# Concurrent and parallel programming

SAPIENZA
UNIVERSITÀ DI ROMA

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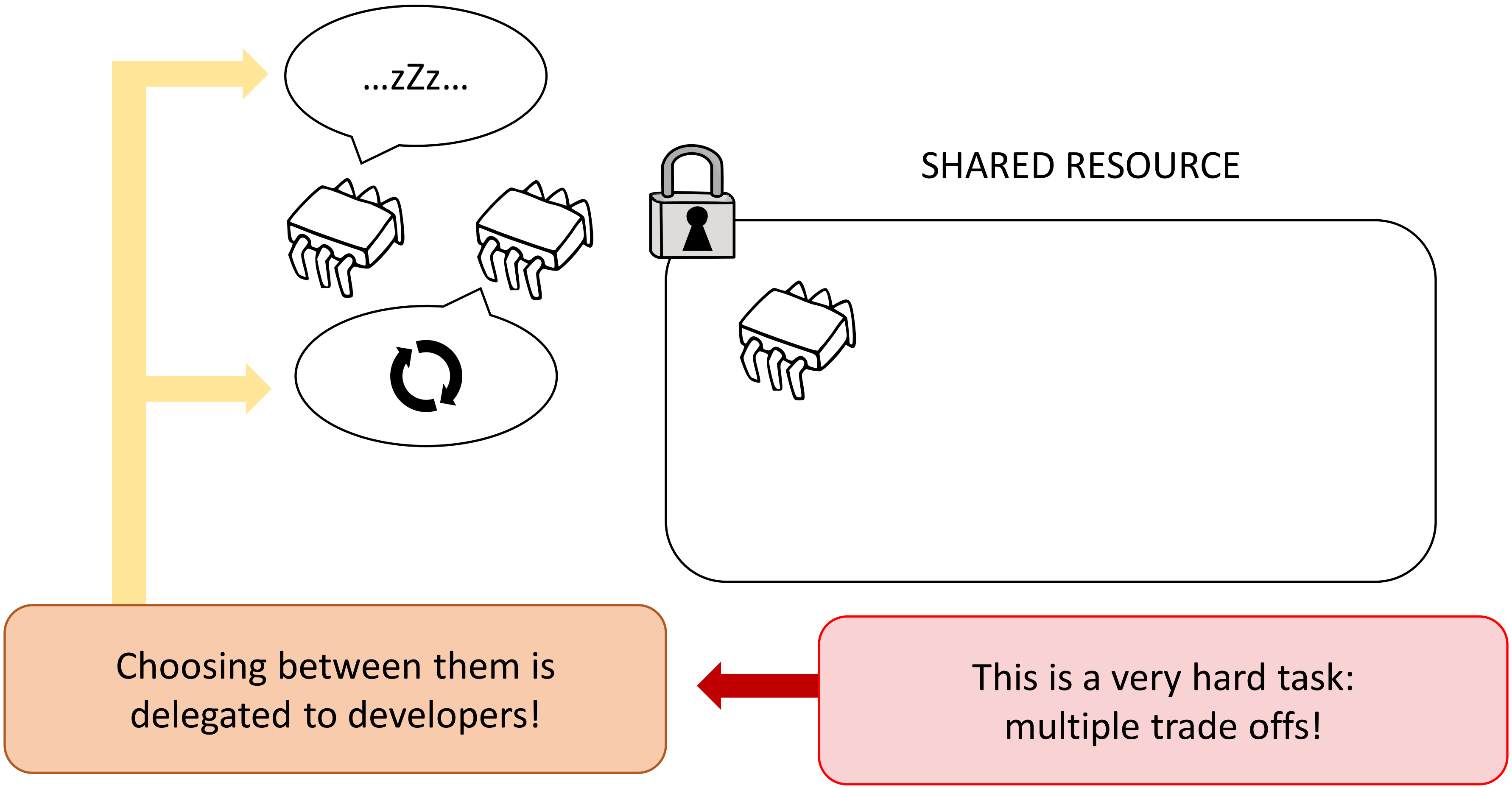
Romolo Marotta

# Lock implementations

# Blocking coordination

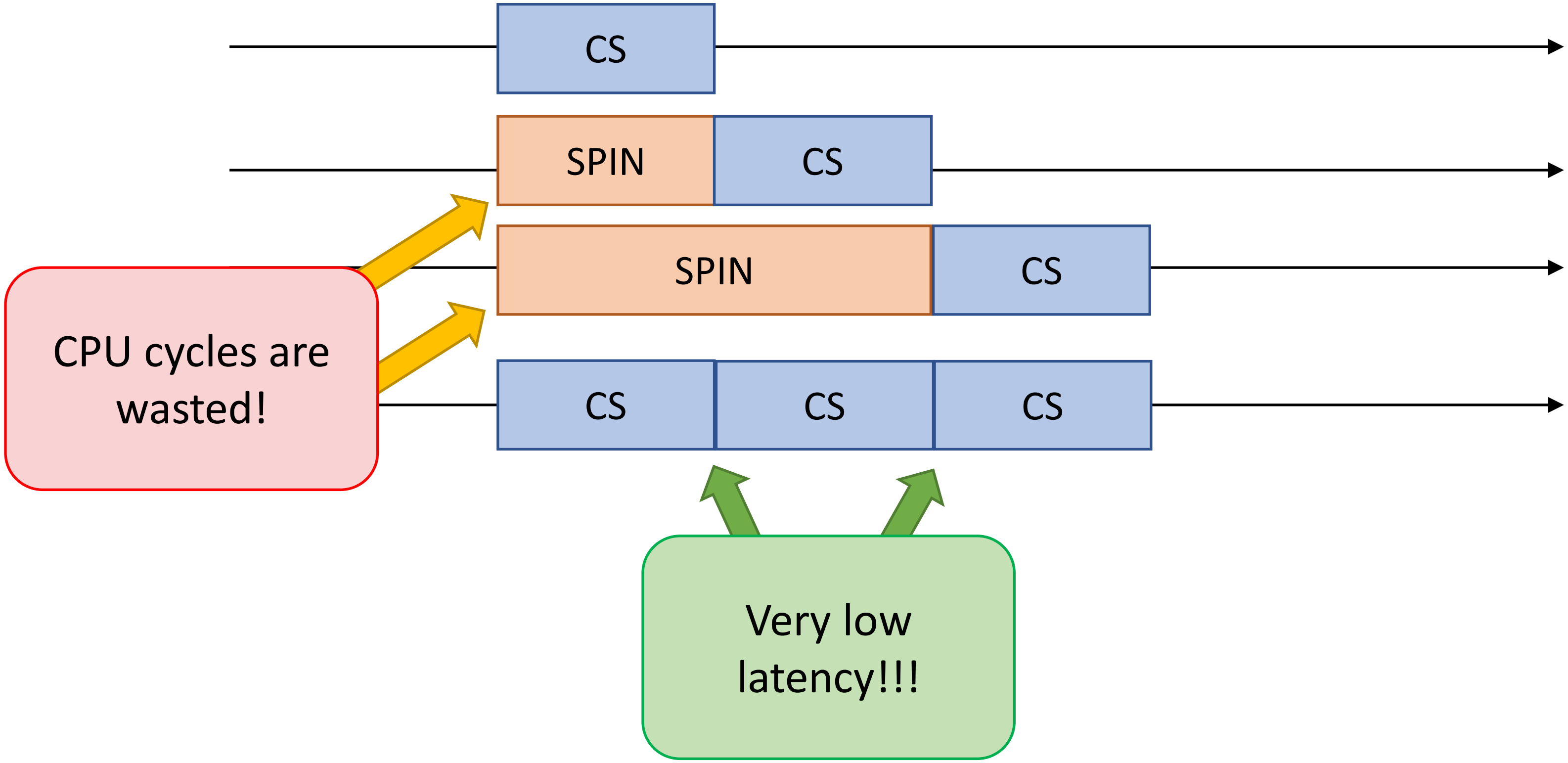


Choosing between them is delegated to developers!

This is a very hard task: multiple trade offs!

# Spinning vs Sleeping

| **Benefits** | **Spinning** |
|---|---|
| Guaranteed low latency | ✓ |
| Computing power savings | ✗ |



CS

SPIN CS

SPIN CS

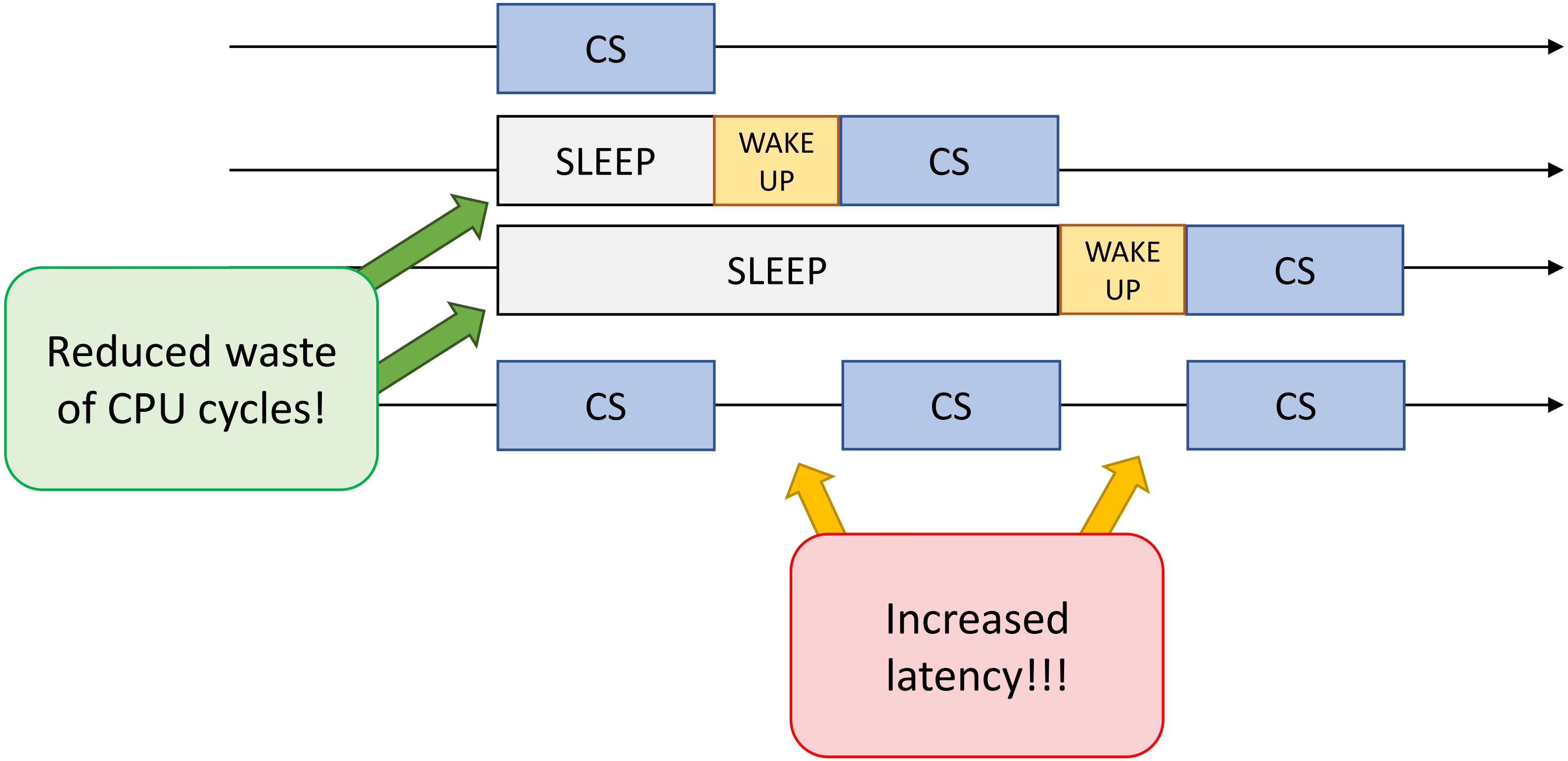
CS CS CS

CPU cycles are wasted!

Very low latency!!!

# Spinning vs Sleeping

| | **Waiting Policy** | |
|---|---|---|
| **Benefits** | **Spinning** | **Sleeping** |
| Guaranteed low latency | ✓ | ✗ |
| Computing power savings | ✗ | ✓ |
| Autonomic Adaptivity | ✗ | ✗ |



Reduced waste of CPU cycles!

Increased latency!!!

# Spin vs Sleep – is that all?

- Choosing the proper back off scheme is very challenging
- Even implementing a simple spin lock is not trivial
  - Trade off between low and high contented case
  - You should have heard about algorithms for Mutual Exclusion in Distributed Systems lectures
    - E.g. Dijkstra, Bakery algorithm, Peterson...
  - Those algorithm essentially implements spin locks by resorting only on read/write operations
- Here, we will focus on spin locking algorithms that exploit stronger synchronization primitives… RMW!

# Test-and-set spin lock

- Test-and-set lock is the simplest spin lock
- Acquiring threads always try to set a variable via RMW

```
int lock = 0;
void acquire(int *lock){
  while(XCHG(lock, 1));
}
```

```
void release(int *lock){
  *lock = 0;
}
```

# A small benchmark

- We have an array of integers
- Each thread reverse the array

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|

→

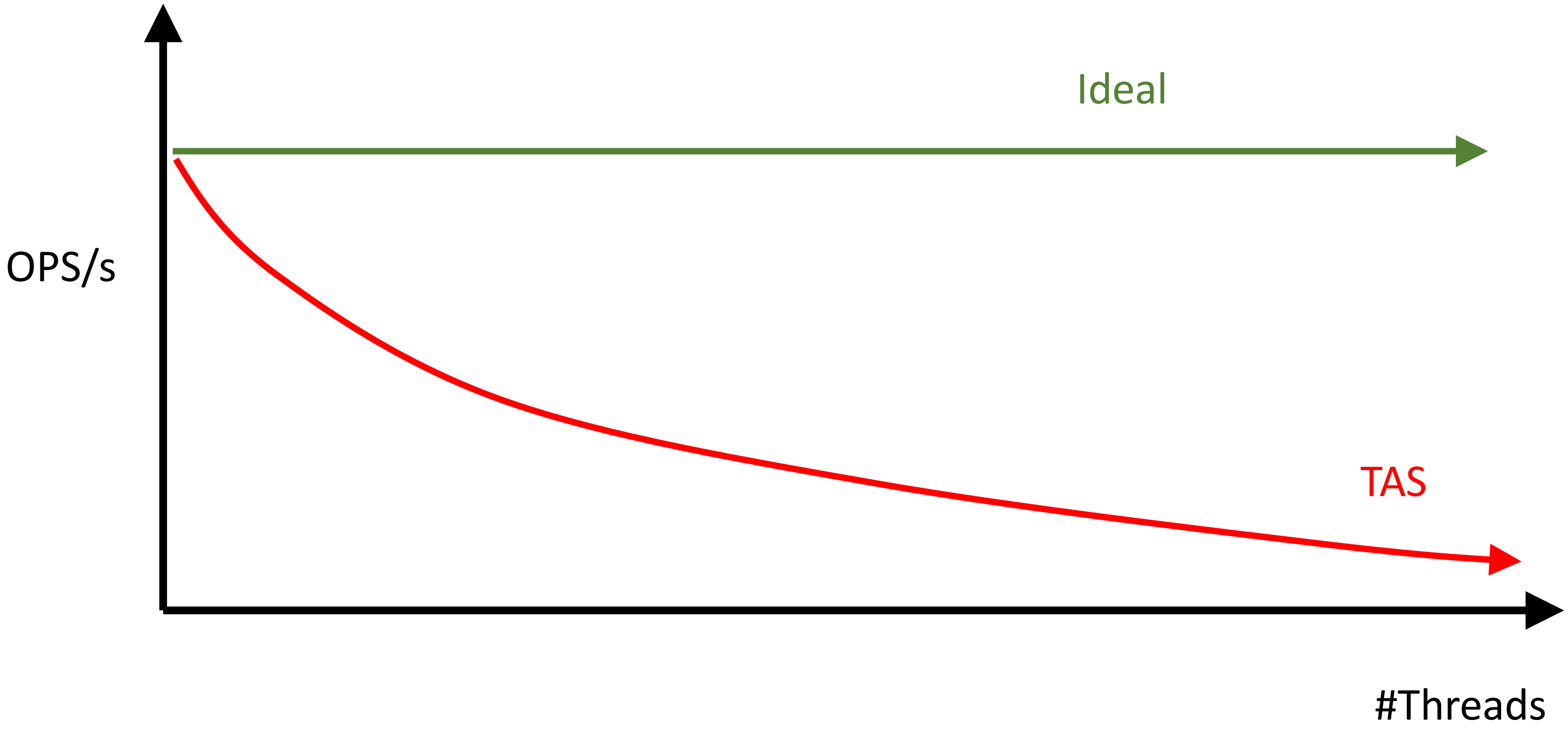
| 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|

- This is done within a critical section

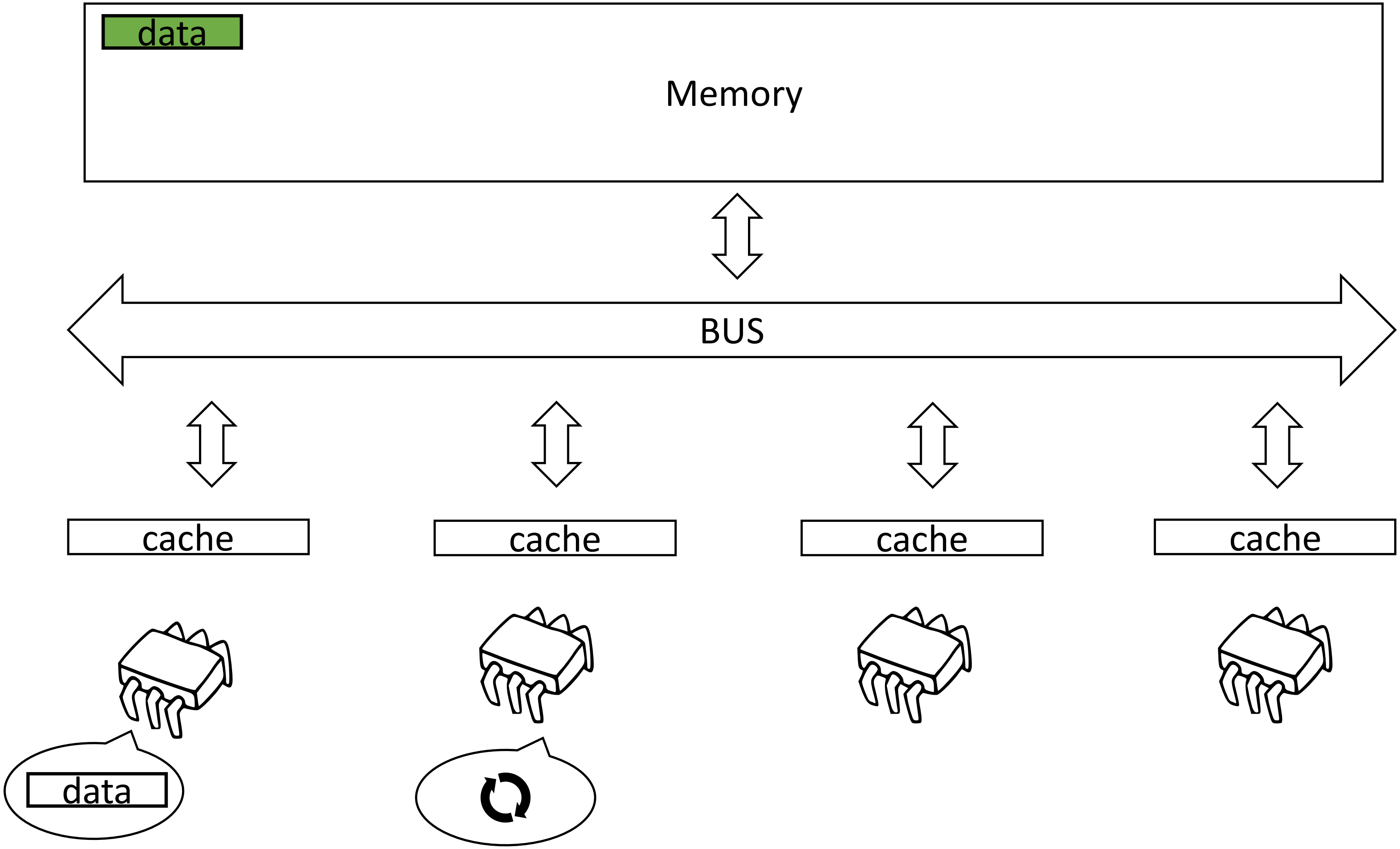
```
while(!stop){
  acquire(&lock);
  flip_array();
  release(&lock);
}
```

