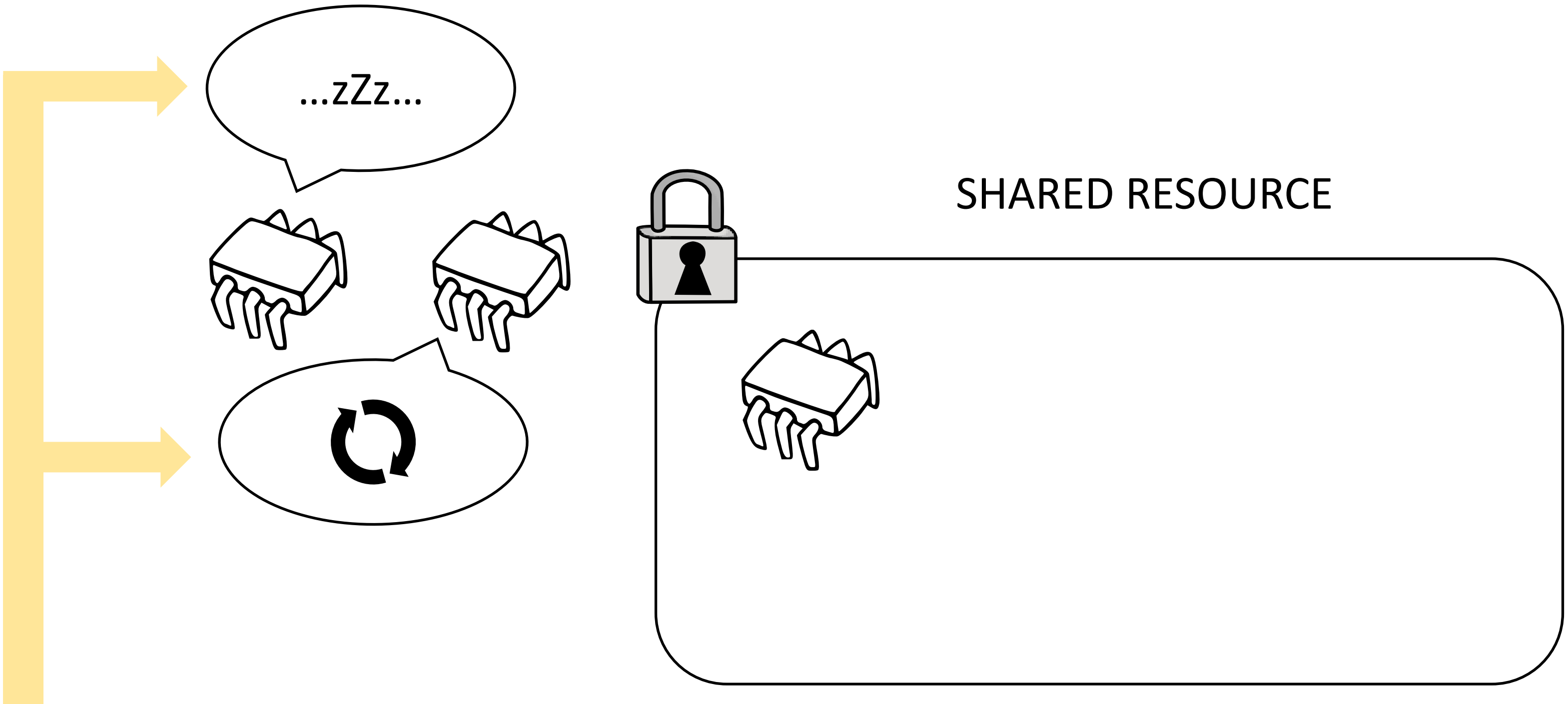
Programmazione concorrente

Laurea Magistrale in Ingegneria Informatica
Università Tor Vergata
Docente: Romolo Marotta

Locks

1. Spin locks
2. FIFO Spin locks
3. Hybrid (Spin+Sleep) locks

Blocking coordination

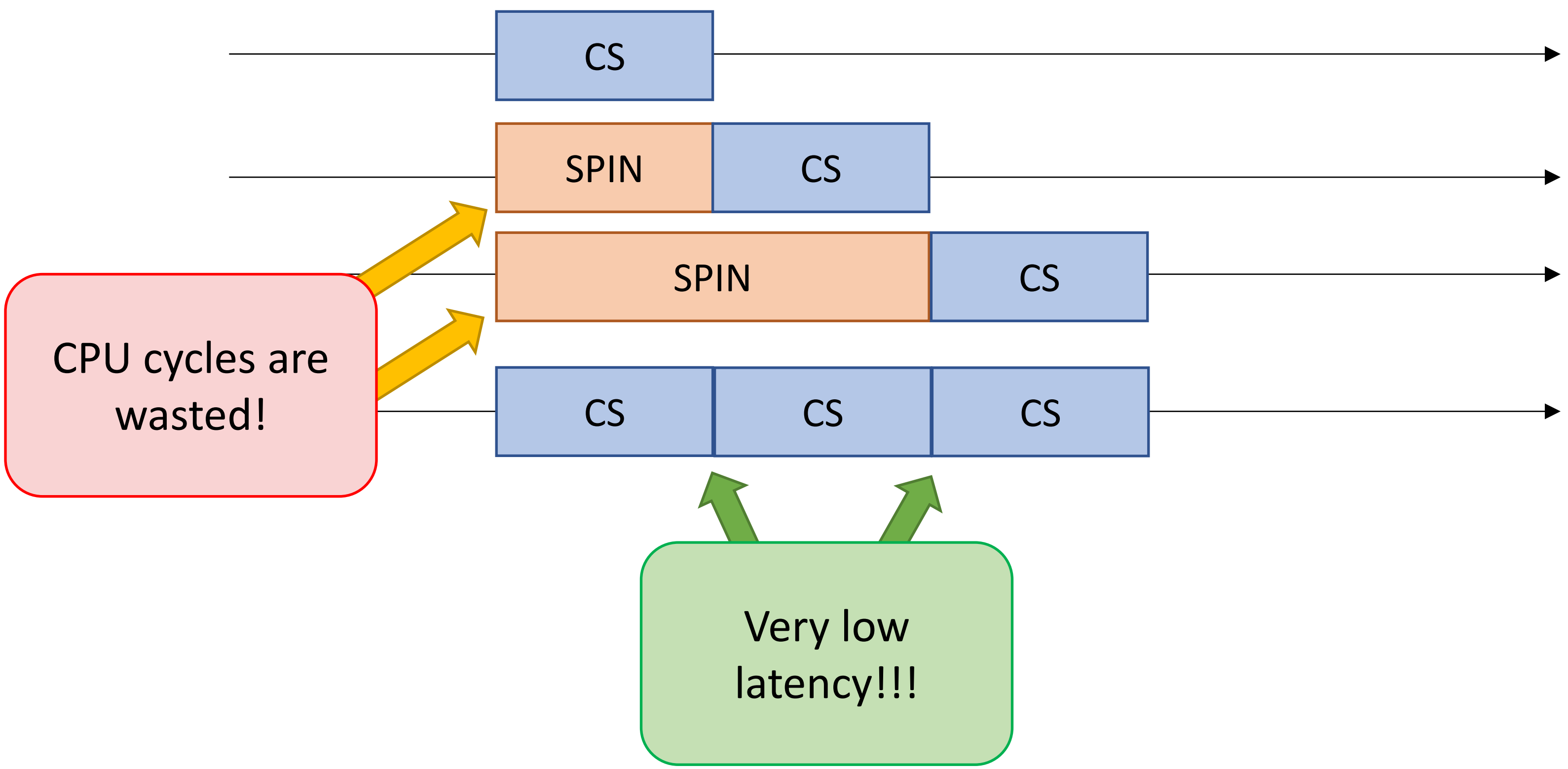


Choosing between them is delegated to developers!

This is a very hard task: multiple trade offs!

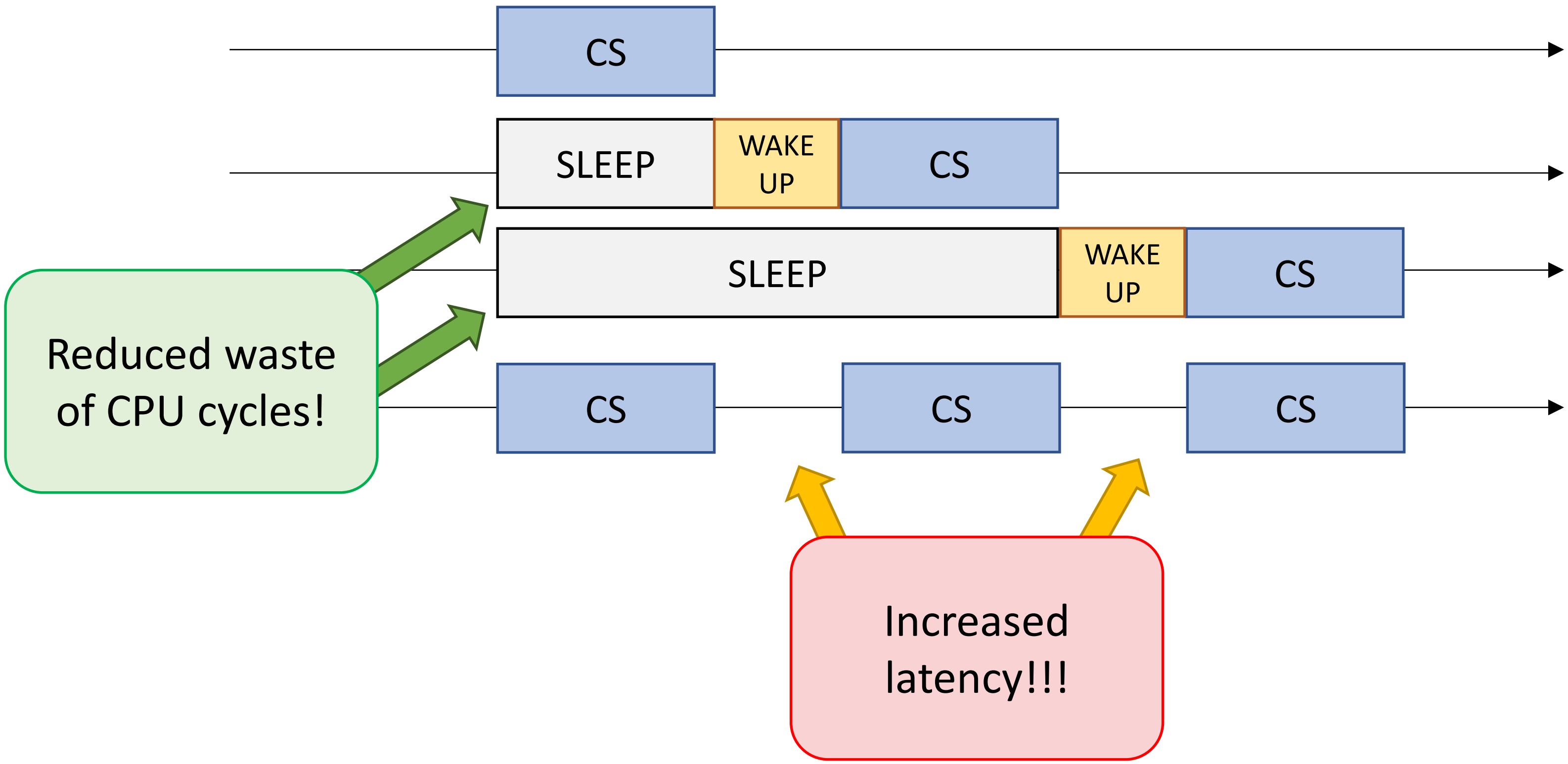
Spinning vs Sleeping

Benefits	Spinning
Guaranteed low latency	✓
Computing power savings	✗



Spinning vs Sleeping

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



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

→

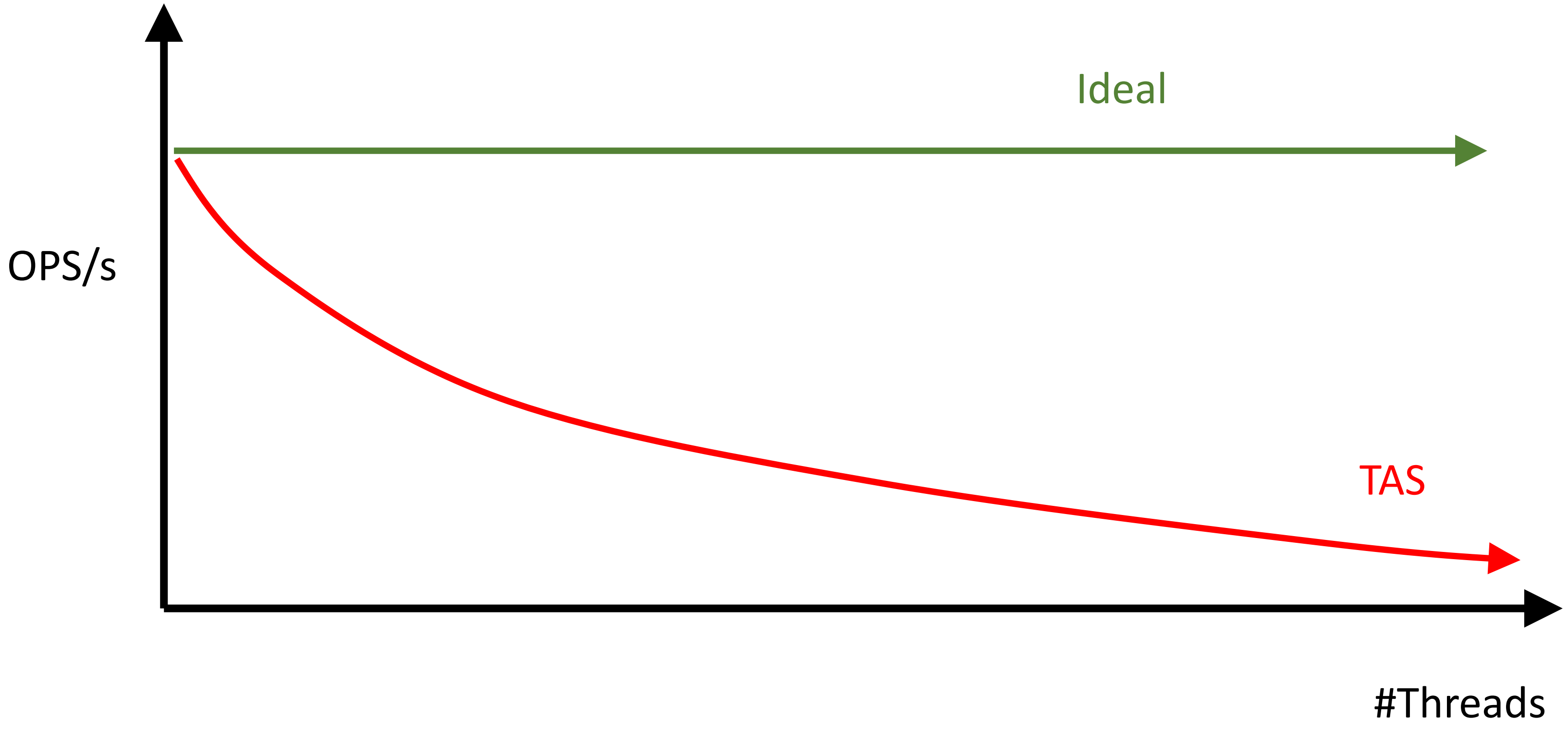
6	5	4	3	2	1

- This is done within a critical section

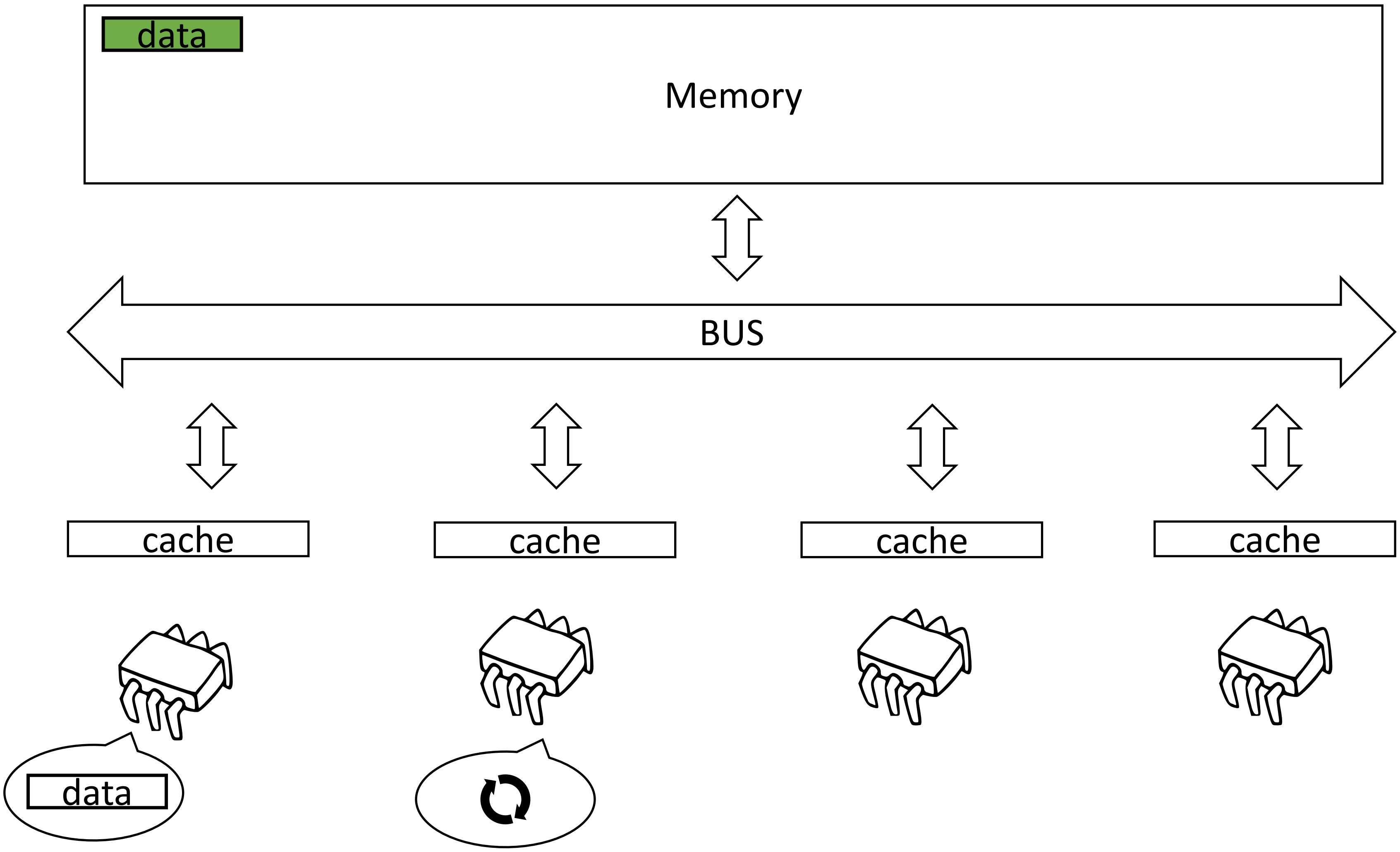
```
while(!stop){
  acquire(&lock);
  flip_array();
  release(&lock);
}
```

