OPERATING SYSTEMS

SYNCHRONIZATION

Producer: Thread A

i1: count = count + 1

Consumer: Thread B

i2: count = count - 1

CRITICAL SECTIONS

- Counter increment/decrement should happen without interruption/thread switching.
- We call this 'Atomic' execution.
- The section that require atomic execution are called "critical sections".
- It doesn't have to be one instruction, we could have multiple instructions that need to be executed atomically.

```
in = out = 0;
```

Thread A

```
while (true) {
item = produce_item;
while
(counter == BUFFER_SIZE) {}/* do nothing */;
buffer[in] = item;
in = (in + 1) % BUFFER_SIZE;
counter1++;
counter2++;
}
```

Critical Section

Thread B

```
while (true) {
while (counter == 0) {}/* do nothing
item = buffer[out];
out = (out + 1) % BUFFER_SIZE;
counter1--;
Counter2--
consume_item(item);
```

Critical Section

SYNCHRONIZATION

Producer: Thread A		Consumer: Thread B
i1: count = count + 1		i2: count = count - 1
a1: load count a2: add 1 a3: store count	Register/ALU "view"	b1: load count b2: subtract 1 b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

SYNCHRONIZATION

Producer: Thread A

i1: count = count + 1

a1: load count a2: add 1 a3: store count

Register/ALU "view"

Consumer: Thread B

i2: count = count - 1

b1: load count b2: subtract 1 b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

Assume initial value of count = 4

SYNCHRONIZATION

Producer: Thread A

i1: count = count + 1

a1: load count
a2: add 1
a3: store count

Register/ALU "view"

Consumer: Thread B

i2: count = count - 1

b1: load count
b2: subtract 1
b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

Assume initial value of count = 4

Notice that all of the instructions in both threads are executed sequentially … a1<a2<a3, and b1<b2<b3

Worksheet Q1

What are the final values of count for these 4 histories?

a1 < b1 < a2 < a3 < b2 < b3

a1 < a2 < b1 < b2 < b3 < a3

a1 < a2 < a3 < b1 < b2 < b3

b1 < b2 < a1 < b3 < a2 < a3

SYNCHRONIZATION

Thread A

i1: count = count + 1
a1: load count a2: add 1 a3: store count

Register/ALU "view"

Thread B

i2: count = count - 1
b1: load count b2: subtract 1 b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

Assume initial value of count = 4

Which is the desired final value of `count`?

a1 < b1 < a2 < a3 < b2 < b3 — count = 3

a1 < a2 < b1 < b2 < b3 < a3 — count = 5

a1 < a2 < a3 < b1 < b2 < b3 — count = 4

b1 < b2 < a1 < b3 < a2 < a3 — count = 5

SYNCHRONIZATION

Thread A		Thread B
i1: count = count + 1		i2: count = count - 1
a1: load count a2: add 1 a3: store count	Register/ALU "view"	b1: load count b2: subtract 1 b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

Assume initial value of count = 4

What is the one property of the desired history that is different from the non-desirable histories?

a1 < b1 < a2 < a3 < b2 < b3 — count = 3

a1 < a2 < b1 < b2 < b3 < a3 — count = 5

a1 < a2 < a3 < b1 < b2 < b3 — count = 4

b1 < b2 < a1 < b3 < a2 < a3 — count = 5

SYNCHRONIZATION

Thread A		Thread B
i1: count = count + 1		i2: count = count - 1
a1: load count a2: add 1 a3: store count	Register/ALU "view"	b1: load count b2: subtract 1 b3: store count

Remember that "executing" an instruction involves multiple architecture-level steps, including loading registers, loading ALUs, executing ALUs, fetching results from ALU, etc.

Assume initial value of count = 4

What is the one property of the desired history that is different from the non-desirable histories?

History	Result
a1 < b1 < a2 < a3 < b2 < b3	count = 3
a1 < a2 < b1 < b2 < b3 < a3	count = 5
a1 < a2 < a3 < b1 < b2 < b3	count = 4
b1 < b2 < a1 < b3 < a2 < a3	count = 5

SYNCHRONIZATION PRIMITIVES

- System may provide mechanisms for atomic execution …
- OS should provide synchronization primitives that use atomic execution and offer the user more “abstract” solution:
  - Mutex Locks
  - Semaphores
  - Monitors

MUTEX

Most operating systems allow, via a system call, the use of a **<u>mutex</u>** … this allows the application programmer to solve a critical section problem

Mutex
+acquire()
+release()

This high level idea is the following : **have the OS provide system calls for a lock that can be used to control access to a critical section.**

```
do {
   // acquire lock
     Critical section
   // release lock
   // other stuff (remainder)
} while(true);
```

```
do {
   // acquire lock
     Critical section
   // release lock
   // other stuff (remainder)
} while(true);
```

MUTEX LOCKS

- Calls to either acquire() or release() must be performed atomically.
- What does that mean?
  - Thread should not be interrupted while performing the locking/releasing sequence:
  - disable interrupt OR
  - use a single instruction for locking/releasing:
    - test and set()
    - compare and swap()

```
do {
    acquire lock
        critical section
    release lock
        remainder section
} while (true);
```

```
acquire() {
   while (!available)
      ; /* busy wait */
   available = false;;
}
```

```
release() {
   available = true;
}
```

CRITICAL SECTIONS

- Worksheet Q2: Add mutex code to ensure atomicity of critical section.

Mutex
+acquire()
+release()

```
in = out = 0;
```

Thread A

```
while (true) {
item = produce_item;
while
(counter == BUFFER_SIZE) {}/* do nothing */;
buffer[in] = item;
in = (in + 1) % BUFFER_SIZE;
counter++;
}
```

Critical Section

Thread B

```
while (true) {
while (counter == 0) {}/* do nothing
item = buffer[out];
out = (out + 1) % BUFFER_SIZE;
counter--;
consume_item(item);
```

Critical Section

WESTERN
WASHINGTON UNIVERSITY

MUTEX SOLUTION FOR PRODUCER/CONSUMER

```
in = out = 0;
Mutex mutex = Mutex.Init();
```

Thread A

```
while (true) {
item = produce_item;
while
(counter == BUFFER_SIZE) {}/* do nothing */;
buffer[in] = item;
in = (in + 1) % BUFFER_SIZE;
counter++;
}
```

Thread B

```
while (true) {
while (counter == 0) {}/* do nothing
item = buffer[out];
out = (out + 1) % BUFFER_SIZE;
counter--;
consume_item(item);
```

MUTEX SOLUTION FOR PRODUCER/CONSUMER

Initialize mutex object by main thread.

Use the mutex by both threads

```
in = out = 0;
Mutex mutex=Mutex.Init();
```

Thread A

```
while (true) {
item = produce_item;
while
(counter == BUFFER_SIZE) {}/* do nothing */;
buffer[in] = item;
in = (in + 1) % BUFFER_SIZE;
mutex.acquire()
counter++;
mutex.release()
}
```

Thread B

```
while (true) {
while (counter == 0) {}/* do nothing
item = buffer[out];
out = (out + 1) % BUFFER_SIZE;
mutex.acquire()
counter--;
mutex.release()
consume_item(item);
```

SEMAPHORES: MORE CONTROL

- Mutex lock allow only one thread to use critical section.

