Concurrency:
Mutual Exclusion (Locks)

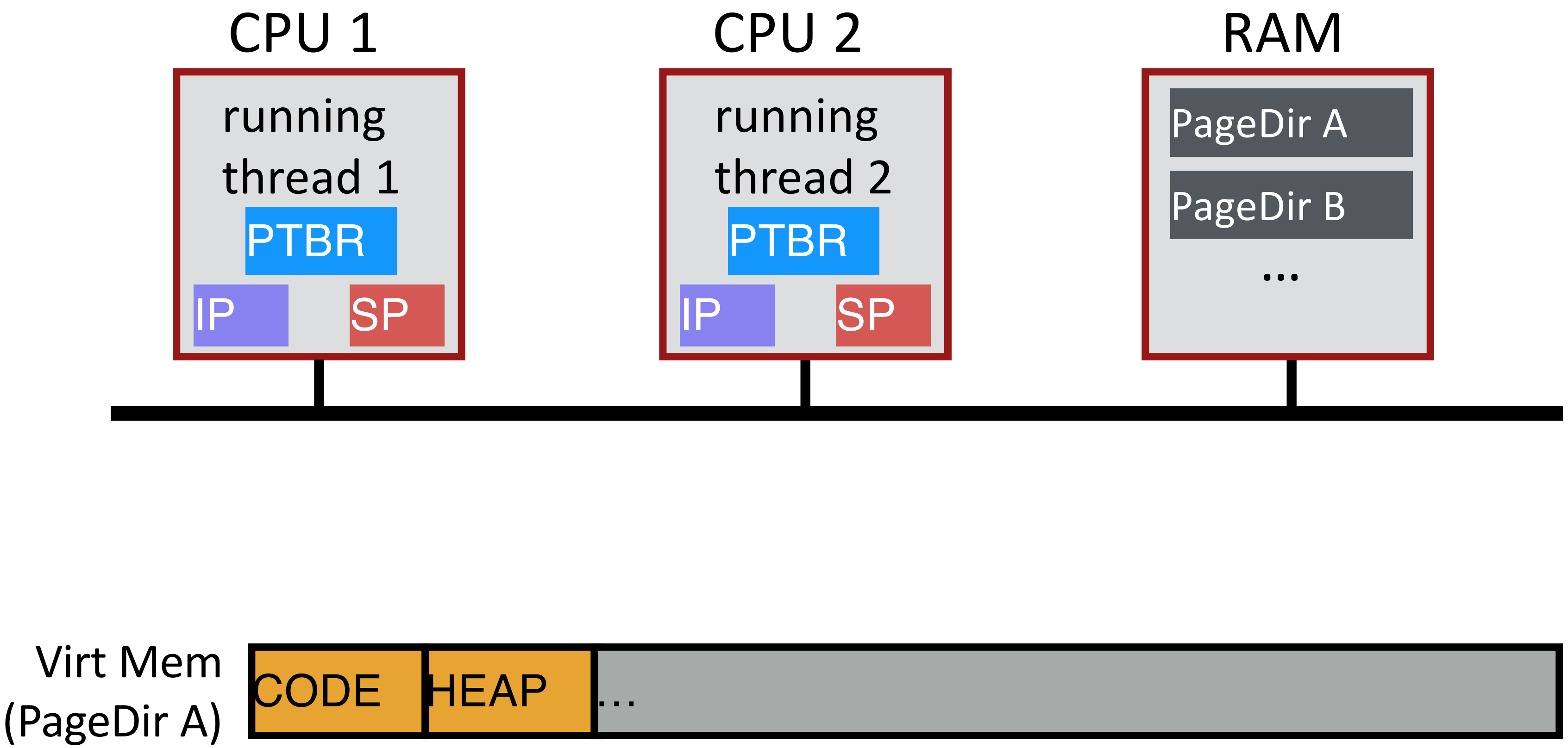
Questions Answered in this Lecture:

- What are *locks* and how do we implement them?
- How do we use hardware primitives (atomics) to support efficient locks?
- How do we extend locks to multiprocessors?
- How do we use locks to implement concurrent data structures?

Thanks to Remzi & Andrea Arapci-Dusseau for slide material

Announcements

- p2a is due Friday; p1a grades should be posted tonight or tomorrow
- Midterm will be posted Wednesday 10/14 @ 2pm. It will be open book, due 24 hours later



CPU 1

running thread 1

PTBR

IP

SP

CPU 2

running thread 2

PTBR

IP

SP

RAM

PageDir A

PageDir B

...

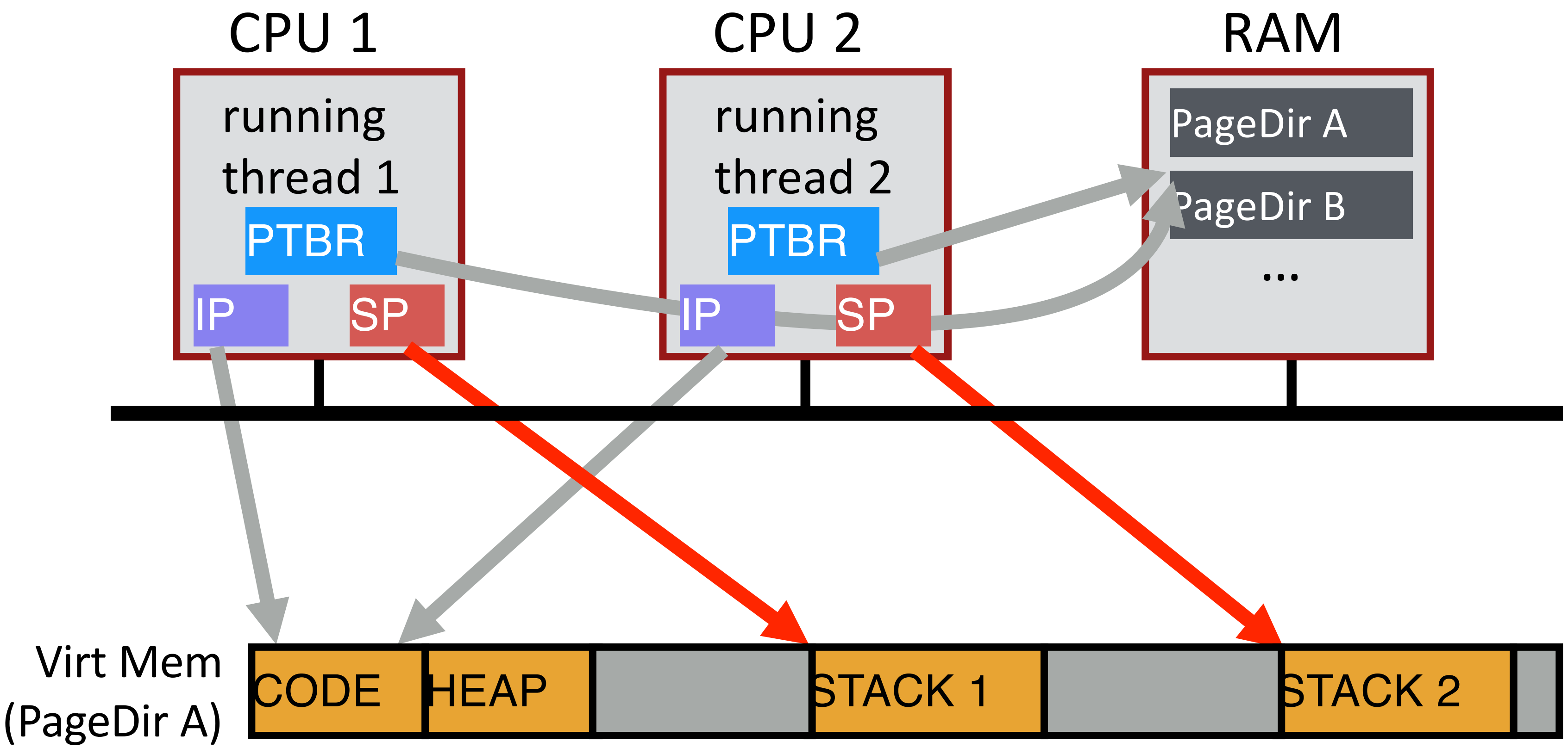
Virt Mem (PageDir A)

CODE

HEAP

...