- Performance Metric:
  - Throughput = #Flips per second

Results



Memory Model



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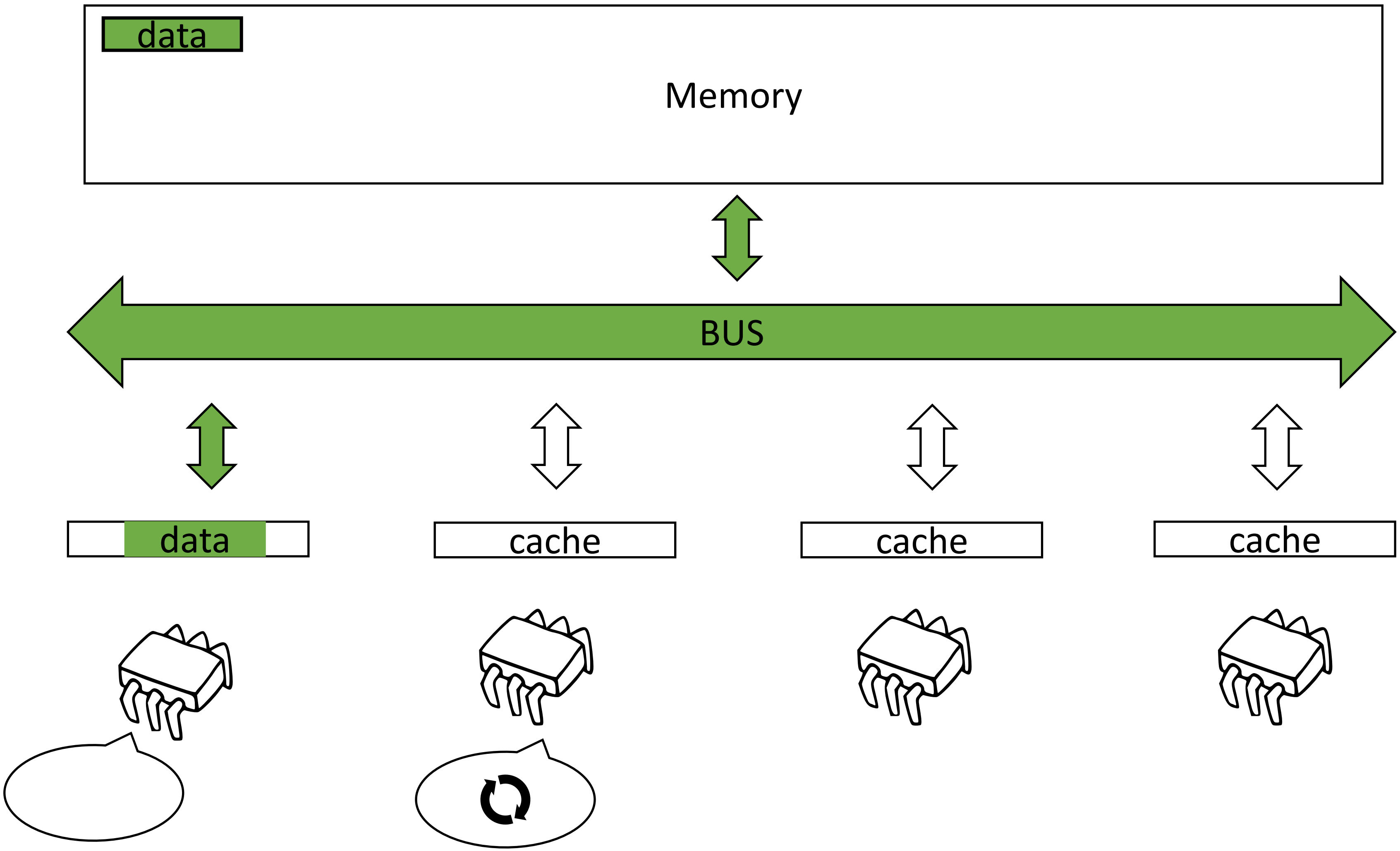

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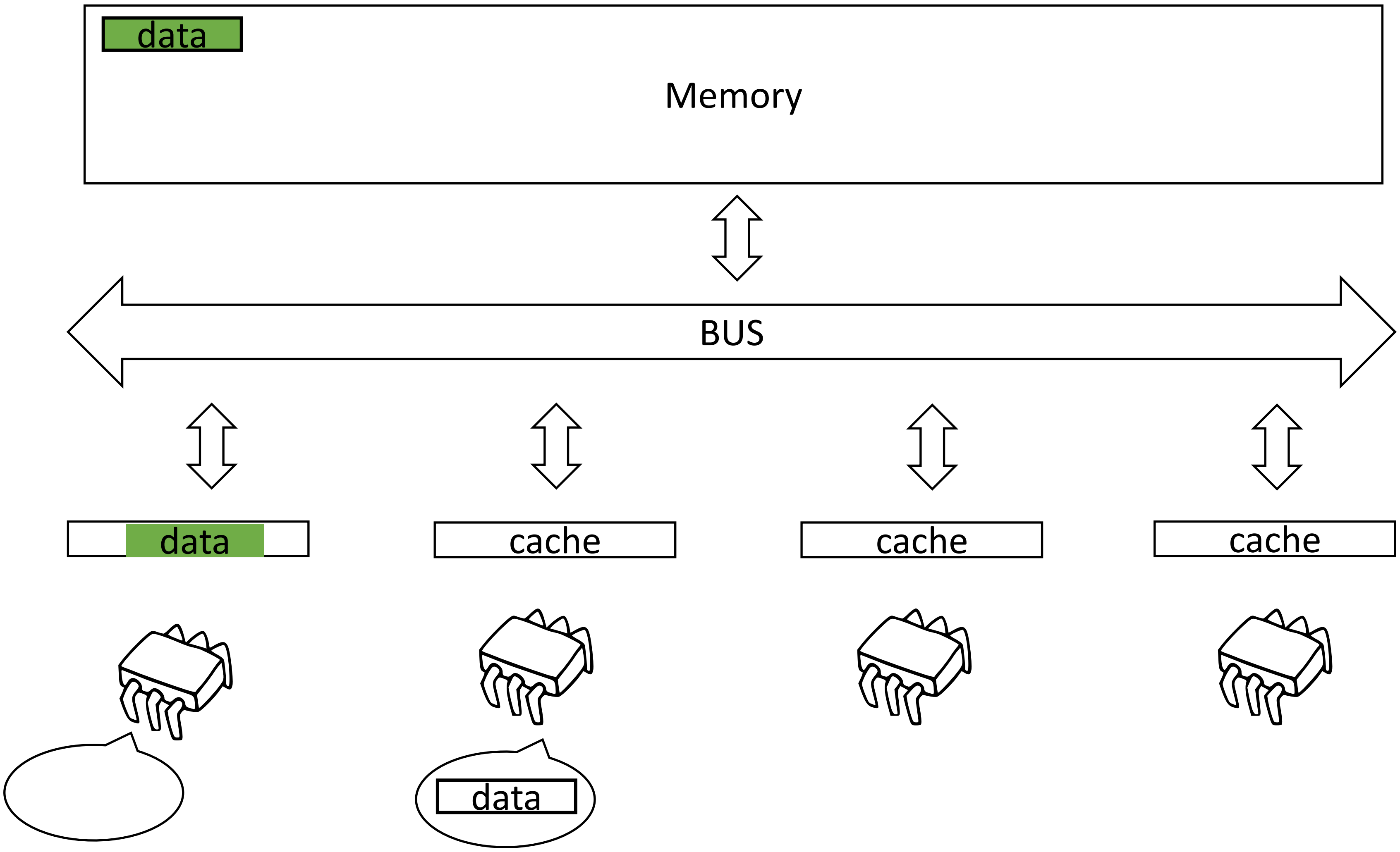

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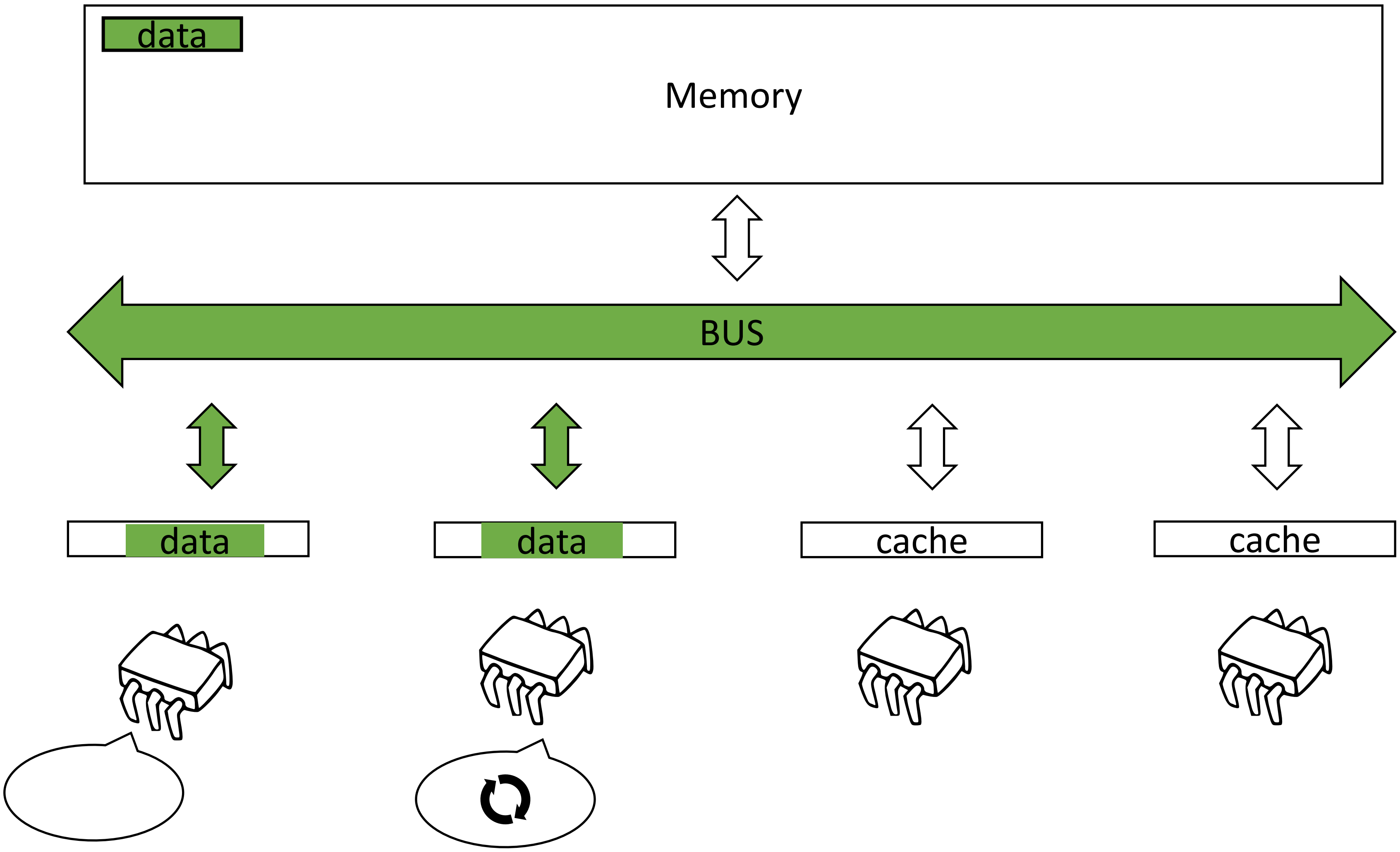

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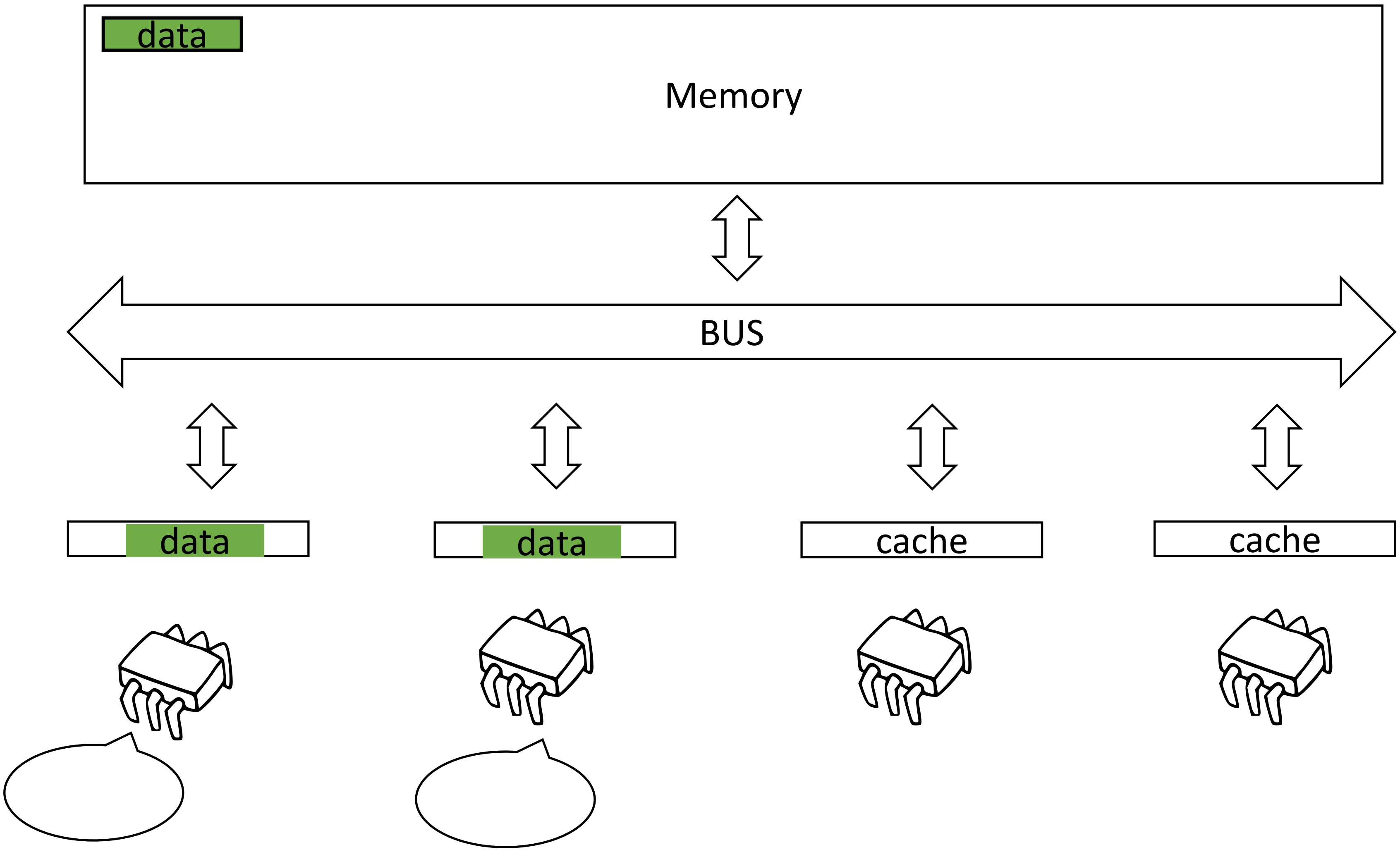