T1 *T2* *T3*

Semaphore
2

critical 1 critical 2 critical 3

Semaphore
int value
+ Semaphore(int) + increment signal + decrement wait

SEMAPHORES: MORE CONTROL

- Mutex lock allow only one thread to use critical section.
- Solution: semaphores
  - Can only access critical section if S>0.
  - Can control number of threads running critical section by initializing S (and capping it) to an integer value.

```
wait(S) {
    while (S < 0) {
    //busy wait
    }
    S--;
}
```

Use wait() instead of acquire().

Critical Section

```
singal(S) {
    S++;
}
```

Use signal() instead of release().

SEMAPHORES

- Uses a counter S that can only be accesses through atomic operations wait() and signal ().
- Must use wait () before accessing critical section
- Can only access critical section if S>0.
- Can control number of threads running critical section
- Can control order of threads.

```
wait(S) {
    while (S < 0) {
    //busy wait
    }
    S--;
}
```

Critical Section

```
singal(S) {
    S++;
}
```

Semaphore
int value
Thread* list_of_waiting
+wait()
+signal()

SEMAPHORES: AVOIDING BUSY WAITING

- Busy waiting wastes CPU cycles.
- When it expected time to wait is short, it is rather beneficial compared to expensive context switch.
- Otherwise, CPU time is lost.

```
wait(S) {
    while (S < 0) {
    //busy wait
    }
    S--;
}
```

Critical Section

```
singal(S) {
    S++;
}
```

SEMAPHORES: AVOIDING BUSY WAITING

- Busy waiting wastes CPU cycles.
- When it expected time to wait is short, it is rather beneficial compared to expensive context switch.
- Otherwise, CPU time is lost.
- Solution: block() and wakeup()

```
wait(S) {
    while (S < 0) {
    //busy wait
    }
    S--;
}
```

Critical Section

```
singal(S) {
    S++;
}
```

THREAD BLOCKING

- To avoid wasting CPU time while waiting on a semaphore (or a lock), threads can block themselves using a block() call.
- In linux, block() is implemented using 'sleep()' system call.
- Threads can place themselves in a waiting queue for the specific semaphore.
- And *afterwards* block themselves.

sleep(3) - Linux man page

Name

sleep - sleep for the specified number of seconds

Synopsis

```
#include <unistd.h>
unsigned int sleep(unsigned int seconds);
```

Description

sleep() makes the calling thread sleep until *seconds* seconds have elapsed or a signal arrives which is not ignored.

SEMAPHORE WITH WAITING QUEUE

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
    int value;
    struct process *list;
} semaphore;
```

Add list of waiting threads/processes.

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
    int value;
    struct process *list;
} semaphore;
```

Add list of waiting threads/processes.

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
     int value;
     struct process *list;
} semaphore;

wait(semaphore *S) {
          S->value--;
          if (S->value < 0) {
               add this process to S->list;
               block();
          }
}
```

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
    int value;
    struct process *list;
} semaphore;

wait(semaphore *S) {
        S->value--;
        if (S->value < 0) {
            add this process to S->list;
            block();
        }
}
```

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
     int value;
     struct process *list;
} semaphore;

wait(semaphore *S) {
          S->value--;
          if (S->value < 0) {
                add this process to S->list;
                block();
          }
}

signal(semaphore *S) {
          S->value++;
          if (S->value <= 0) {
                remove a process P from S->list;
                wakeup(P);
          }
}
```

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
    int value;
    struct process *list;
} semaphore;

wait(semaphore *S) {
        S->value--;
        if (S->value < 0) {
            add this process to S->list;
            block();
        }
}

signal(semaphore *S) {
        S->value++;
        if (S->value <= 0) {
            remove a process P from S->list;
            wakeup(P);
        }
}
```

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
     int value;
     struct process *list;
} semaphore;

wait(semaphore *S) {
          S->value--;
          if (S->value < 0) {
                add this process to S->list;
                block();
          }
}

signal(semaphore *S) {
          S->value++;
          if (S->value <= 0) {
                remove a process P from S->list;
                wakeup(P);
          }
}
```

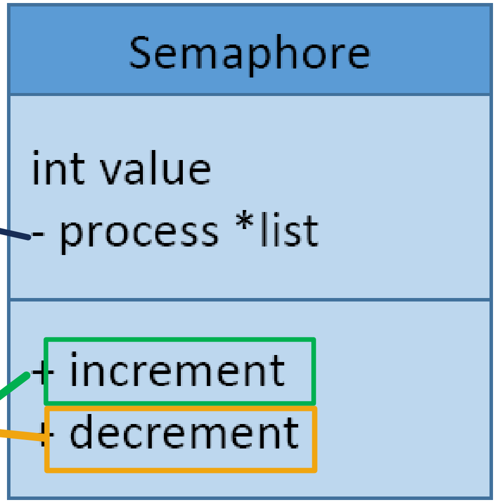
Semaphore
int value - process *list
+ increment + decrement

SEMAPHORE WITH WAITING QUEUE

```
typedef struct {
     int value;
     struct process *list;
} semaphore;

wait(semaphore *S) {
          S->value--;
          if (S->value < 0) {
               add this process to S->list;
               block();
          }
}

