

Advanced Operating Systems

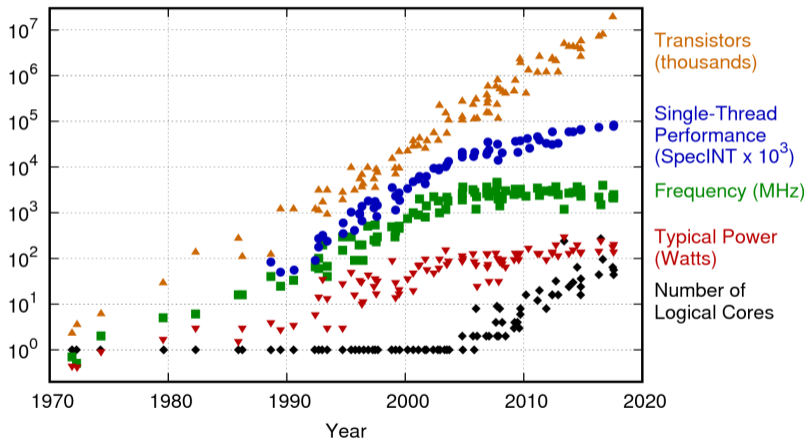
Synchronization in Parallel Systems

TILL SMEJKAL

June 8th, 2026

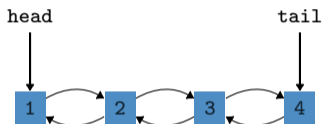
Why do we need synchronization?

42 Years of Microprocessor Trend Data

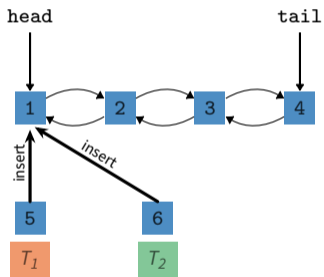


Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

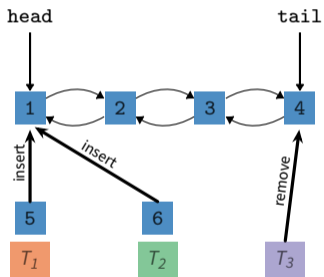
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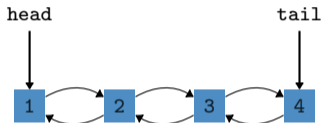
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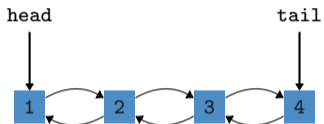


Why do we need synchronization?



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1 struct ele_t *new_ele = new ele_t;  
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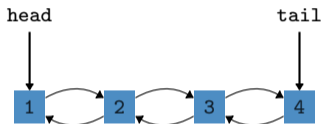
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 T_1 T_2

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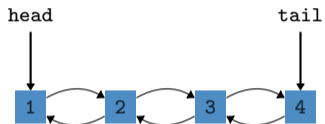
5

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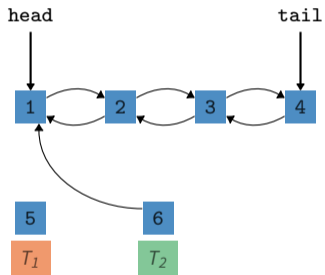

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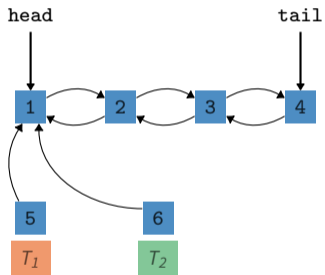

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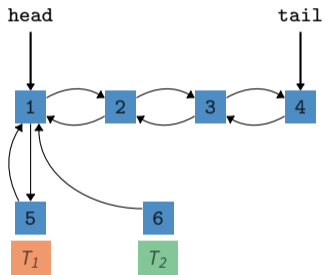
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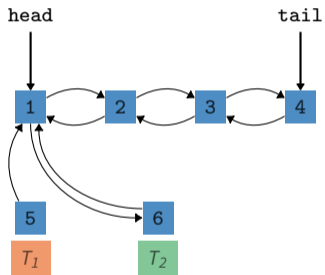
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Why do we need synchronization?



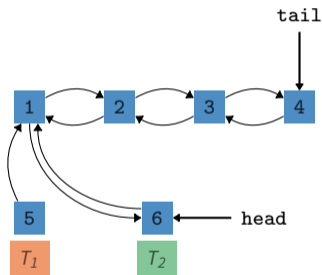
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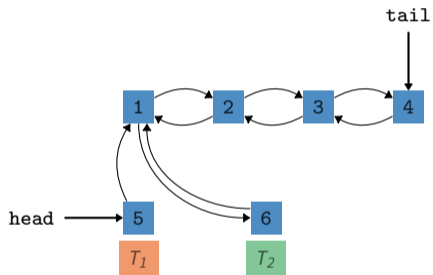


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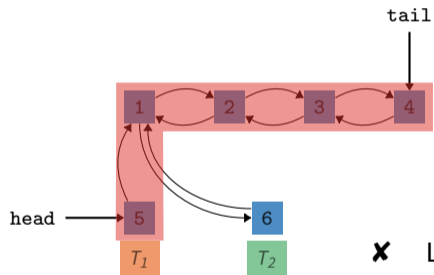
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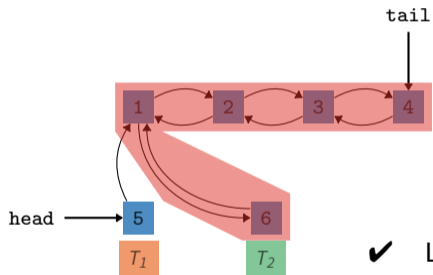
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- ✗ List structure correct
- ✓ head points to start of list

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Content

Basic Principles

Implementing Entersection & Leavesection

Atomicity on Hardware

- Cache Lock
- Observe Cache
- Atomic Instructions

Synchronization with Locks – Part I

- Test & Set Lock
- Test & Test & Set Lock
- Ticket Lock

Synchronization without Locks

Synchronization with Locks – Part II

- MCS Lock

Basic Principles

Atomicity Assumption

$$A \parallel B = A;B \vee B;A$$

Basic Principles

Atomicity Assumption

Parallel execu-
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$A \parallel B = A;B \vee B;A$

Sequentiell execu-
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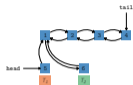
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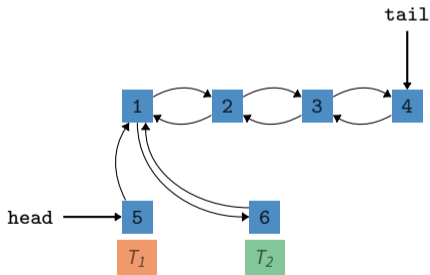
- Otherwise, the outcome of $A \parallel B$ is undefined
- Usually problematic for parallel *Read-Modify-Write* operations

Basic Principles

Mutual Exclusion



A || B



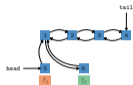
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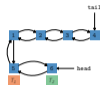
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Basic Principles

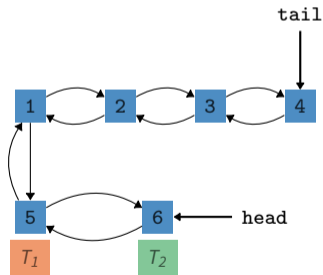
Mutual Exclusion



A || B



A;B



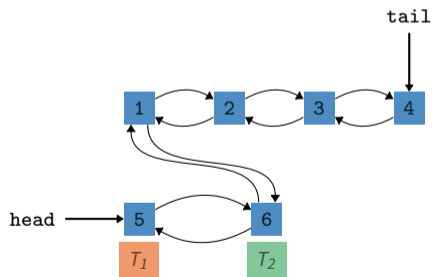
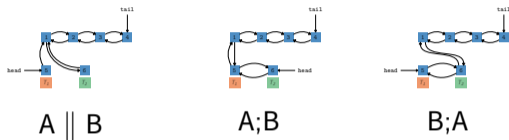
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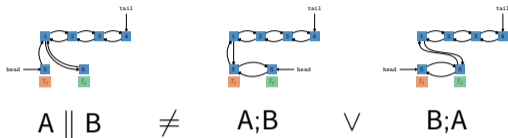
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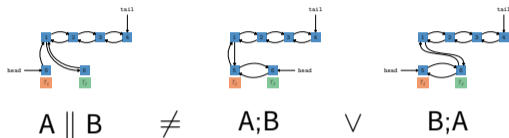
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Basic Principles

Mutual Exclusion



Need to ensure that only one thread at a time can execute the *Read-Modify-Write* operation.

