Synchronization

ECE 469, Mar 27

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Threads

- Separate the concepts of a “thread of control” (PC, SP, registers) from the rest of the process (address space, resources, accounting, etc.)

- Modern OSes support two entities:
  - the *task* (process), which defines an address space, a resource container, accounting info
  - the *thread* (lightweight process), which defines a single sequential execution stream within a task (process)

Programming with Threads

- Flexible, but error-prone, since there no protection between threads
  - In C/C++,
    - automatic variables are private to each thread
    - global variables and dynamically allocated memory (malloc) are shared

- Need synchronization!

The need for synchronization!

- Cooperating processes may share data via
  - shared address space (code, data, heap) by using threads
  - Files
  - (Sending messages)
- What can happen if processes try to access shared data (address) concurrently?
  - Sharing bank account with sibling:

    At 3pm: If (balance > $10) withdraw $10
- How hard is the solution?

"Too much milk" Problem

Person A

1. Look in fridge: out of milk
2. Leave for Walmart
5. Arrive at Walmart
6. Buy milk
7. Arrive home

Person B

3. Look in fridge: out of milk
4. Leave for Walmart
8. Arrive at Walmart
9. Buy milk
10. Arrive home

- How to put in a locking mechanism?

Possible Solution 1

Person A

```
if ( noMilk ) {
  if (noNote) {
     leave note;
     buy milk;
     remove note;
  }
}
```

Person B

```
if ( noMilk ) {
  if (noNote) {
     leave note;
     buy milk;
     remove note;
  }
}
```

Will this work?

Person A

```
1.if ( noMilk ) {
  2.if (noNote) {
    5.leave note;
    buy milk;
    remove note;
  }
}
```

Person B

```
3.if ( noMilk ) {
  4.if (noNote) {
    6.leave note;
    buy milk;
    remove note;
  }
}
```

- Process can get context switched after checking milk and note, but before leaving note

Possible Solution 2

Person A

```
leave noteA
if (no noteB) {
  if (noMilk) {
    buy milk
  }
}
remove noteA
```

Person B

```
leave noteB
if (no noteA) {
  if (noMilk) {
    buy milk
  }
}
remove noteB
```

Will this work?

Person A

```
leave noteA
if (no noteB) {
   if (noMilk) {
      buy milk
   }
}
remove noteA
```

Person B

```
leave noteB
if (no noteA) {
   if (noMilk) {
      buy milk
   }
}
remove noteB
```

- We may not have Milk: Both process can leave note and skip buying milk

Possible Solution 3

Process A

```
leave noteA
while (noteB)
  do nothing;
if (noMilk)
  buy milk;
remove noteA
```

Process B

```
leave noteB
if (noNoteA) {
  if (noMilk) {
    buy milk
  }
}
remove noteB
```

Works, but complicated!

Process A

```
leave noteA
while (noteB)
  do nothing;
if (noMilk)
  buy milk;
remove noteA
```

Process B

```
leave noteB
if (noNoteA) {
  if (noMilk) {
    buy milk
  }
}
remove noteB
```

- A's code is different from B's
- busy waiting is a waste

How can we solve this?

- Root cause: Data Race

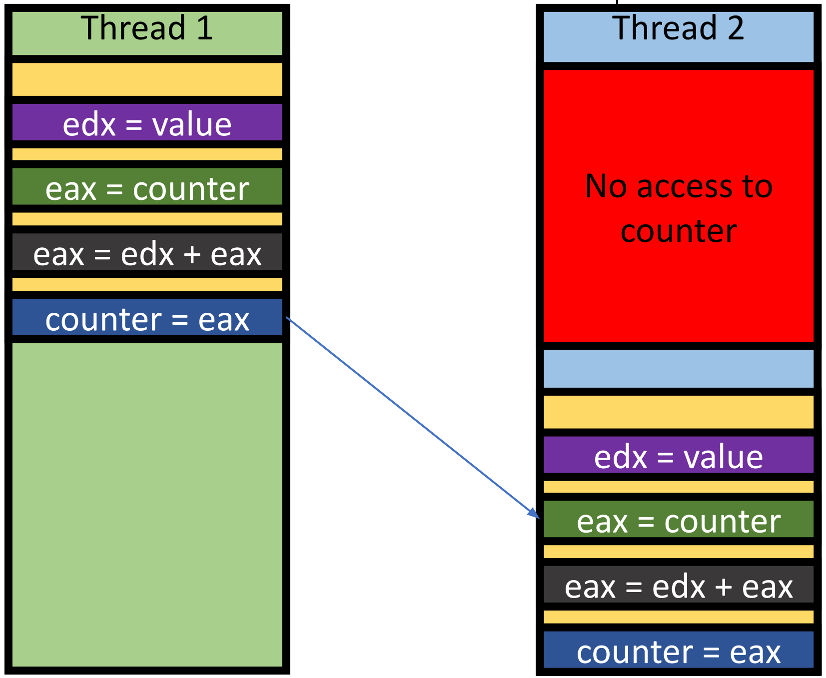
- A thread's execution result could be inconsistent if other threads intervene its execution…

- counter += value
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`

```
mov     0x20087b(%rip),%edx          # 0x201010 <value>
mov     0x20087d(%rip),%eax          # 0x201018 <counter>
add     %edx,%eax
mov     %eax,0x200875(%rip)          # 0x201018 <counter>
```

How can we prevent data races?

- What we need?
  - Exclusive access to counter (shared variable)



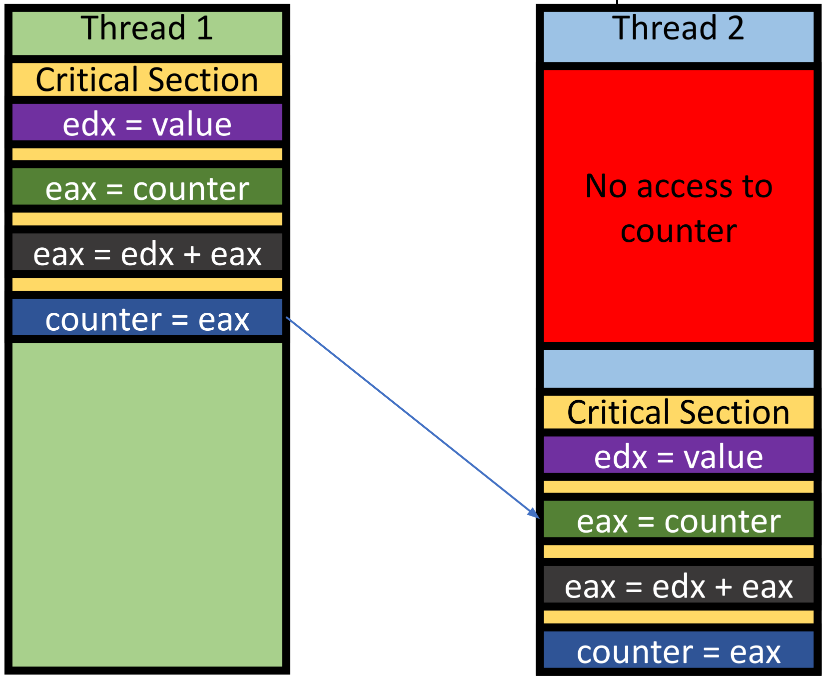
How can we prevent data races?

- *Critical section* – a section of code, or collection of operations, in which only one process shall be executing at a given time

- *Mutual exclusion (Mutex)* - mechanisms that ensure that only one person or process is doing certain things at one time (others are excluded)

How can we prevent data races?

- Mutual Exclusion / Critical Section
  - Combine multiple instructions as a chunk
  - Let only one chunk execution runs
  - Block other executions



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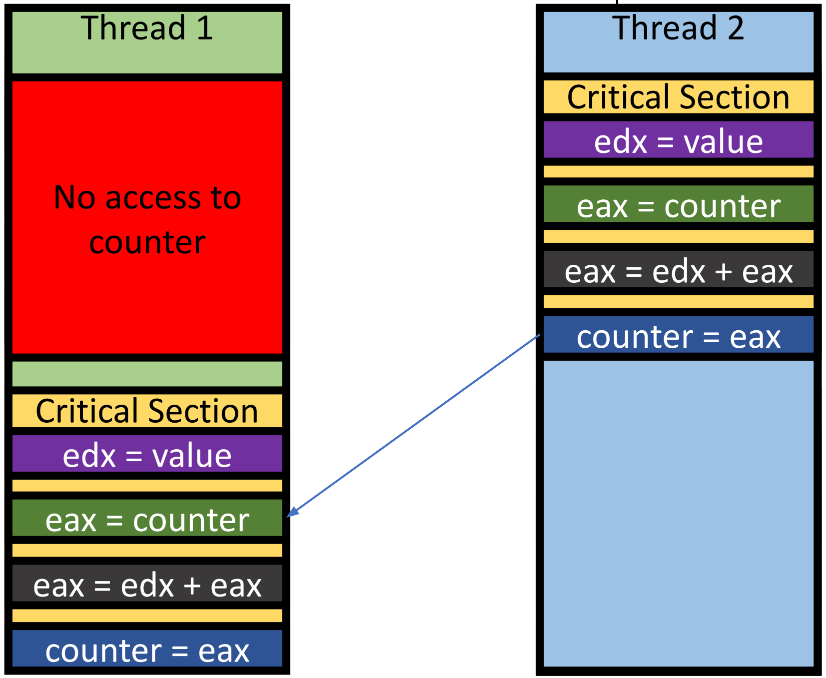


Mutex Considerations

- Mutex can synchronize multiple threads and yield consistent result
  - No read before previous thread store the shared data
- Making the entire program as critical section is meaningless
  - Running time will be the same as single-threaded execution
- Apply critical section **as short as possible** to maximize benefit of having concurrency
  - Non-critical sections will run concurrently!