- Performance Metric:
  - Throughput = #Flips per second

# Results



# Memory Model



data

Memory

BUS

cache

cache

cache

cache

data

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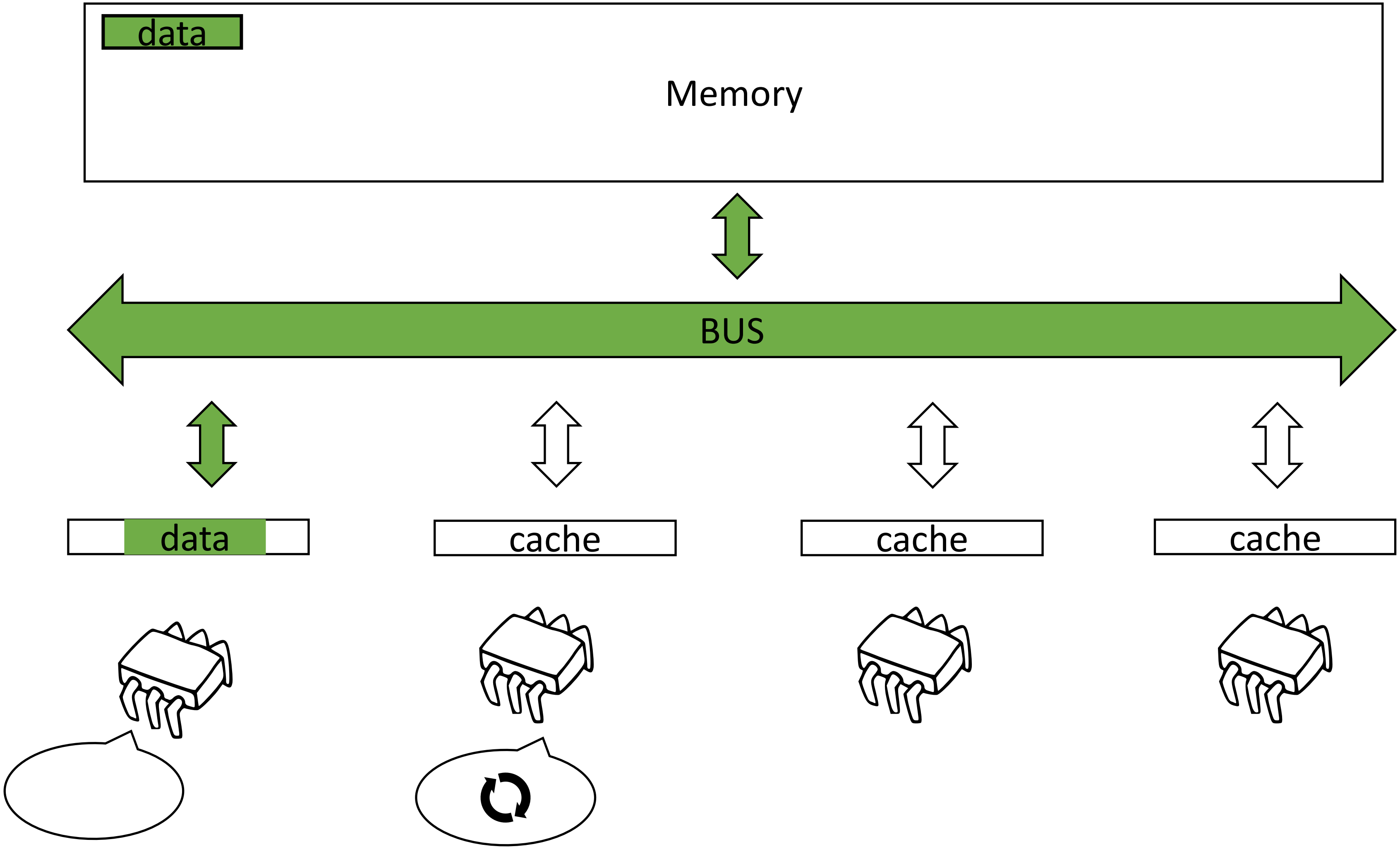

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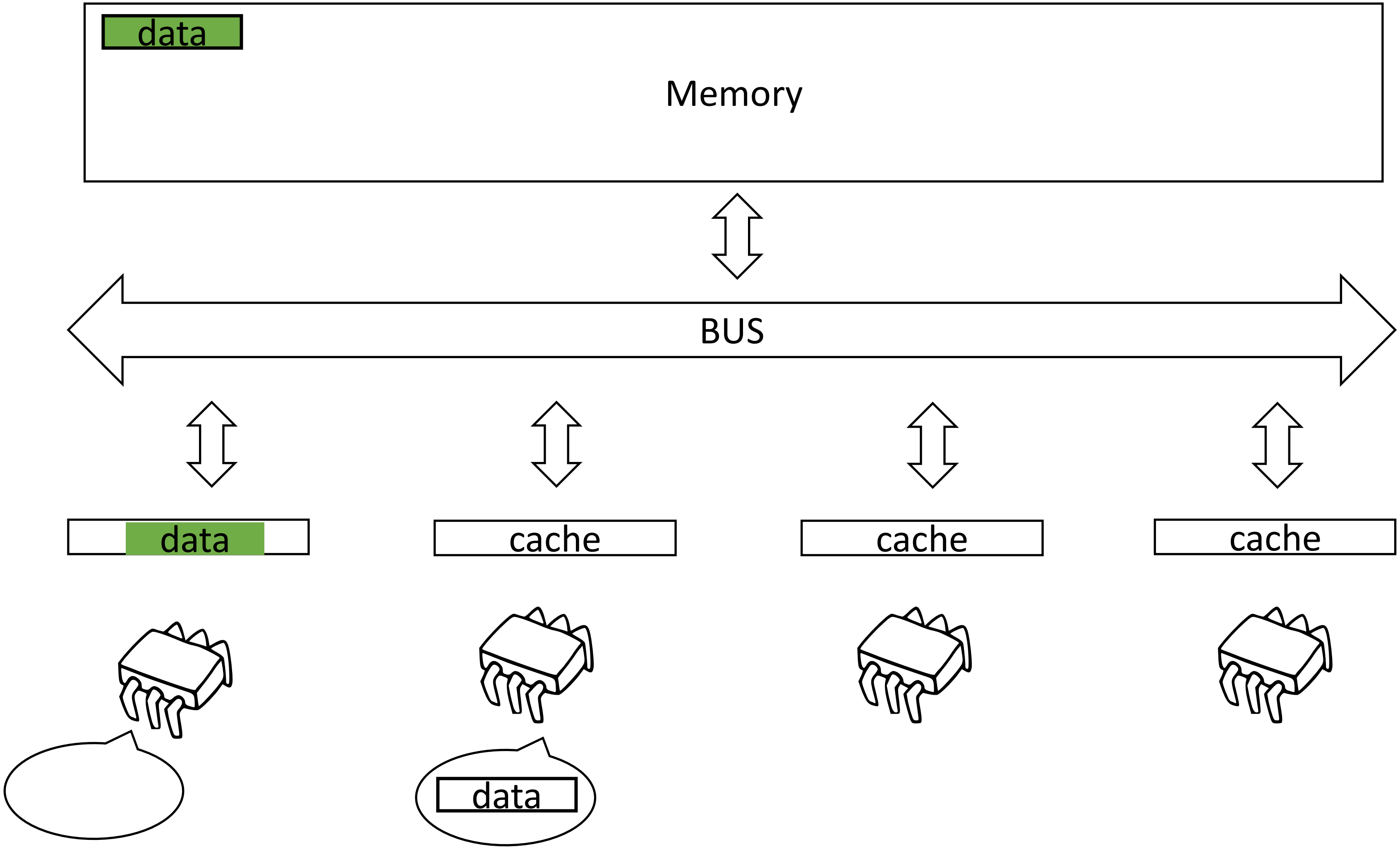

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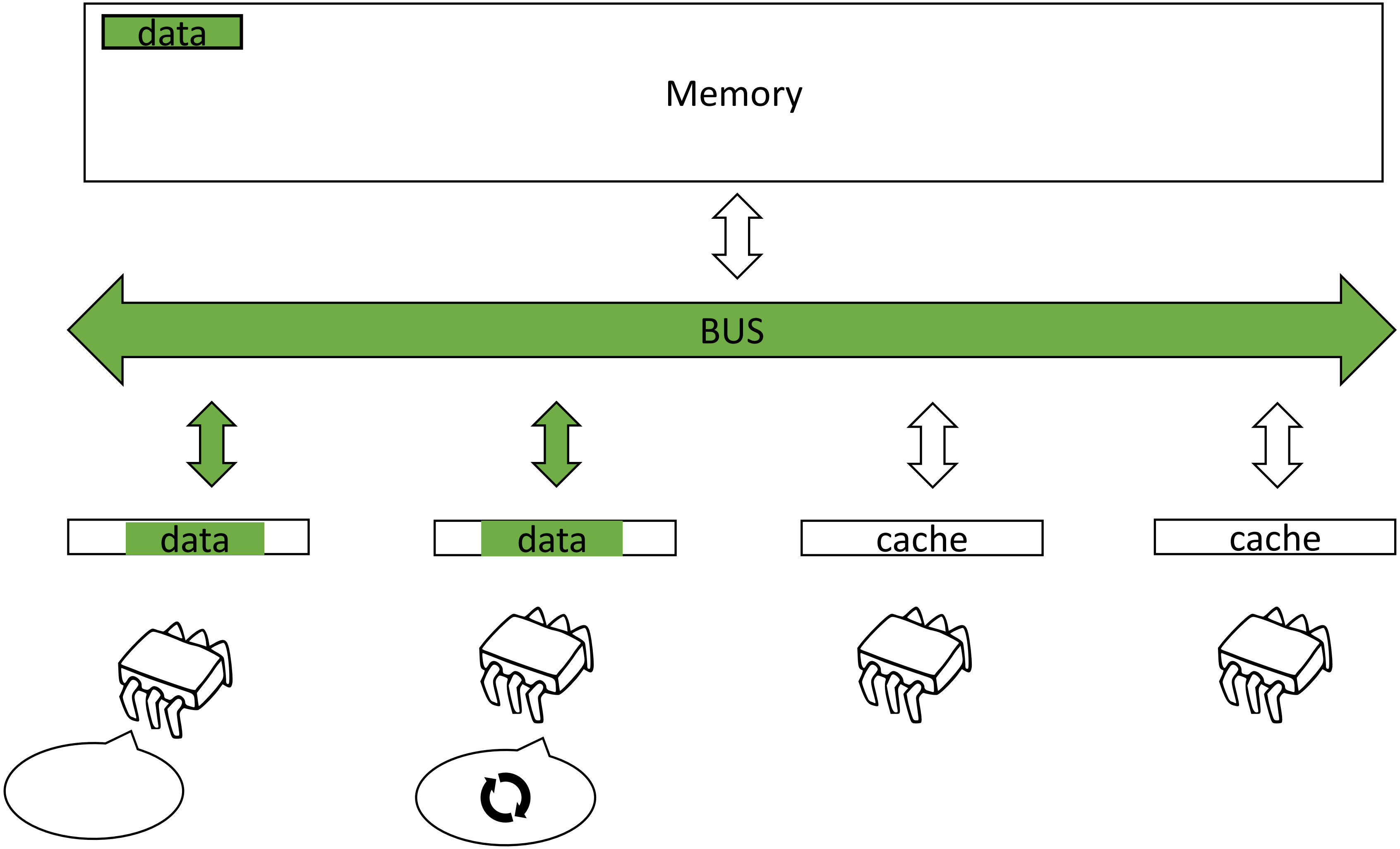

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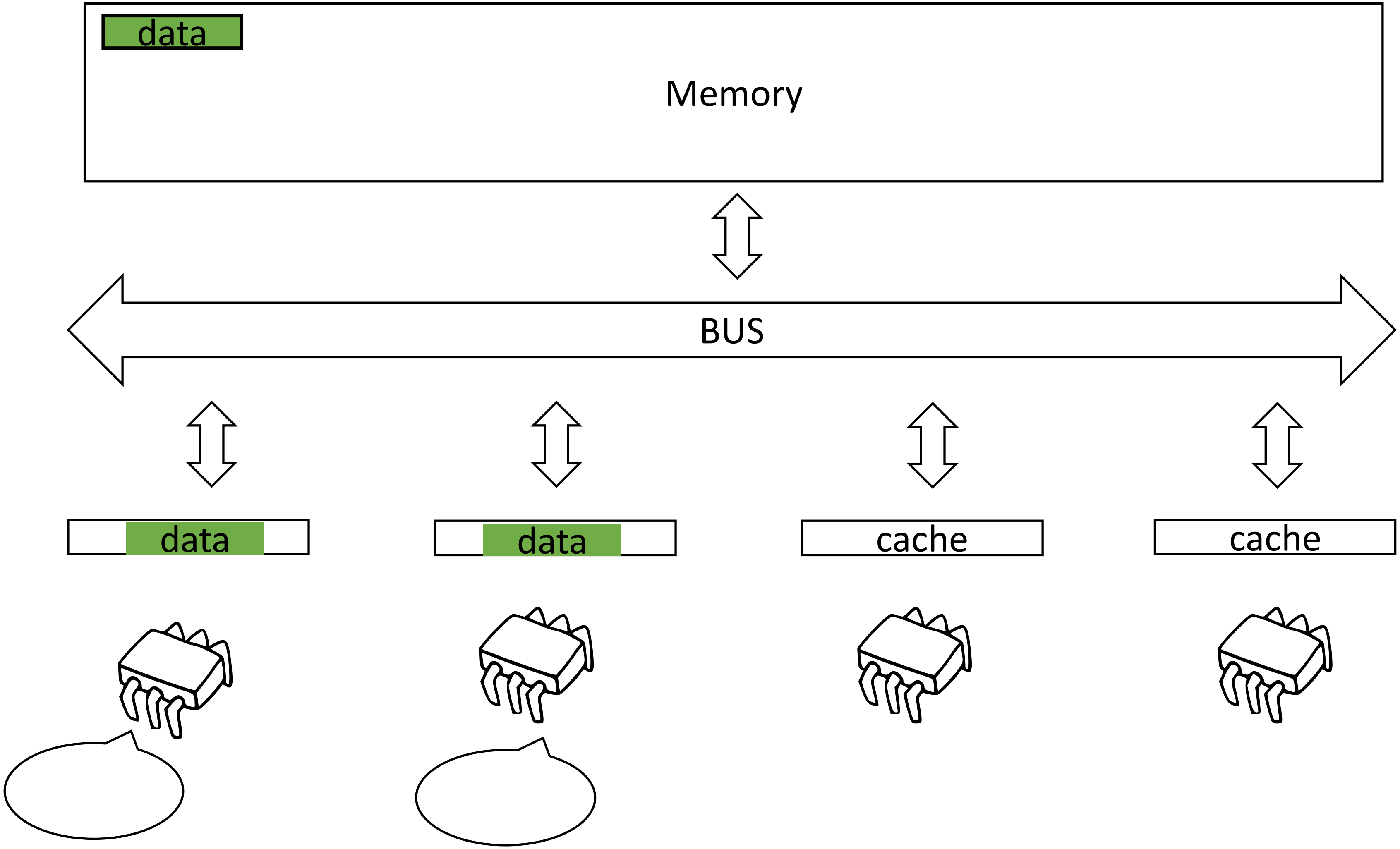

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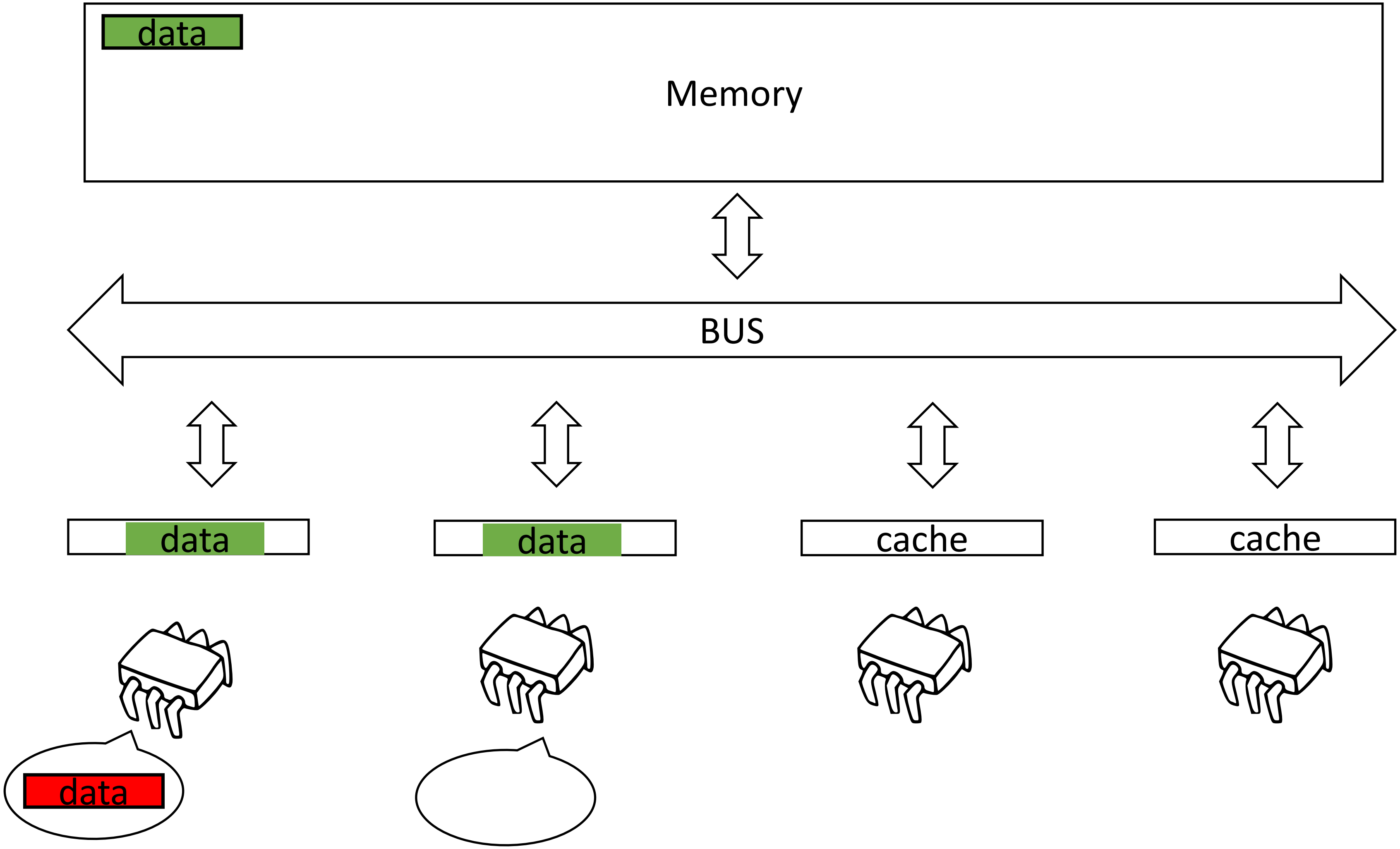