signal(semaphore *S) {
          S->value++;
          if (S->value <= 0) {
               remove a process P from S->list;
               wakeup(P);
          }
}
```



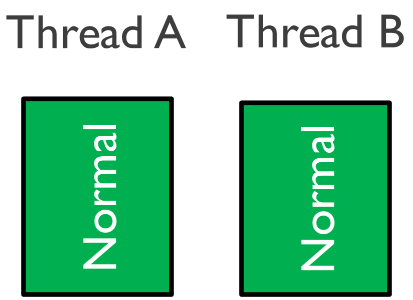
CRITICAL SECTION

No Execution

Normal Execution

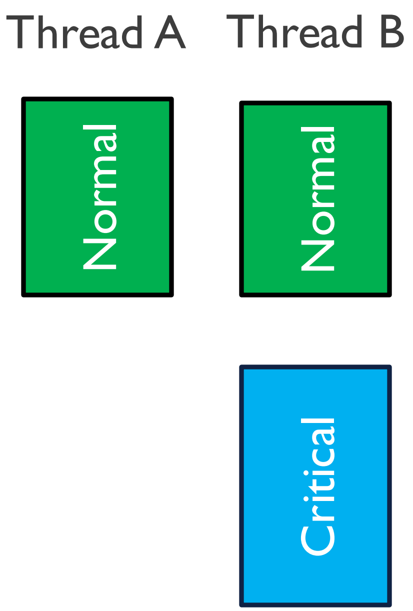
Atomic Execution

Critical Section Execution



CRITICAL SECTION

- No Execution
- Normal Execution
- Atomic Execution