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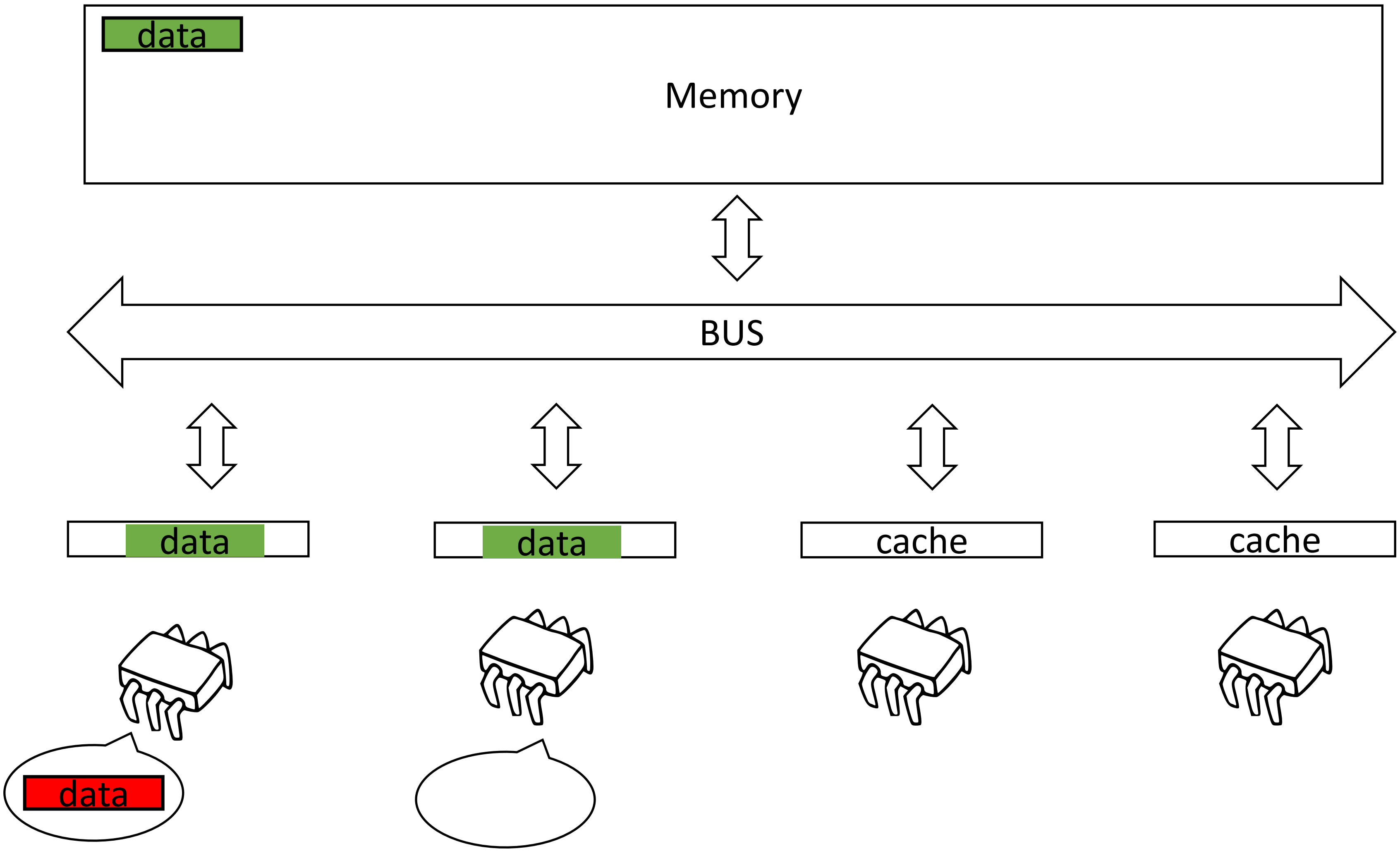

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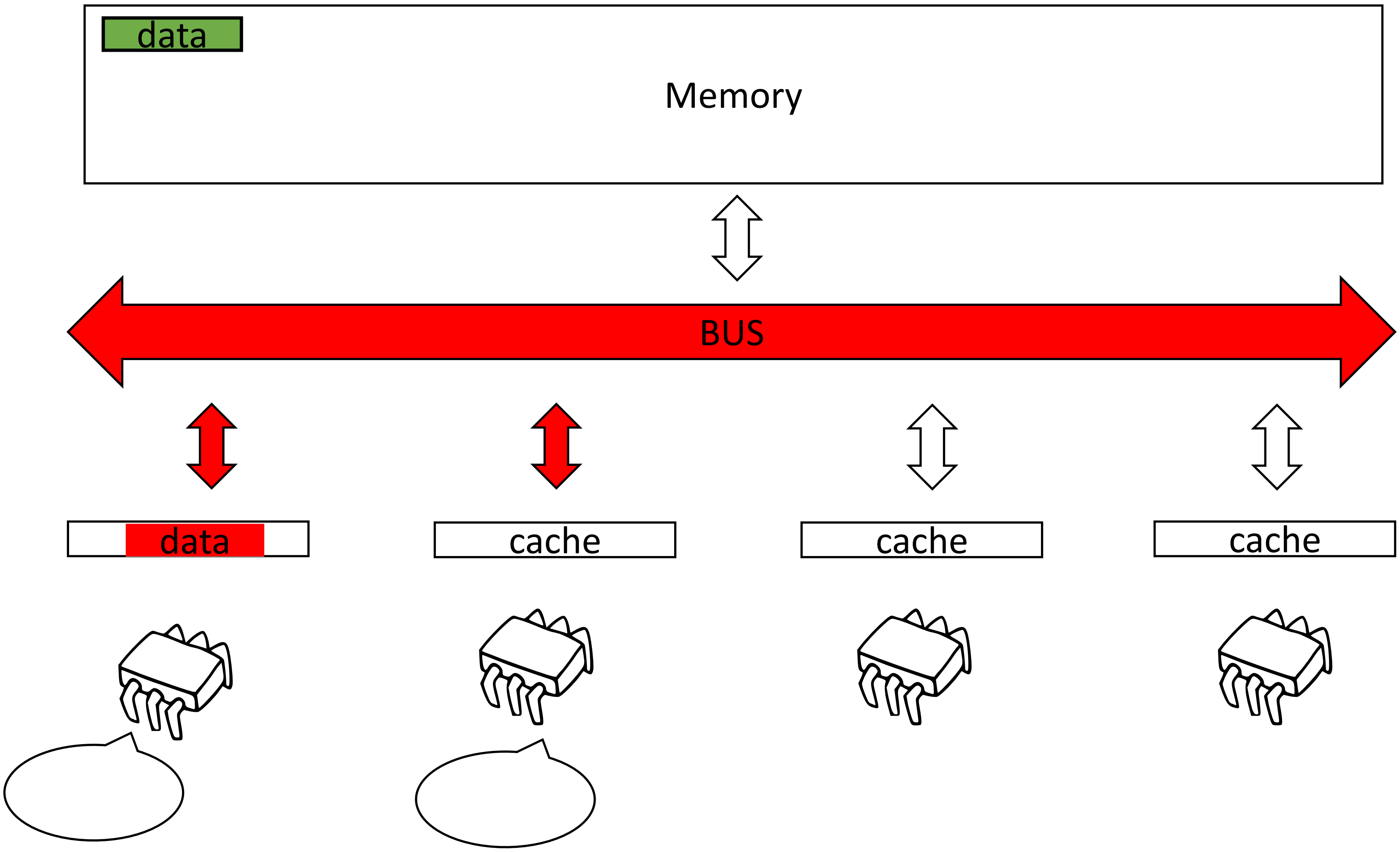

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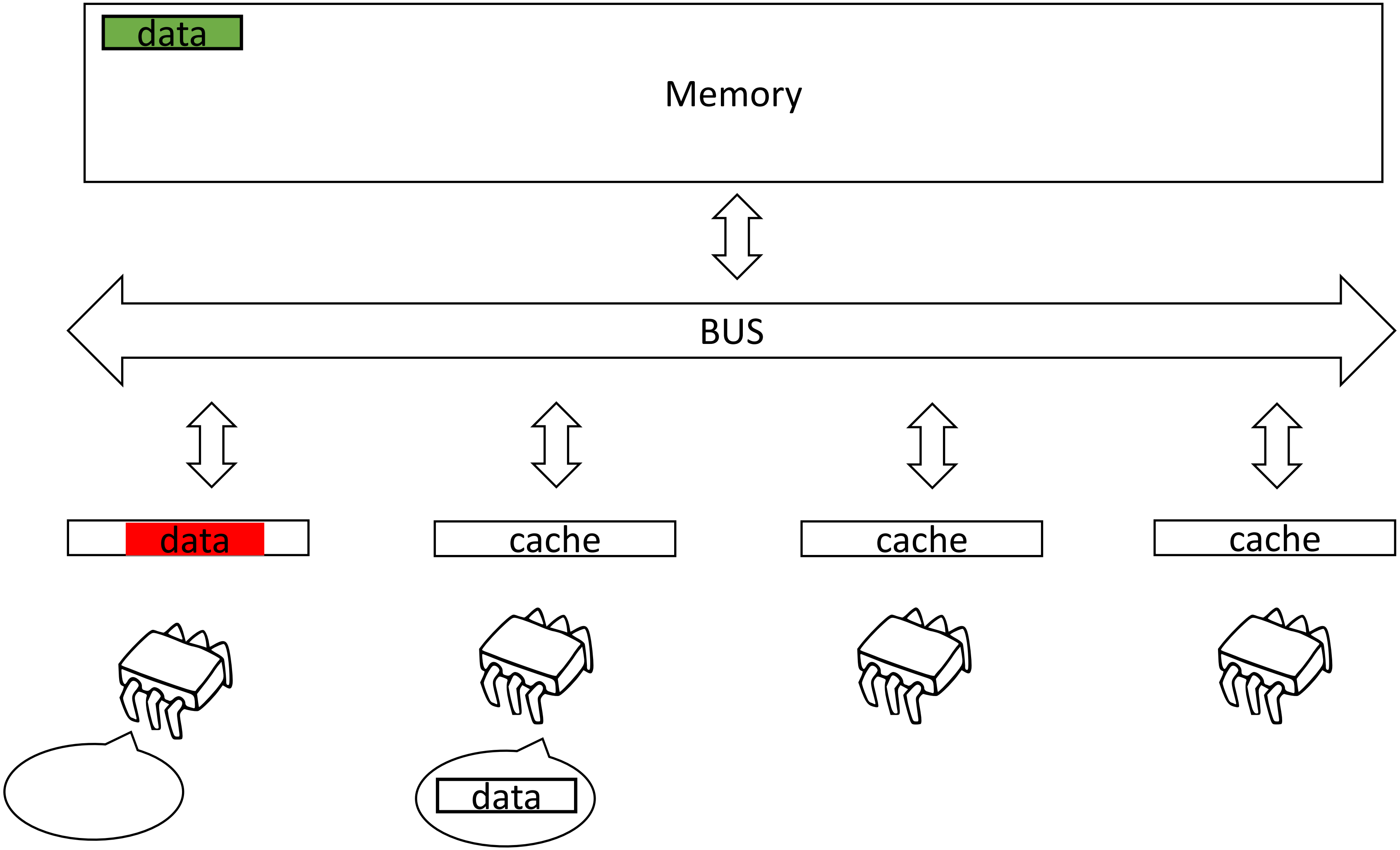

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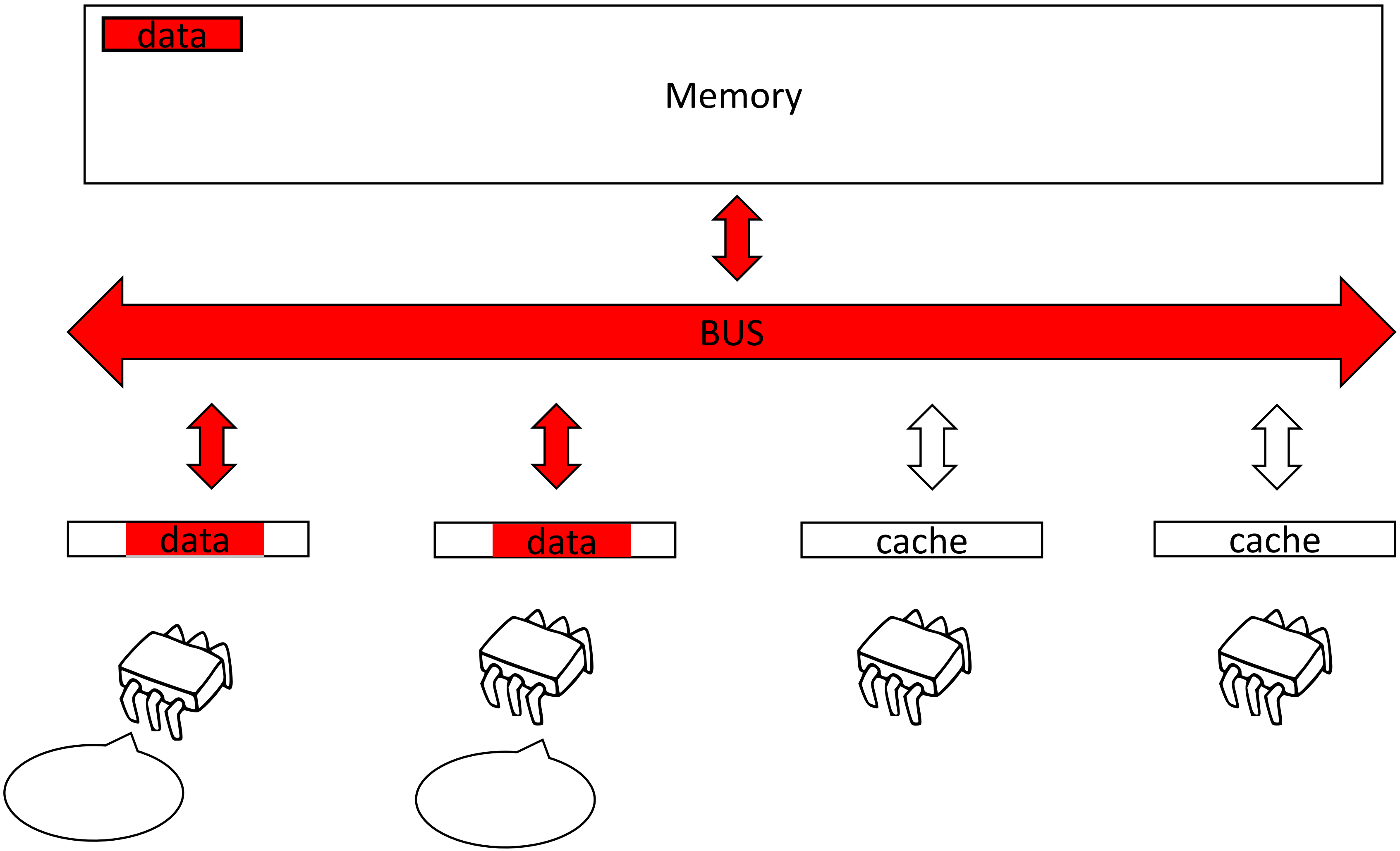

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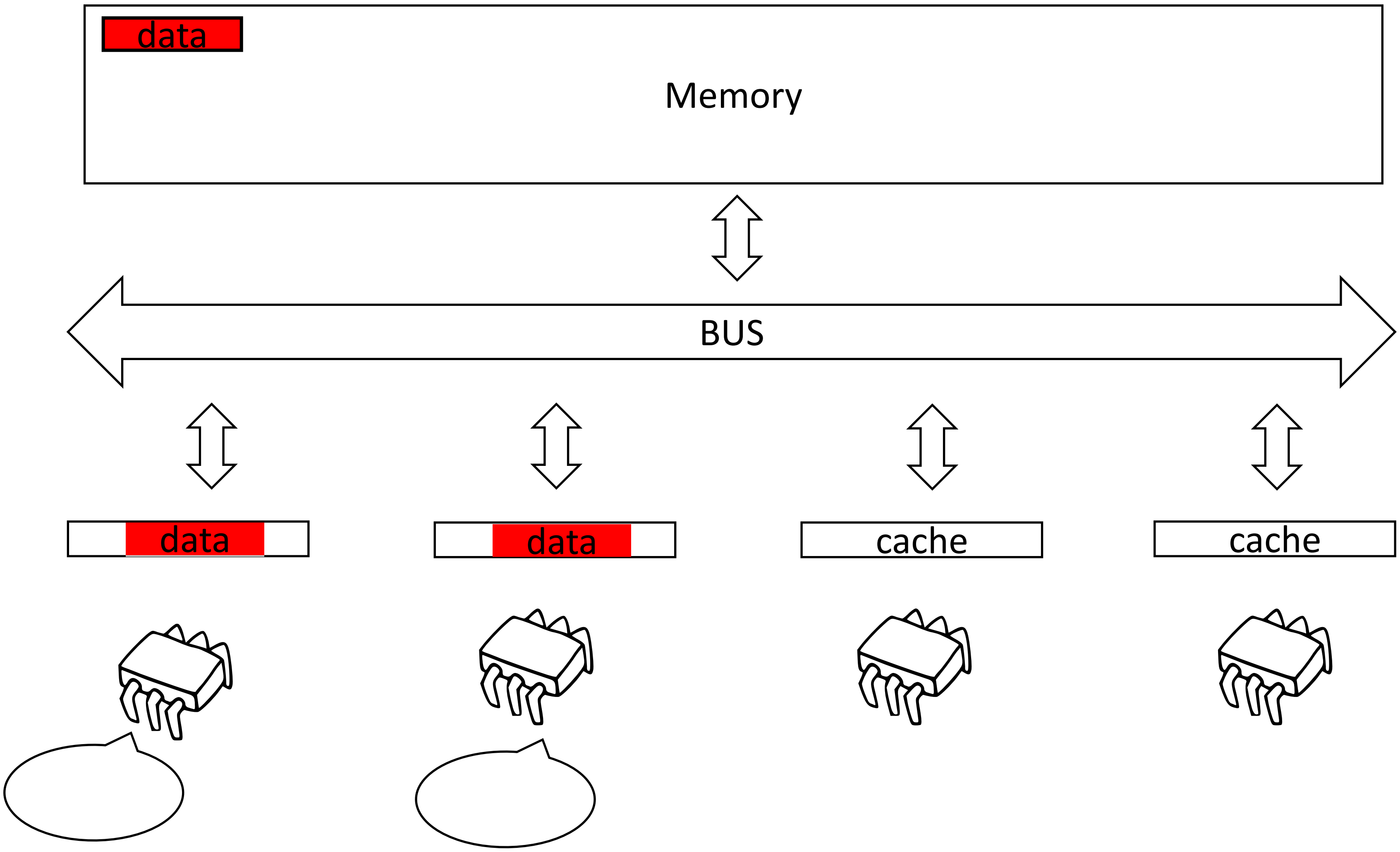