Implementing Mutual exclusion

- Data races occur because of scheduler interleaving executing of different threads

- How to avoid this? Prevent interleaving

Preventing Interleaving

- `cli`, in a single processor computer
  - Clear interrupt bit
- CPU will never get interrupt until it runs `sti`
  - Set interrupt bit
- There will be no other execution
  - **Any problems?**

- counter += value
  - **`cli`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`sti`**

Preventing Interleaving

- `cli`, in a single processor computer
  - Clear interrupt bit
- CPU will never get interrupt until it runs `sti`
  - Set interrupt bit
- There will be no other execution
  - Any problems?
    - Multi CPU?
    - `cli/sti` available in Ring 0

- counter += value
  - **`cli`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`sti`**

Mutual Exclusion through locks

- Lock
  - Prevent others enter the critical section
- Unlock
  - Release the lock, let others acquire the lock

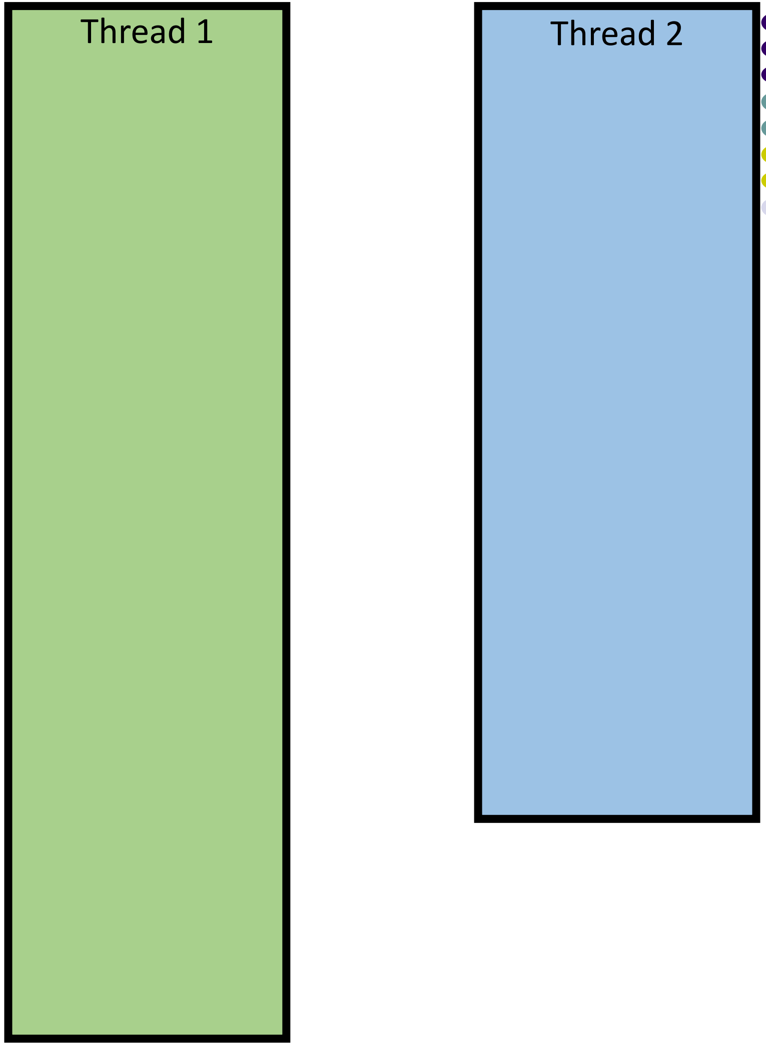
- counter += value
  - **lock()**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **unlock()**

Mutual Exclusion through locks

- Lock
  - Prevent others enter the critical section
- How?
  - Check if any other execution in the critical section
    - If it is, wait; busy-waiting with while()
  - If not, acquire the lock!
    - Others cannot get into the critical section
  - Run critical section
  - Unlock, let other execution know that I am out!

- counter += value
  - **`lock()`**
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - **`unlock()`**

Mutex Example



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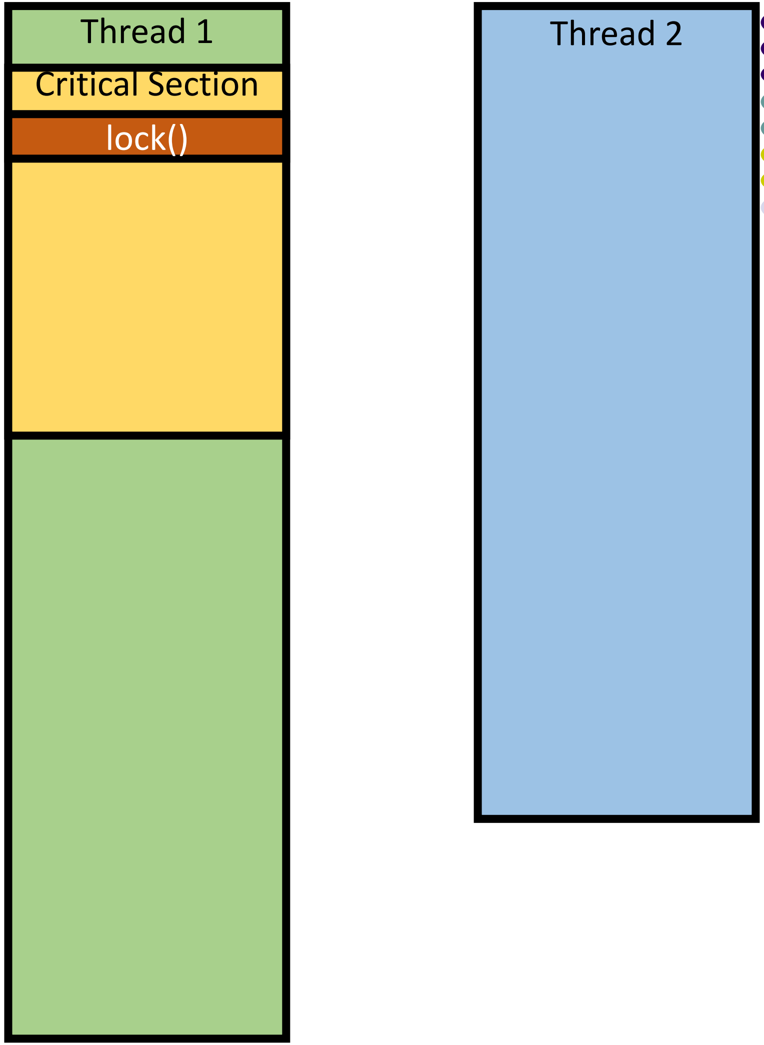

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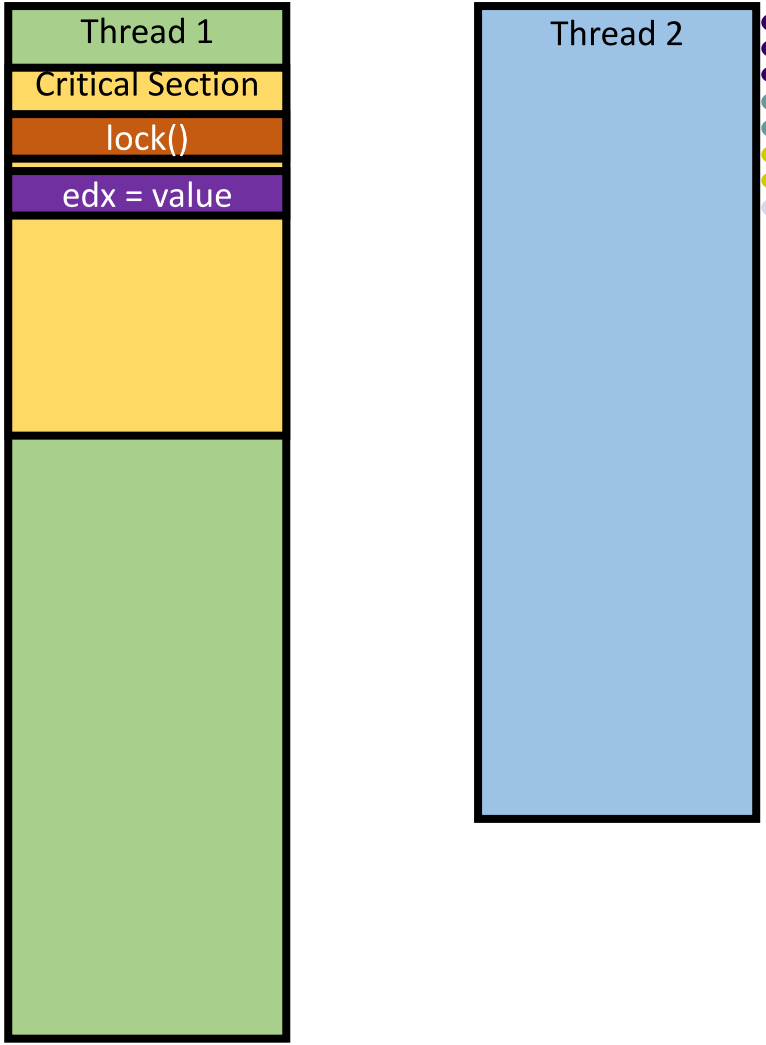

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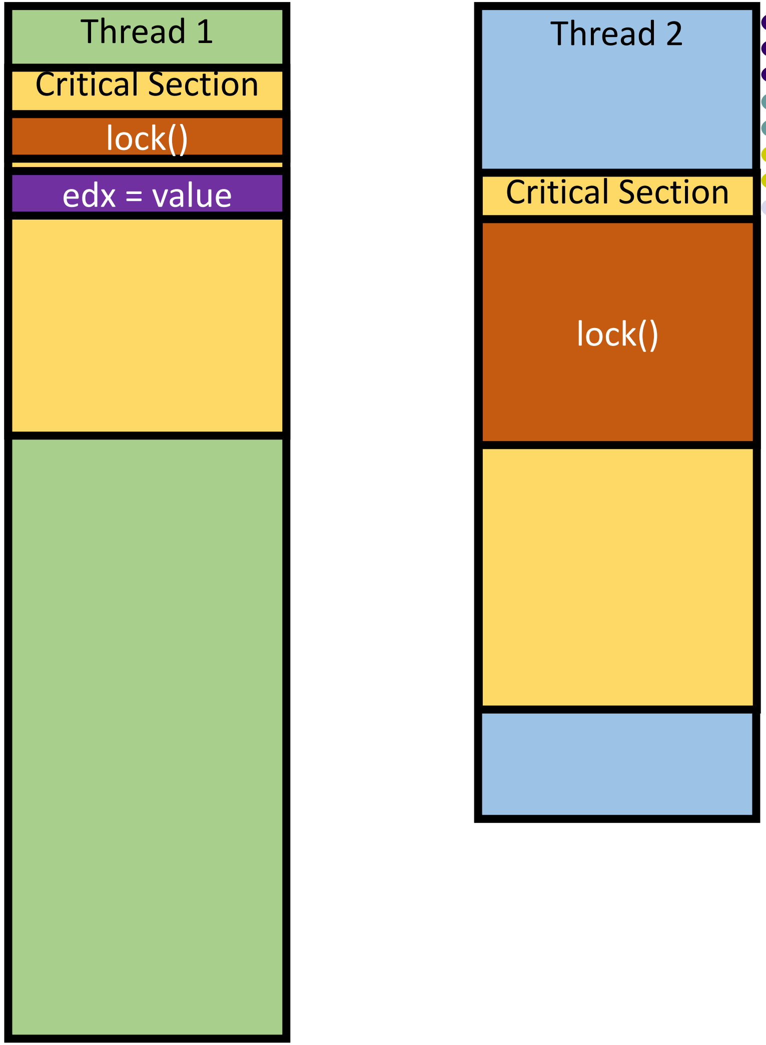

