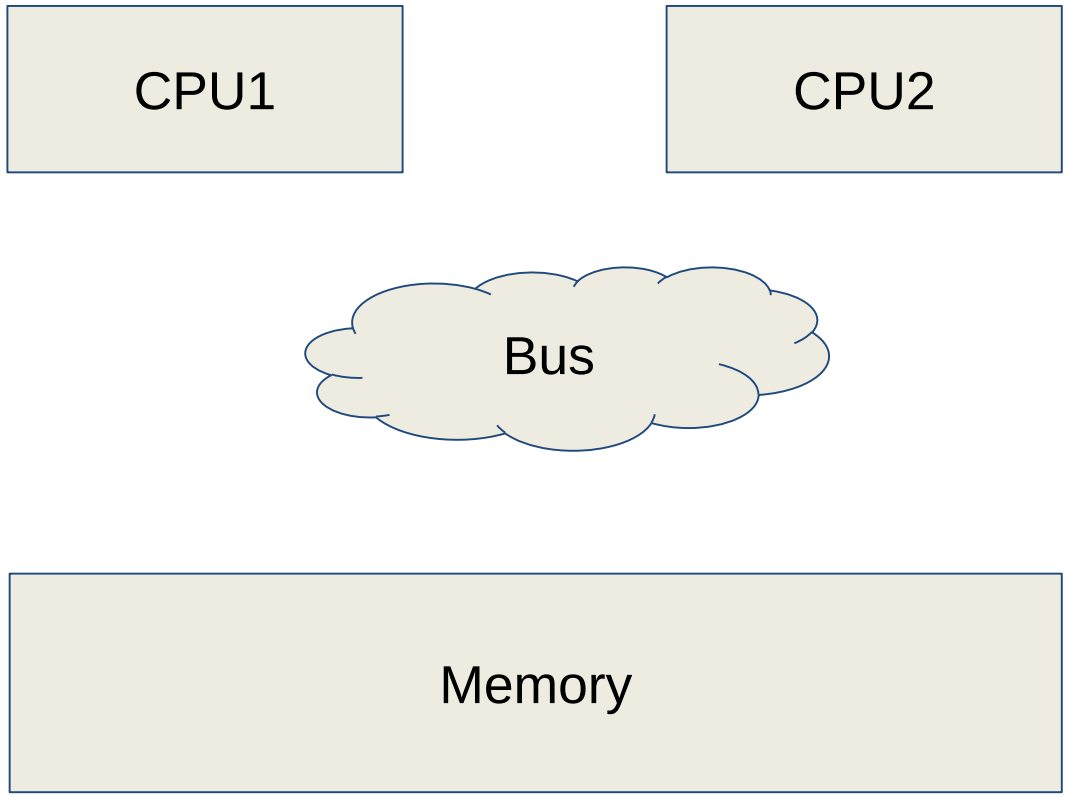
Многопоточное Программирование: Железо и спин-локи

Роман Елизаров, JetBrains, elizarov@gmail.com
Никита Коваль, JetBrains, ndkoval@ya.ru

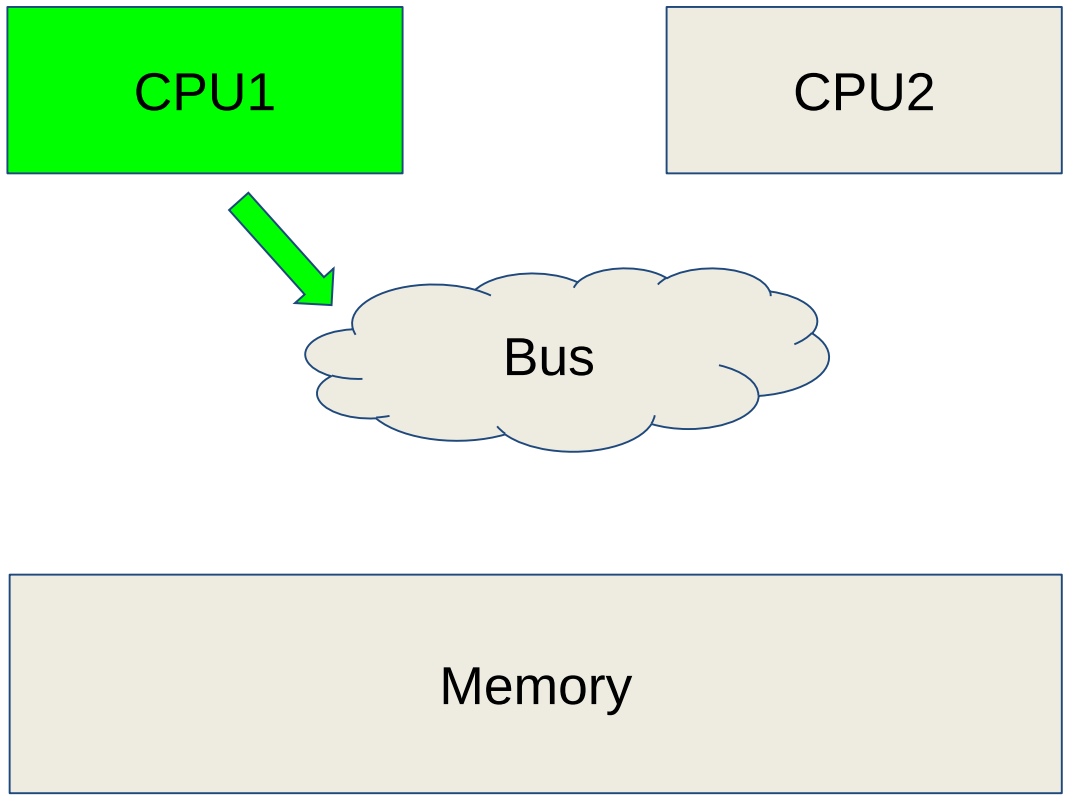
ИТМО 2020

ITMO UNIVERSITY

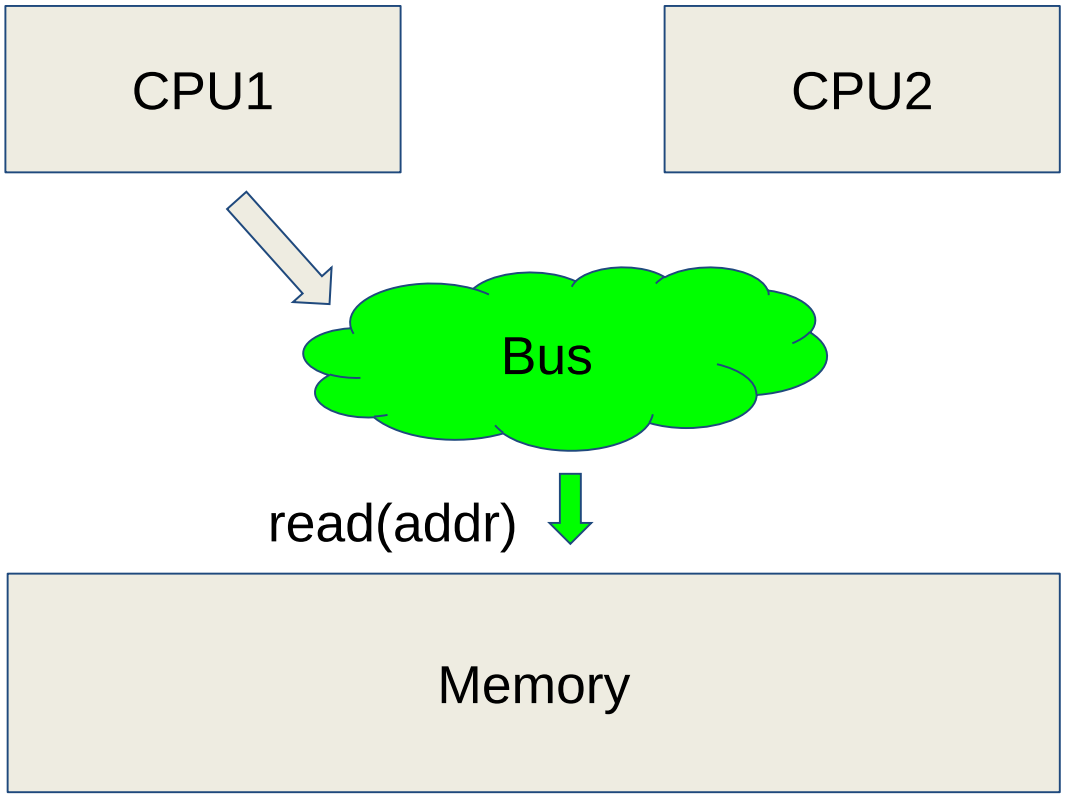
Работа с общей память



Работа с общей память



Работа с общей память



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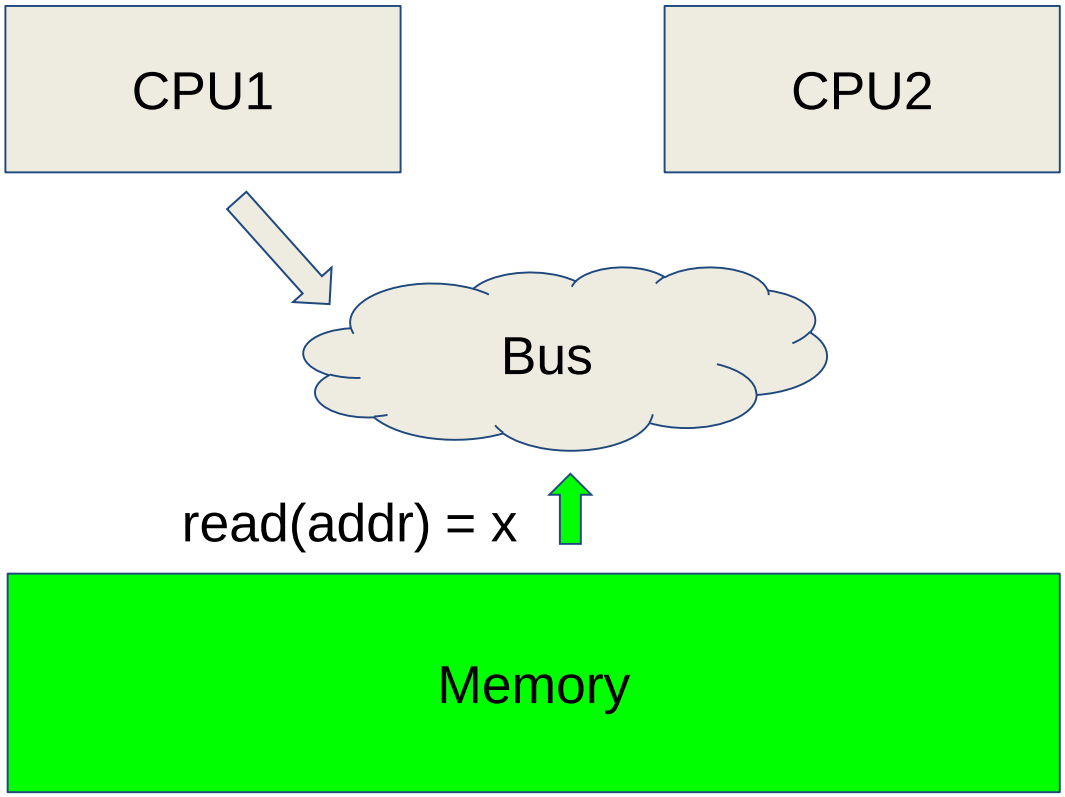
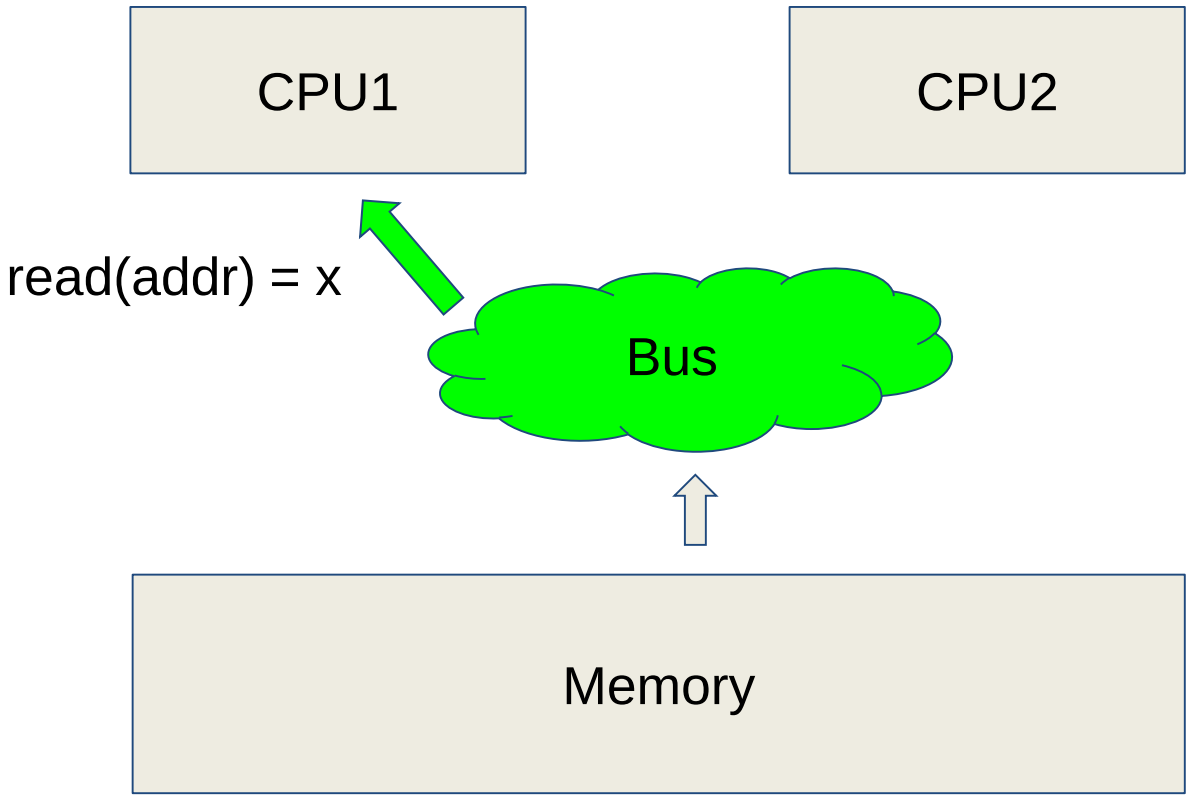
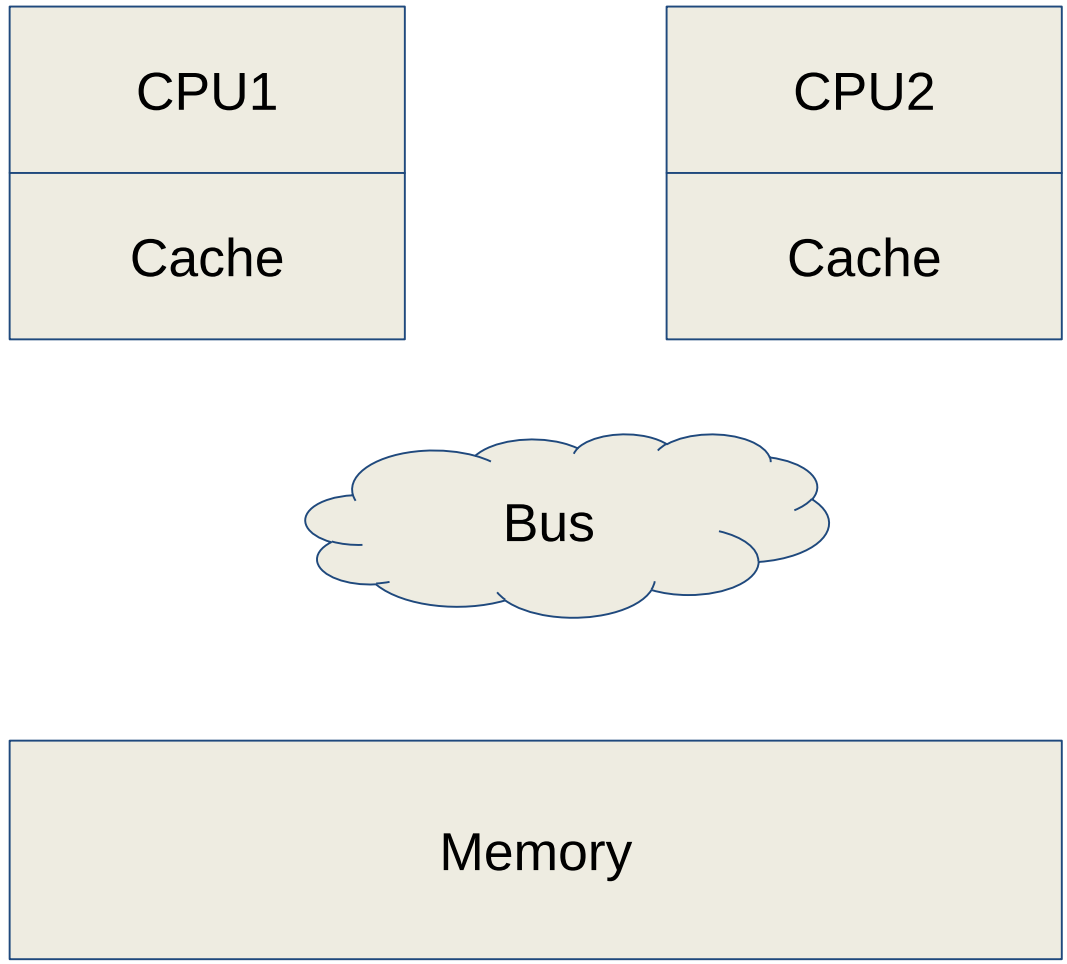


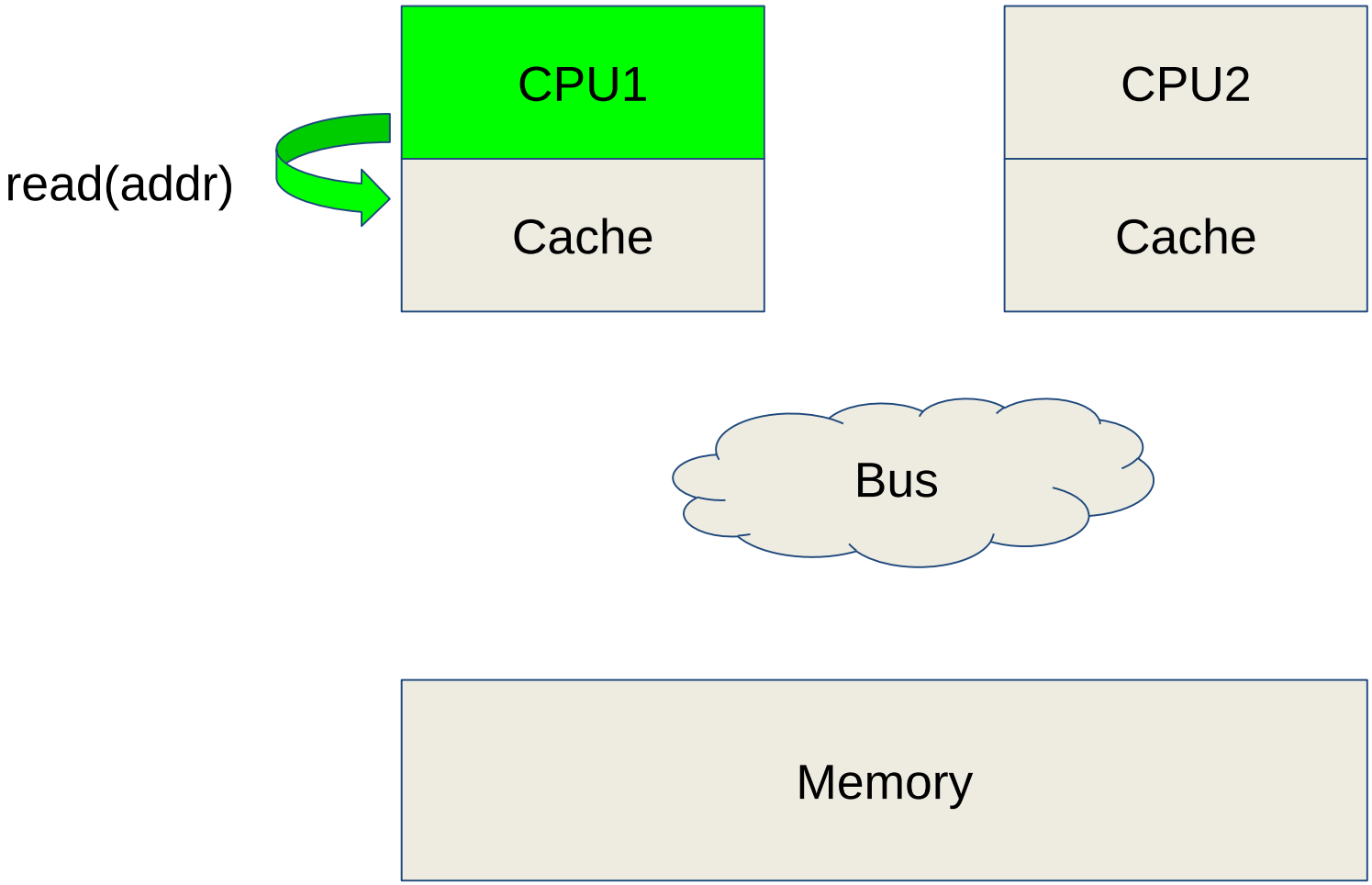
Работа с общей память



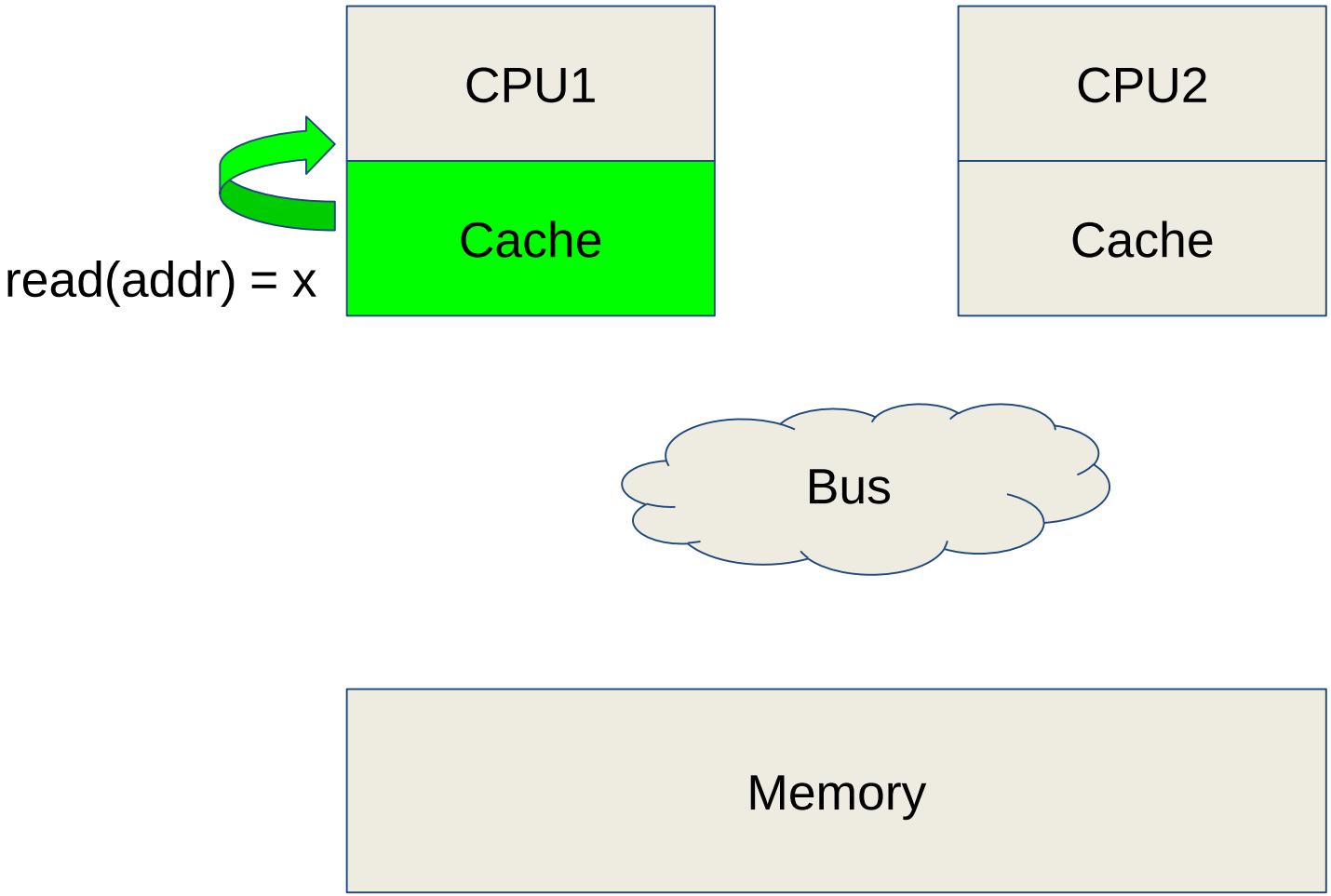
Кэш



Кэш



Кэш



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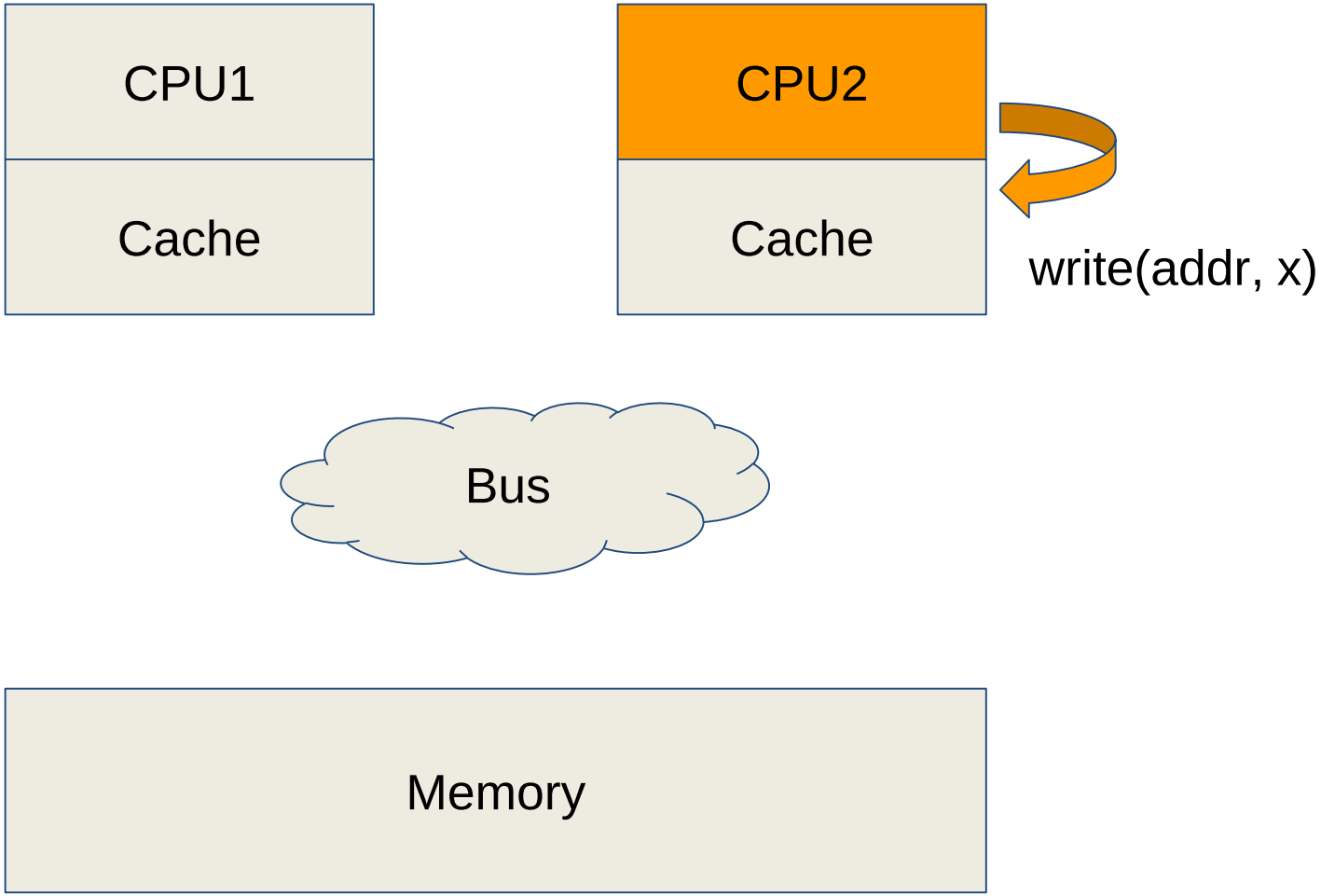