Lock implementations

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));
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void release(int *lock){
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}
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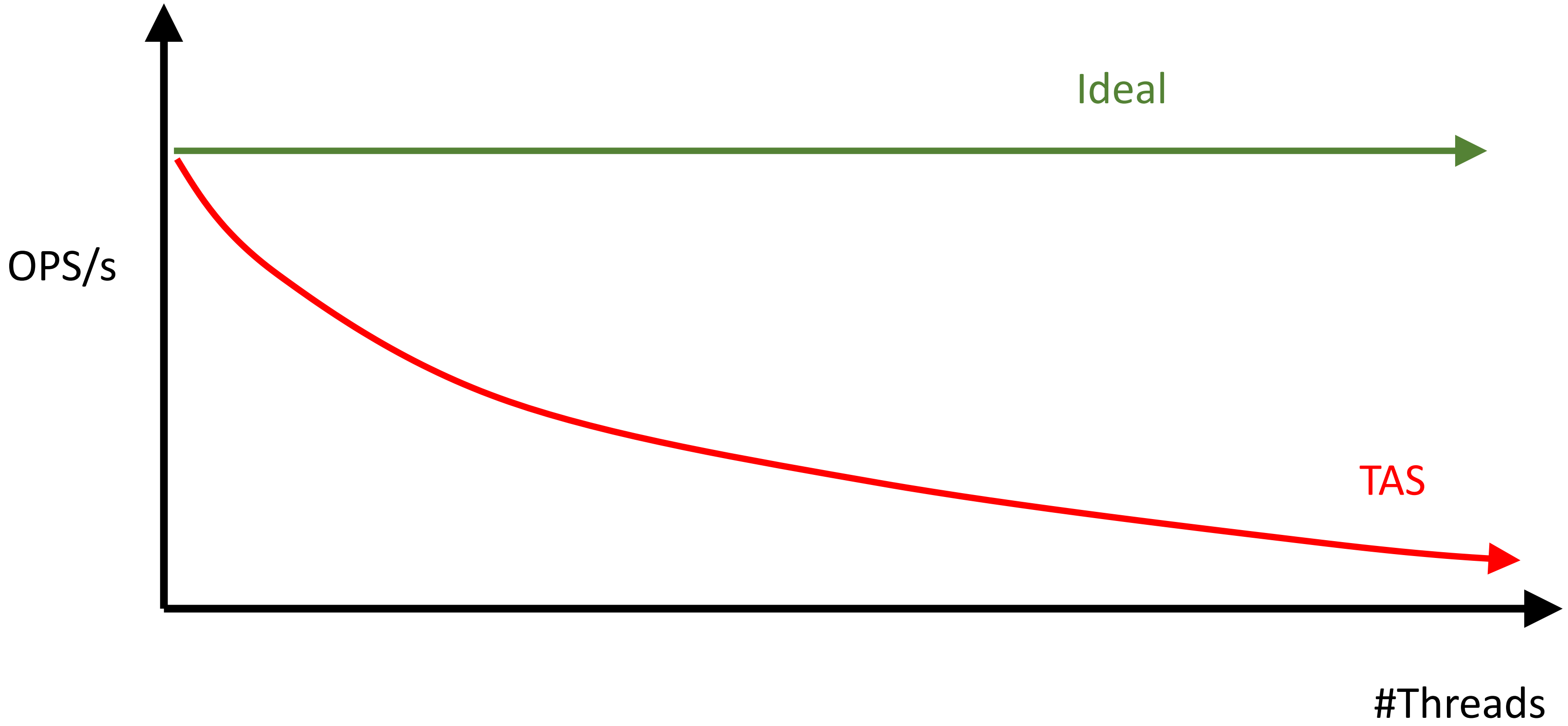

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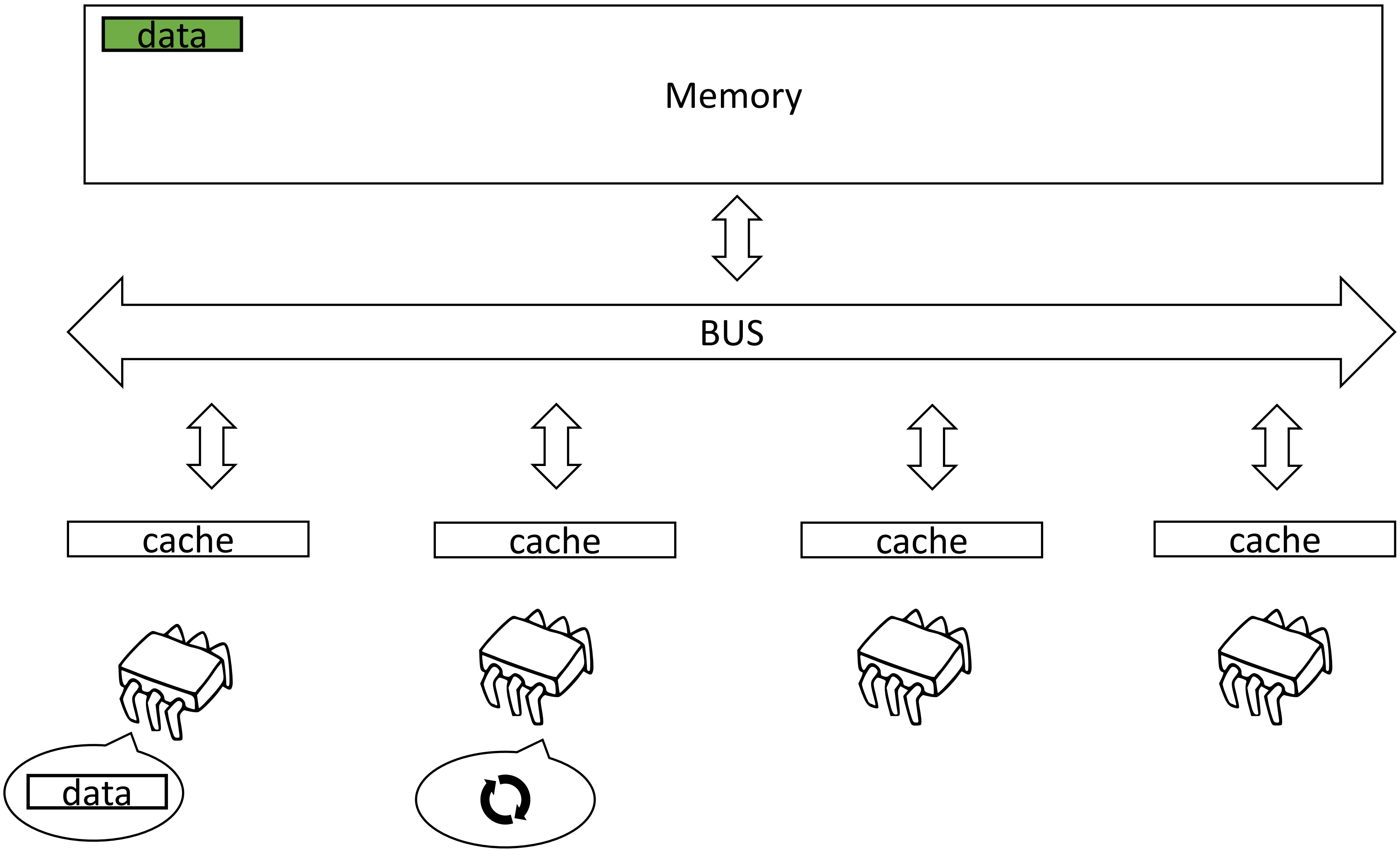

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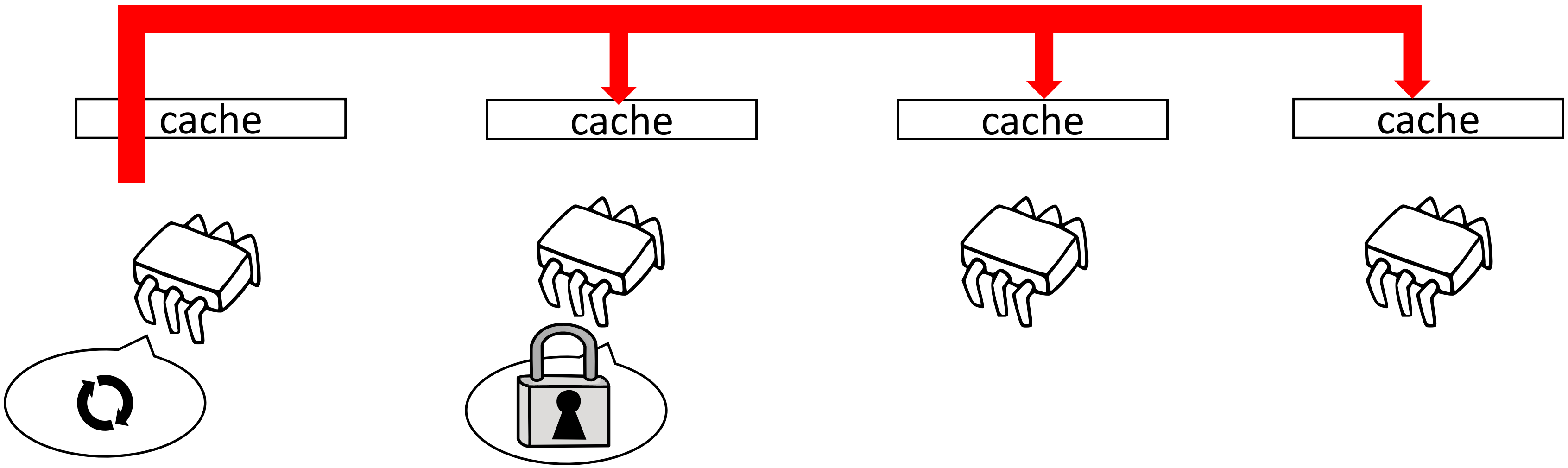

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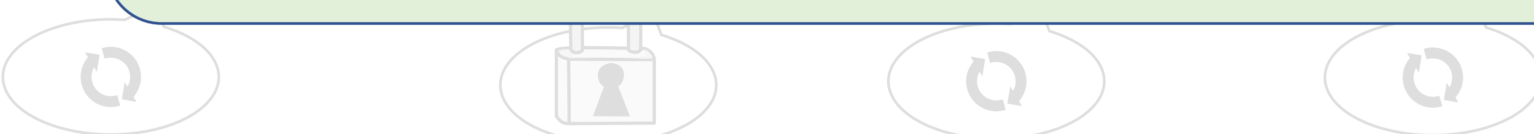
We can reduce the impact of memory traffic by introducing exponential back off! But how to set it properly?



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

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

```
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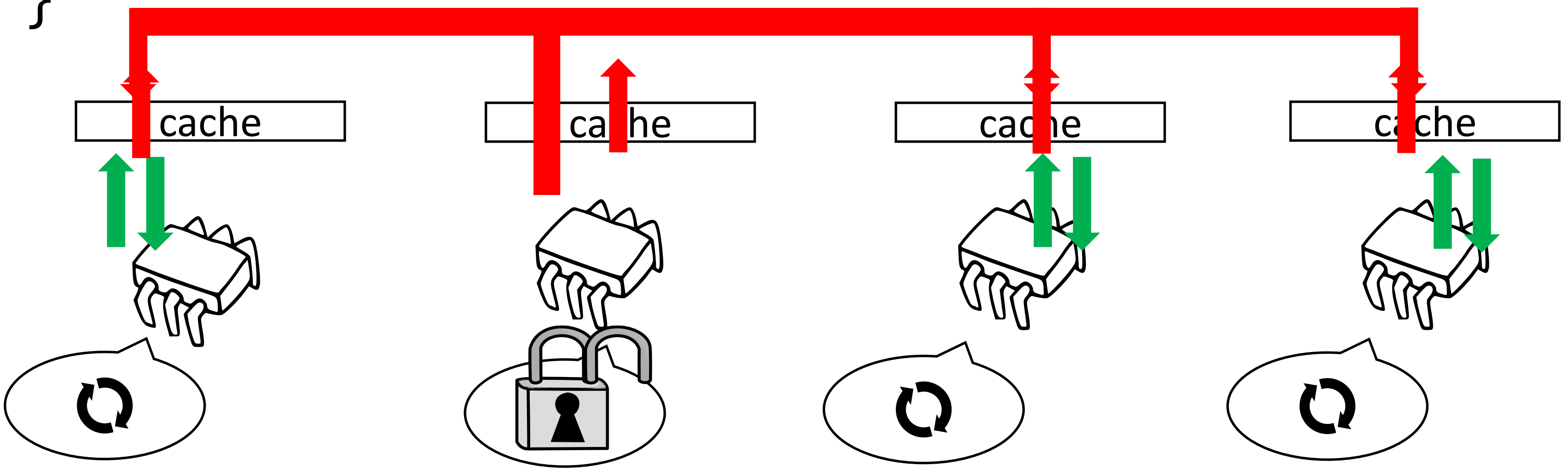
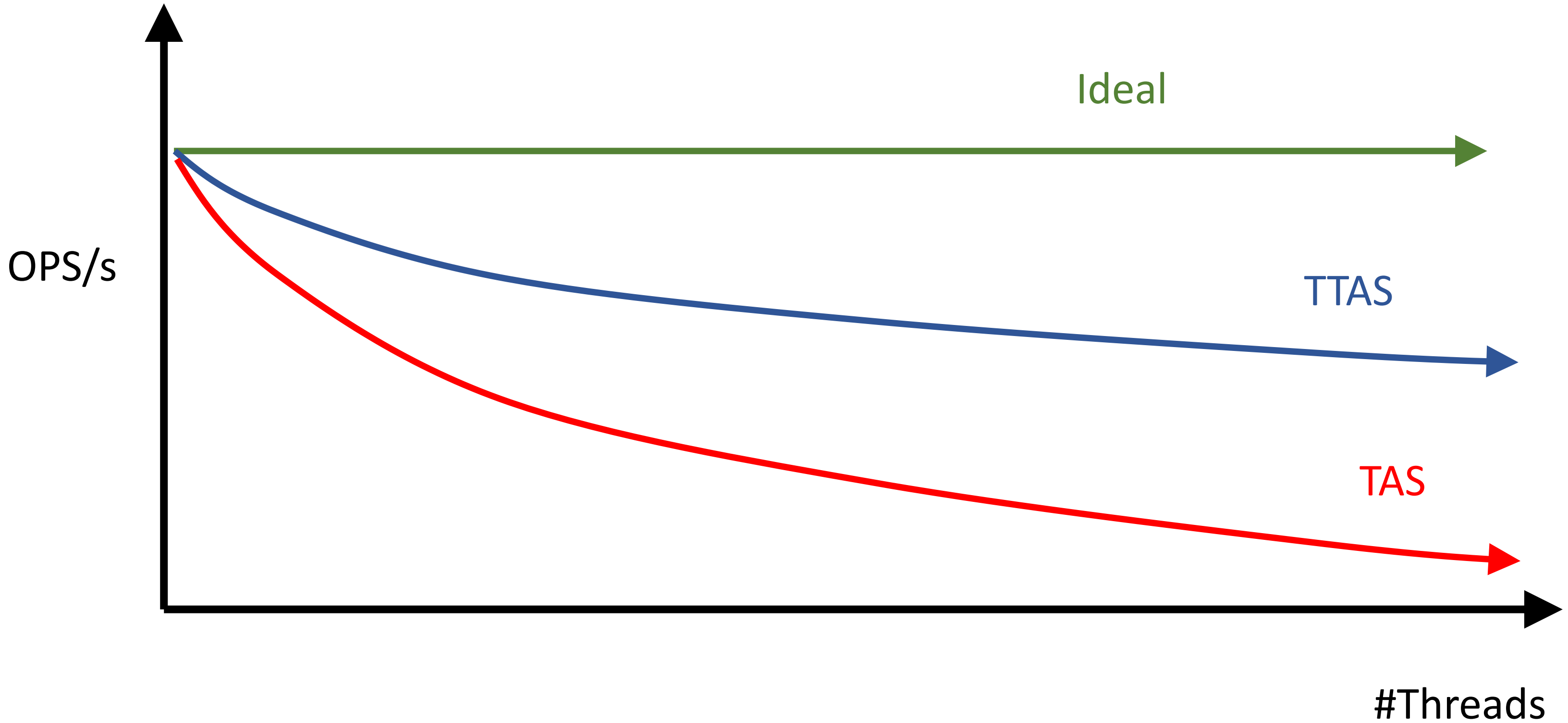
  *lock = 0;
}
```



Results



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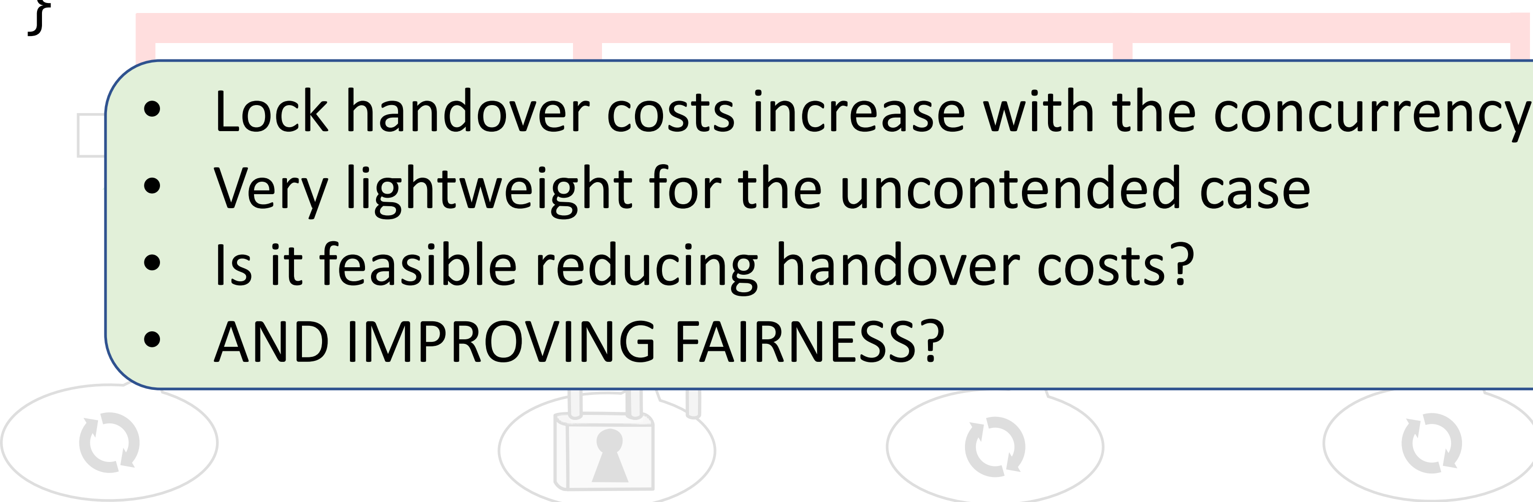


- Lock handover costs increase with the concurrency level
- Very lightweight for the uncontended case
- Is it feasible reducing handover costs?
- AND IMPROVING FAIRNESS?