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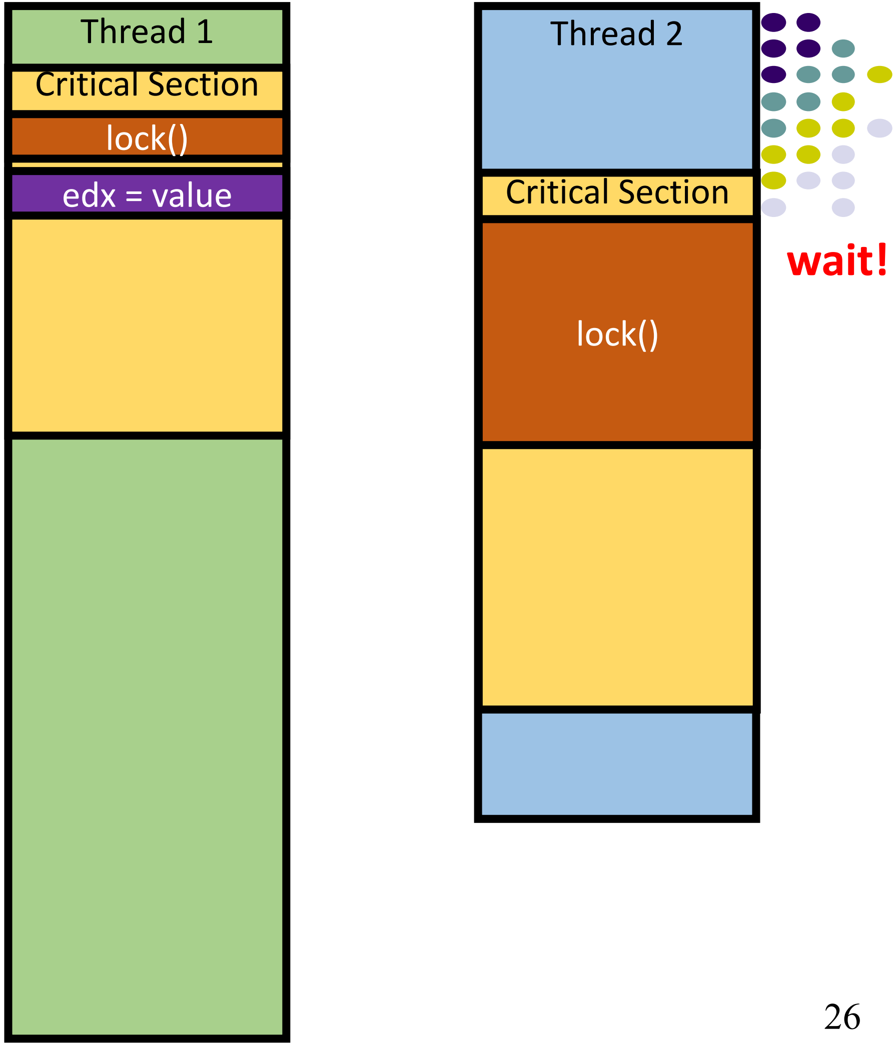

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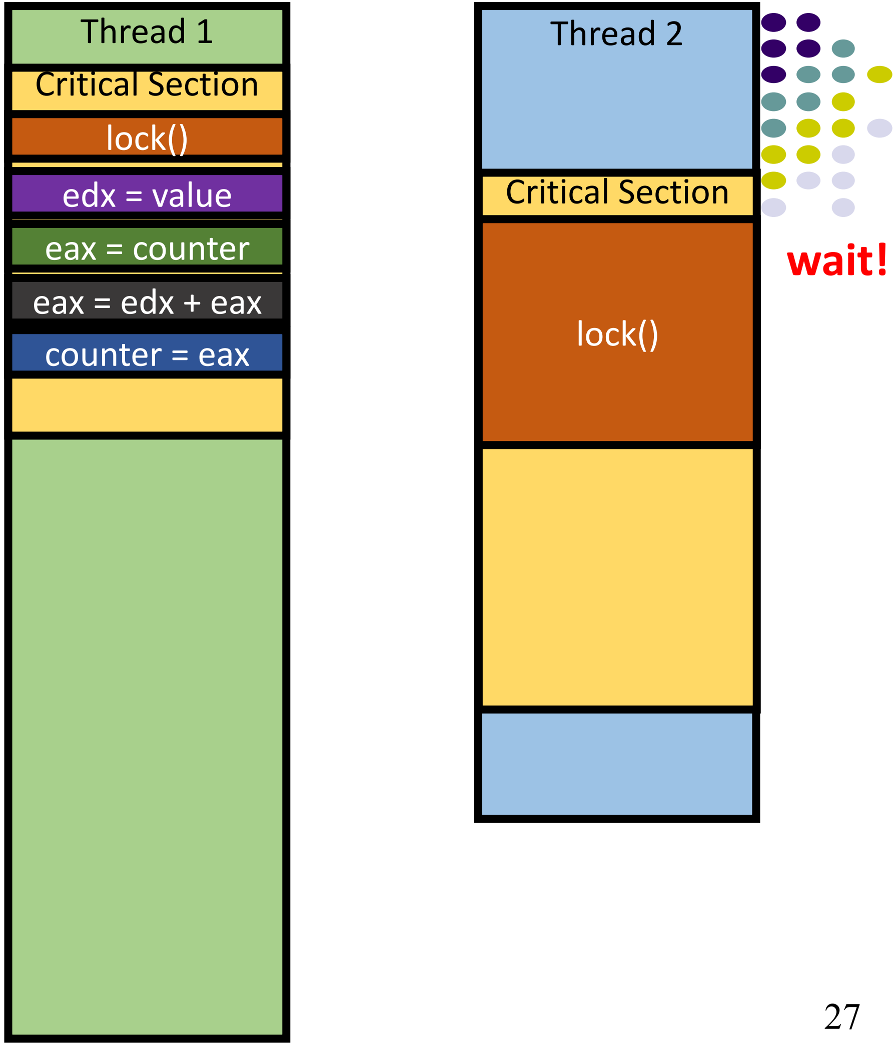

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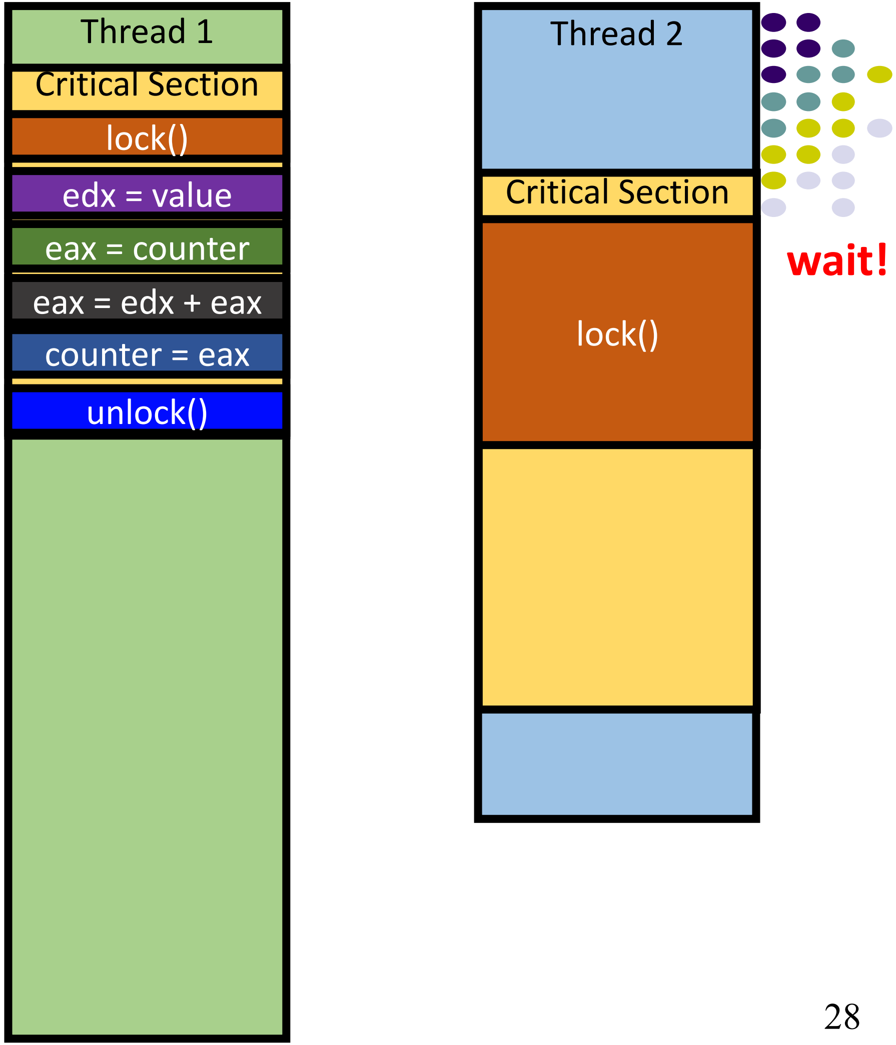

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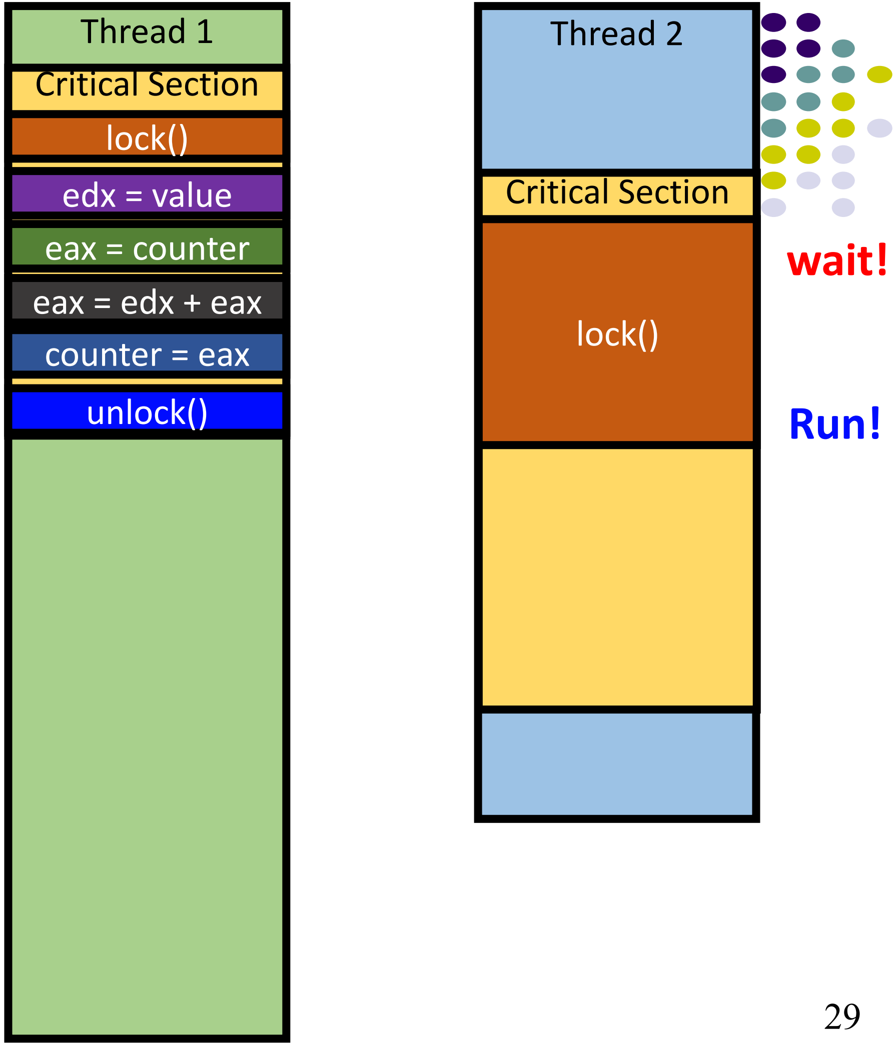