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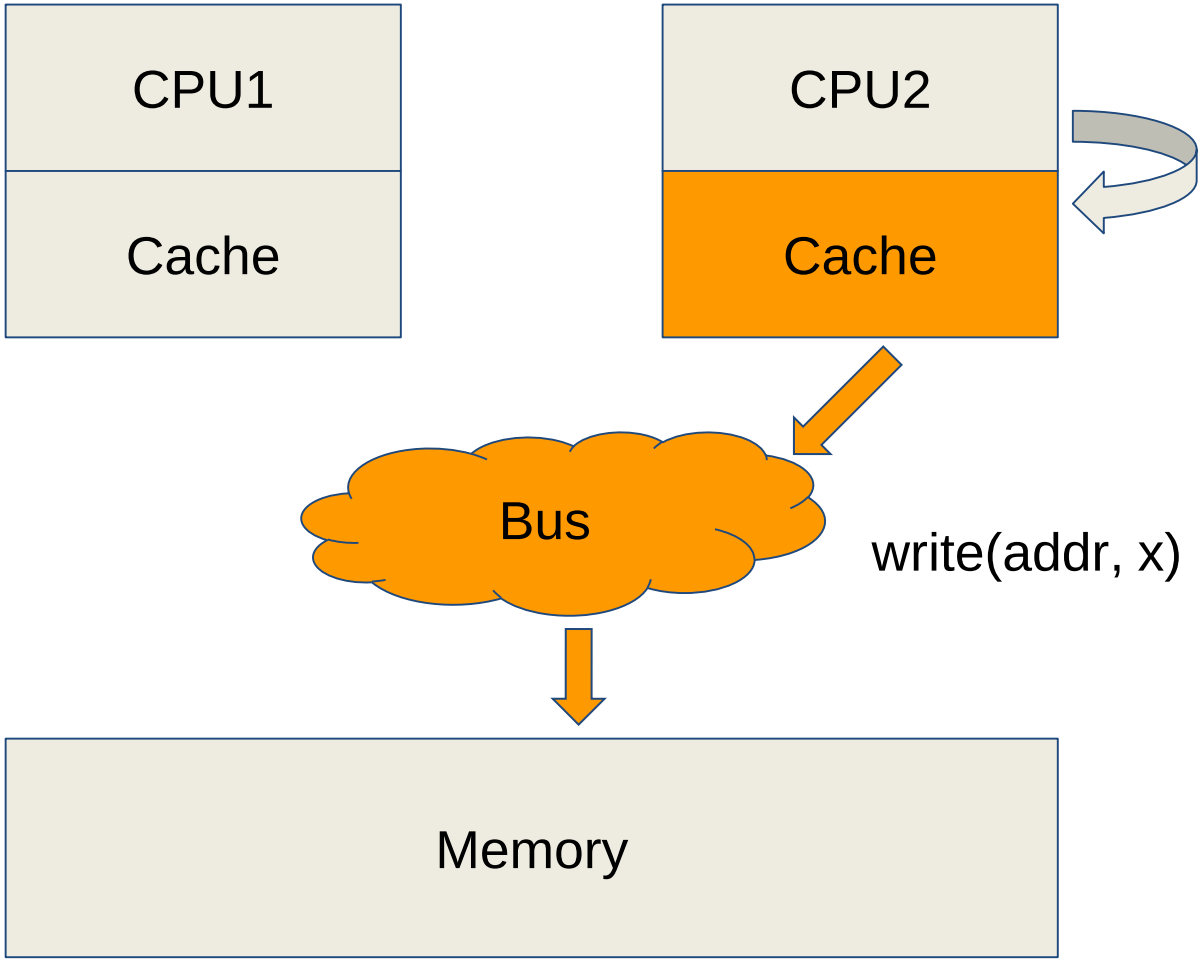

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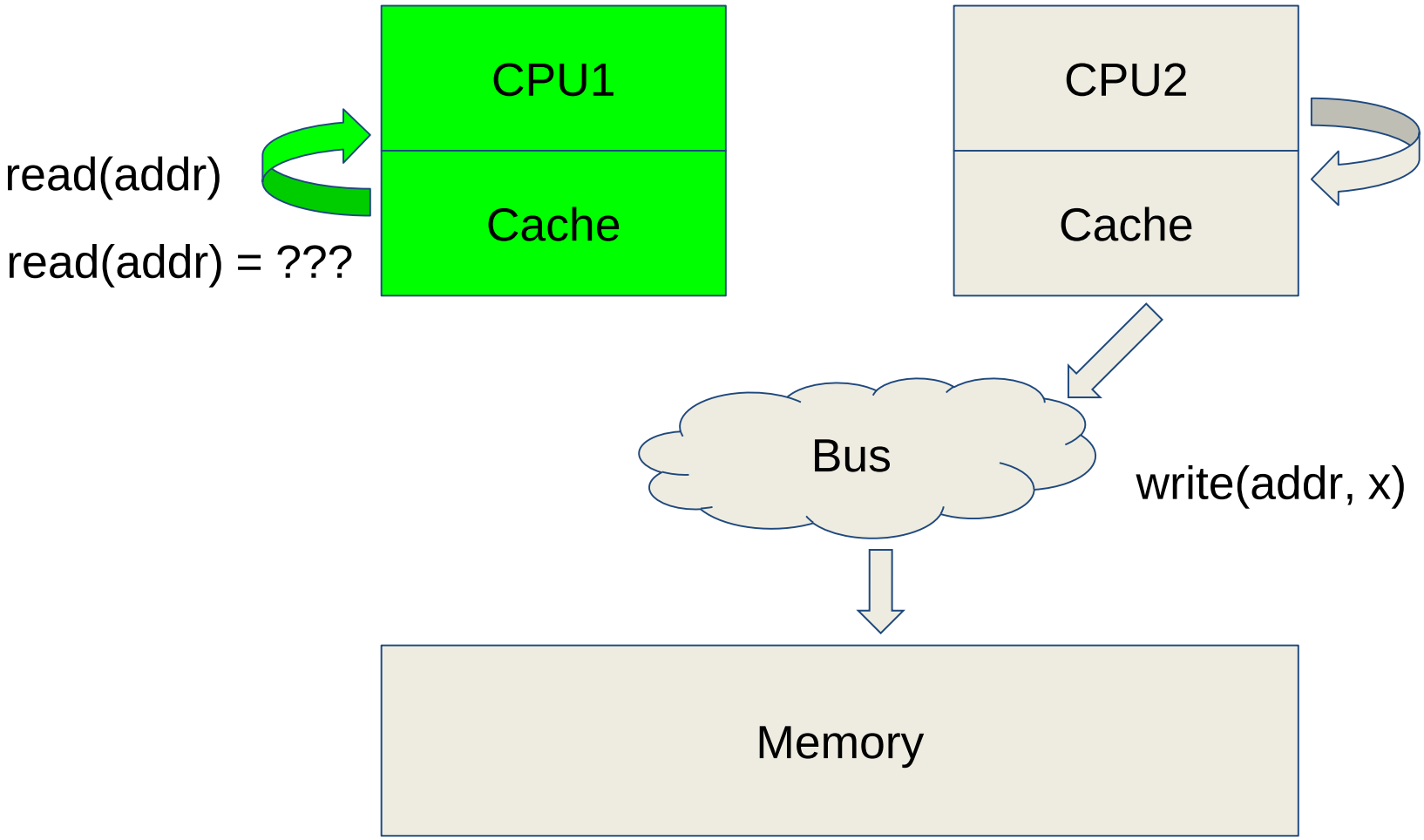
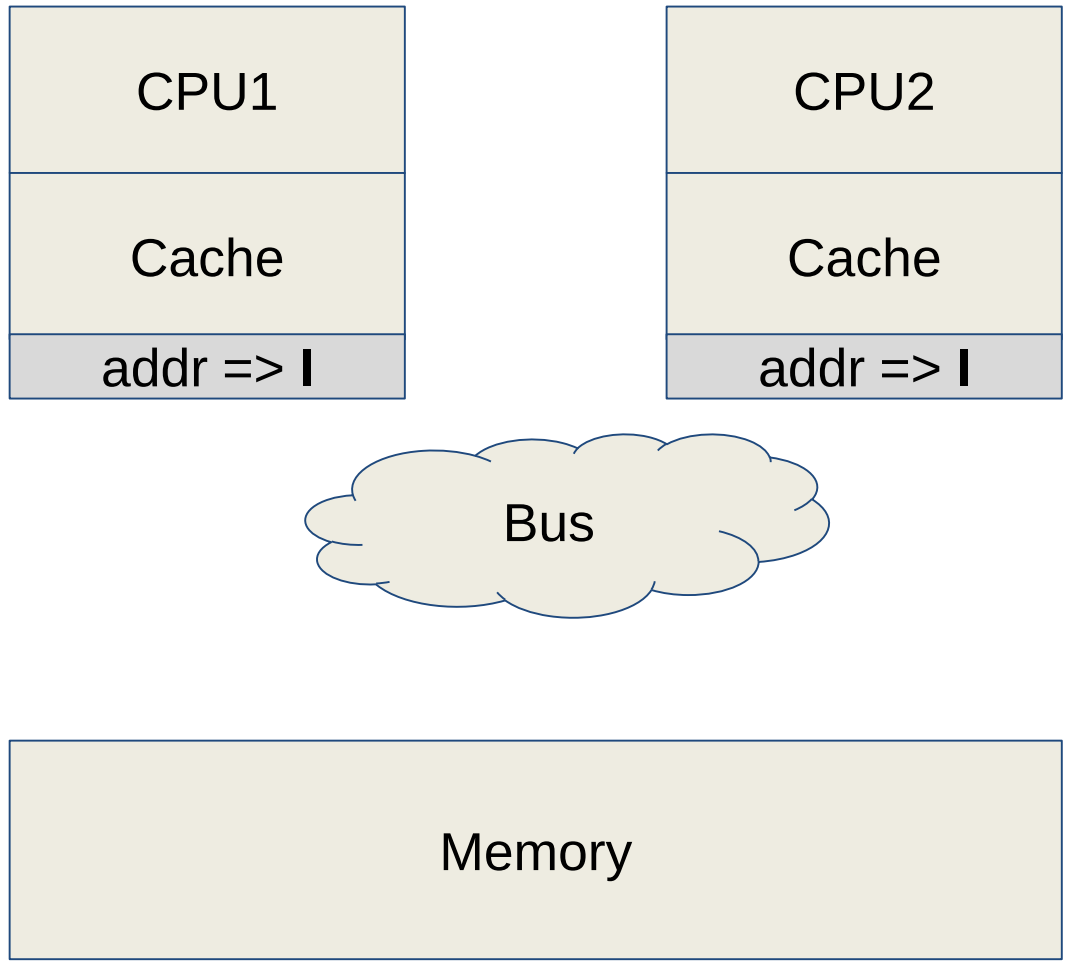


Протокол MESI

M	Modified
E	Exclusive
S	Shared
I	Invalid

MESI наглядно



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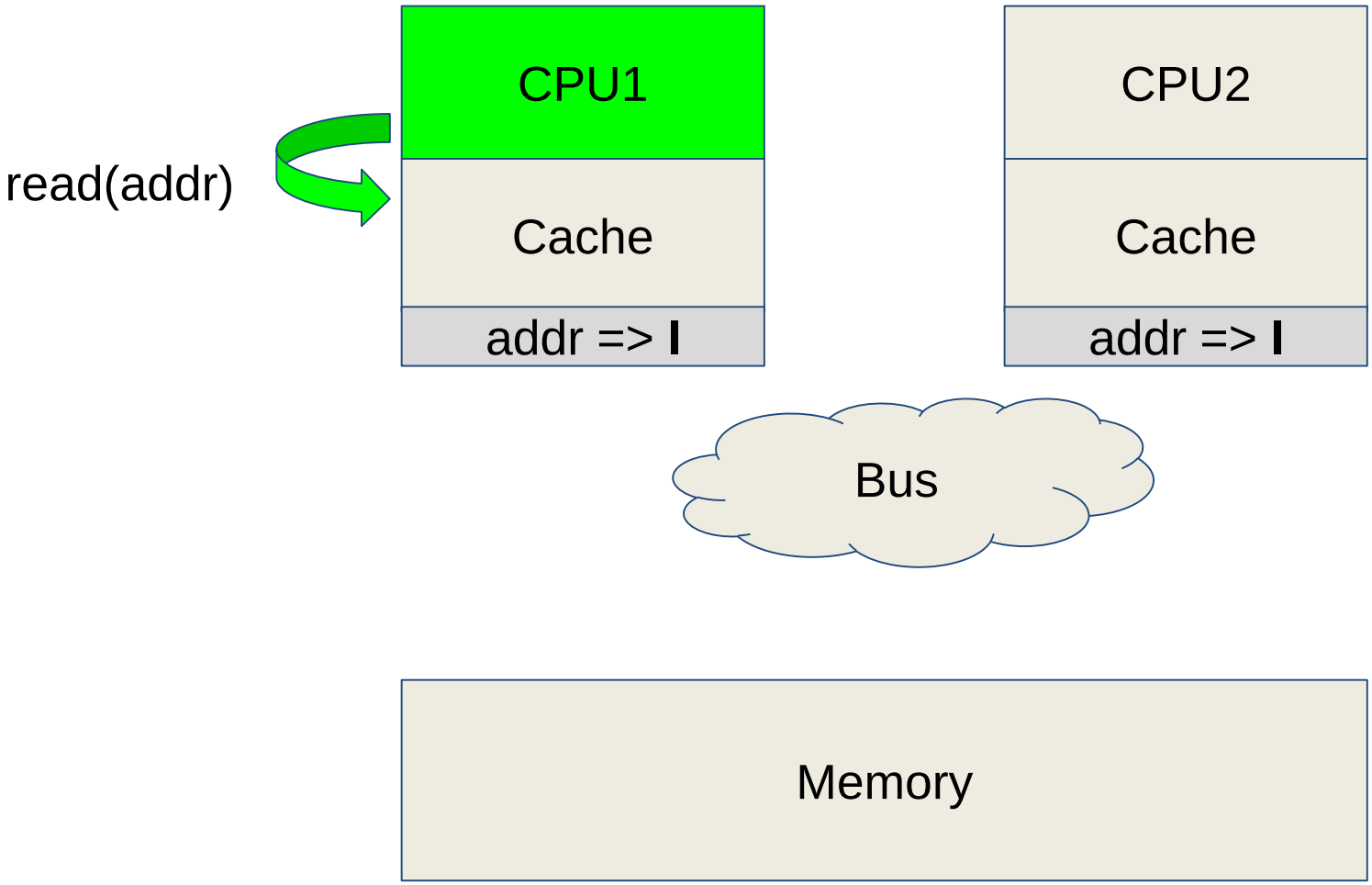
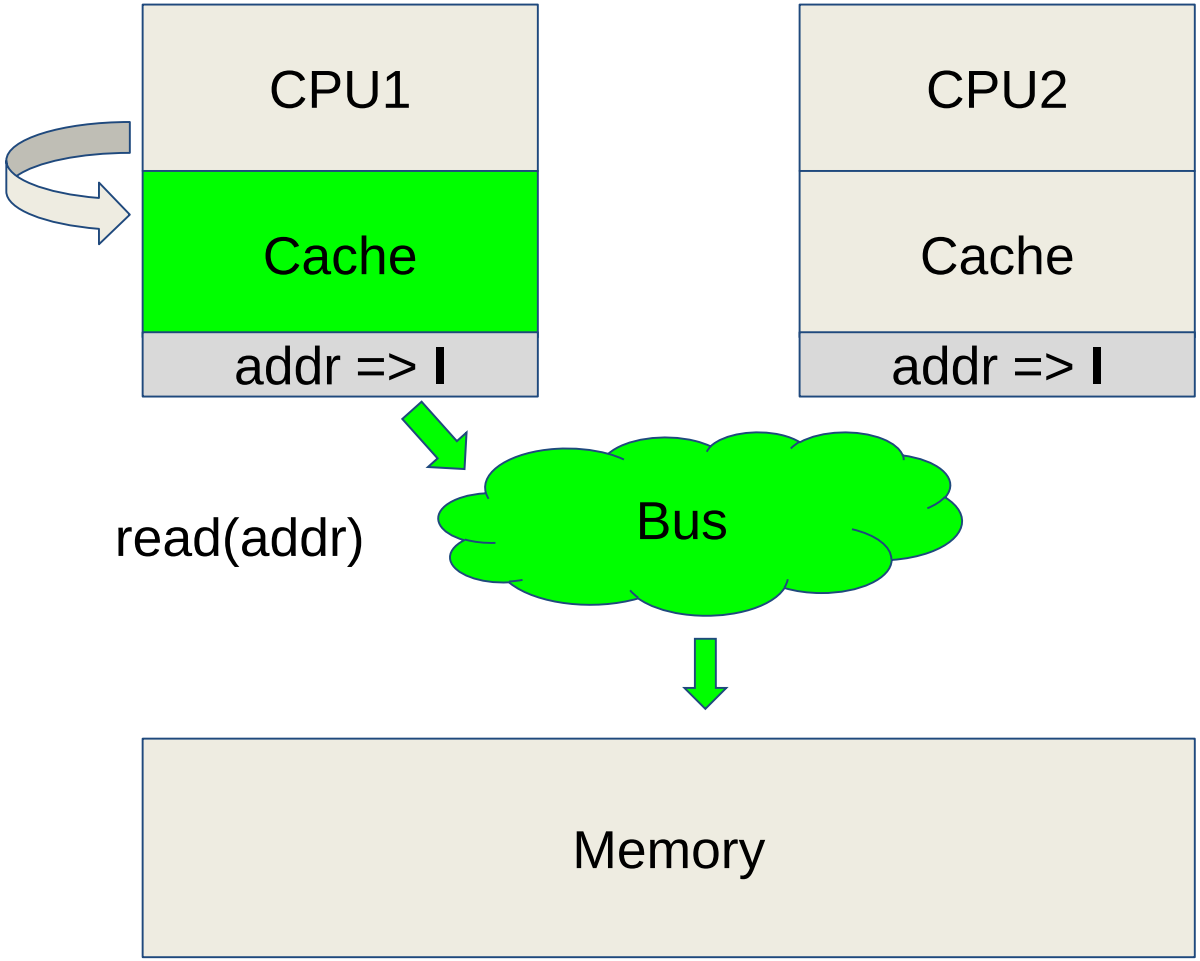


MESI наглядно



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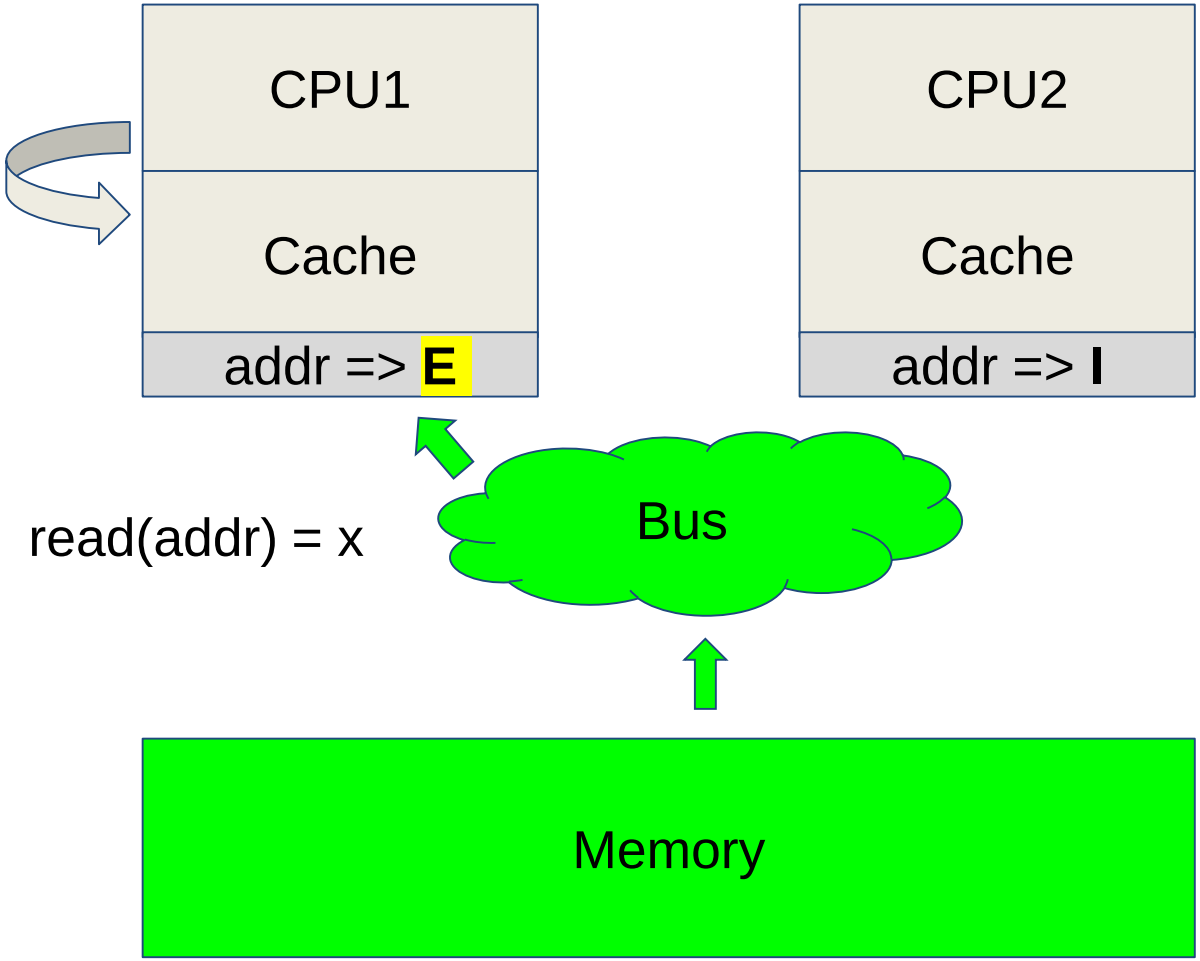
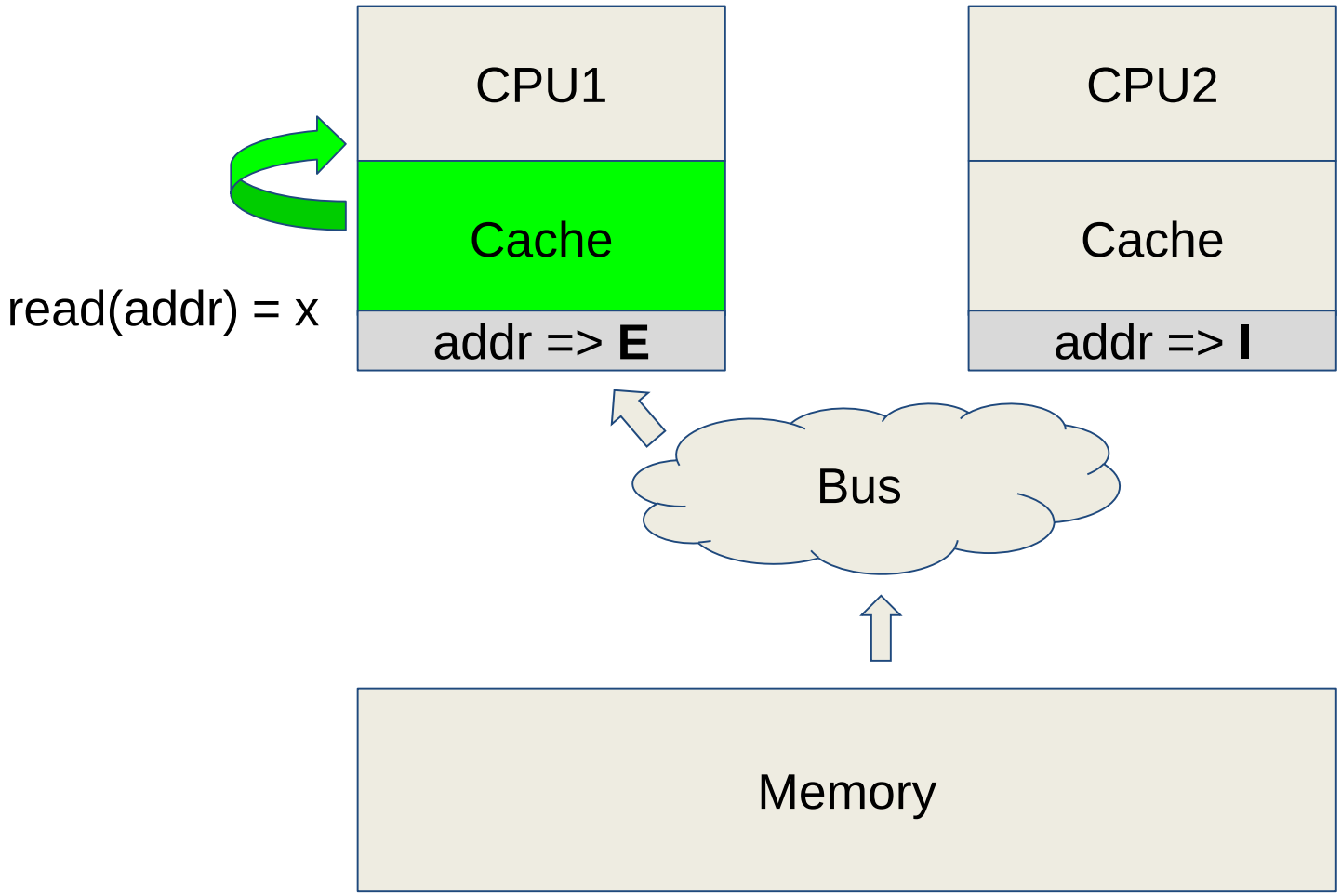


MESI наглядно



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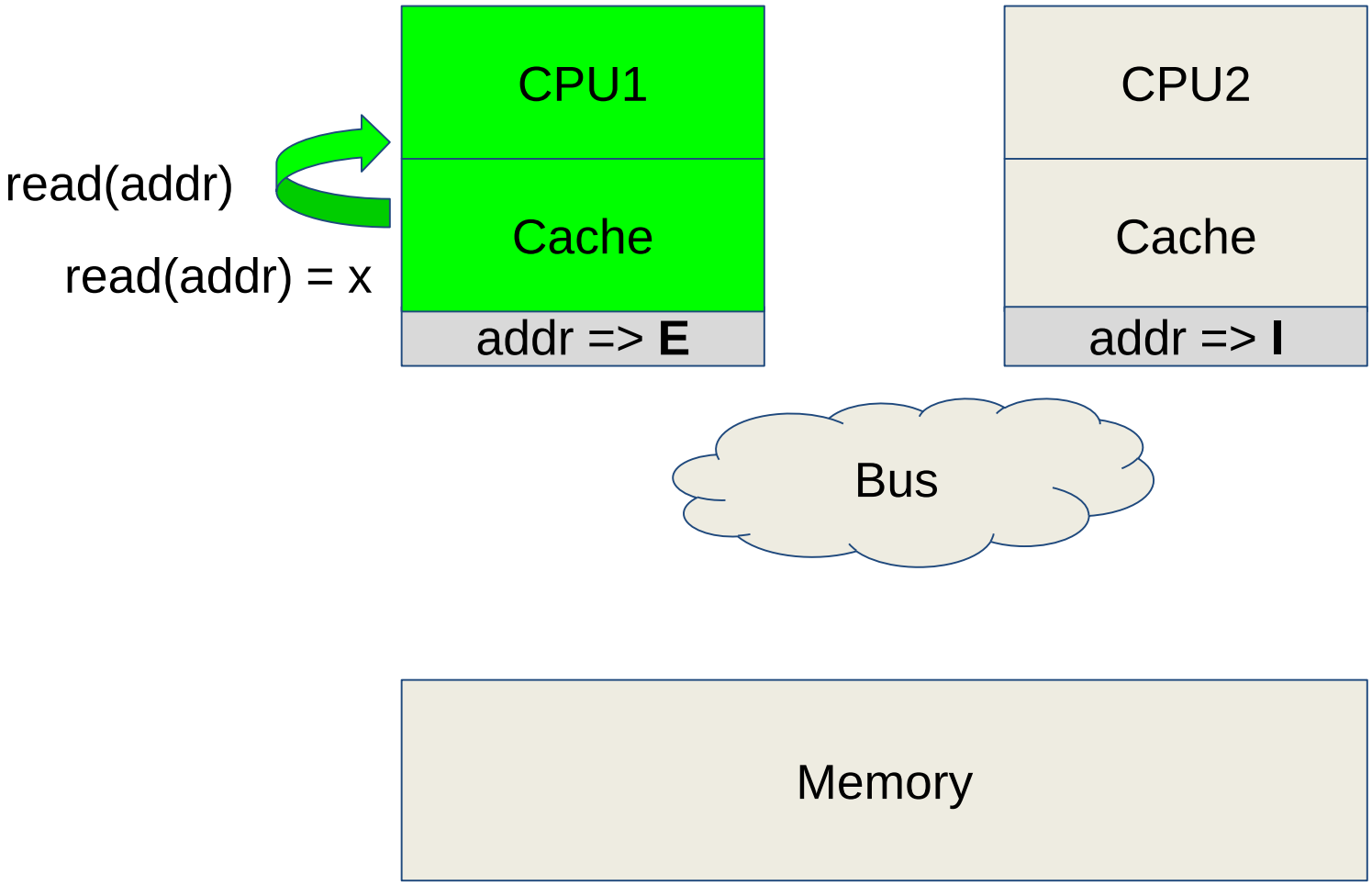
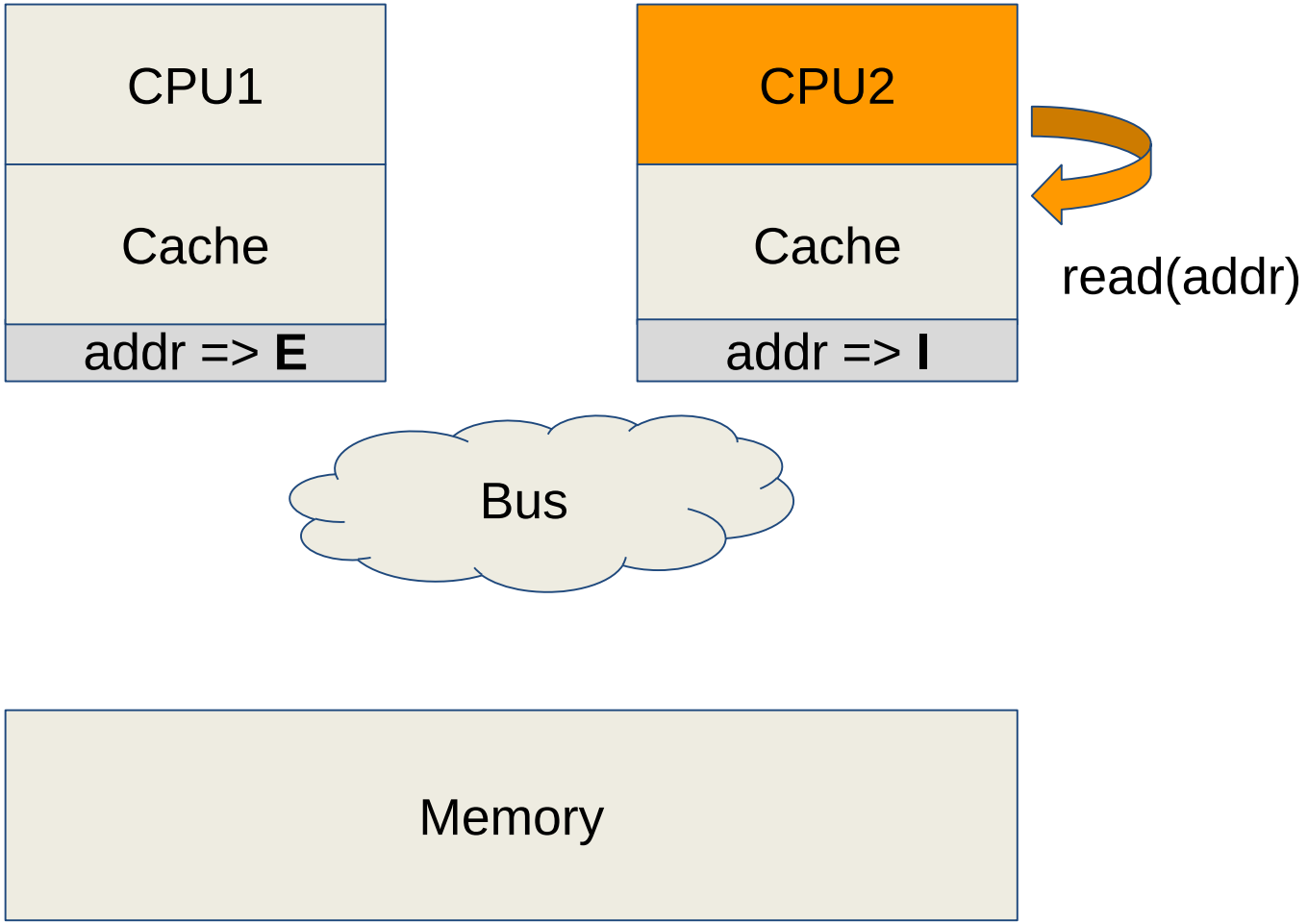