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; }
```

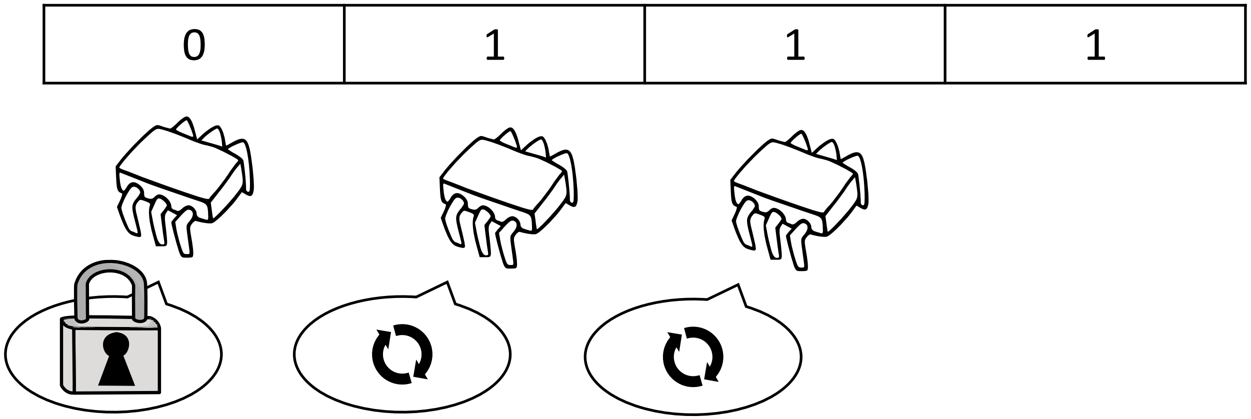
Ticket locks

- 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 1 2~~ 3



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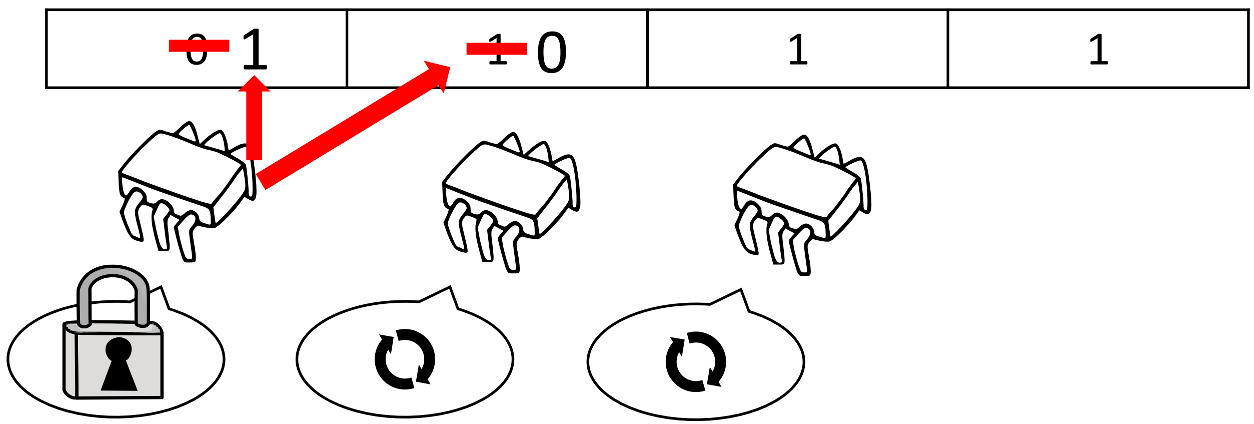
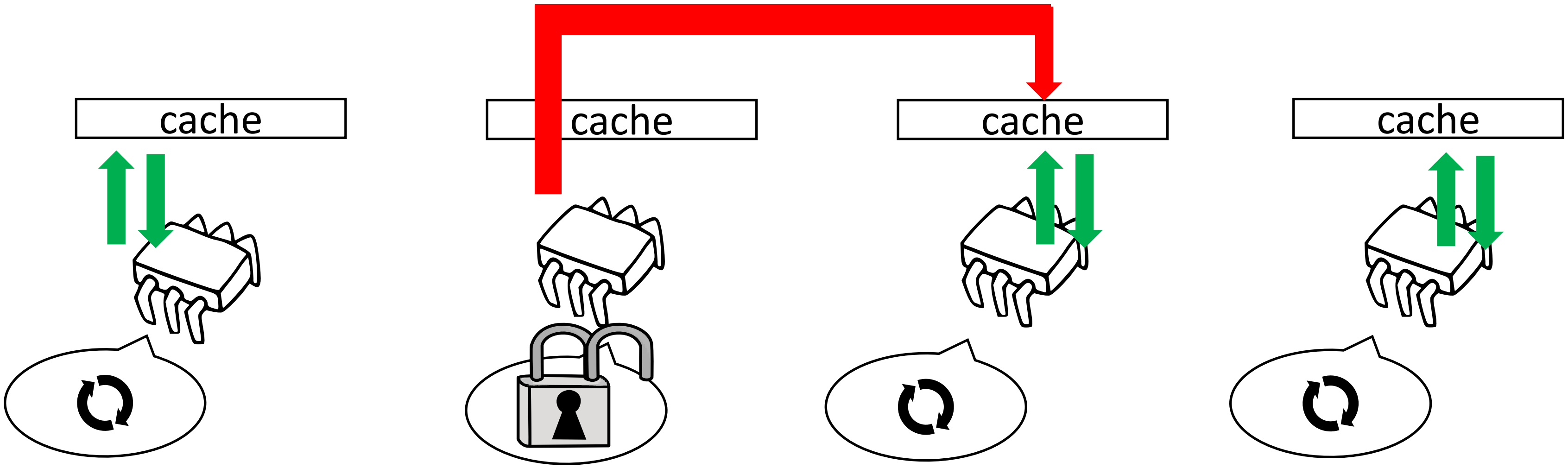


Anderson queue lock

```
void acquire(anderson_lock *lock){
  mytck = fetch&add(lock->ticket, 1);
  while(lock->array[mytck]);
  lock->array[mytck] = 1;
}
```

