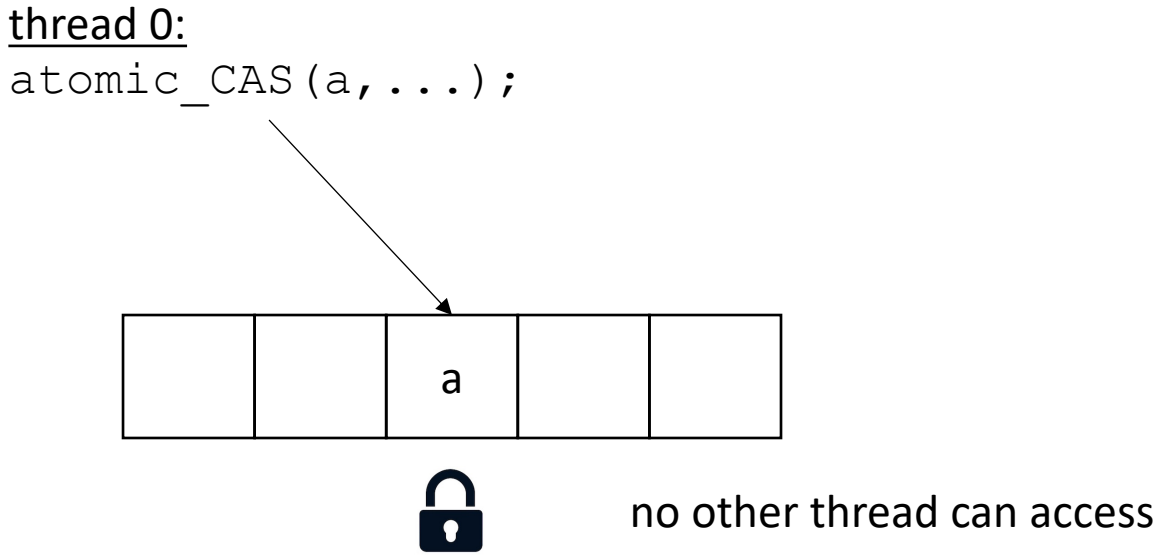

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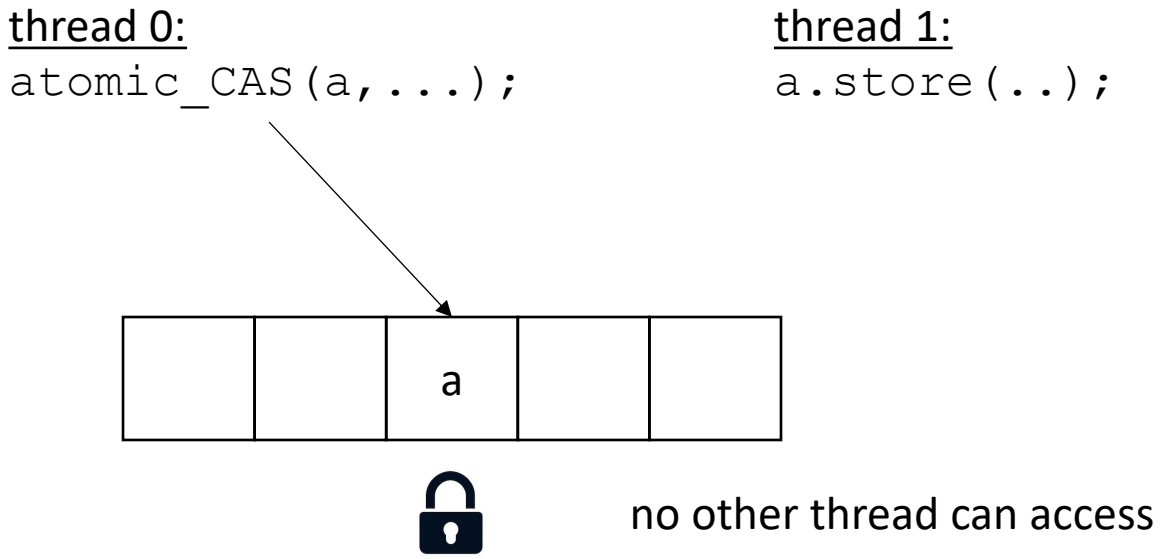

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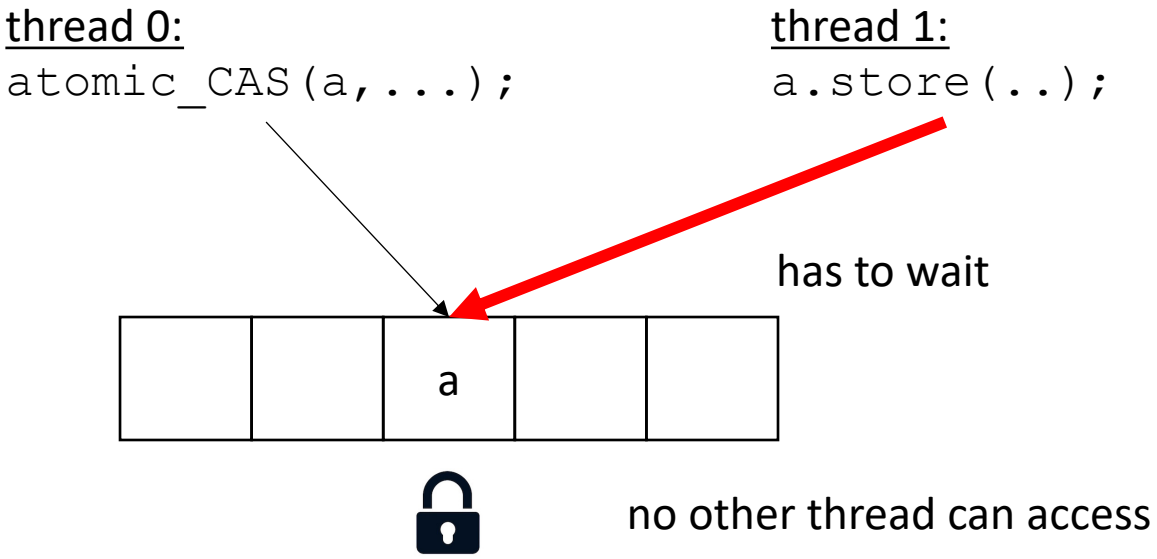

