HARVARD
School of Engineering
and Applied Sciences

Thread synchronization

CS61, Lecture 20

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November 9, 2010

Announcements

- Lab 4 due on Tuesday Nov 16
- Thursday is Veterans Day: no lecture

Topics for today

- Why to synchronize multiple threads
- Race conditions

  Concurrent access to shared resource without synch.
- Mutual exclusion and critical sections

  A way to to prevent races.
- Locks

  A simple mechanism to synchronize threads.
- Efficiently implementing locks
- Reading: 12.4

Synchronization

- Threads cooperate in multithreaded programs in several ways:
  - Access to shared variables and other memory
    - e.g., multiple threads accessing a memory cache in a Web server
  - To coordinate their execution
    - e.g., Pressing stop button on browser cancels download of current page
    - "stop button thread" has to signal the "download thread"
- For correctness, we have to control this cooperation
- We must assume that **threads can interleave executions arbitrarily** and **run at different rates**
  - In some sense this is the "worst case" scenario.
  - Our goal: to control thread cooperation using synchronization
    - enables us to restrict the interleaving of executions

Shared Resources

- We'll focus on coordinating access to shared resources
- Basic problem:
  - Two concurrent threads are accessing a shared variable
  - If the variable is read/modified/written by both threads, then access to the variable must be controlled
  - **Otherwise, unexpected results may occur**
- Tools for solutions
  - Mechanisms to control access to shared resources
    - Low-level mechanisms: locks
    - Higher level mechanisms: mutexes, semaphores, monitors, and condition variables
  - Patterns for coordinating access to shared resources
    - bounded buffer, producer-consumer, …
- This stuff is complicated and rife with pitfalls

Shared Variable Example

- Suppose we implement a function to withdraw money from a bank account:

```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

- Now suppose that you and your roommate share a bank account with a balance of $1500.00 (not that this is necessarily a good idea...)
  - What happens if you both go to separate ATM machines, and simultaneously withdraw $100.00 from the account?

Example continued

- We represent the situation by creating a separate thread for each ATM user doing a withdrawal
  - Both threads run on the same bank server system

```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

```
int withdraw(account, amount) {
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

- What are the possible balance values after each thread runs?

Interleaved Execution

- The execution of the two threads can be **interleaved**
  - Assume **preemptive scheduling**
    - i.e., Thread may be context switched arbitrarily, without cooperation from the thread
  - Each thread may context switch after **each** assembly instruction
  - We need to worry about the worst-case scenario!

Execution sequence as seen by CPU

```
balance = get_balance(account);
balance -= amount;
```

context switch

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
```

context switch

```
put_balance(account, balance);
```

- What's the account balance after this sequence?
  - And who's happier, the bank or you???

Interleaved Execution

- The execution of the two threads can be **interleaved**
  - Assume **preemptive scheduling**
    - i.e., Thread may be context switched arbitrarily, without cooperation from the thread
  - Each thread may context switch after **each** assembly instruction
    (or, in some cases, part of an assembly instruction!)
  - We need to worry about the worst-case scenario!

account.bal = $1500

```
balance = get_balance(account);
balance -= amount;
```

local balance = $1400

Execution sequence as seen by CPU

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
```

local balance = $1400

account.bal = $1400

```
put_balance(account, balance);
```

account.bal = $1400

- What's the account balance after this sequence?
  - And who's happier, the bank or you???

Last lecture's lie

- Sleeping does not help!
- Last lecture I showed some examples to highlight which locations were shared between threads

```
int i = 0; // global variable
void bar() {
  i++;
  sleep(1);
  printf("i is %d.\n", i);
}
```

```
int i = 0; // global variable
void bar() {
  i++;
  sleep(1);
  printf("i is %d.\n", i);
}
```

- Possible outputs: 1 2, 1 2, 2 2, 2 2
- All are possible, not all equally likely.

It’s gets worse...

- Most programmers assume that memory is **sequentially consistent**
  - state of memory is due to some interleaving of threads, with instructions in each thread executed in order
  - E.g., Given [A, B, C] and [D, E], memory is result of some ordering such as

A	A	A	A	A	D	D	D	D
B	B	B	D	D	A	A	E	A
C	D	D	B	B	B	B	A	E
D	C	E	C	E	C	E	B	B
E	E	C	E	C	E	C	C	C

… etc.

- **This is not true in most systems!**

Example

- Suppose we have two threads
  - (`x` and `y` are global, `a` and `b` are thread-local, all variables initially 0)