```
void release(int *lock){
 lock->array[mytck+1] = 0;
}
```

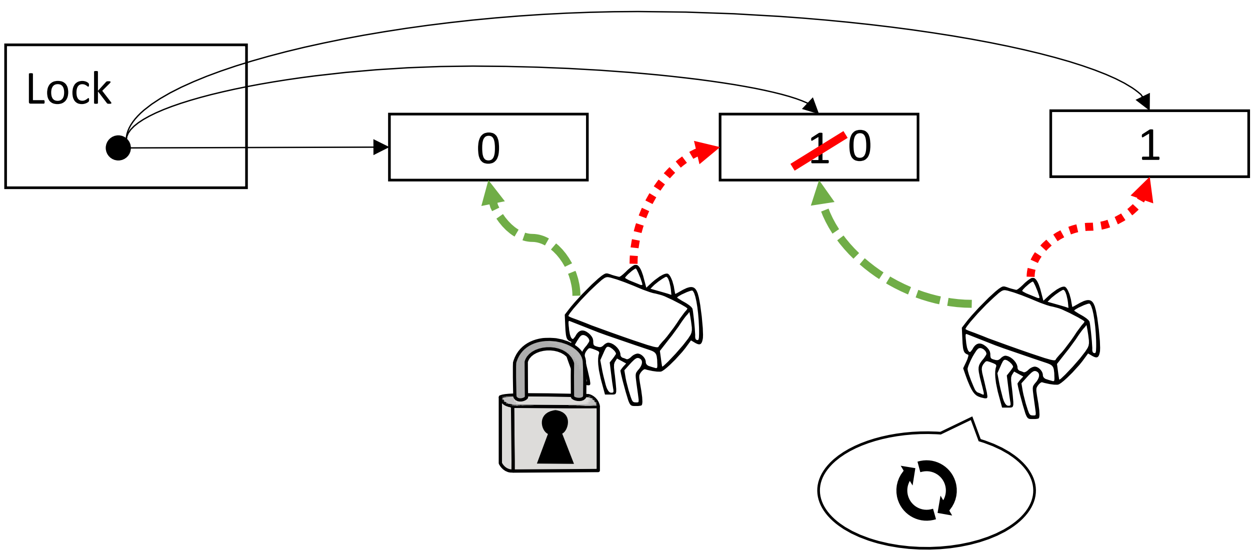


Anderson queue lock

- 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

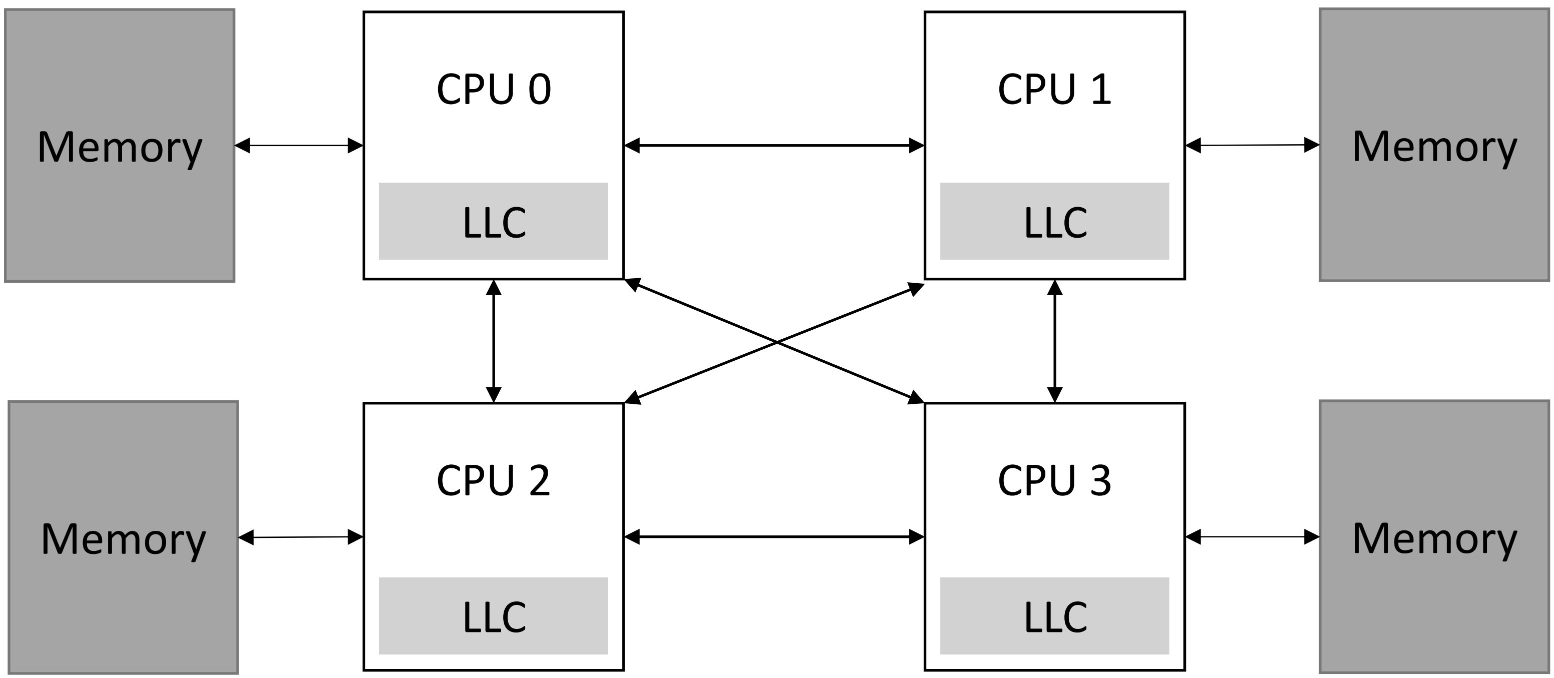
- An (implicit) linked list maintains the order between waiting threads
- An empty list represent an uncontended lock
- An arriving thread swaps the node with its private node
- Spin on the previous node
- Release on the new node



CLH queue lock

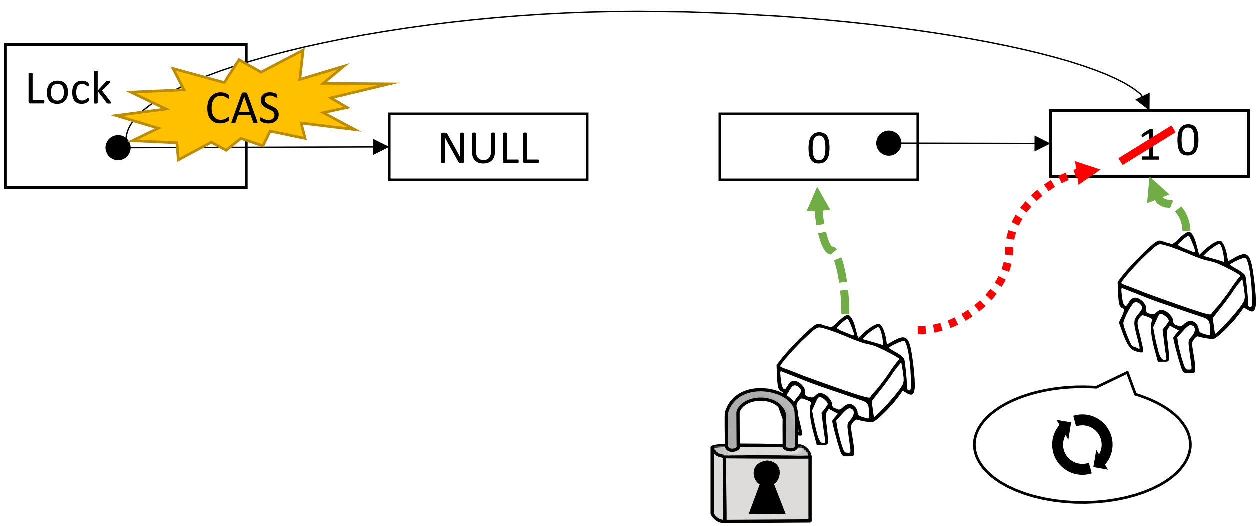
- Pros:
  - One variable updated once at each acquisition (like Ticket lock)
  - Write-1-Read-1 variable updated once per release (better than (T)TAS and Ticket)
- Cons:
  - Slightly increased memory footprint
- Let:
  - T be the number of threads
  - L be the number of locks
- Space Usage
  - CLH =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



MCS lock

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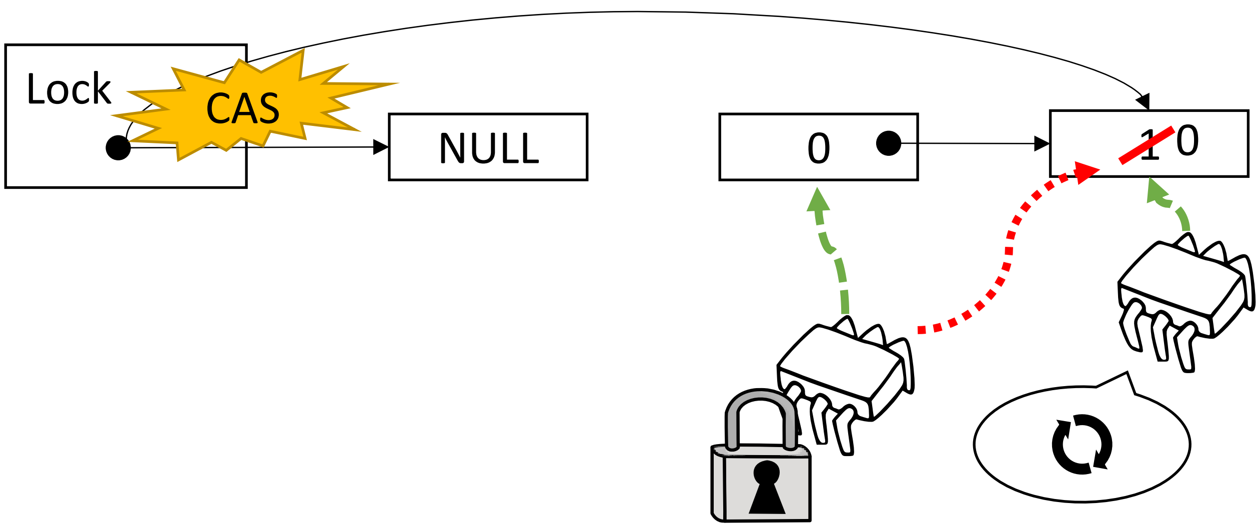

MCS lock

- An explicit linked list maintains the order between waiting threads
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- Spin on the just inserted node
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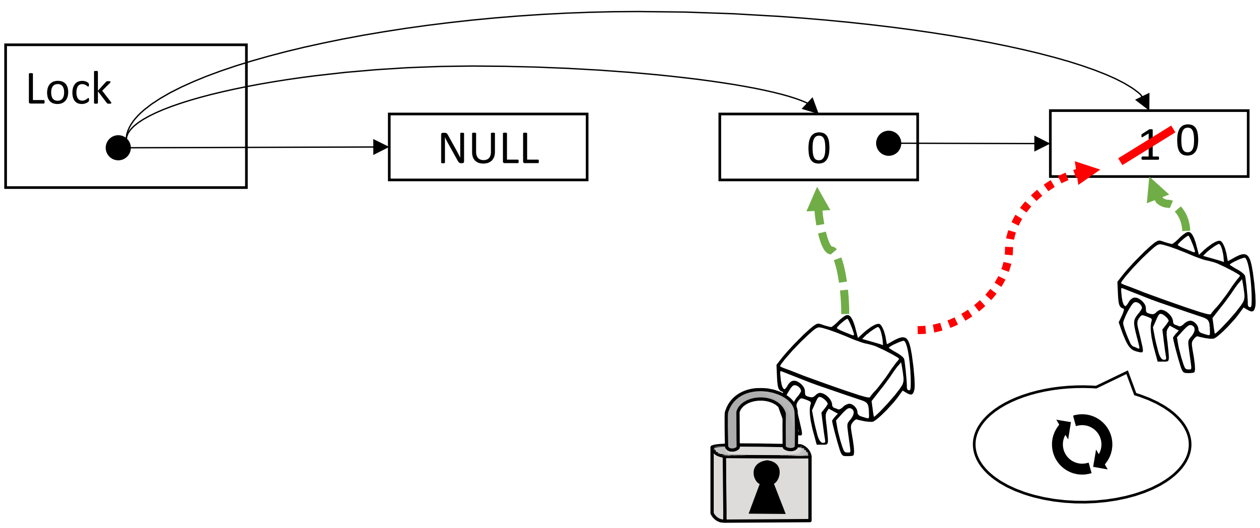
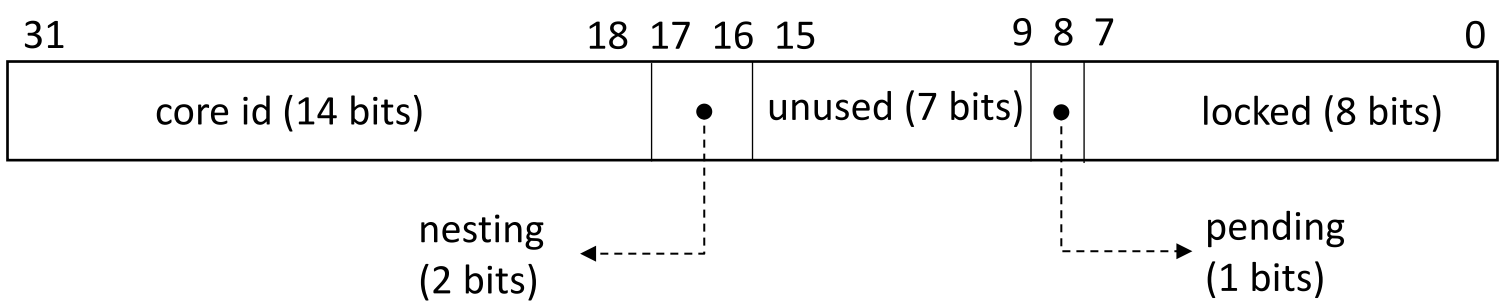


MCS queue lock

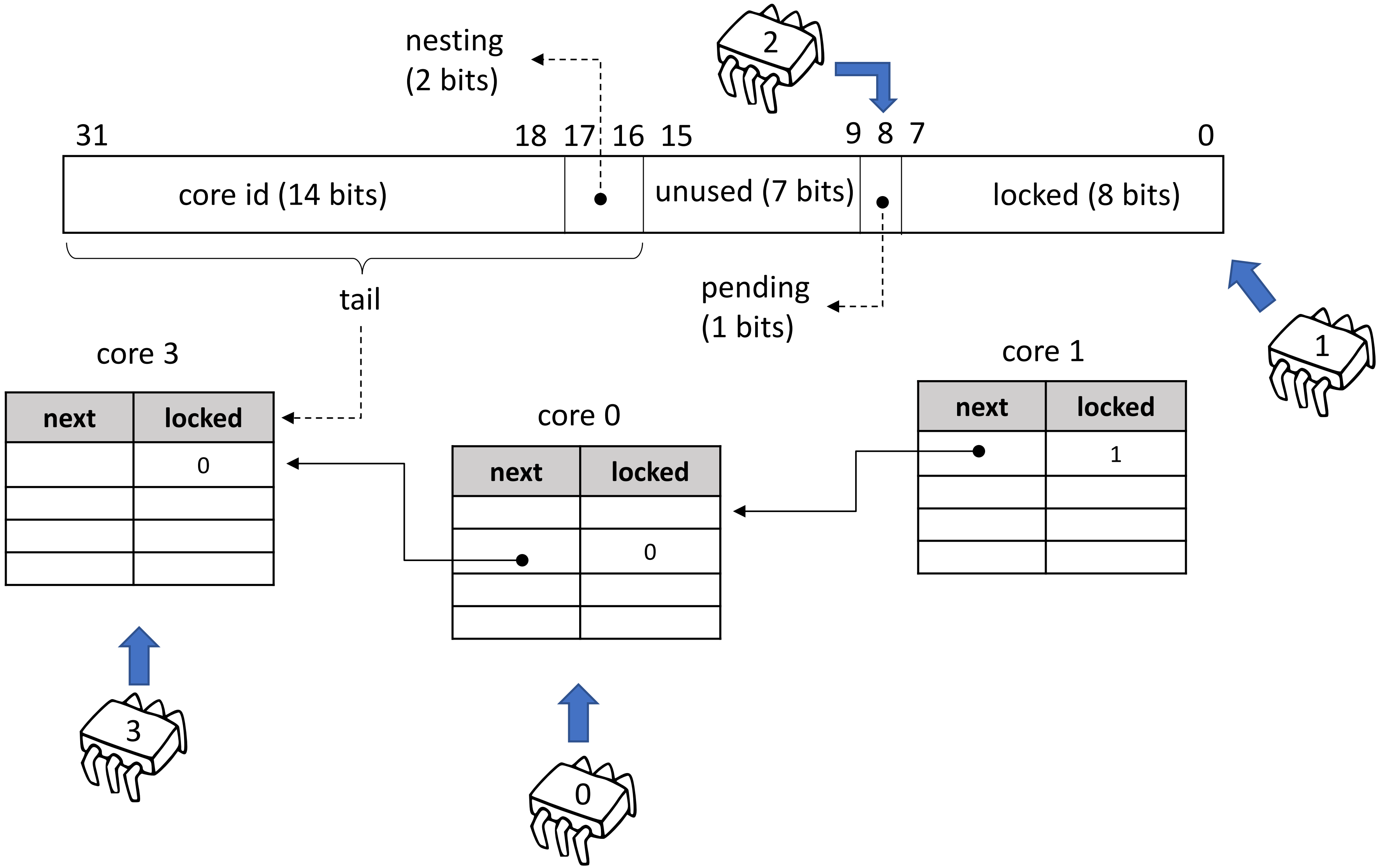
- Pros:
  - One variable updated once at each acquisition (like Ticket lock)
  - Write-1-Read-1 variable updated once per release (better than (T)TAS and Ticket)
  - No-remote spinning
- Cons:
  - Slightly increased memory footprint
- Let:
  - T be the number of threads
  - L be the number of locks
- 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



MCS in practice: the Linux kernel case



A small benchmark

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

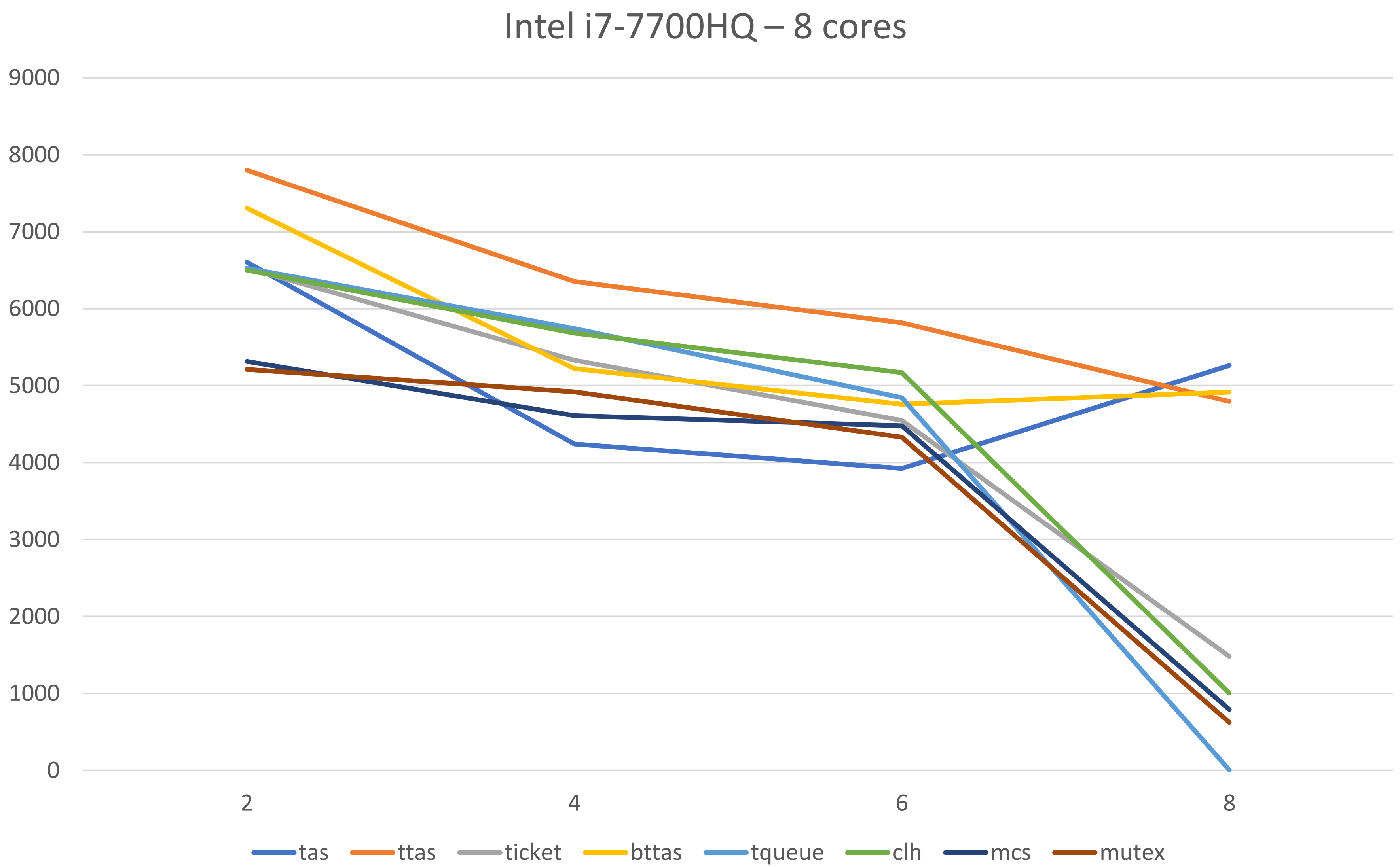
- This is done within a critical section

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

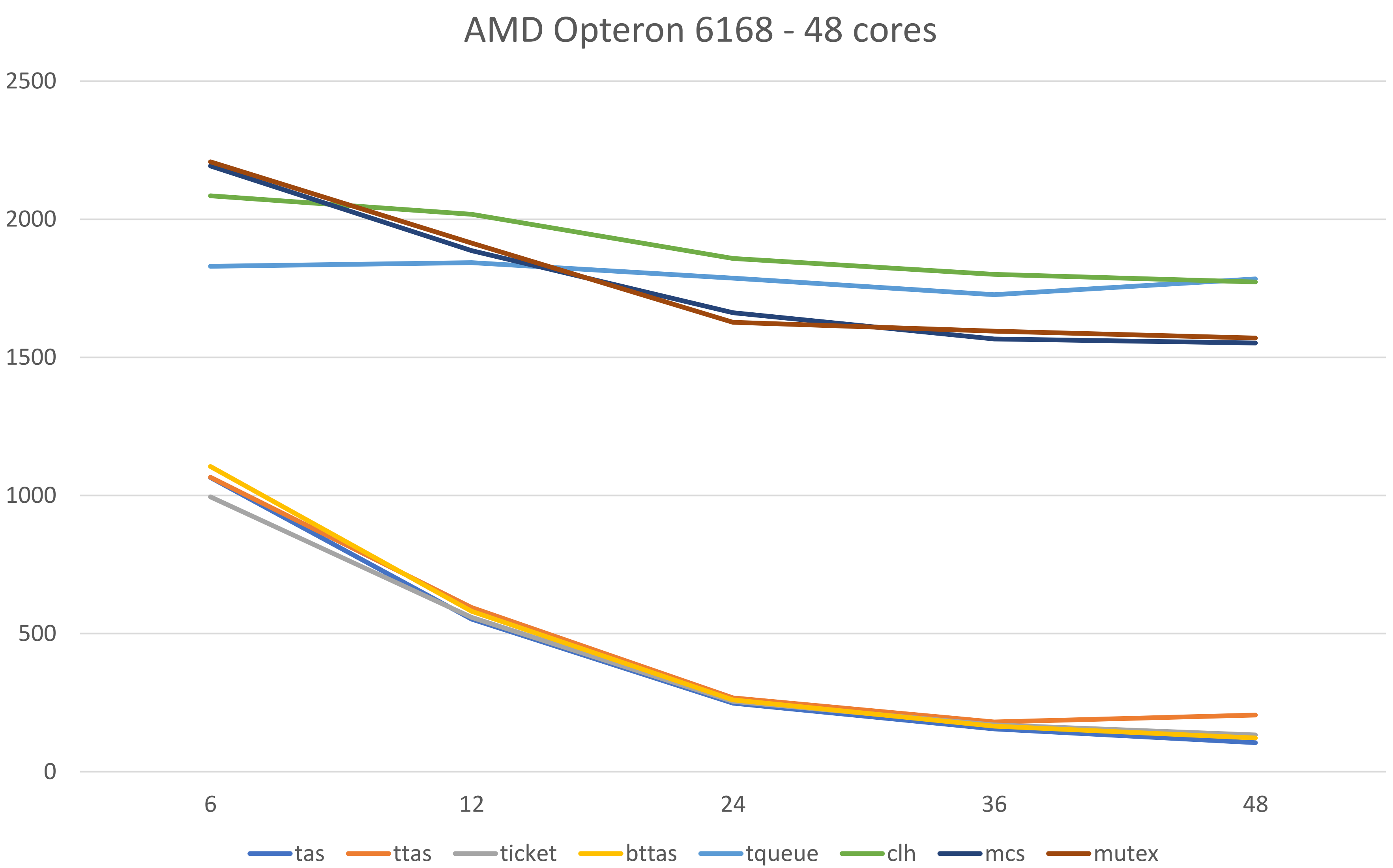
- Performance Metric:
  - Throughput = #Flips per second

One lock
to rule them all…

Performance

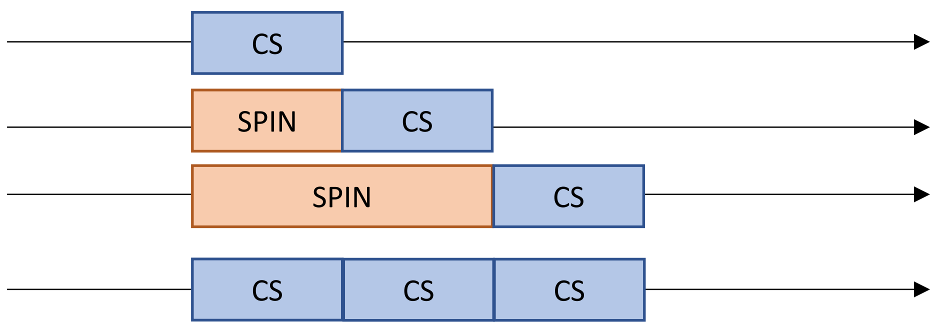


Performance



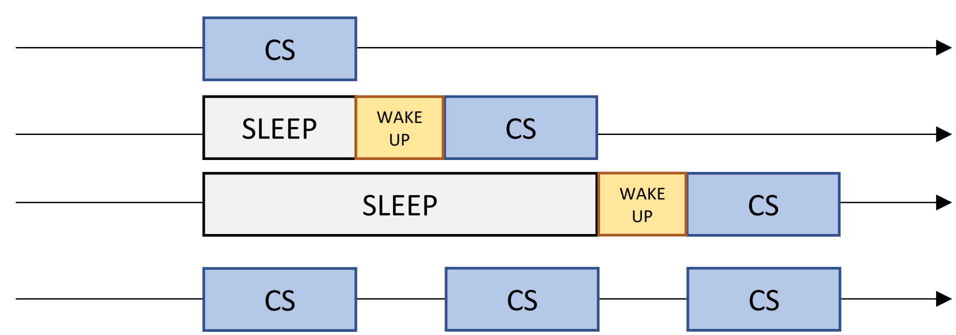
At the beginning was… Spin vs Sleep

	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	
spin with pause	
if still busy, sleep	

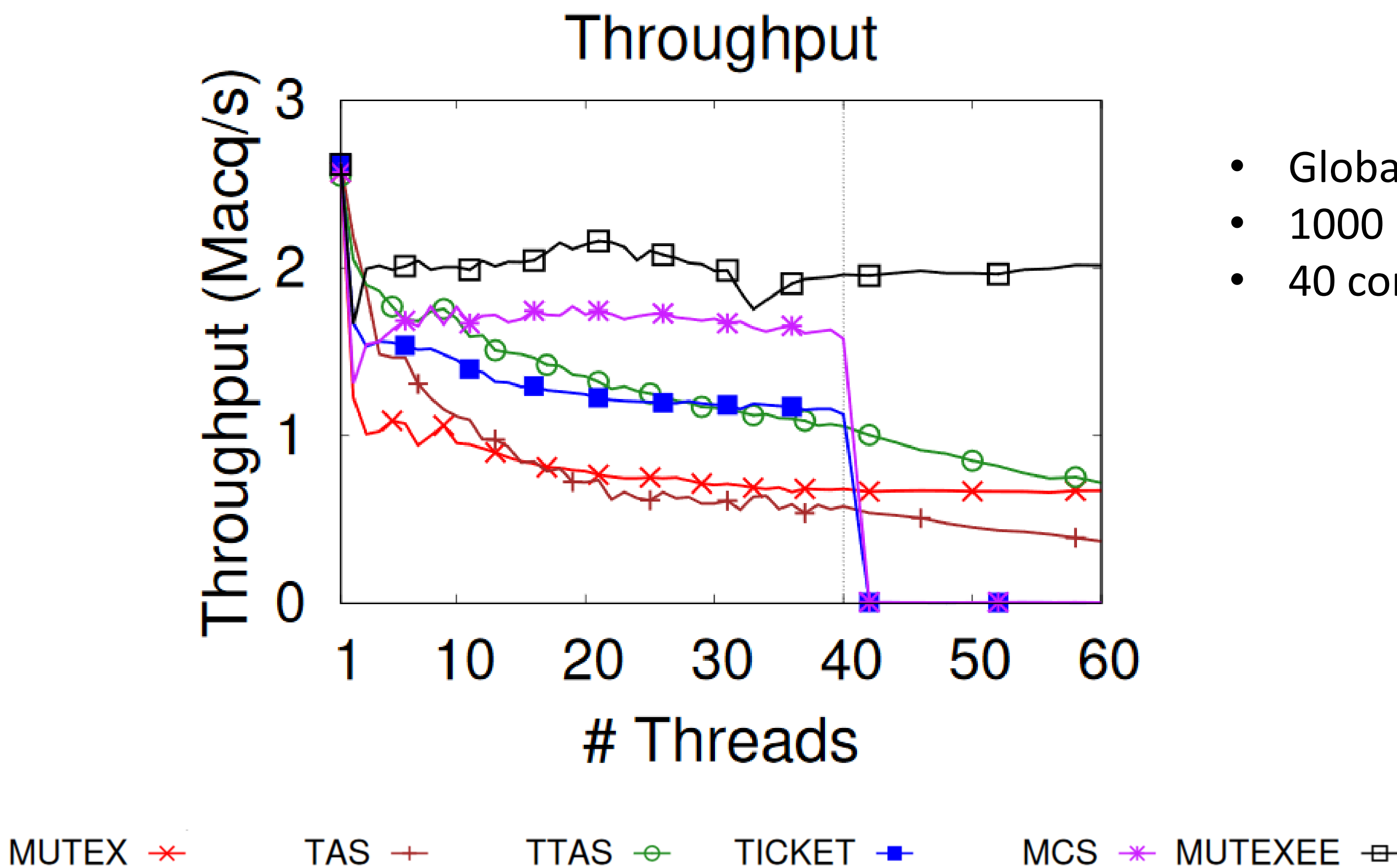
unlock()

MUTEX	MUTEXEE
release in user space (lock->locked = 0)	
wake up a thread	

Credits: Falsafi et all. “Unlocking energy”

An example - MutexEE

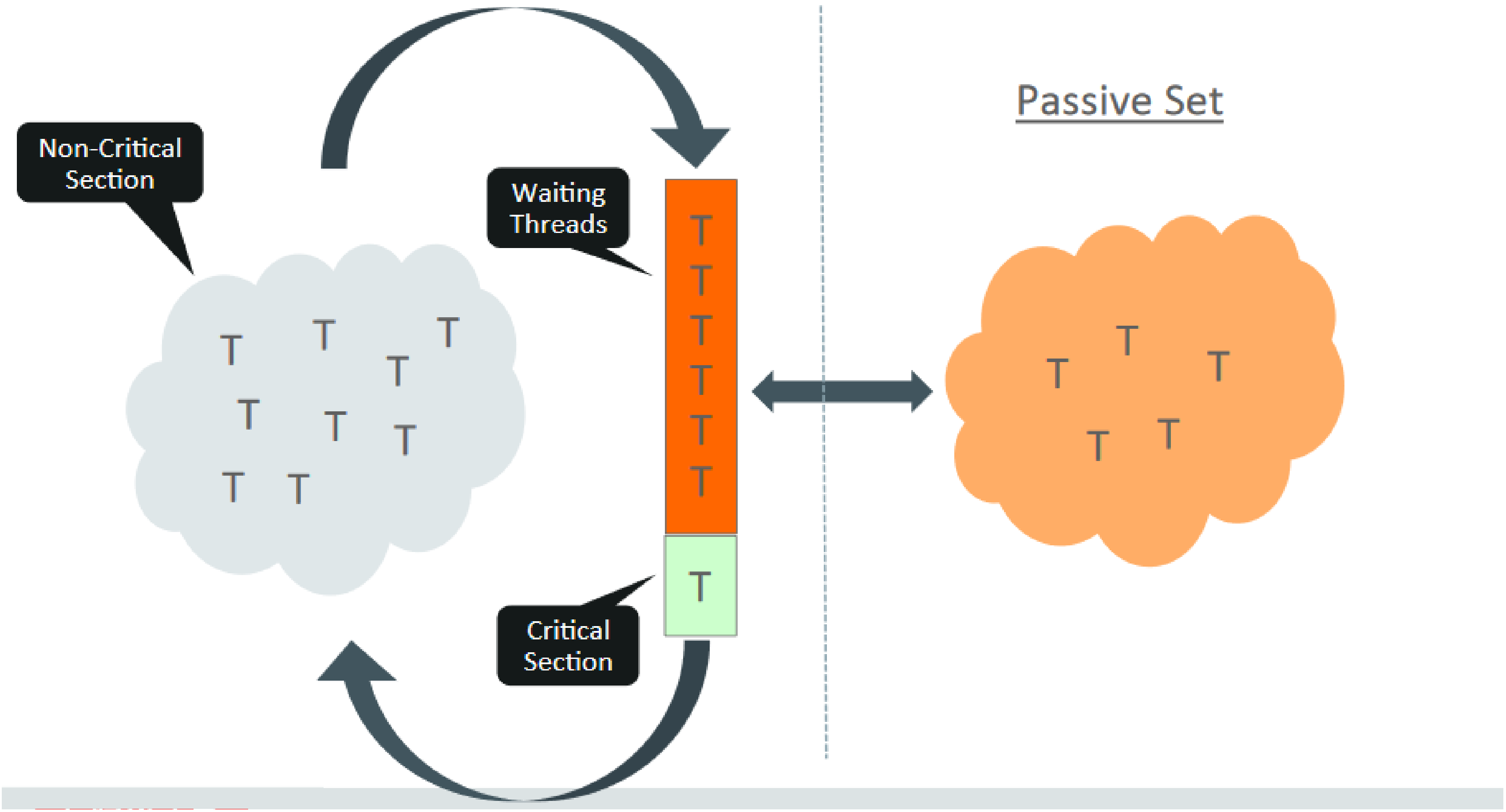