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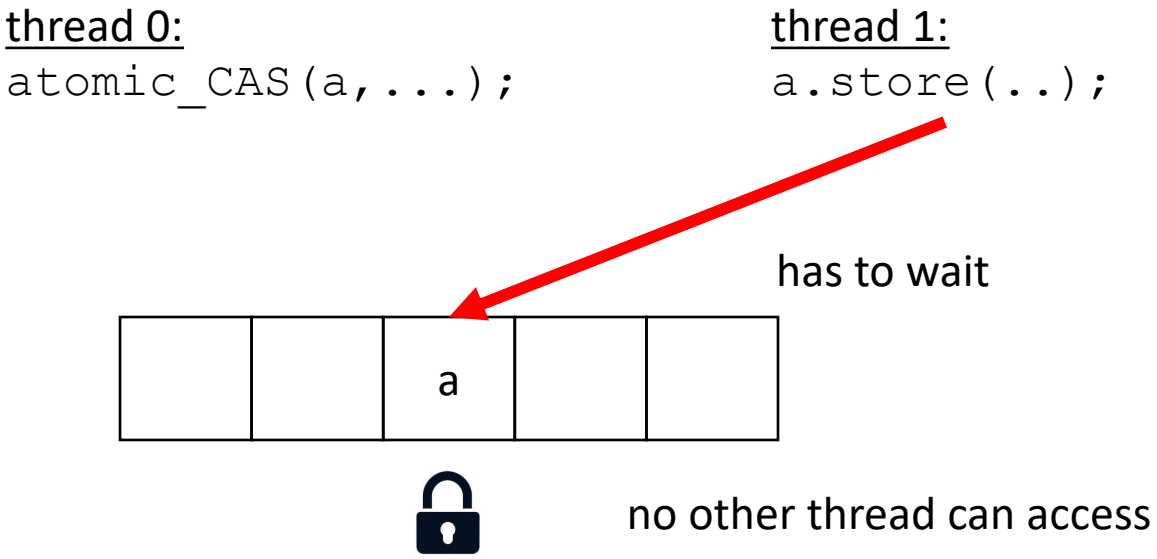

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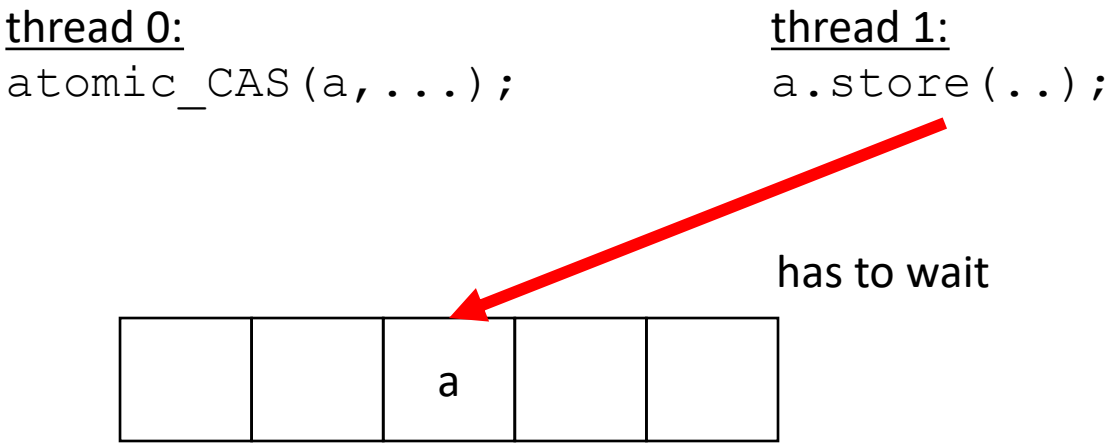

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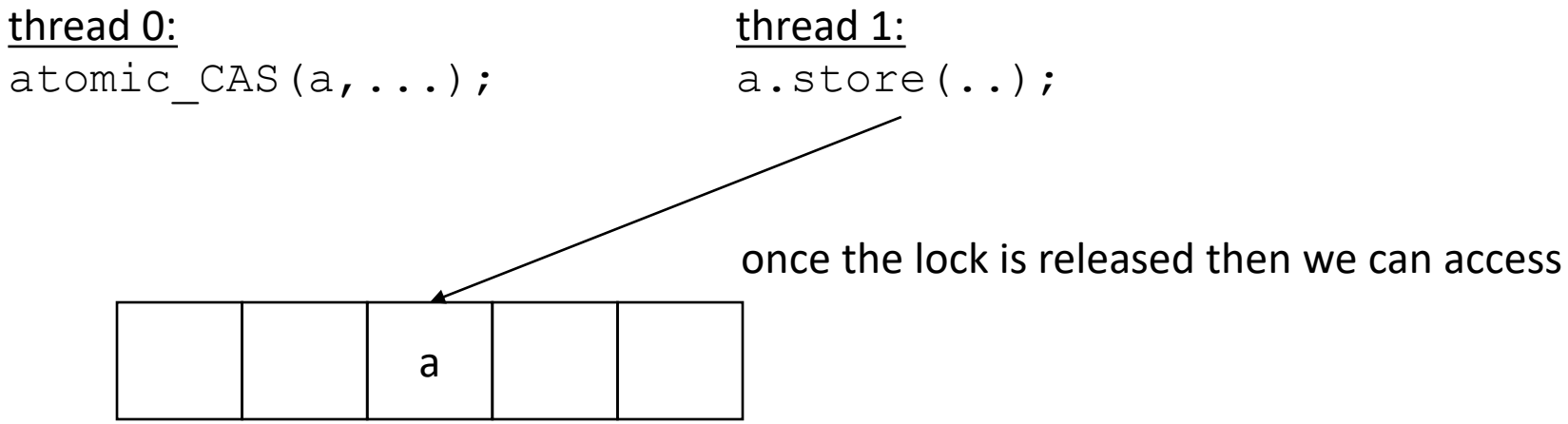