- Critical Section Execution



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Normal Execution

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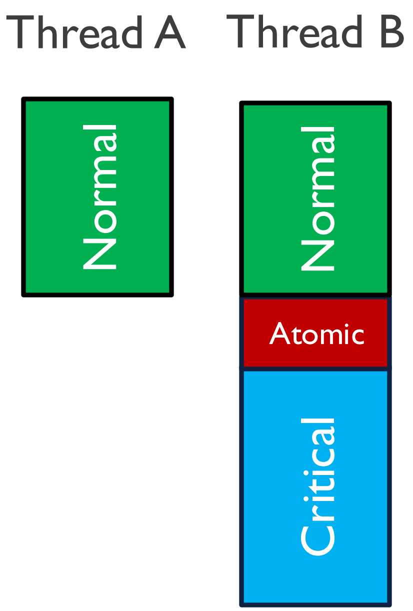
Critical Section Execution



acquire(), decrement(), wait() ..

CRITICAL SECTION

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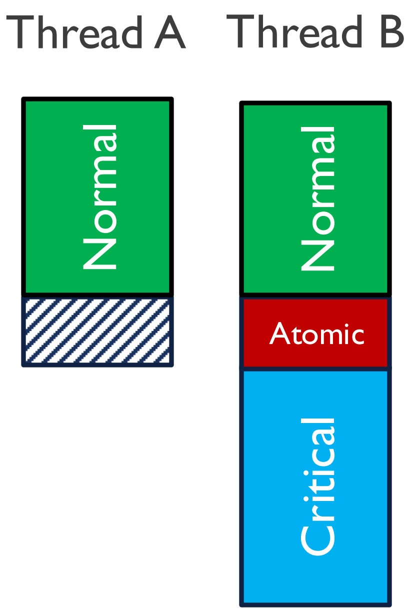
Atomic Execution

Critical Section Execution