- MutexEE is a pthread_mutex optimized for throughput and energy efficiency



- Global lock
- 1000 cycles CS
- 40 cores

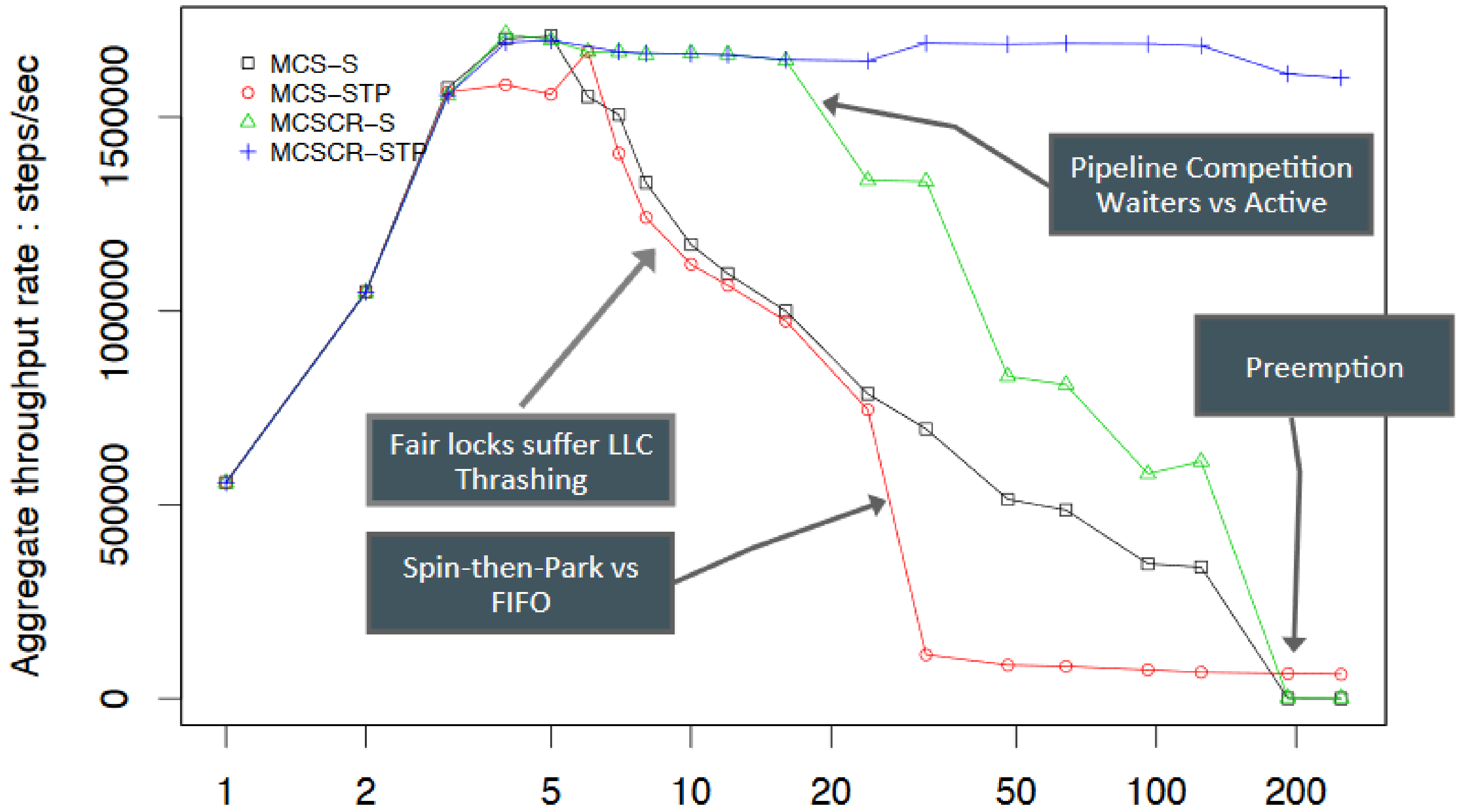
Credits: Falsafi et all. “Unlocking energy”

An example 2 – Malthusian locks



Credits: Dave Dice "Malthusian locks"

An example 2 – Malthusian locks



Credits: Dave Dice “Malthusian locks”

Hierarchical locks

HPC wants maximum usage of CPU power

- Sleeping might be required for better management of I/O
- Large number of cores per machine

⇒NUMA (again)

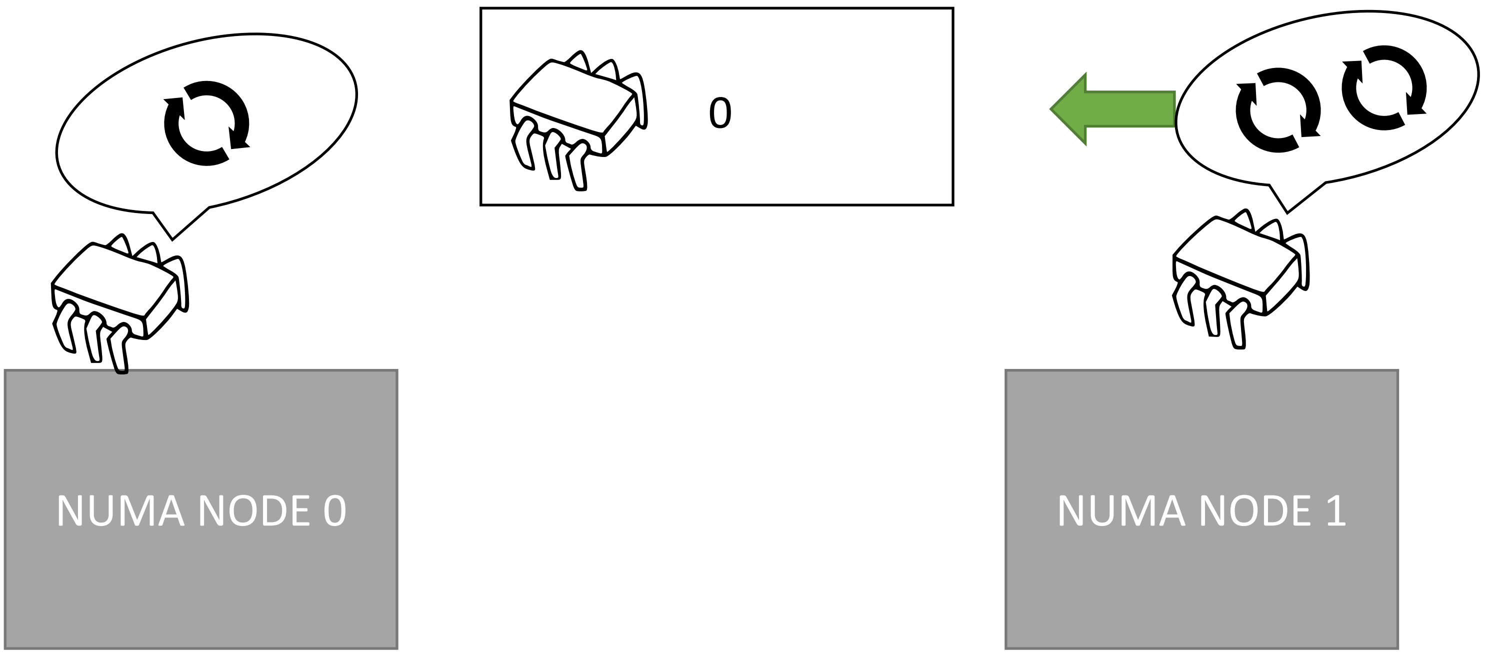
- FIFO locks cannot avoid transfer to remote NUMA nodes

Again, we can trade fairness in favor of throughput

Optimizing Critical Section Execution

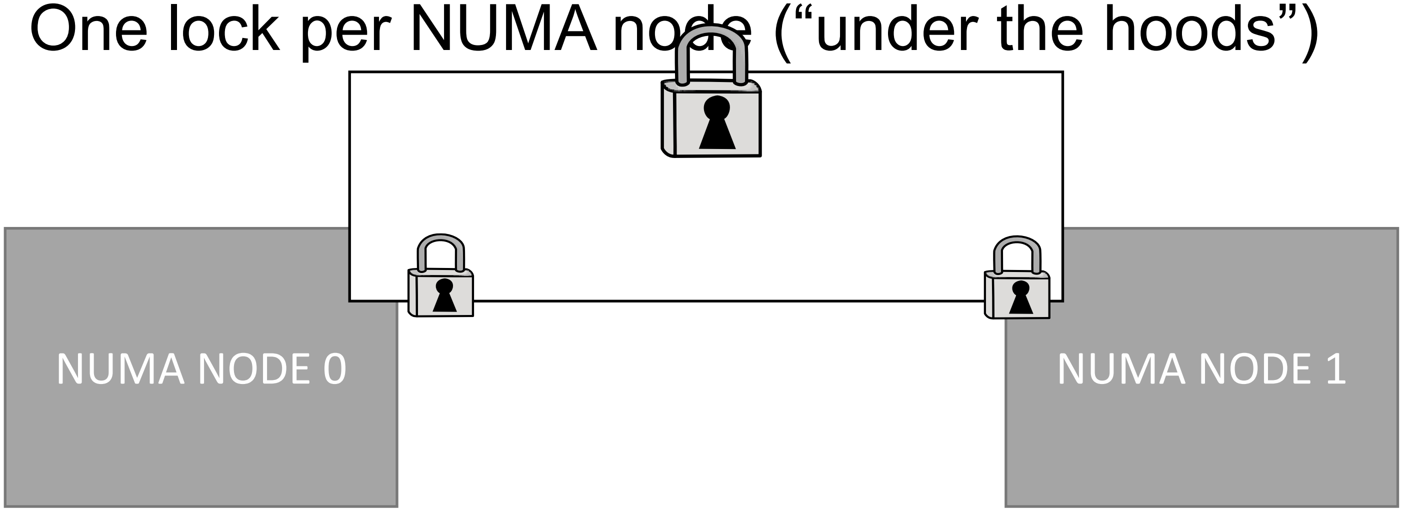
Hierarchical locks

- Transfer the lock to threads that reside on the same NUMA node
- Hierarchical TTAS
  - Shorter backoff for local threads, longer for remote ones



Hierarchical locks

- Transfer the lock to threads that reside on the same NUMA node
- Hierarchical TTAS
  - Shorter backoff for local threads, longer for remote ones
- Hierarchical QUEUE LOCKS (lock cohorting)
  - One global lock (the application one)
  - One lock per NUMA node ("under the hoods")



Optimizing the waiting phase

We have seen several approaches to optimize the lock acquisition phase:

- Back-off scheme
- Cache-awareness TTAS, FIFO locks
- Non-trivial combinations of both sleep and spin phases

What can we do to improve the execution of threads running the critical section?

- Improve locality and cache usage

How?

Observation:

- A lock (typically) protects data (instead of code)

Idea!

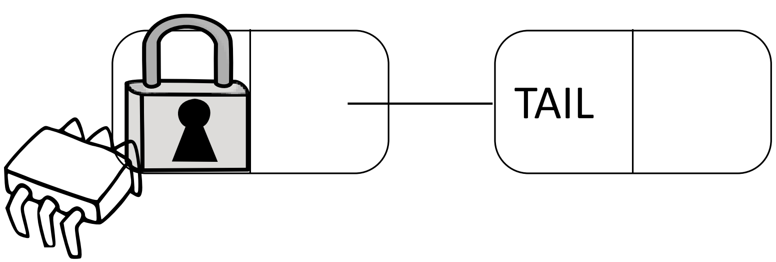
- There is a good chance that threads willing to acquire a lock want to access “similar” sets of data

$\Rightarrow$Allow thread holding the lock to execute the critical section for waiting threads

- Reduces lock handover costs
- Increases locality

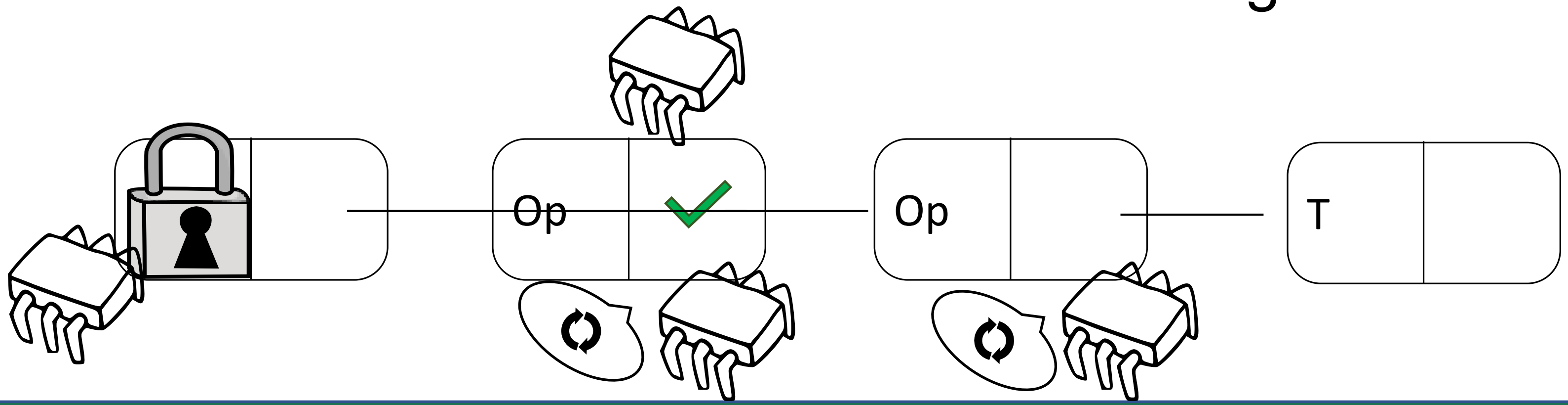
Flat Combining

- Use a linked list for holding waiting threads
- Each node maintains:
  - The waiting thread ID
  - The critical section descriptor
- Thread check waiting queue before releasing the lock
  - If empty exit



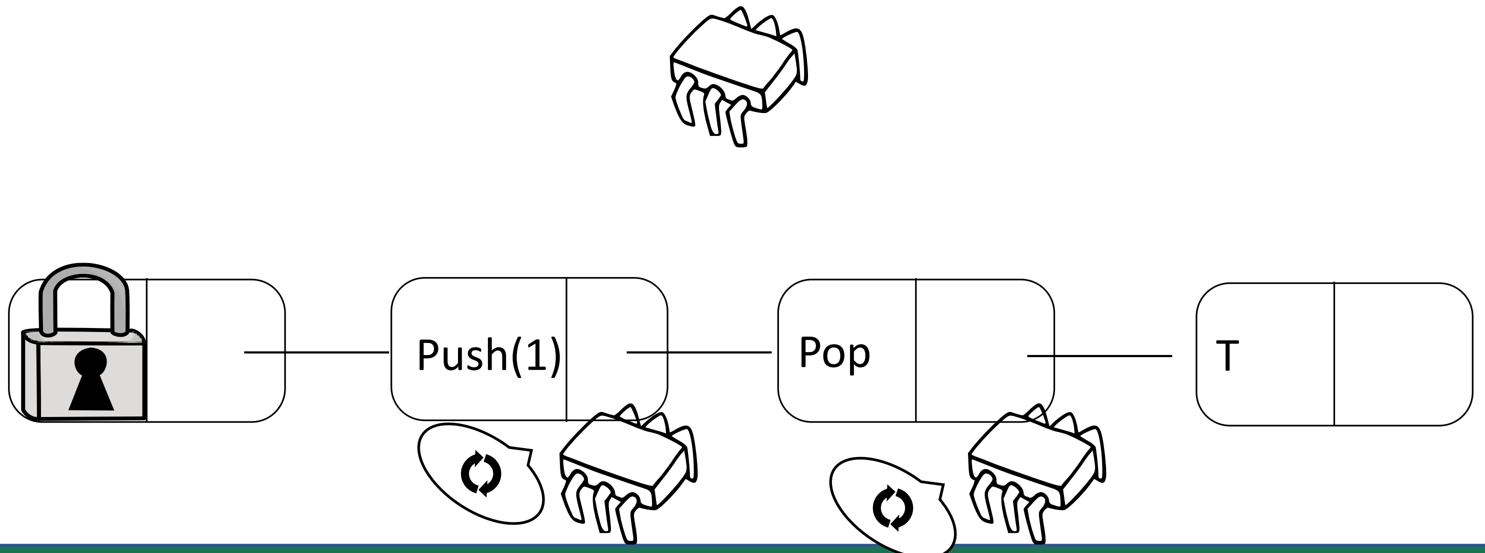
Flat Combining

- Use a linked list for holding waiting threads
- Each node maintains:
  - The waiting thread ID
  - The critical section descriptor
- Thread check waiting queue before releasing the lock
  - If empty exit
  - Otherwise take a node from the waiting queue and execute the critical section for the waiting thread



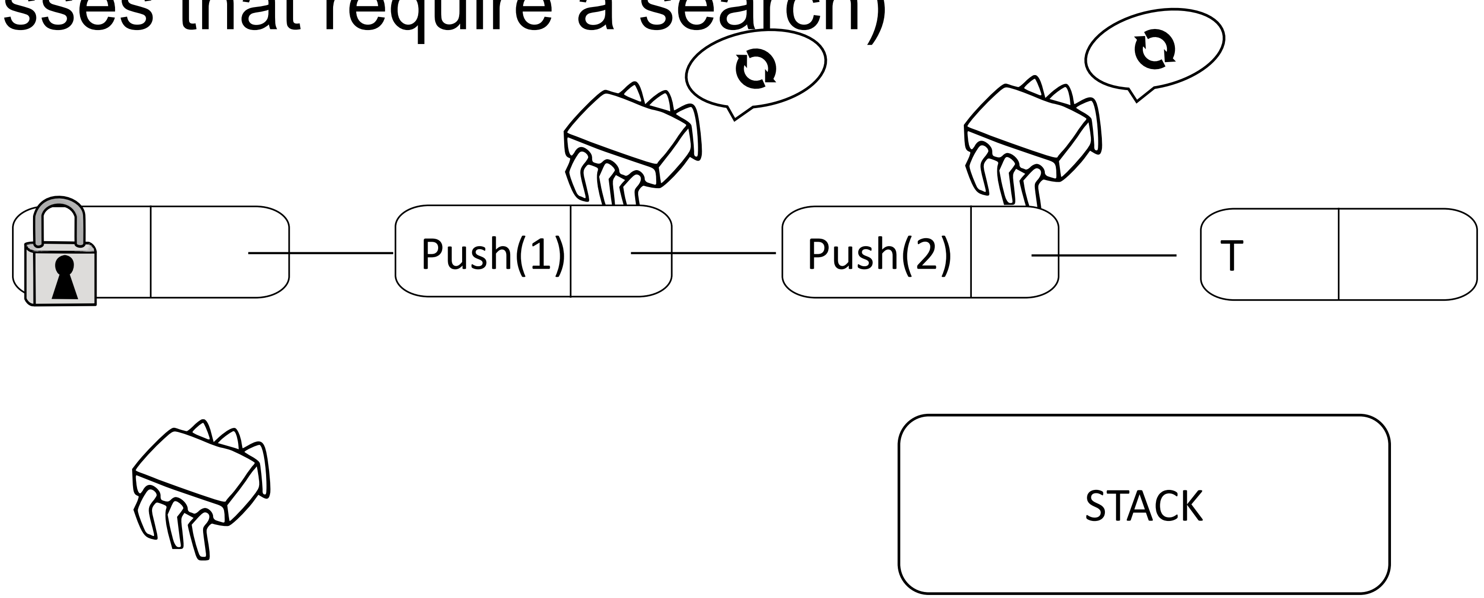