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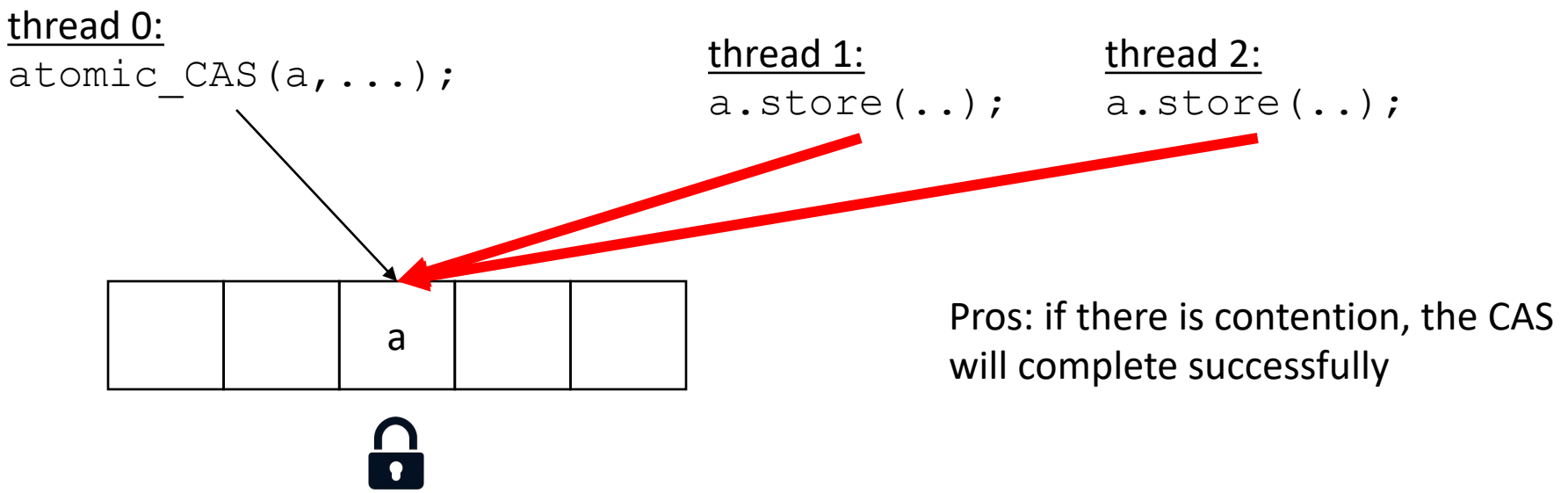

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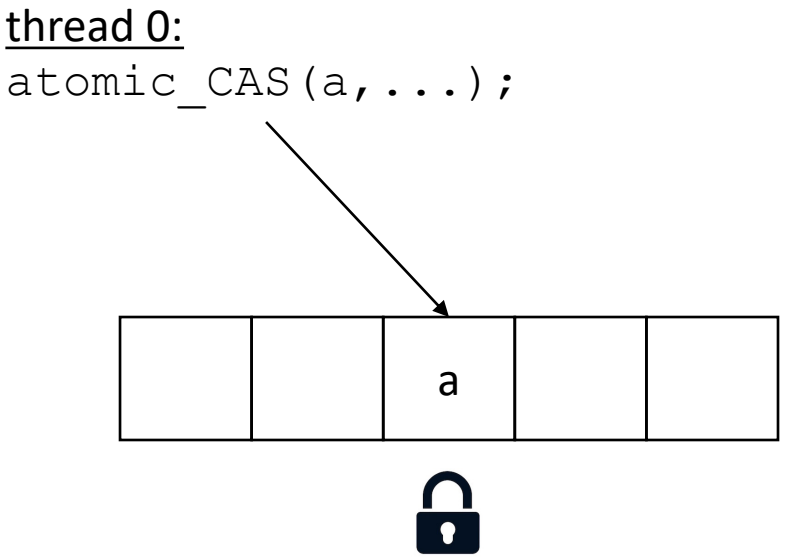

Cons: if no other threads are contending, lock overhead is high

Optimistic Concurrency

- ARM has load/store exclusive
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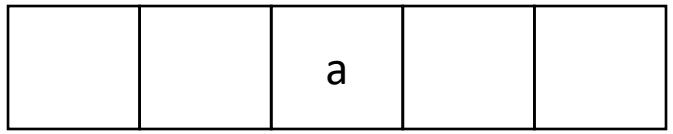
- Assume ***no*** conflicts will happen. Detects and reacts to them.