MESI наглядно



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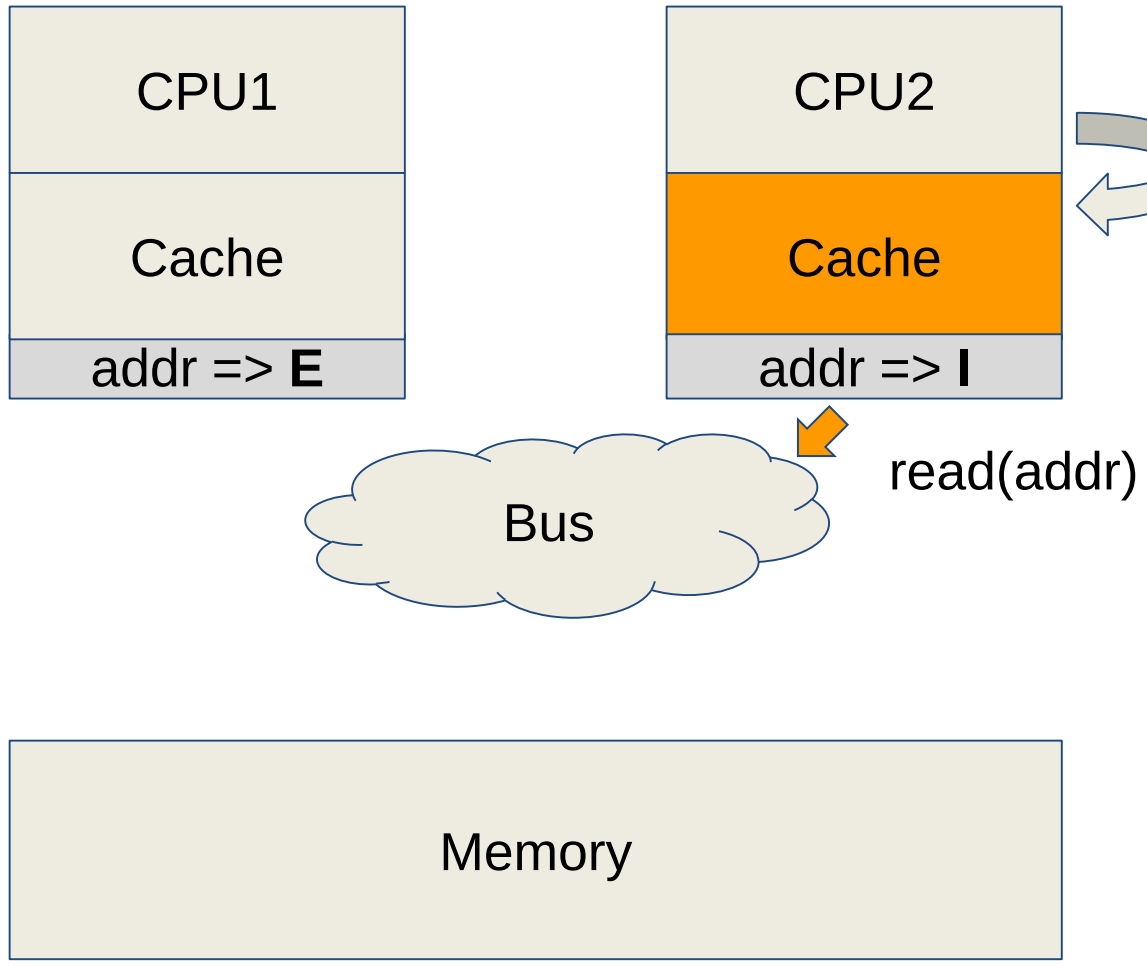

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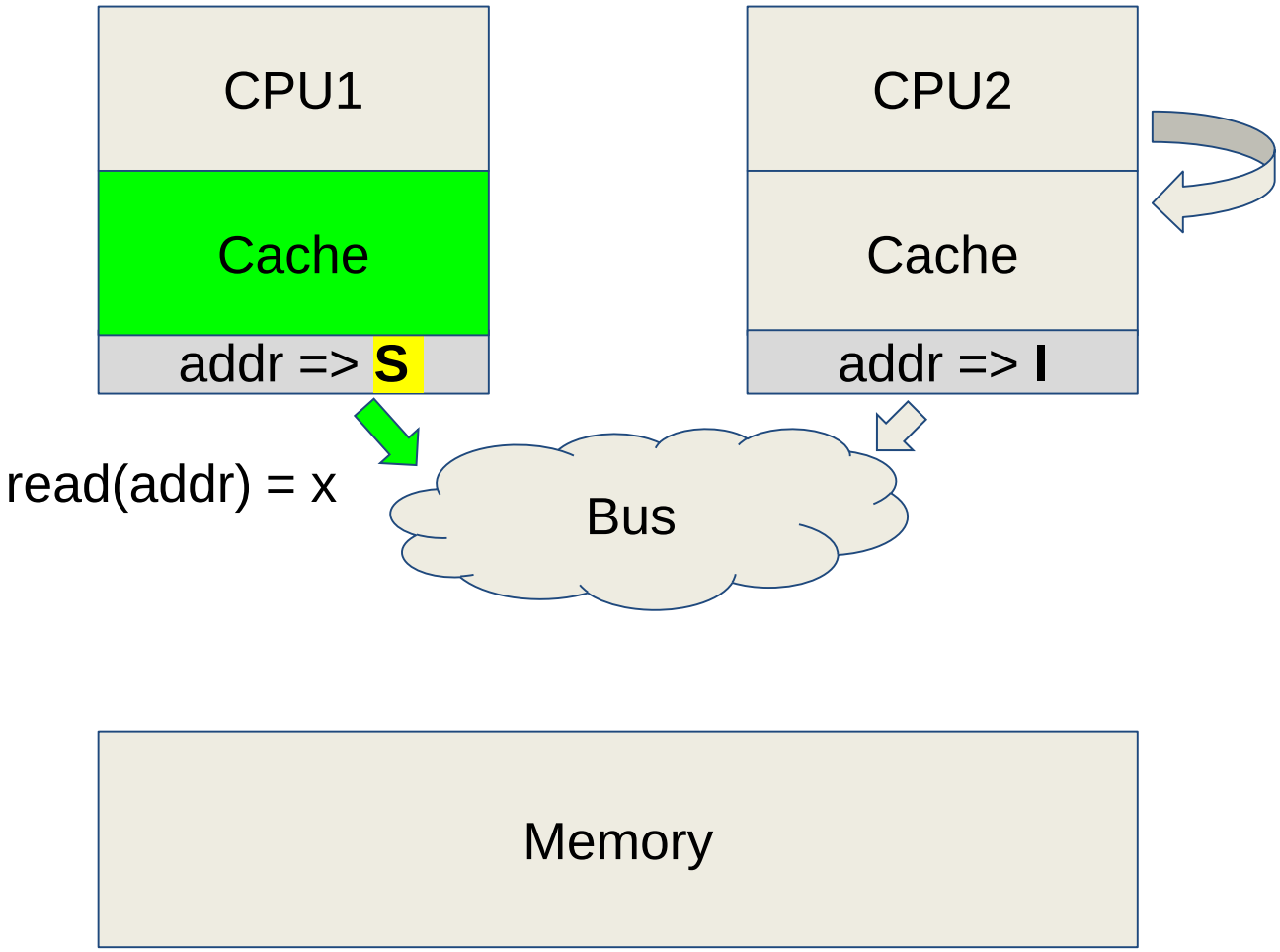

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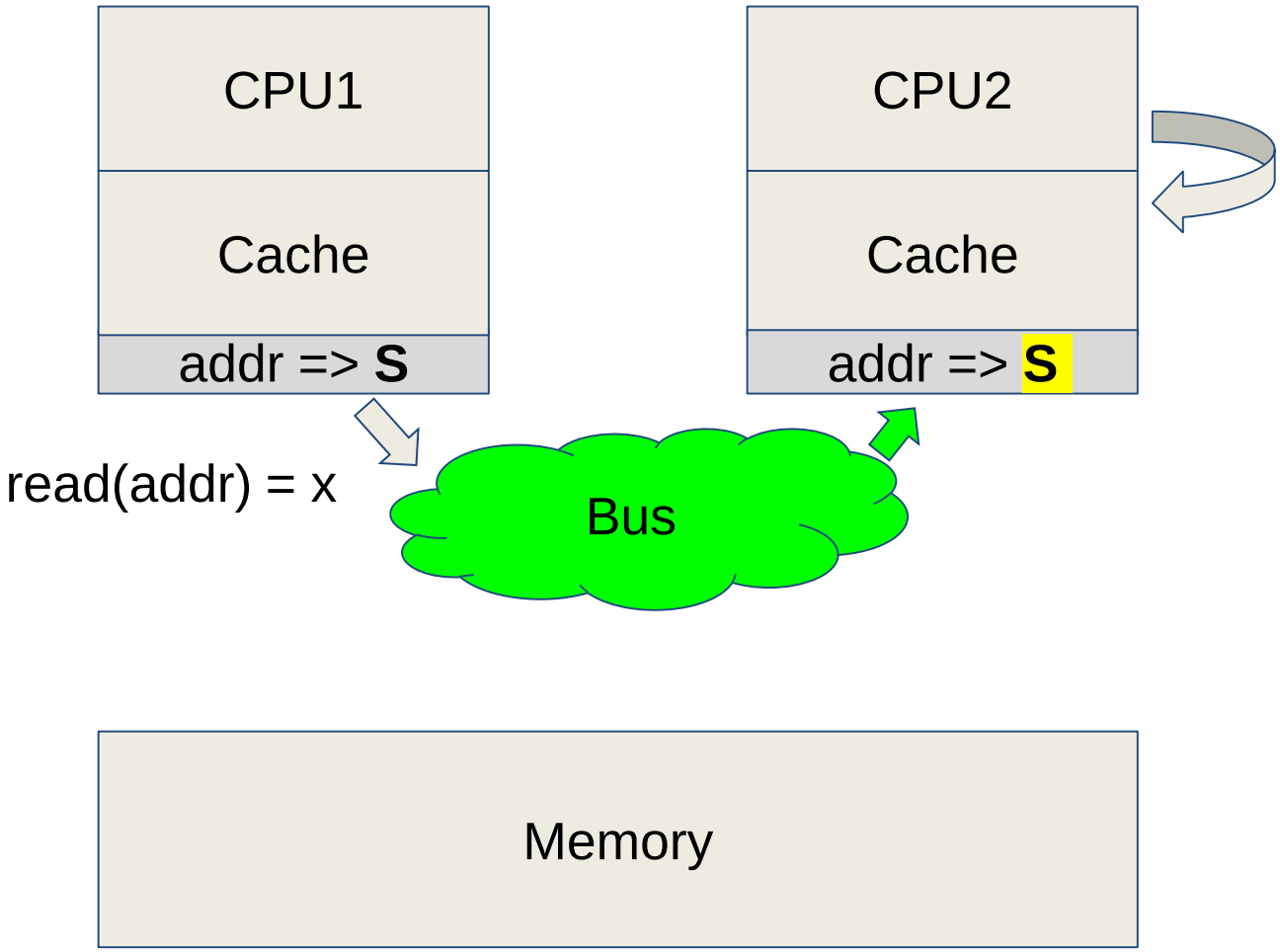

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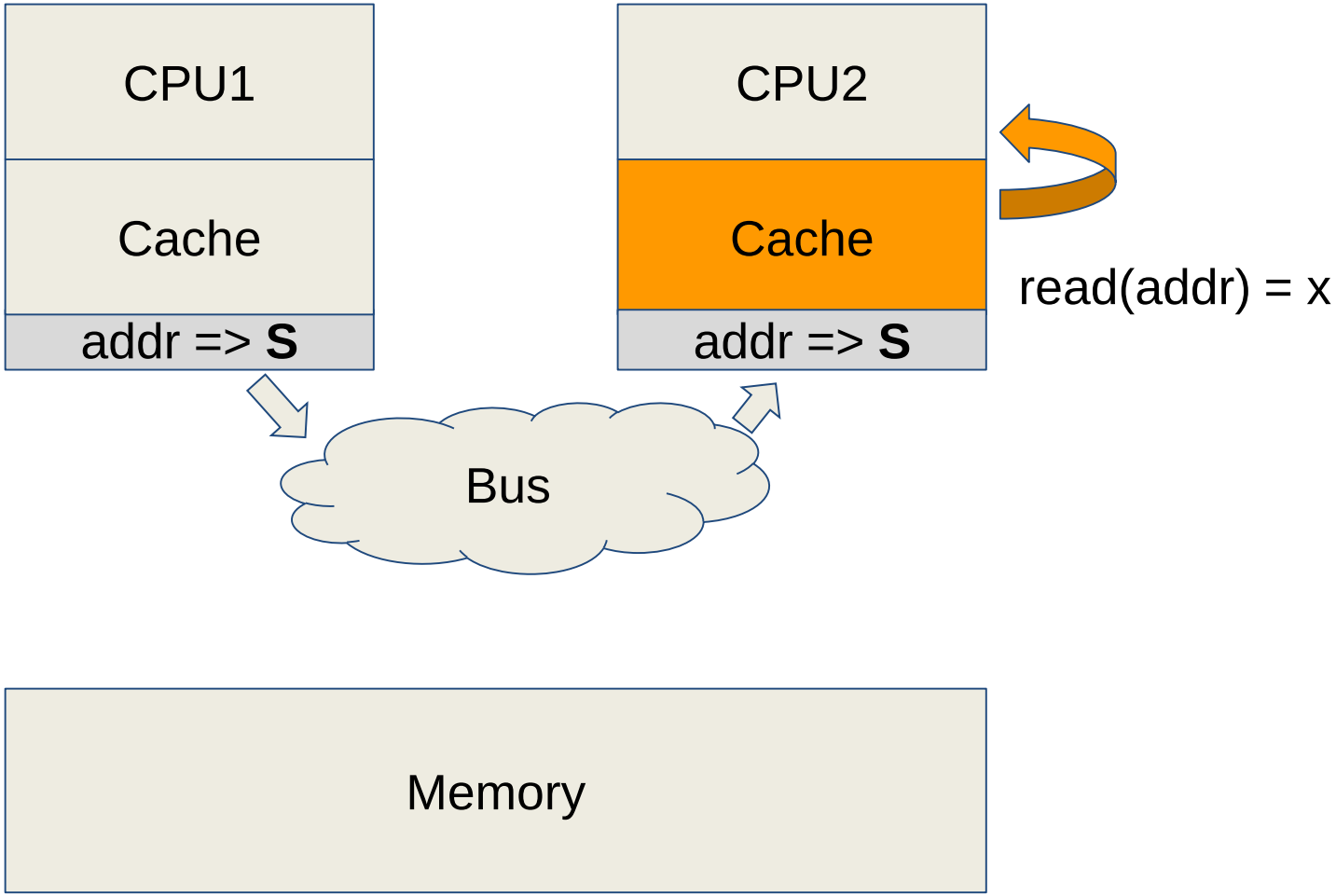

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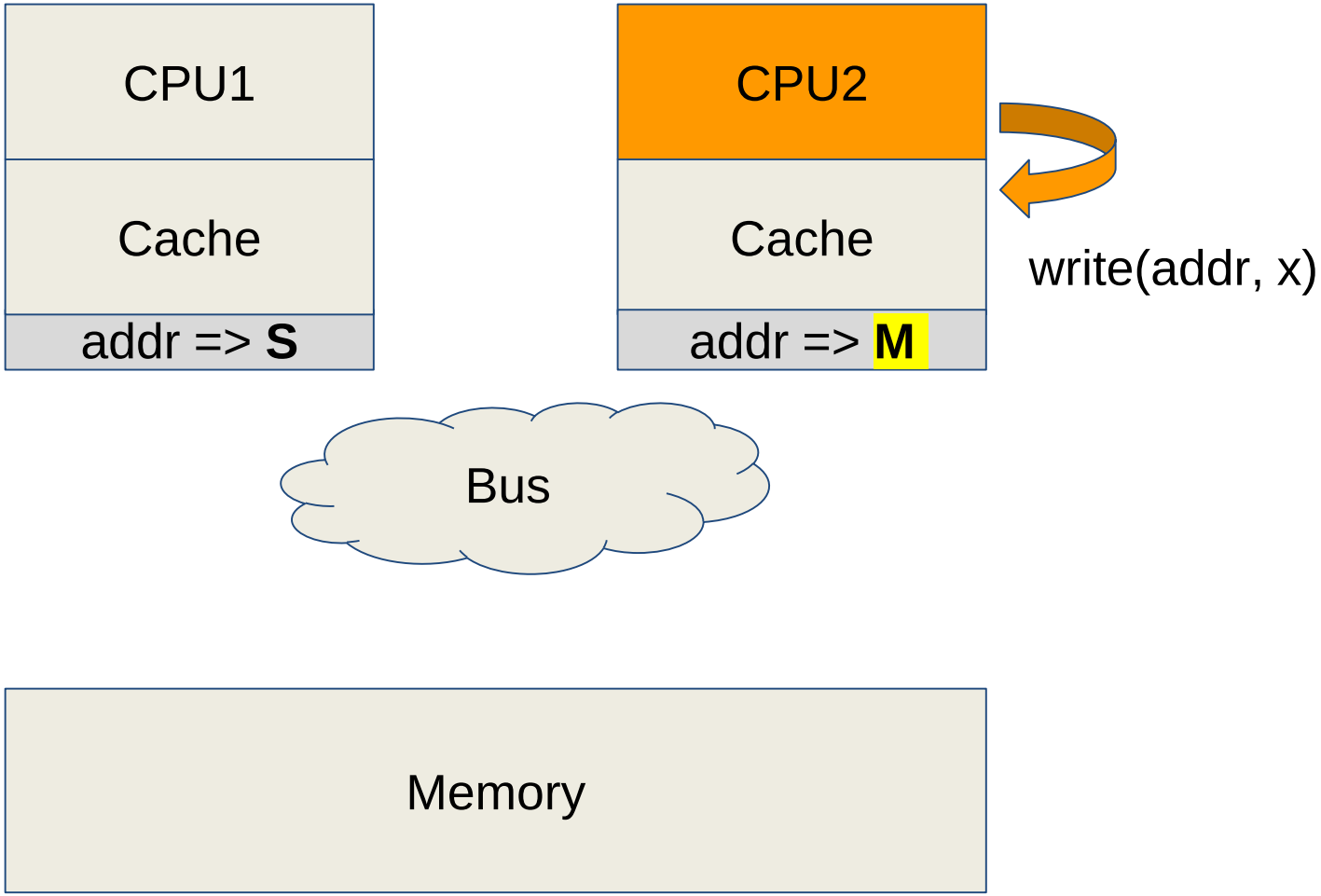

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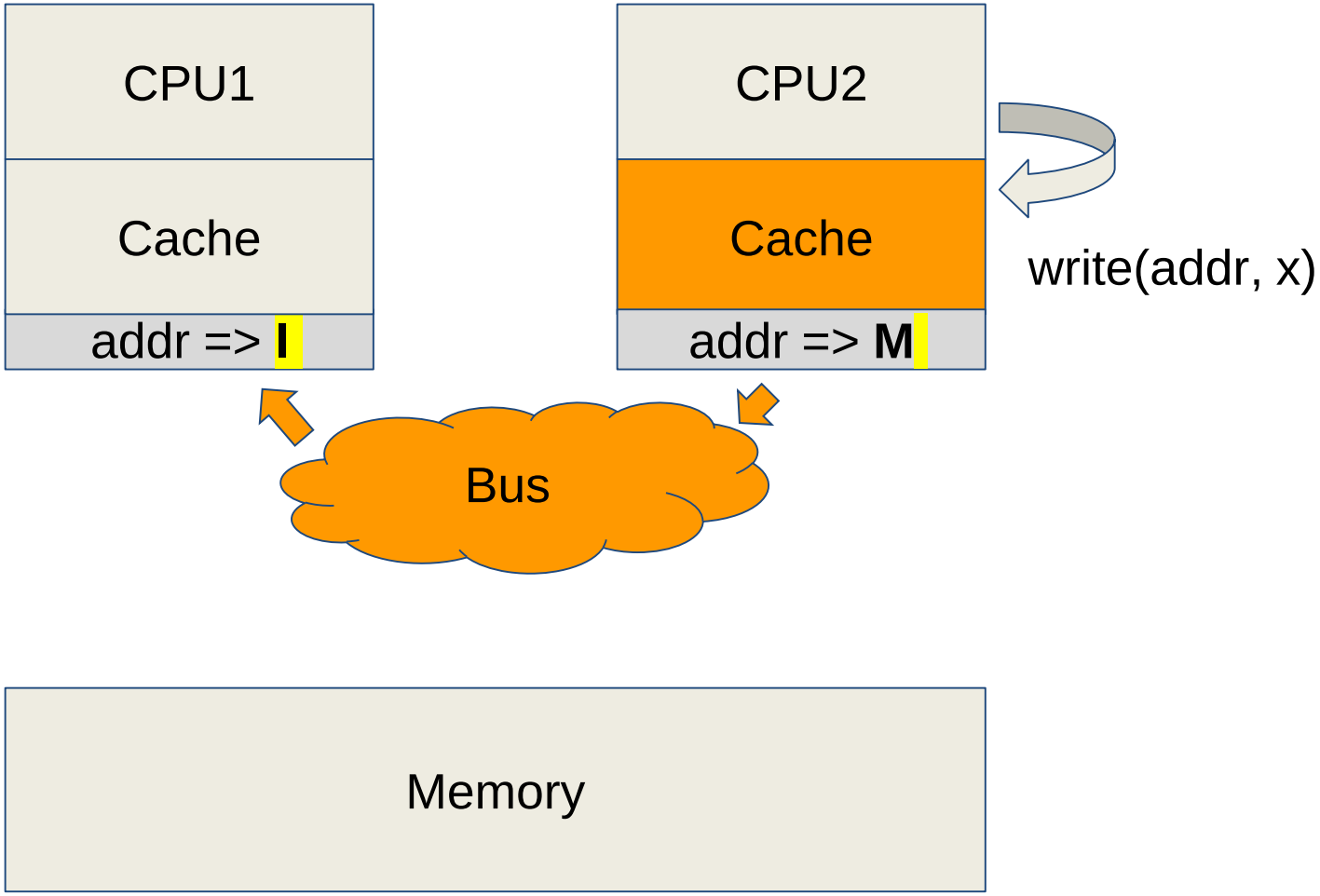

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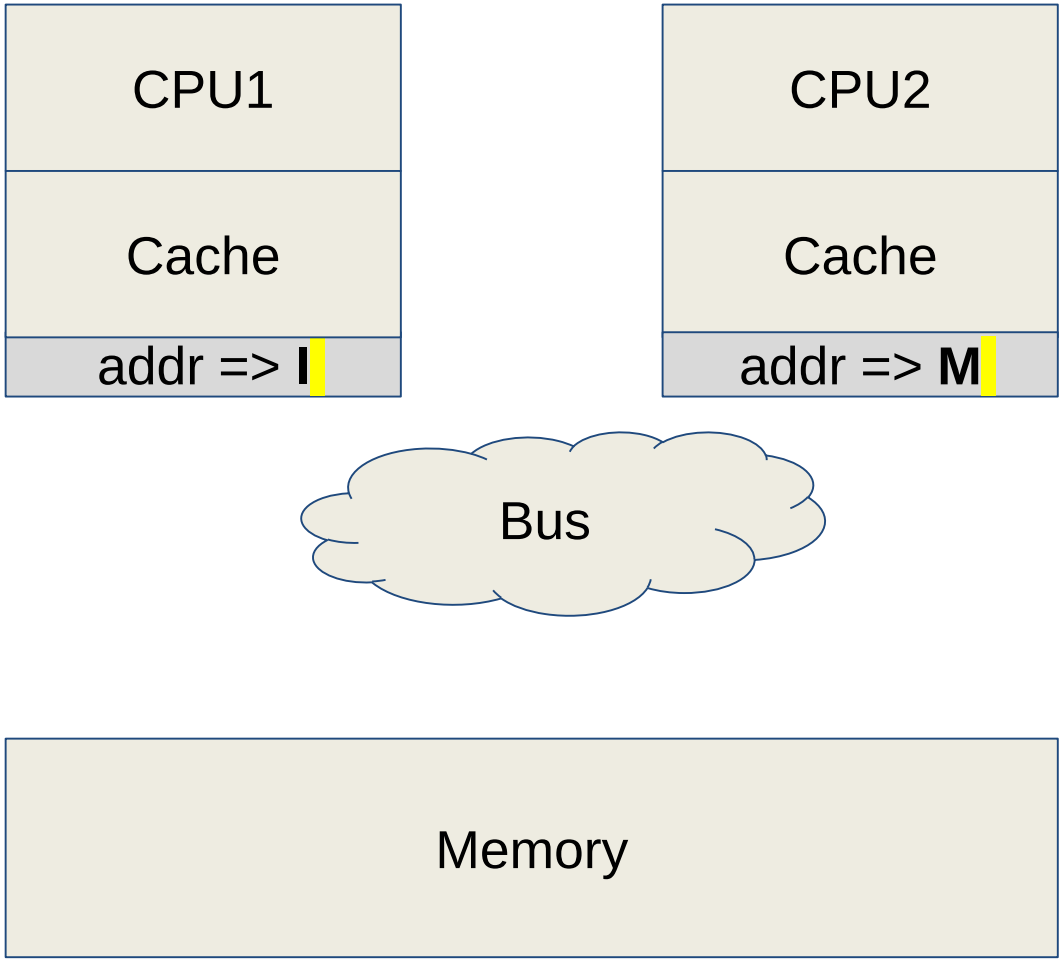
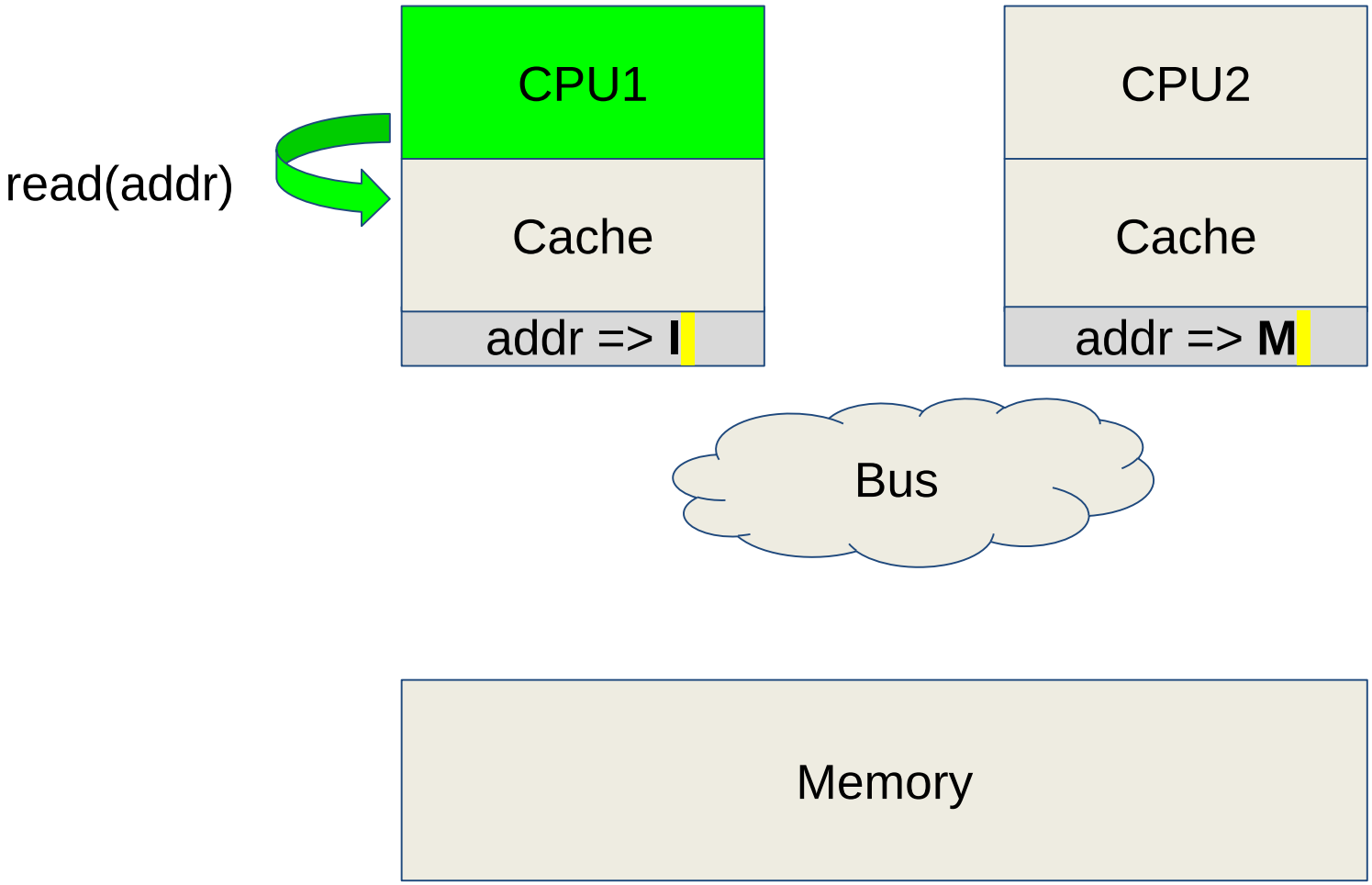