Flat Combining

- It might allow further (asymptotic) optimizations (e.g., data structures)
- Operations can be combined to each other BEFORE interacting with protected data

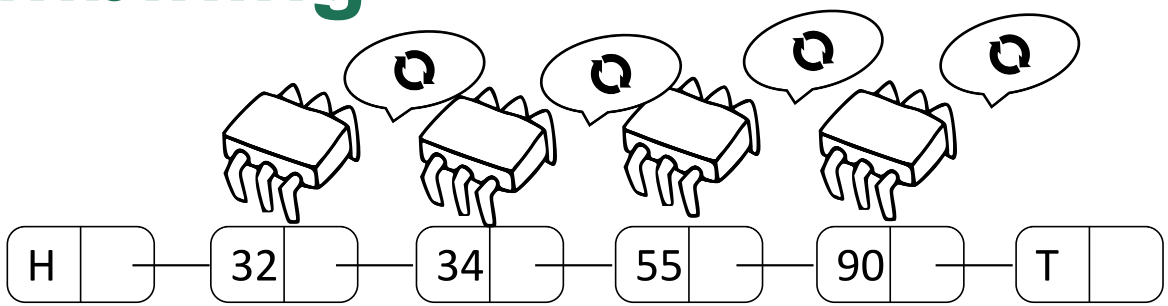


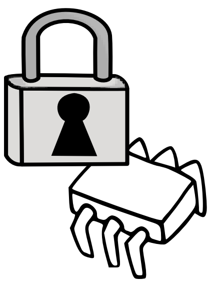
Flat Combining

- It might allow further (asymptotic) optimizations (e.g., data structures)
- Operations can be combined to each other BEFORE interacting with protected data
- Operations can be applied in batch (relevant for accesses that require a search)

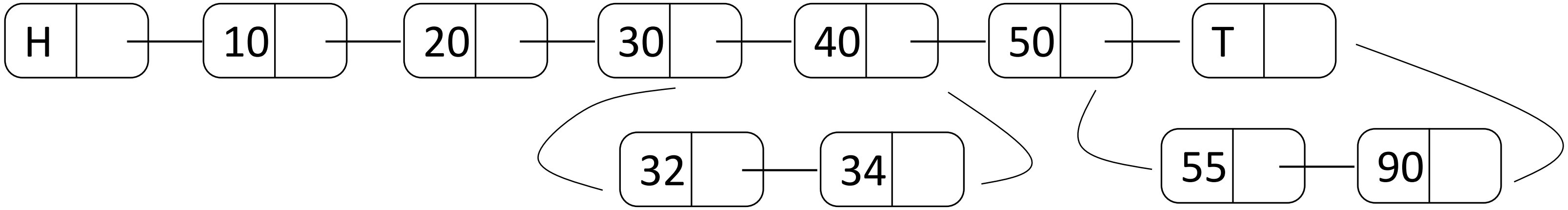


Flat Combining





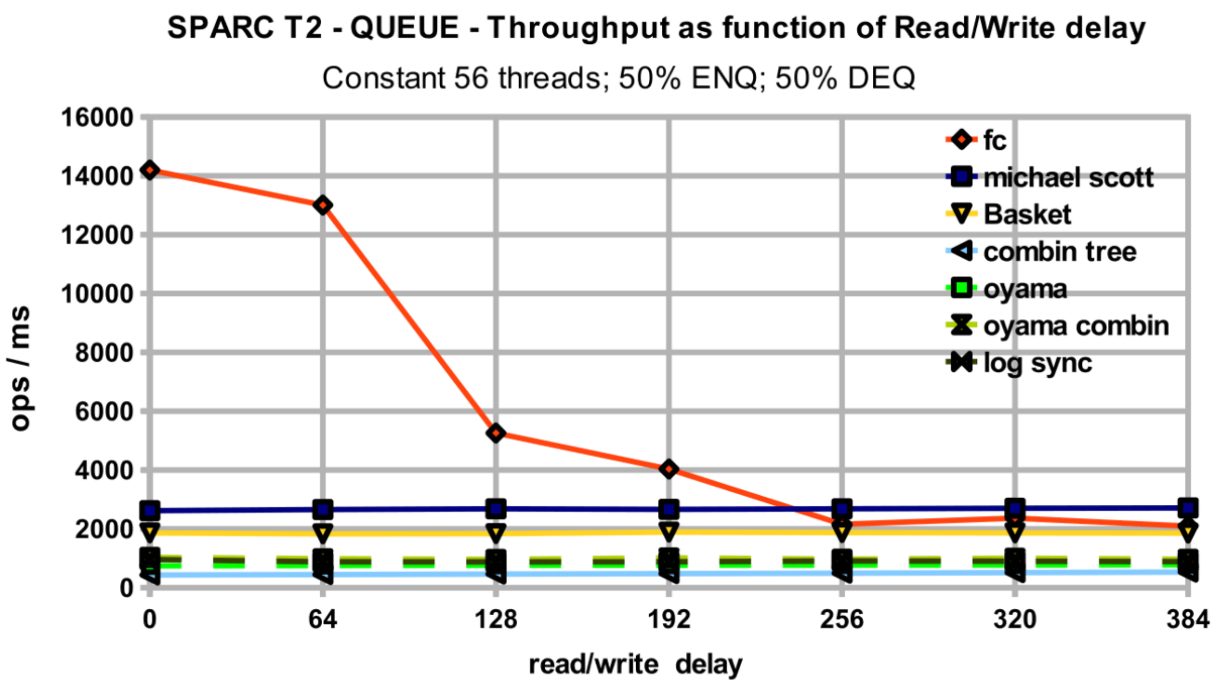
No need for restarting the search from scratch!



Flat Combining

Is it a silver bullet? Can replace complex lock-free algorithms?

NO!



HIGH CONTENTION LOW

Credits: Hendler et all. “Flat combining and the synchronization-parallelism tradeoff”

Flat Combining

Is it a silver bullet? Can replace complex lock-free algorithms?

- No, performance depends on the actual contention!
- Combining requires hand-written code!

How to improve for NUMA?

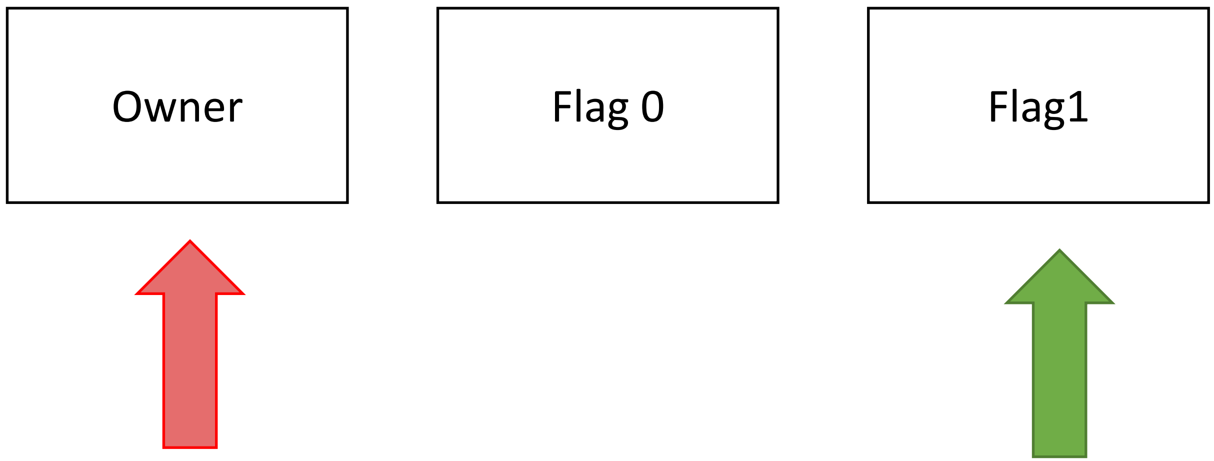
- Hierarchical Flat Combining

Approaches targeting peculiar workloads

- Read-Write locks
  - Threads that do not want to perform updates can acquire the lock with other "readers"
  - Threads willing to perform updates ("writers") take exclusive lock
- Easy to implement:
  - Lock < 0 : acquired by a writer
  - Lock = 0 : available
  - Lock = N > 0 : locked by N readers
- RW locks work well in read-mostly workloads, but:
  - It has a greater impact to readers (exclusive accesses to the lock variable)
  - Can be optimized by splitting the read counter

RW locks

Multiple RW locks (each one has its own cache line)

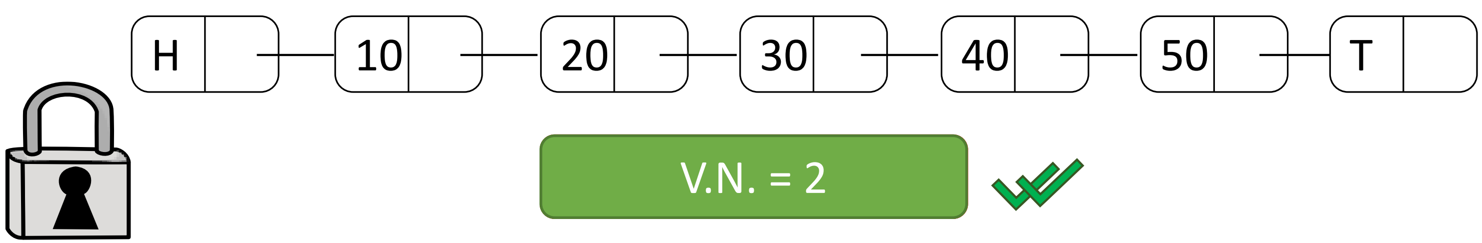


Writer acquire Owner
and spin until all flags
are 0

If Owner is free
Readers acquire their
assigned Flag (e.g. the
one of their numa node)
Then, check again Owner

Approaches targeting peculiar workloads (2)

- When read-only accesses are predominant, we can make reader DO NOT use any lock
- Version Numbers
- Writer:
  - Acquire a (writer) lock
  - Increase Version Number
  - Apply Update
  - Increase Version Number
  - Release Lock
- Reader:
  - Wait even Version Number
  - Do job
  - If Version Number is unchanged OK else retry



Approaches targeting peculiar workloads (3)

- When read-only accesses are predominant, we can make reader DO NOT use any lock
- Version Numbers
- Read-Copy-Update
  - Single shared-data entry point

These solutions NEEDS memory management
as non-blocking algorithms!!!