thread 0:

```
tmp = load_exclusive(a,...);
tmp += 1;
store_exclusive(a, tmp);
```

For this example consider an atomic increment



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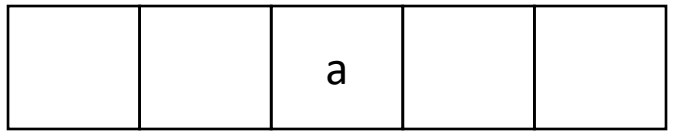

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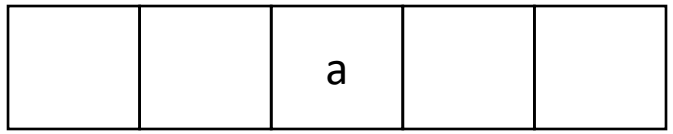

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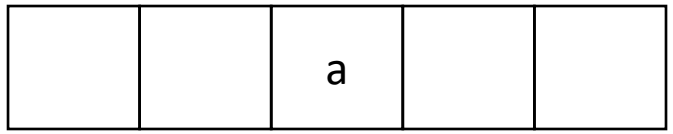

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before we store, we have to check if there was a conflict.

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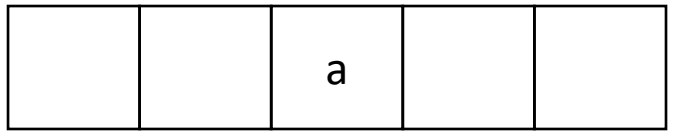

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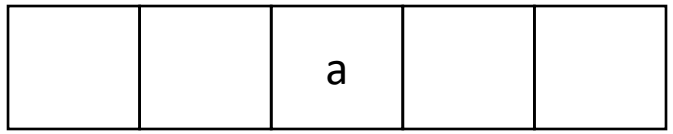

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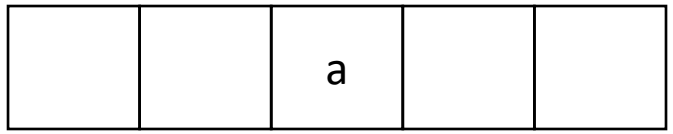

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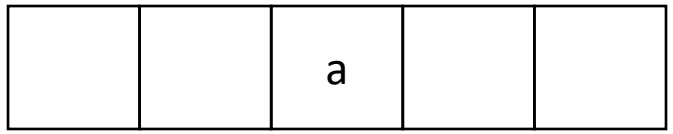

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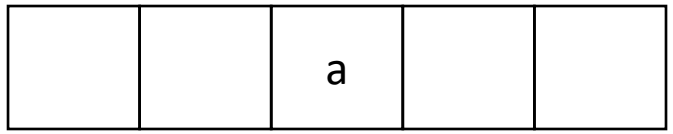

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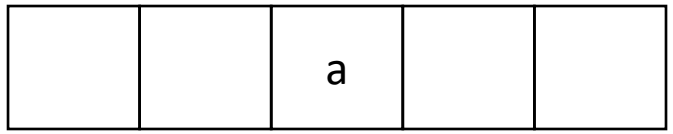

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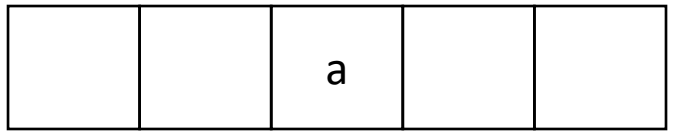

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solution: loop until success:

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```
do {
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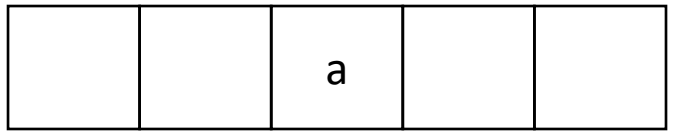
tmp += 1;
} while(!store_exclusive(a, tmp));
```



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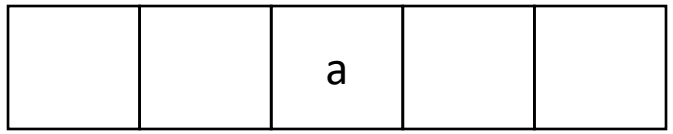

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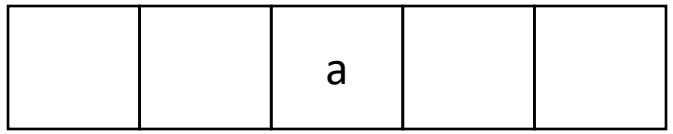

T0_exclusive = 1

Pros: very efficient when there is no conflicts!

Cons: conflicts are very expensive!

Spinning thread might starve (but not indefinitely) if other threads are constantly writing.

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do {
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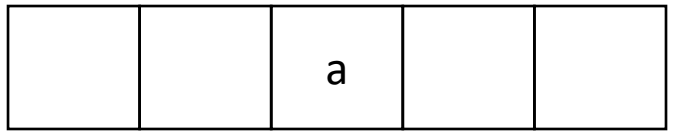
ARM implements all atomics this way!



T0_exclusive = 1

Godbolt example

- Show compiler examples

Optimizations: relaxed peeking

- Relaxed Peeking
  - the Writes in RMWs cost extra; rather than always modify, we can do a simple check first

```
void lock() {
  bool e = false;
  int acquired = false;
  while (acquired == false) {
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
    e = false;
  }
}

bool try_lock() {
  bool e = false;
  return atomic_compare_exchange_strong(&flag, &e, true);
}
```

Optimizations: relaxed peeking

- Relaxed Peeking
  - the Writes in RMWs cost extra; rather than always modify, we can do a simple check first