⇒ **Mutual Exclusion**

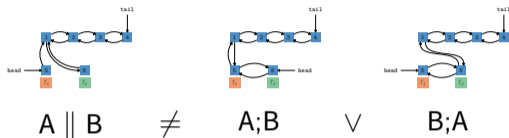
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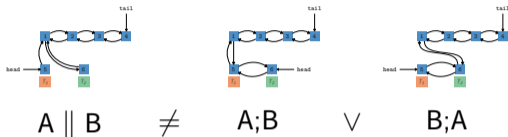
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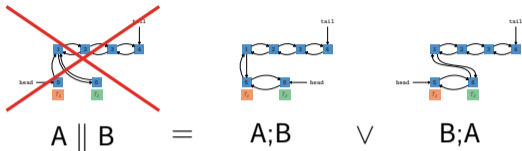
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Should run with mutual exclusion!

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Should run with mutual exclusion!

Basic Principles

Entersection & Leavesection

Simple protocol to establish mutual exclusion for critical sections.

```
1 struct ele_t *new_ele = new ele_t;
2 entersection();
3 new_ele->next = head;
4 head->prev = new_ele;
5 head = new_ele;
6 leavesection();
```

} CS

```
1 void entersection() {
2     while (!cs_free) wait();
3     cs_free = false;
4 }
```

```
1 void leavesection() {
2     cs_free = true;
3     wake_next();
4 }
```

Basic Principles

Entersection & Leavesection

Simple protocol to establish mutual exclusion for critical sections.

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Rules:

- entersection and leavesection *must always* exist in pairs
- entersection *must always* be before the corresponding leavesection

Basic Principles

Entersection & Leavesection

Simple protocol to establish mutual exclusion for critical sections.

```
1 struct ele_t *new_ele = new ele_t;
2 lock();
3 new_ele->next = head;
4 head->prev = new_ele;
5 head = new_ele;
6 unlock();
```

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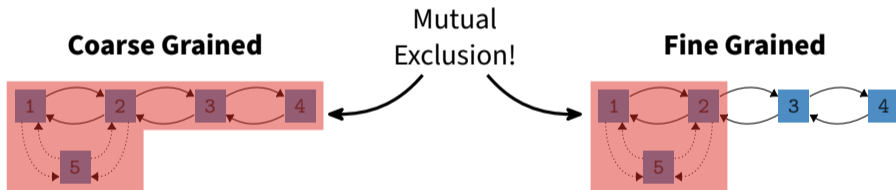
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Basic Principles

Coarse Grained vs. Fine Grained

Critical Sections should be as long as necessary but also as short as possible.

- Length of critical sections are important for scalability → Amdahl's Law



- Worse scalability (no parallel operations)
- + Easier to implement

- + Better scalability (parallel operations possible)
- More difficult to implement
- Deadlocks may happen

Implementing Entersection & Leavesection

Peterson Algorithm

```
1 bool free[2] = {true, true};
2 int turn = 0;
3
4 void lock() {
5     int other = 1 - TID;          /* TID: ID of the current thread ({0,1}) */
6     free[TID] = false;
7     turn = other;
8     while (!free[other] && turn == other) {}
9 }
10
11 void unlock() {
12     free[TID] = true;
13 }
```

- Works for two threads (more threads are possible but it gets complicated)
- Requires atomic load and stores and sequential consistency (or additional fence)

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1;
6 }
7
8 void unlock() {
9     l = 0;
10 }
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture

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```

Diagram illustrating the lock acquisition logic:

```
1 == 0
   |
   v
while (l == 1) {}
```

An arrow points from the text "1 == 0" to the condition in the while loop, and another arrow points from the while loop to the code line "while (l == 1) {}".

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Diagram illustrating the naive spinlock implementation. The code shows a lock variable `l` initialized to 0. The `lock()` function enters a `while` loop that checks if `l == 1`. An arrow points to the condition `l == 1` with the text `l == 0` above it, indicating that the condition is false and the loop body is not executed.

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Diagram illustrating a naive spinlock implementation. The code shows a lock variable `l` initialized to 0. The `lock()` function enters a `while` loop that checks if `l == 1`. If true, it spins. If false, it sets `l = 1`. The `unlock()` function sets `l = 0`. Annotations show a green arrow pointing to the `lock()` function call and an orange arrow pointing to the `while` loop condition. A vertical arrow labeled `l == 0` points to the `while` loop, indicating the state of the lock variable during the spin.

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Diagram illustrating a naive spinlock implementation. The code shows a lock variable `l` initialized to 0. The `lock()` function enters a `while` loop that spins as long as `l == 1`. A diagram shows the condition `l == 0` above the loop, with an arrow pointing down to the loop body, indicating that the loop body is executed because the condition is false.

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```
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```

```
7
```

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8 void unlock() {
```

```
9     l = 0;
```

```
10 }
```

```
1 == 0
```



```
1 == 0
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Diagram illustrating the lock acquisition logic:

- Line 4: `while (l == 1) {}` - A loop that spins while the lock is held.
- Line 5: `l = 1;` - The lock is acquired.
- Annotations: A green arrow points to the condition `l == 1` in line 4. A red arrow points to the loop body in line 4. A red arrow points to the assignment `l = 1;` in line 5.

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1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1; ←
6 } ←
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1; ←
6 }
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */ ←
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1;
6 } ←
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */ ←
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1;
6 }
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */ ←
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {}
5     l = 1;
6 }
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */ ← ⚡
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Implementing Entersection & Leavesection

Naive Spinlock (*Wrong!*)

```
1 int l = 0;
2
3 void lock() {
4     while (l == 1) {} } CS (internal)
5     l = 1;
6 }
7
8 void unlock() {
9     l = 0;
10 }
```

```
1 /* do other stuff */
2 lock();
3 /* critical section */ ← ⚡
4 unlock();
```

- Works for any number of threads
- Simple approach which can work on any hardware architecture
- Requires solving internal critical section → hardware support

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 cmp [x] $0;  
2 jne retry;
```

Core 2

```
1 mov $1 [x];
```

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 load [x] %eax;  
2 cmp %eax $0;  
3 jne retry;
```

Core 2

```
1 store $1 [x];
```

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 load [x] %eax;  
2 cmp %eax $0;  
3 jne retry;
```

Core 2

```
1 store $1 [x];
```

Core 1

Memory

x:0

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax; ←
2 cmp %eax $0;
3 jne retry;

```

Core 2

```

1 store $1 [x];

```

Core 1

eax:0

Memory

x:0

← Load(x)

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax; ←
2 cmp %eax $0;
3 jne retry;

```

Core 2

```

1 store $1 [x]; ←

```

Core 1

eax:0

Memory

x:1

Core 2

Store(x)

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax;
2 cmp %eax $0;
3 jne retry;

```

Core 2

```

1 store $1 [x];

```

Core 1

eax:0

Memory

x:1

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 load [x] %eax;
2 cmp %eax $0;
3 jne retry;
```

Comparison with 0
although x == 1 already

Core 2

```
1 store $1 [x];
```

Core 1

eax:0

Memory

x:1

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 add [x] $1;
```

Core 2

```
1 mov $2 [x];
```

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 load [x] %eax;  
2 add %eax $1;  
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

Memory

x:0

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax; ←
2 add %eax $1;
3 store %eax [x];

```

Core 2

```

1 store $2 [x];

```

Core 1

eax:0

Memory

x:0

Load(x)

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax; ←
2 add %eax $1;
3 store %eax [x];

```

Core 2

```

1 store $2 [x]; ←

```

Core 1

eax:0

Memory

x:2

← Store(x)

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax;
2 add %eax $1;
3 store %eax [x];

```

Core 2

```

1 store $2 [x];

```

Core 1

eax:1

Memory

x:2

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```

1 load [x] %eax;
2 add %eax $1;
3 store %eax [x];

```

Core 2

```

1 store $2 [x];

```

Core 1

eax: 1

Memory

x: 1

Store(x)

Core 2

Atomicity on Hardware

Atomicity Assumption on Hardware

$$A \parallel B = A;B \vee B;A$$

- Always guaranteed for single-core systems
- Usually not guaranteed for multi-core systems
- Especially problematic for *Read-Modify-Write* instructions