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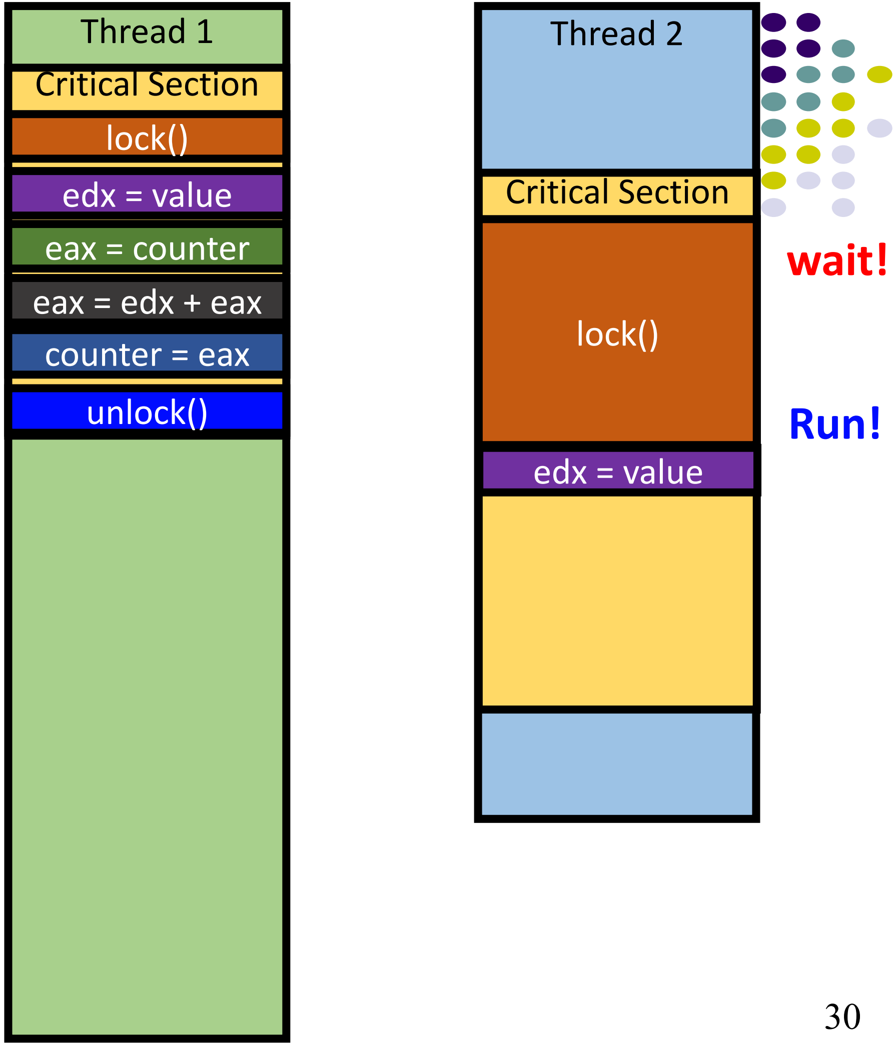

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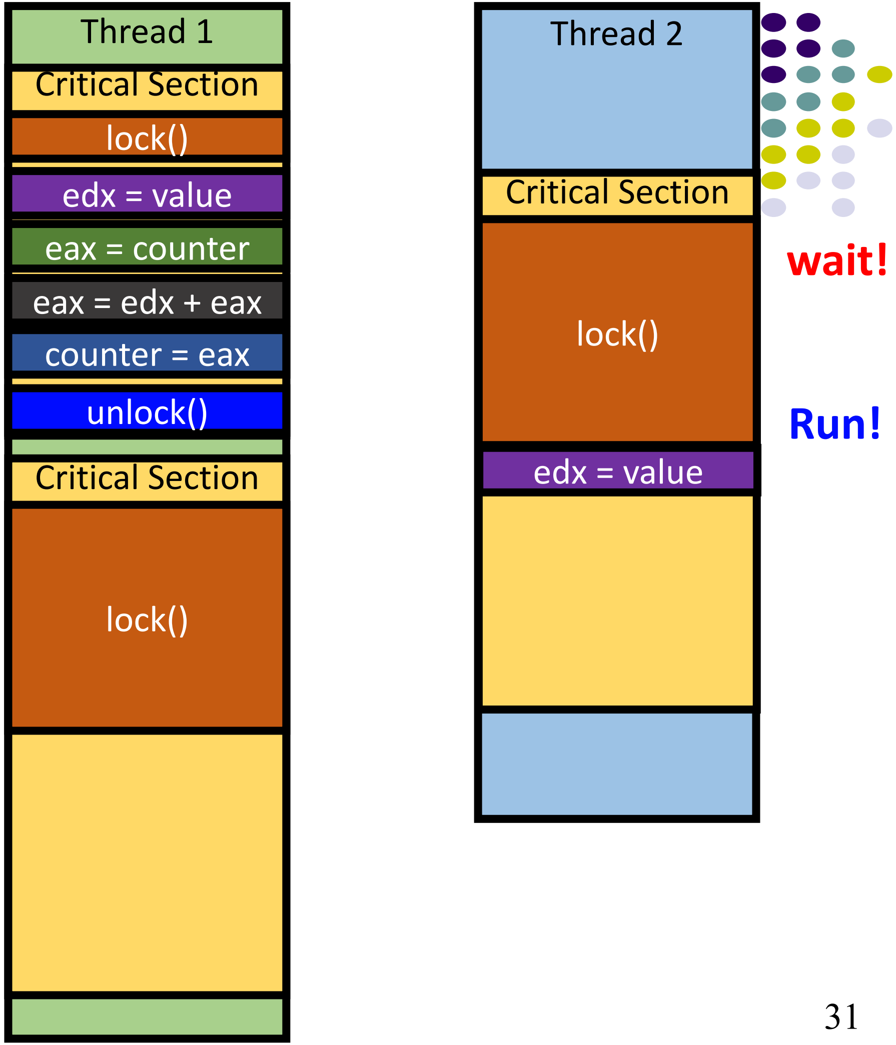

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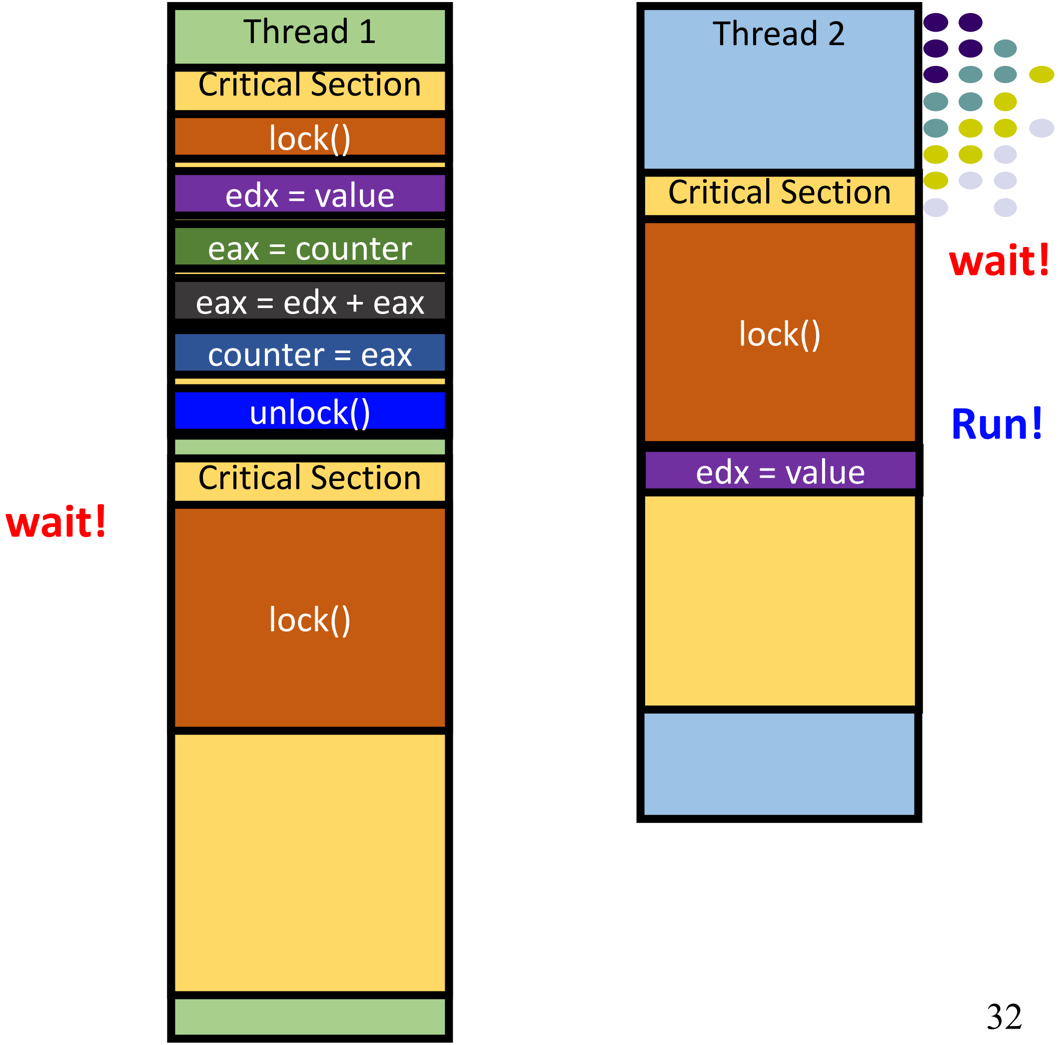