```
void lock() {
  bool e = false;
  bool acquired = false;
  while (!acquired) {
    while (flag.load() == true);
    e = false;
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
  }
}
```

Optimizations: relaxed peeking

- What about the load in the loop? Remember the memory fence? Do we need to flush our caches every time we peek?
- We only need to flush when we actually acquire the mutex

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Optimizations: relaxed peeking

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```
void lock(int thread_id) {
  bool e = false;
  bool acquired = false;
  while (!acquired) {
    while (flag.load(memory_order_relaxed) == true);
    e = false;
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
  }
}
```

```
void lock(int thread_id) {
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  bool acquired = false;
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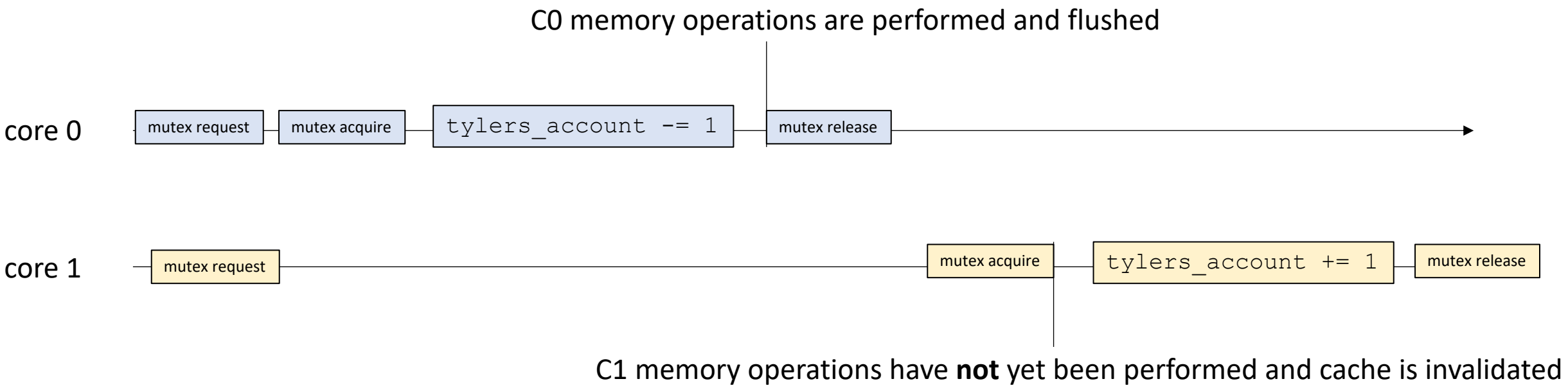

Relaxed atomics

- Enter expert mode!
  - explicit atomics with relaxed semantics
  - Beware! they do not provide a memory fence!
  - Only use when a memory fence is issued later before leaving your mutex implementation. Good for “peeking” before you actually execute your RMW.

Optimizations: backoff

- Even using relaxed peeking, two issues remain:
  - Loads still cause bus traffic (even if its not as bad as RMWs)
  - In non-parallel systems, concurrent threads can get in the way of progress

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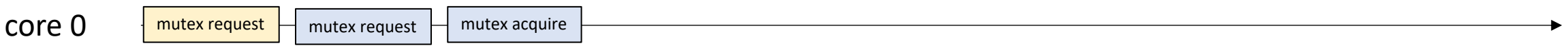