```
x=1;
y=2;
```

```
a = y;
b = x;
printf("%d", a+b);
```

  - What are the possible outputs?
    - 0 | `a=y` | `b=x` | `x=1` | `y=2`
    - 1 | `a=y` | `x=1` | `b=x` | `y=2` and others
    - 3 | `x=1` | `y=2` | `a=y` | `b=x` and others
    - 2 Requires `a=2` and `b=0`. Is possible, but no such order!

Relaxed memory models

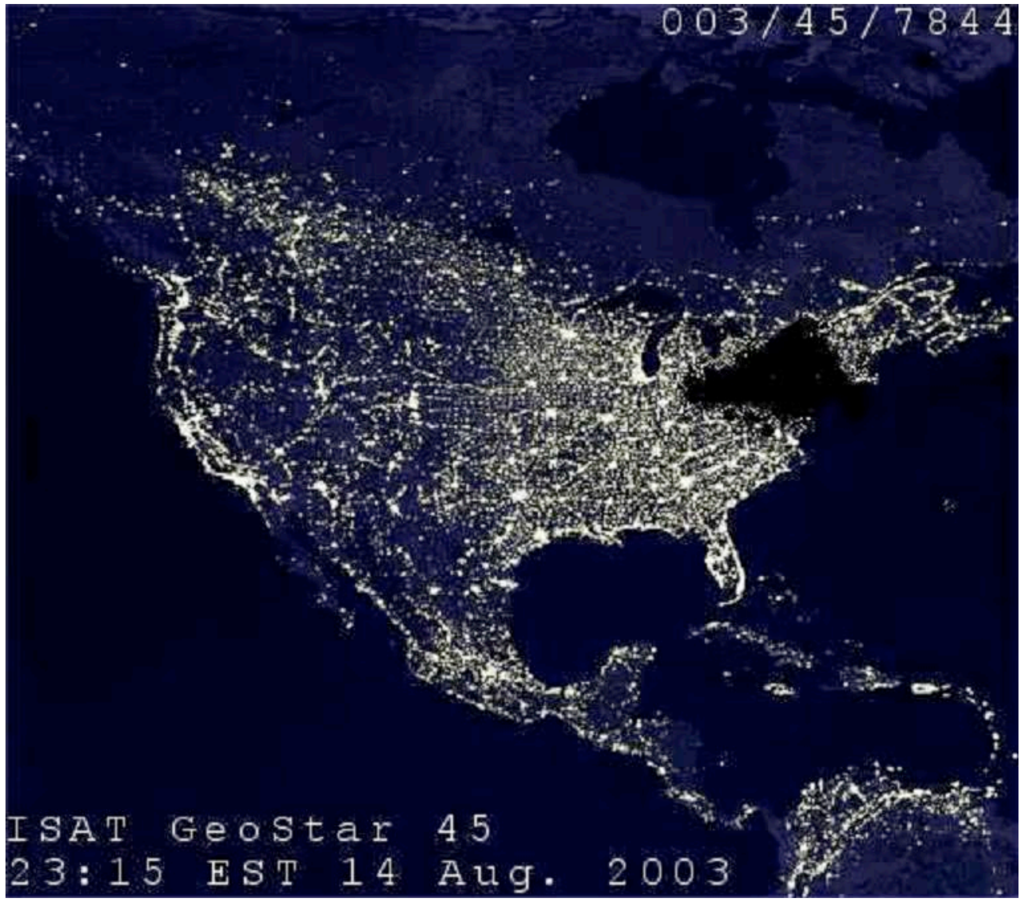
- What's going on?
- Several things, including:
  - With multiple processors, multiple caches
    - A cache may not write values from cache to memory in same order as updates
    - Processor may have cache hits for some locations and not others
  - Compiler optimizations
    - Compiler may change order of instructions
- A model of how memory behaves provides
  - 1) programmers with a way to think about memory
  - 2) compiler writers with limits on what optimizations they can do
- **Relaxed memory models** provide a weaker model than sequential consistency
  - Can be complicated!

Race Conditions