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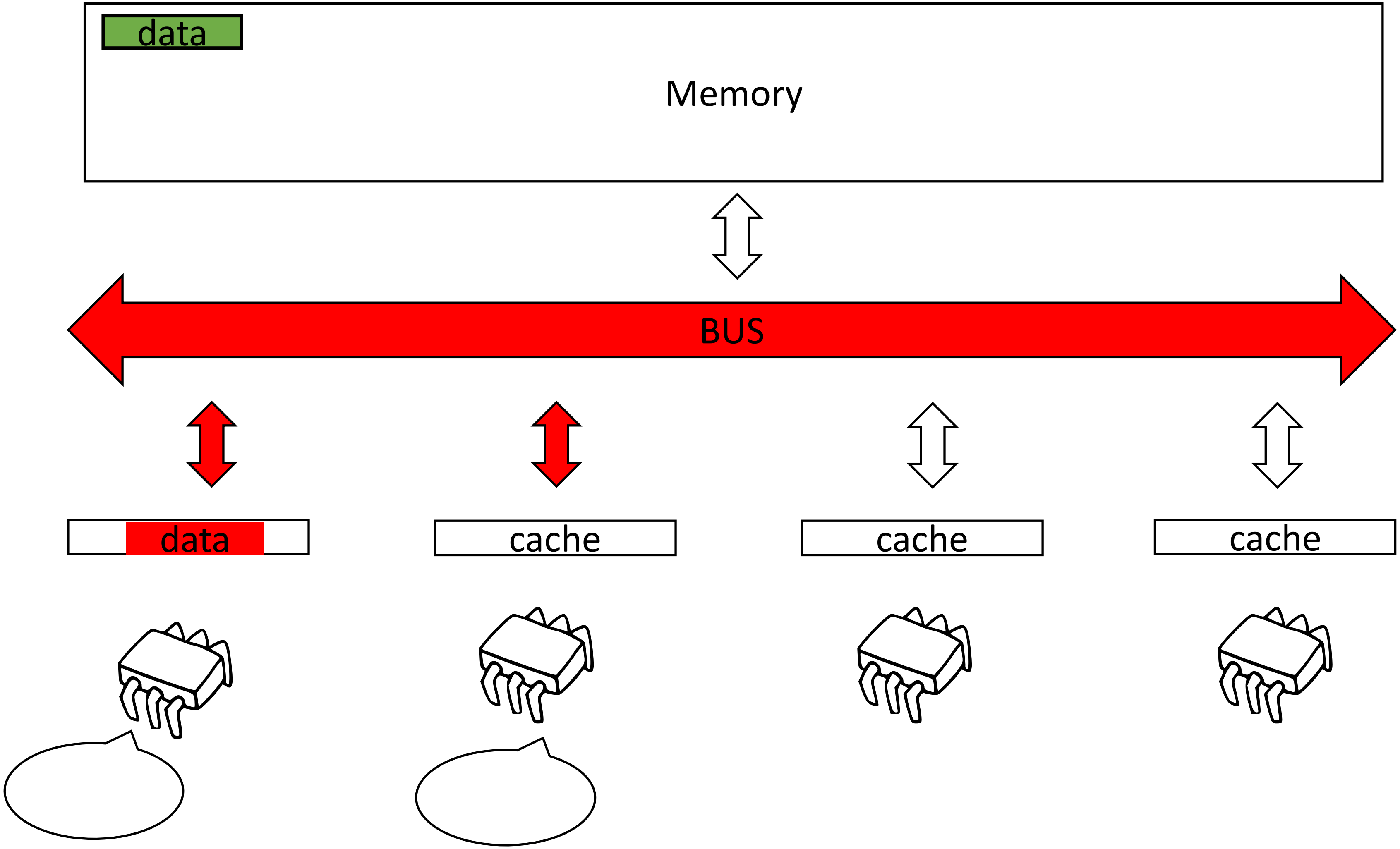

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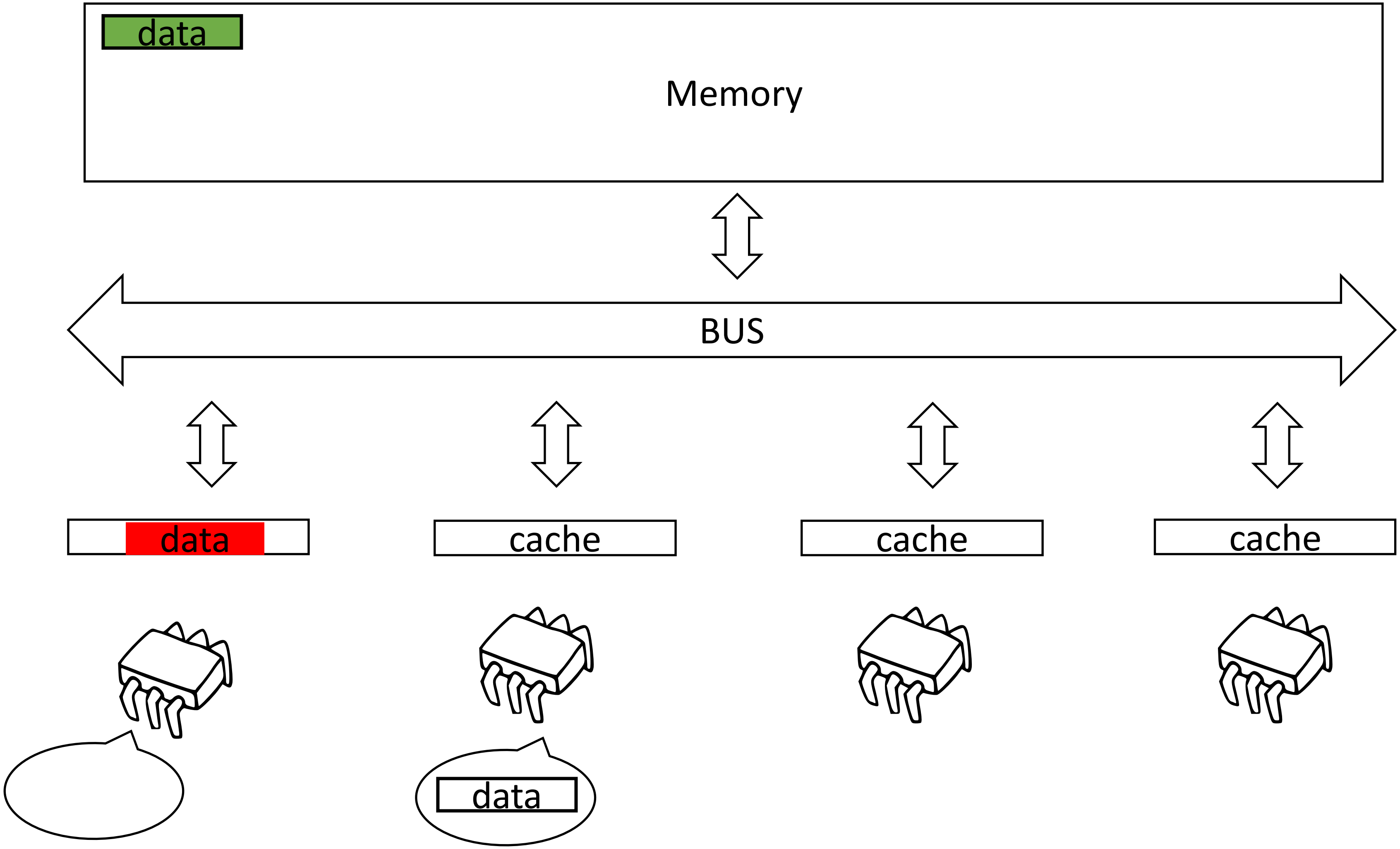

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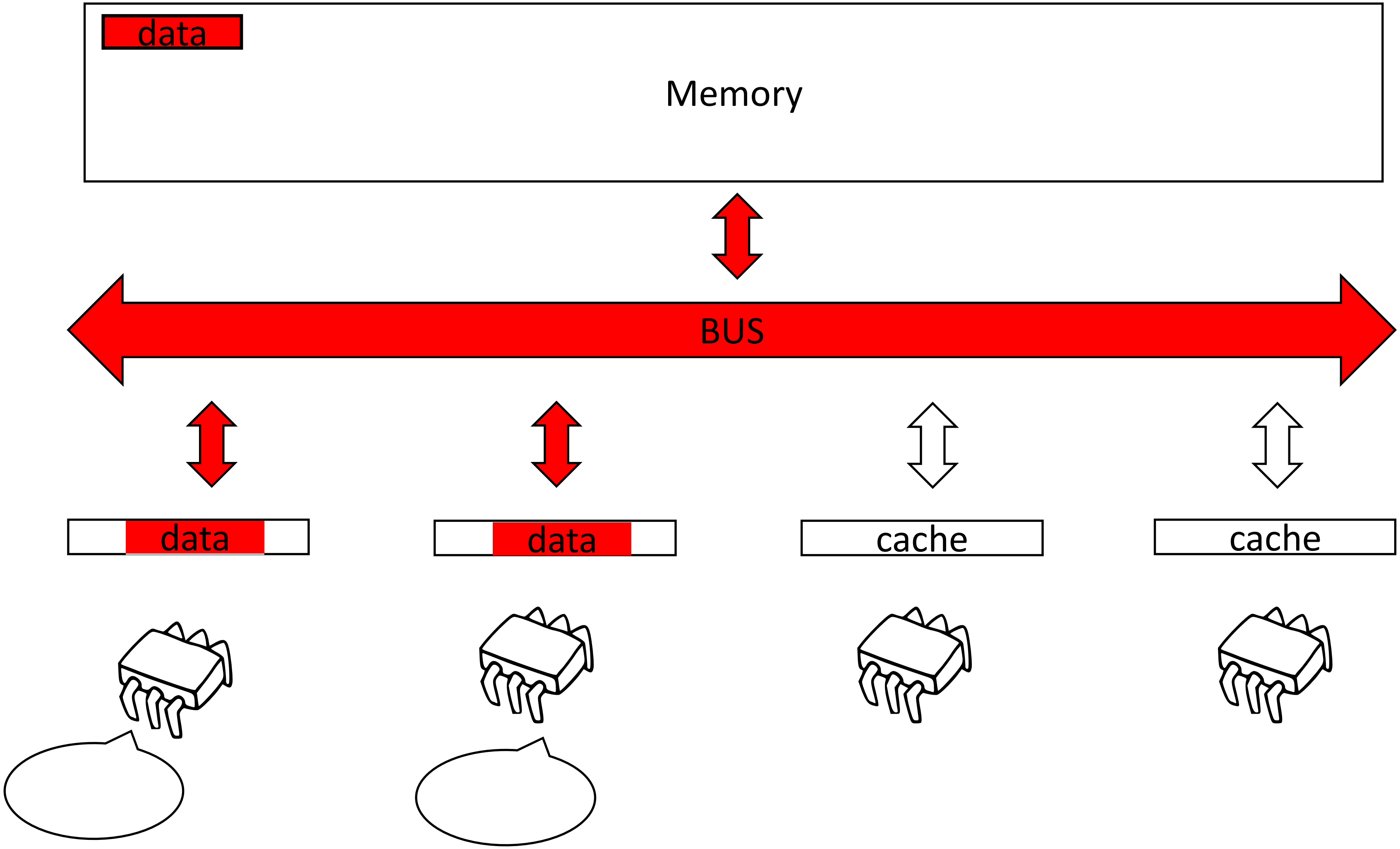

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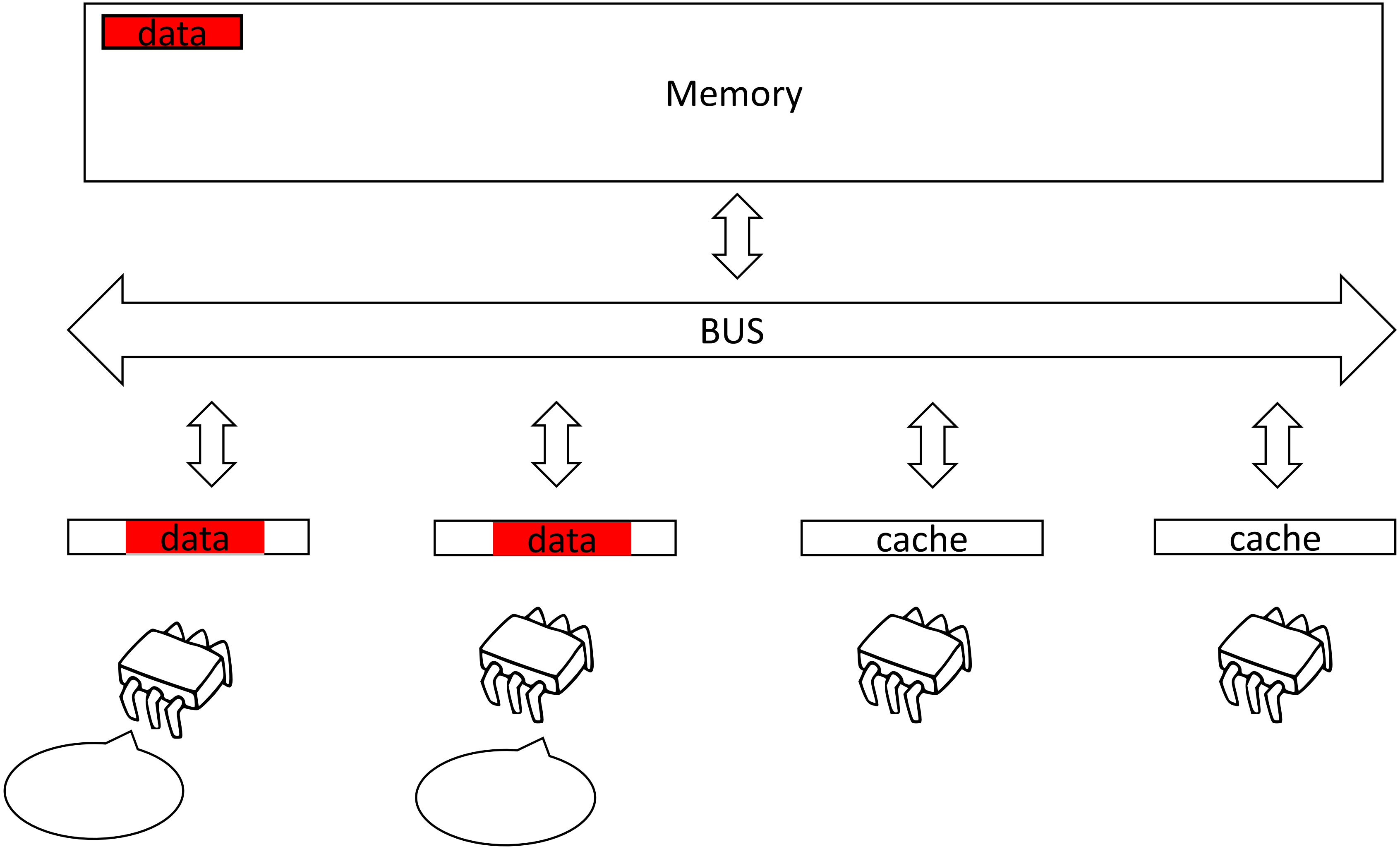

# Test-and-set spin lock

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- Acquiring threads always try to set a variable via RMW

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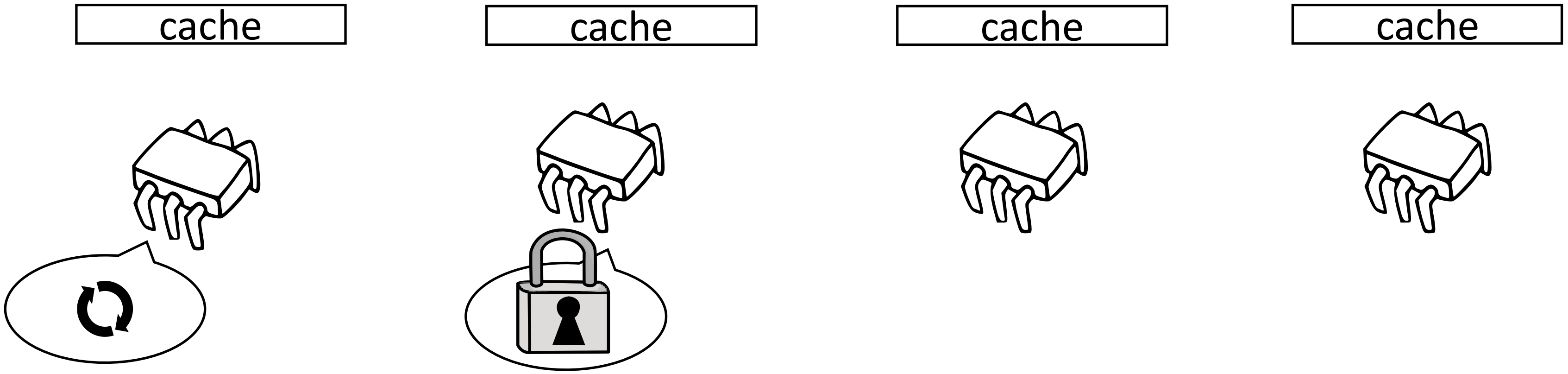

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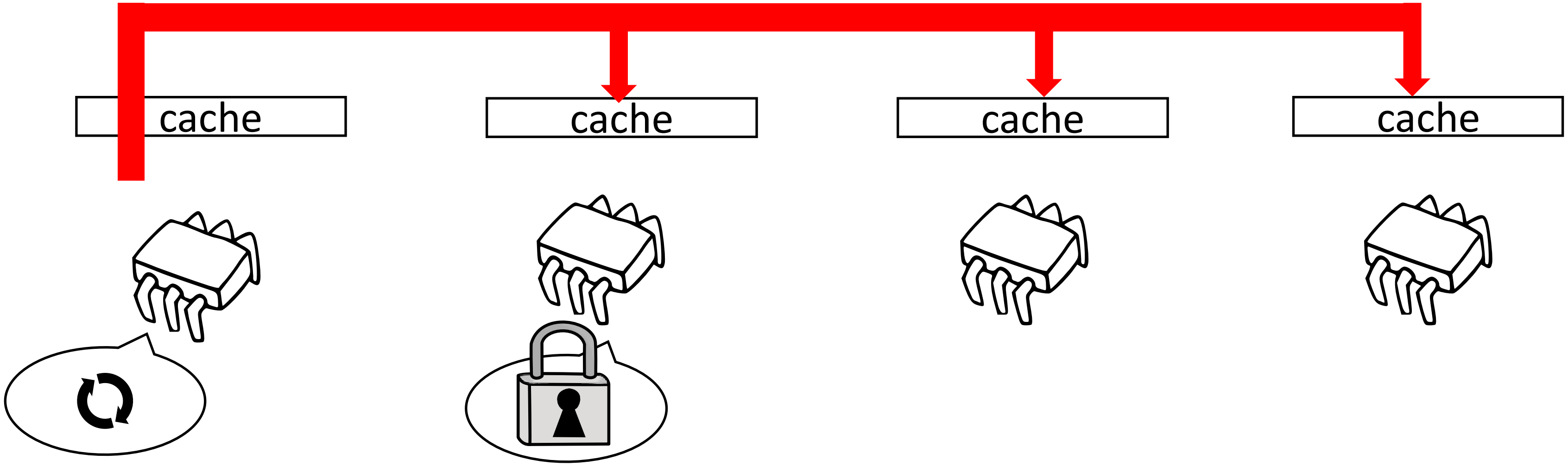

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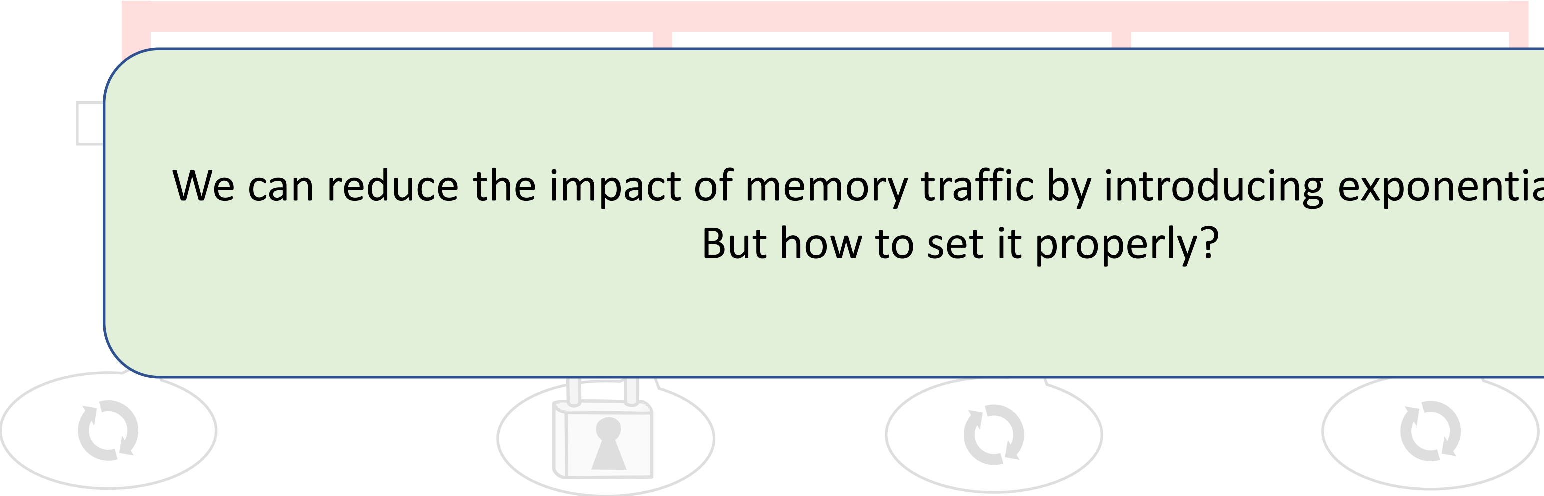

We can reduce the impact of memory traffic by introducing exponential back off!
But how to set it properly?