  - **In non-parallel systems, concurrent threads can get in the way of progress**

Say threads 0 and 1 are executing concurrently



Optimizations: backoff

- Even using relaxed peeking, two issues remain:
  - Loads still cause bus traffic (even if its not as bad as RMWs)
  - **In non-parallel systems, concurrent threads can get in the way of progress**

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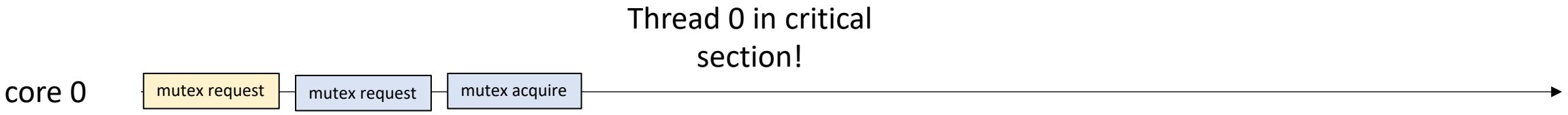

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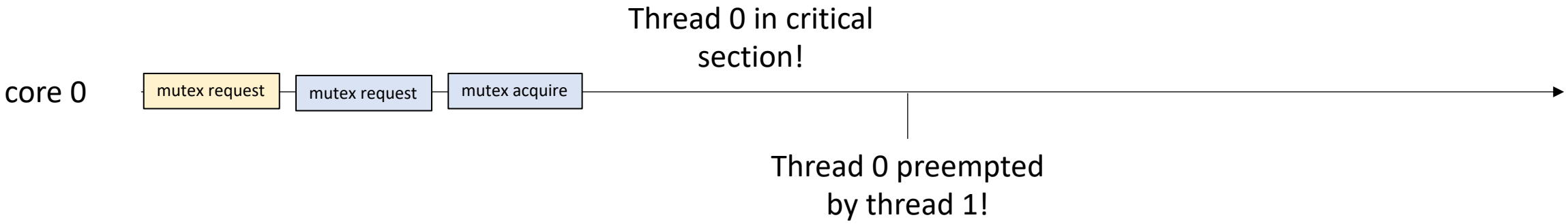

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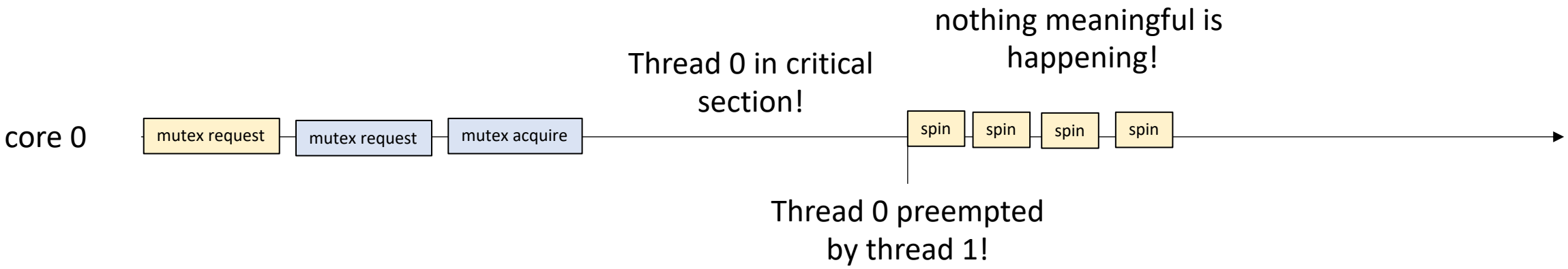

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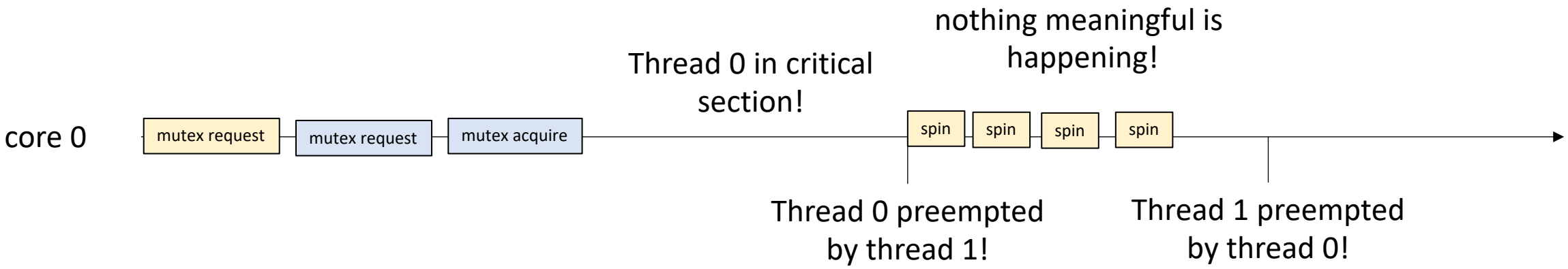

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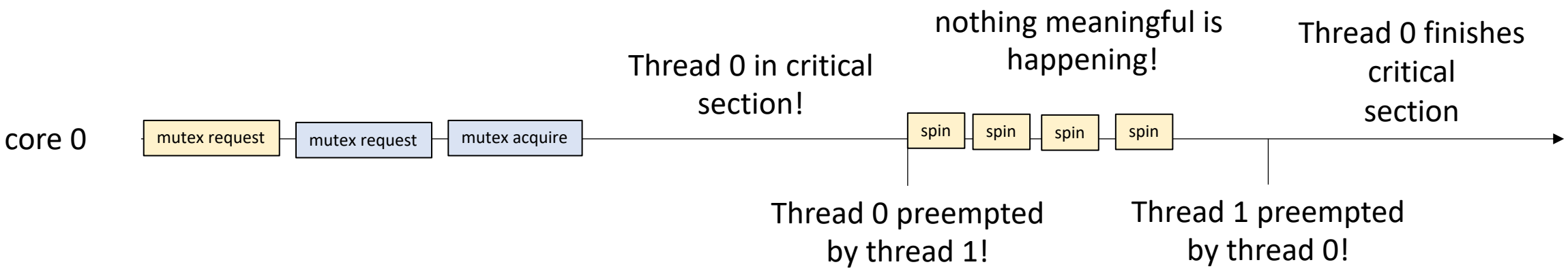

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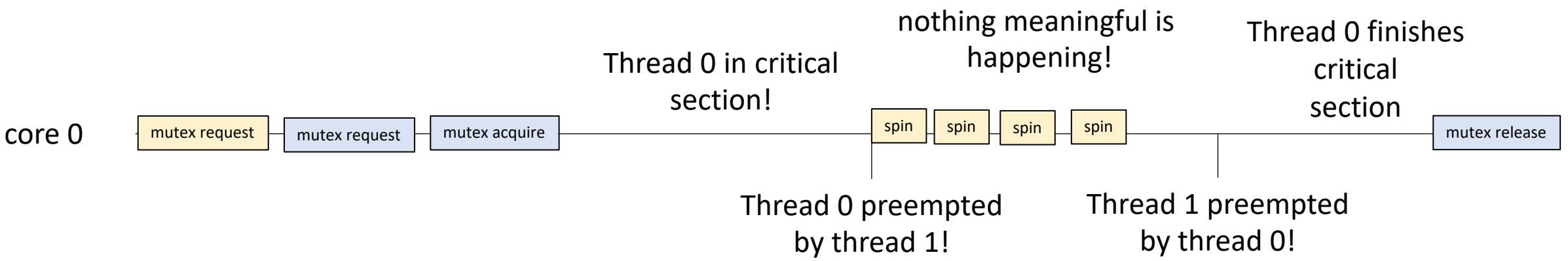
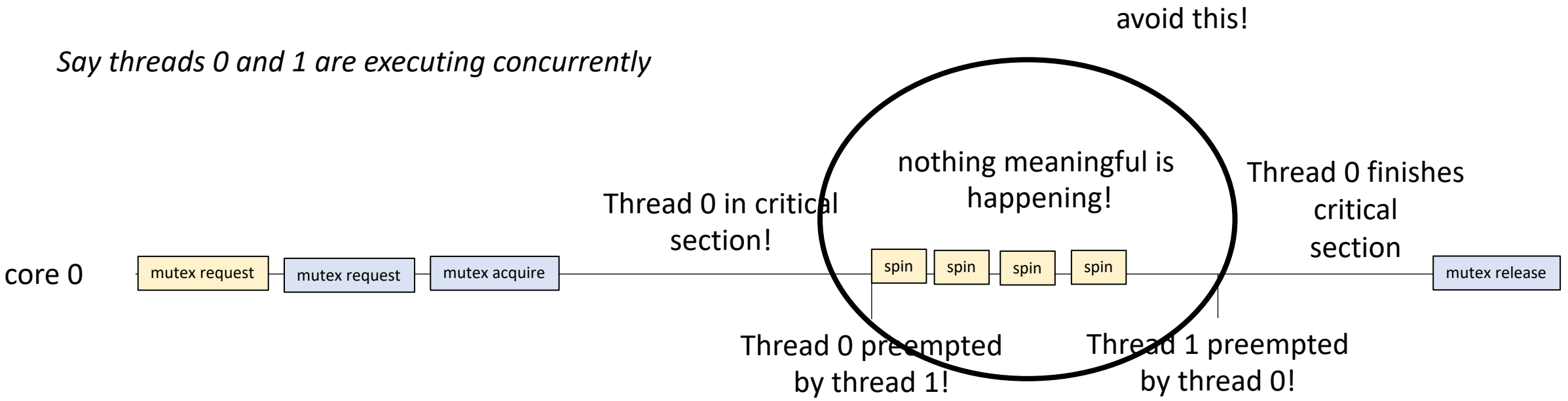


Optimizations: backoff

- Two issues remain:
  - Loads still cause bus traffic (even if its not as bad as RMWs)
  - **In non-parallel systems, concurrent threads can get in the way of progress**



Optimizations: backoff

- C++
  - `this_thread::yield();`

- Hints to the operating system that we should take a break while other threads (potentially the threads that have the mutex) get scheduled.

Optimizations: backoff

where do we put it?

- C++
  - `this_thread::yield();`

- Hints to the operating system that we should take a break while other threads (potentially the threads that have the mutex) get scheduled.