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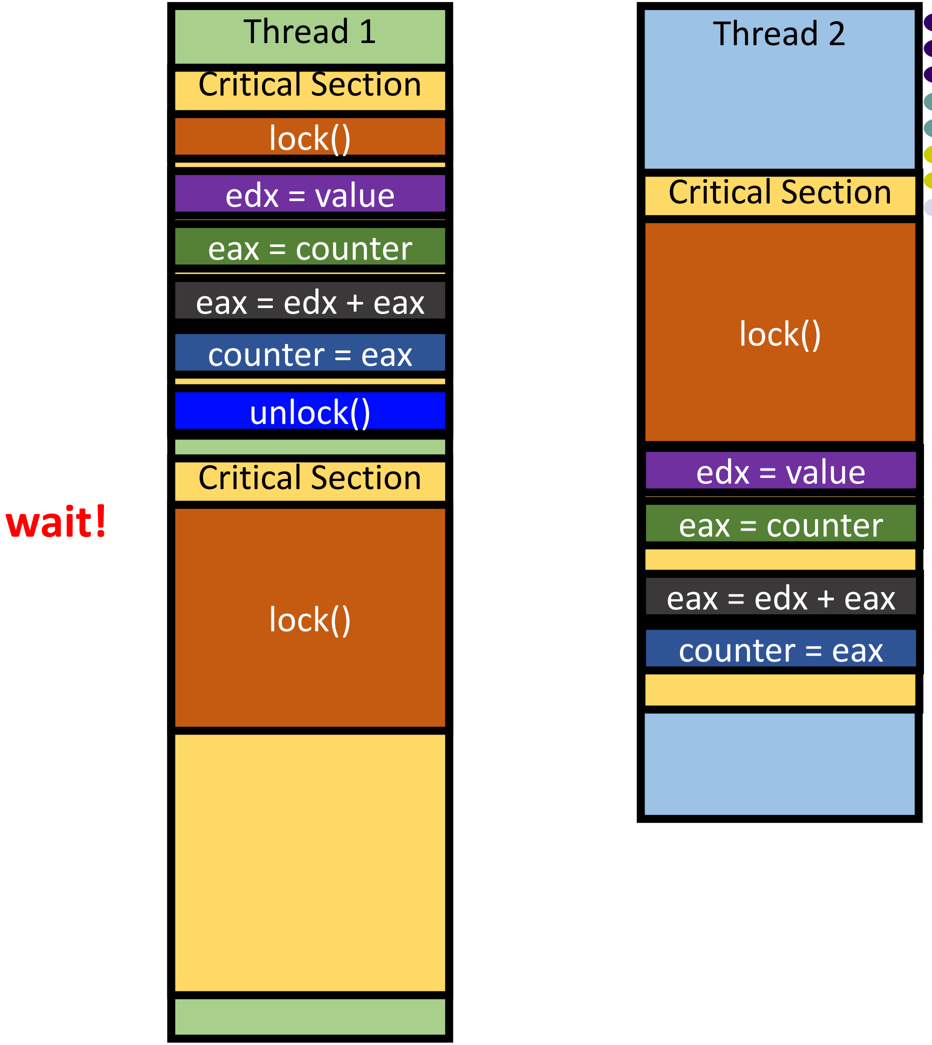

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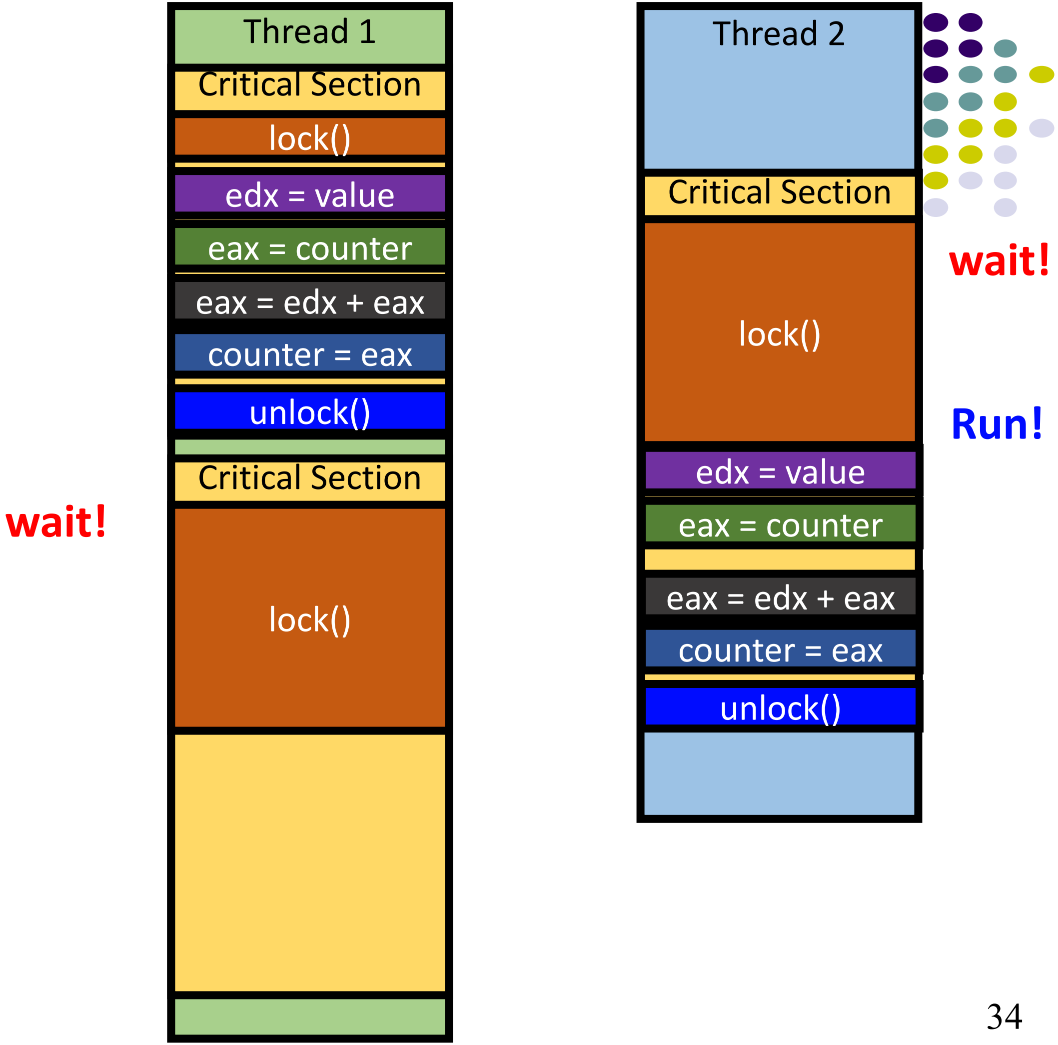

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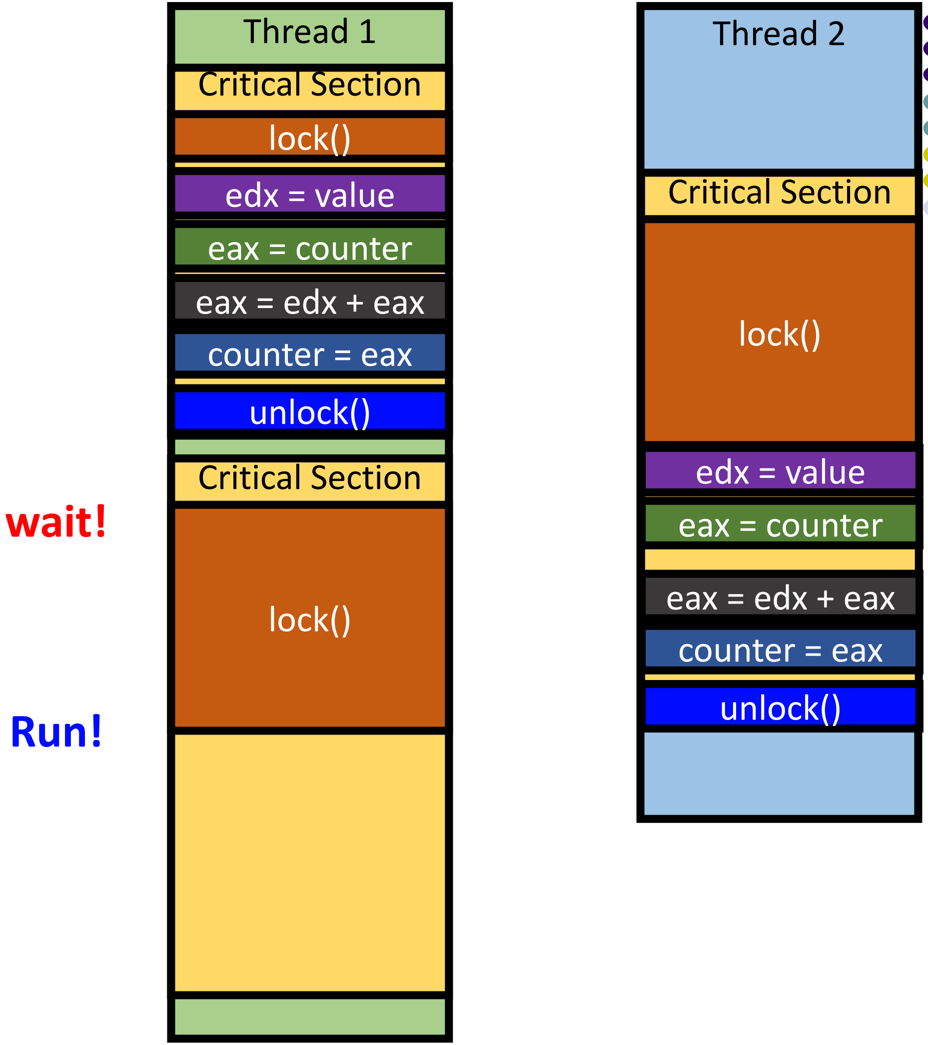