# Test-and-test-and-set spin lock

- Like test-and-set, but spins by reading the value of the lock
- Traffic is generated only upon lock handover

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int lock = 0;
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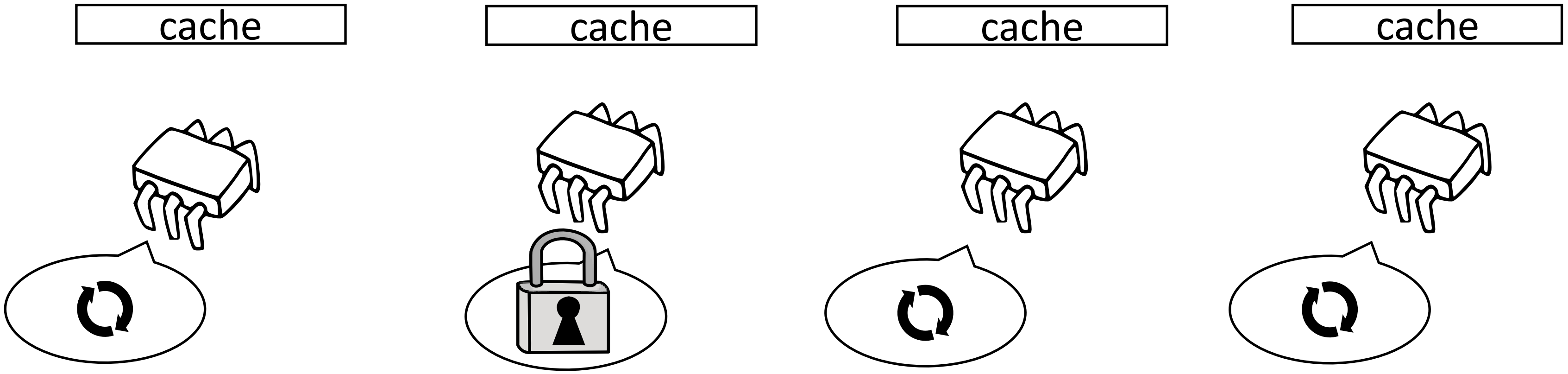

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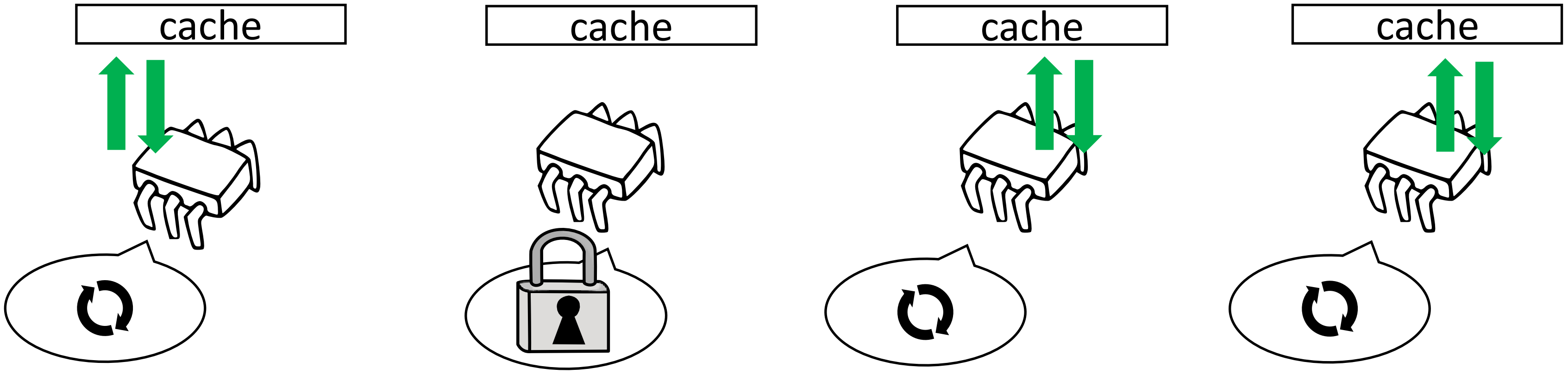

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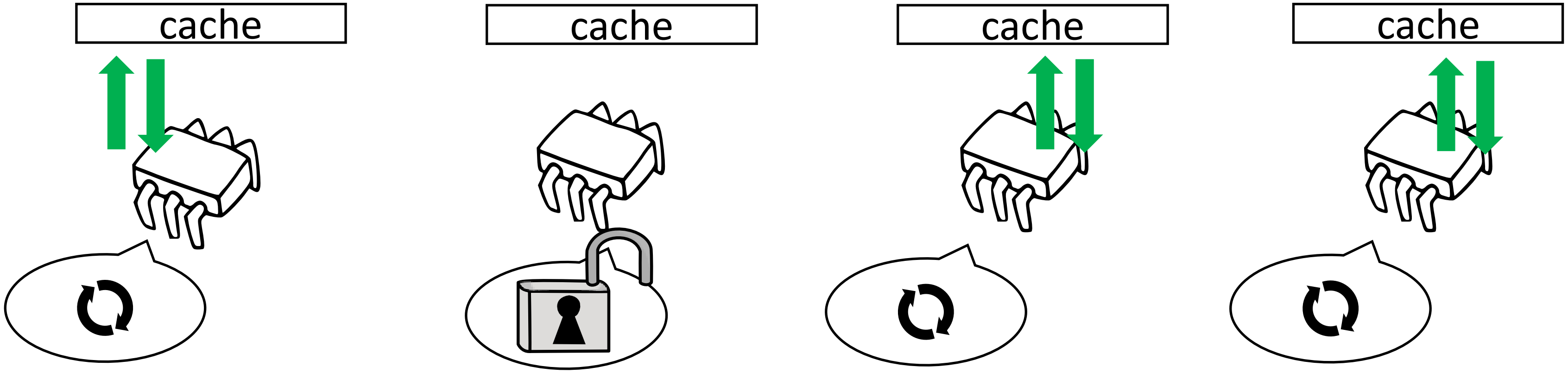

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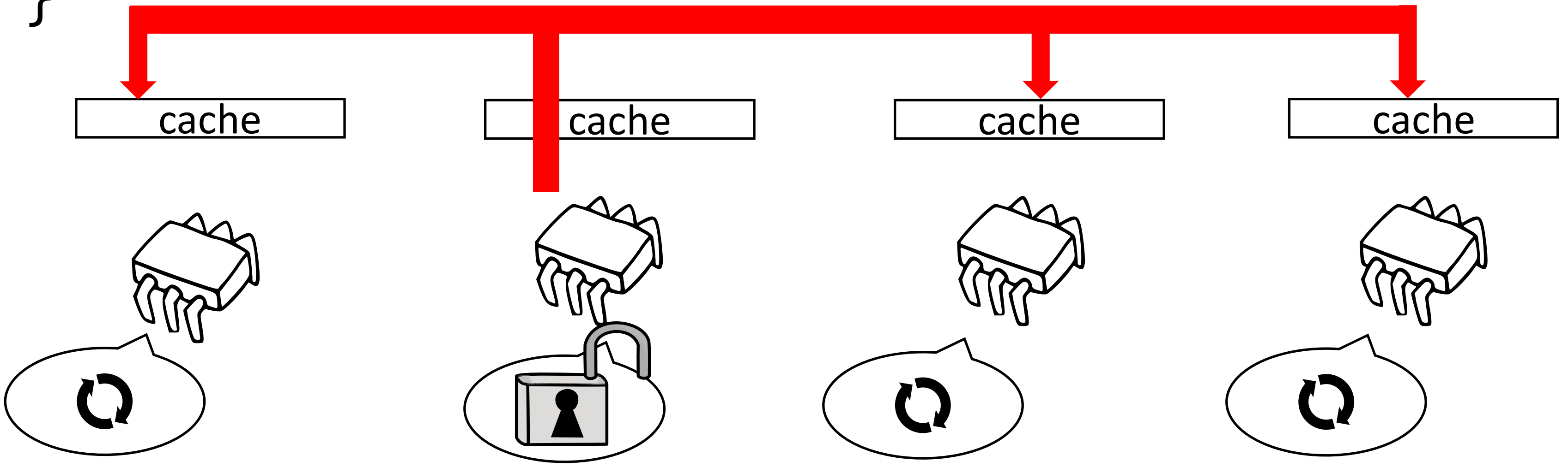

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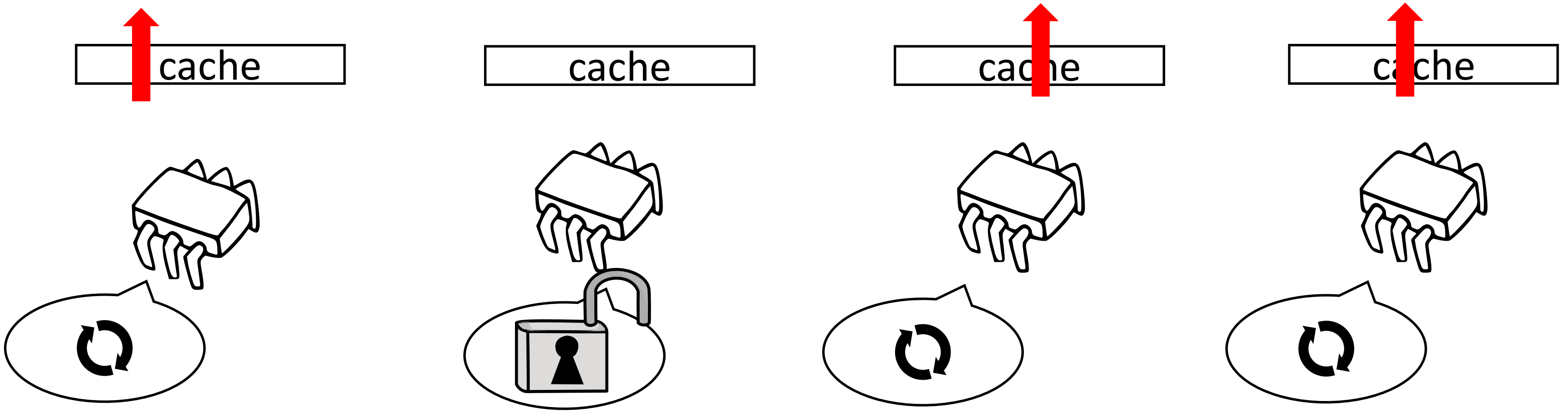

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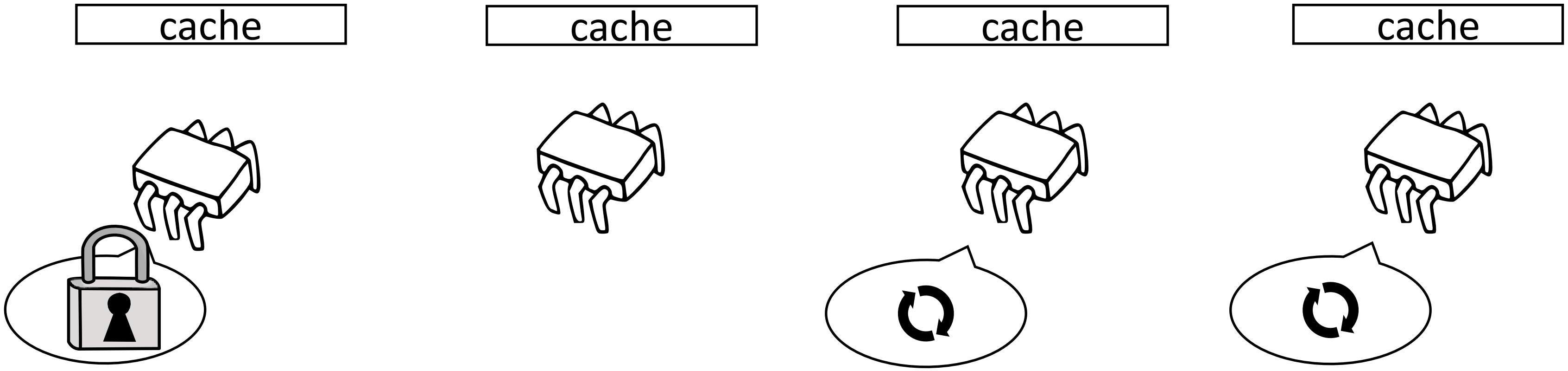
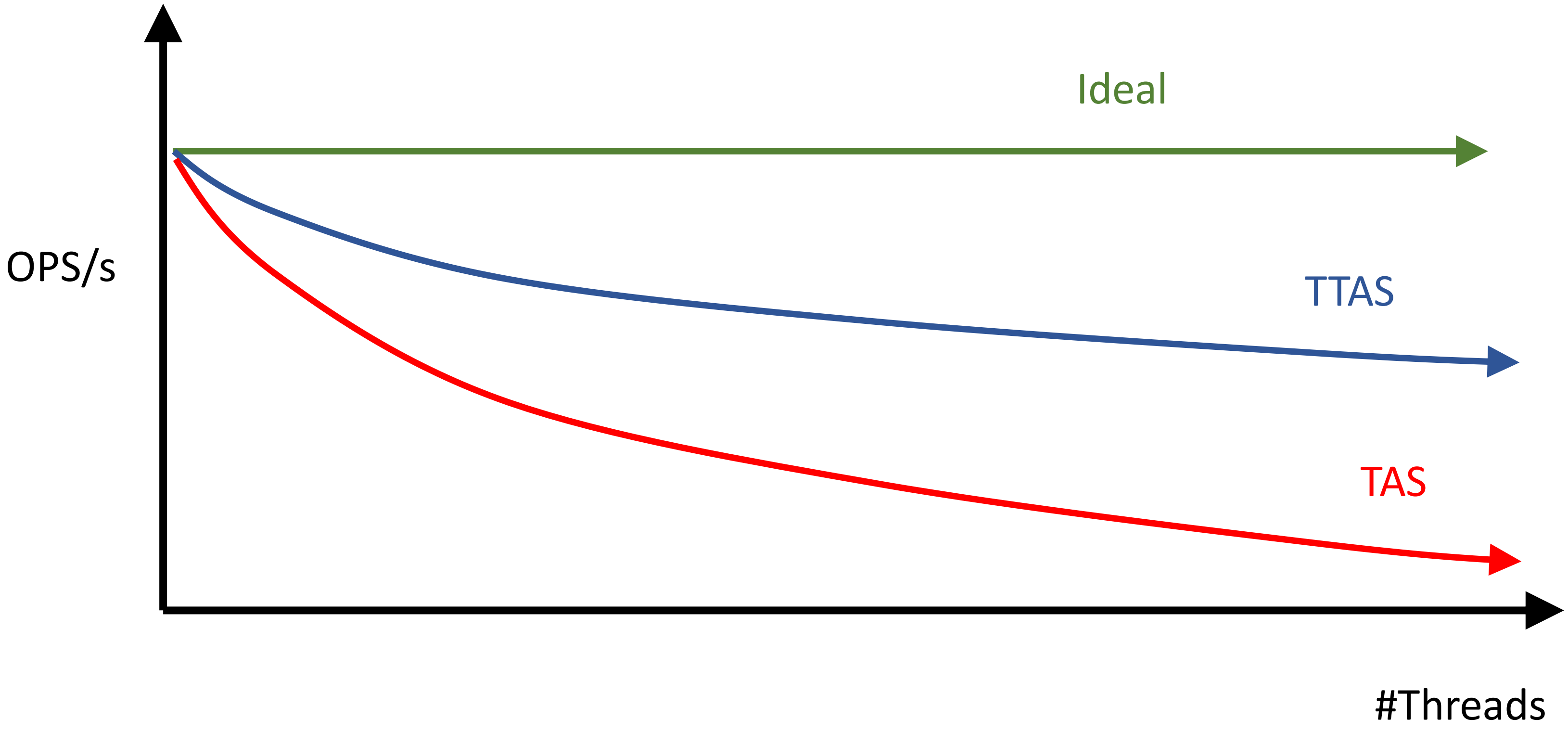


# Results



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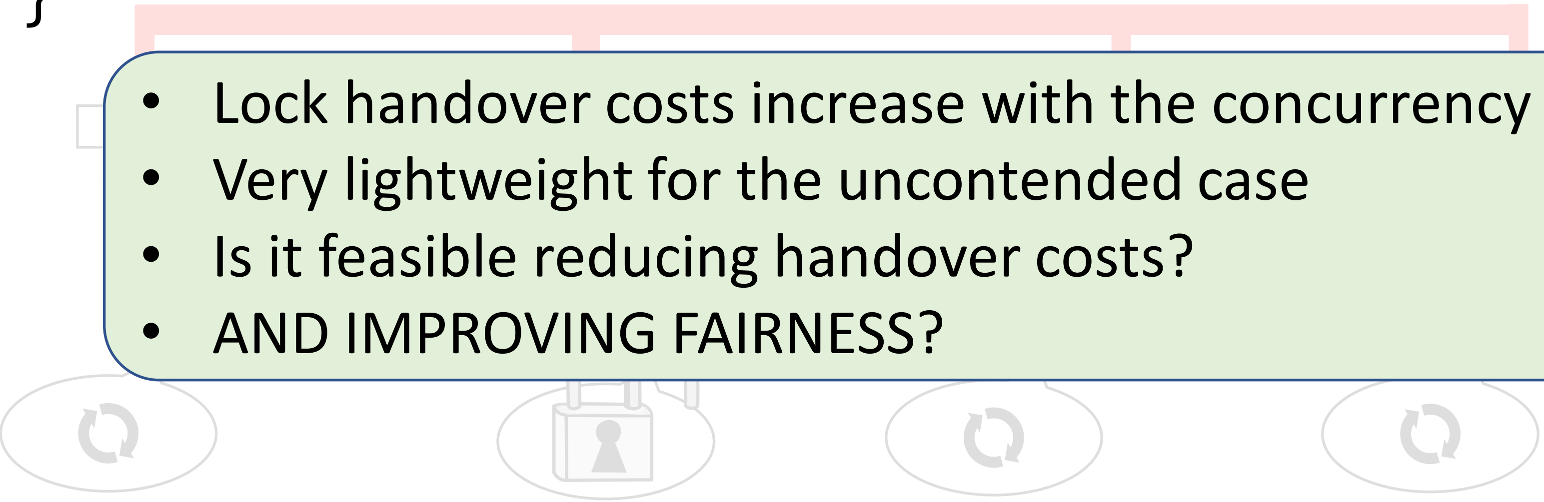


- Lock handover costs increase with the concurrency level
- Very lightweight for the uncontended case
- Is it feasible reducing handover costs?
- AND IMPROVING FAIRNESS?