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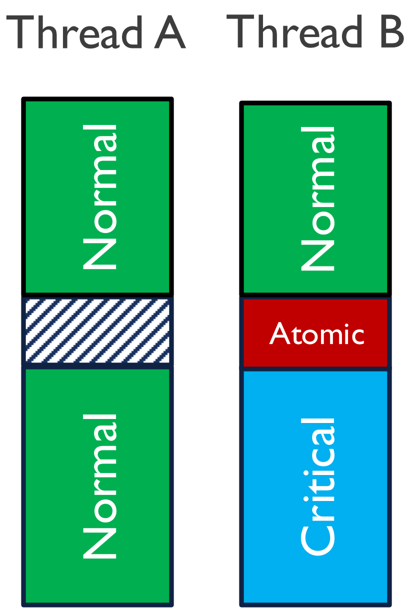

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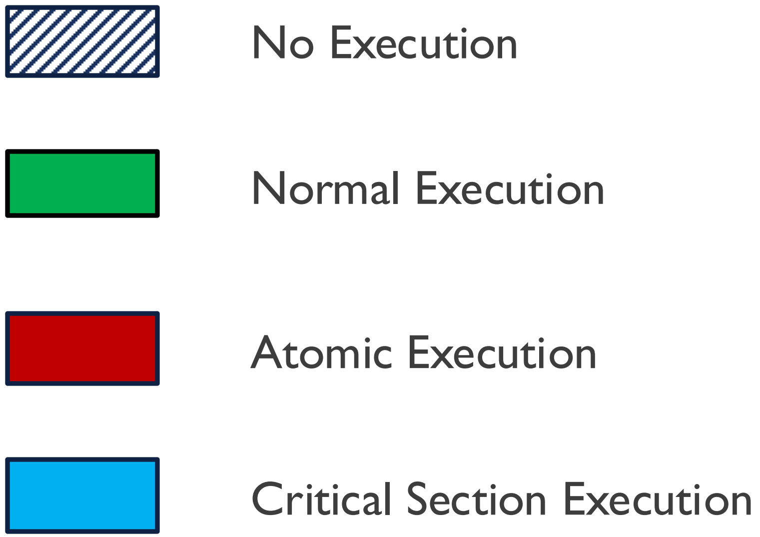

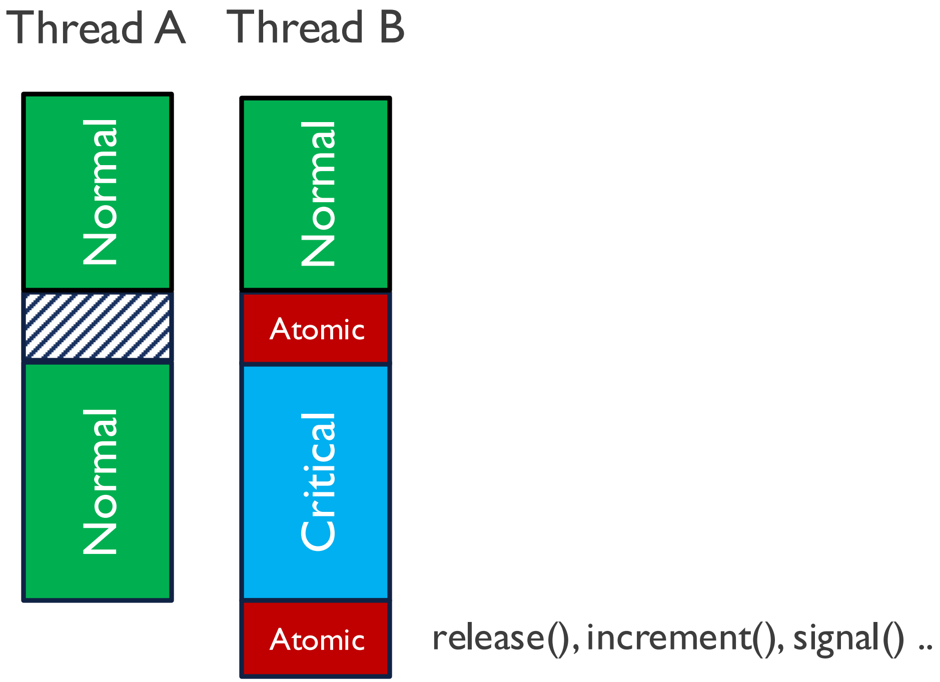

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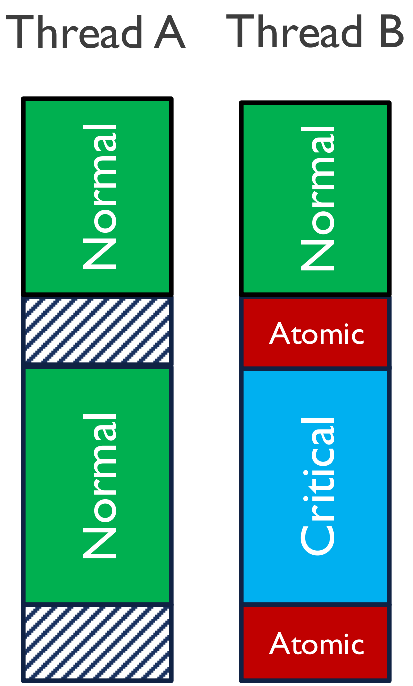

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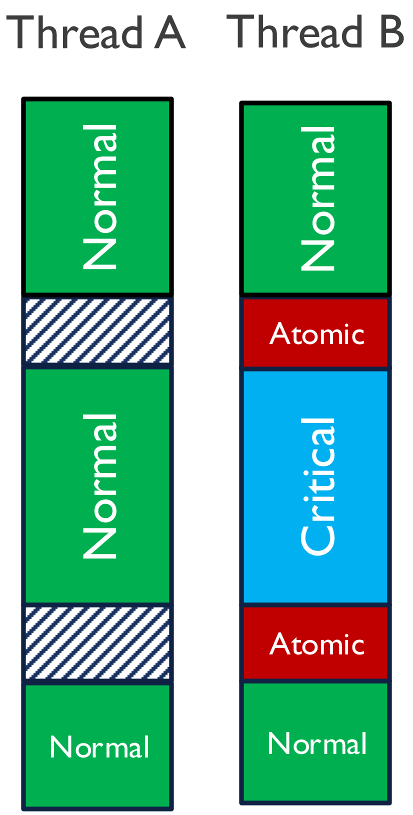
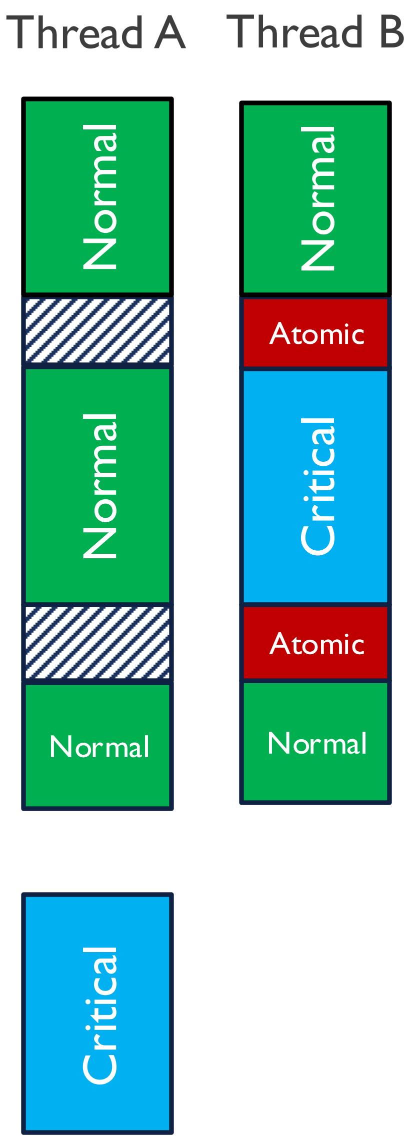