Core 1

```
1 load [x] %eax;
2 add %eax $1;
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```

x == 1 although
A;B: x == 2 or B;A: x == 3

Core 1

eax: 1

Memory

x: 1 ⚡

Core 2

Atomicity on Hardware

Atomic Hardware Instructions

How to make instructions atomic?

- Bus Lock
 - Lock whole memory bus until all memory accesses of instruction are completed
 - Used in older x86 CPUs (Intel® Pentium 3 and older)
 - Uses `lock` assembler attribute

Atomicity on Hardware

Atomic Hardware Instructions

How to make instructions atomic?

- Bus Lock
 - Lock whole memory bus until all memory accesses of instruction are completed
 - Used in older x86 CPUs (Intel® Pentium 3 and older)
 - Uses `lock` assembler attribute
- Cache Lock
 - Delay cache coherency traffic until all memory accesses of instruction are completed
 - Used in newer x86 CPUs (Intel® Pentium 4 and newer)
 - Special atomic instructions (e.g. `cmpxchg` or `xadd`)

Atomicity on Hardware

Atomic Hardware Instructions

How to make instructions atomic?

- Bus Lock
 - Lock whole memory bus until all memory accesses of instruction are completed
 - Used in older x86 CPUs (Intel® Pentium 3 and older)
 - Uses `lock` assembler attribute
- Cache Lock
 - Delay cache coherency traffic until all memory accesses of instruction are completed
 - Used in newer x86 CPUs (Intel® Pentium 4 and newer)
 - Special atomic instructions (e.g. `cmpxchg` or `xadd`)
- Observe Cache
 - Install watchdog on load and check at corresponding store if a concurrent access happened and abort
 - Used on arm and Alpha CPUs
 - Uses special `ldrex` and `strex` instructions

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 add $1 [x];
```

Core 2

```
1 mov $2 [x];
```

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;  
2 add $1 %eax;  
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;  
2 add $1 %eax;  
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

x:0 → S

Memory

x:0

Core 2

x:0 → S

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```

1 loadx [x] %eax; ←
2 add $1 %eax;
3 store %eax [x];

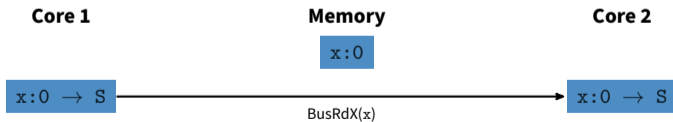
```

Core 2

```

1 store $2 [x];

```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```

1 loadx [x] %eax; ←
2 add $1 %eax;
3 store %eax [x];

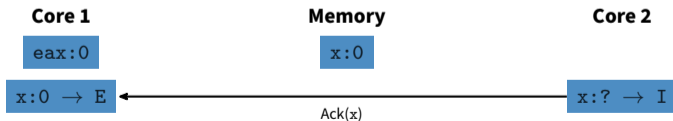
```

Core 2

```

1 store $2 [x];

```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax; ←
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

eax:1

x:0 → E

Memory

x:0

Core 2

x:? → I

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax; ←
3 store %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```

Core 1

eax:1

x:0 → E

Memory

x:0

Core 2

x:? → I

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

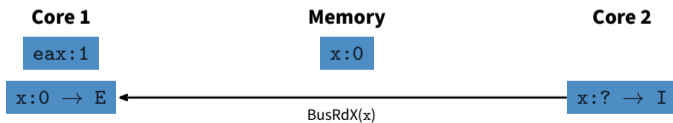
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax; ←
3 store %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

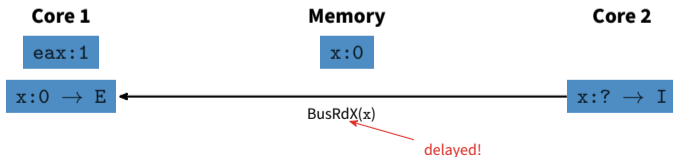
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax; ←
3 store %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

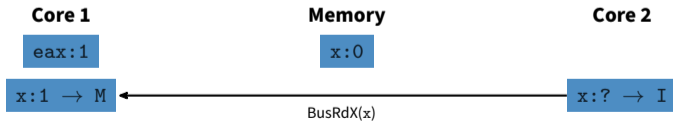
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax;
3 store %eax [x]; ←
```

Core 2

```
1 store $2 [x]; ←
```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

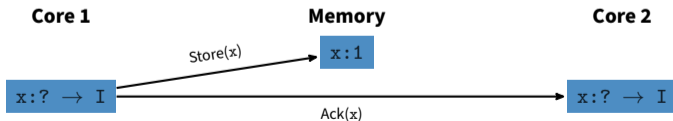
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax;
3 store %eax [x]; ←
```

Core 2

```
1 store $2 [x]; ←
```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

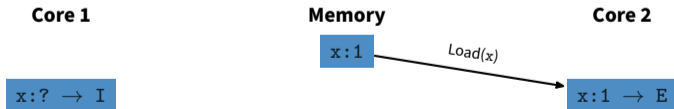
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax;
3 store %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```



Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;
2 add $1 %eax;
3 store %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```

Core 1

x:? → I

Memory

x:1

Core 2

x:2 → M

Atomicity on Hardware

Atomic Instructions with Cache Lock

General Idea

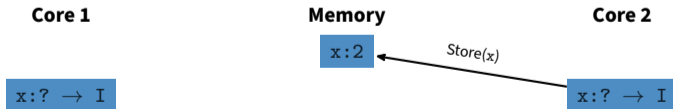
Delay all cache coherency traffic (*snoop messages*) until all memory accesses of an *atomic* Read-Modify-Write instruction are finished.

Core 1

```
1 loadx [x] %eax;  
2 add $1 %eax;  
3 store %eax [x];
```

Core 2

```
1 store $2 [x];
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 add $1 [x];
```

Core 2

```
1 mov $2 [x];
```

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;  
2 add $1 %eax;  
3 strex %eax [x];
```

Core 2

```
1 store $2 [x];
```

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;  
2 add $1 %eax;  
3 strex %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

x:0 → S

Memory

x:0

Core 2

x:0 → S

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

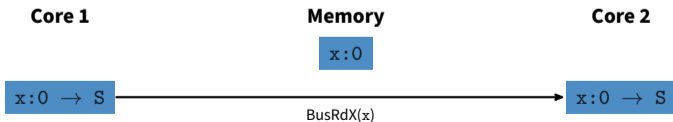
```

1 ldrex [x] %eax; ←
2 add $1 %eax;
3 strex %eax [x];
  
```

Core 2

```

1 store $2 [x];
  
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

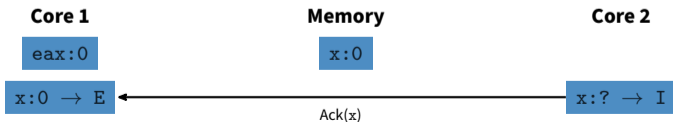
```

1 ldrex [x] %eax; ←
2 add $1 %eax;
3 strex %eax [x];
  
```

Core 2

```

1 store $2 [x];
  
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

eax:1

x:0 → E

Memory

x:0

Core 2

x:? → I

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax;
3 strex %eax [x]; ←
```

Core 2

```
1 store $2 [x];
```

Core 1

x:1 → M

Memory

x:0

Core 2

x:? → I

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

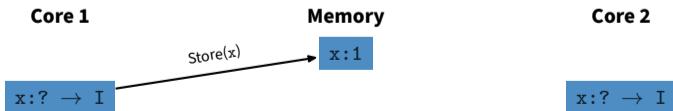
Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax;
3 strex %eax [x]; ← ✓ Success
```

Core 2

```
1 store $2 [x];
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

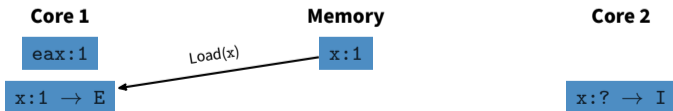
```

1 ldrex [x] %eax; ←
2 add $1 %eax;
3 strex %eax [x];
  
```

Core 2

```

1 store $2 [x];
  
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
```

Core 2

```
1 store $2 [x];
```

Core 1

eax:2

x:1 → E

Memory

x:1

Core 2

x:? → I

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

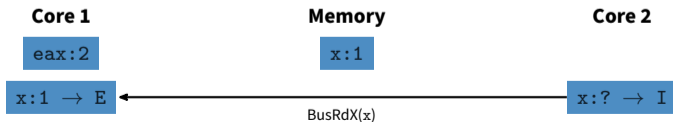
```

1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
  
```

Core 2

```

1 store $2 [x]; ←
  
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

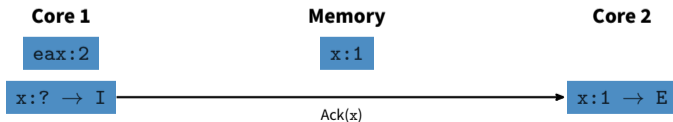
```

1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
  
```

Core 2

```

1 store $2 [x]; ←
  
```



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
```

Core 2

```
1 store $2 [x]; ←
```

Core 1

eax:2

x:? → I

Memory

x:1

Core 2

x:2 → M

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```

1 ldrex [x] %eax;
2 add $1 %eax; ←
3 strex %eax [x];
  
```

Core 1

eax:2

x:? → I

Core 2

```

1 store $2 [x];
  
```

Memory

x:2

Core 2

x:? → I

Store(x)



Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```
1 ldrex [x] %eax;
2 add $1 %eax;
3 strex %eax [x]; ←
```

Core 2

```
1 store $2 [x];
```

Core 1

eax:2

x:? → I

Memory

x:2

Core 2

Atomicity on Hardware

Atomic Instructions with Observe Cache

General Idea

Install a watchdog when the *atomic* instruction references the memory location and check for parallel accesses before storing to the memory location again. In case of parallel accesses, abort the store and retry the whole *atomic* instruction.