Review: which registers are shared between threads? Which are different?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running thread 2
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RAM
PageDir A
PageDir B
...
Virt Mem (PageDir A)
CODE
HEAP
STACK 1
STACK 2

Review: What do we need for correctness?

- Want 3 instructions to execute as an uninterruptable group
- That is, we want them to be an ***atomic unit***

```
mov 0x123, %eax
add %0x1, %eax
mov %eax, 0x123
```

critical section

More general:

Need mutual exclusion for critical sections

- if process **A** is in critical section **C**, process **B** can't be

(okay if other processes do unrelated work)

Other Examples

- Consider multi-threaded programs that do more than increment a shared balance
- E.g., multi-threaded program with a shared linked-list
  - All concurrent operations:
    - Thread A inserts element a
    - Thread B inserts element b
    - Thread C looks up element c

Shared Linked List

```
void list_insert(list_t *L, int key) {
        node_t *new = malloc(sizeof(node_t));
        assert(new);
        new->key  = key;
        new->next = L->head;
        L->head = new;
}

int list_lookup(list_t *L, int key) {
        node_t *tmp = L->head;
        while (tmp) {
                if (tmp->key == key)
                        return 1;
                tmp = tmp->next;
        }
        return 0;
}
```

```
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

typedef struct __list_t {
        node_t *head;
} list_t;

void list_init(list_t *L) {
        L->head = NULL;
}
```

What can go wrong?
What schedule leads to a problem?

Linked-List Race

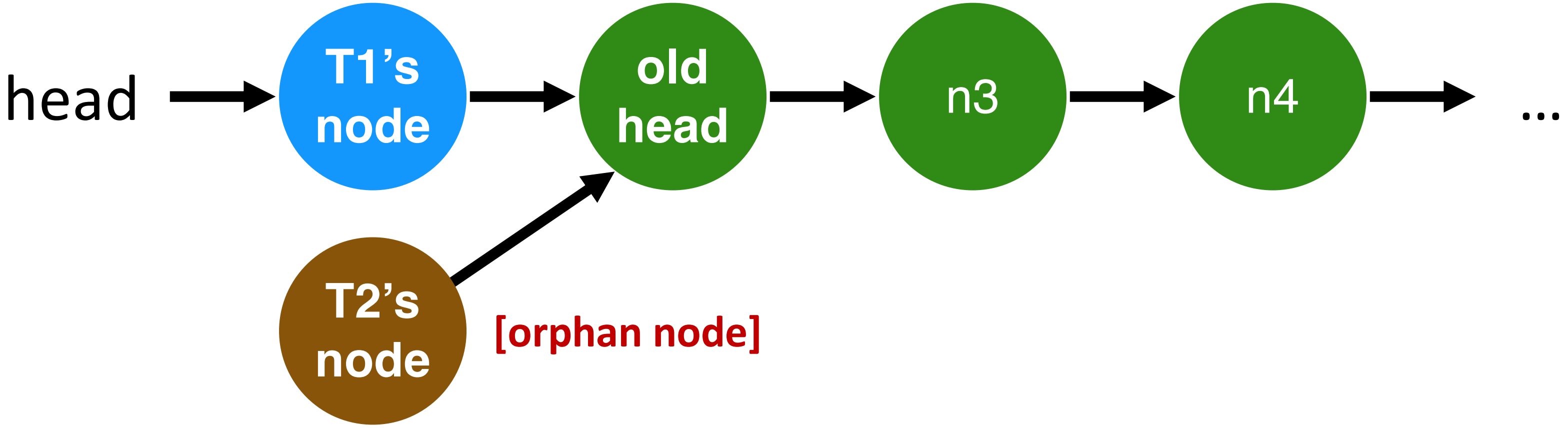
Thread 1	Thread 2
`new->key  = key`	
`new->next = L->head`	
	`new->key  = key`
	`new->next = L->head`
	`L->head   = new`
`L->head = new`	

time

Both entries point to old head

Only one entry (which one?) can be the new head.

Resulting Linked List



Concurrent Linked List

```
void list_insert(list_t *L, int key) {
        node_t *new = malloc(sizeof(node_t));
        assert(new);
        new->key = key;
        new->next = L->head;
        L->head = new;
}

int list_lookup(list_t *L, int key) {
        node_t *tmp = L->head;
        while (tmp) {
                if (tmp->key == key)
                        return 1;
                tmp = tmp->next;
        }
        return 0;
}
```

```
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

typedef struct __list_t {
        node_t *head;
} list_t;

void list_init(list_t *L) {
        L->head = NULL;
}
```

How do we add locks to this?

Concurrent Linked List

```
void list_insert(list_t *L, int key) {
        node_t *new = malloc(sizeof(node_t));
        assert(new);
        new->key = key;
        new->next = L->head;
        L->head = new;
}

int list_lookup(list_t *L, int key) {
        node_t *tmp = L->head;
        while (tmp) {
                if (tmp->key == key)
                        return 1;
                tmp = tmp->next;
        }
        return 0;
}
```

```
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

typedef struct __list_t {
        pthread_mutex_t lock;
        node_t *head;
} list_t;

void list_init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}
```