MESI наглядно



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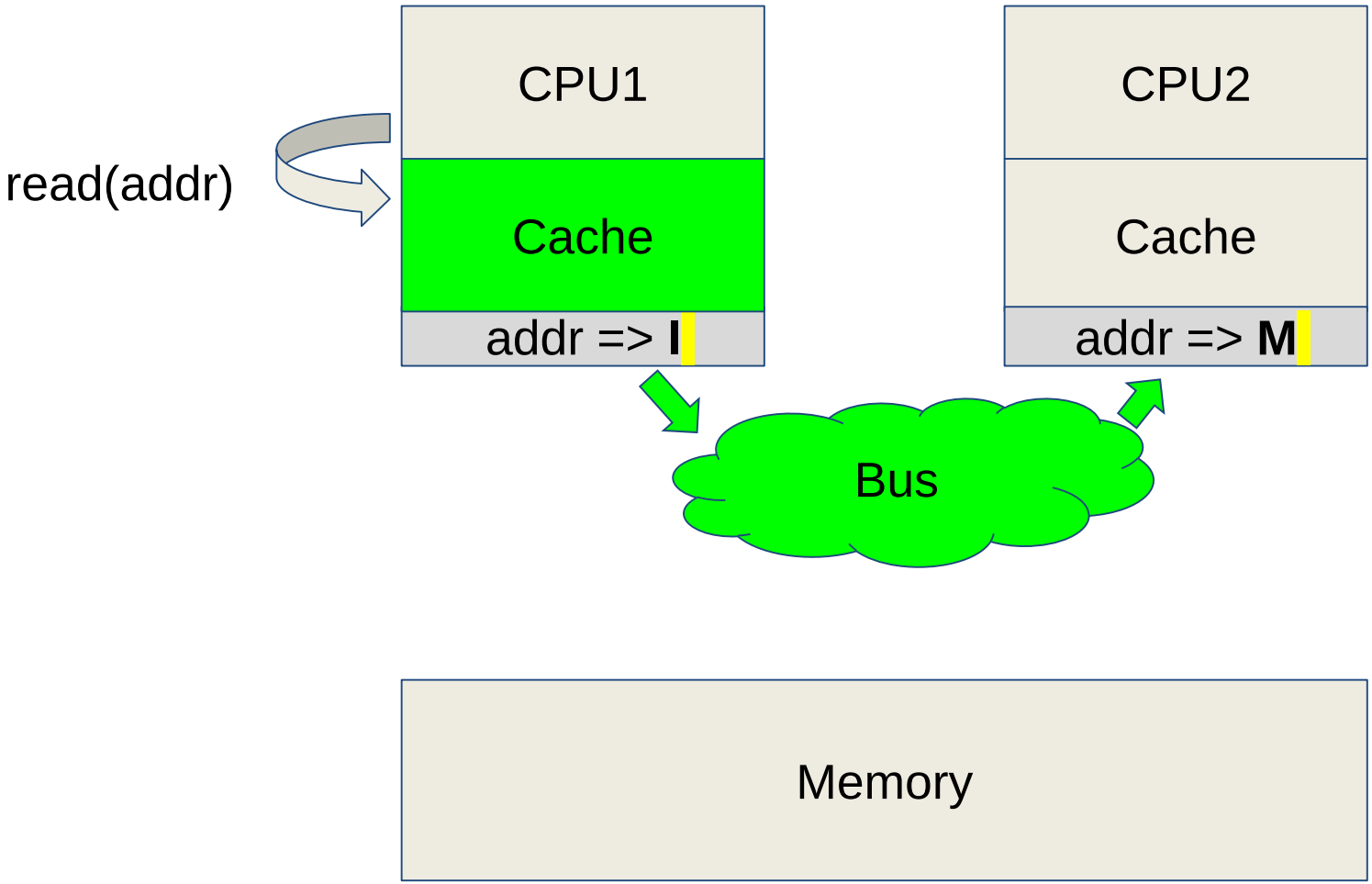
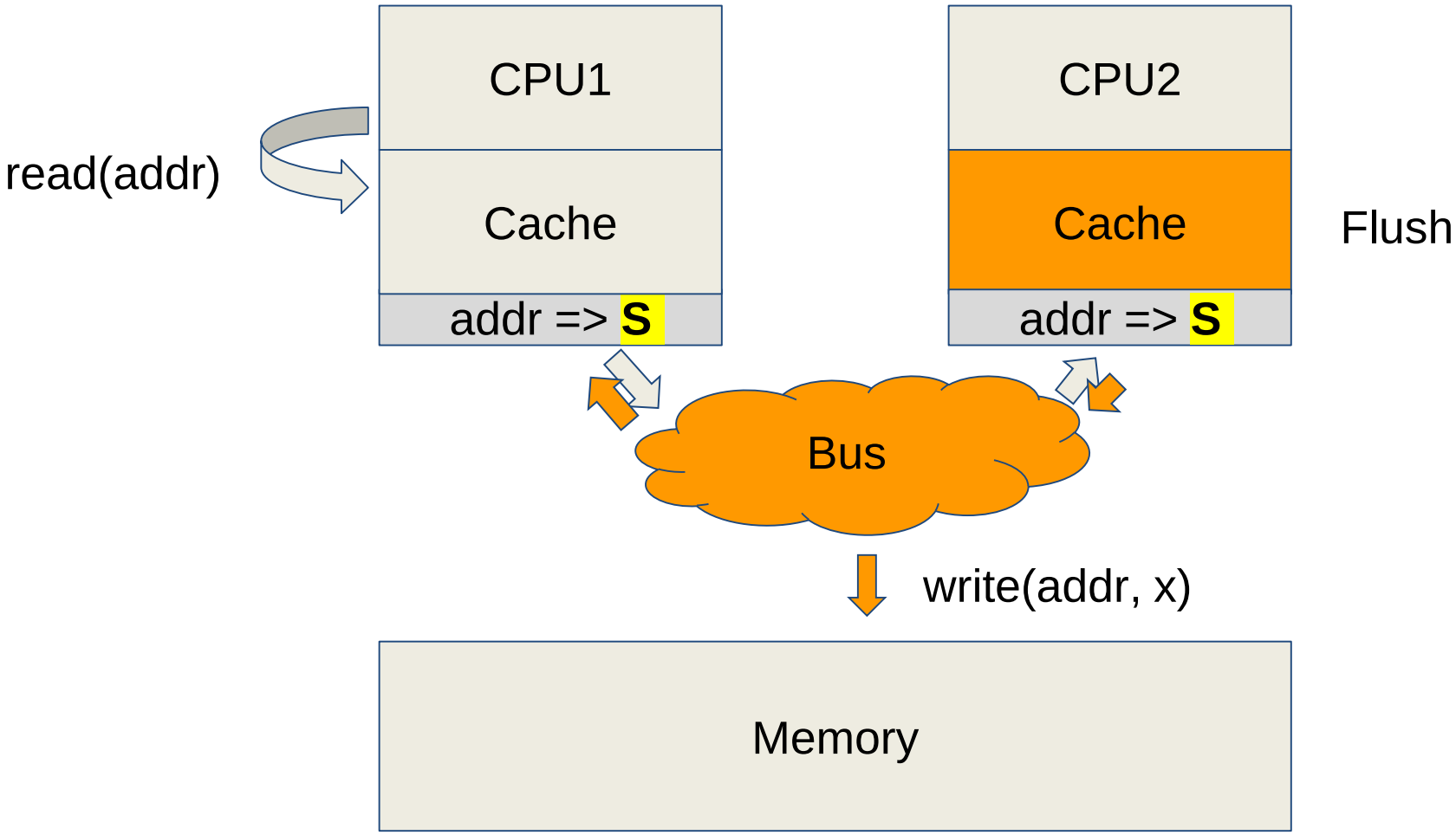
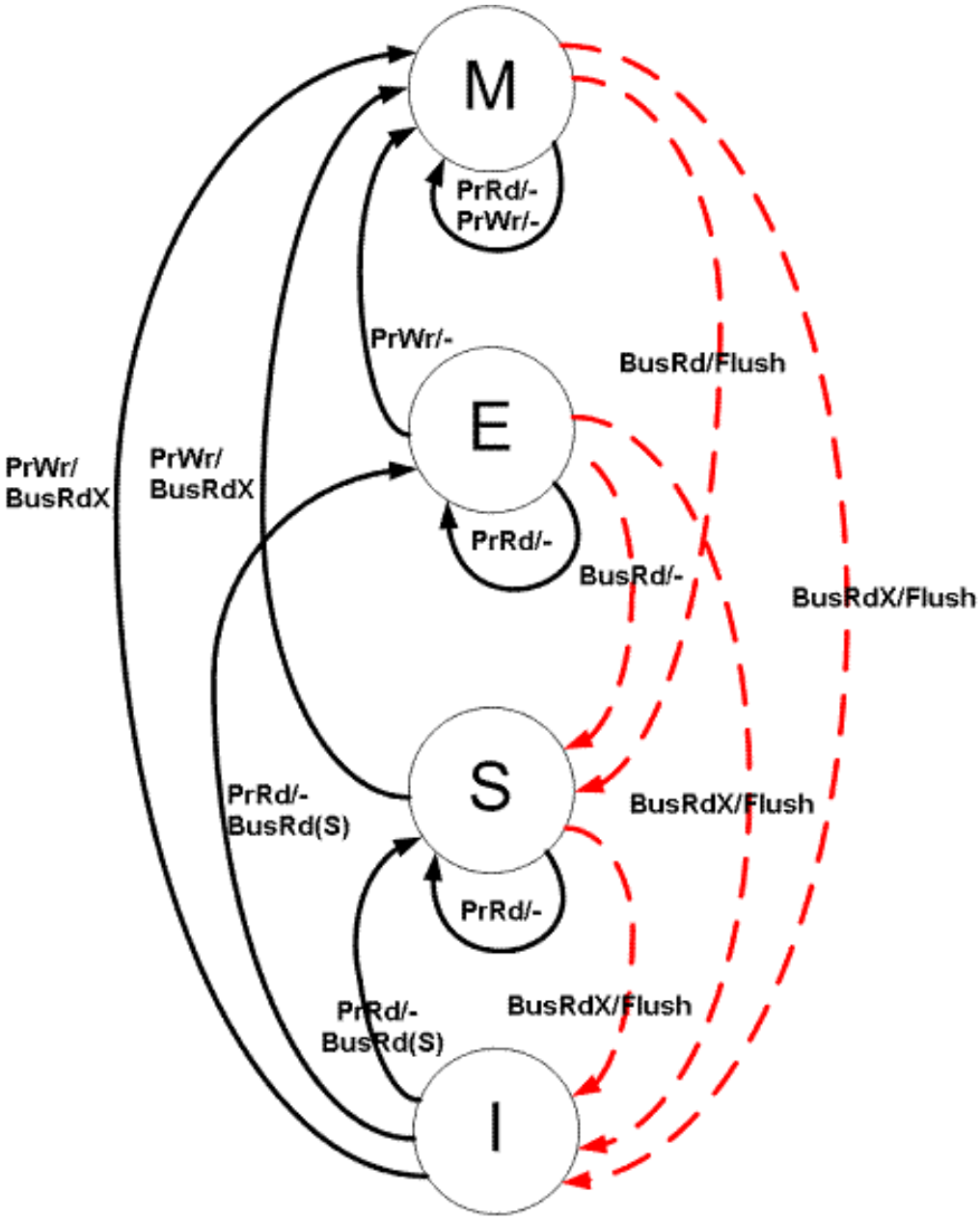


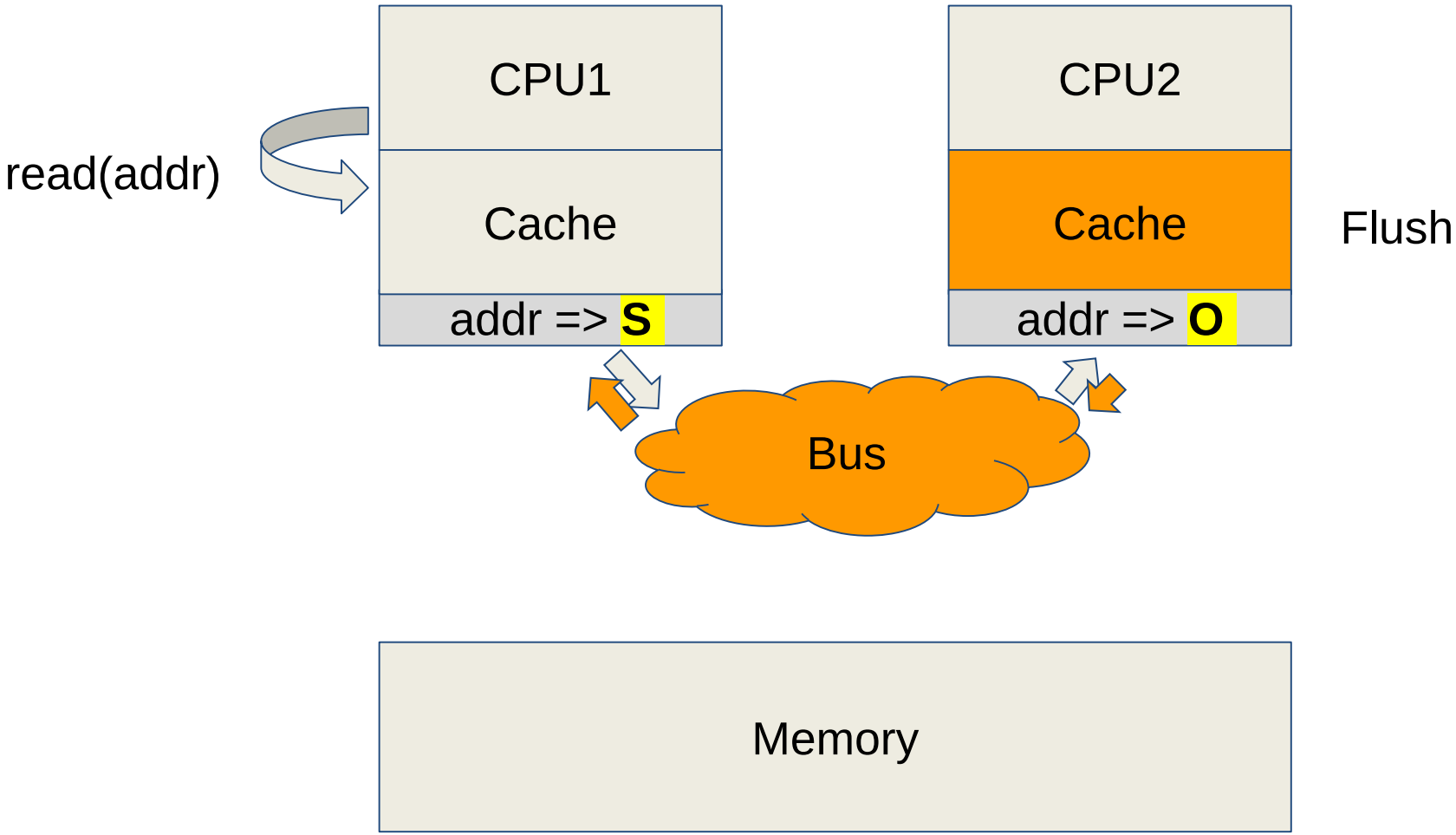
MESI наглядно



Весь MESI


M
PrRd/-
PrWr/-
PrWr/-
BusRd/Flush
E
PrWr/
BusRdX
PrWr/
BusRdX
PrRd/-
BusRd/-
BusRdX/Flush
S
PrRd/-
BusRd(S)
BusRdX/Flush
PrRd/-
PrRd/-
BusRd(S)
BusRdX/Flush
I

MESI -> MOSI (O == Owned)



Больше ада

- **MESIF** = MESI + Forward (Intel)
- **MOESI** = MESI + Owned (AMD)

Test-And-Set (aka get-and-set)

```
// Последовательная спецификация
class TASRegister:
    shared r

    def getAndSet(x): atomically do
        old = r
        r = x
        return old

    def read():
        return r

    def write(x):
        r = x
```

Test-And-Set lock

```
class TASLock:
    boolean locked

    def lock():
        while locked.getAndSet(true):
            pass

    def unlock():
        locked = false
```

Test-And-Set lock

```
class TASLock:
    boolean locked

    def lock():
        while locked.getAndSet(true):
            pass

    def unlock():
        locked = false
```

Сброс всех кешей (Exlusive!)

Test-And-Test-And-Set lock

```
class TTSLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break

    def unlock():
        locked = false
```

Test-And-Test-And-Set lock

```
class TTSLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break

    def unlock():
        locked = false
```

Крутится без шума на шине (Shared)

Test-And-Test-And-Set lock

```
class TTSLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break

    def unlock():
        locked = false
```

Крутится без шума на шине (Shared)

Invalidation storm

Test-And-Test-And-Set lock

```
class TTSLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break

    def unlock():
        locked = false
```

Все ломятся сюда

Invalidation storm

Backoff

```
class TTSBackoffLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break
            delay()

    def unlock():
        locked = false
```

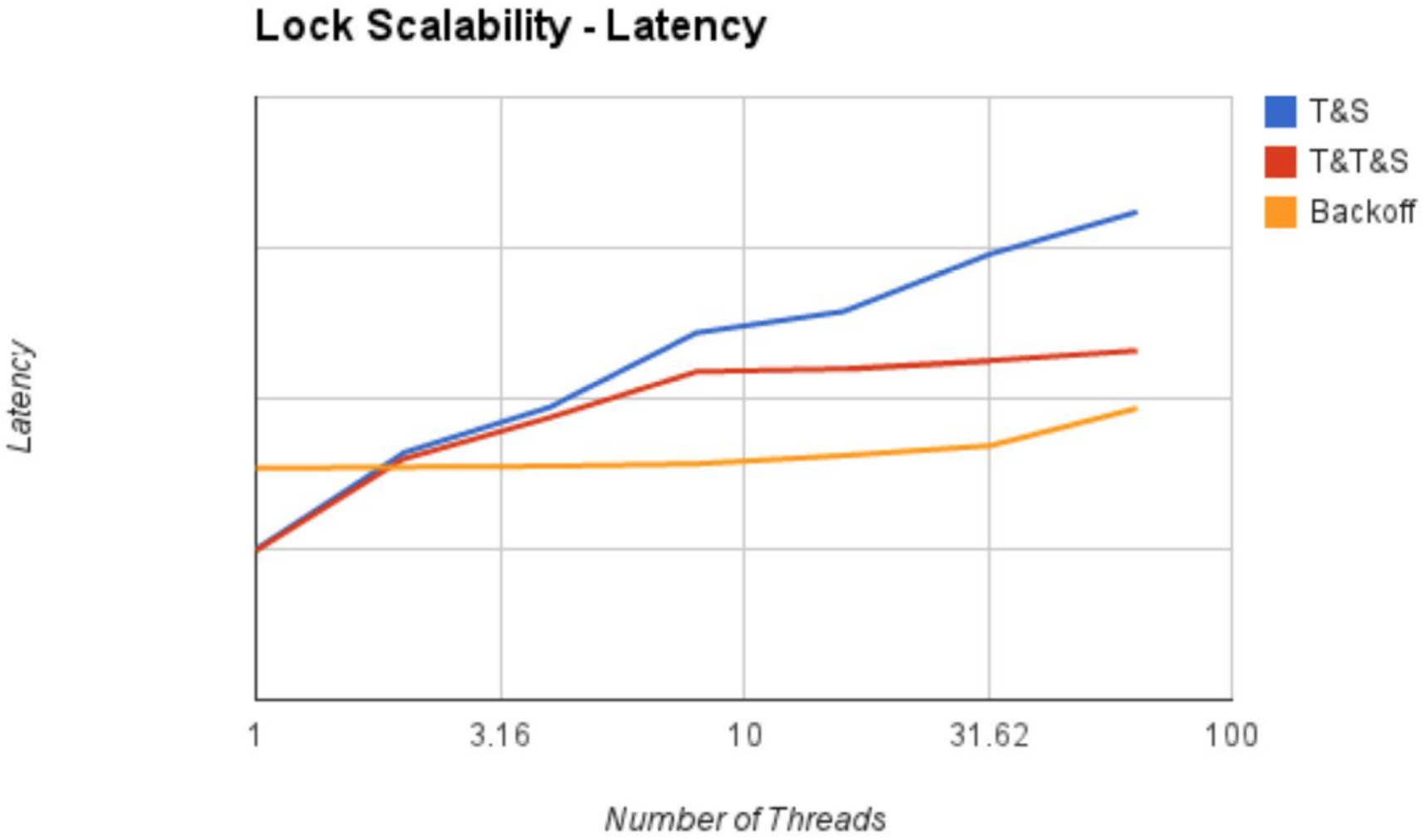
Подождать при неудаче

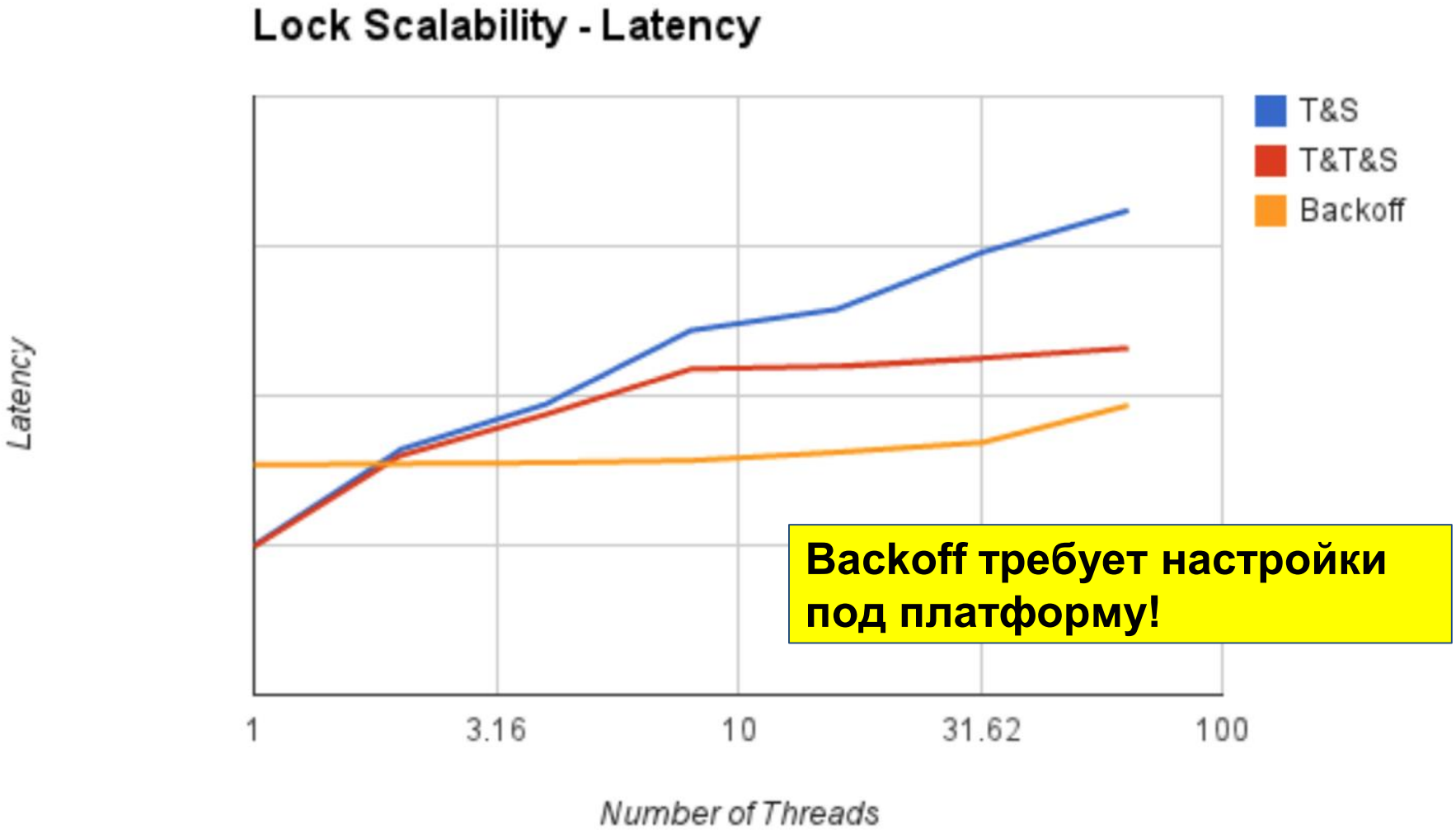
Backoff

```
class TTSBackoffLock:
    boolean locked

    def lock():
        loop:
            while locked: pass
            if !locked.getAndSet(true):
                break
            delay()

    def unlock():
        locked = false
```

Подождать при неудаче

1. Случайное время
2. Экспоненциально увеличивать


Lock Scalability - Latency
T&S
T&T&S
Backoff
Latency
1
3.16
10
31.62
100
Number of Threads



Backoff требует настройки под платформу!