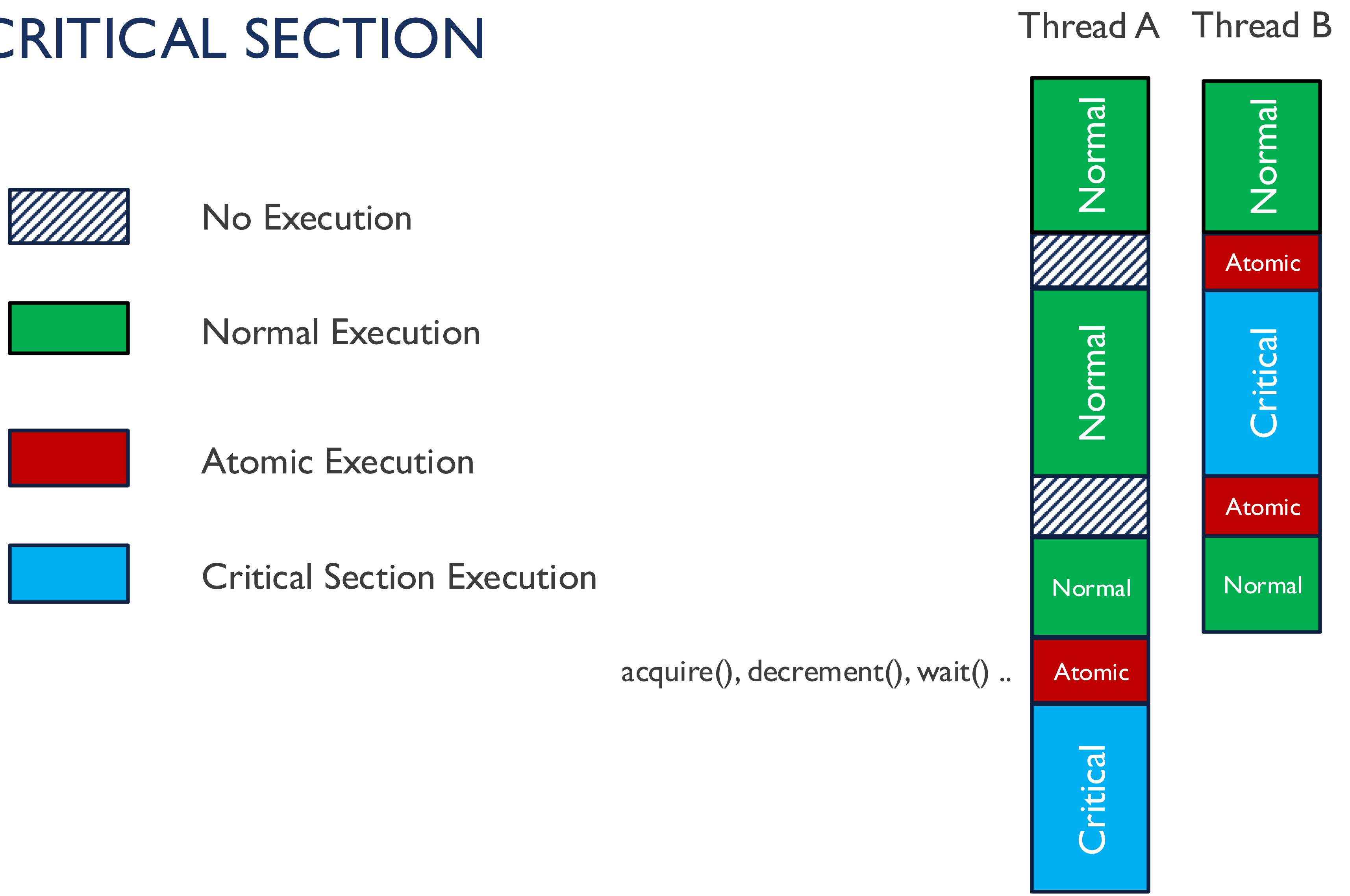


CRITICAL SECTION

(hatched)	No Execution
(green)	Normal Execution
(red)	Atomic Execution
(blue)	Critical Section Execution



CRITICAL SECTION



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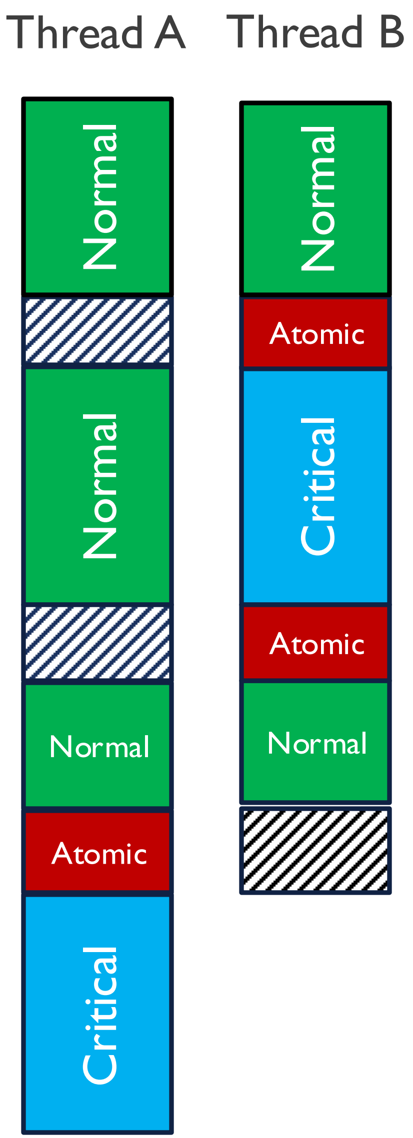

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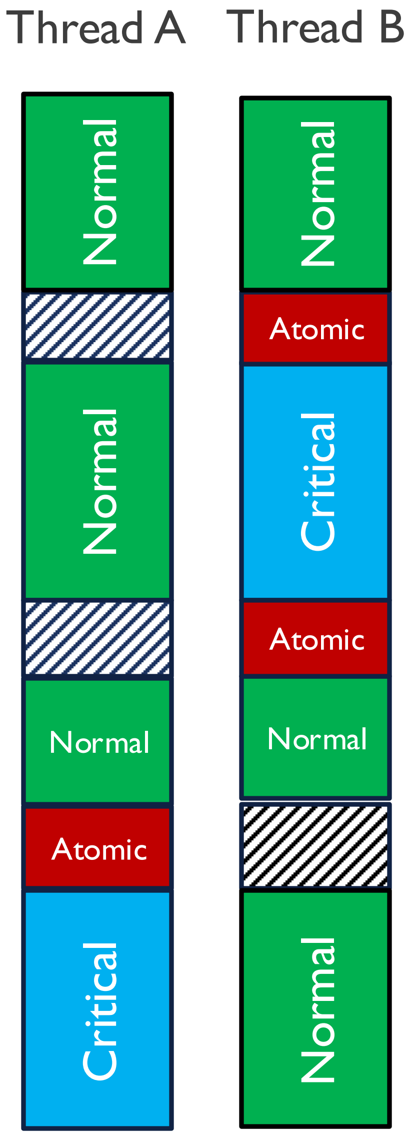

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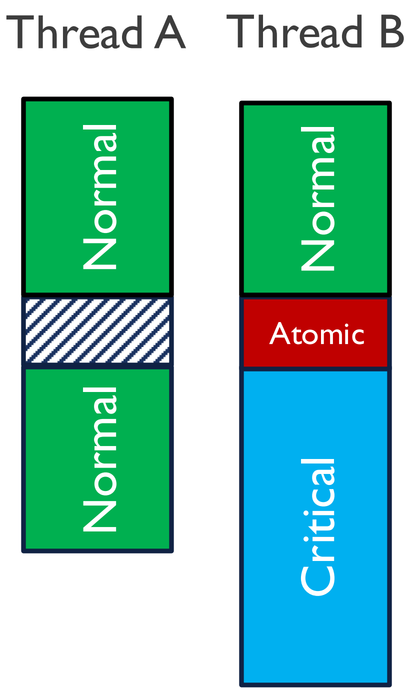