`pthread_mutex_t lock;`

One lock per list

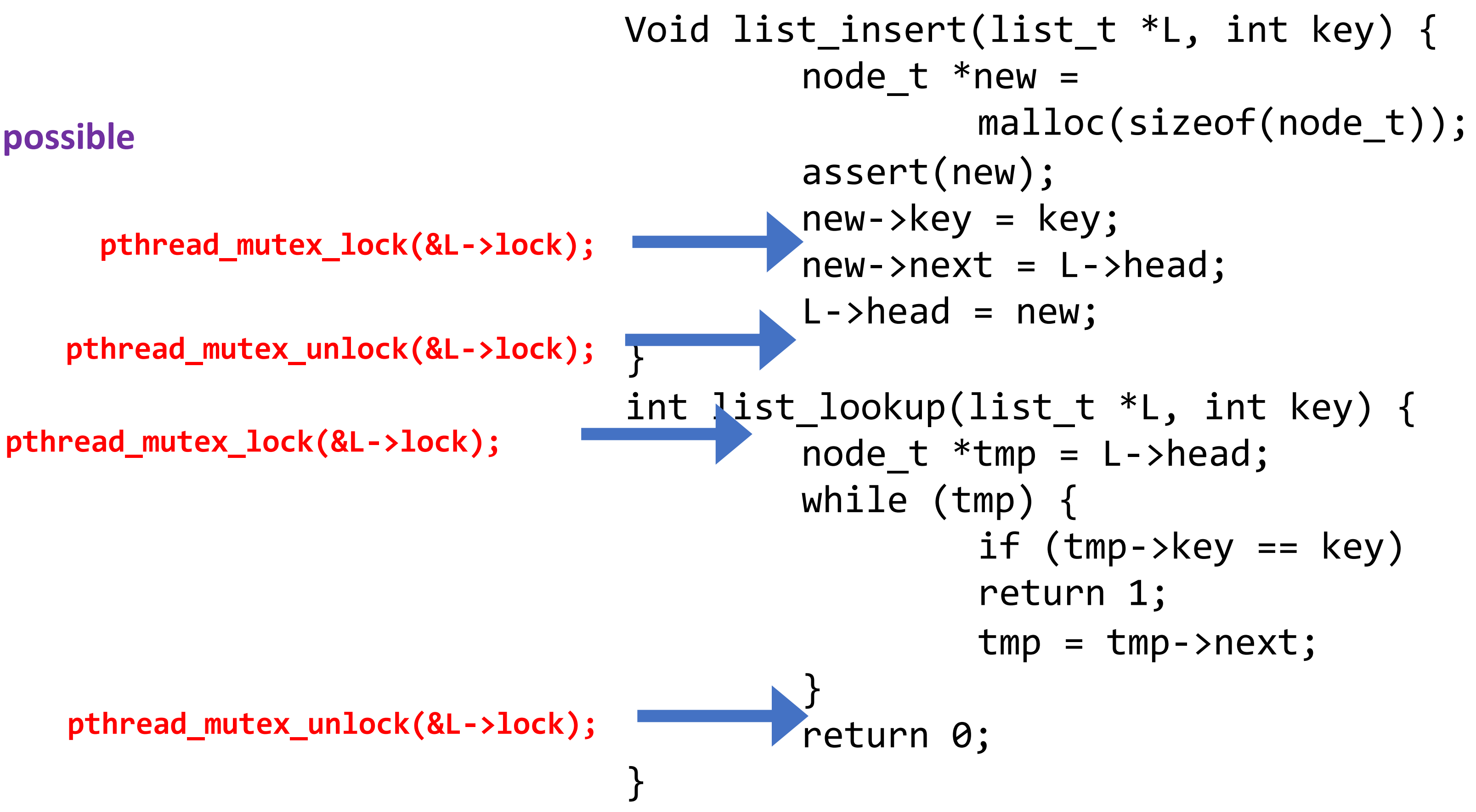
Locking Linked Lists : Approach #1

Consider everything critical section

Can critical section be smaller?

```
                                      Void list_insert(list_t *L, int key) {
pthread_mutex_lock(&L->lock);   →             node_t *new =
                                                      malloc(sizeof(node_t));
                                              assert(new);
                                              new->key = key;
                                              new->next = L->head;
                                              L->head = new;
pthread_mutex_unlock(&L->lock); →     }
                                      int list_lookup(list_t *L, int key) {
pthread_mutex_lock(&L->lock);   →             node_t *tmp = L->head;
                                              while (tmp) {
                                                      if (tmp->key == key)
                                                      return 1;
                                                      tmp = tmp->next;
pthread_mutex_unlock(&L->lock); →             }
                                              return 0;
                                      }
```

Locking Linked Lists : Approach #2



Critical section as small as possible

```
pthread_mutex_lock(&L->lock);

pthread_mutex_unlock(&L->lock);

pthread_mutex_lock(&L->lock);

pthread_mutex_unlock(&L->lock);
```

```
Void list_insert(list_t *L, int key) {
        node_t *new =
                malloc(sizeof(node_t));
        assert(new);
        new->key = key;
        new->next = L->head;
        L->head = new;
}
int list_lookup(list_t *L, int key) {
        node_t *tmp = L->head;
        while (tmp) {
                if (tmp->key == key)
                return 1;
                tmp = tmp->next;
        }
        return 0;
}
```

Locking Linked Lists : Approach #3

What about lookup?

```
Void list_insert(list_t *L, int key) {
        node_t *new =
                malloc(sizeof(node_t));
        assert(new);
        new->key = key;
        new->next = L->head;
        L->head = new;
}
int list_lookup(list_t *L, int key) {
        node_t *tmp = L->head;
        while (tmp) {
                if (tmp->key == key)
                return 1;
                tmp = tmp->next;
        }
        return 0;
}
```

`pthread_mutex_lock(&L->lock);`

`pthread_mutex_unlock(&L->lock);`

`pthread_mutex_lock(&L->lock);`

If no `list_delete()`, locks not necessary

`pthread_mutex_unlock(&L->lock);`

Synchronization

Build higher-level synchronization primitives in OS

- Operations that ensure correct ordering of instructions across threads

Motivation: Build them once and get them right

Monitors Locks Semaphores

Condition Variables

Loads Stores Test&Set

Disable Interrupts

Lock Implementation Goals

Correctness

- **Mutual exclusion**
  - Only one thread in critical section at a time
- **Progress (deadlock-free)**
  - If several simultaneous requests, must allow one to proceed
- **Bounded (starvation-free)**
  - Must eventually allow each waiting thread to enter

Fairness

Each thread waits for same amount of time

Performance

CPU is not used unnecessarily (e.g., spinning)

Implementing Synchronization

- To implement, ***need atomic operations***
- Atomic operation: guarantees ***no other instructions can be interleaved***
- Examples of atomic operations
  - **Code between interrupts *on uniprocessors***
    - **Disable timer interrupts, don't do any I/O**
  - **Loads and stores of words**
    - Load r1, B
    - Store r1, A
  - **Special hardware instructions**
    - ***atomic*** test & set
    - ***atomic*** compare & swap

Implementing Locks: Using Interrupts

Turn off interrupts for critical sections

- Prevent dispatcher from running another thread
- Code between interrupts executes atomically

```
void acquire(lock_t *l) {
        disableInterrupts();
}
void release(lock_t *l) {
        enableInterrupts();
}
```

Disadvantages??

- Only works on uniprocessors
- Process can keep control of CPU for arbitrary length
- Cannot perform other necessary work

Implementing Locks: Using Load+Store

Code uses a single ***shared*** lock variable

```
bool lock = false; // shared variable
void acquire(bool *lock) {
     while (*lock); /* wait */
     *lock = true;
}
void release(bool *lock) {
     *lock = false;
}
```

Why doesn’t this work? Example schedule that fails with 2 threads?

```
*lock == 0 initially

Thread 1                        Thread 2
----------------------------------------------------
while (*lock == 1);
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
                                while (*lock == 1);
                                *lock = 1;
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
*lock = 1;
```

Both threads grab lock!

Problem: Testing lock and setting lock are not atomic

xchg: atomic exchange, or test-and-set

```
// xchg(int *addr, int newval)
// return what was pointed to by addr
// at the same time, store newval into addr

int xchg(int *addr, int newval) {
  int old = *addr;
  *addr = newval;
  return old;
}
```

```
static inline unsigned
xchg(volatile unsigned int *addr, unsigned int newval)
{
    unsigned result;
    asm volatile("lock; xchgl %0, %1" :
                 "+m" (*addr), "=a" (result) :
                 "1" (newval) : "cc");
    return result;
}
```

XCHG Implementation

```
typedef struct __lock_t {
        int flag;
} lock_t;

void init(lock_t *lock) {
        lock->flag = ??;
}

void acquire(lock_t *lock) {
        ???
        // spin-wait (do nothing)
}

void release(lock_t *lock) {
        lock->flag = ??;
}
```

`int xchg(int *addr, int newval)`

XCHG Implementation

```
typedef struct __lock_t {
        int flag;
} lock_t;

void init(lock_t *lock) {
        lock->flag = 0;
}

void acquire(lock_t *lock) {
        while (xchg(&lock->flag, 1) == 1);
        // spin-wait (do nothing)
}

void release(lock_t *lock) {
        lock->flag = 0;
}
```

Other Atomic HW Instructions

```
int CompareAndSwap(int *ptr, int expected, int new) {
  int actual = *addr;
  if (actual == expected)
    *addr = new;
  return actual;
}
```

```
void acquire(lock_t *lock) {
     while(CompareAndSwap(&lock->flag, ?, ?) == ?) ;
     // spin-wait (do nothing)
}
```