CLH Lock

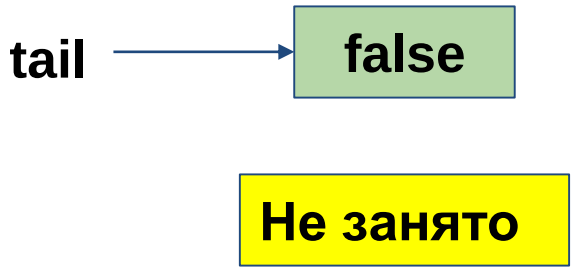
- Travis **C**raig, Anders **L**andin, Erik **H**agersten
- Устраним лишние инвалидации
- Храним очередь ждущих потоков
- First-Come First-Served

CLH Lock

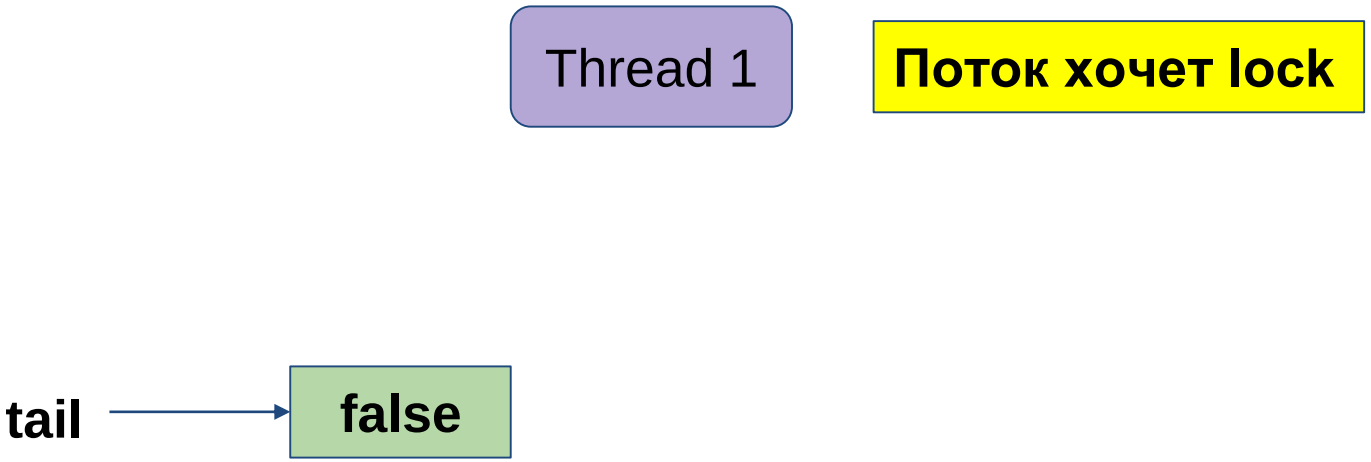
```
class QNode:
    boolean locked // shared, atomic
```

```
class CLHLock:
    tail = QNode() // shared, atomic
```

CLH Lock: Начало: Не занято



CLH Lock: Поток 1

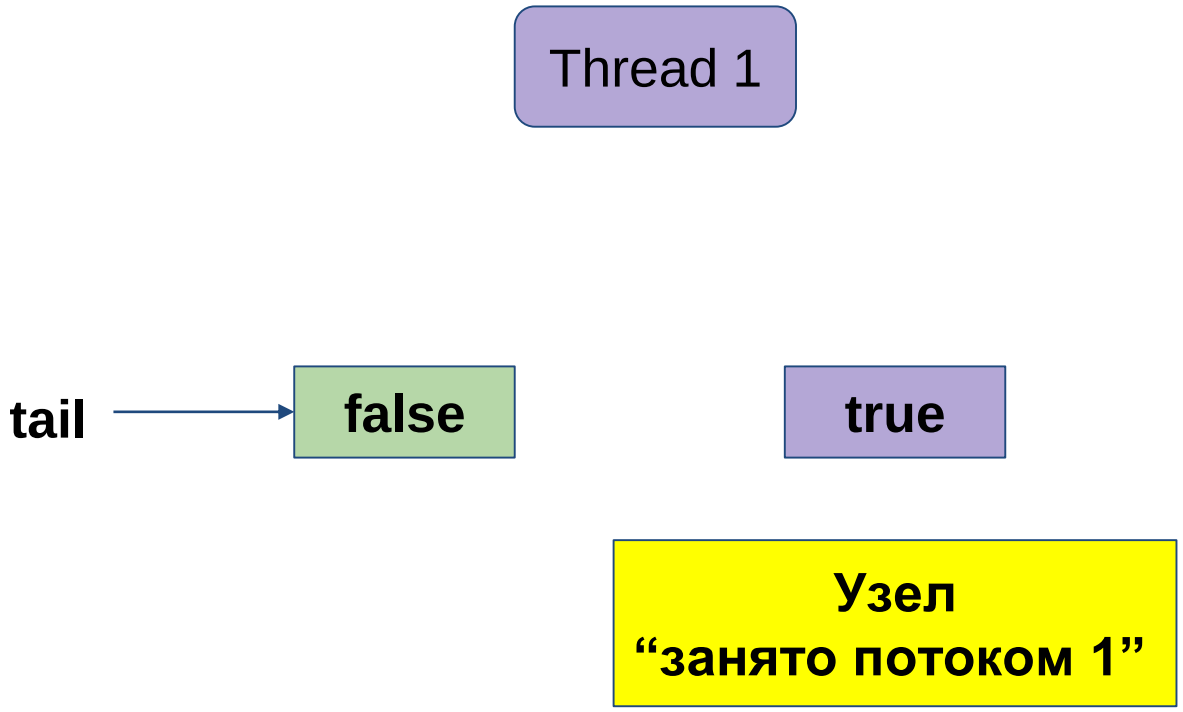


CLH Lock

```
class QNode:
    boolean locked // shared, atomic
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()
```

CLH Lock: Узел 1

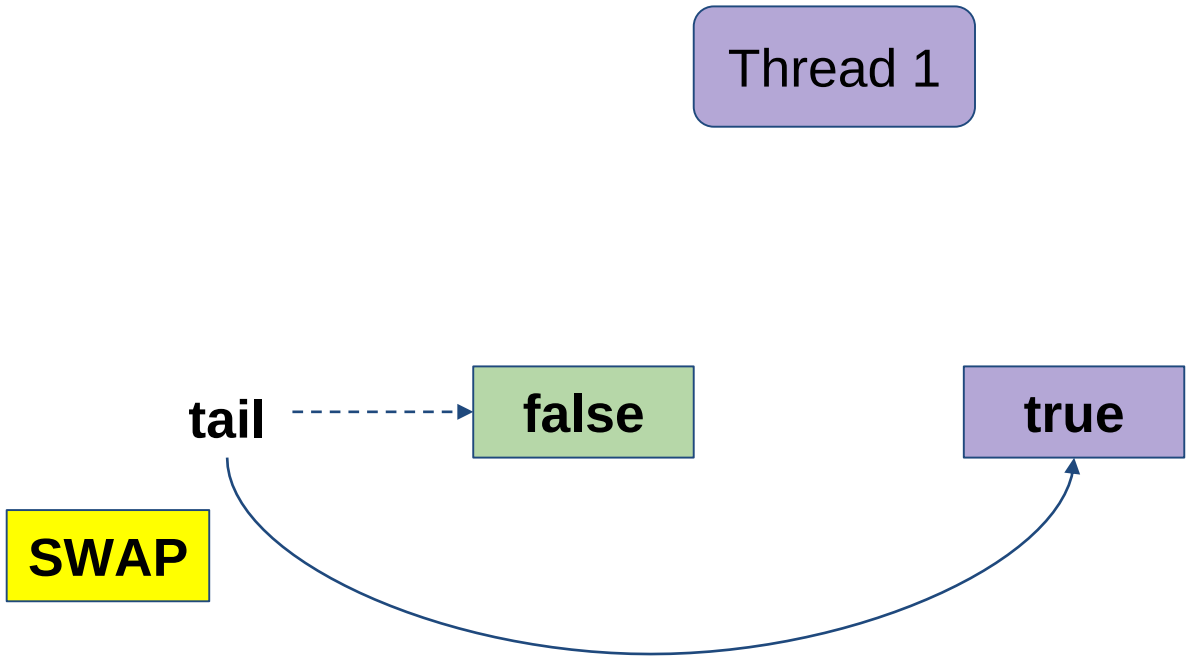


CLH Lock

```
class QNode:
    boolean locked // shared, atomic
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()

    def lock():
        my.locked = true
        pred = tail.getAndSet(my)
        while pred.locked: pass
```

CLH Lock: Захват блокировки

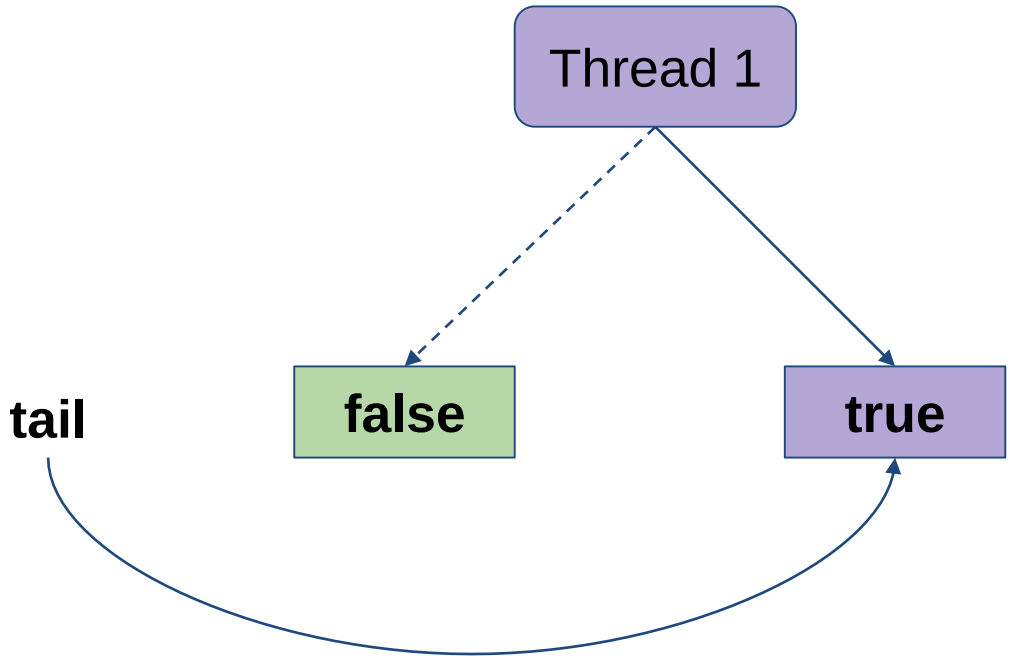


CLH Lock

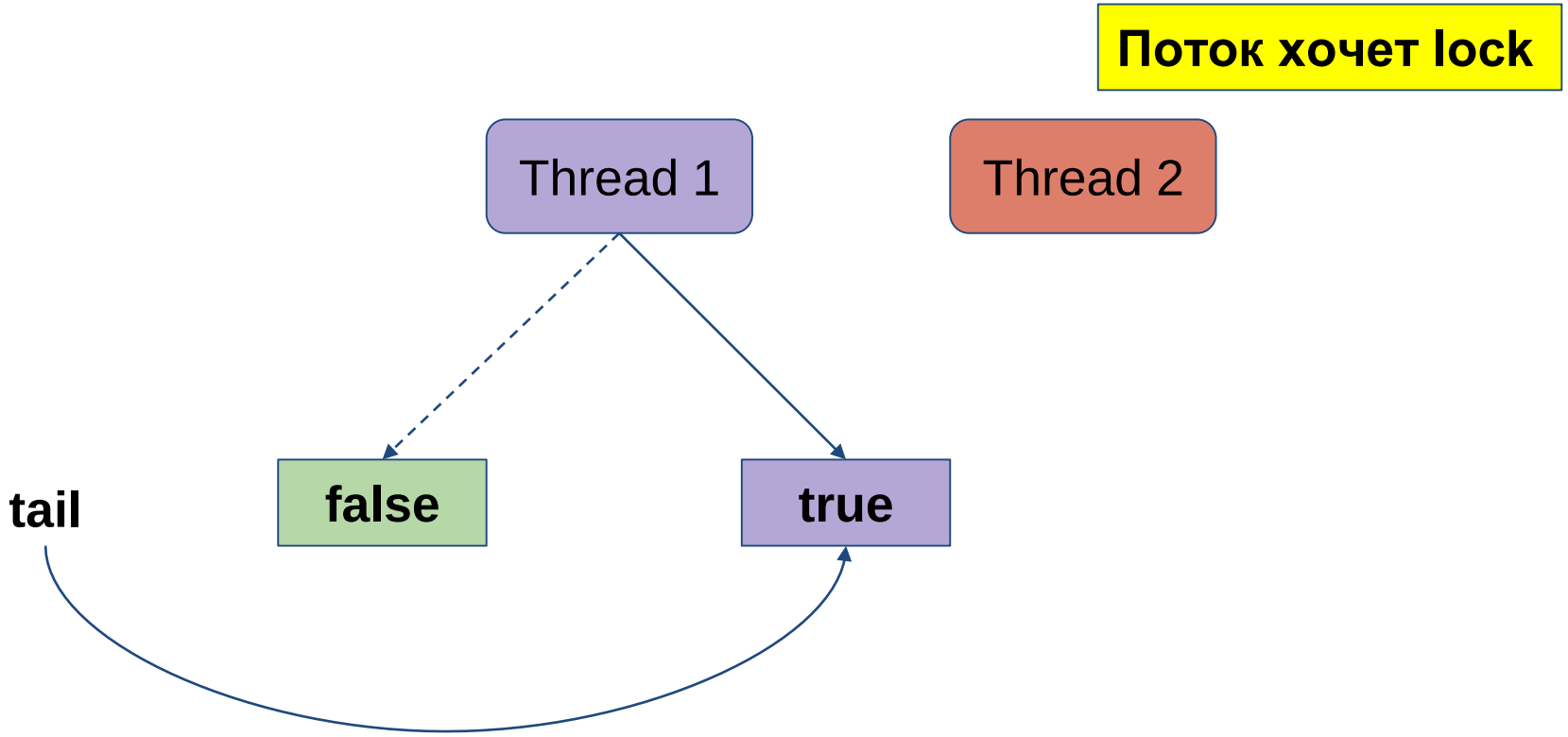
```
class QNode:
    boolean locked // shared, atomic
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()

    def lock():
        my.locked = true
        pred = tail.getAndSet(my)
        while pred.locked: pass
```