```
void lock(int thread_id) {
  bool e = false;
  bool acquired = false;
  while (!acquired) {
    while (flag.load(memory_order_relaxed) == true);
    e = false;
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
  }
}
```

Optimizations: backoff

```
void lock(int thread_id) {
  bool e = false;
  bool acquired = false;
  while (!acquired) {
    while (flag.load(memory_order_relaxed) == true) {
      this_thread::yield();
    }
    e = false;
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
  }
}
```

Demo

- Example in terminal

Optimizations: backoff

- Other backoff strategies: sleeping
  - `this_thread::sleep_for(10ms);`
  - Finer control over sleep time
- Exponential backoff:
  - Every time the thread wakes up, sleep for 2x as long
- Tuned sleep time:
  - Keep track of a sleep time.
  - Every time you spin, increase the sleep time (remember for next spin)
  - If you acquire, reduce the sleep time

Optimizations: when to use them

- **Spinning** is useful for short waits on non-oversubscribed systems

- **Sleeping** is useful for regular tasks
  - tasks occur at set frequencies
  - critical sections take roughly the same time
  - In these cases, sleep times can be tuned

- **Yielding** is useful for oversubscribed systems, with irregular tasks
  - On modern systems, yield is usually sufficient!

Optimizations: when to use them

- When to use what optimization?
  - Start with C++ mutex, then
  - microbenchmark
  - profile

- Sometimes we want our own custom backoff strategies.
  - We can optimize around existing mutexes!

try_lock

- another common mutex API method: try_lock()
- one-shot mutex attempt (implementation defined)
- You can then implement your own sleep/yield strategy around this

```
void lock() {
  bool e = false;
  bool acquired = false;
  while (!acquired) {
    while (flag.load(memory_order_relaxed) == true) {
      this_thread::yield();
    }
    e = false;
    acquired = atomic_compare_exchange_strong(&flag, &e, true);
  }
}

bool try_lock() {
  bool e = false;
  return atomic_compare_exchange_strong(&flag, &e, true);
}
```

try_lock

- straightforward with CAS and exchange mutex
- What about ticket lock?

```
class Mutex {
public:
  Mutex() {
    counter = 0;
    currently_serving = 0;
  }

  void lock() {
    int my_number = atomic_fetch_add(&counter, 1);
    while (currently_serving.load() != my_number);
  }

  void unlock() {
    int tmp = currently_serving.load();
    tmp += 1;
    currently_serving.store(tmp);
  }

private:
  atomic_int counter;
  atomic_int currently_serving;
};
```

Example: UI refresh

- Screen refreshes operate at ~60 FPS.
- Assume a situation where there is mutex for the screen buffer. It can be updated by one thread, once per frame.
- We know that the sleep will be ~16ms

Example: UI refresh

```
void lock_refresh_rate(mutex m) {
  while (m.try_lock() == false) {
    this_thread::sleep_for(16ms);
  }
}
```

try_lock

- C++ provides a try_lock for their mutex operation

- We have now covered the entire C++ mutex object

RW mutexes

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    tylers_account--;
}
```

```
void get_paid() {
    tylers_account++;
}
```

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    tylers_account--;
}
```

```
void get_paid() {
    tylers_account++;
}
```

But what happens more frequently than either of those things?

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    tylers_account--;
}
```

```
void get_paid() {
    tylers_account++;
}
```

which of these operations can safely be executed concurrently?