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Other Atomic HW Instructions

```
int CompareAndSwap(int *ptr, int expected, int new) {
  int actual = *addr;
  if (actual == expected)
    *addr = new;
  return actual;
}
```

```
    void acquire(lock_t *lock) {
         while(CompareAndSwap(&lock->flag, 0, 1) == 1) ;
         // spin-wait (do nothing)
    }
```

Lock Implementation Goals

Correctness

- Mutual exclusion
  - Only one thread in critical section at a time
- Progress (deadlock-free)
  - If several simultaneous requests, must allow one to proceed
- Bounded (starvation-free)
  - Must eventually allow each waiting thread to enter

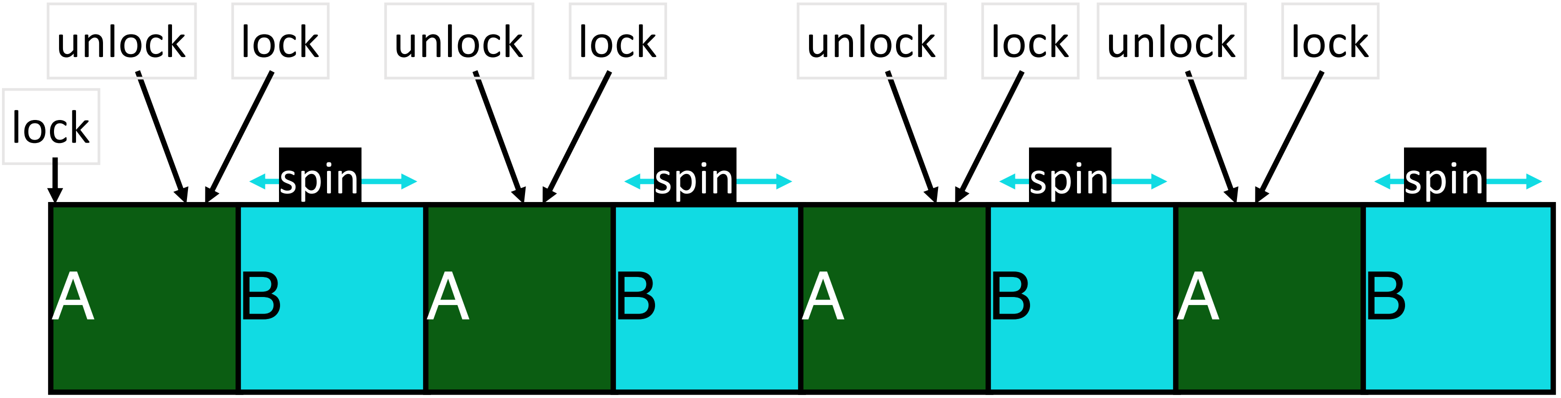
Fairness

Each thread waits for same amount of time

Performance

CPU is not used unnecessarily

Basic Spinlocks are Unfair



Scheduler is independent of locks/unlocks

Fairness: Ticket Locks

Idea: reserve each thread's turn to use a lock

- Each thread spins until their turn.
- Use **new atomic primitive**, **fetch-and-add**:

```
int fetchAndAdd(int *ptr) {
  int old = *ptr;
  *ptr = old + 1;
  return old;
}
```

```
Acquire: Grab ticket;
Spin while not thread's ticket != turn
Release: Advance to next turn
```

Ticket Lock Example

A lock():
B lock():
C lock():
A unlock():
B runs
A lock():
B unlock():
C runs
C unlock():
A runs
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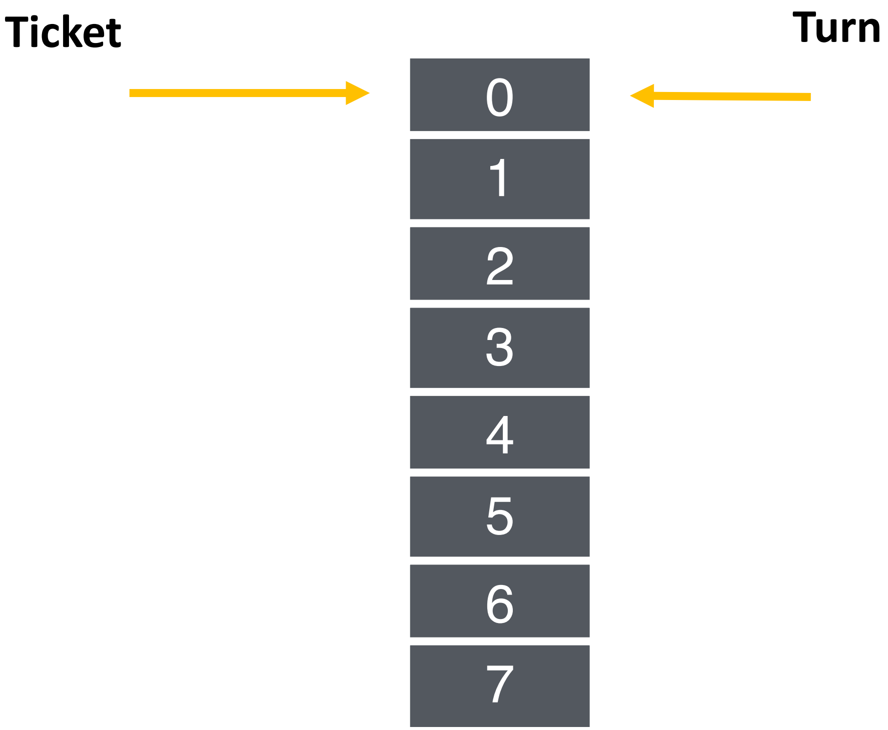

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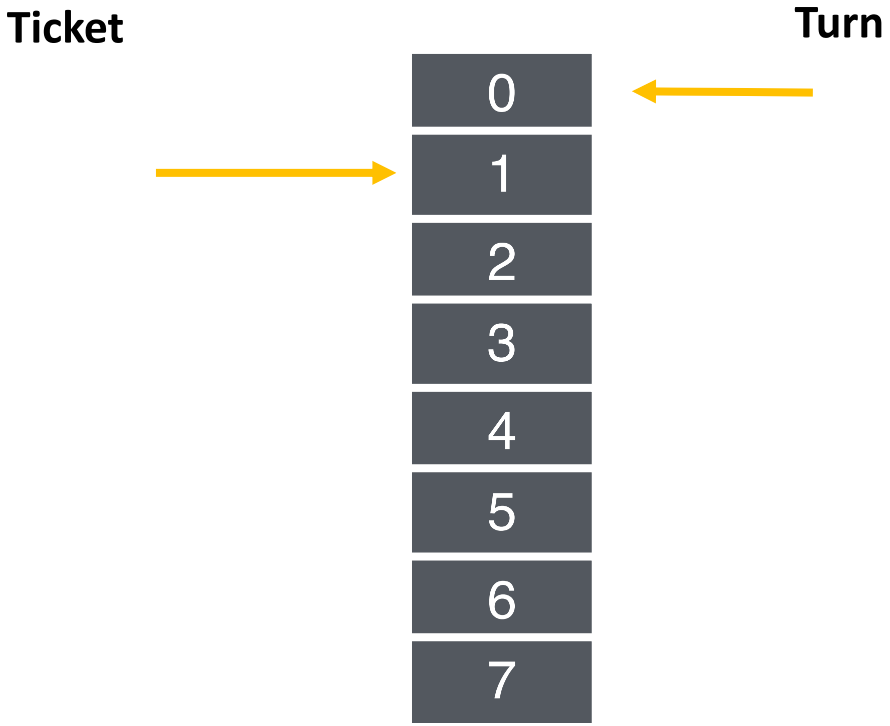