# FIFO locks

# Ticket locks

- Similar to the bakery algorithm but it uses RMW instructions
- Two variables
  - The next available ticket
  - The served ticket

```
typedef struct _tck_lock{
  int ticket  = 0;

  int current = 0;

} tck_lock;
```

```
void acquire(tck_lock *lock){
   int cur_tck;
   int mytck = fetch&add(lock->ticket, 1);
   while(mytck != (cur_tck = lock->current) )
      delay((mytck-cur_tck)*BASE);
}
void release(tck_lock *lock){ lock->current += 1; }
```

# Ticket locks

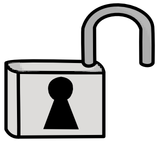
- Ensure fairness
- Similar structure w.r.t. TTAS spinlock
  - One variable updated once at each acquisition (better than TTAS)
  - Write-1-Read-N variable updated at each release (same as TTAS)
- How?

# Anderson queue lock

- Use similar to ticket lock
- Use the ticket to obtain an individual cache line

Ticket = 0

| | | | |
|---|---|---|---|
| 0 | 1 | 1 | 1 |



# Anderson queue lock

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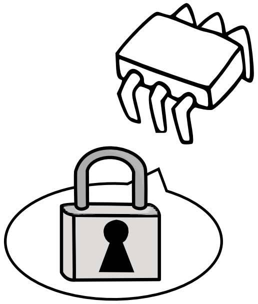
Ticket = ~~0~~ 1

|   |   |   |   |
|---|---|---|---|
| 0 | 1 | 1 | 1 |



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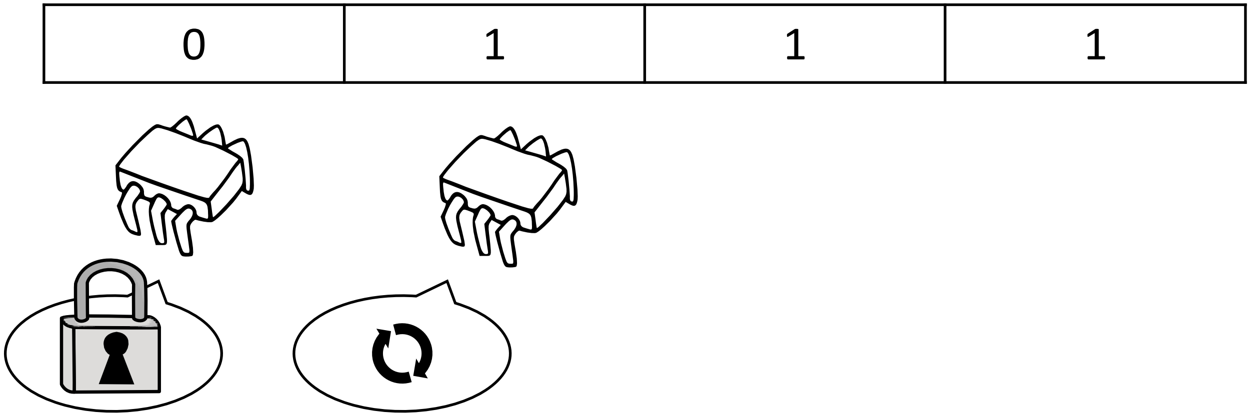
Ticket = ~~0~~ ~~1~~ 2



| | | | |
|---|---|---|---|
| 0 | 1 | 1 | 1 |

# Anderson queue lock

- Use similar to ticket lock
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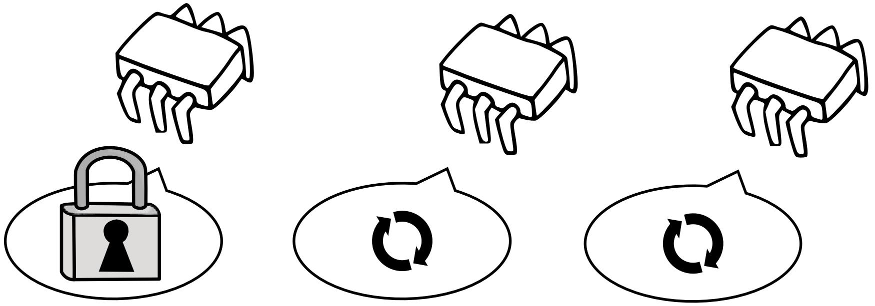
Ticket = ~~0 1 2~~ 3

| | | | |
|---|---|---|---|
| 0 | 1 | 1 | 1 |



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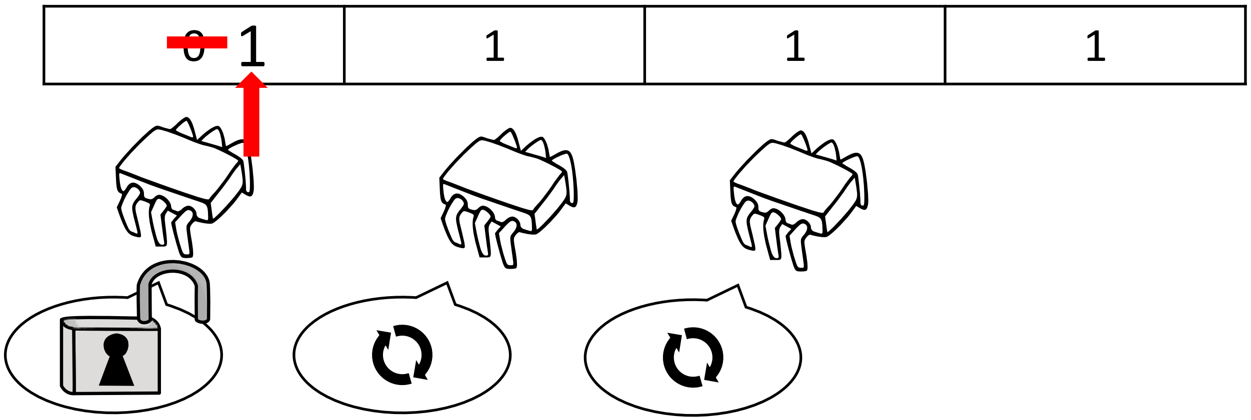

| ~~0~~ 1 | 1 | 1 | 1 |
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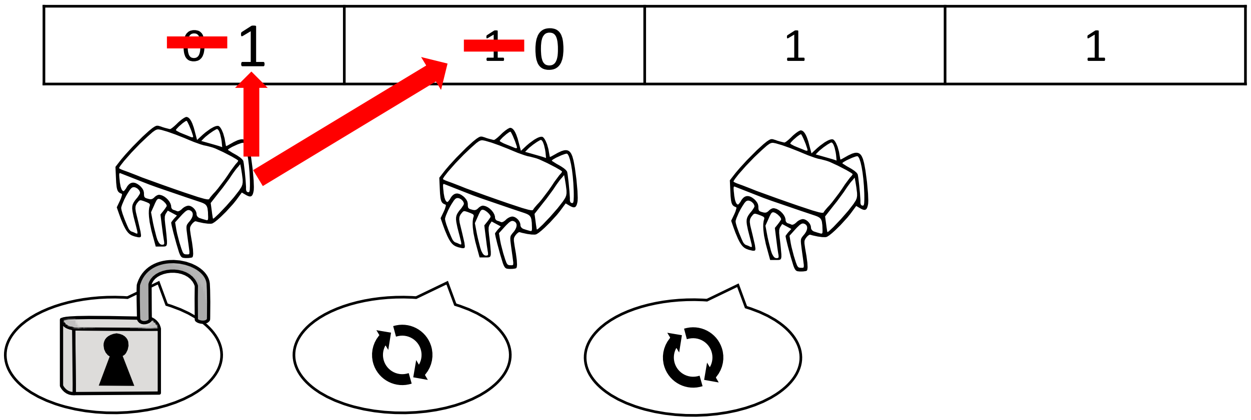

| | | | |
|---|---|---|---|
| ~~0~~ 1 | ~~1~~ 0 | 1 | 1 |

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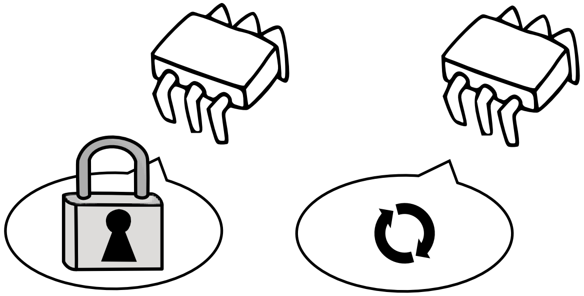

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  mytck = fetch&add(lock->ticket, 1);
  while(lock->array[mytck]);
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```
void release(int *lock){
 lock->array[mytck+1] = 0;
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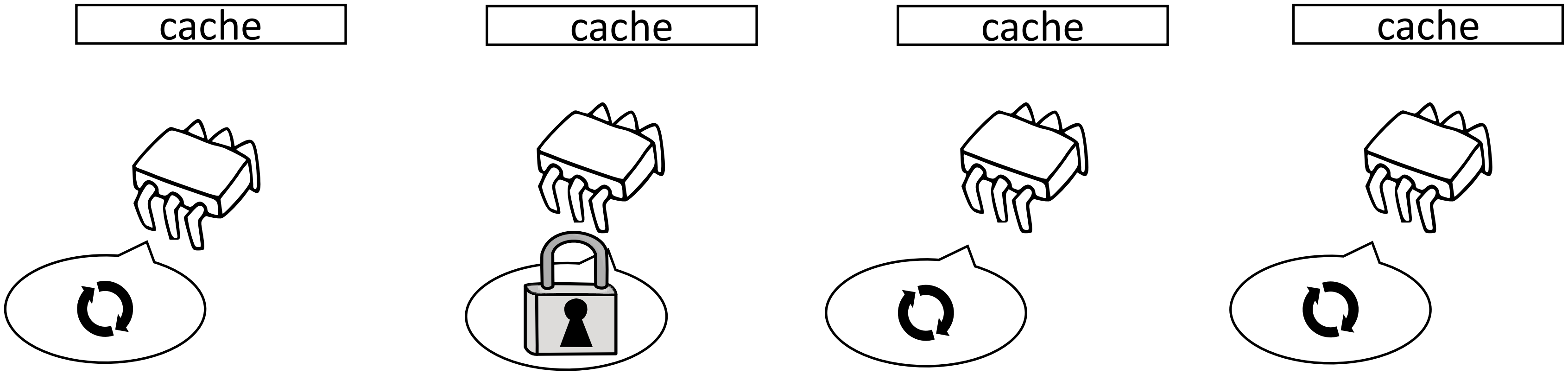
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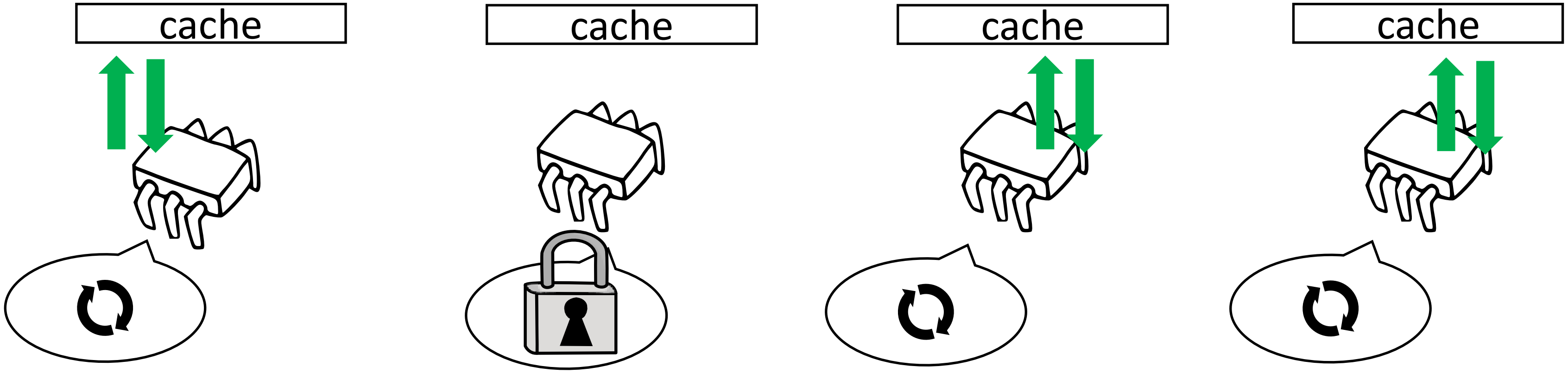

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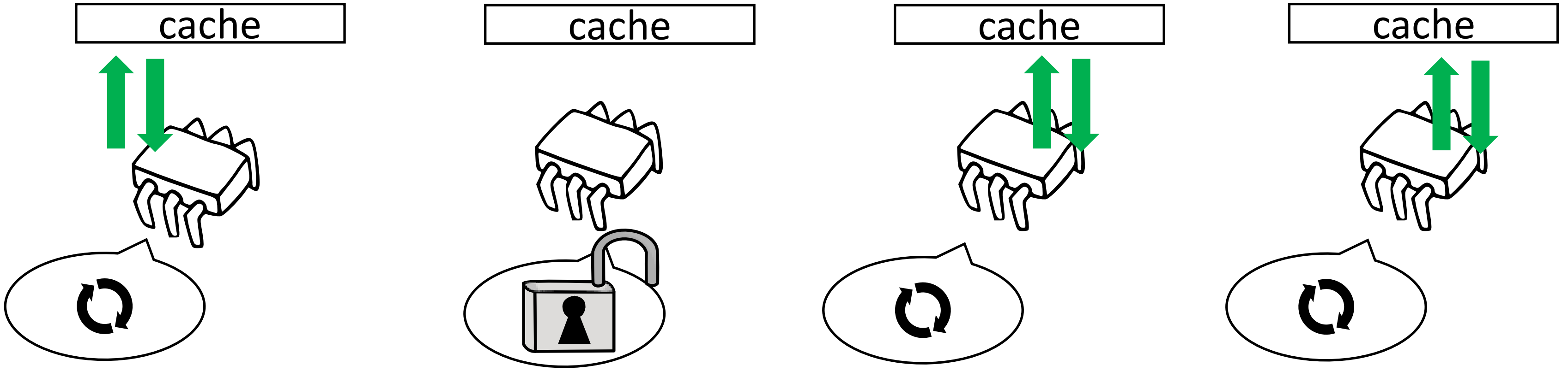

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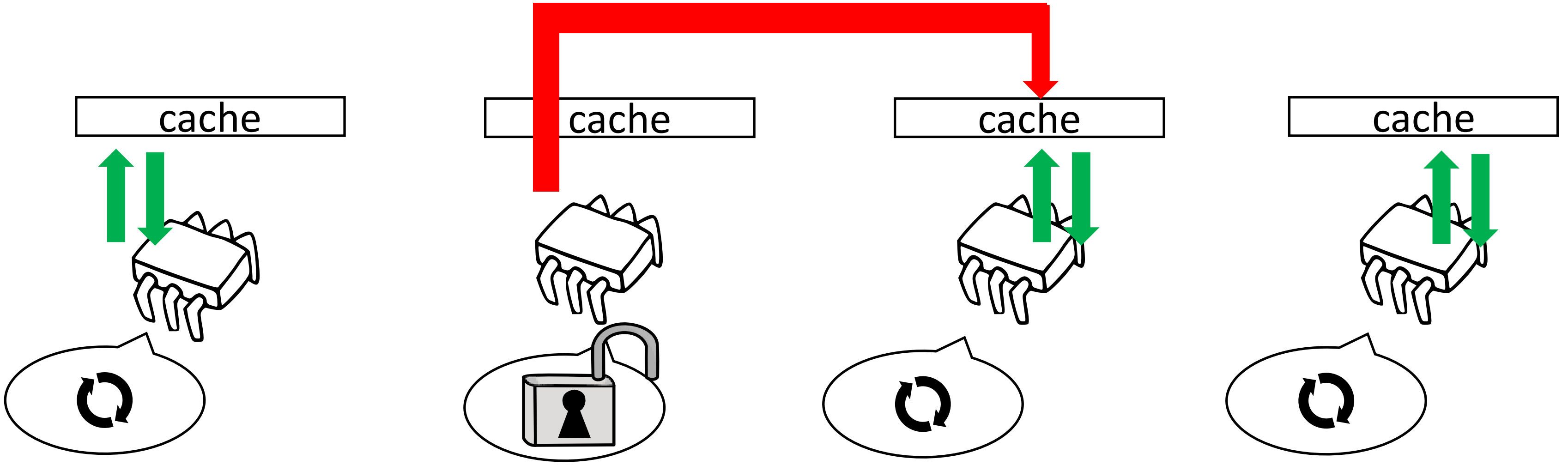

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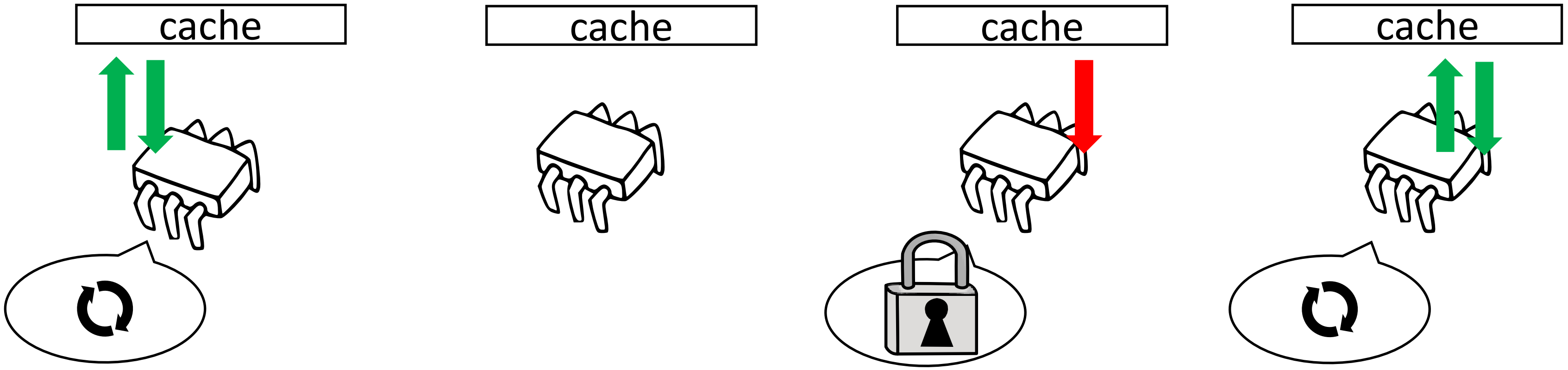
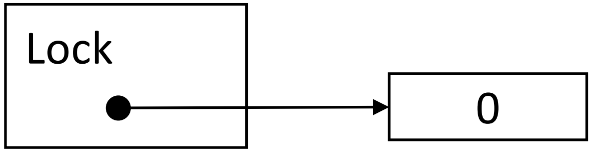