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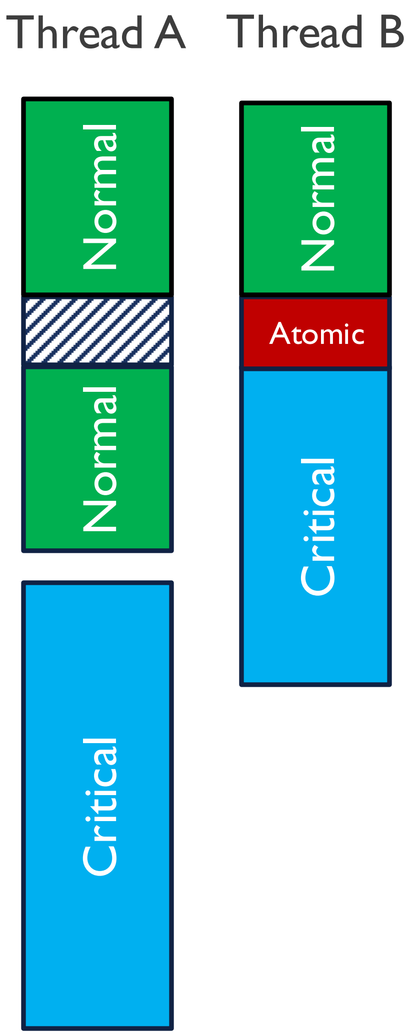

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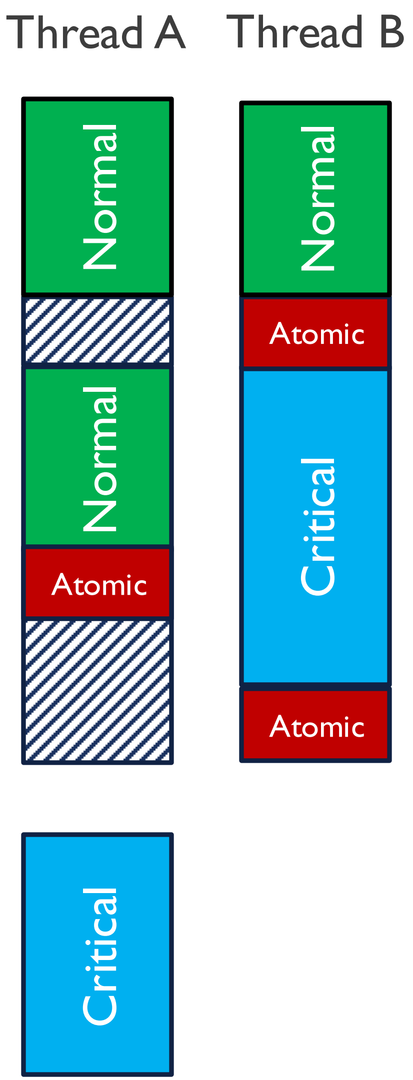

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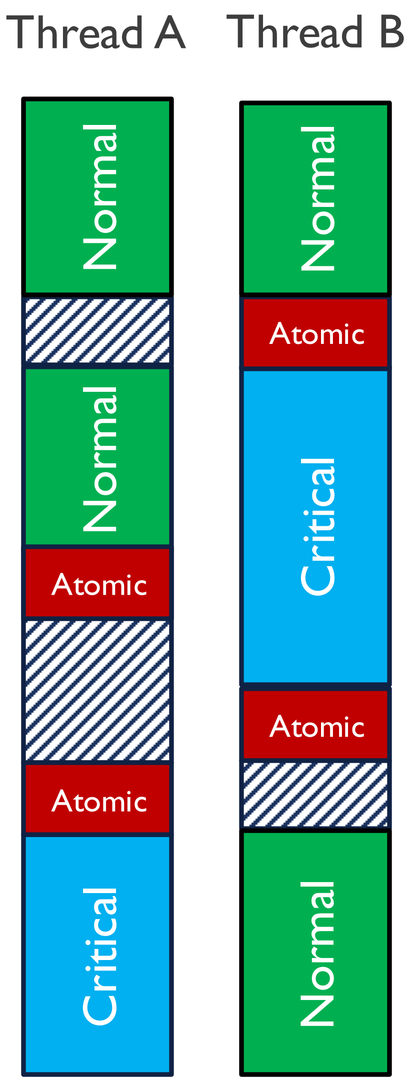
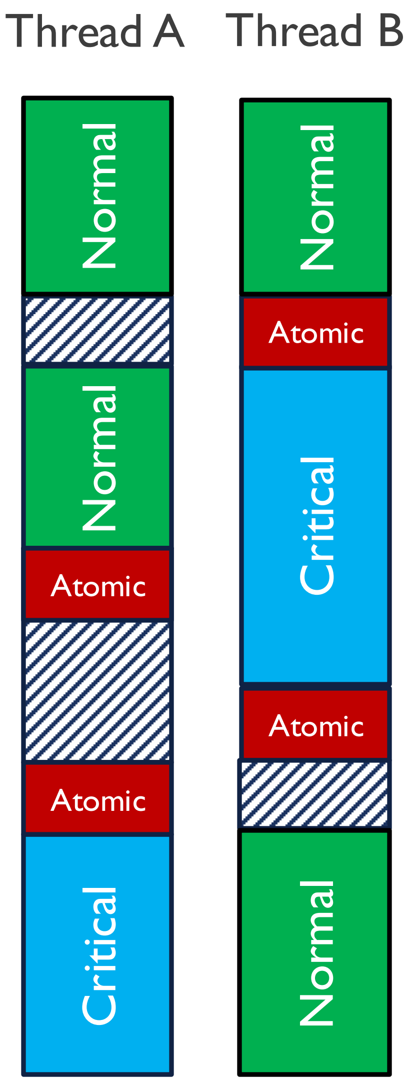


CRITICAL SECTION



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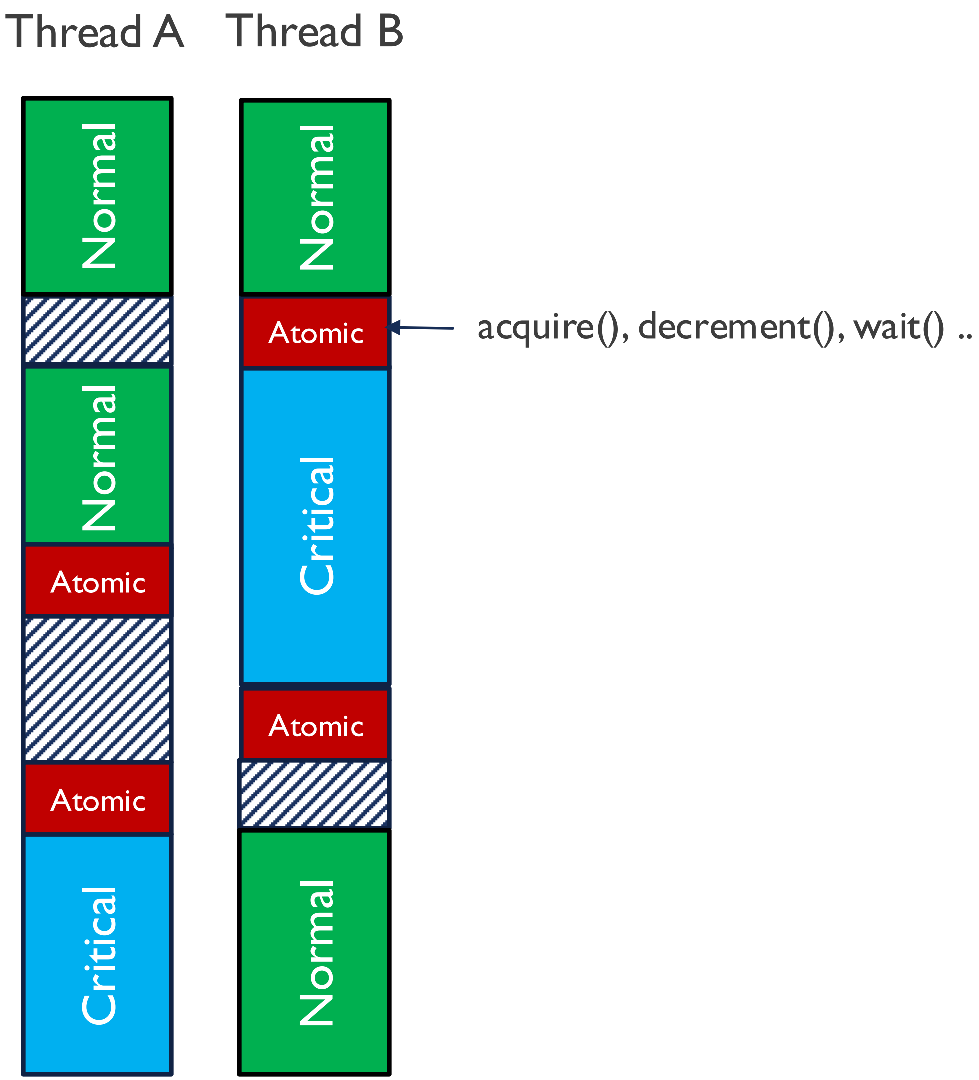