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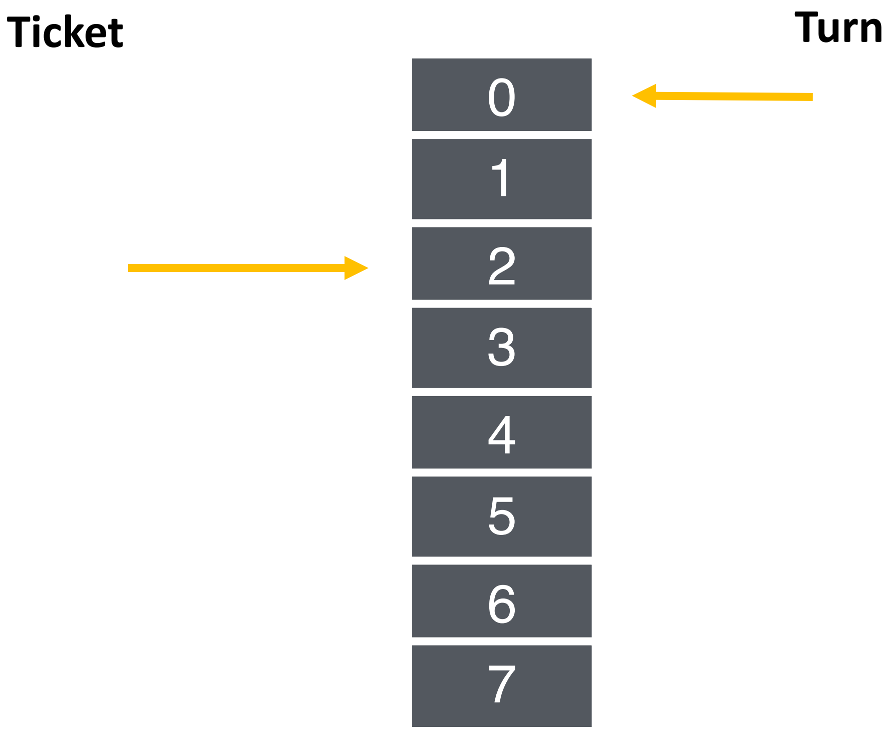

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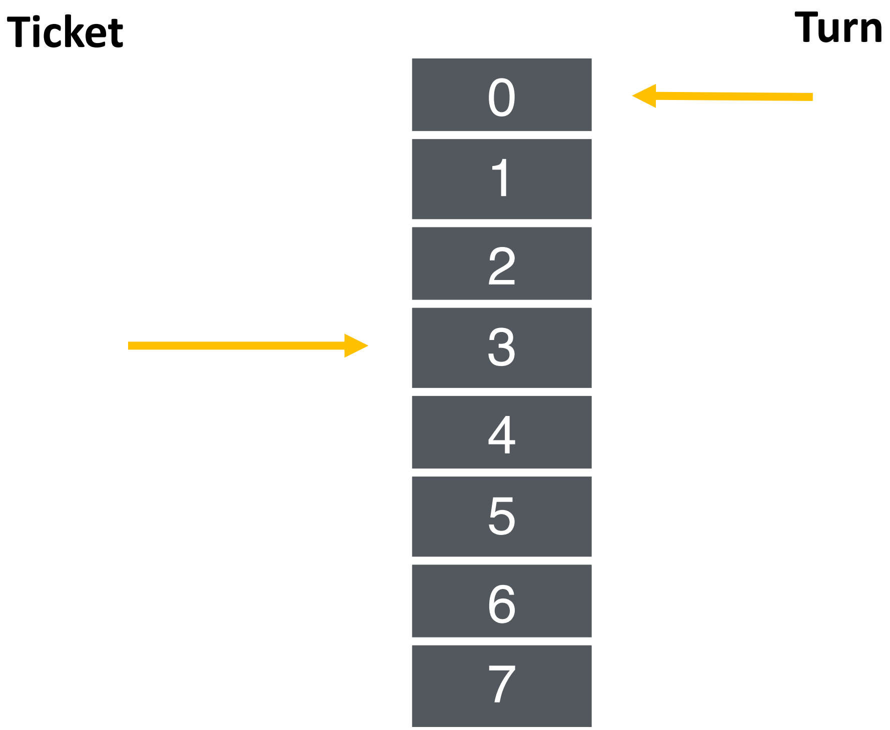

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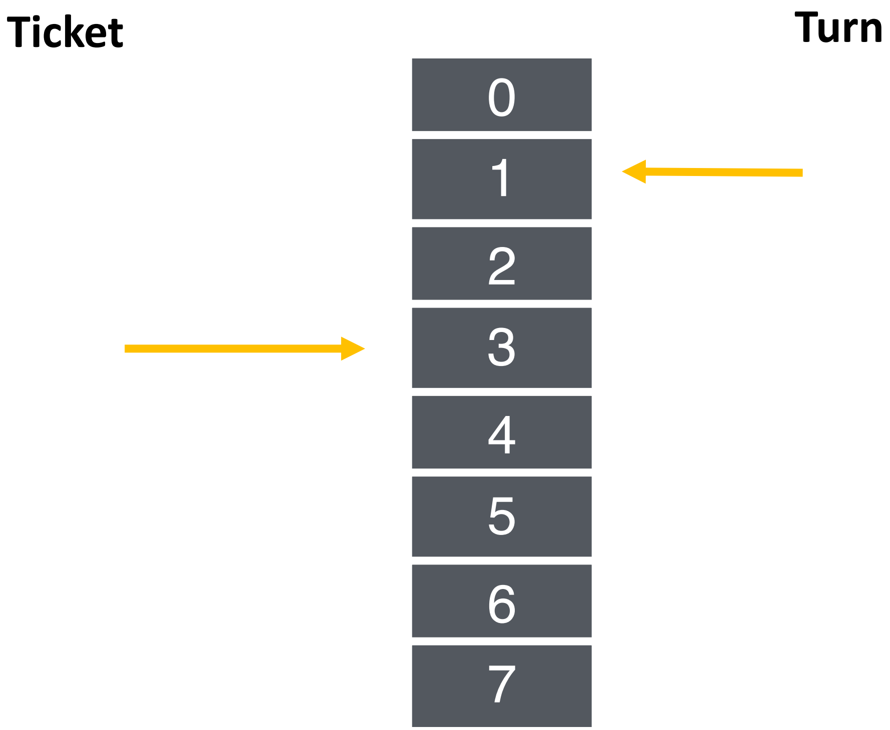

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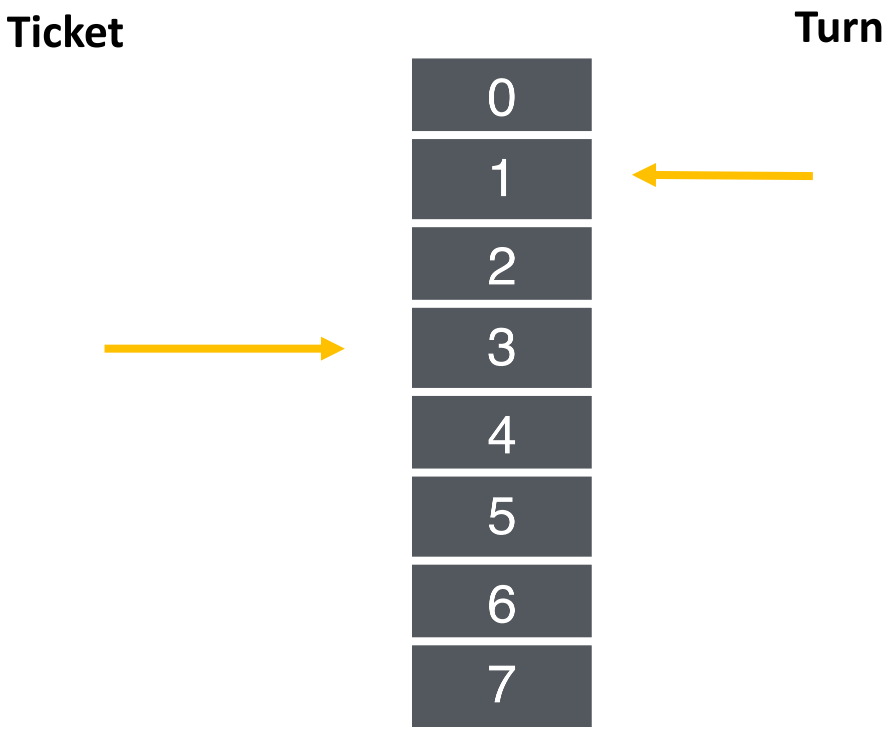