Core 1

```

1 ldrex [x] %eax;
2 add $1 %eax;
3 strex %eax [x]; ← ✖ Abort
  
```

Core 2

```
1 store $2 [x];
```

Core 1

eax:2

x:? → I

Memory

x:2

Core 2

Atomicity on Hardware

Examples of Atomic Instructions

- `swap(mem1, mem2)`

```
1 mov [mem1] %eax;  
2 mov [mem2] [mem1];  
3 mov %eax [mem2];
```

- `xadd(mem, reg)`

```
1 mov [mem] %eax;  
2 add [mem] reg;  
3 return %eax;
```

- `cas(mem, expected, desired)`

```
1 cmp [mem] [expected];  
2 jne fail;  
3 mov [desired] [mem];  
4 return true;  
5 fail: return false;
```

Synchronization with Locks

Properties

Main Properties

- Mutual Exclusion
 - Required by every *correct* implementation of the Entersection & Leavesection protocol
- Overhead
 - Acquiring a lock should be a cheap operation
 - If the lock is currently free, acquiring the lock should be especially cheap
- Fairness
 - Every thread should be able to acquire the lock eventually

Synchronization with Locks

Properties

Advanced Properties

- Concurrent access to critical section
 - Allow multiple threads to acquire the lock simultaneously
- Abort pending lock operations
 - Abort acquiring a currently taken lock after a timeout
 - Kill threads currently acquiring a lock
- Lock holder preemption
 - Prevent the threads currently holding the lock from making progress
- Priority inversion
 - Prevent higher priority threads from making progress because of a lower priority thread holding a shared lock
- Spinning vs. Blocking

Test & Set Lock

```
1 struct ts_lock_t {
2     volatile int lock;
3 };
4
4 void lock(ts_lock_t *l) {
5     do {
6         int tmp = 1;
7         swap(&(l->lock), &(tmp));
8     } while (tmp == 1);
9 }
10
11 void unlock(ts_lock_t *l) {
12     l->lock = 0;
13 }
```

- Very easy to implement
- Only requires one atomic instruction

But

- High cache-coherency bus traffic when lock is taken
- No fairness between threads

Test & Set Lock

Overhead

```
1 struct ts_lock_t {
2     volatile int lock;
3 };
4 void lock(ts_lock_t *l) {
5     do {
6         int tmp = 1;
7         swap(&(l->lock), &(tmp));
8     } while (tmp == 1);
9 }
11 void unlock(ts_lock_t *l) {
12     l->lock = 0;
13 }
```

```
1 struct ts_lock_t l;
2
3 void thread_fn(void) {
4     /* Other stuff */
5     lock(&l);
6     /* CS */
7     unlock(&l);
8 }
```

Test & Set Lock

Overhead

```

1 struct ts_lock_t {
2     volatile int lock;
3 };

4 void lock(ts_lock_t *l) {
5     do {
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2
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5     lock(&l);
6     /* CS */
7     unlock(&l);
8 }

```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

```

1 struct ts_lock_t {
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```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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```

Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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```

Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Set Lock

Overhead

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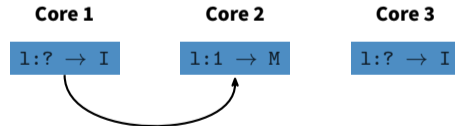
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Test & Set Lock

Overhead

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```

Core 1

l:? → I

Core 2

l:1 → M

Core 3

l:? → I

Test & Set Lock

Overhead

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Core 1

l:? → I

Core 2

l:1 → M

Core 3

l:? → I

Test & Set Lock

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Core 1

l:? → I

Core 2

l:1 → M

Core 3

l:? → I

Test & Set Lock

Overhead

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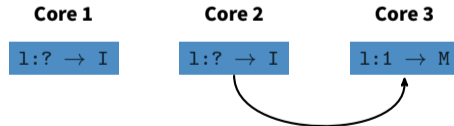
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Test & Set Lock

Overhead

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```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:1 → M

Test & Set Lock

Overhead

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```

```

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```

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7     unlock(&l);
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```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:1 → M

Test & Set Lock

Overhead

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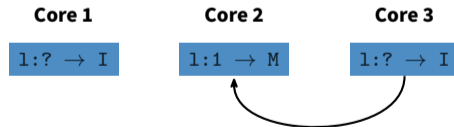
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```

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```



Test & Set Lock

Overhead

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```

```

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2
3 void thread_fn(void) {
4     /* Other stuff */
5     lock(&l);
6     /* CS */ ←
7     unlock(&l);
8 }

```

Core 1

l:? → I

Core 2

l:1 → M

Core 3

l:? → I

Test & Test & Set Lock

```
1 struct tts_lock_t {
2     volatile int lock;
3 };
4 void lock(tts_lock_t *l) {
5     do {
6         int tmp = 1;
7         do {} while (l->lock == 1);
8         swap(&(l->lock), &(tmp));
9     } while (tmp == 1);
10 }
11 void unlock(tts_lock_t *l) {
12     l->lock = 0;
13 }
```

- As simple as Test & Set Lock but with less cache traffic
- Most widespread lock implementation

But

- No fairness between threads

Test & Test & Set Lock

Overhead

```
1 struct tts_lock_t {
2     volatile int lock;
3 };
4 void lock(tts_lock_t *l) {
5     do {
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1 struct tts_lock_t l;
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3 void thread_fn(void) {
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```

Test & Test & Set Lock

Overhead

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```

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2
3 void thread_fn(void) {
4     /* Other stuff */ ←
5     lock(&l);
6     /* CS */
7     unlock(&l);
8 }

```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

1 struct tts_lock_t {
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```

1 struct tts_lock_t l;
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7     unlock(&l);
8 }

```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

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```

Core 1

l:? → I

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

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```

1 struct tts_lock_t l;
2
3 void thread_fn(void) {
4     /* Other stuff */ ←
5     lock(&l);
6     /* CS */
7     unlock(&l);
8 }

```

Core 1

l:0 → E

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

1 struct tts_lock_t {
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4     /* Other stuff */ ←
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```

Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

1 struct tts_lock_t {
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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

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Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

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8         swap(&(l->lock), &(tmp));
9     } while (tmp == 1);
10 }

11 void unlock(tts_lock_t *l) {
12     l->lock = 0;
13 }

```

```

1 struct tts_lock_t l;
2
3 void thread_fn(void) {
4     /* Other stuff */ ←
5     lock(&l);
6     /* CS */ ←
7     unlock(&l);
8 }

```

Core 1

l:1 → M

Core 2

l:? → I

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

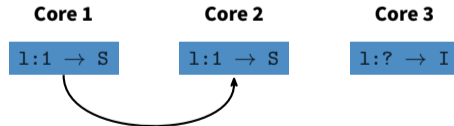
1 struct tts_lock_t {
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3 };
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Test & Test & Set Lock

Overhead

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7     unlock(&l);
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```

Core 1

l:1 → S

Core 2

l:1 → S

Core 3

l:? → I

Test & Test & Set Lock

Overhead

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5     lock(&l);
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7     unlock(&l);
8 }