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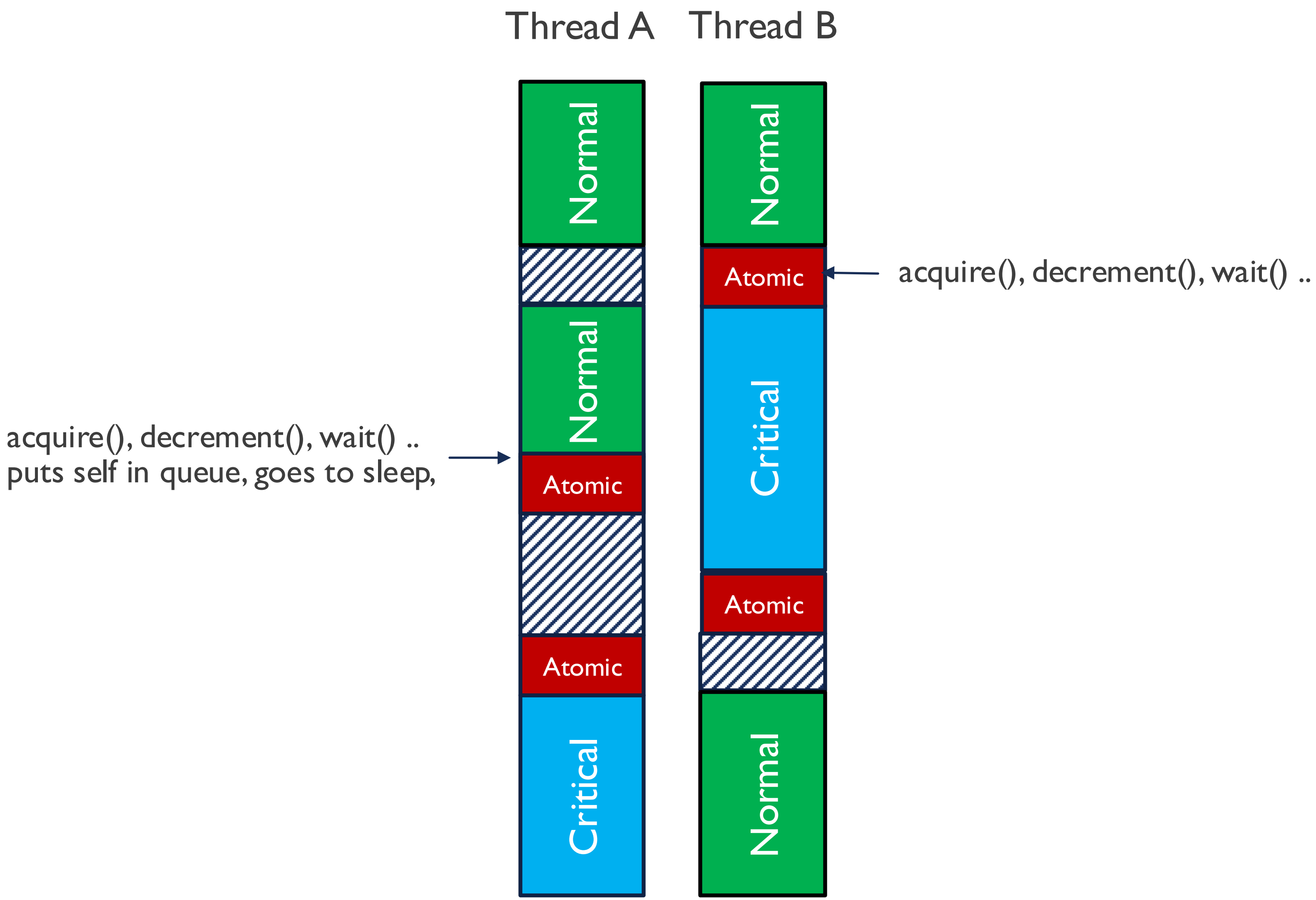

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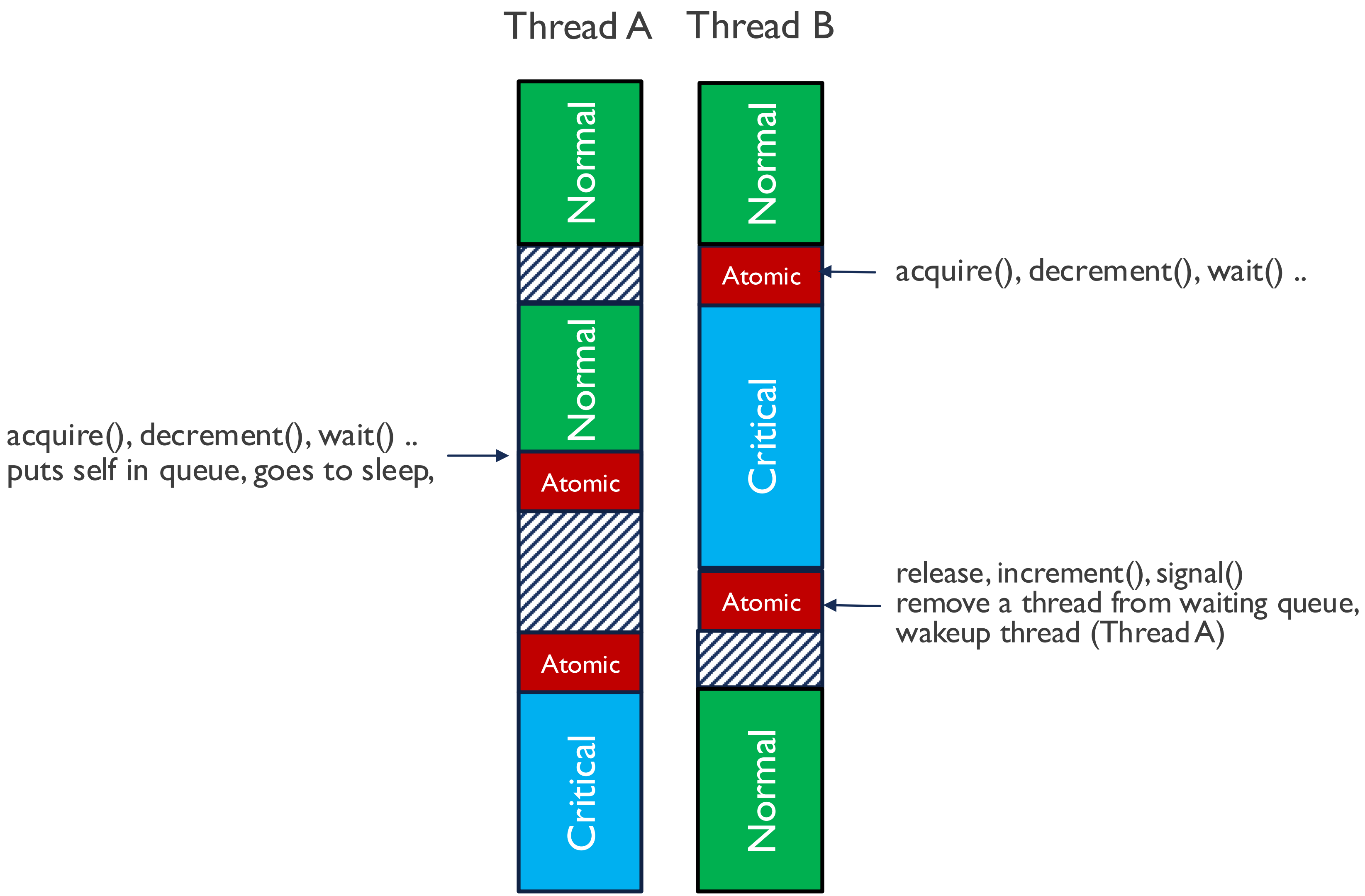

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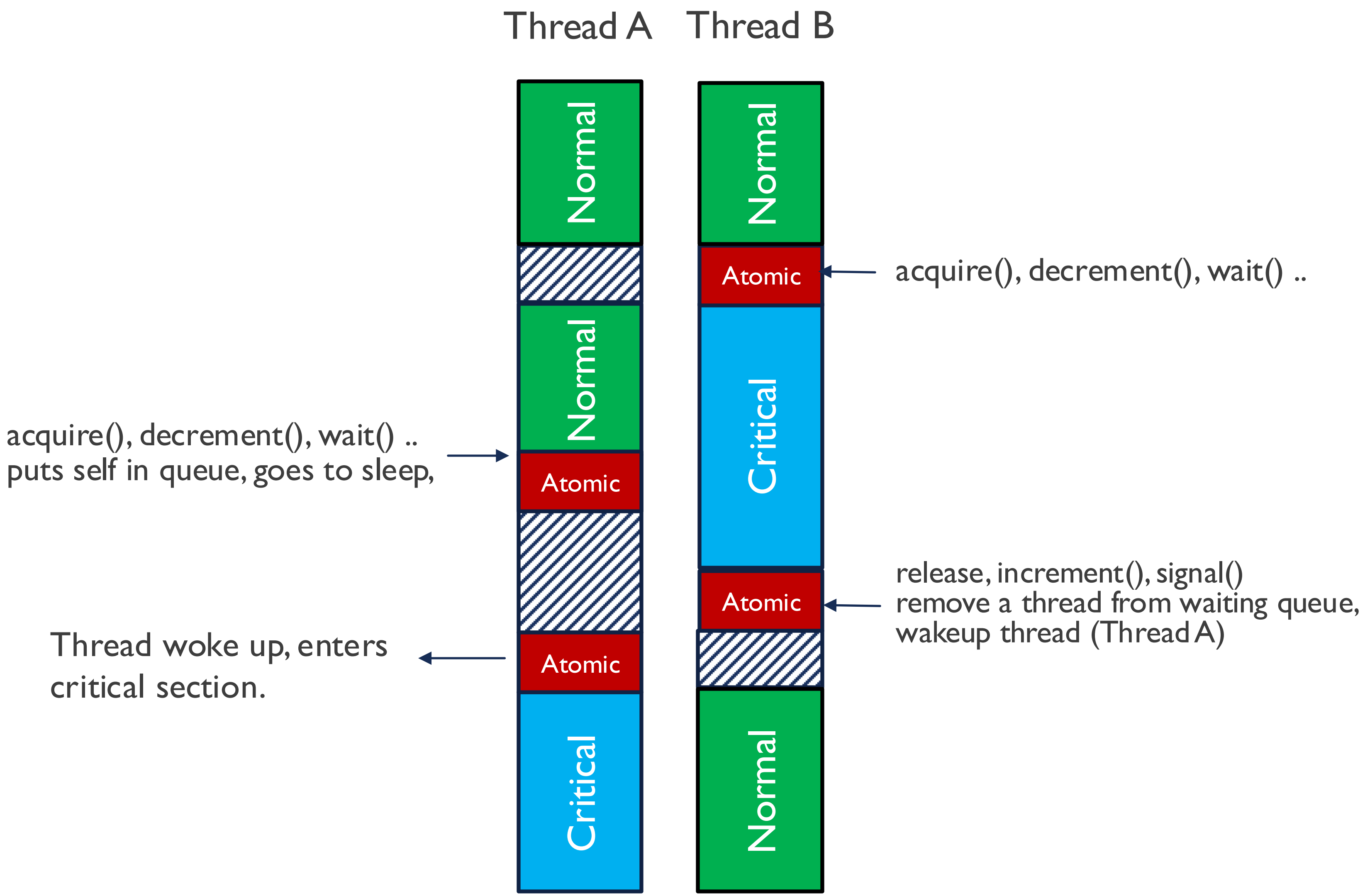

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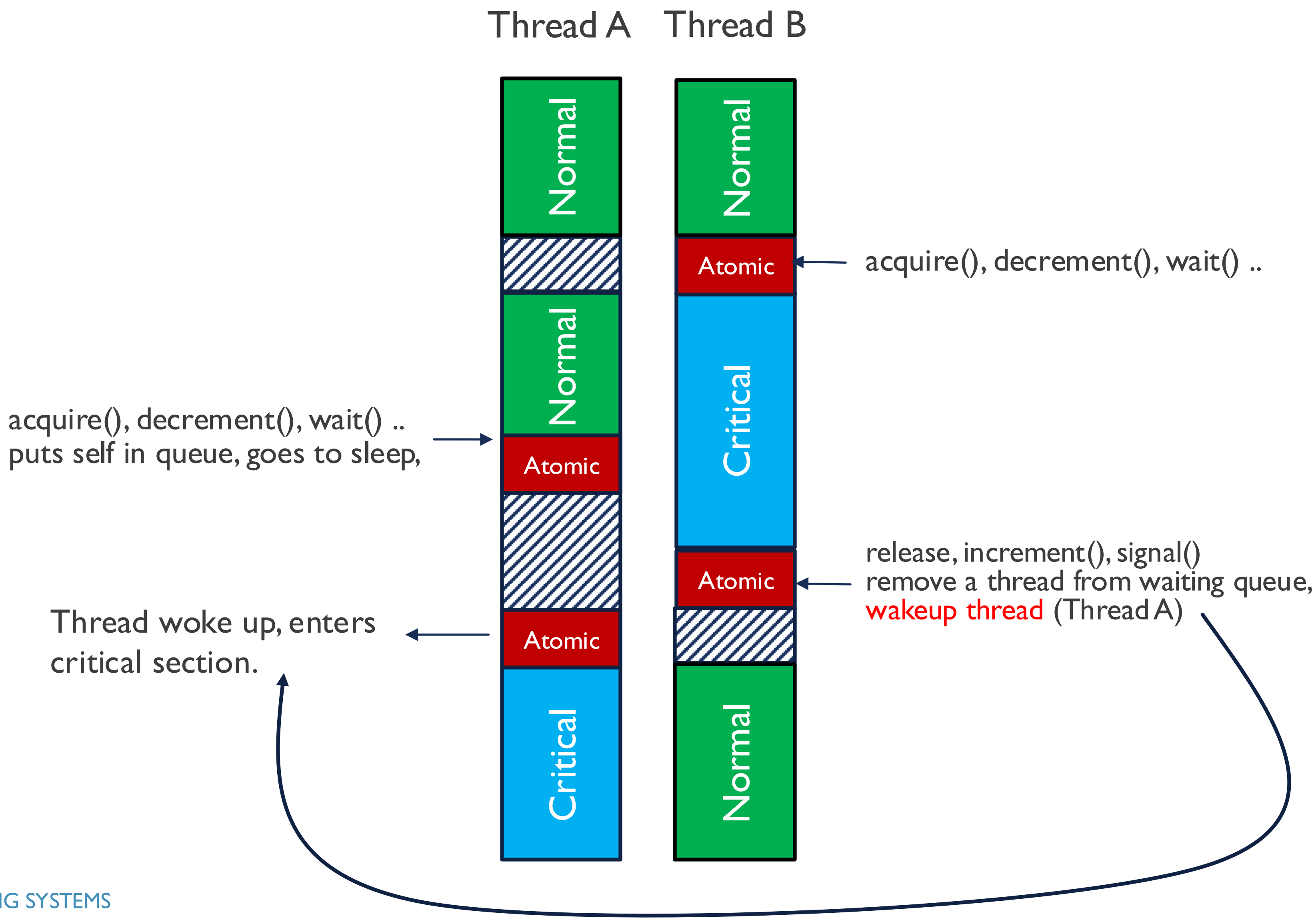

CRITICAL SECTION