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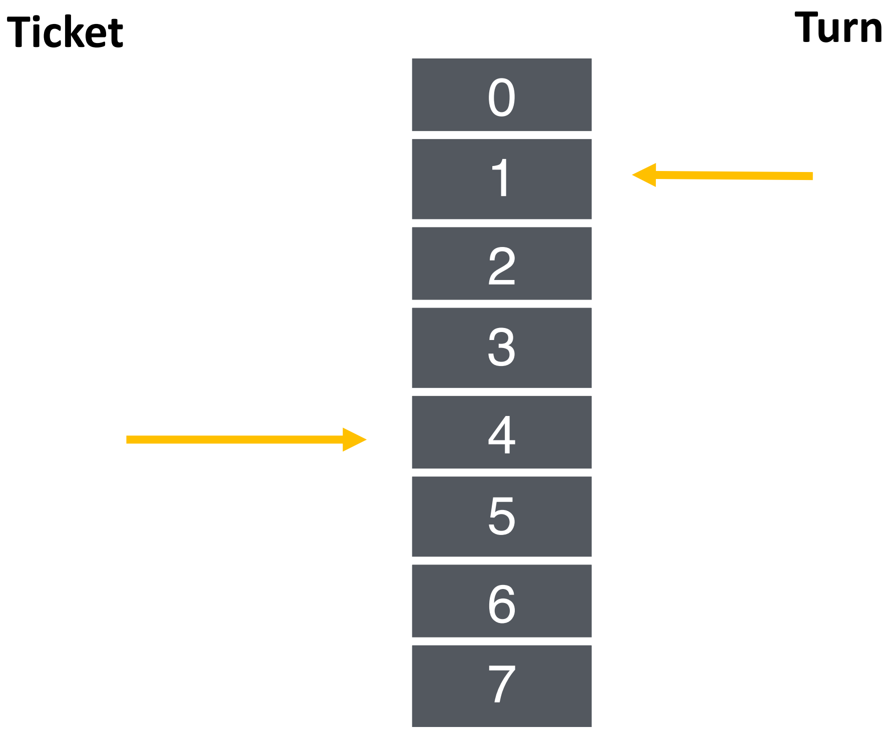

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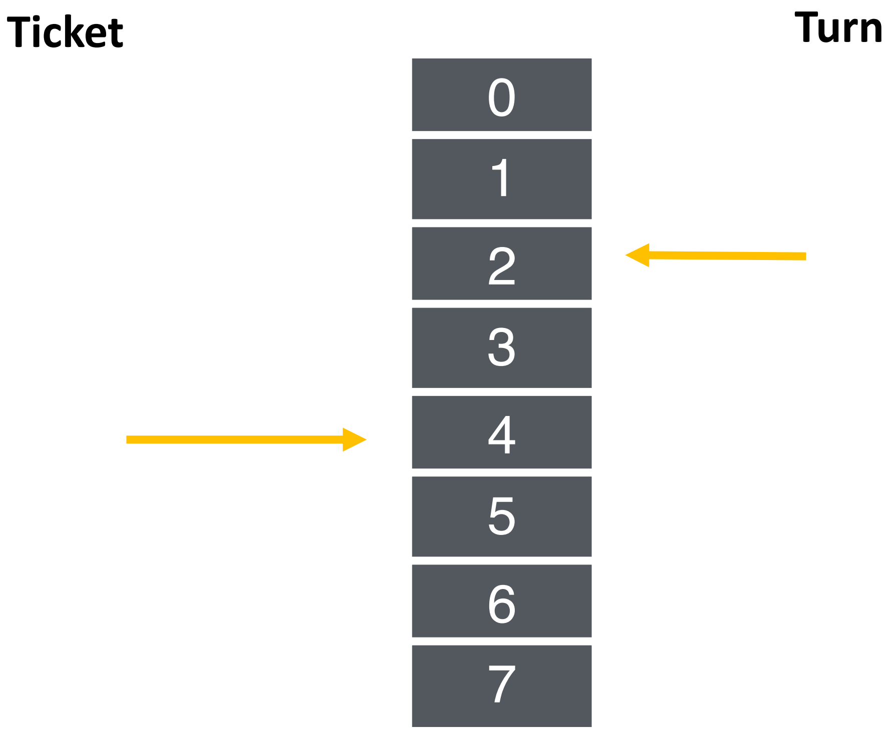

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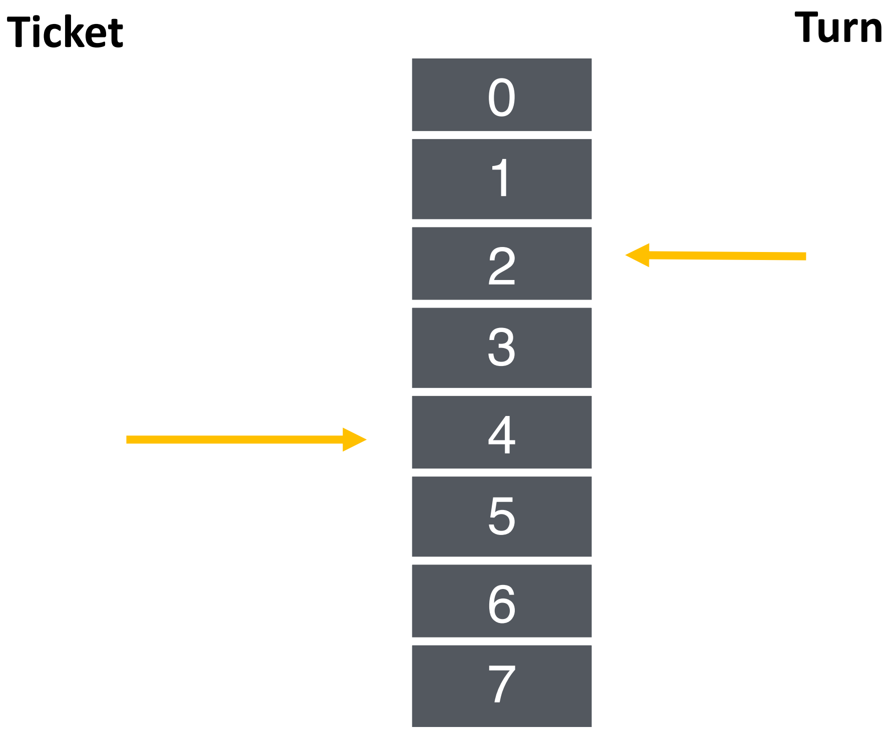