# Anderson queue lock

- Pros:
  - One variable updated once at each acquisition (like Ticket lock)
  - Write-1-Read-1 variable updated once per release (better than (T)TAS and Ticket)
- Cons:
  - Increased memory footprint
  - Each lock needs to know the maximum number of threads
- Let:
  - T be the number of threads
  - L be the number of locks
- Space Usage
  - Anderson = O(LT)
  - TAS, TTAS, Ticket = O(L)

# CLH lock

- An (implicit) linked list maintains the order between waiting threads
- An empty list represent an uncontended lock
- An arriving thread swaps the node with its private node
- Spin on the previous node
- Release on the new node



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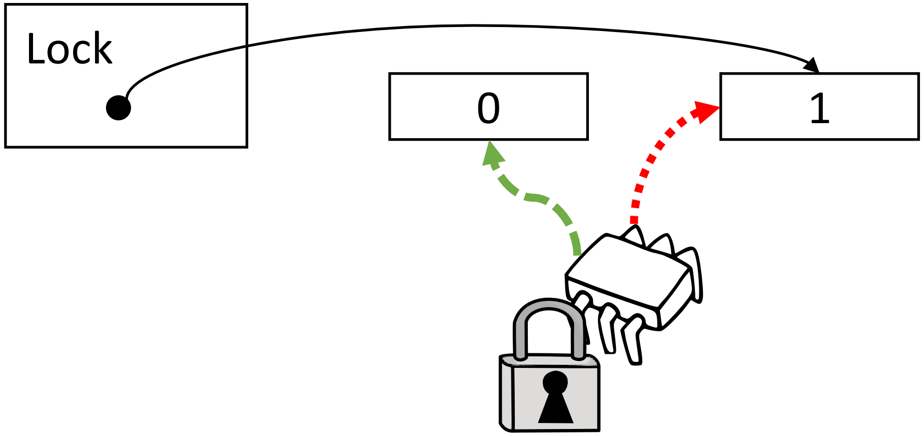

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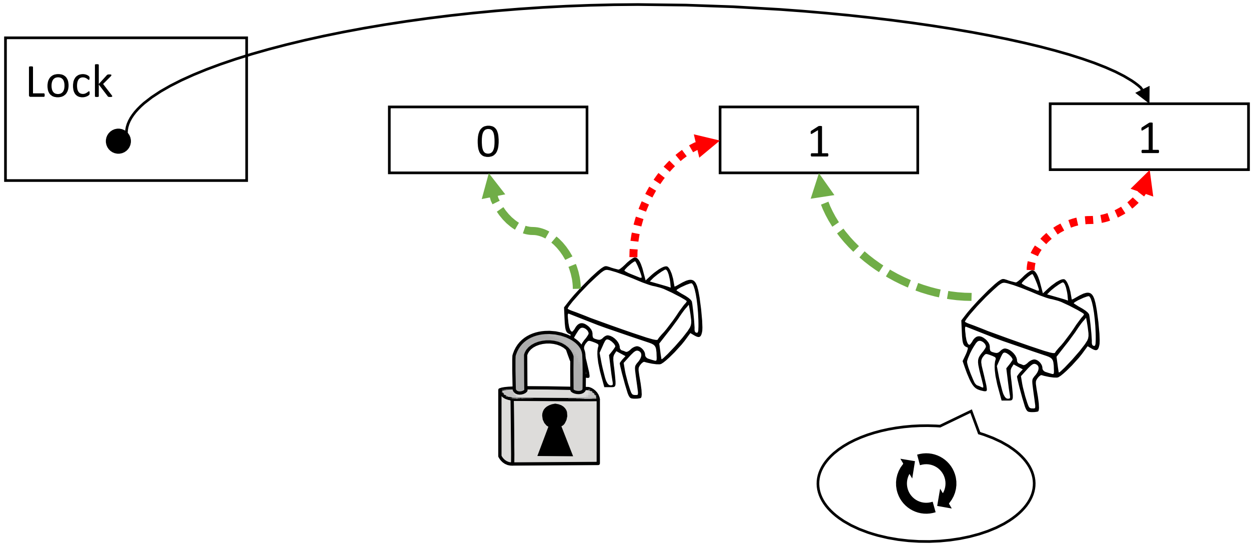

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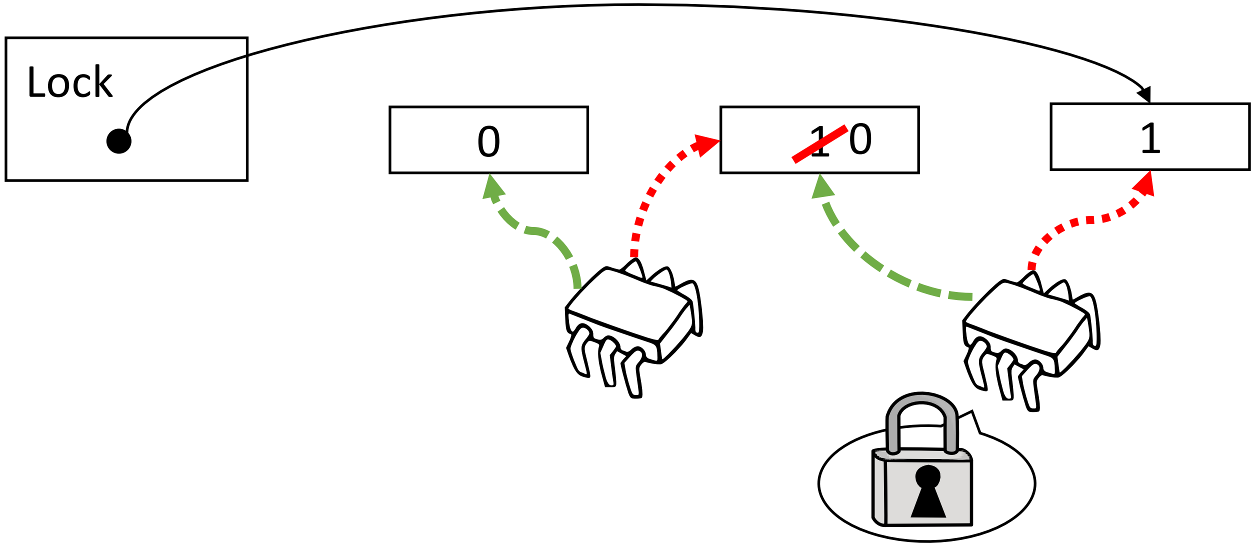

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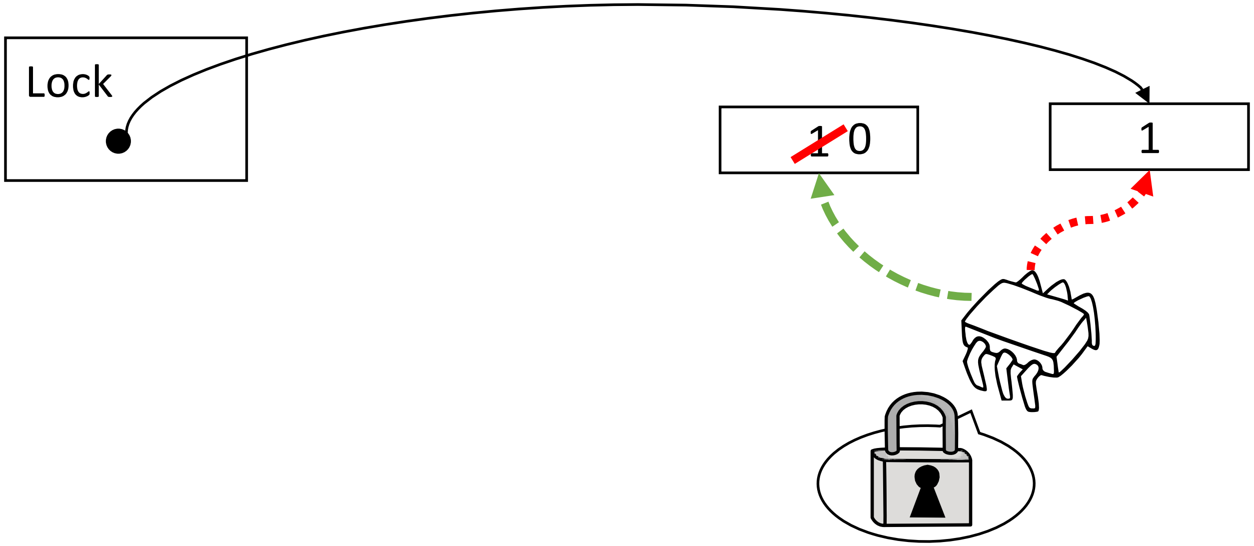

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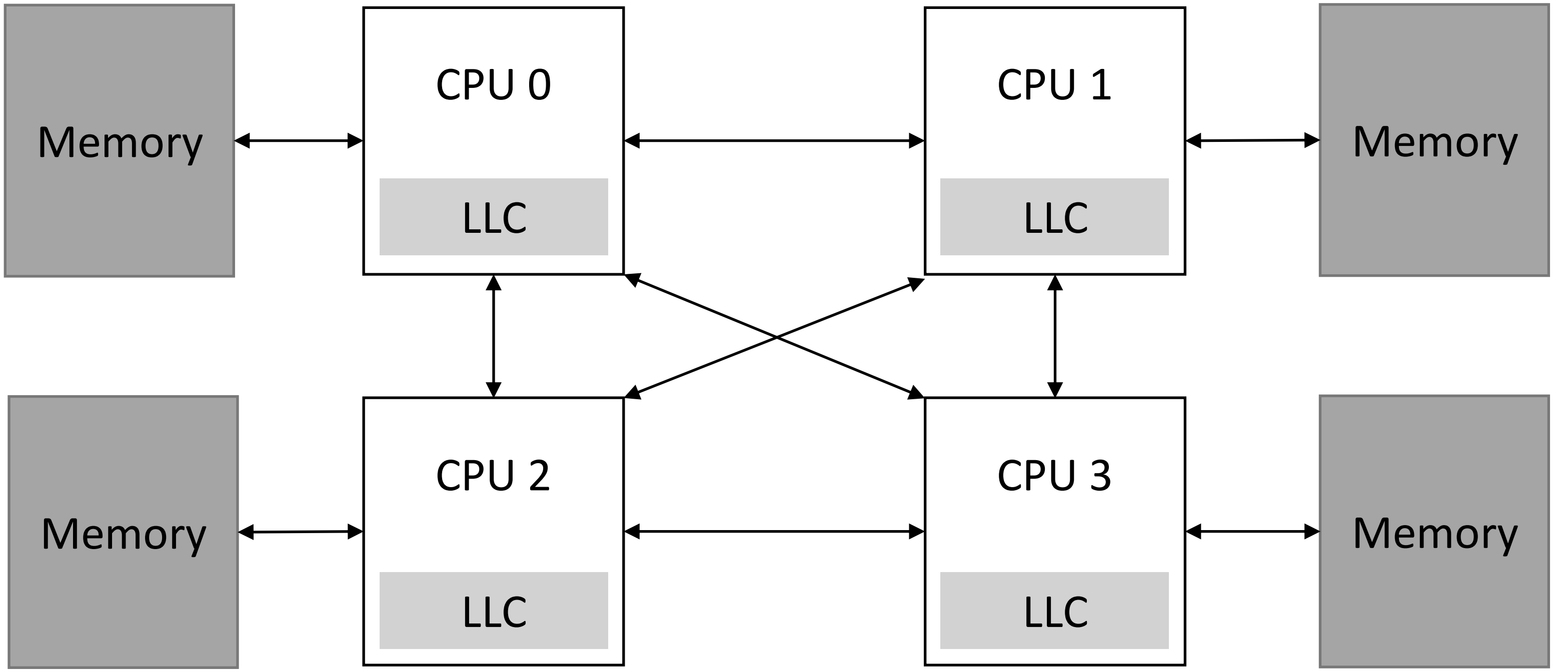
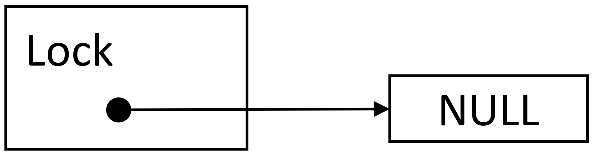
- Pros:
  - One variable updated once at each acquisition (like Ticket lock)
  - Write-1-Read-1 variable updated once per release (better than (T)TAS and Ticket)
- Cons:
  - Slightly increased memory footprint
- Let:
  - T be the number of threads
  - L be the number of locks
- Space Usage
  - CLH = O(L+T)
  - Anderson = O(LT)
  - TAS, TTAS, Ticket = O(L)

# NUMA


Memory
CPU 0
LLC
CPU 1
LLC
Memory
Memory
CPU 2
LLC
CPU 3
LLC
Memory

# MCS lock

- An explicit linked list maintains the order between waiting threads
- An empty list represent an uncontended lock
- An arriving thread swaps the node with its private node
- Spin on the just inserted node
- Release on the new node



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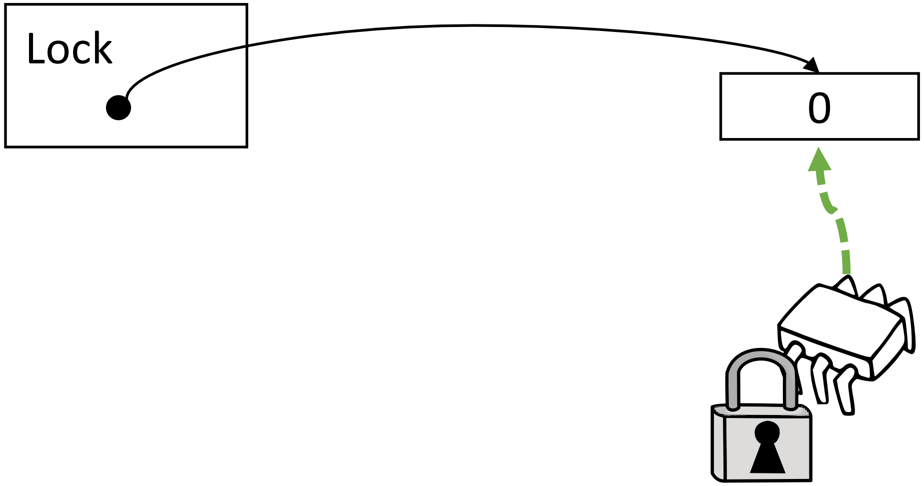

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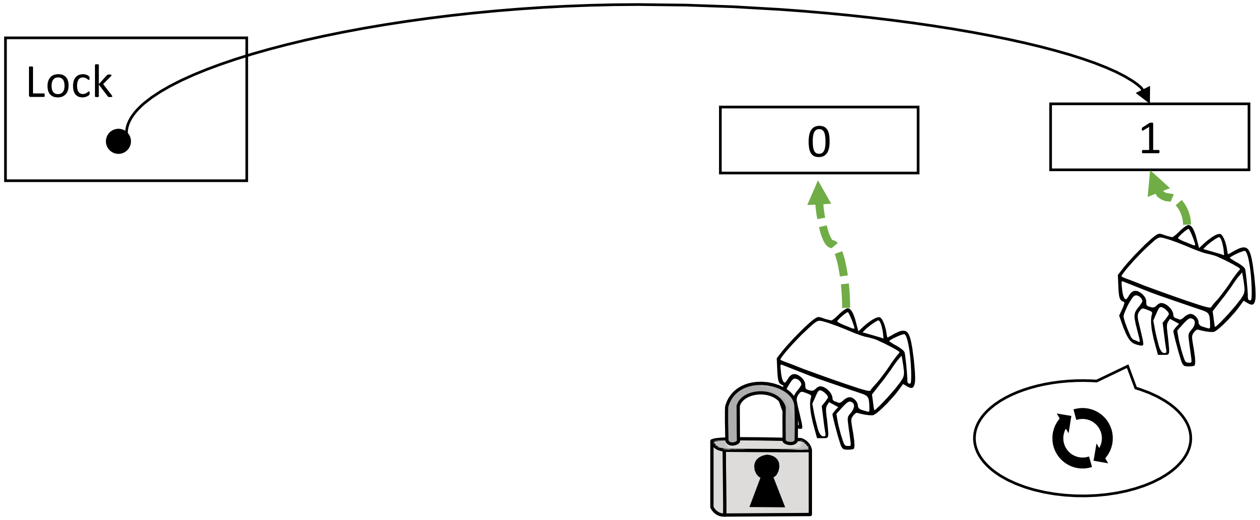

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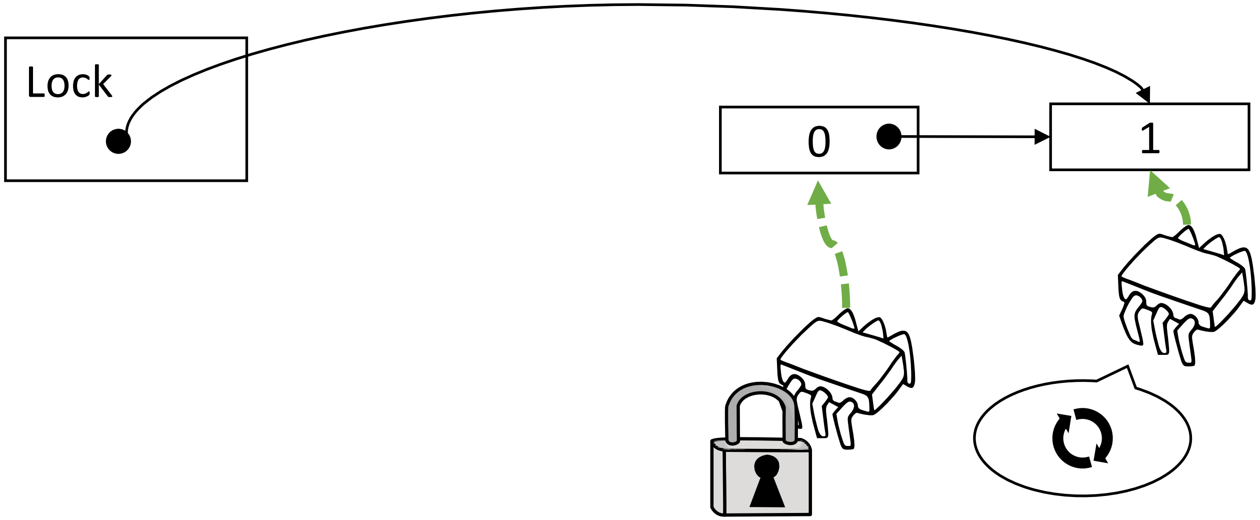