Remember the definition of a data-conflict: at least one write

But what happens more frequently than either of those things?

```
int check_balance() {
    return tylers_account;
}
```

Different actors accessing it concurrently
Credit monitors
Accountants
Personal

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    tylers_account--;
}
```

```
void get_paid() {
    tylers_account++;
}
```

But what happens more frequently than either of those things?

```
int check_balance() {
    return tylers_account;
}
```

No reason why this function can't be called concurrently. It only needs to be protected if another thread calls one of the other functions.

Reader-Writer Mutex

- different lock and unlock functions:
  - Functions that only read can perform a “read” lock
  - Functions that might write can perform a regular lock
  - regular locks ensures that the writer has exclusive access (from other reader and writers)
  - but multiple reader threads can hold the lock in reader state

Reader-Writer Mutex

```
class rw_mutex {
 public:
  void reader_lock();
  void reader_unlock();
  void lock();
  void unlock();
};
```

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    tylers_account--;
}
```

```
void get_paid() {
    tylers_account++;
}
```

```
int check_balance() {
    return tylers_account;
}
```

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

```
int check_balance() {
    return tylers_account;
}
```

Reader-Writer Mutex

Global variable: `int tylers_account`

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Reader-Writer Mutex Implementation

- Primitives that we built the previous mutexes with:
  - atomic load, atomic store, atomic RMW
- We have a new tool!
  - Regular mutex!

Reader-Writer Mutex Implementation

- We will use a mutex internally.
- We will keep track of how many readers are currently “holding” the mutex.
- We will keep track of if a writer is holding the mutex.

```
class rw_mutex {
 public:
  rw_mutex() {
    num_readers = 0;
    writer = false;
  }

  void reader_lock();
  void reader_unlock();
  void lock();
  void unlock();

 private:
  mutex internal_mutex;
  int num_readers;
  bool writer;
};
```

Reader-Writer Mutex Implementation

- Reader locks

```
void reader_lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer) {
      acquired = true;
      num_readers++;
    }
    internal_mutex.unlock();
  }
}

void reader_unlock() {
  internal_mutex.lock();
  num_readers--;
  internal_mutex.unlock();
}
```

Reader-Writer Mutex Implementation

- Regular locks

```
void lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer && num_readers == 0) {
      acquired = true;
      writer = true;
    }
    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = false
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
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}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

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int check_balance() {
    m.reader_lock();
    int t = tylers_account;
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    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = false
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer && num_readers == 0) {
      acquired = true;
      writer = true;
    }
    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

writer = false
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = true
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
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Thread 2

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    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

writer = true
num_readers = 0

Thread 0

```
void buy_coffee() {
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Thread 1

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void get_paid() {
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}
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Thread 2

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int check_balance() {
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}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void reader_lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer) {
      acquired = true;
      num_readers++;
    }
    internal_mutex.unlock();
  }
}

void reader_unlock() {
  internal_mutex.lock();
  num_readers--;
  internal_mutex.unlock();
}
```

writer = true
num_readers = 0

reset!

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
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    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void reader_lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer) {
      acquired = true;
      num_readers++;
    }
    internal_mutex.unlock();
  }
}

void reader_unlock() {
  internal_mutex.lock();
  num_readers--;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 1

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 1

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void reader_lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer) {
      acquired = true;
      num_readers++;
    }
    internal_mutex.unlock();
  }
}

void reader_unlock() {
  internal_mutex.lock();
  num_readers--;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 1

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 2

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer && num_readers == 0) {
      acquired = true;
      writer = true;
    }
    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 2

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void reader_lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer) {
      acquired = true;
      num_readers++;
    }
    internal_mutex.unlock();
  }
}

void reader_unlock() {
  internal_mutex.lock();
  num_readers--;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 2

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 1

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

can we lock yet?

```
void lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer && num_readers == 0) {
      acquired = true;
      writer = true;
    }
    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 1

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
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Thread 2

```
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Thread 3

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writer = False
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Thread 0

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```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

writer = False
num_readers = 0

Thread 0

```
void buy_coffee() {
    m.lock();
    tylers_account--;
    m.unlock();
}
```

Thread 1

```
void get_paid() {
    m.lock();
    tylers_account++;
    m.unlock();
}
```

Thread 2

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

Thread 3

```
int check_balance() {
    m.reader_lock();
    int t = tylers_account;
    m.reader_unlock();
    return t;
}
```

```
void lock() {
  bool acquired = false;
  while (!acquired) {
    internal_mutex.lock();
    if (!writer && num_readers == 0) {
      acquired = true;
      writer = true;
    }
    internal_mutex.unlock();
  }
}

void unlock() {
  internal_mutex.lock();
  writer = false;
  internal_mutex.unlock();
}
```

writer = False
num_readers = 0

Reader Writer lock

- This implementation potentially starves writers
  - The common case is to have lots of readers!

- Think about ways how an implementation might be more fair to writers.

How this looks in C++

```
#include <shared_mutex>
using namespace std;

shared_mutex m;

m.lock_shared()   // reader lock
m.unlock_shared() // reader unlock
m.lock()          // regular lock
m.unlock()        // regular unlock
```