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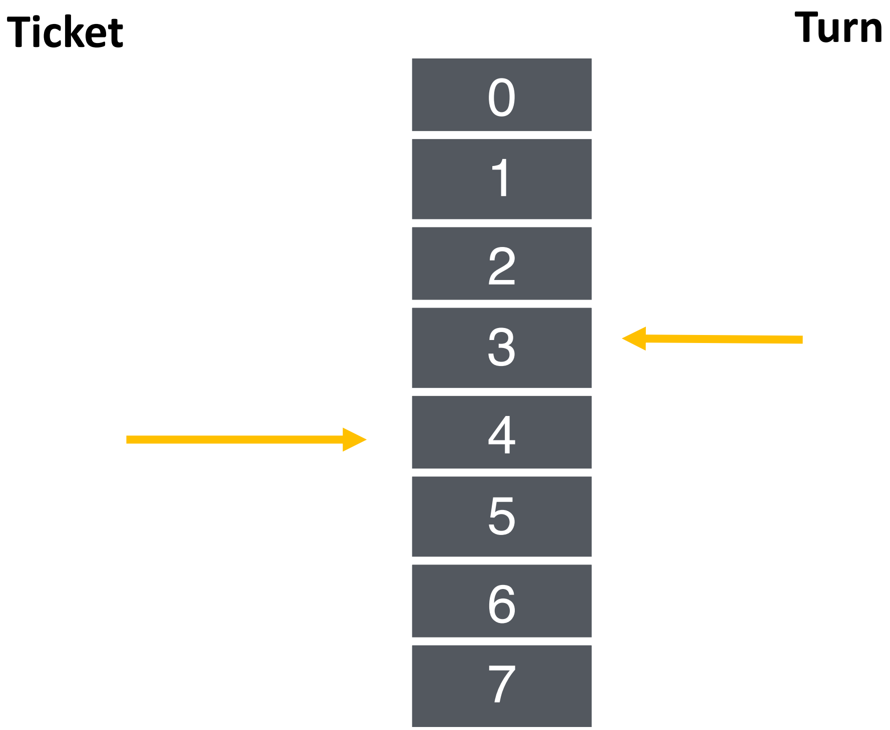

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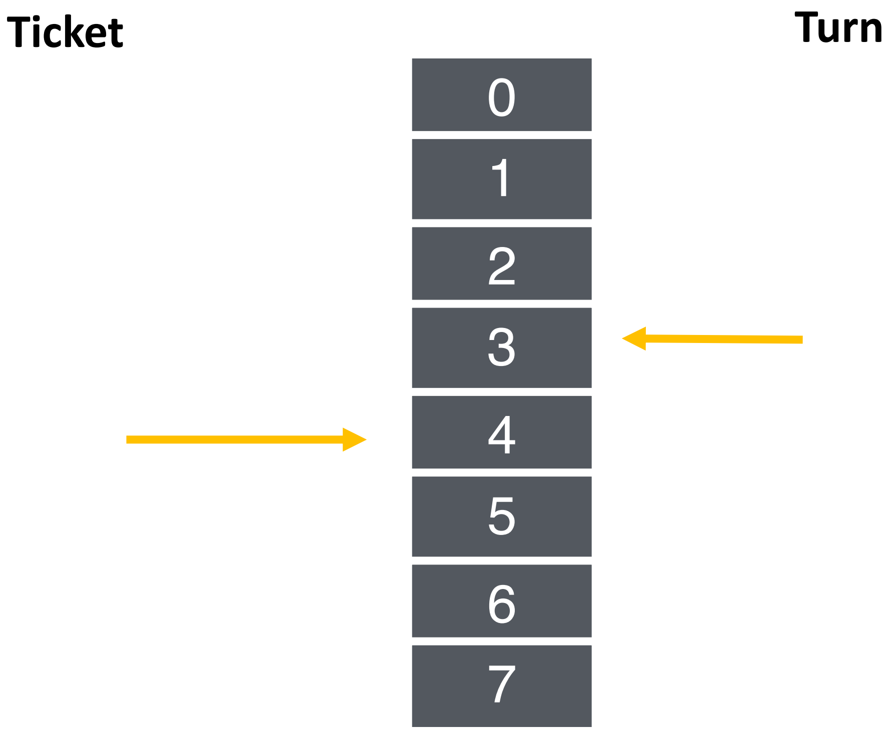

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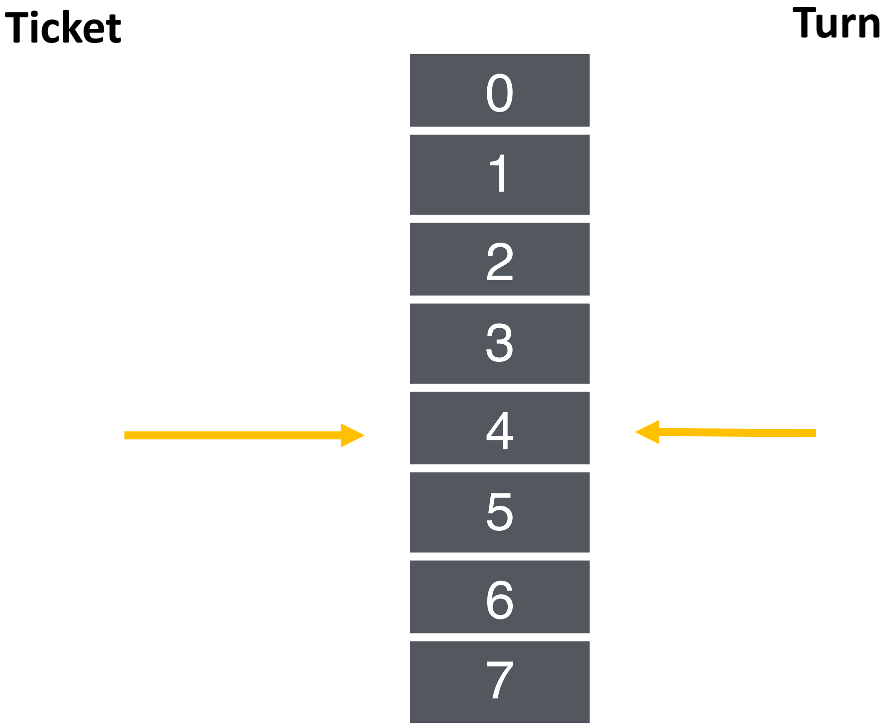

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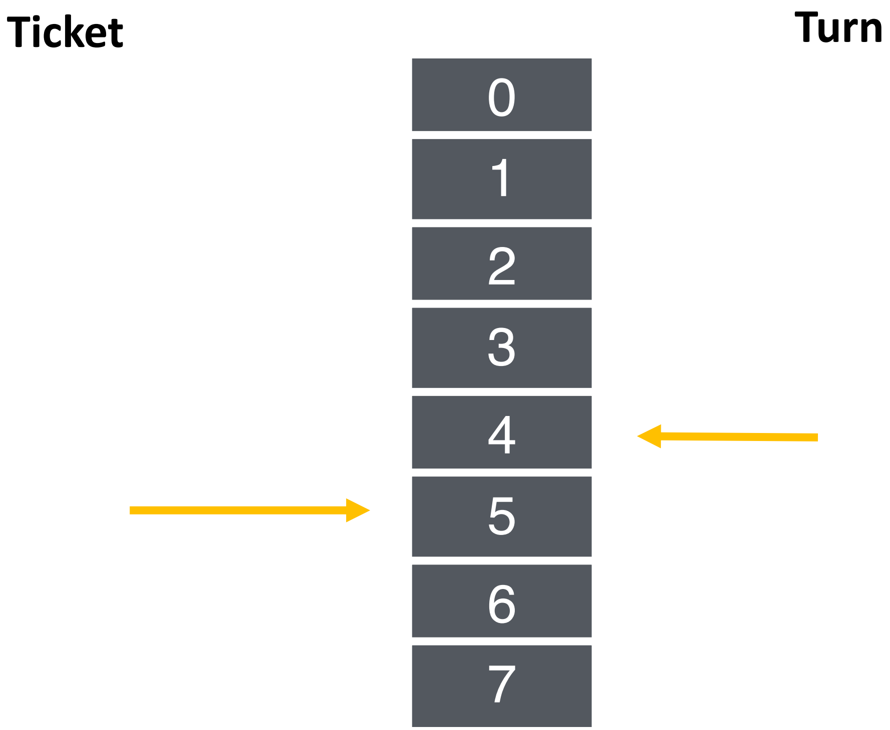