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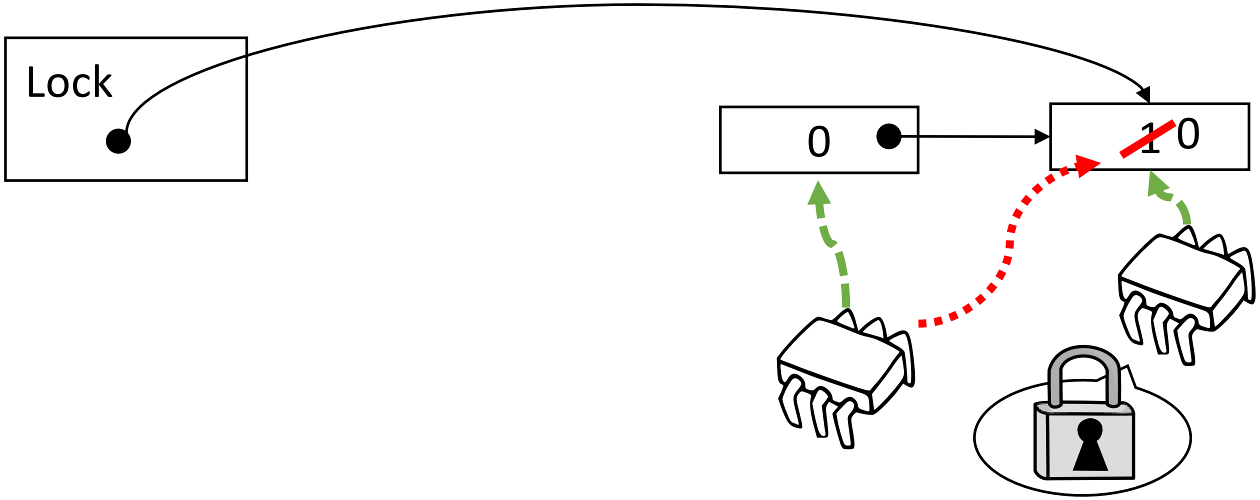

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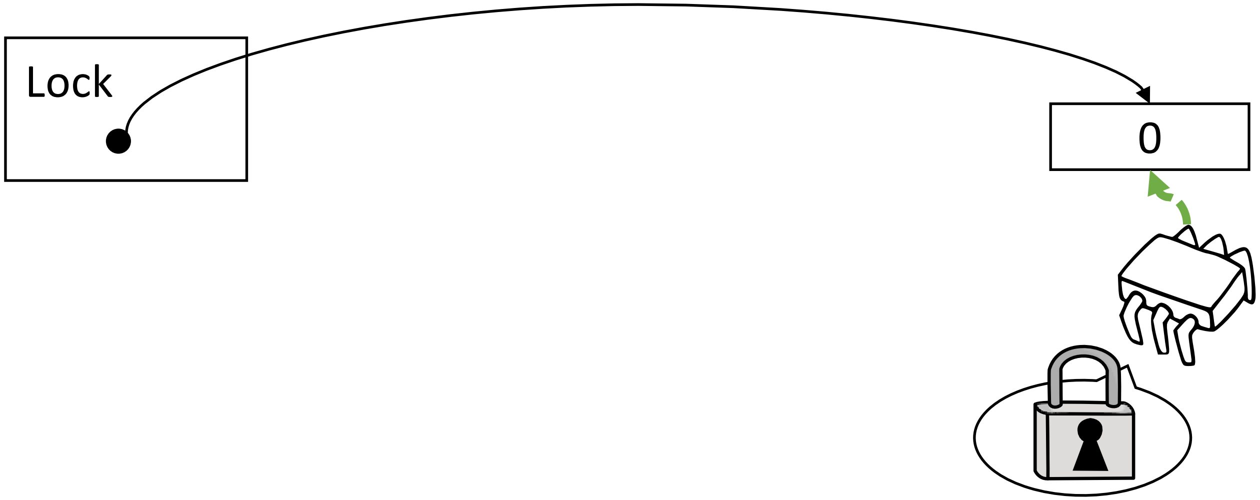

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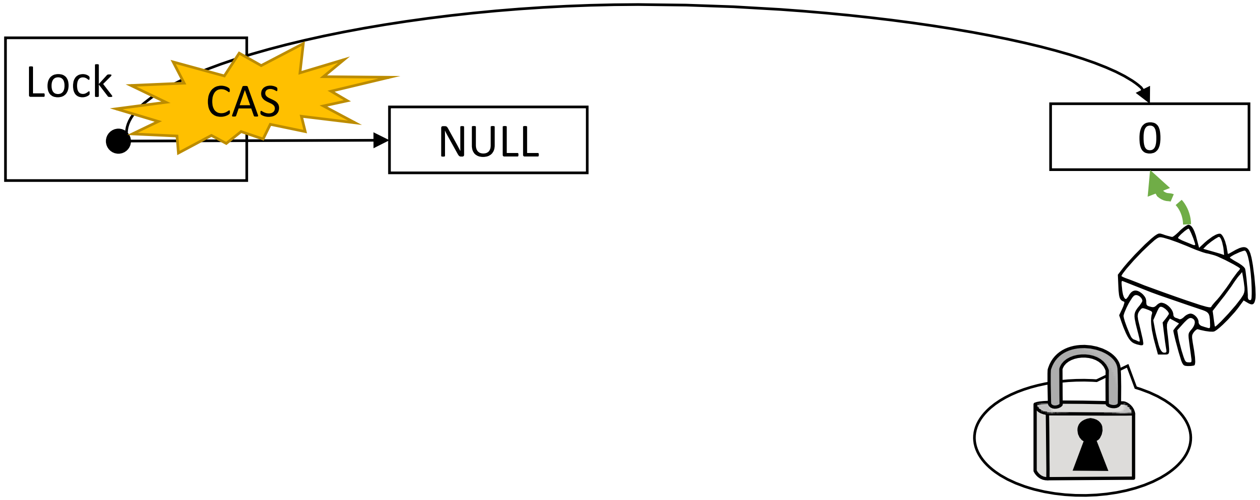

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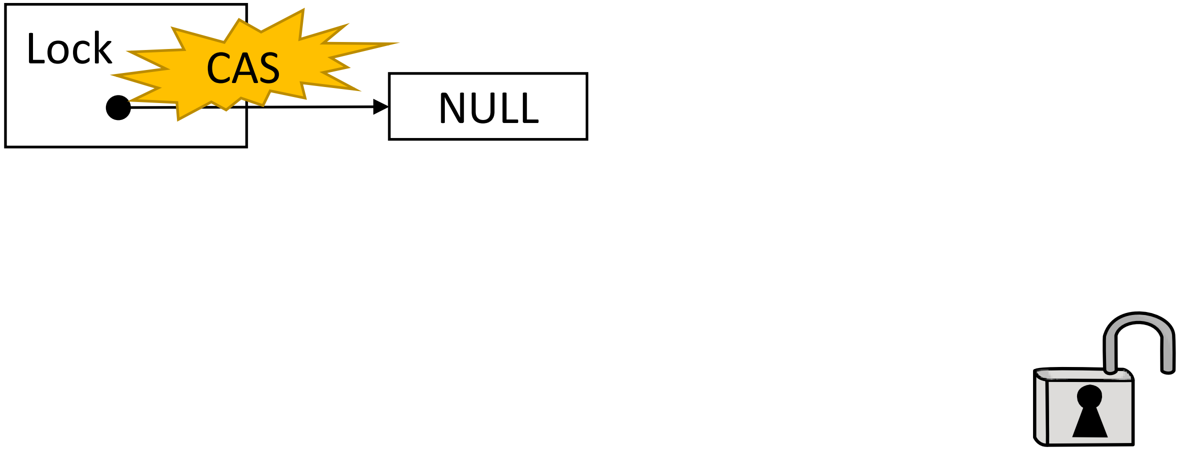
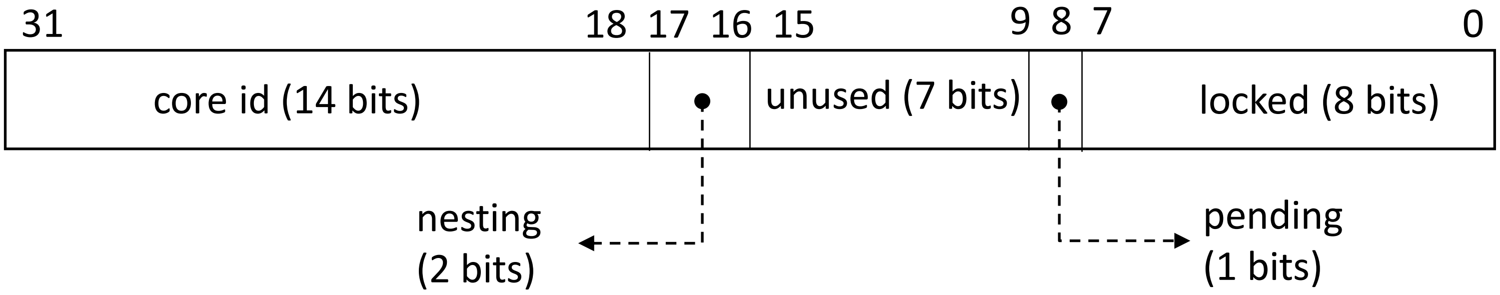


# MCS queue lock

- Pros:
  - One variable updated once at each acquisition (like Ticket lock)
  - Write-1-Read-1 variable updated once per release (better than (T)TAS and Ticket)
  - No-remote spinning
- Cons:
  - Slightly increased memory footprint
- Let:
  - T be the number of threads
  - L be the number of locks
- Space Usage
  - MCS, CLH = O(L+T)
  - Anderson = O(LT)
  - TAS, TTAS, Ticket = O(L)

# MCS in practice: the Linux kernel case

- The Linux kernel uses a particular implementation of a MCS lock: Qspinlock
- Additional challenge:
  - Maintain compatibility with classical 32-bit locks
  - MCS uses pointers (64-bit)
- Compact data:
  1. No recursion of same context in critical sections
  2. 4 different contexts (task, softirq, hardirq, nmi)
  3. Finite number of cores
- Use an additional bit for fast lock handover



31 18 17 16 15 9 8 7 0

core id (14 bits)

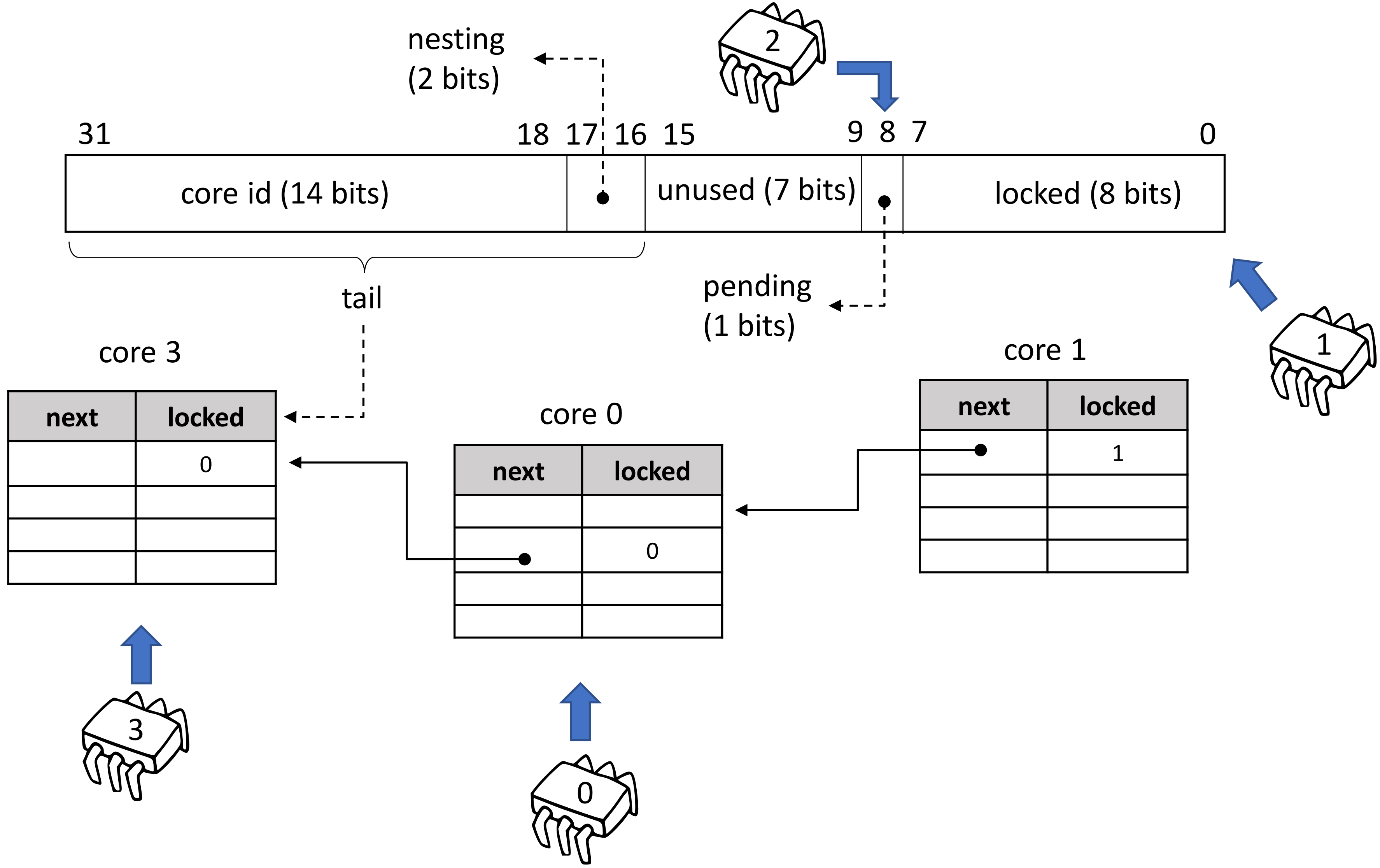
unused (7 bits)

locked (8 bits)

nesting (2 bits)

pending (1 bits)

# MCS in practice: the Linux kernel case



nesting
(2 bits)

2

31 18 17 16 15 9 8 7 0

core id (14 bits)

unused (7 bits)

locked (8 bits)

tail

pending
(1 bits)

core 3

| next | locked |
|---|---|
| | 0 |
| | |
| | |
| | |

core 0

| next | locked |
|---|---|
| | |
| ● | 0 |
| | |
| | |

core 1

| next | locked |
|---|---|
| ● | 1 |
| | |
| | |
| | |

1

3

0

# A small benchmark

- We have an array of integers
- Each thread reverse the array

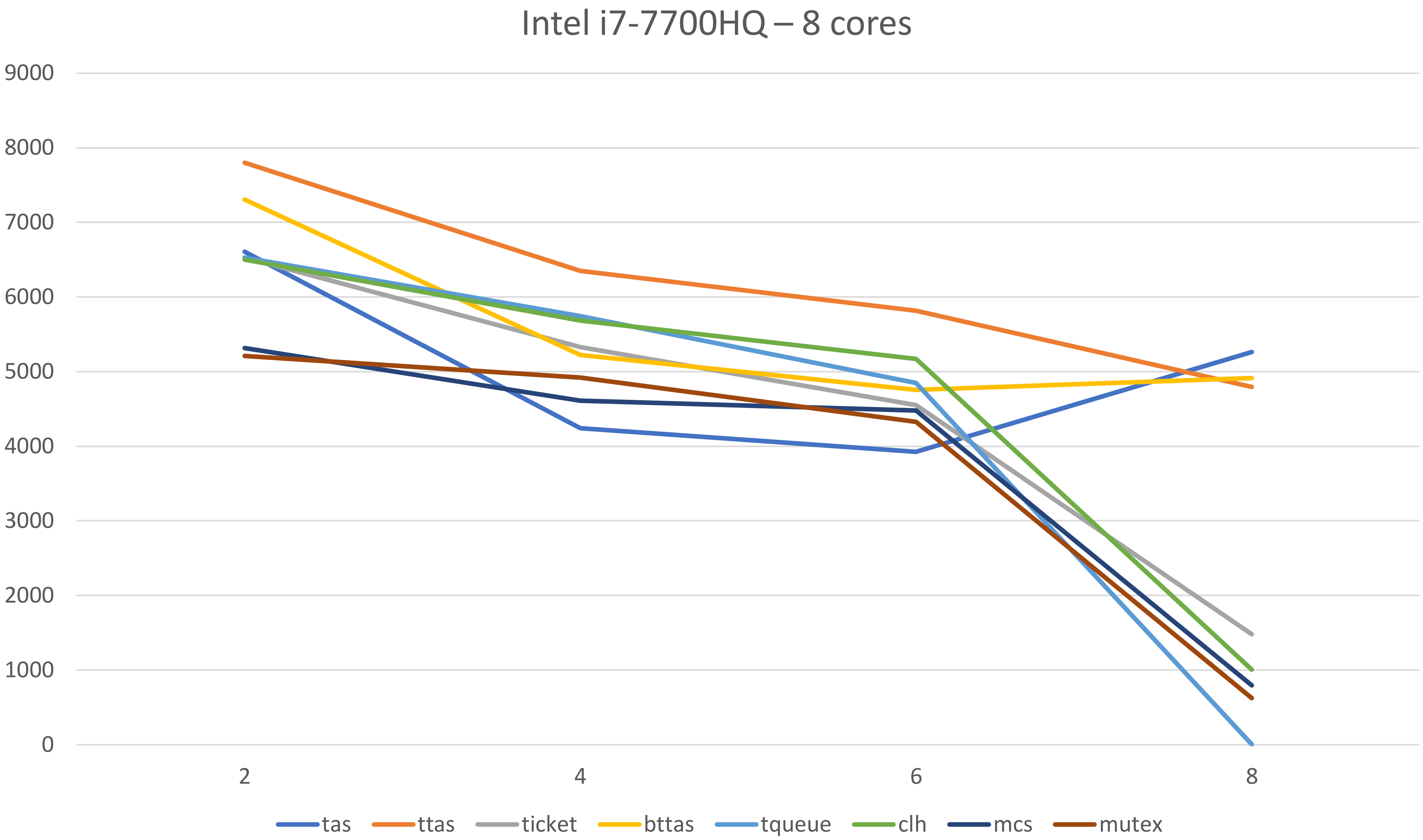
- This is done within a critical section

```
while(!stop){
  acquire(&lock);
  flip_array();
  release(&lock);
}
```

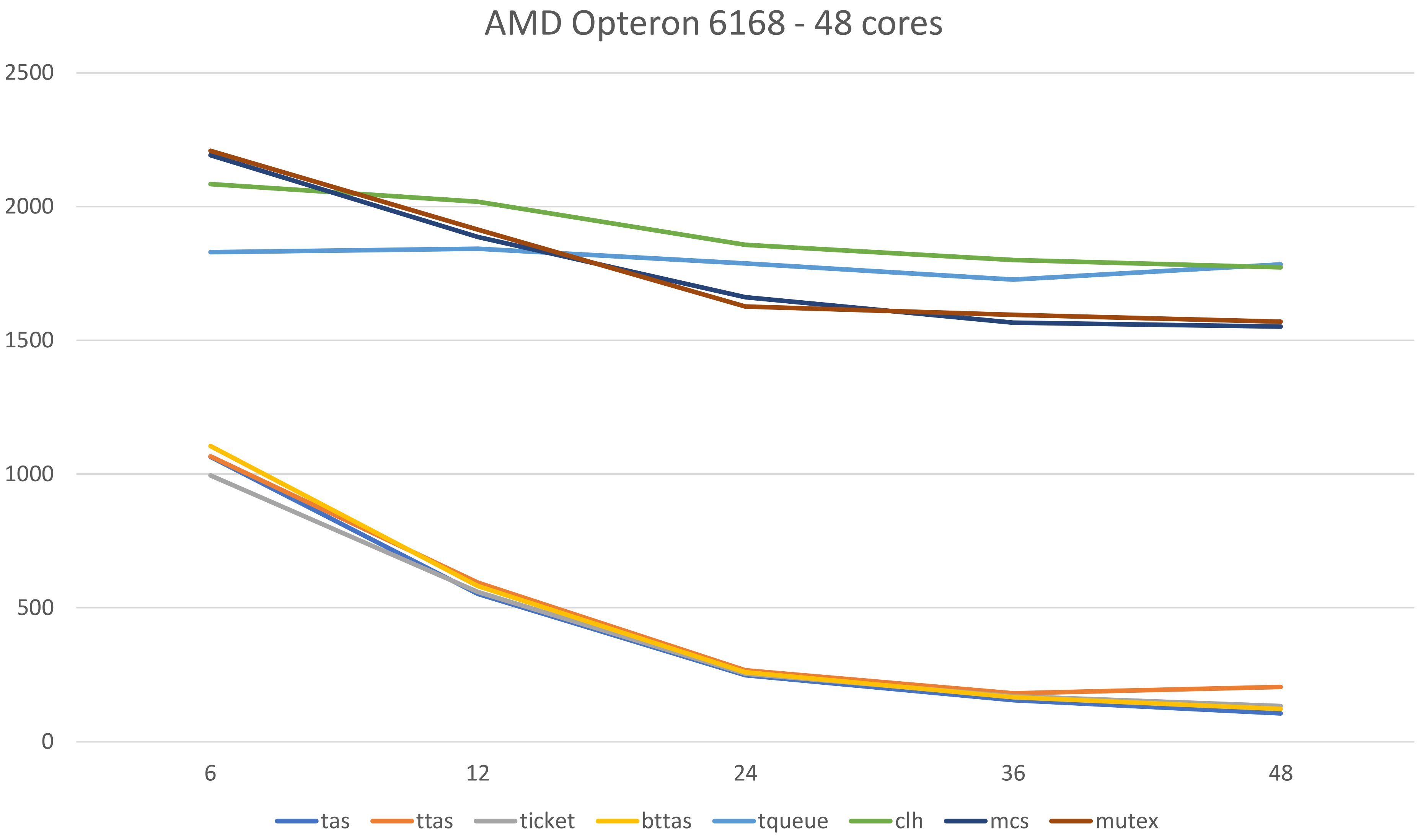
- Performance Metric:
  - Throughput = #Flips per second