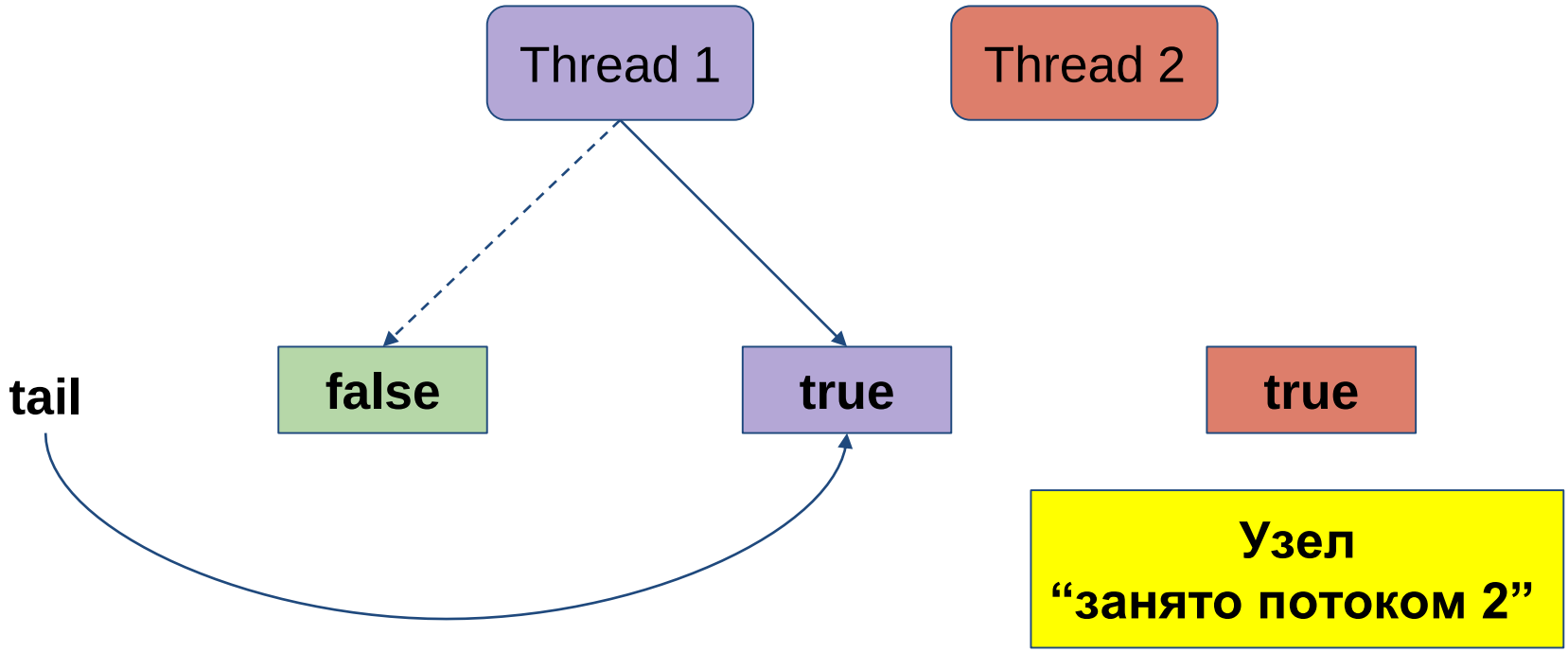
CLH Lock: Занято 1-м потоком



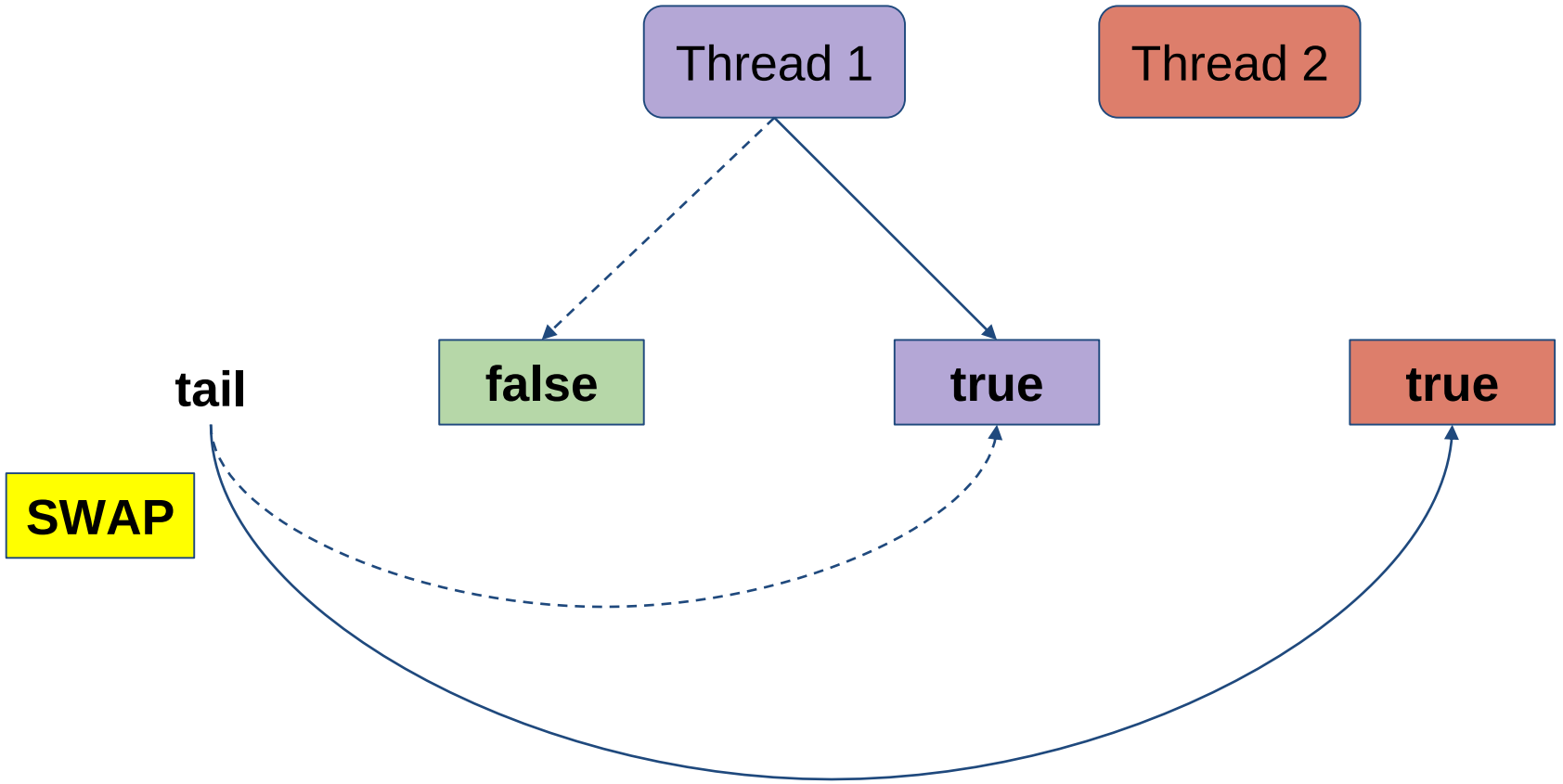
CLH Lock: Поток 2



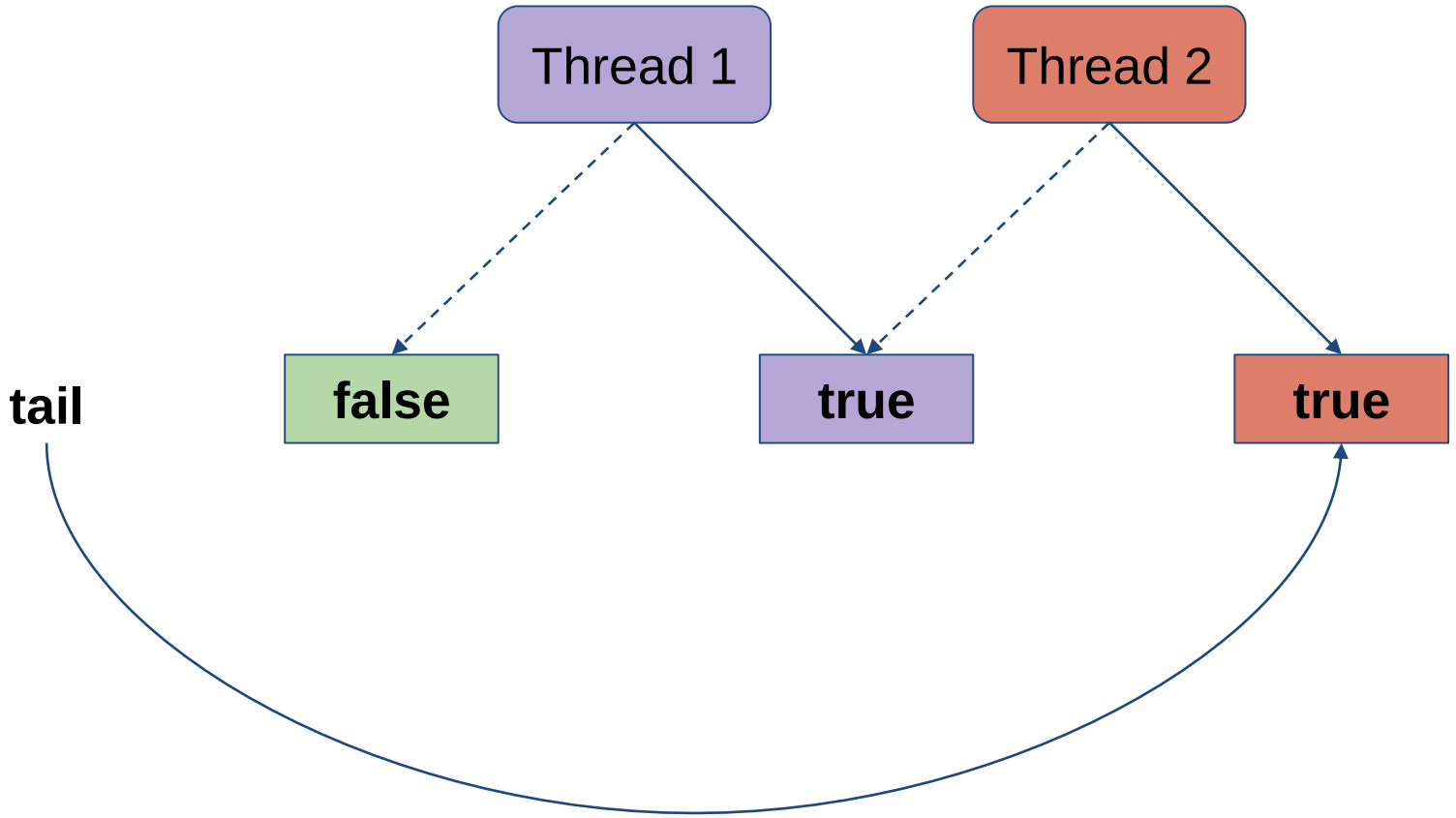
CLH Lock: Узел 2



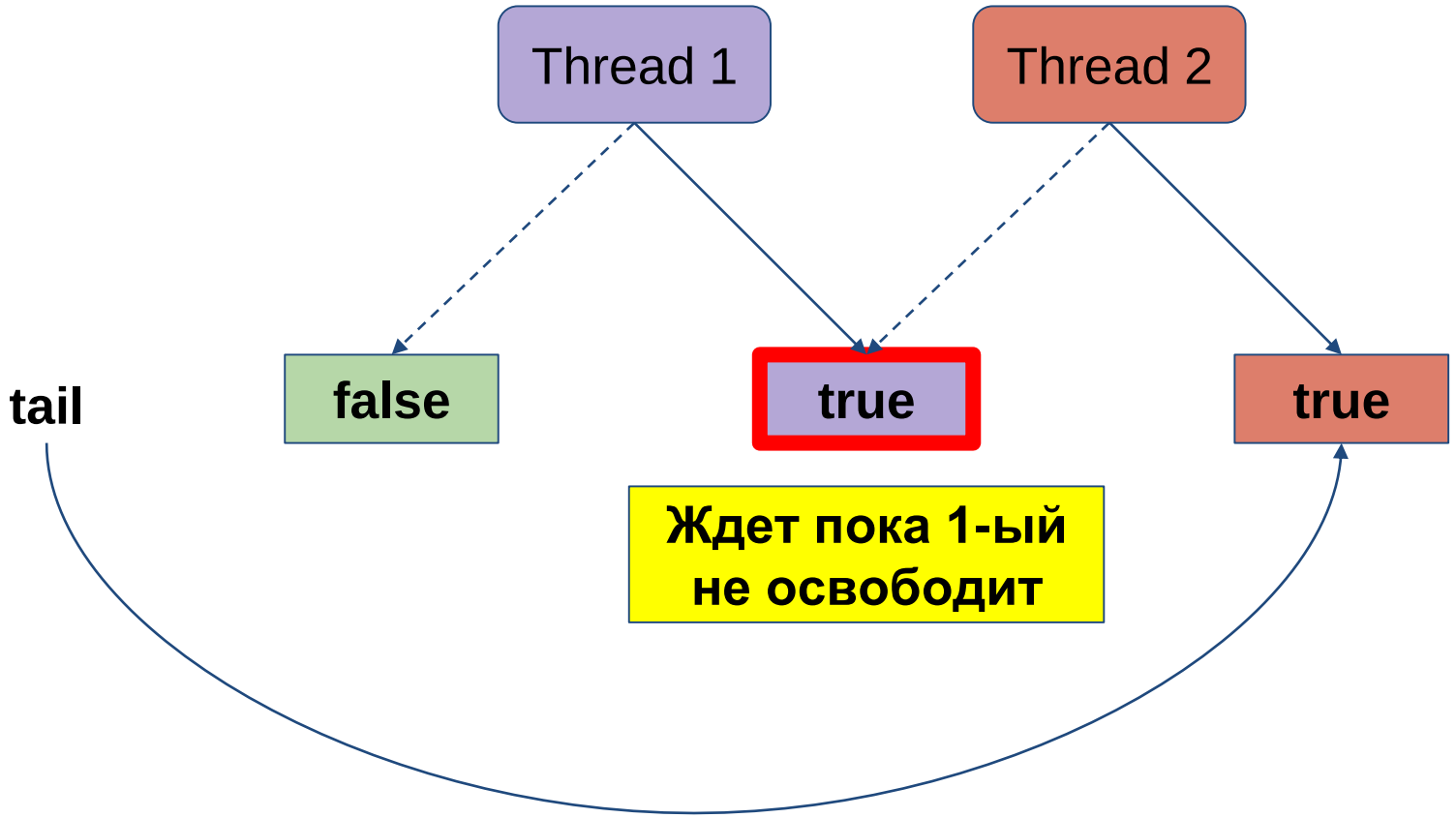
CLH Lock: Добавление в очередь



CLH Lock: Поток 2 в очереди



CLH Lock: Поток 2 ждет



CLH Lock

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class QNode:
    boolean locked // shared, atomic
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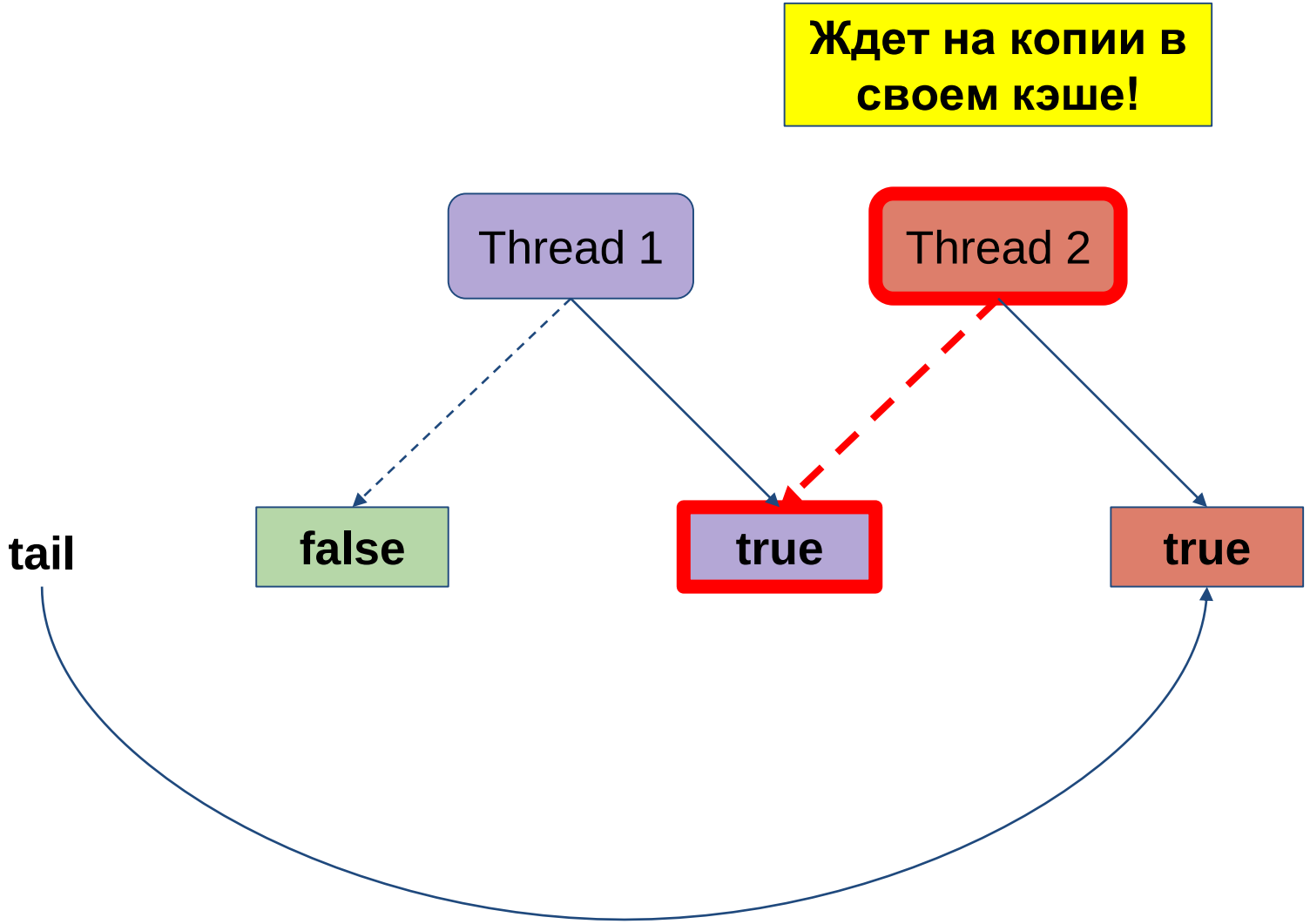
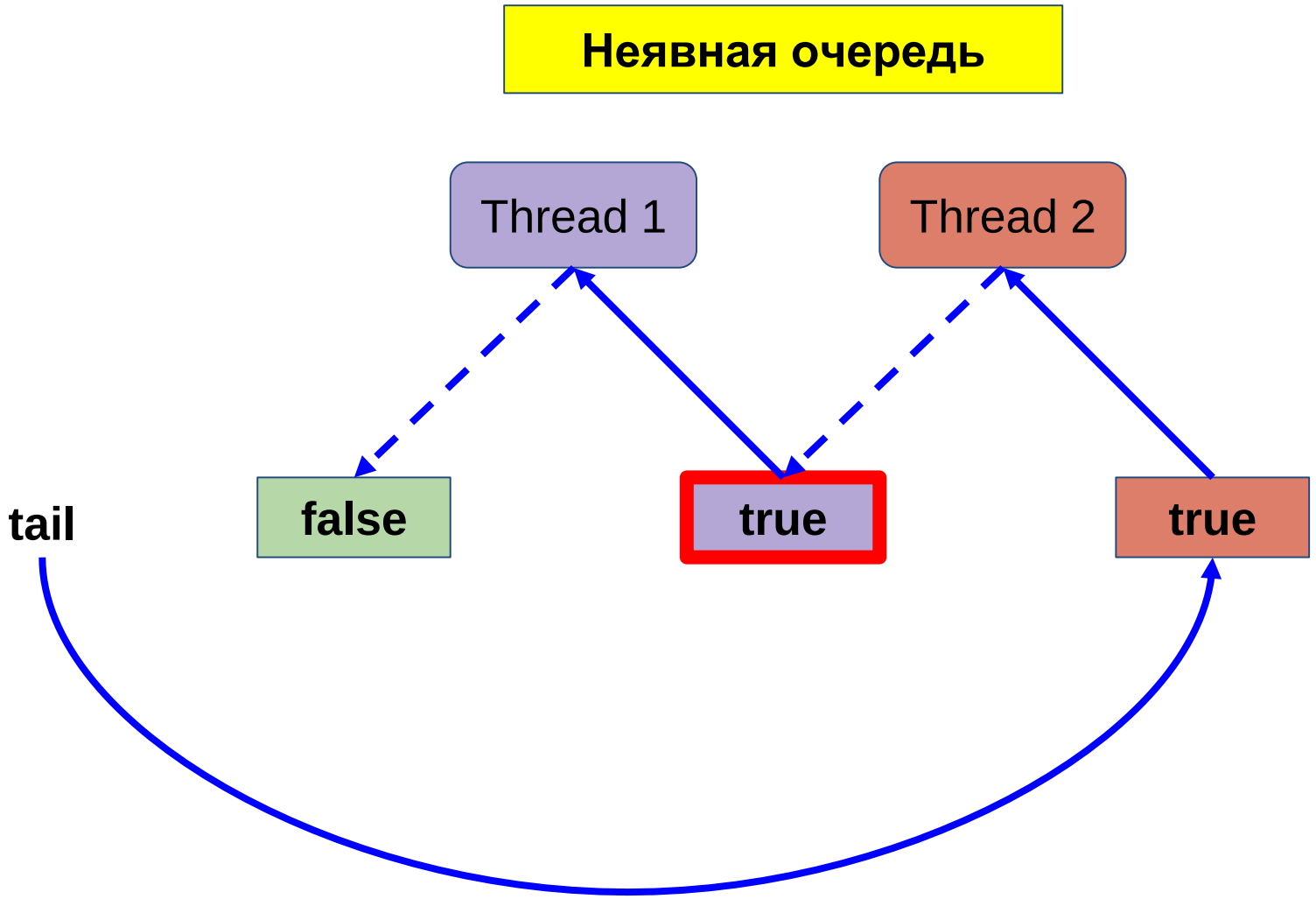
```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()

    def lock():
        my.locked = true
        pred = tail.getAndSet(my)
        while pred.locked: pass
```

CLH Lock: Поток 2 ждет



CLH Lock: Где очередь?



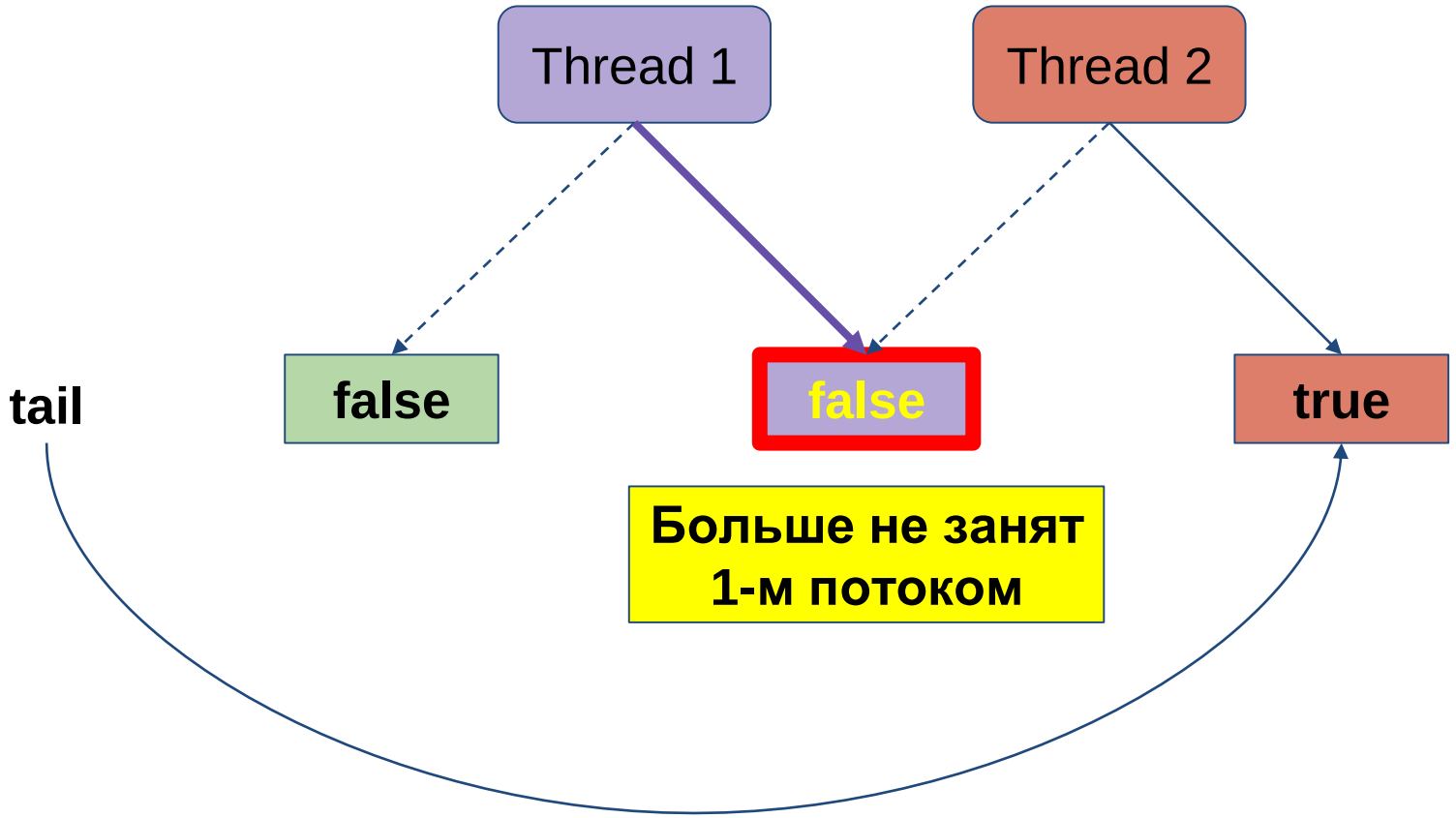
CLH Lock: unlock

```
class QNode:
    boolean locked // shared, atomic
```

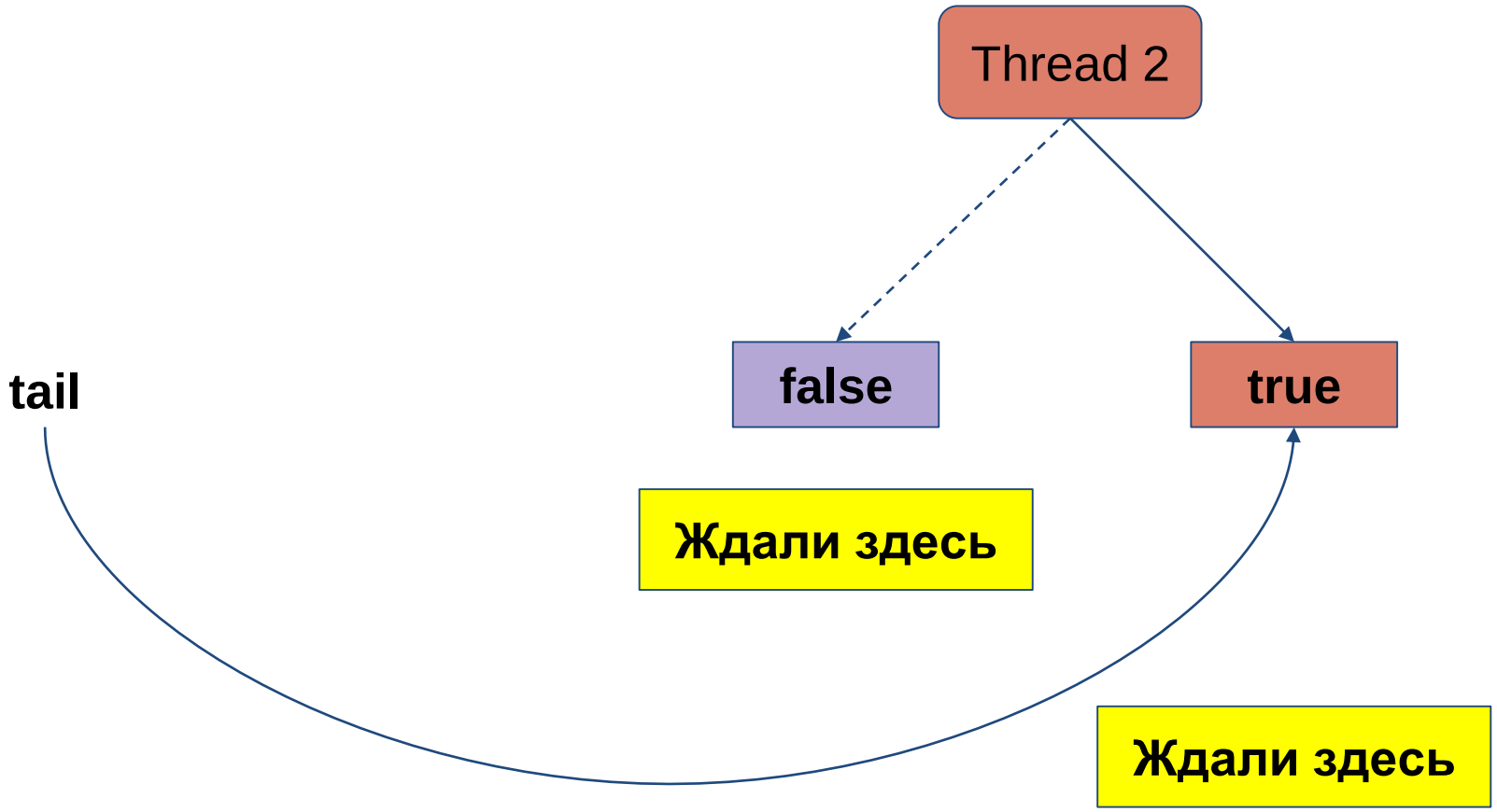
```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()

    def lock():
        my.locked = true
        pred = tail.getAndSet(my)
        while pred.locked: pass

    def unlock():
        my.locked = false
        my = pred
```

No invalidation storm!

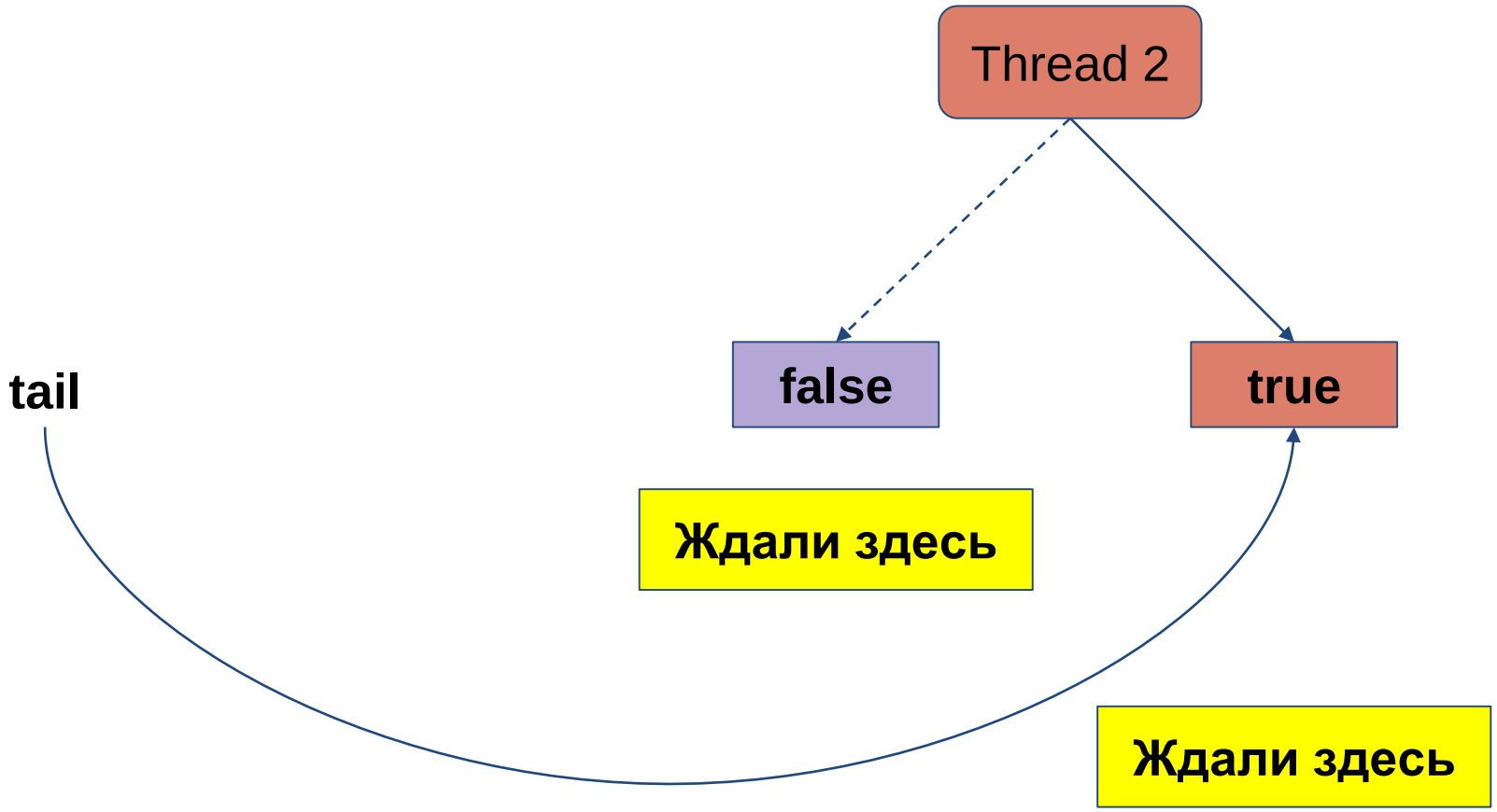
CLH Lock: Поток 1 освобождает



CLH Lock: Занято 2-м потоком



CLH Lock: Занято 2-м потоком



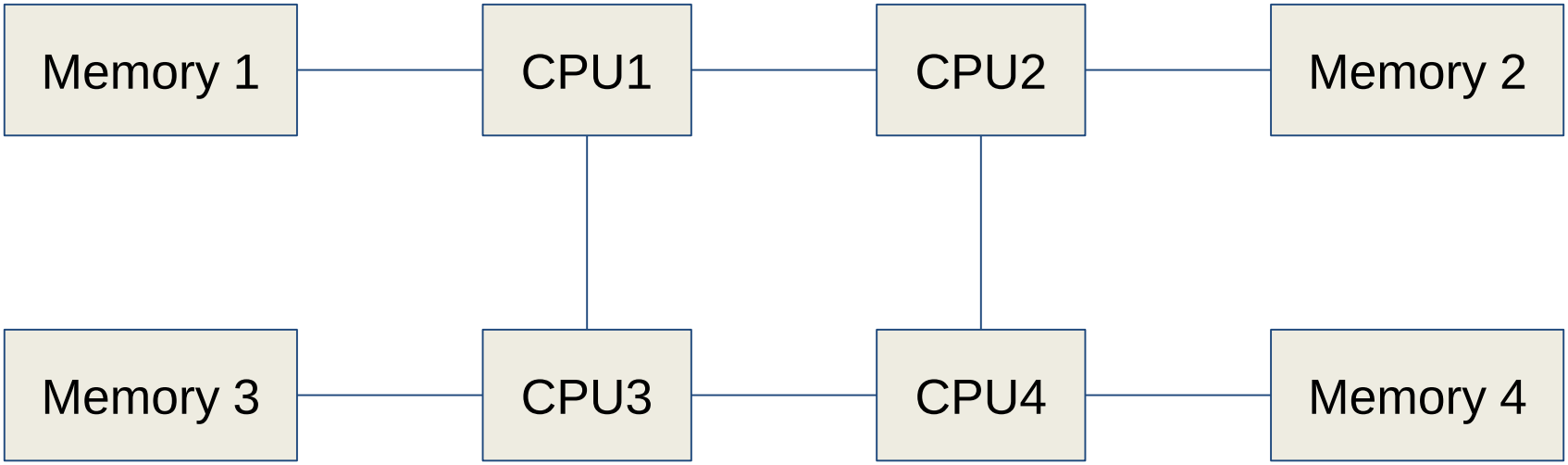
CLH Lock: Красивый memory reuse

```
class QNode:
    boolean locked // shared, atomic
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = QNode()
    threadlocal pred

    def lock():
        my.locked = true
        pred = tail.getAndSet(my)
        while pred.locked: pass

    def unlock():
        my.locked = false
        my = pred
```

NUMA

Non-**U**niform **M**emory **A**ccesss



CLH Lock

- **Хорошо**
  - Освобождение блокировки влияет только на один поток
  - Занимает мало памяти

- **Плохо**
  - Ждет на “чужой памяти”, а она может быть “далеко” (NUMA!)

MCS Lock

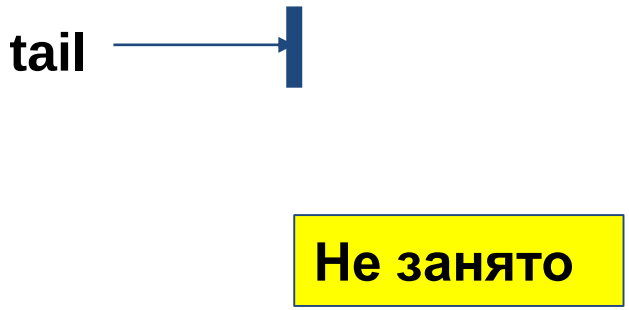
- John **M**ellor-**C**rummey and Michael **S**cott
  - Algorithms for scalable synchronization on shared-memory multiprocessors, 1991
- Ждем на своей памяти
- First-Come First-Served