```

Core 1

l:1 → S

Core 2

l:1 → S

Core 3

l:? → I

Test & Test & Set Lock

Overhead

```

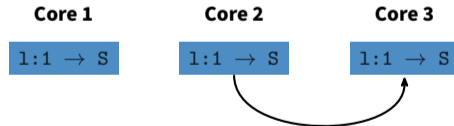
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Test & Test & Set Lock

Overhead

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Core 1

l:1 → S

Core 2

l:1 → S



Core 3

l:1 → S

Test & Test & Set Lock

Overhead

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7     unlock(&l);
8 }

```

Core 1

l:1 → S

Core 2

l:1 → S

Core 3

l:1 → S



Test & Test & Set Lock

Fairness

```
1 struct tts_lock l;
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3 void thread_fn(void) {
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18 }
```

 T_1  T_2  T_3

Test & Test & Set Lock

Fairness

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```



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```

 T₁ T₂ T₃

Test & Test & Set Lock

Fairness

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 T₁ T₂ T₃

Test & Test & Set Lock

Fairness

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 T₁ T₂ T₃

Test & Test & Set Lock

Fairness

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16         swap(&(l->lock), &(tmp));
17     } while (tmp == 1);
18 }

```


 T₁

 T₂

 T₃

Test & Test & Set Lock

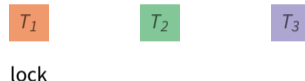
Fairness

```

1 struct tts_lock l;
2
3 void thread_fn(void) {
4     while (true) {
5         /* Other stuff */ ←
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18 }

```



Test & Test & Set Lock

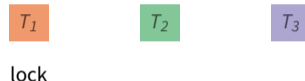
Fairness

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3 void thread_fn(void) {
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16         swap(&(l->lock), &(tmp));
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18 }

```



Test & Test & Set Lock

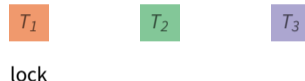
Fairness

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Test & Test & Set Lock

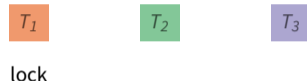
Fairness

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Test & Test & Set Lock

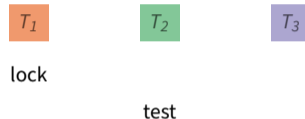
Fairness

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Test & Test & Set Lock

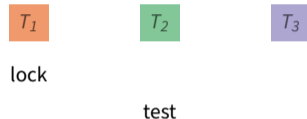
Fairness

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Test & Test & Set Lock

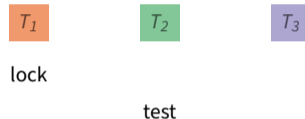
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Test & Test & Set Lock

Fairness

```

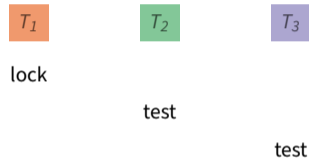
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Test & Test & Set Lock

Fairness

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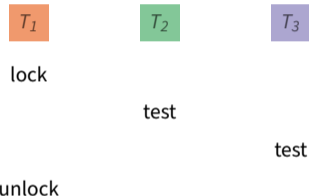
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Test & Test & Set Lock

Fairness

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```


 T₁

lock

unlock


 T₂

test


 T₃

test

Test & Test & Set Lock

Fairness

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```


 T₁

lock

unlock


 T₂

test

lock


 T₃

test

Test & Test & Set Lock

Fairness

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 T₁

lock

unlock


 T₂

test

lock


 T₃

test

Test & Test & Set Lock

Fairness

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```



lock

unlock



test

lock



test

test

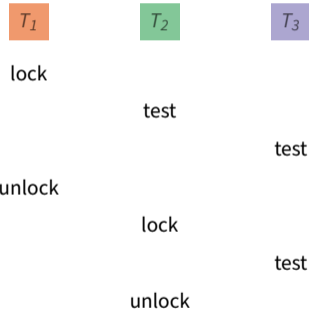
Test & Test & Set Lock

Fairness

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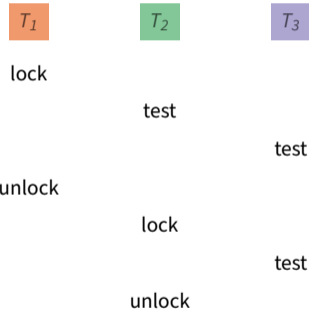
Test & Test & Set Lock

Fairness

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Test & Test & Set Lock

Fairness

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```


 T₁

lock

unlock


 T₂

test

lock

unlock


 T₃

test

test

Test & Test & Set Lock

Fairness

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```


 T₁

lock

unlock


 T₂

test

lock

unlock


 T₃

test

test

Test & Test & Set Lock

Fairness

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```


 T₁

lock

unlock


 T₂

test

lock

unlock


 T₃

test

test

Test & Test & Set Lock

Fairness

```

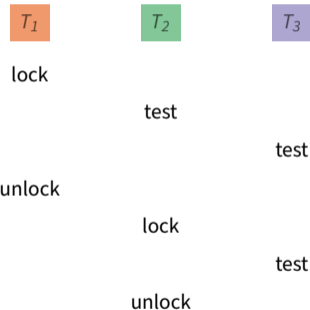
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```



Test & Test & Set Lock

Fairness

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18 }

```



lock

unlock

lock



test

lock

unlock



test

test

Test & Test & Set Lock

Fairness

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18 }

```


 T₁

lock

unlock

lock


 T₂

test

lock

unlock


 T₃

test

test

test

Ticket Lock

```
1 struct ticket_lock_t {
2     int next;
3     volatile int current;
4 };

5 void lock(ticket_lock_t *l) {
6     int t = xadd(&(l->next), 1);
7     do {} while (l->current != t);
8 }

10 void unlock(ticket_lock_t *l) {
11     l->current++;
12 }
```

- As simple and cheap as Test & Test & Set Lock
- Ensures fairness between threads

But

- High bus traffic on `unlock`
- Aborting `lock` is difficult

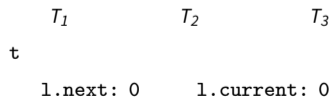
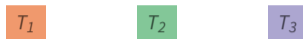
Ticket Lock

Fairness

```

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3 void thread_fn(void) {
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14     do {} while (l->current != t);
15 }
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18     l->current++;
19 }

```



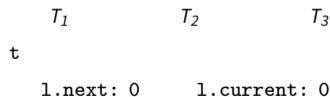
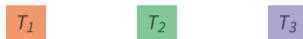
Ticket Lock

Fairness

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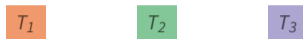
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```



lock

T_1 T_2 T_3

t

l.next: 0 l.current: 0

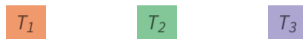
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lock

	T_1	T_2	T_3
t	0		
	l.next: 1	l.current: 0	

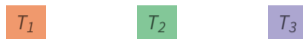
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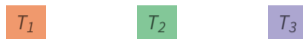
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lock