# One lock
# to rule them all…

# Performance

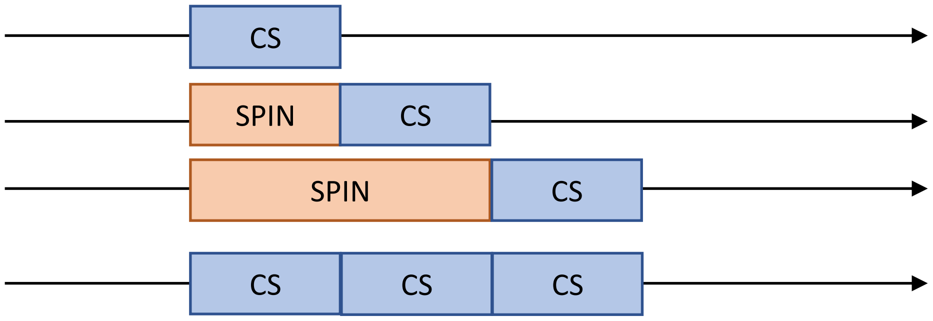


# Performance



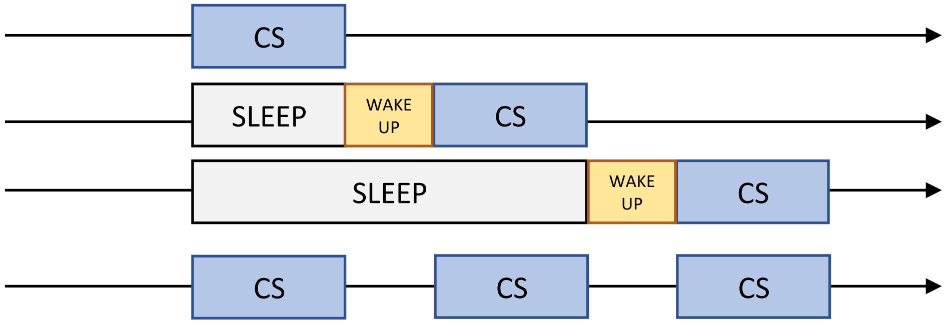
# At the beginning was… Spin vs Sleep

| | Waiting Policy | |
|---|---|---|
| **Benefits** | **Spinning** | **Sleeping** |
| Guaranteed low latency | ✓ | ✗ |
| Computing power savings | ✗ | ✓ |



SPIN:
++Waste of CPU Cycles
--Latency

Sleep:
--Waste of CPU Cycles
++Latency



# How to avoid costs for sleeping?

A general approach exists:

- Reducing the frequency of sleep/wake-up pairs
- How?

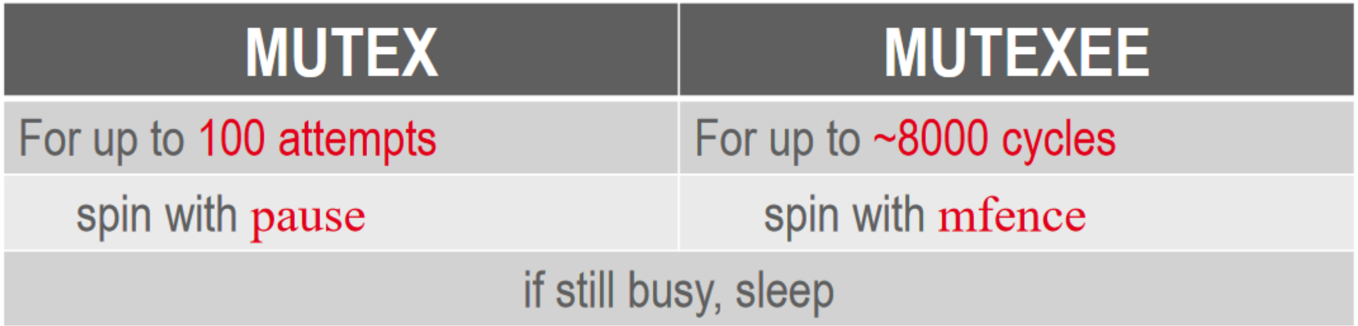
→ Trading Fairness in favor of Throughput

- Make some thread sleep longer than others
- If the lock is highly contented, some thread willing to access the critical section will arrive soon
- If the lock is scarcely contented, we pay lower latency as TTAS locks

# An example - MutexEE

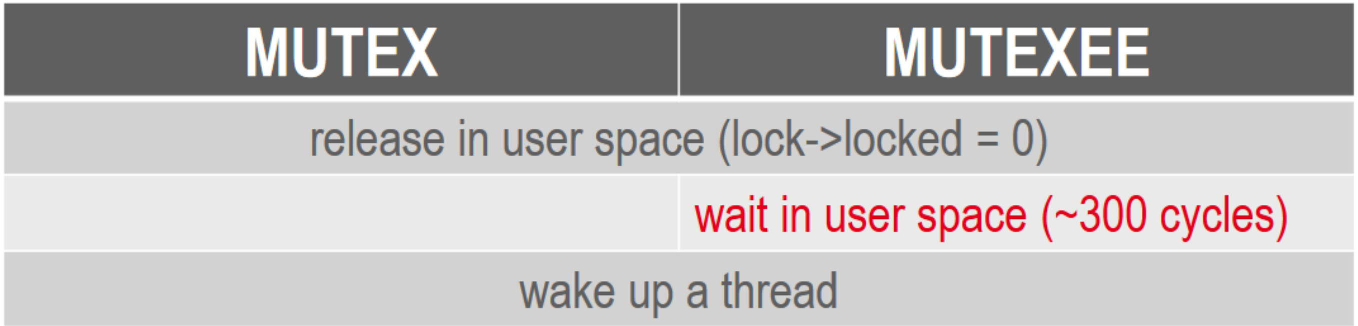
- MutexEE is a pthread_mutex optimized for throughput and energy efficiency

**lock()**



| MUTEX | MUTEXEE |
|---|---|
| For up to 100 attempts | For up to ~8000 cycles |
| spin with pause | spin with mfence |
| if still busy, sleep | |

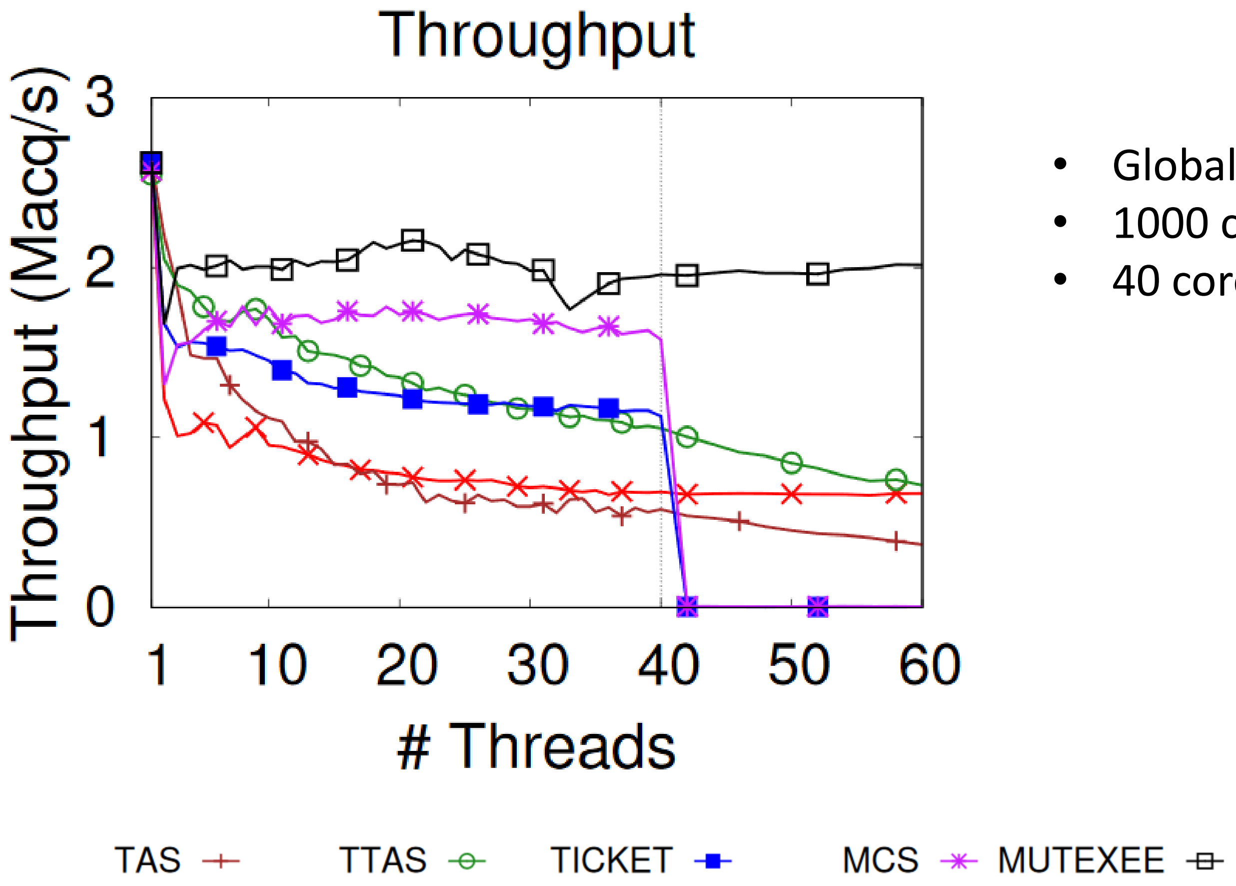
**unlock()**



| MUTEX | MUTEXEE |
|---|---|
| release in user space (lock->locked = 0) | |
| | wait in user space (~300 cycles) |
| wake up a thread | |

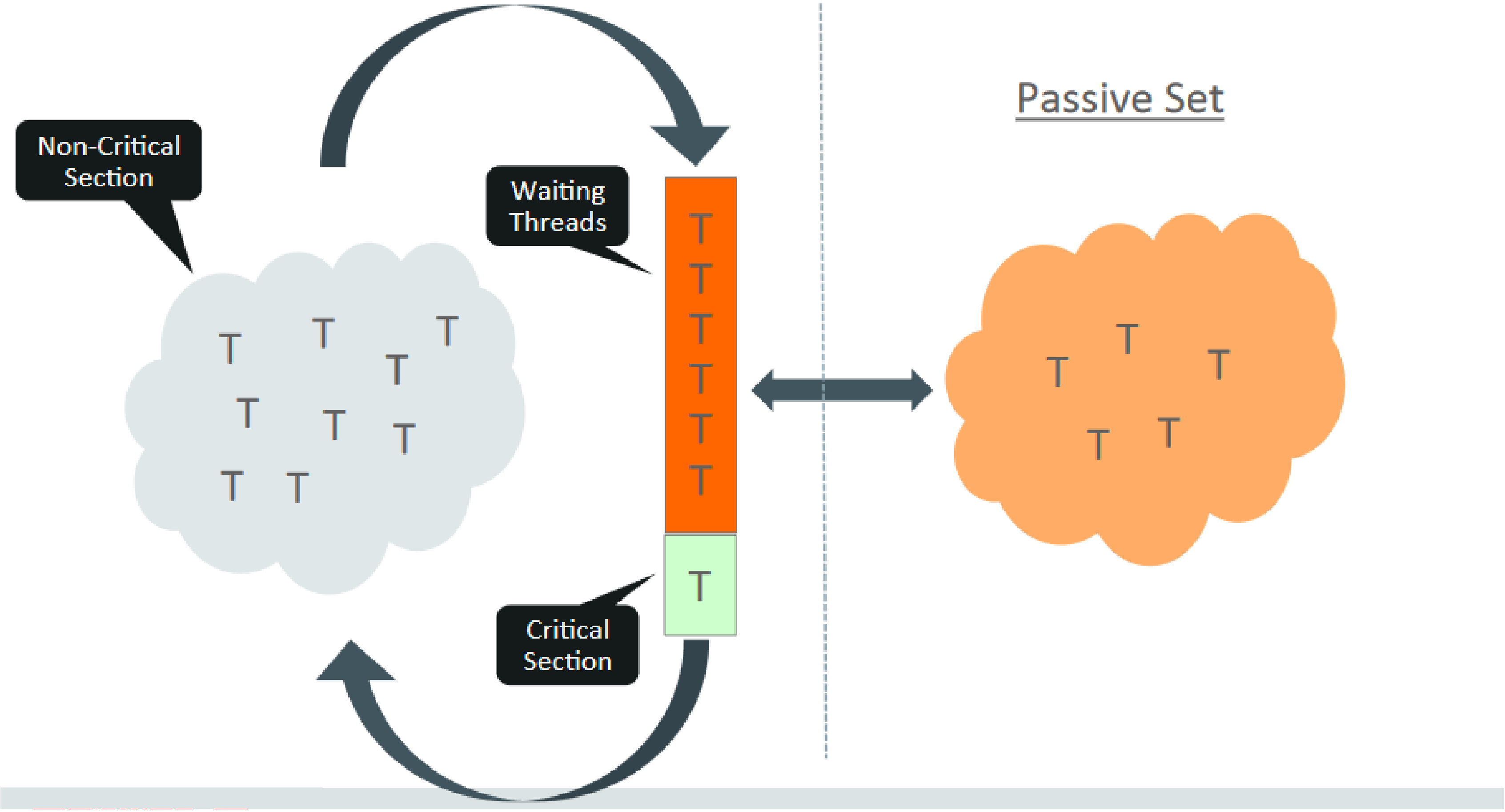
# An example - MutexEE

- MutexEE is a pthread_mutex optimized for throughput and energy efficiency



- Global lock
- 1000 cycles CS
- 40 cores

# An example 2 – Malthusian locks



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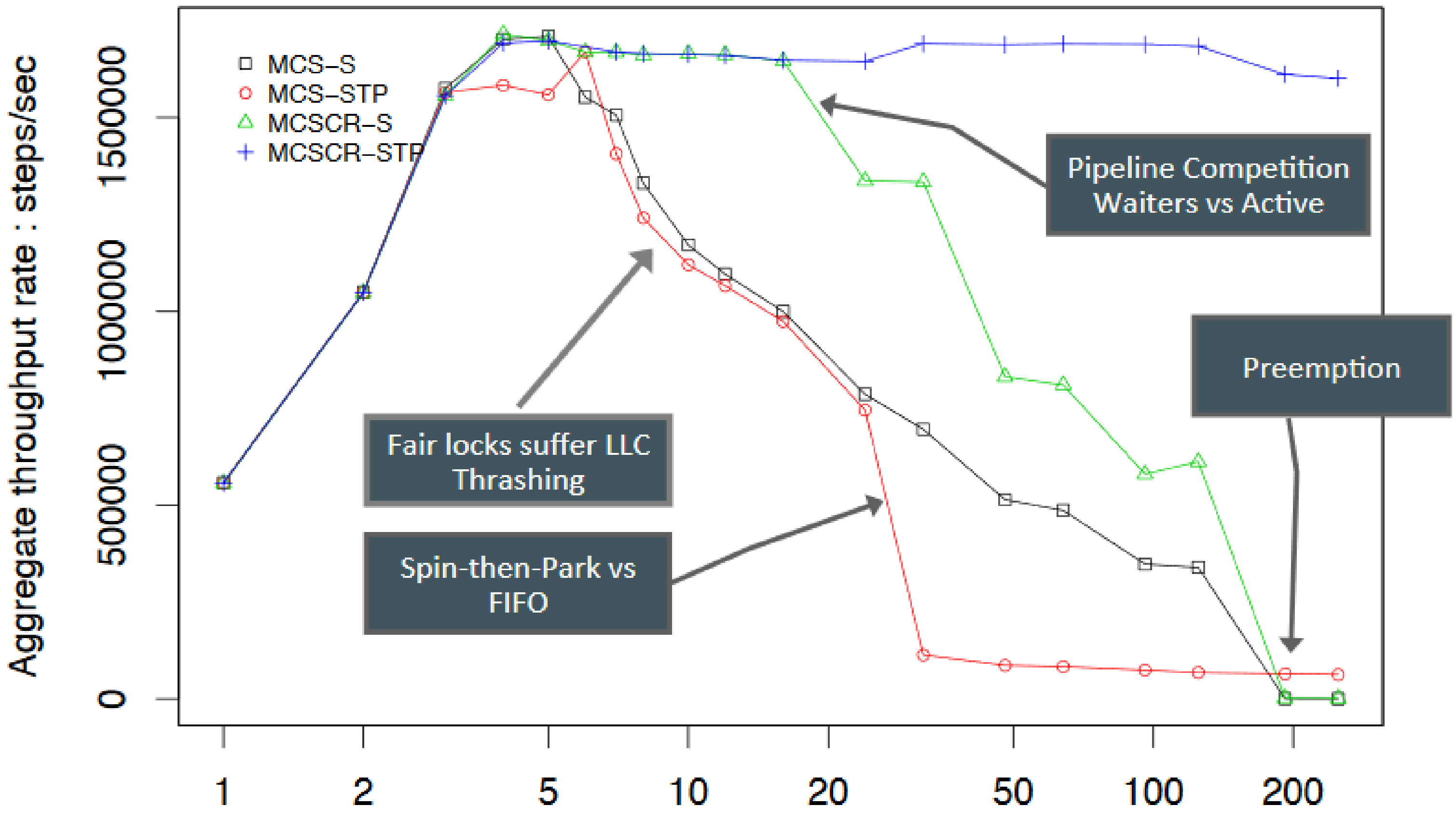

Pipeline Competition Waiters vs Active

Preemption

Fair locks suffer LLC Thrashing

Spin-then-Park vs FIFO

# Recommended readings

- *The Performance of Spin-Lock Alternatives for Shared-Memory Multiprocessors*
  Anderson T.E., IEEE TPDS 1990
- *Algorithms for Scalable Synchronization on Shared-Memory Multiprocessors*
  Mellor-Crummey et al, ACM TCS 1991
- *Unlocking Energy*
  Falsafi et al, USENIX 2016
- *Malthusian Locks*
  Dice D., In ACM EuroSys'17