Ticket Lock Implementation

```
typedef struct __lock_t {
        int ticket;
        int turn;
}

void lock_init(lock_t *lock)
{
        lock->ticket = 0;
        lock->turn   = 0;
}
```

```
void acquire(lock_t *lock) {

        int myturn = FAA(&lock->ticket);

        while (lock->turn != myturn); // spin

}

void release (lock_t *lock) {

        FAA(&lock->turn);

}
```

Spinlock Performance

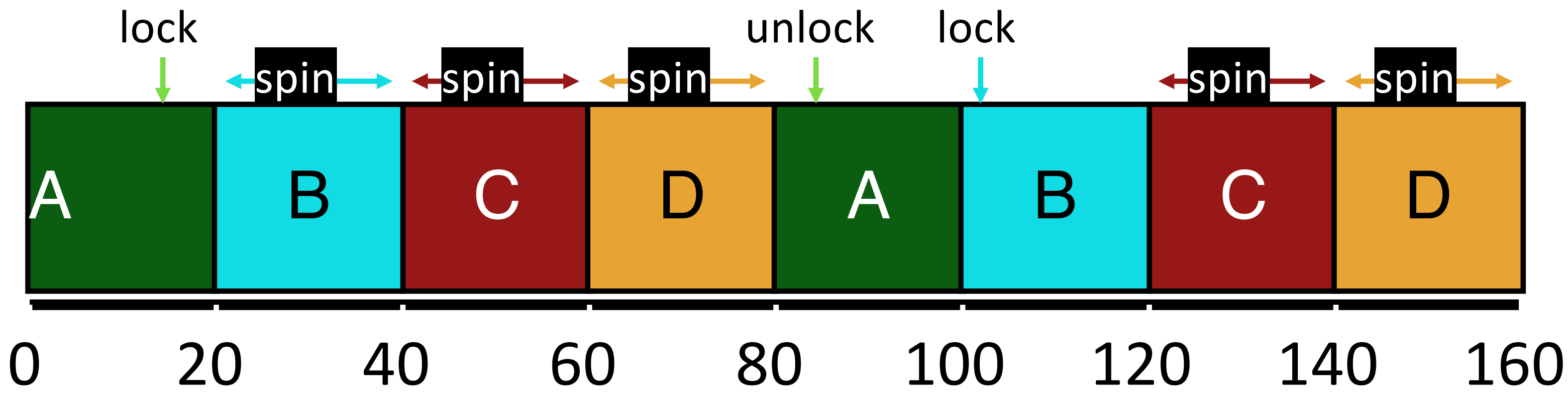
Fast when…

- many CPUs
- locks held a short time
- advantage: avoid context switch

Slow when…

- one CPU
- locks held a long time
- disadvantage: spinning is wasteful

CPU Scheduler is Ignorant



CPU scheduler may run **B** instead of **A**
even though **B** is waiting for **A**

Ticket Lock with `yield()`

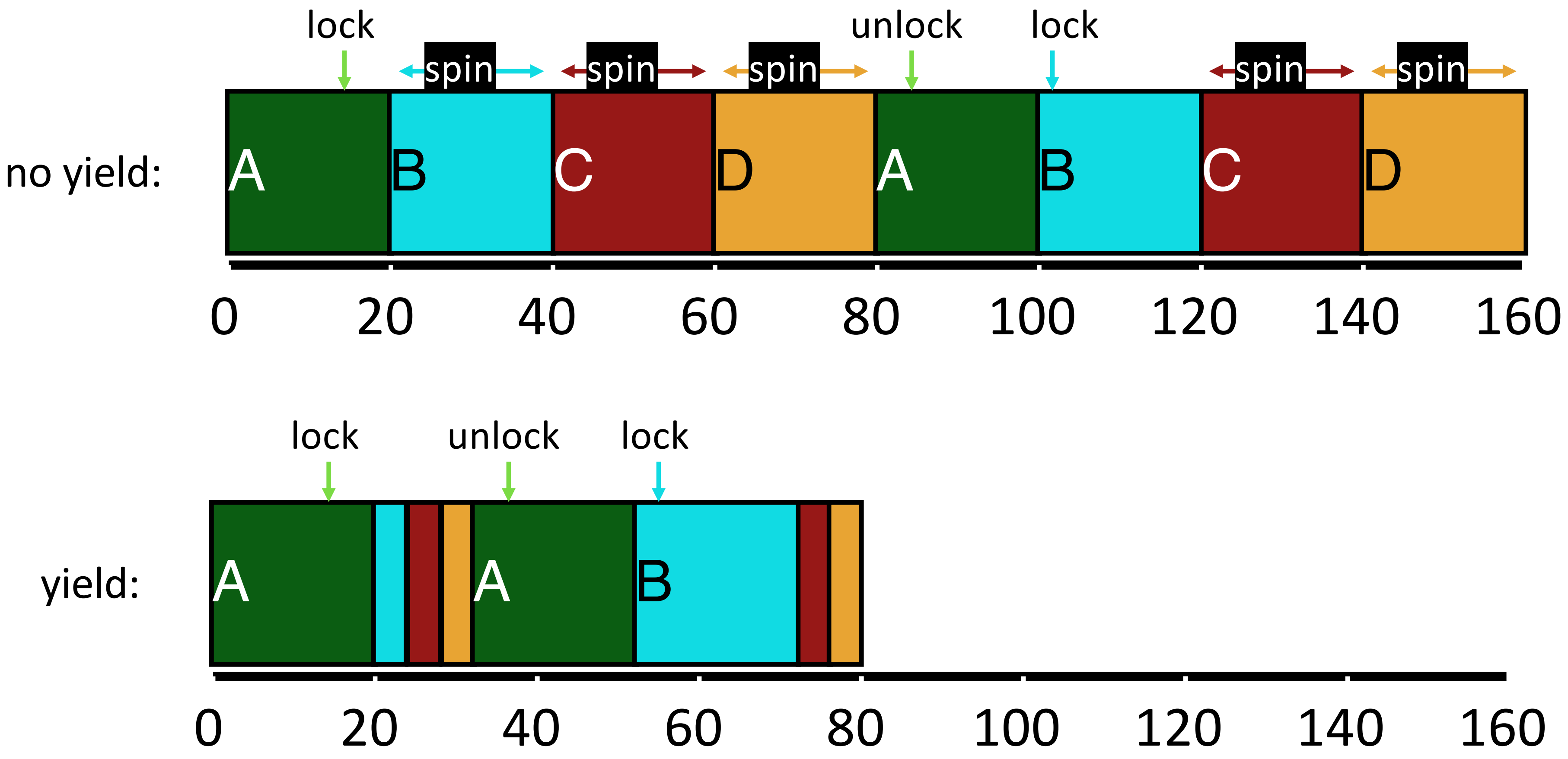
```
typedef struct __lock_t {
        int ticket;
        int turn;
}

void lock_init(lock_t *lock)
{
        lock->ticket = 0;
        lock->turn = 0;
}
```

```
void acquire(lock_t *lock) {
        int myturn = FAA(&lock->ticket);
        while (lock->turn != myturn)
                yield();
}

void release (lock_t *lock) {
        FAA(&lock->turn);
}
```

Yield Instead of Spin



Spinlock Performance

Waste…

- Without yield: O(threads * **time_slice**)
- With yield: O(threads * **context_switch**)

So even with yield, spinning is slow with high thread contention

Next improvement: Block and put thread on waiting queue instead of spinning