MCS Lock

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = null // shared, atomic
```

MCS Lock: Начало: Не занято

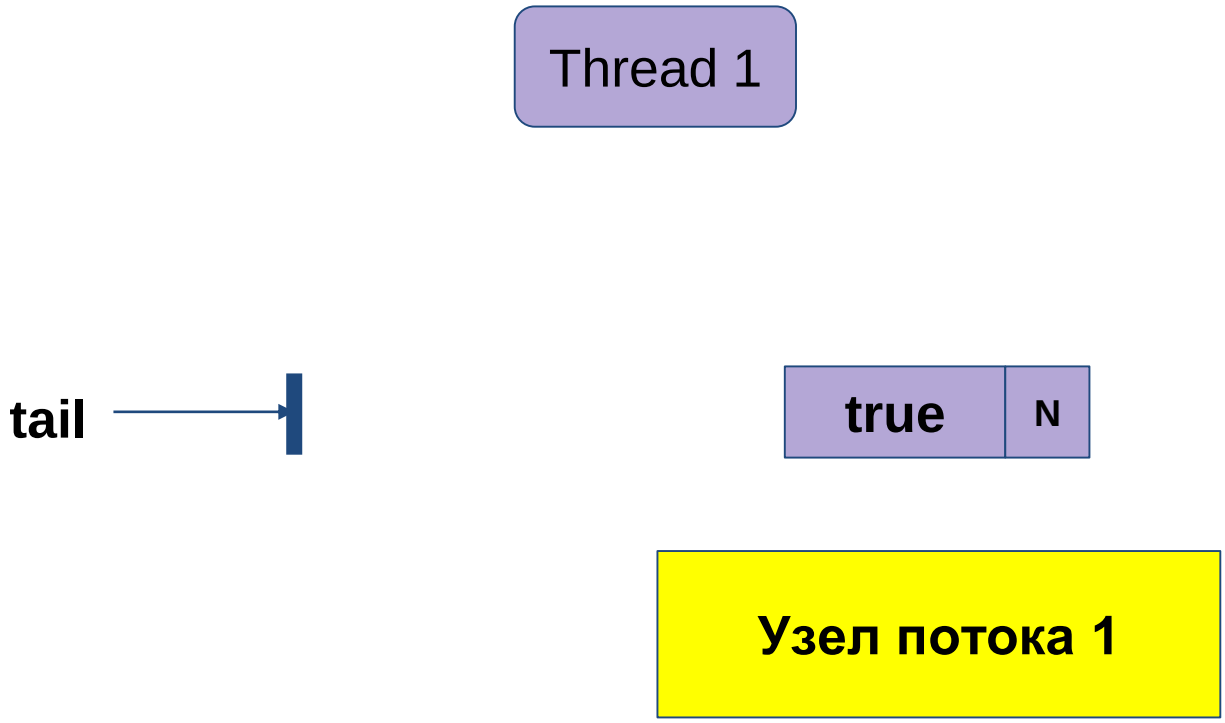


MCS Lock: Поток 1

Thread 1

Поток хочет lock

MCS Lock: Узел 1

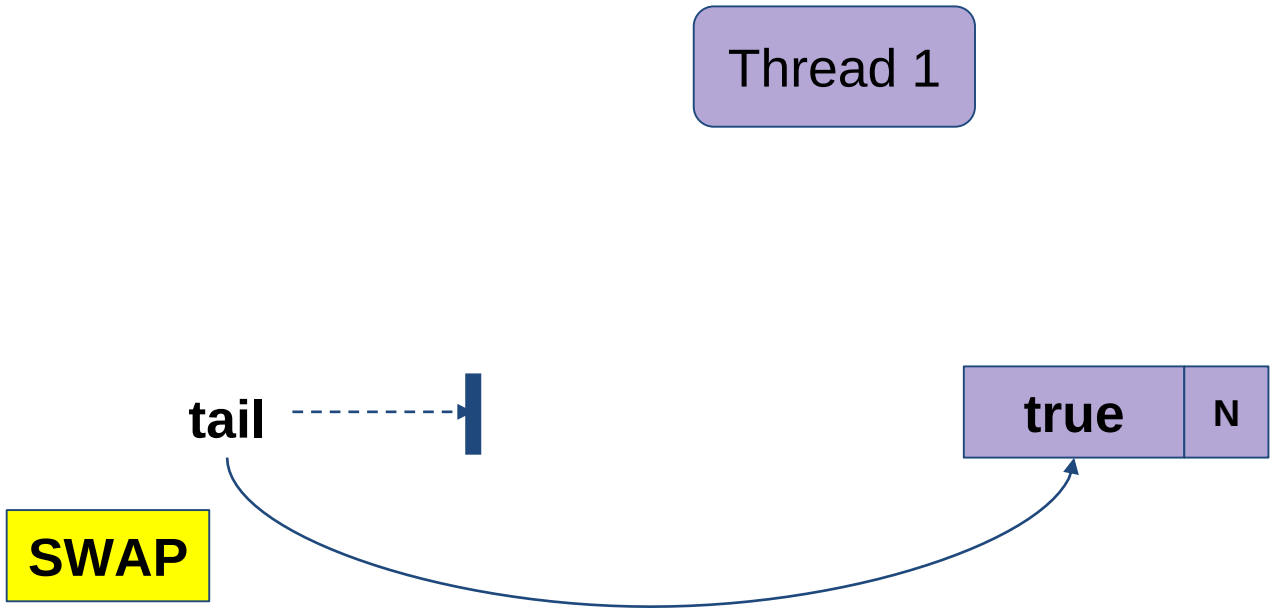


MCS Lock

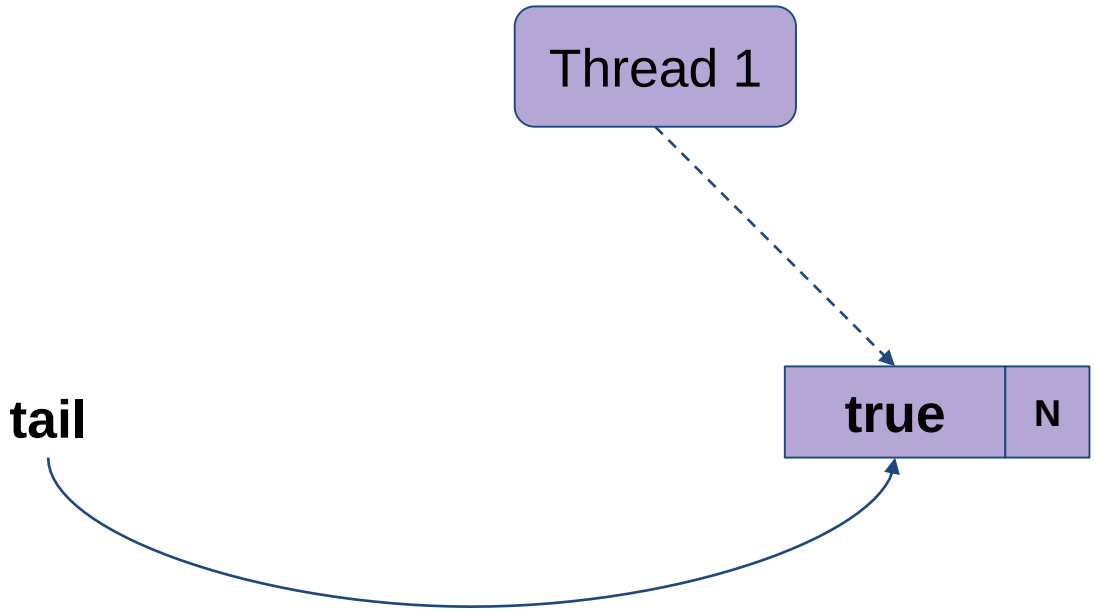
```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def lock():
        my = QNode() // new alloc!
        my.locked = true
        pred = tail.getAndSet(my)
        if pred != null:
            pred.next = my
            while my.locked: pass
```

MCS Lock: Захват



MCS Lock: Явный список

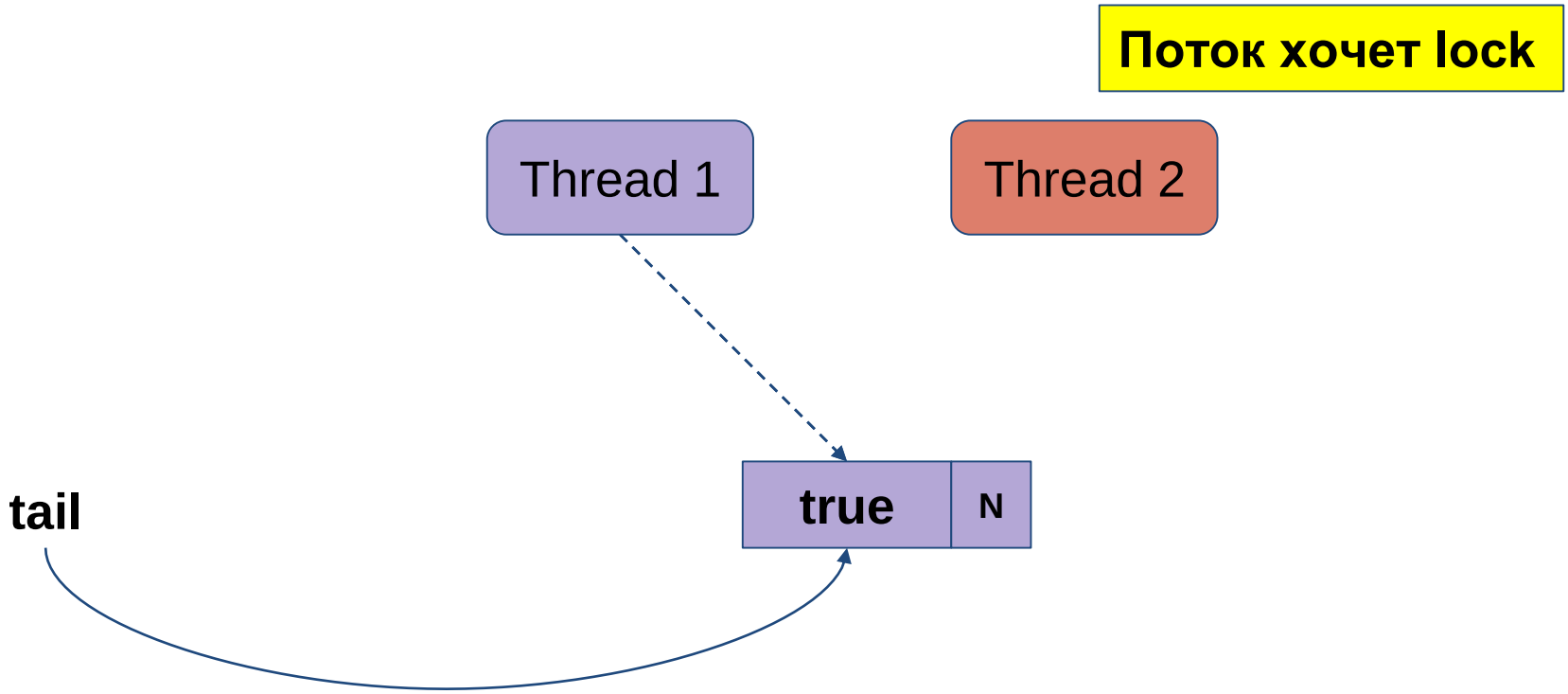


MCS Lock

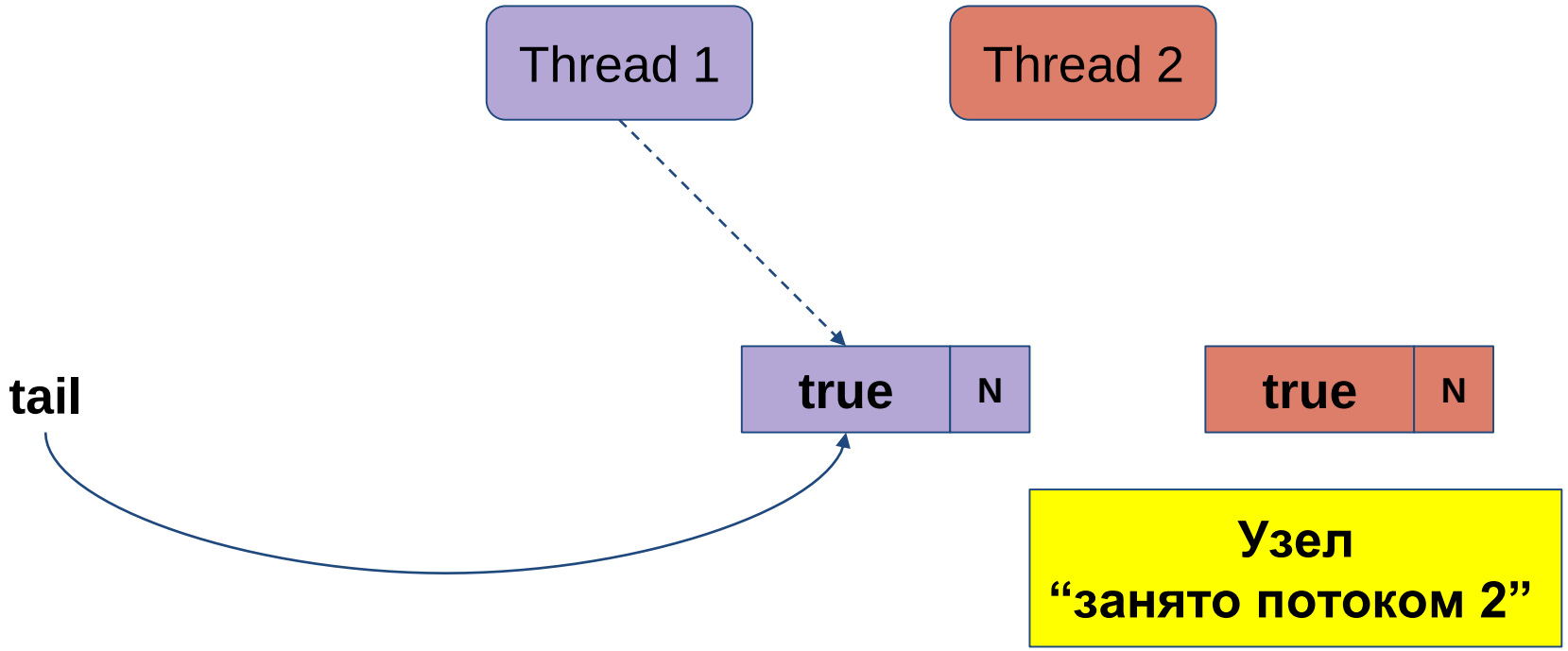
```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def lock():
        my = QNode() // new alloc!
        my.locked = true
        pred = tail.getAndSet(my)
        if pred != null:
            pred.next = my
            while my.locked: pass
```

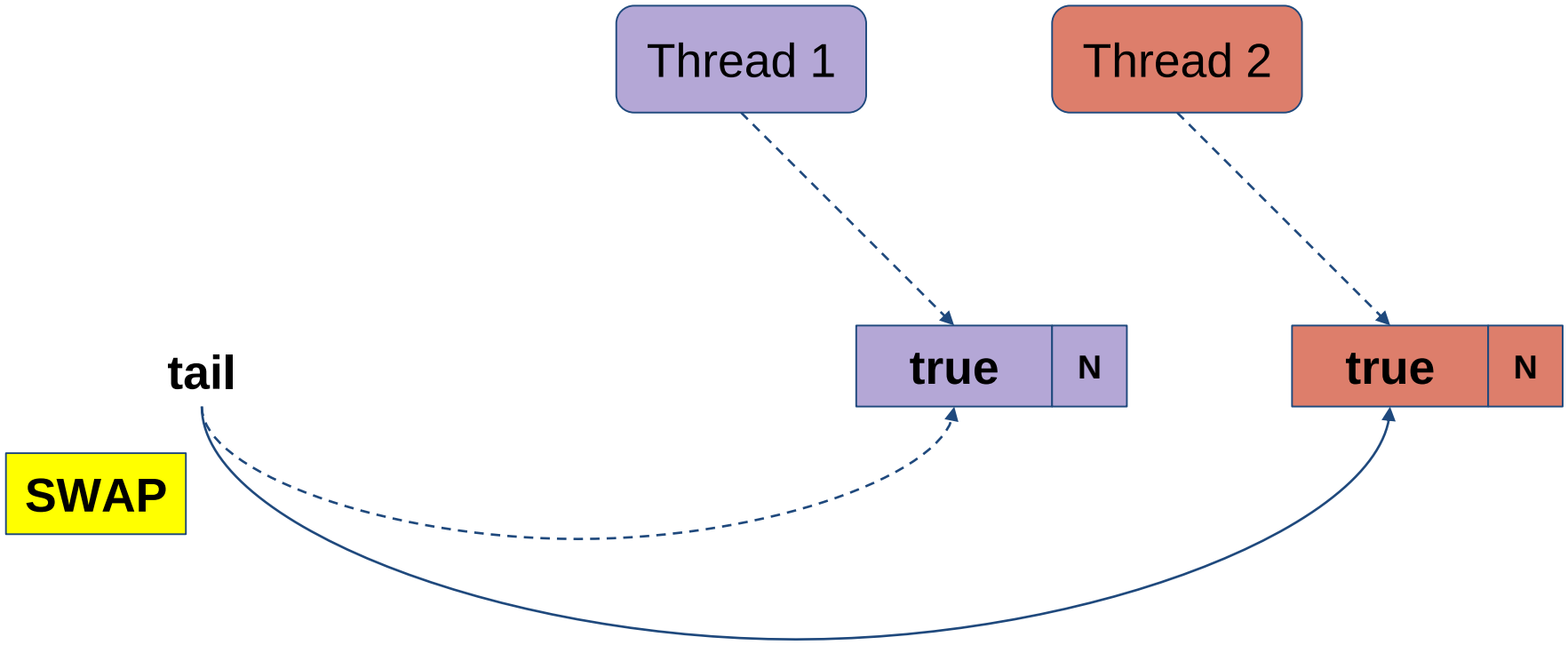
MCS Lock: Поток 2



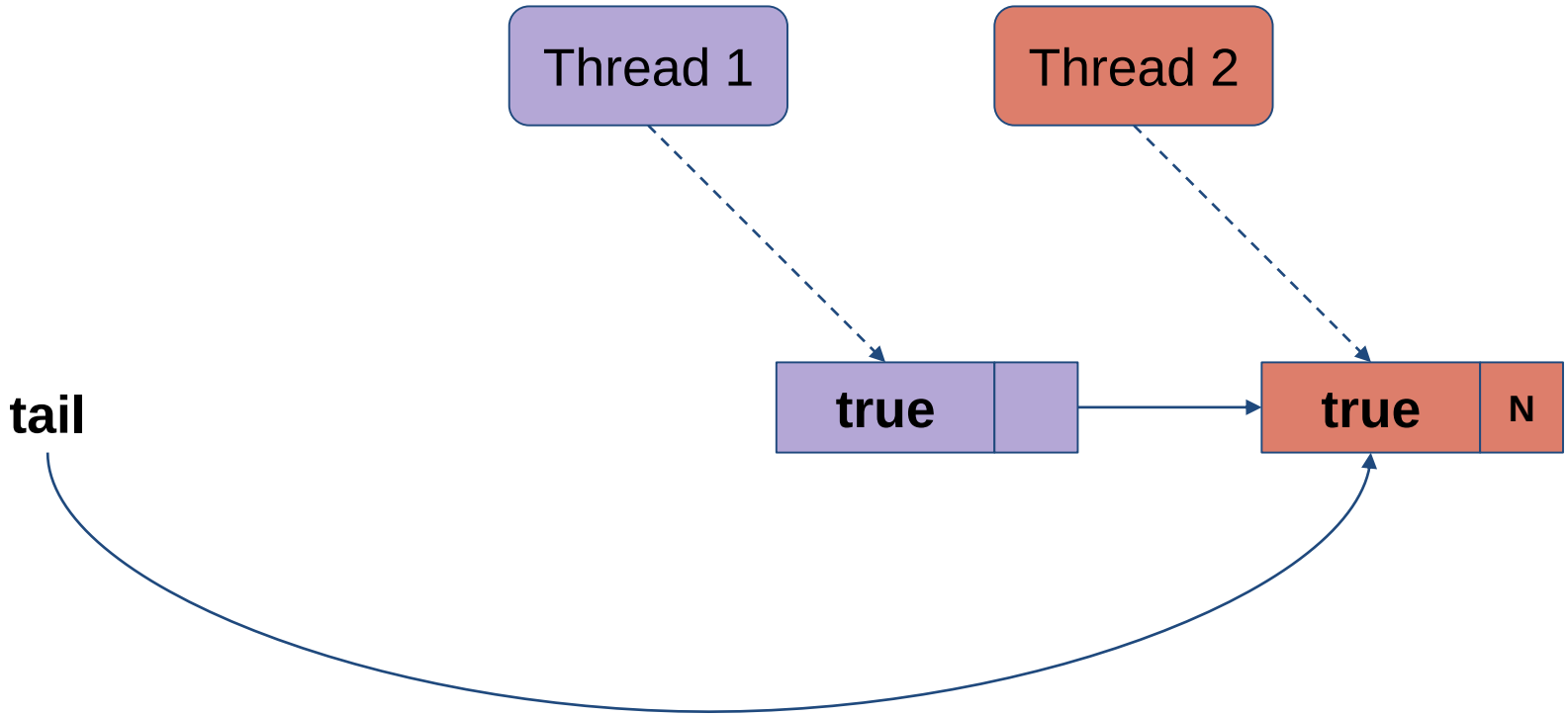
MCS Lock: Узел 2



MCS Lock: Добавление в очередь



MCS Lock: Создали список

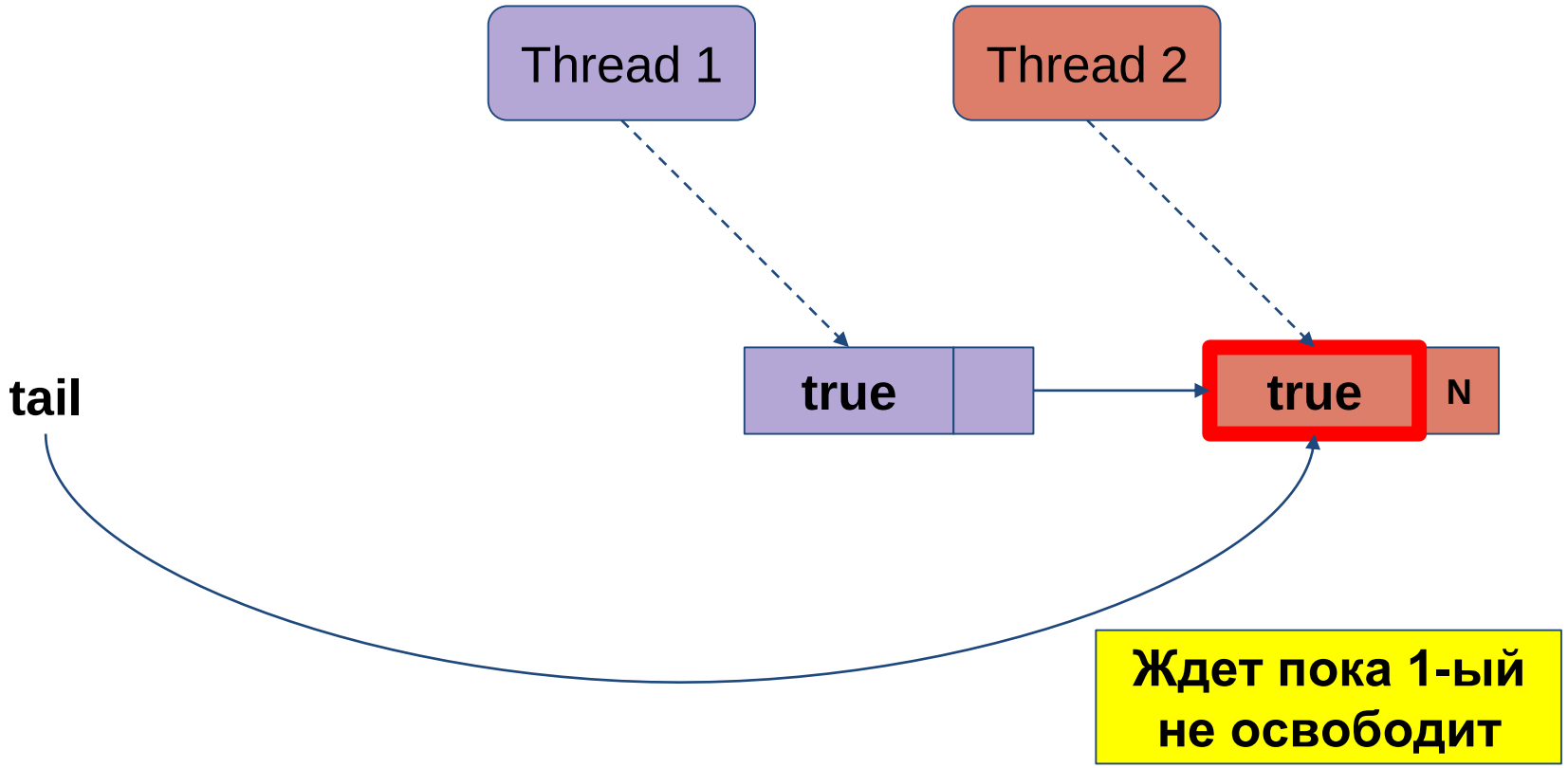


MCS Lock

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def lock():
        my = QNode()
        pred = tail.getAndSet(my)
        if pred != null:
            pred.next = my
            while my.locked: pass
```

MCS Lock: Ждем на своем объекте

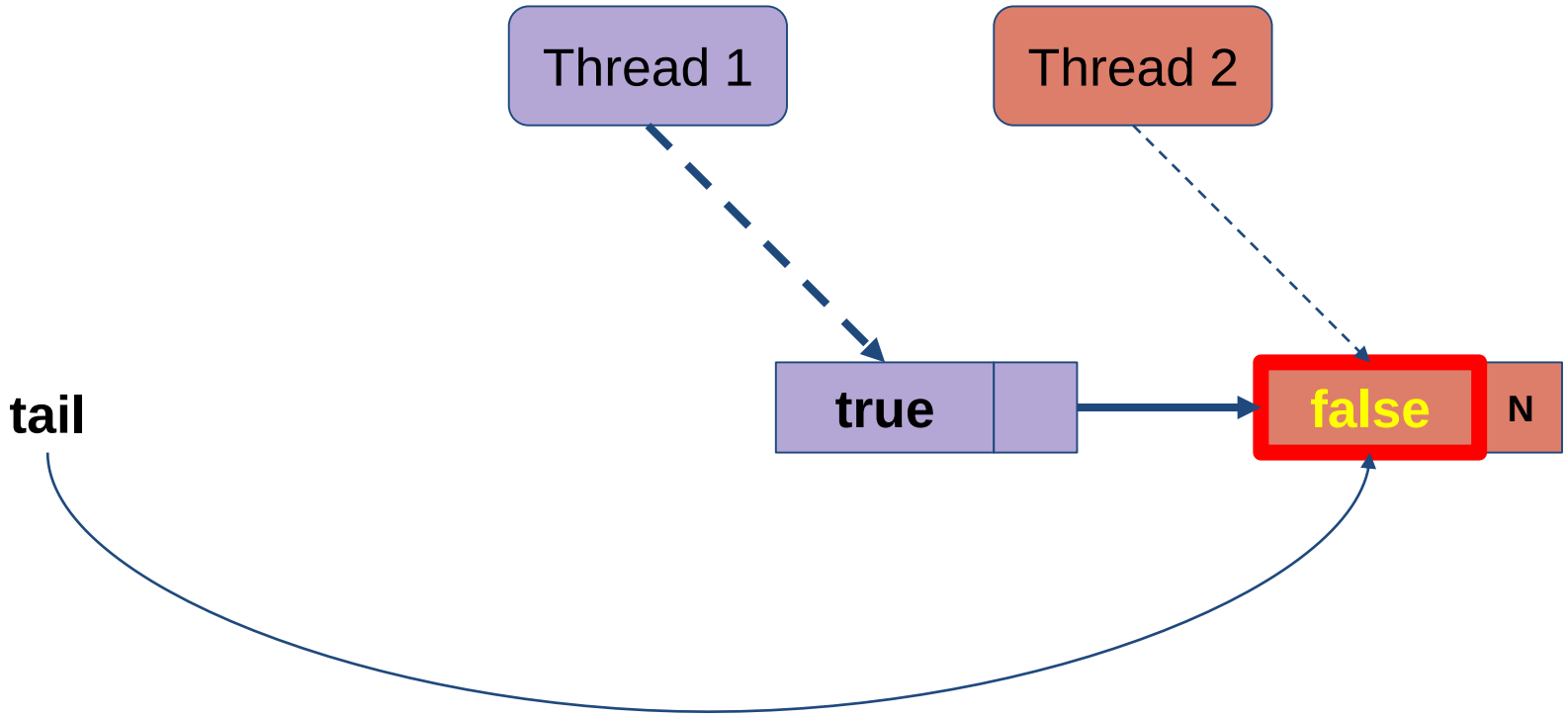


MCS Lock

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def lock():
        my = QNode()
        pred = tail.getAndSet(my)
        if pred != null:
            pred.next = my
            while my.locked: pass
```

MCS Lock: Поток 1 освобождает

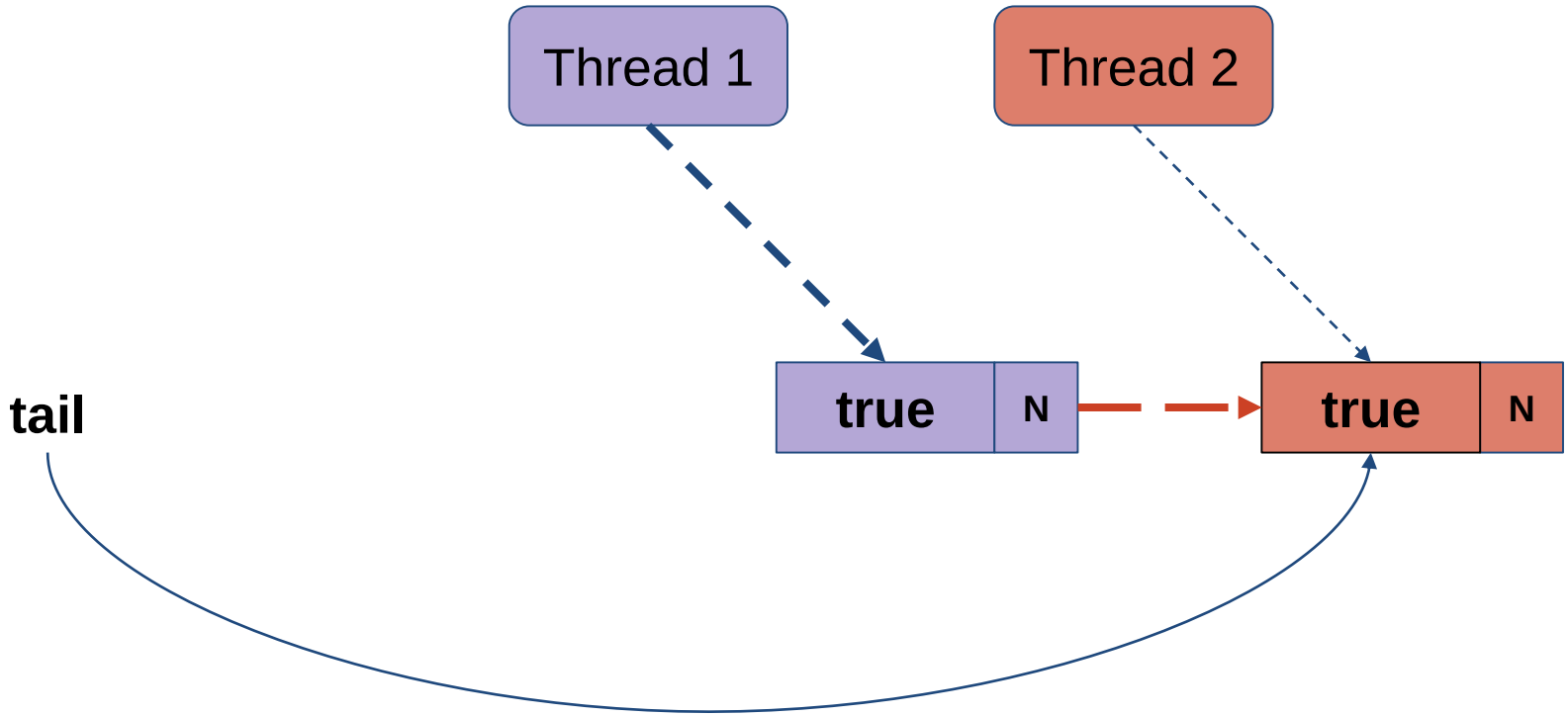


MCS Lock

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def unlock():
        if my.next == null:
            if tail.CAS(my, null): return
            else:
                while my.next == null: pass
        my.next.locked = false
```

MCS Lock: А что если ссылки еще нет?

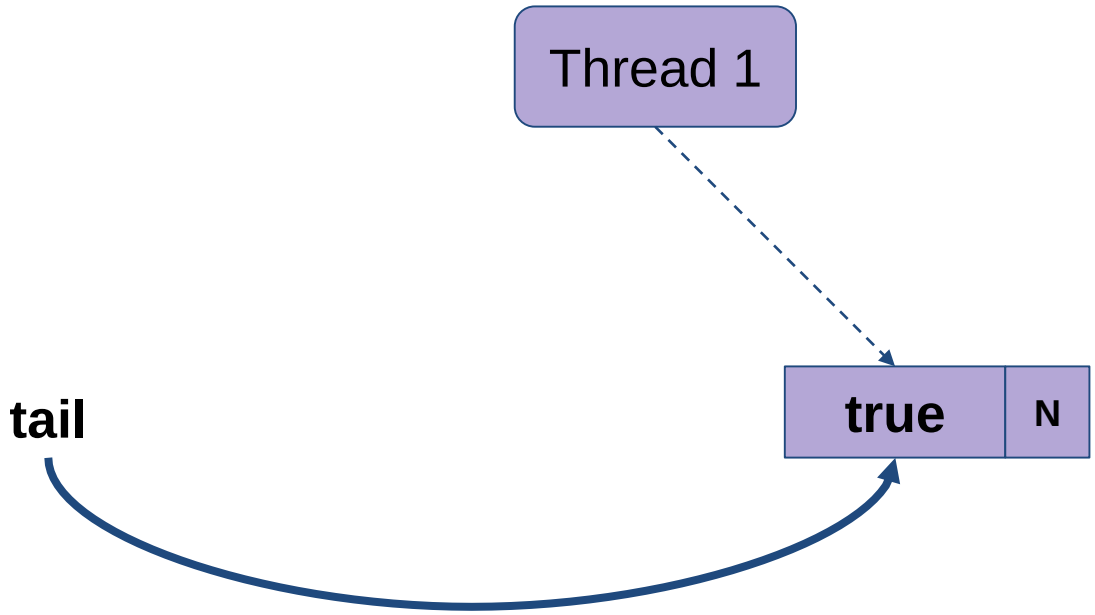


MCS Lock

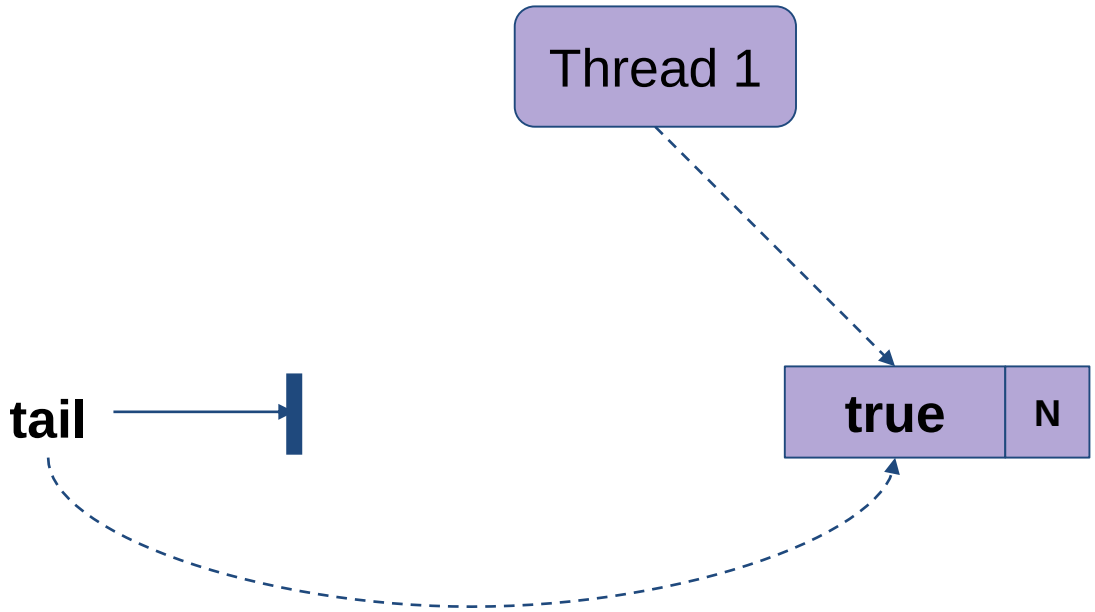
```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def unlock():
        if my.next == null:
            if tail.CAS(my, null): return
            else:
                while my.next == null: pass
        my.next.locked = false
```