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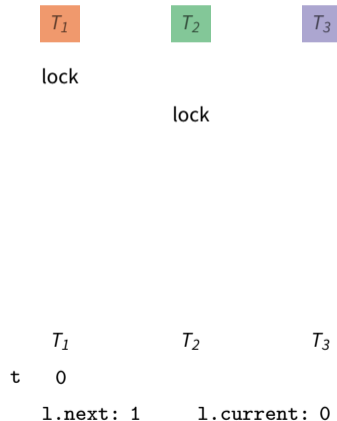
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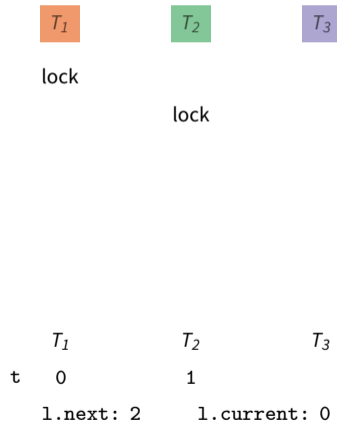
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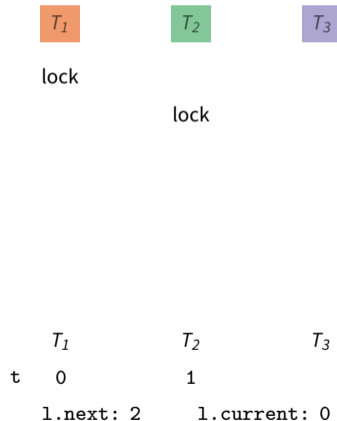
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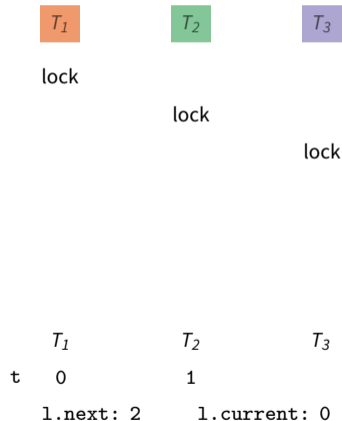
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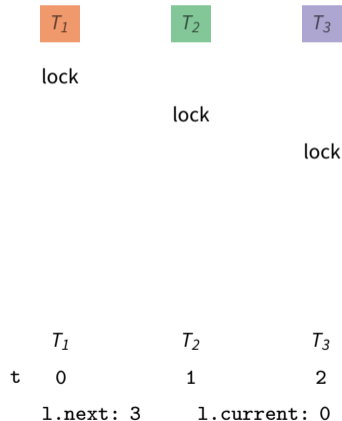
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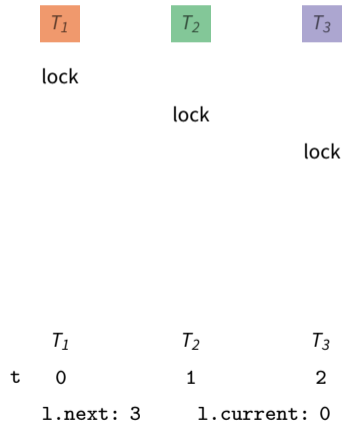
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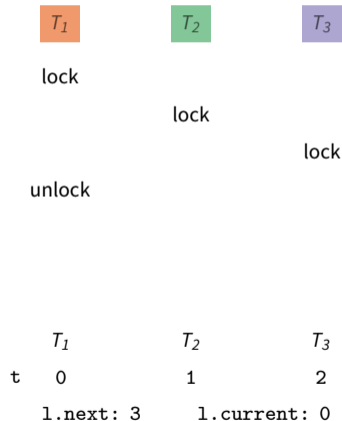
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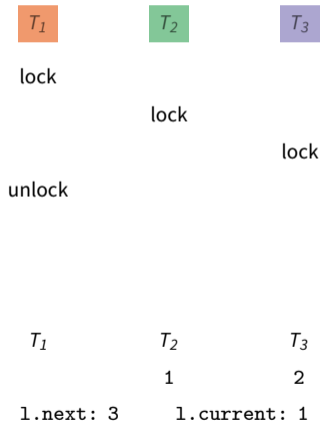
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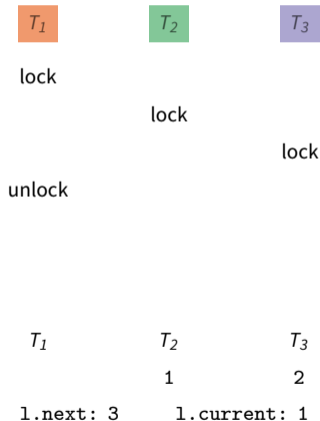
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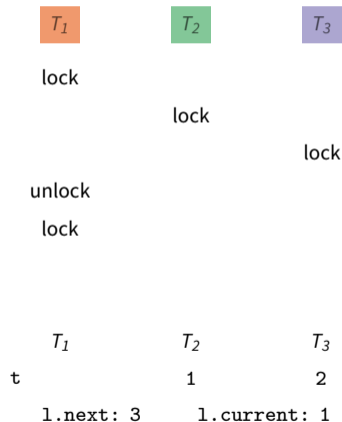
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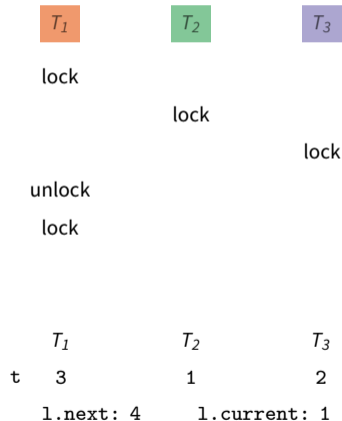
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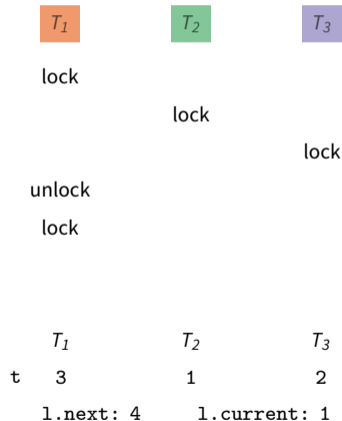
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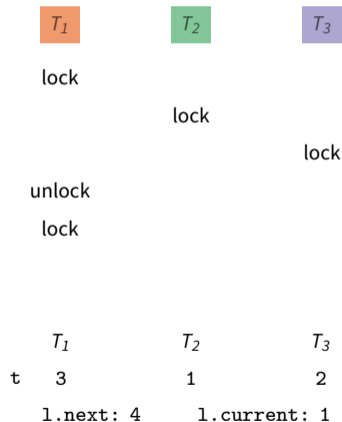
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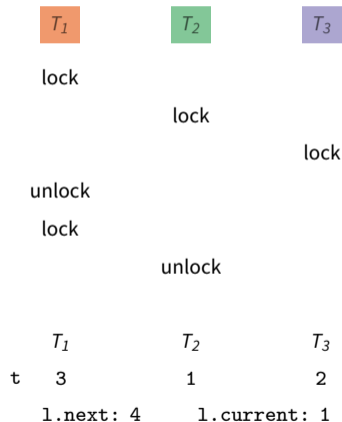
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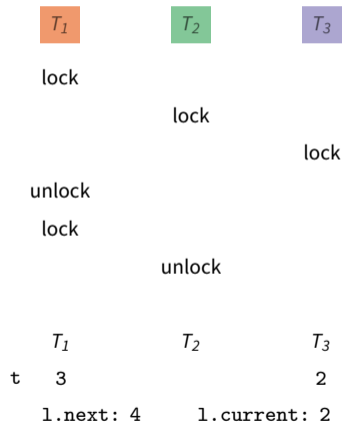
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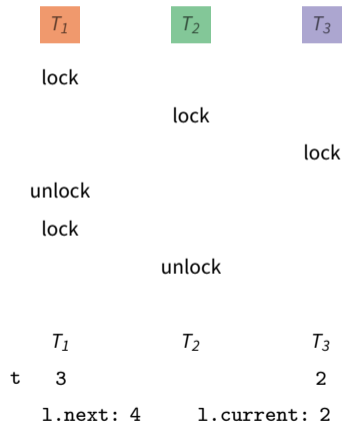
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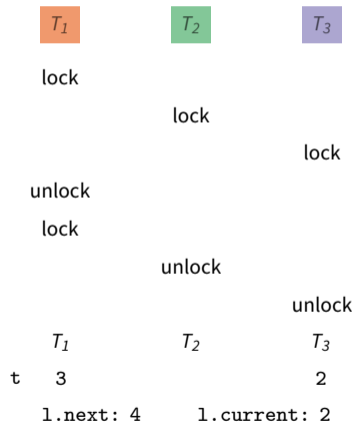
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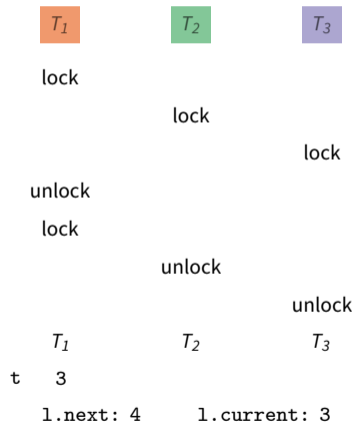
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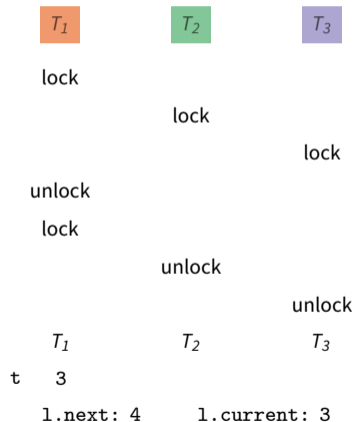
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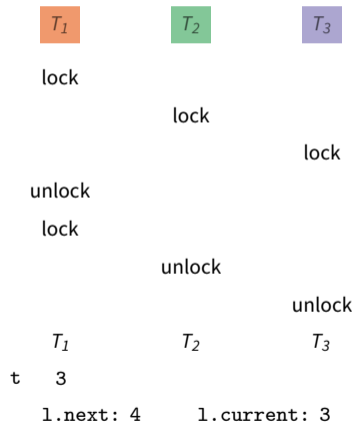
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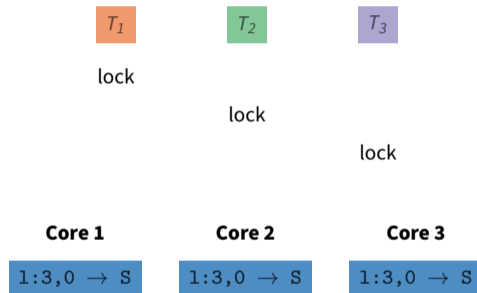
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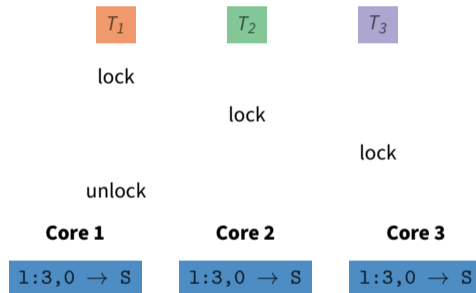
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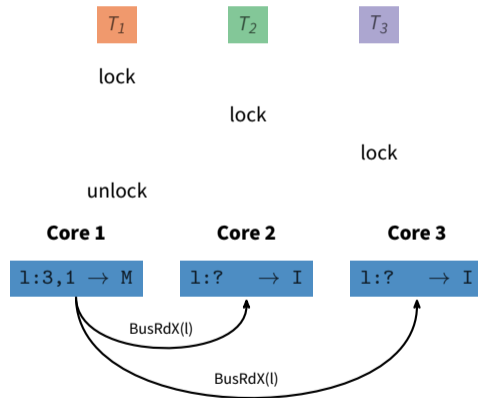
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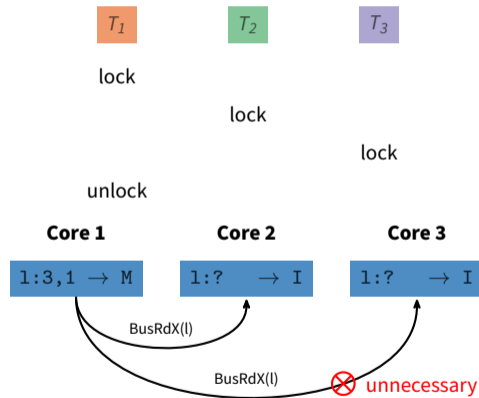
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Lock-Free Data Structures