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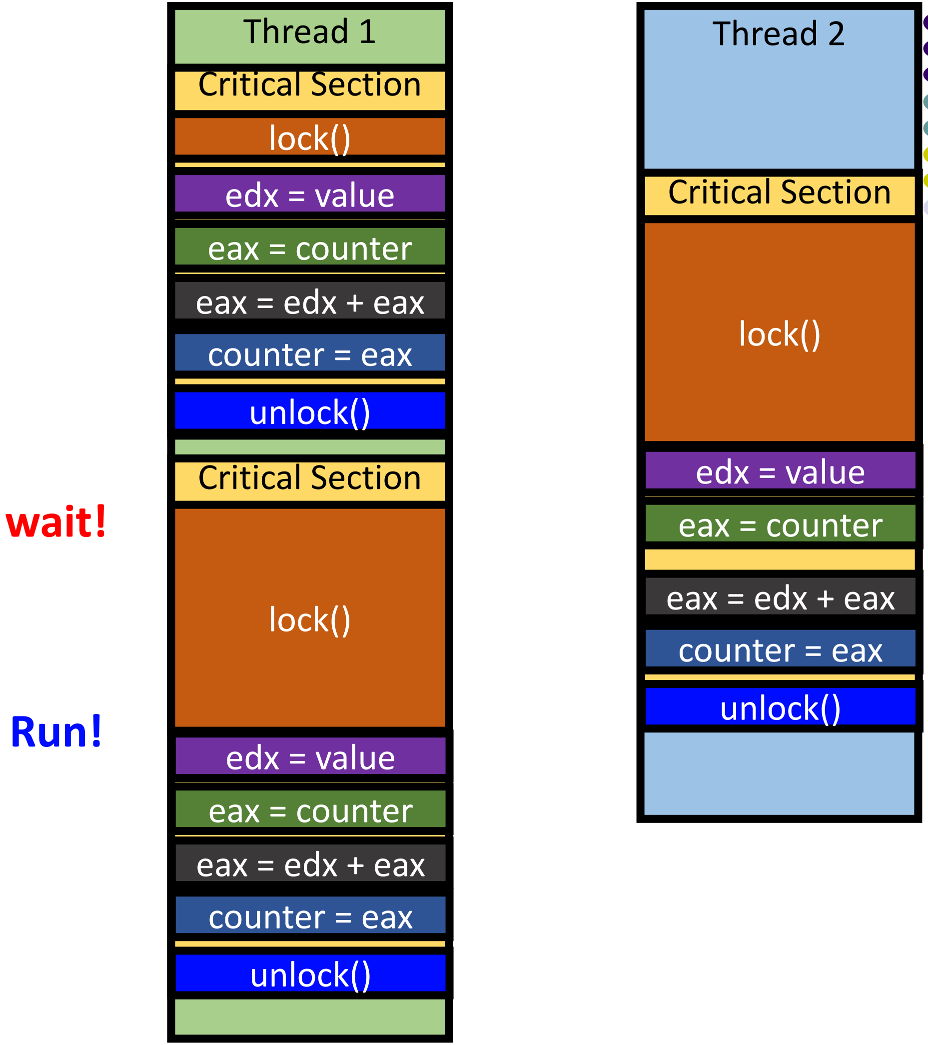
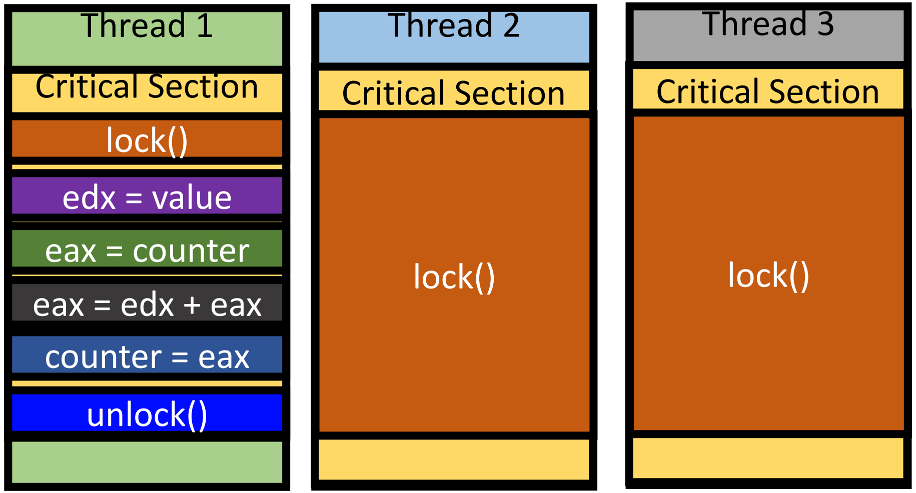


Implementing lock

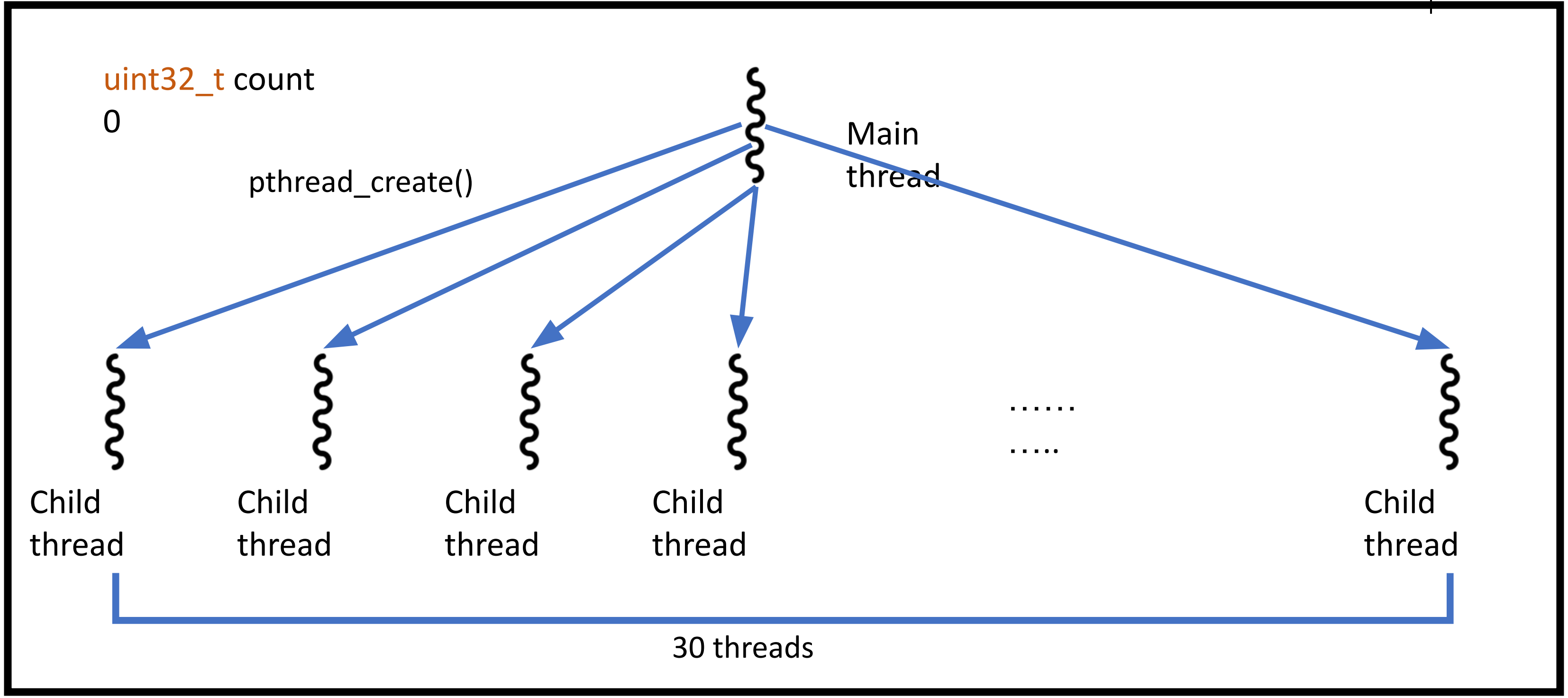
- Only one can run in critical section
- Others must wait!
  - Until nobody runs in critical section
- How can we create such
  - Lock() / Unlock() ?



lock example

- https://github.com/purs3lab/ee469_examples/tree/master/lock_example
- Run 30 threads, each count upto 50
- Build code
  - $ make
- Run code
  - $ ./lock xchg   # shows the result of using xchg lock

lock example



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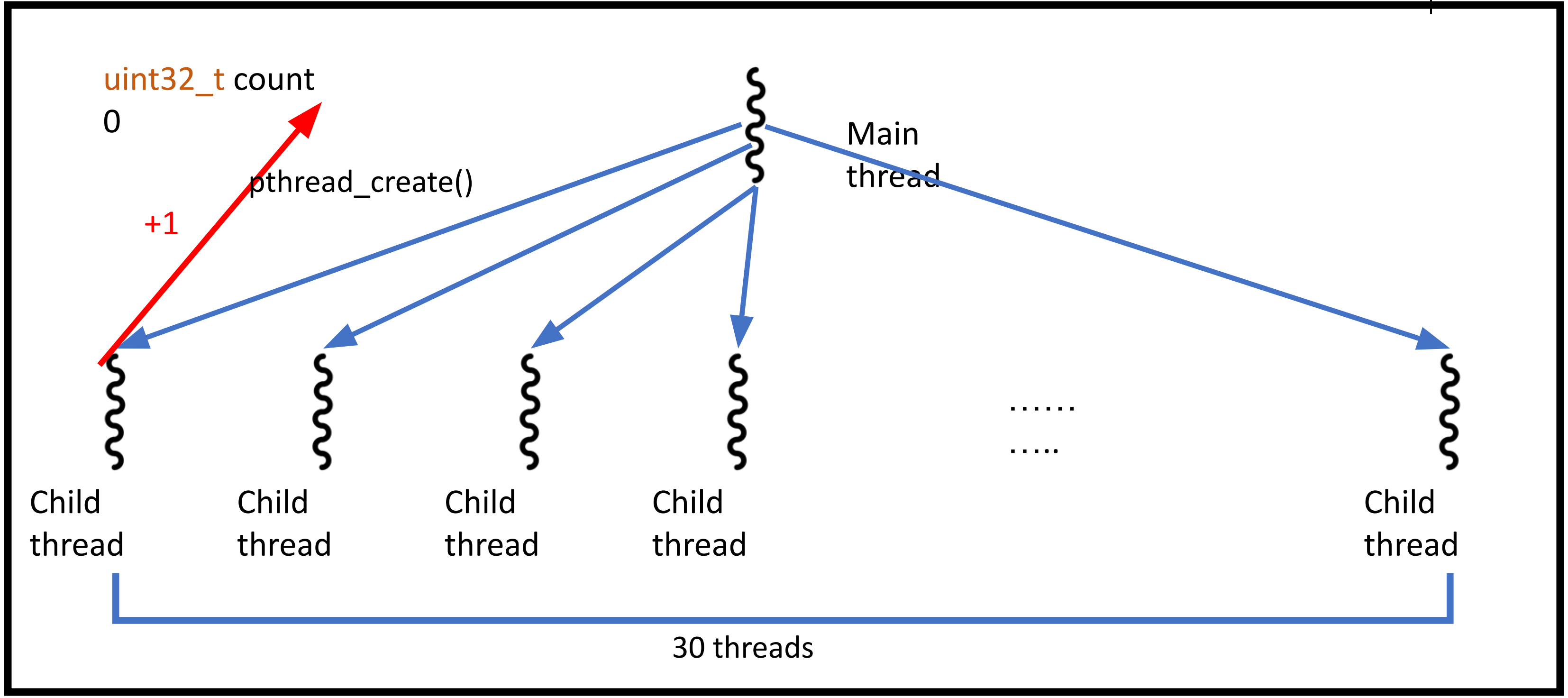