MCS Lock: Случай A: Других в очереди нет



MCS Lock: Случай A: Других в очереди нет

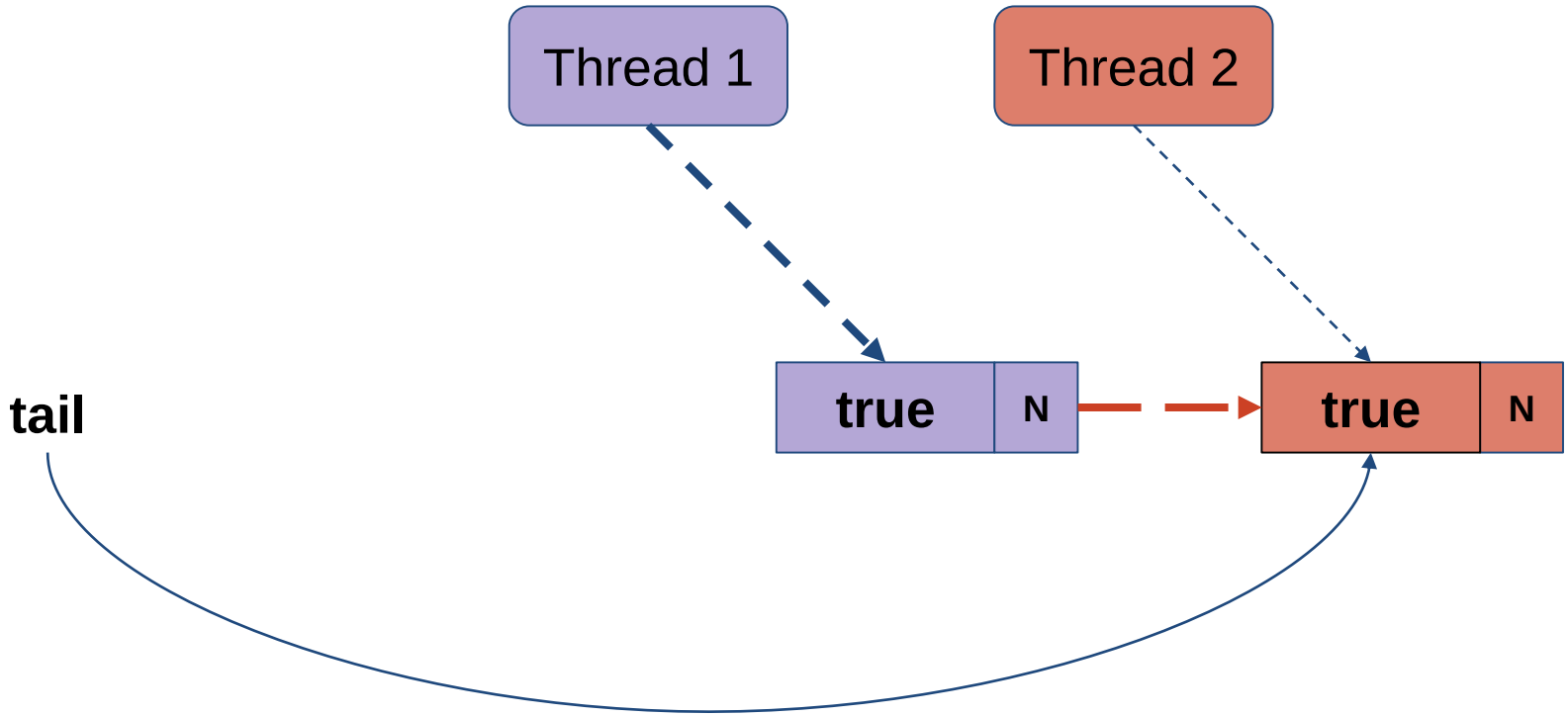


MCS Lock

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def unlock():
        if my.next == null:
            if tail.CAS(my, null): return
            else:
                while my.next == null: pass
        my.next.locked = false
```

MCS Lock: Случай Б: Другой не успел



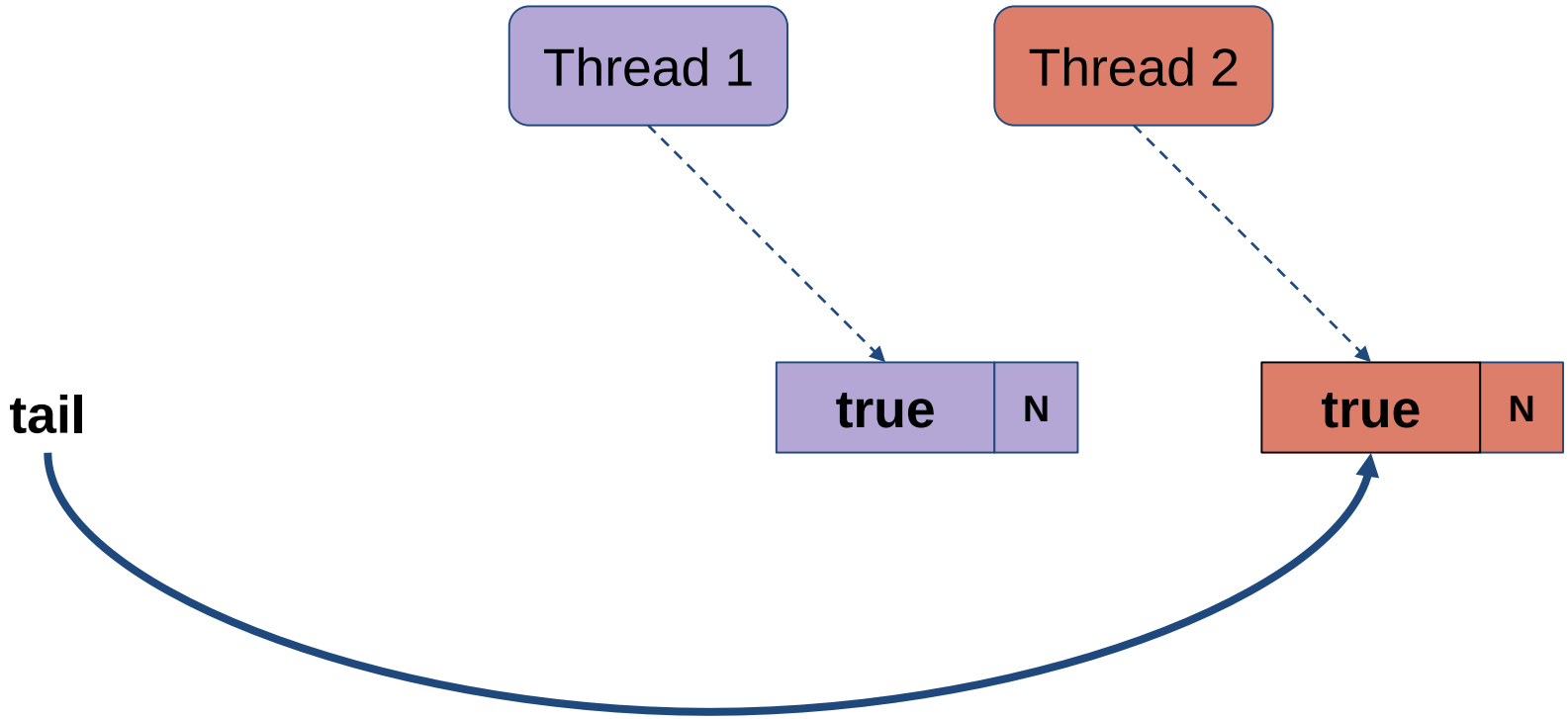
MCS Lock: Пишем сначала tail, потом next

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def lock():
        my = QNode()
        pred = tail.getAndSet(my)
        if pred != null:
            pred.next = my
            while my.locked: pass
```

Могли застрять между

MCS Lock: Случай Б: Другой не успел

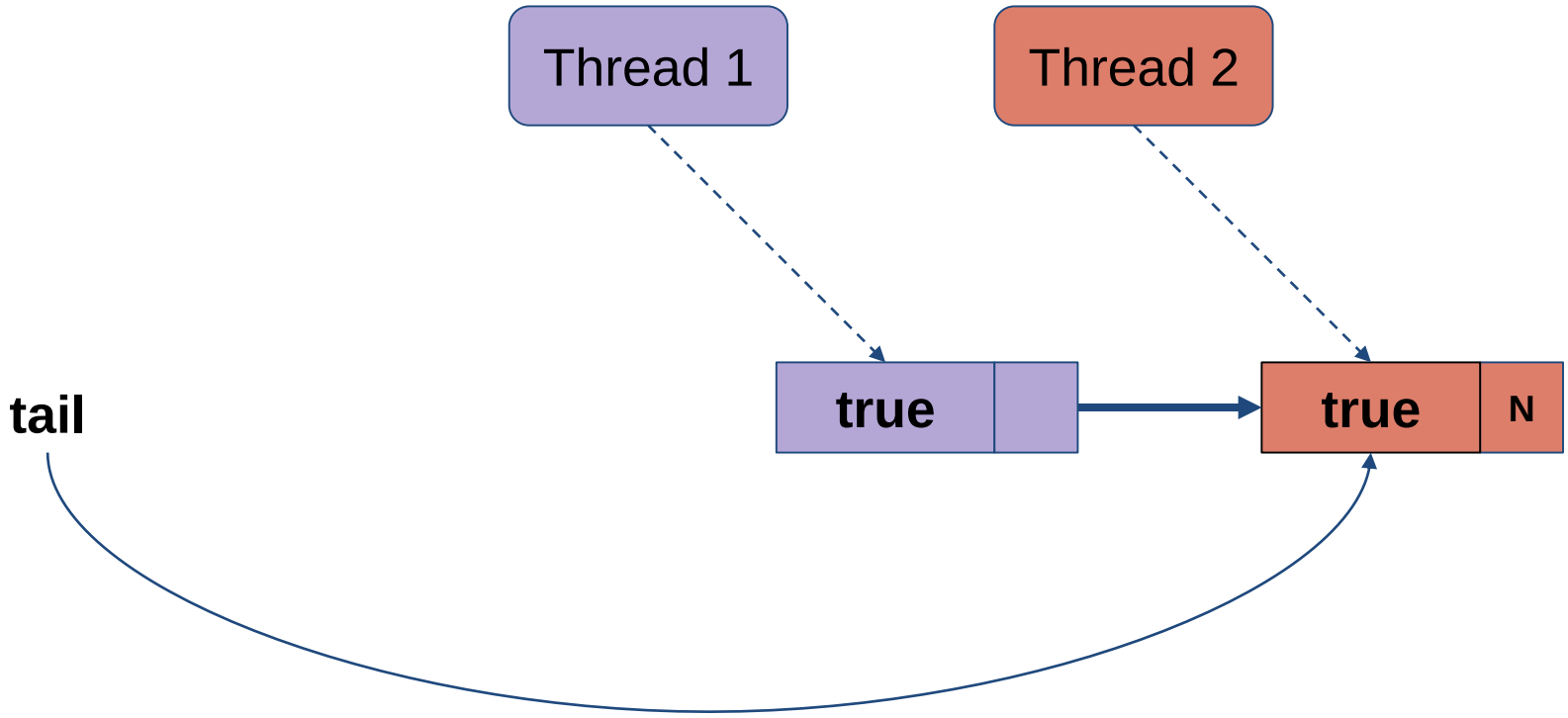


MCS Lock: Дождемся пока появится!

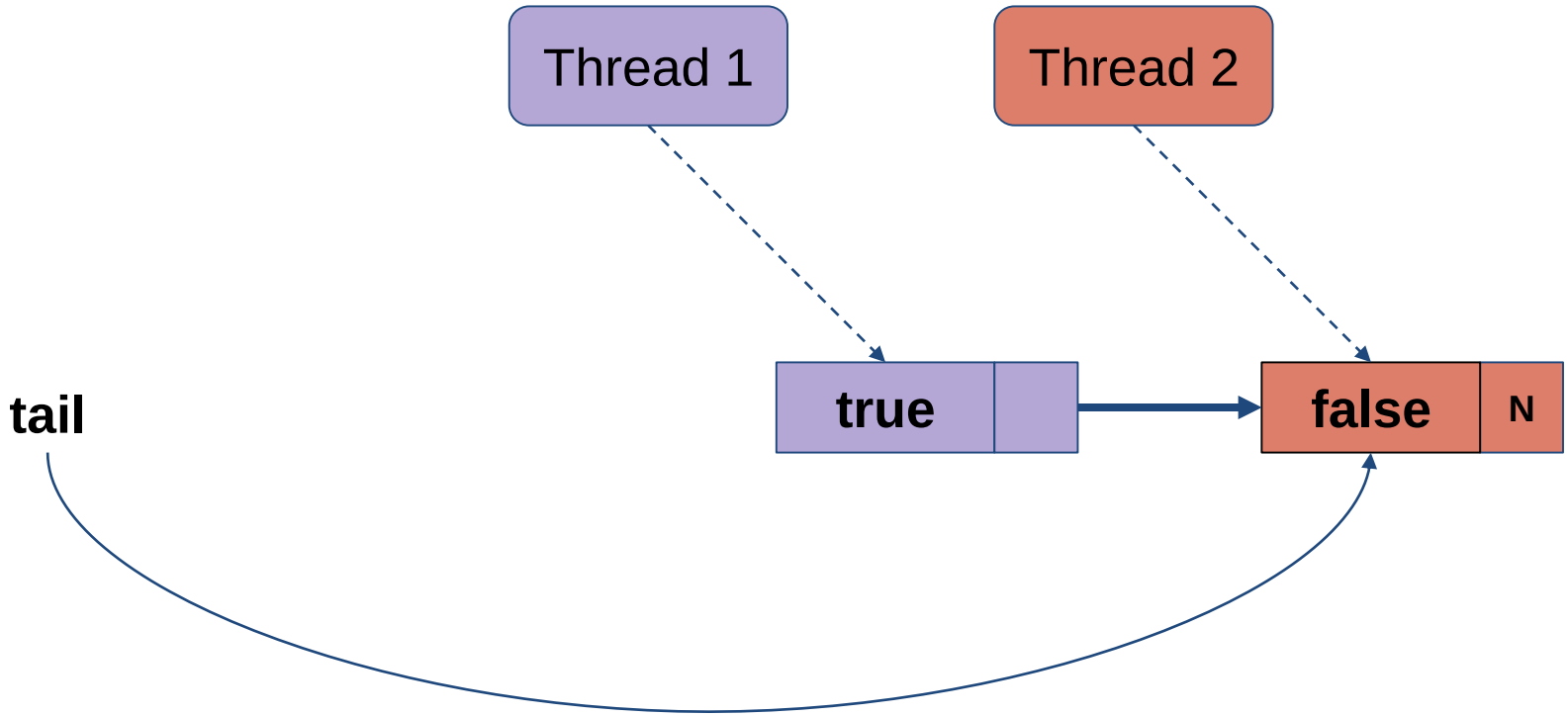
```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def unlock():
        if my.next == null:
            if tail.CAS(my, null): return
            else:
                while my.next == null: pass
        my.next.locked = false
```

MCS Lock: Случай Б: Другой не успел



MCS Lock: Освободим лок



MCS Lock: Освободим лок

```
class QNode:
    boolean locked // shared, atomic
    QNode next = null
```

```
class CLHLock:
    tail = QNode() // shared, atomic
    treadlocal my = null

    def unlock():
        if my.next == null:
            if tail.CAS(my, null): return
            else:
                while my.next == null: pass
        my.next.locked = false
```

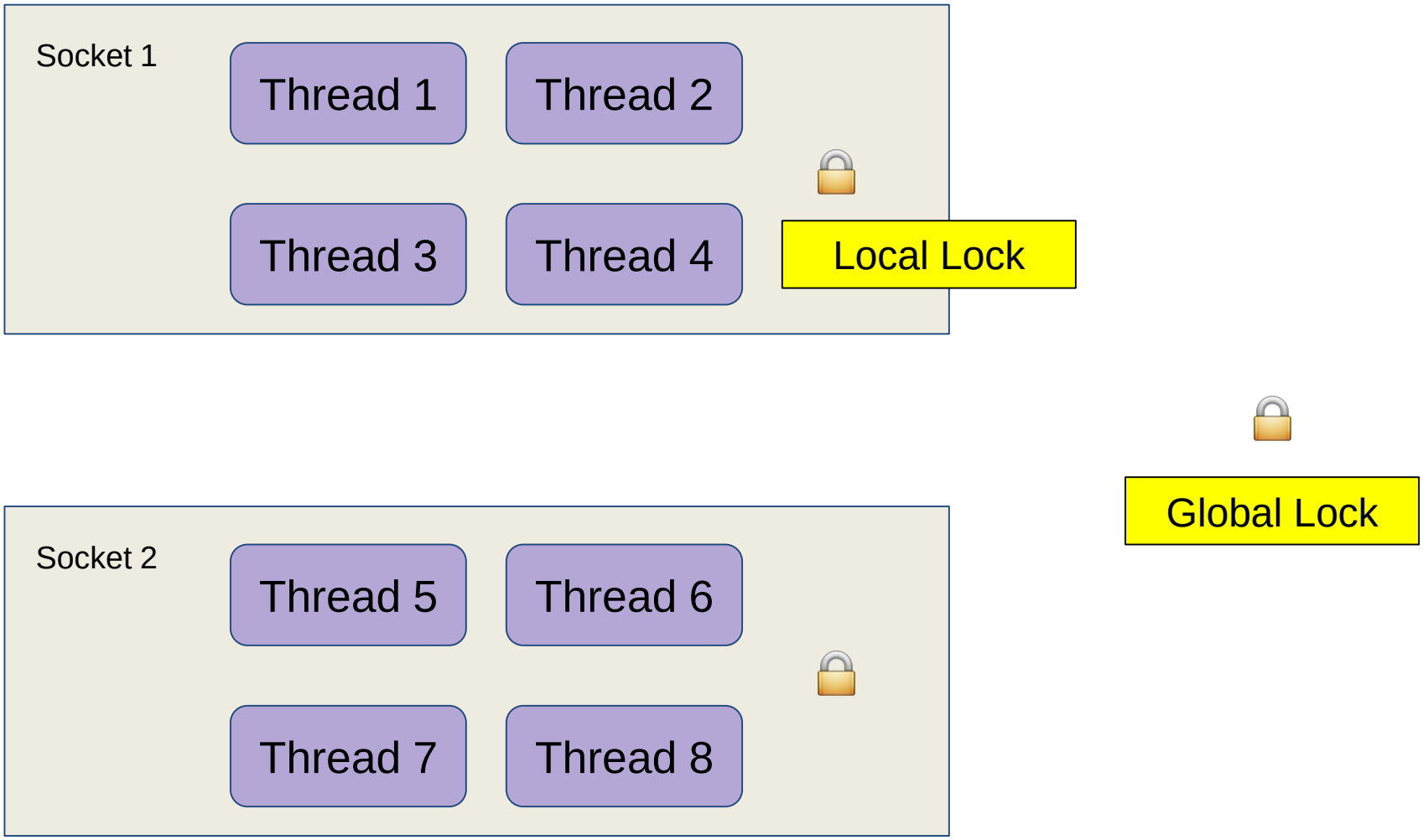
MCS Lock

- **Хорошо**
  - Ждет на “своей” памяти

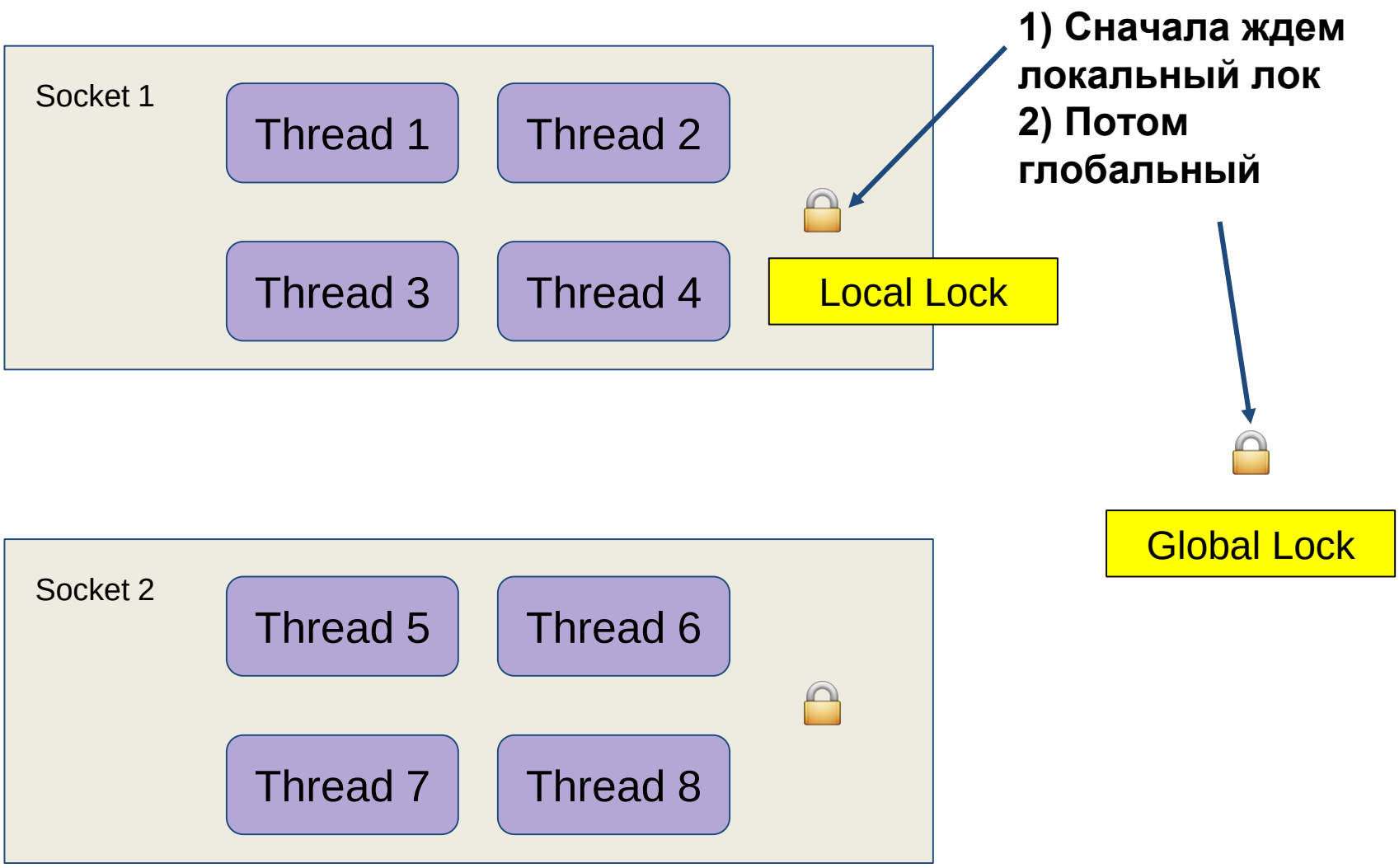
- **Плохо**
  - tail изменяется всеми потоками -- будет большая конкуренция
  - Любой FCFS лок будет от этого страдать!

NUMA: Нечестность окупается!

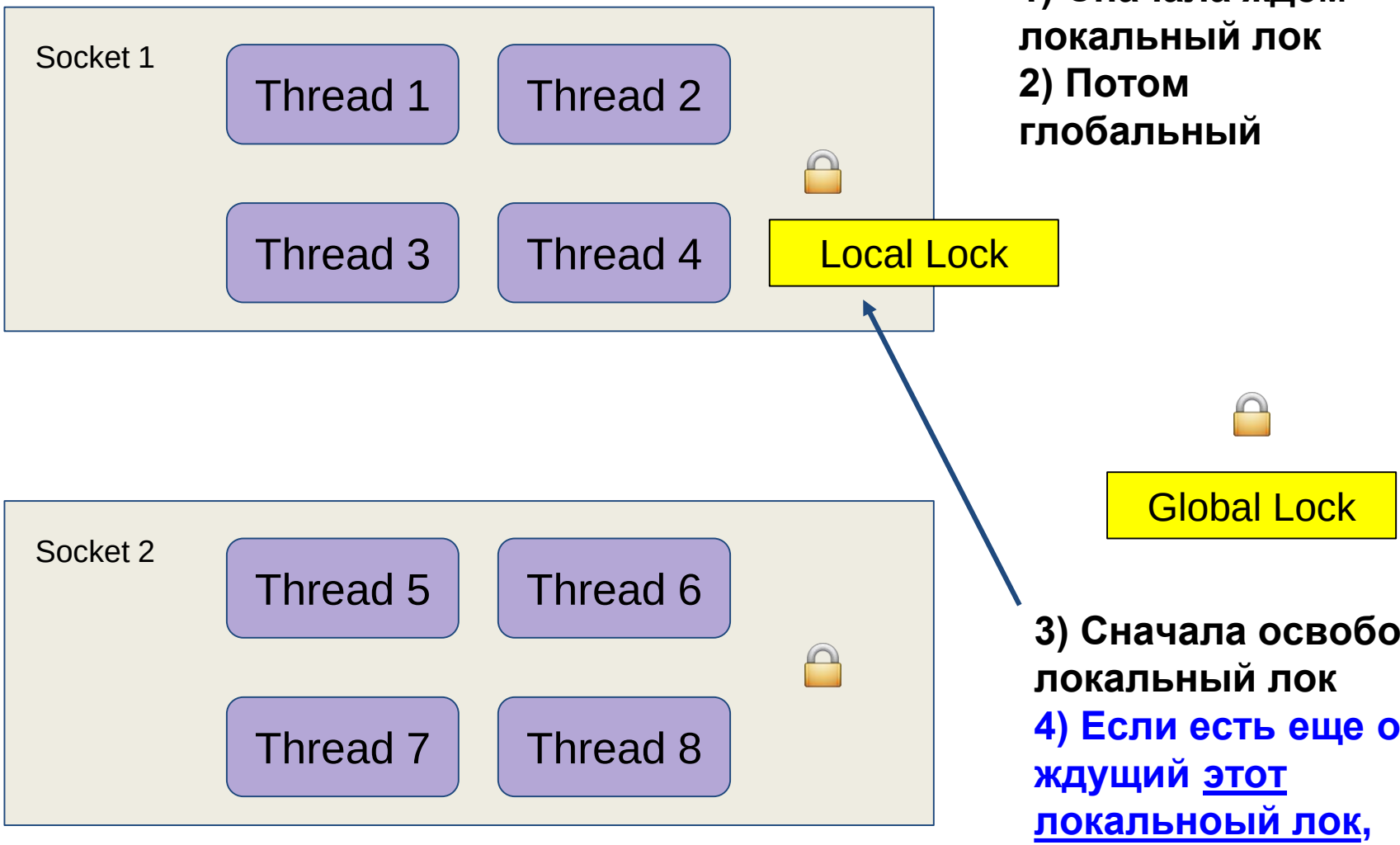
NUMA: Lock Cohorting



NUMA: Lock Cohorting



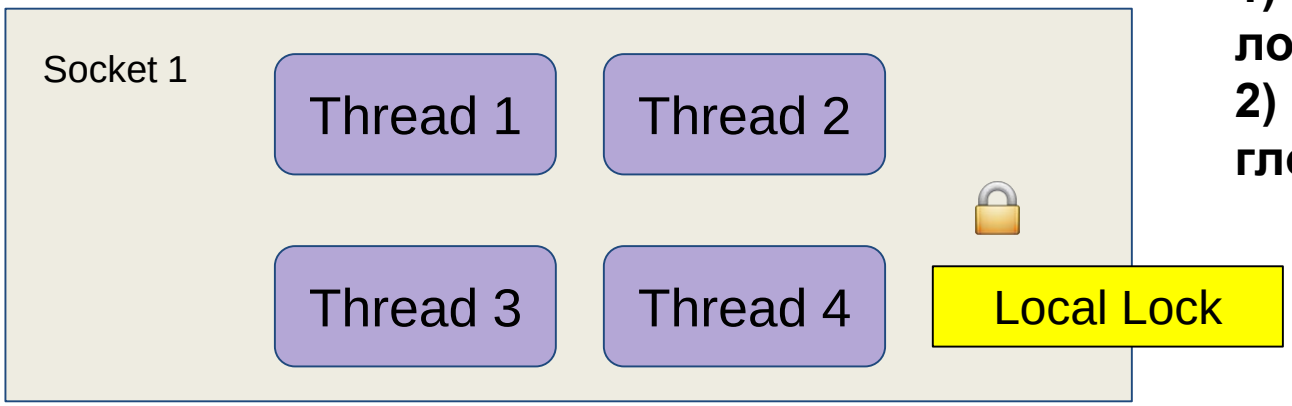
NUMA: Lock Cohorting



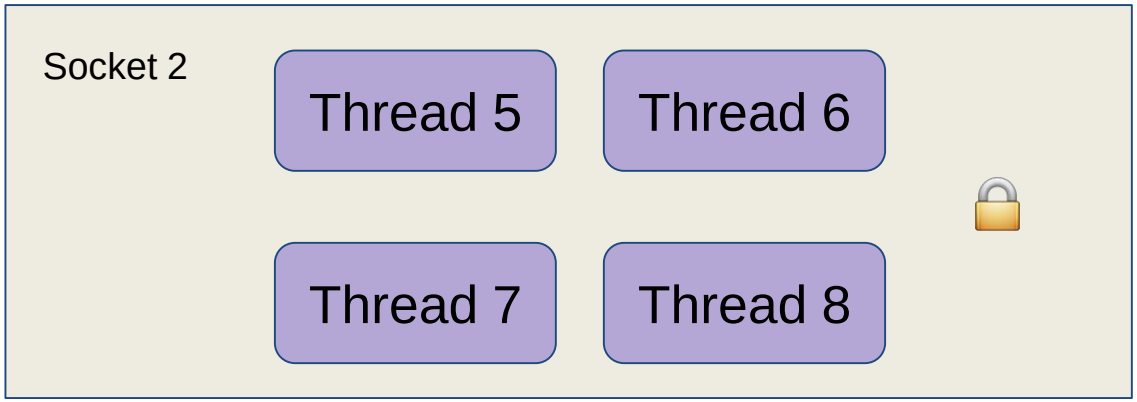
1) Сначала ждем локальный лок
2) Потом глобальный

3) Сначала освободим локальный лок
4) Если есть еще один ждущий этот локальноый лок, разбудим его

NUMA: Lock Cohorting



1) Сначала ждем локальный лок
2) Потом глобальный



3) Сначала освободим локальный лок
4) Если нет еще ждущего, то освободим глобальный лок

NUMA: Какие локи могут участвовать в когорте?

- Global Lock: **Thread-Oblivious**
  - Брать и освобождать могут любые потоки
  - Например TTS (Backoff) Lock

- Local Lock: **Cohort Detection**
  - Должен уметь понимать есть ли другие локи, которые его ждут
  - Например MCS Lock