Many data structures can be implemented without the usage of locks but instead directly with atomic hardware instructions.

- Single-Linked List

```
1 void insert(ele_t *new_ele, ele_t *prev) {
2     do {
3         new_ele->next = prev->next;
4     } while (!cas(&(prev->next), new_ele->next, new_ele));
5 }
```

Lock-Free Data Structures

Many data structures can be implemented without the usage of locks but instead directly with atomic hardware instructions.

- Single-Linked List
- Double-Linked List

```
1 void insert(ele_t *new_ele, ele_t *prev) {
2     do {
3         new_ele->next = prev->next;
4         new_ele->prev = prev;
5     } while (!dcas(&(prev->next), &(prev->next->prev),
6                 new_ele->next, new_ele->prev,
7                 new_ele, new_ele));
8 }
```

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- Double-Linked List
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Many data structures can be implemented without the usage of locks but instead directly with atomic hardware instructions.

- Single-Linked List
- Double-Linked List
- Binary Tree
- Red-Black Tree

Mellor-Crummey and Scott (MCS Lock)

```
1 struct mcs_node_t {          6 struct mcs_lock_t {
2     mcs_node_t *next;      7     mcs_node_t *queue;
3     bool free;            8 };
4 };
10 void lock(mcs_lock_t *l, mcs_node_t *cur) {
11     cur->next = NULL; cur->free = false;
12     auto prev = fetch_and_store(&(l->queue), cur);
13     if (prev) {
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21         if (cas(&(l->queue), cur, NULL)) return;
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23     }
24     cur->next->free = true;
25 }
```

- Fair between threads
- Only local spinning
- No unnecessary cache trashing
- Easy to abort `lock` operation

But:

- Difficult to implement correctly

MCS Lock

Fairness & Overhead

```

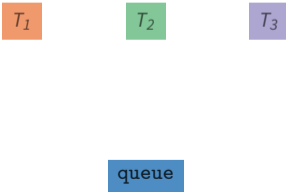
1 struct mcs_node_t {
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8         /* CS */
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```



MCS Lock

Fairness & Overhead

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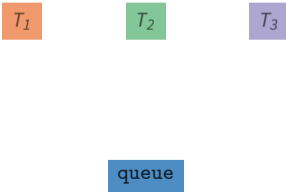
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MCS Lock

Fairness & Overhead

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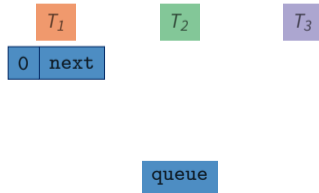
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MCS Lock

Fairness & Overhead

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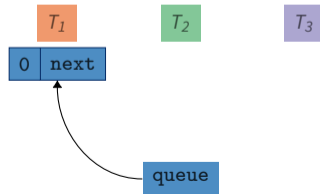
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MCS Lock

Fairness & Overhead

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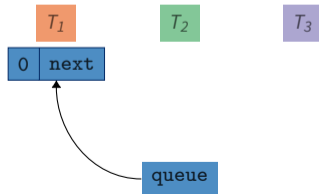
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MCS Lock

Fairness & Overhead

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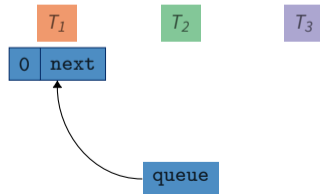
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MCS Lock

Fairness & Overhead

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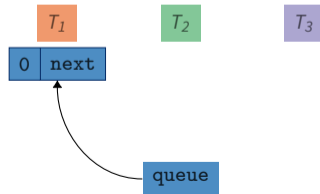
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MCS Lock

Fairness & Overhead

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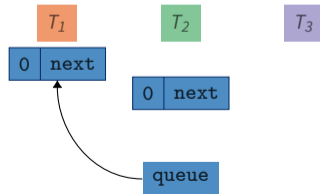
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MCS Lock

Fairness & Overhead

```

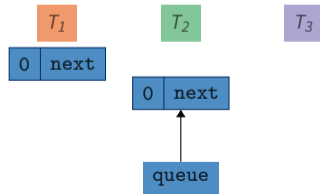
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MCS Lock

Fairness & Overhead

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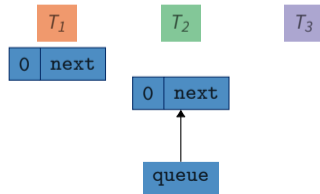
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MCS Lock

Fairness & Overhead

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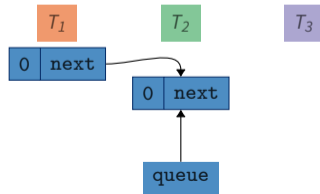
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MCS Lock

Fairness & Overhead

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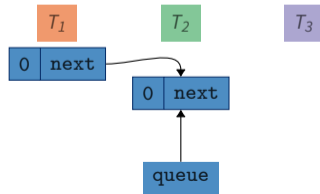
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MCS Lock

Fairness & Overhead

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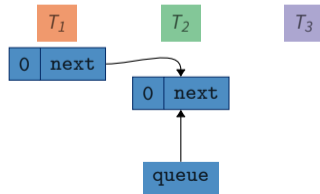
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MCS Lock

Fairness & Overhead

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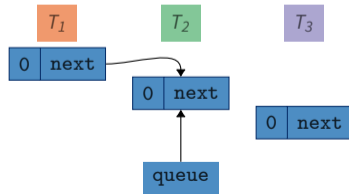
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MCS Lock

Fairness & Overhead

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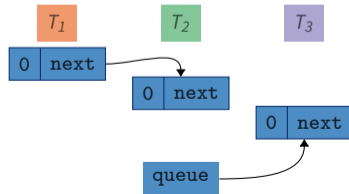
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MCS Lock