Each thread will increase count by 1 for 50 times

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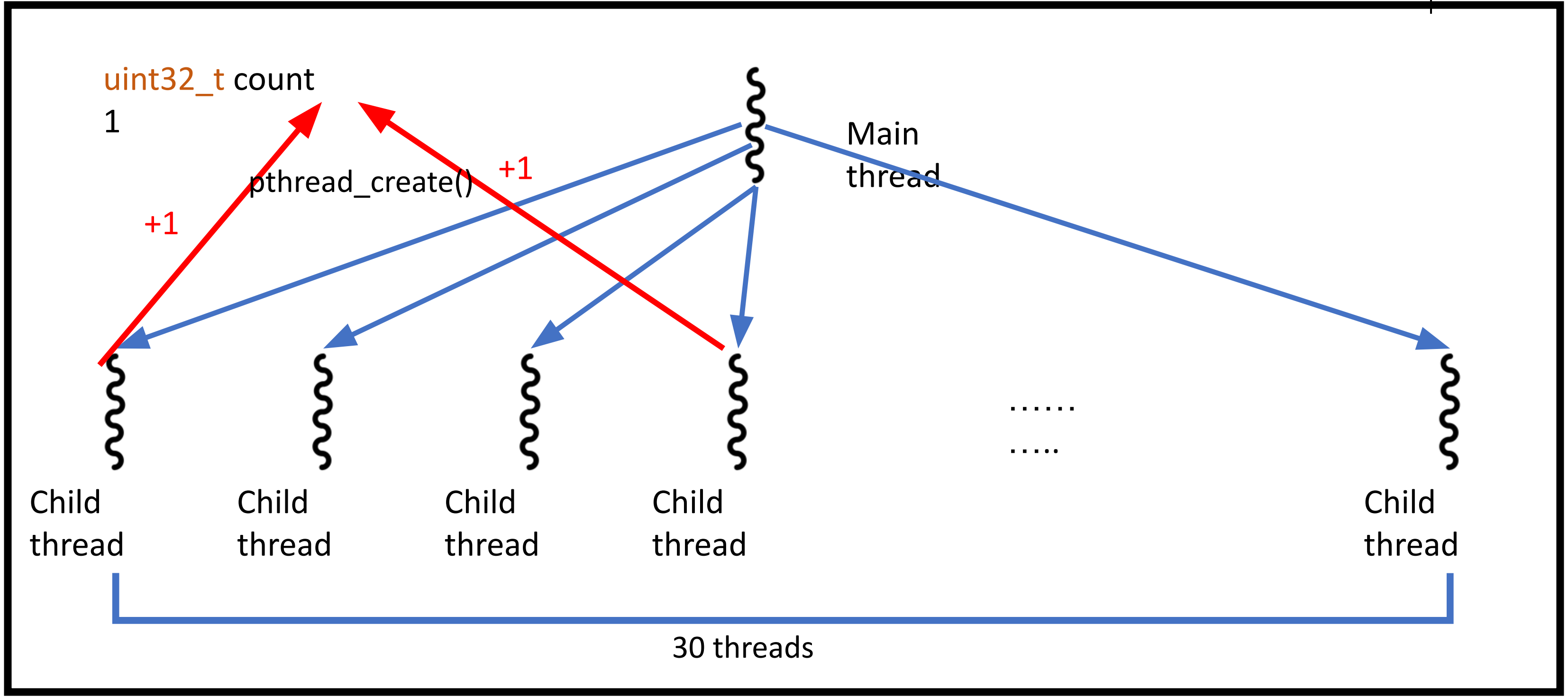

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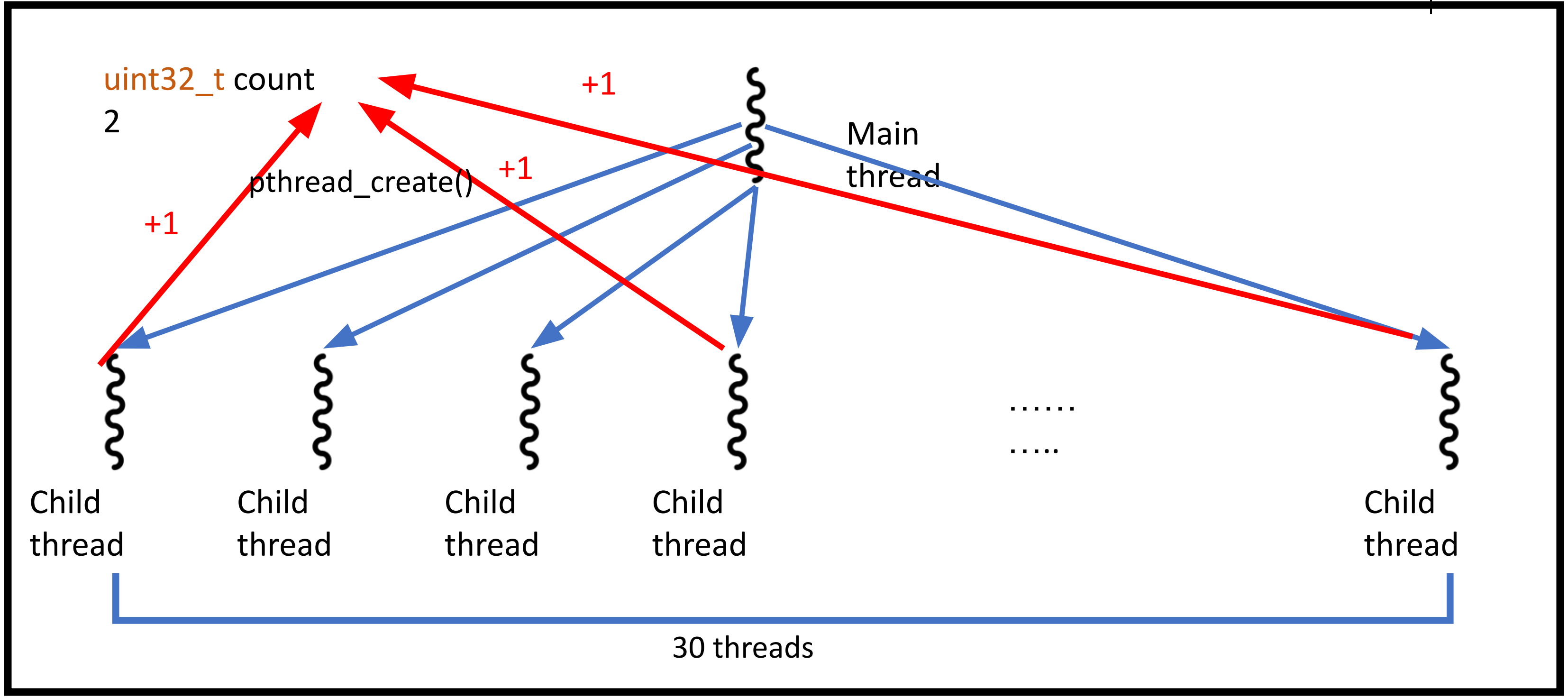

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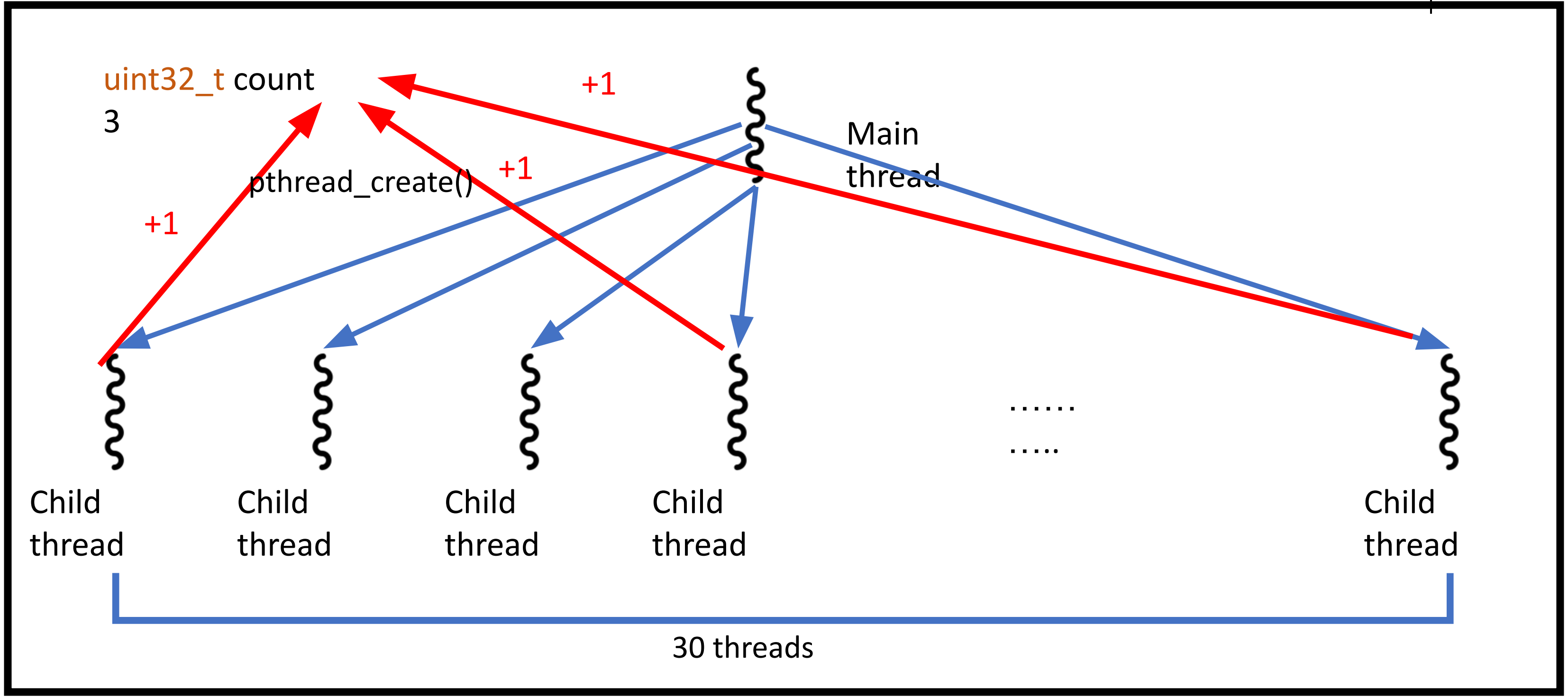

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lock example

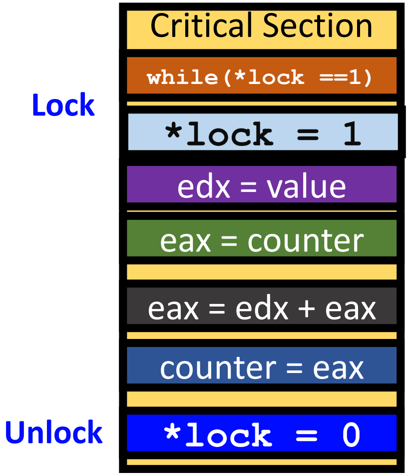
- Running
  - $ ./lock no # using no lock at all
  - $ ./lock bad # using a bad lock implementation
  - $ ./lock xchg # using xchg lock
  - $ ./lock cmpxchg # using lock cmpxchg
  - $ ./lock tts # using soft test-and-test & set with xchg
  - $ ./lock backoff # using exponential backoff cmpxchg
  - $ ./lock mutex # using pthread mutex

Manual Spinlock (bad_lock)

```
void
bad_lock(volatile uint32_t *lock) {
    while (*lock == 1);
    *lock = 1;
}
```

- Spinlock
  - Run a loop to check if critical section is empty
  - Set a lock variable, e.g., `lock`
  - Lock semantic
    - Nobody runs critical section if *`lock` == 0, so one can run the section
      - At the start of the section, set *`lock` = 1
    - Somebody runs in critical section if *`lock` == 1, so one must wait

  - lock(`lock`)
    - Wait until l becomes 0, e.g., `while(*lock == 1);`
      - Then, nobody runs in the critical section!
    - set *`lock` = 1
  - unlock(lock)
    - Set *`lock` = 0



Manual Spinlock (bad_lock)

- What will happen if we implement lock
  - As bad_lock / bad_lock?

- bad_lock
  - Wait until lock becomes 0 (loops if 1)
  - And then, set lock as 1
    - Because it was 0, we can set it as 1
  - Others must wait!

- bad_unlock
  - Just set *lock as 0

```
void *
count_bad_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        bad_lock(&lock);
        sched_yield();
        count += 1;
        bad_unlock(&lock);
    }
}
```

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bad_lock(volatile uint32_t *lock) {
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Sets lock=1 to block others

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Critical Section

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Critical Section

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Sets lock=1 to block others

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Sets lock=0 to release

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bad_lock(volatile uint32_t *lock) {
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}

void
bad_unlock(volatile uint32_t *lock) {
    *lock = 0;
}
```

Why does bad_lock doesn’t work?

```
void
bad_lock(volatile uint32_t *lock) {
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Why does bad_lock doesn’t work?

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mov     (%rdi),%eax
cmp     $0x1,%eax
je      0x400b60 <bad_lock>
movl    $0x1,(%rdi)
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LOAD

STORE

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Another thread might get scheduled here.

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void
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Why does bad_lock doesn't work?

- There is a room for race condition!

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```

Recall: Why does this work for humans?

- Human can perform *test* (look for other person & milk) and *set* (leave note) at the same time.

Atomic Test and Set

- We need a way to test
  - if lock == 0
- And we would like to set
  - lock = 1
- And do this atomically

- Hardware support is required
  - `xchg` in x86 does this
  - An atomic test-and-set operation

```
mov     (%rdi),%eax
cmp     $0x1,%eax
je      0x400b60 <bad_lock>
movl    $0x1,(%rdi)
```

Not like these four instructions…

xchg: Atomic Value Exchange in x86

- `xchg [memory], %reg`
  - Exchange the content in `[memory]` with the value in `%reg` atomically
- E.g.,
  - `mov $1, %eax`
  - `xchg $lock, %eax`
- This will set `%eax` as the value in `lock`
  - `%eax` will be `0` if `lock==0`, will be `1 if lock==1`
- At the same time, this will set `lock = 1` (the value was in `%eax`)
- CPU applies 'lock' at hardware level (cache/memory) to do this
  - Hardware guarantees no data race when running `xchg`

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- E.g.,
  - `mov $1, %eax`
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xchg: Atomic Value Exchange in x86

- E.g.,
  - `mov $1, %eax`
  - `xchg $lock, %eax` **Swap lock and eax atomically**
- This will set `%eax` as the value in `lock`
  - `%eax` will be `0` if `lock==0`, will be `1 if lock==1`
- How can we determine if a thread acquired the lock?
  - if `eax == 0`
    - This means the `lock` was 0, and after running `xchg`, `lock` will be 1 (`eax` was 1)
    - We acquired the lock!!! (`lock` was 0 and now the `lock` is 1)
  - if `eax == 1`
    - This means the `lock` was 1, and after running `xchg`, `lock` will be 1
    - We did not acquired the lock (it was 1)
    - `lock == 1` means some other thread acquired this…

Lock using xchg

- xchg_lock
  - Use atomic ‘xchg’ instruction to
  - Load and store values atomically
  - Set value to 1, and compare ret
    - If 0, then you can acquire the lock
    - If 1, lock as 1, you must wait
- xchg_unlock
  - Use atomic ‘xchg’
  - Set value to 0
    - Do not need to check
    - You are the only thread that runs in the
    - Critical section..

```
void *
count_xchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        xchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

```
void
xchg_lock(volatile uint32_t *lock) {
    while(xchg(lock, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

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        count += 1;
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    }
}
```

Critical Section

```
void
xchg_lock(volatile uint32_t *lock) {
    while(xchg(lock, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

Does xchg_lock works?

- Yes!!

```
Running 30 threads each counting to 50 using xchg lock
Result:1500, Time taken: 2358.591000 ms
```

- Any issues?

Issues with xchg_lock

- xchg will always update the value
  - If lock == 0
    - lock = 1
    - eax = 0
  - If lock == 1
    - lock = 1
    - eax = 1
- We use while() to check the value in lock
  - Will be cached into L1 cache of the CPU
- After updating a value in cache
  - We need to invalidate the cache in other CPUs…

Issues with xchg_lock

- xchg will always update the value
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    Swap with eax == 1, update lock to 1
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    - eax = 1

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  - We need to invalidate the cache in other CPUs…

No need to write when lock == 1

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  - xchg can’t do that

No need to write when lock == 1

- Let's not do that
  - xchg can't do that

- New method: `Test and test-and-set`
  - Check the value first (if lock == 0) `TEST`
  - If it is,
    - Do `test-and-set`
  - Otherwise (if lock == 1),
    - Do nothing
    - DO NOT UPDATE lock if lock == 1 (**No cache invalidate**)

Lock using test and set

- tts_xchg_lock
- Algorithm
  - Wait until lock becomes 0
  - After lock == 0
    - xchg (lock, 1)
    - This only updates lock = 1 if lock was 0
- Why **xchg, why not *lock = 1 directly**
  - while and xchg are not atomic
  - Load/Store must happen at
    - The same time!

```
void *
count_tts_xchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        tts_xchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

```
void
tts_xchg_lock(volatile uint32_t *lock) {
    while (1) {
        while(*lock == 1);
        if (xchg(lock, 1) == 0) {
            break;
        }
    }
}
```

Lock using test and set

- tts_xchg_lock
- Algorithm
  - Wait until lock becomes 0
  - After lock == 0
    - xchg (lock, 1)
    - This only updates lock = 1 if lock was 0

- Why xchg, why not *lock = 1 directly
  - while and xchg are not atomic
  - Load/Store must happen at
    - The same time!

```
void *
count_tts_xchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        tts_xchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

Critical Section

```
void
tts_xchg_lock(volatile uint32_t *lock) {
    while (1) {
        while(*lock == 1);
        if (xchg(lock, 1) == 0) {
            break;
        }
    }
}
```

Test and Set in x86

- `cmpxchg [update-value], [memory]`
  - Compare the value in `[memory]` with `%eax`
  - If matched, exchange value in `[memory]` with `[update-value]`
  - Otherwise, do not perform exchange

Test

Test-and-set

- cmpxchg(lock, 0, 1)
  - Arguments: Lock, test value, update value
  - Returns old value of lock

Lock using cmpxchg_lock

- Cmpxchg_lock
  - Use cmpxchg to set lock = 1
    - Do not update if lock == 1
    - Only write 1 to lock if lock == 0
- Xchg_unlock
  - Use xchg_unlock to set lock = 0
  - Because we have 1 writer and
  - This always succeeds…

```
void *
count_cmpxchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        cmpxchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

```
void
cmpxchg_lock(volatile uint32_t *lock) {
    while(cmpxchg(lock, 0, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

Lock using cmpxchg_lock

- Cmpxchg_lock
  - Use cmpxchg to set lock = 1
    - Do not update if lock == 1
    - Only write 1 to lock if lock == 0
- Xchg_unlock
  - Use xchg_unlock to set lock = 0
  - Because we have 1 writer and
  - This always succeeds…

Critical Section

```
void *
count_cmpxchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        cmpxchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

```
void
cmpxchg_lock(volatile uint32_t *lock) {
    while(cmpxchg(lock, 0, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

Reading fine print : x86 is too COMPLEX!

This *[cmpxchg]* instruction can be used with a LOCK prefix to allow the instruction to be executed atomically. To simplify the interface to the processors bus, the destination operand receives a write cycle without regard to the result of the comparison. The destination operand is written back if the comparison fails; otherwise, the source operand is written into the destination. (The processor never produces a locked read without also producing a locked write.)

Cmpxchg designed to be Test and Test & Set instruction
However, Intel CPU gets too complex, so they decided to always update value regardless the result of comparision

tts_xchg_lock v/s cmpxchg_lock

- tts_xchg_lock is faster then cmpxchg_lock

Not everything in hardware is fast!

Observation 2: AddressSanitizer, despite being a software-only approach, performs on par with ICC-MPX and better than GCC-MPX. This unexpected result testifies that the HW-assisted performance improvements of MPX are offset by its complicated design. At the same time,

Using hardware features smartly

- backoff_cmpxchg_lock(lock)
- Try cmpxchg
  - If succeeded, acquire the lock.
  - If failed
    - Wait 1 cycle (pause) for 1st trial
    - Wait 2 cycles for 2nd trial
    - Wait 4 cycles for 3rd trial
    - …
    - Wait 65536 cycles for 17th trial..
    - Wait 65536 cycles for 18th trial..

```
void
backoff_cmpxchg_lock(volatile uint32_t *lock) {
    uint32_t backoff = 1;
    while(cmpxchg(lock, 0, 1)) {
        for (int i=0; i<backoff; ++i) {
            __asm volatile("pause");
        }
        if (backoff < 0x10000) {
            backoff <<= 1;
        }
    }
}
```

- https://en.wikipedia.org/wiki/Exponential_backoff

Summary

- Mutex is implemented with Spinlock
  - Waits until lock == 0 with a while loop (that's why it's called spin)
- Naïve code implementation
  - Load/Store must be atomic
- xchg is a "test and set" atom
  - Consistent, however, many c
- Lock cmpxchg is a "test and
  - But Intel implemented this a
- We can implement test-and-
  - Faster!
- We can also implement expo
  - Much faster! **Faster Than p**

```
./lock no
Running 30 threads each counting to 50 using no lock
Result:1400, Time taken: 3.913000 ms
./lock bad
Running 30 threads each counting to 50 using bad lock
Result:1465, Time taken: 2.256000 ms
./lock xchg
Running 30 threads each counting to 50 using xchg lock
Result:1500, Time taken: 853.585000 ms
./lock cmpxchg
Running 30 threads each counting to 50 using cmpxchg lock
Result:1500, Time taken: 12997.561000 ms
./lock tts
Running 30 threads each counting to 50 using tts lock
Result:1500, Time taken: 1.779000 ms
./lock backoff
Running 30 threads each counting to 50 using backoff lock
Result:1500, Time taken: 0.939000 ms
./lock mutex
Running 30 threads each counting to 50 using mutex lock
Result:1500, Time taken: 5.313000 ms
```

Other synchronization primitives

- We may want to have more than one thread/process to execute at same time

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

How many producers/consumers can run at a given time?

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

What we want!

- To be more efficient we want to be able to allow **more than one producer/consumer, i.e., equal to the number of items that can be inserted into/removed from the pool**

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

  consume the item;
}
```

Semaphore

A semaphore is like an **integer**, with three differences:

When you create the semaphore, you can initialize its value to any integer, but after that the only operations you are **allowed to perform** are **increment** (increase by one) and **decrement** (decrease by one). *You cannot read the current value of the semaphore.*

When a thread **decrements** the semaphore, if the **result is negative**, the **thread blocks itself** and cannot continue until another thread increments the semaphore.

When a thread **increments** the semaphore, if there are **other threads waiting, one of the waiting threads gets unblocked**.

Semaphore operations

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

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

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    wait(FULL);
    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    wait(FULL);
    lock();
    remove(item from pool);
    unlock();
    signal(EMPTY);
    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Is Semaphore good for producers/consumers?

Need to know the size of buffer!

How to accommodate dynamic pool size?