Fairness & Overhead

```

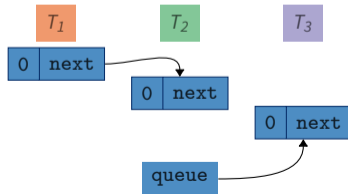
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MCS Lock

Fairness & Overhead

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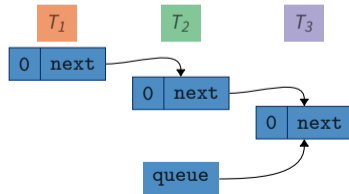
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MCS Lock

Fairness & Overhead

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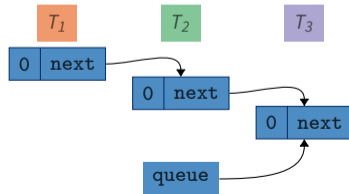
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MCS Lock

Fairness & Overhead

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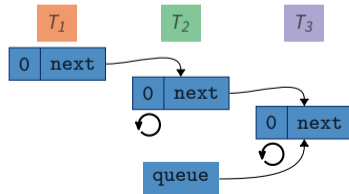
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```



MCS Lock

Fairness & Overhead

```

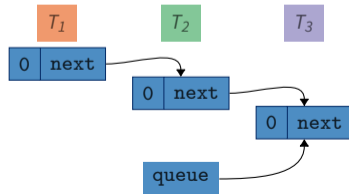
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MCS Lock

Fairness & Overhead

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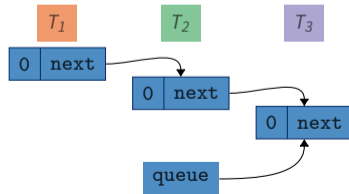
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MCS Lock

Fairness & Overhead

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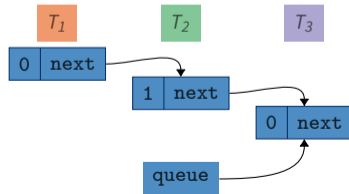
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MCS Lock

Fairness & Overhead

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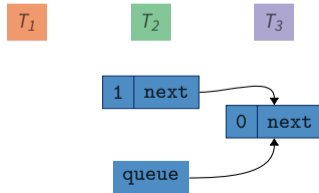
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MCS Lock

Fairness & Overhead

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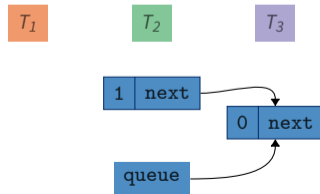
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MCS Lock

Fairness & Overhead

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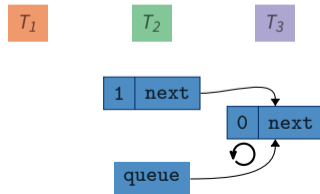
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MCS Lock

Fairness & Overhead

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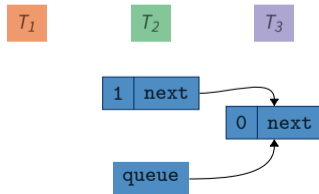
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MCS Lock

Fairness & Overhead

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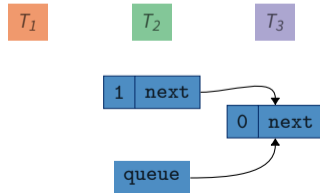
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MCS Lock

Fairness & Overhead

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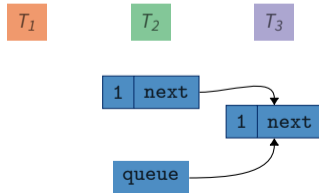
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MCS Lock

Fairness & Overhead

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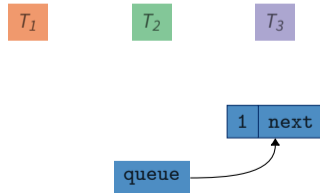
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MCS Lock

Fairness & Overhead

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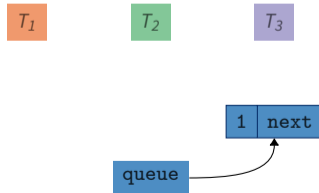
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MCS Lock

Fairness & Overhead

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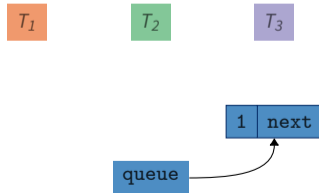
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MCS Lock

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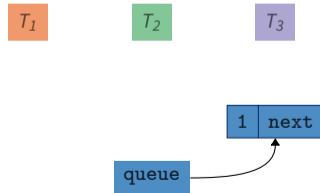
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MCS Lock

Fairness & Overhead

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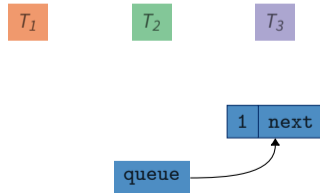
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MCS Lock

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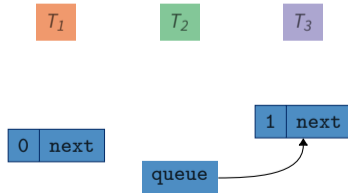
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MCS Lock

Fairness & Overhead

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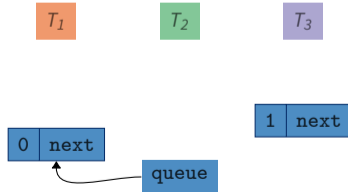
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MCS Lock

Fairness & Overhead

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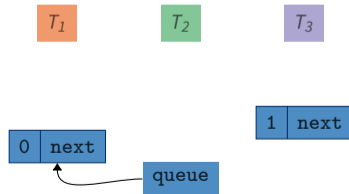
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MCS Lock

Fairness & Overhead

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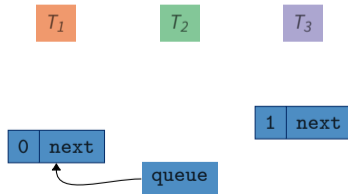
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MCS Lock

Fairness & Overhead

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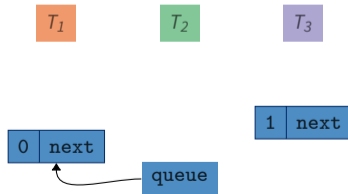
1 struct mcs_node_t {
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3     bool free;
4 };
10 void lock(mcs_lock_t *l, mcs_node_t *cur) {
11     cur->next = NULL; cur->free = false;
12     auto prev = fetch_and_store(&(l->queue), cur);
13     if (prev) {←
14         prev->next = cur;
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19 void unlock(mcs_lock_t *l, mcs_node_t *cur) {
20     if (!cur->next) {
21         if (cas(&(l->queue), cur, NULL)) return;
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MCS Lock

Fairness & Overhead

```

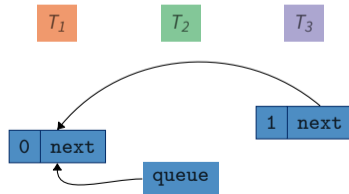
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MCS Lock

Fairness & Overhead

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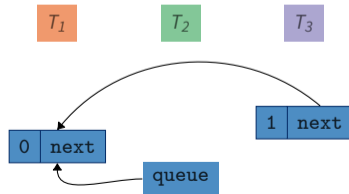
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MCS Lock

Fairness & Overhead

```

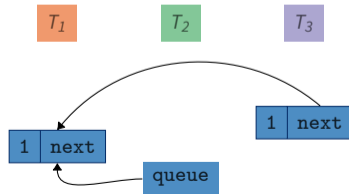
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MCS Lock

Fairness & Overhead

```

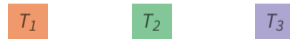
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MCS Lock

Fairness & Overhead

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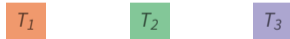
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MCS Lock

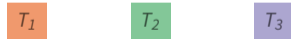
Fairness & Overhead

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MCS Lock

Fairness & Overhead

```

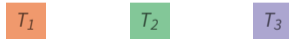
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MCS Lock

Fairness & Overhead

```

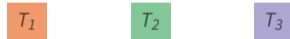
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MCS Lock

Fairness & Overhead

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 T_1

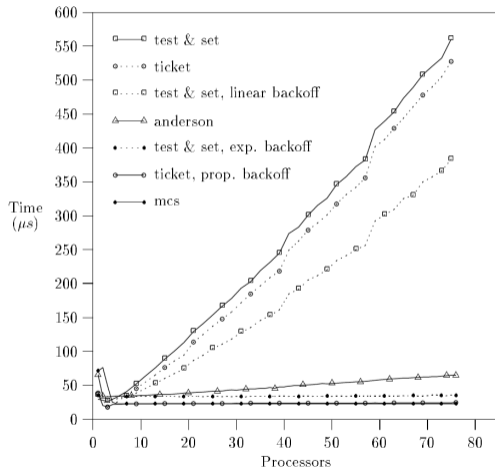
 T_2

 T_3

 queue

MCS Lock

Performance



MCS Lock

Performance