- The problem: concurrent threads accessing a shared resource without any synchronization
  - This is called a **race condition**
  - The result of the concurrent access is non-deterministic, depends on
    - Timing
    - When context switches occurred
    - Which thread ran at at context switch
    - What the threads were doing
- A solution: mechanisms for controlling concurrent access to shared resources
  - Allows us to reason about the operation of programs
  - We want to **re-introduce some determinism** into the execution of multiple threads

Race conditions in real life

- Race conditions are bugs, and difficult to detect
- Northeast Blackout of 2003
  - About 55 million people in North America affected
  - Race condition in monitoring code in part responsible: alarm system failed
  - Code had been running since 1990, over 3 million hours of operation, without manifesting bug



Vincent Laforet

Race conditions in real life

- Race conditions are bugs, and difficult to detect
- Therac-25 radiation therapy machine
  - Designed to give non-lethal doses of radiation to cancer patients
  - Race conditions contributed to incorrect lethal doses
  - Several fatalities in mid-80s.

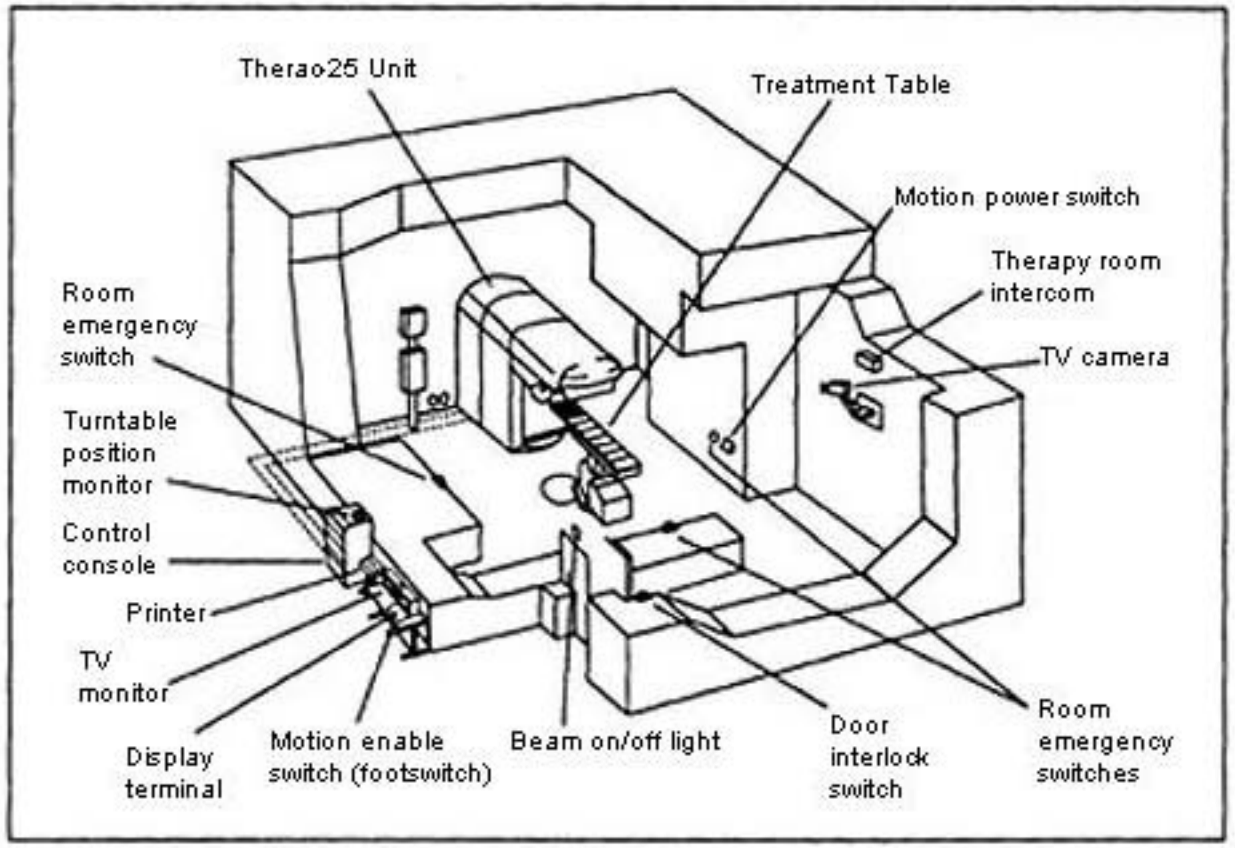
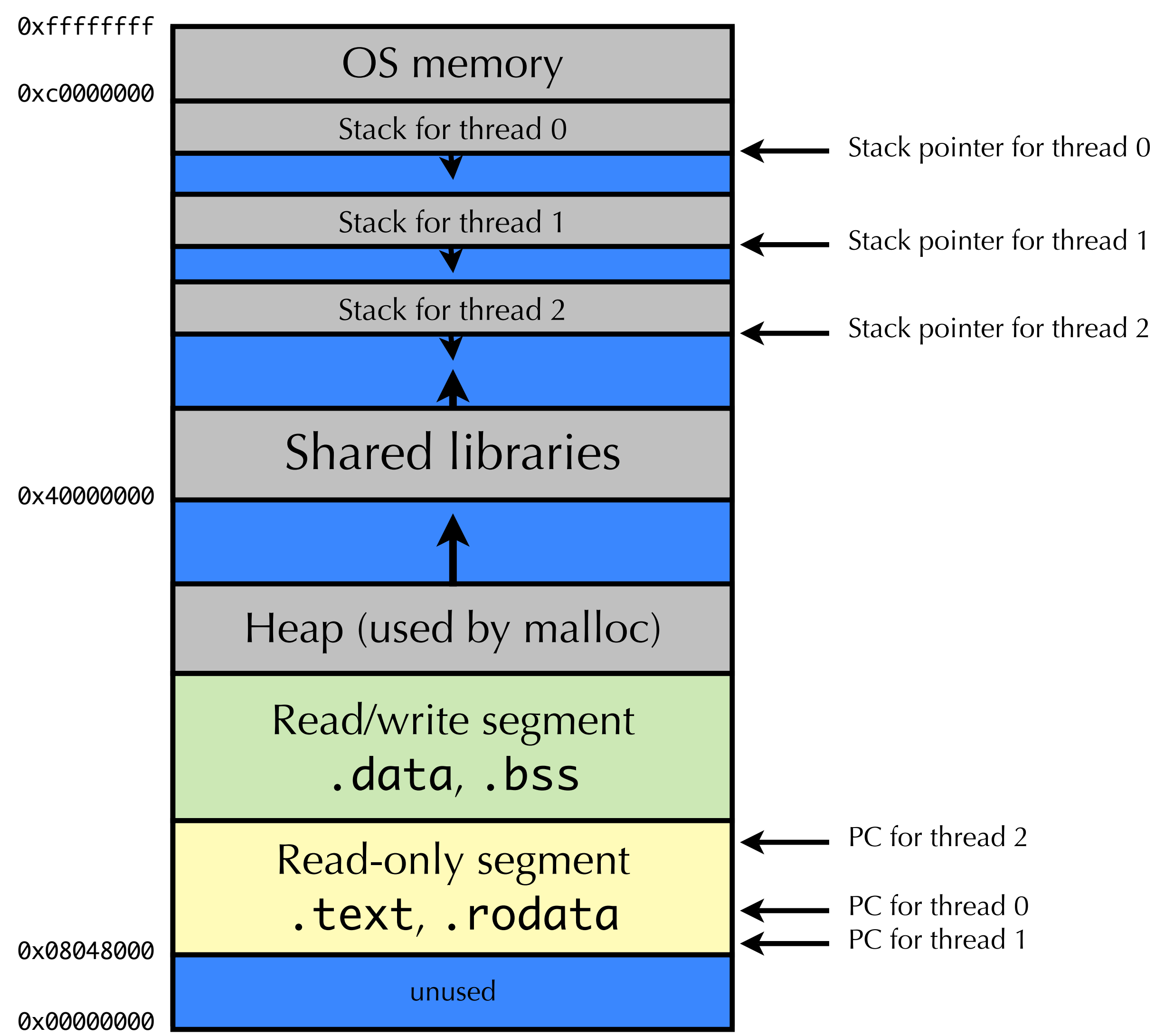


Figure 1. Typical Therac-25 facility

Which resources are shared?

- Local variables in a function are not shared
  - They exist on the stack, and each thread has its own stack
  - Cannot safely pass a pointer from a local variable to another thread
    - Why?
- Global variables are shared
  - Stored in static data portion of the address space
  - Accessible by any thread
- Dynamically-allocated data is shared
  - Stored in the heap, accessible by any thread



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- Race conditions

  Concurrent access to shared resource without synch.

- Mutual exclusion and critical sections

  A way to to prevent races.

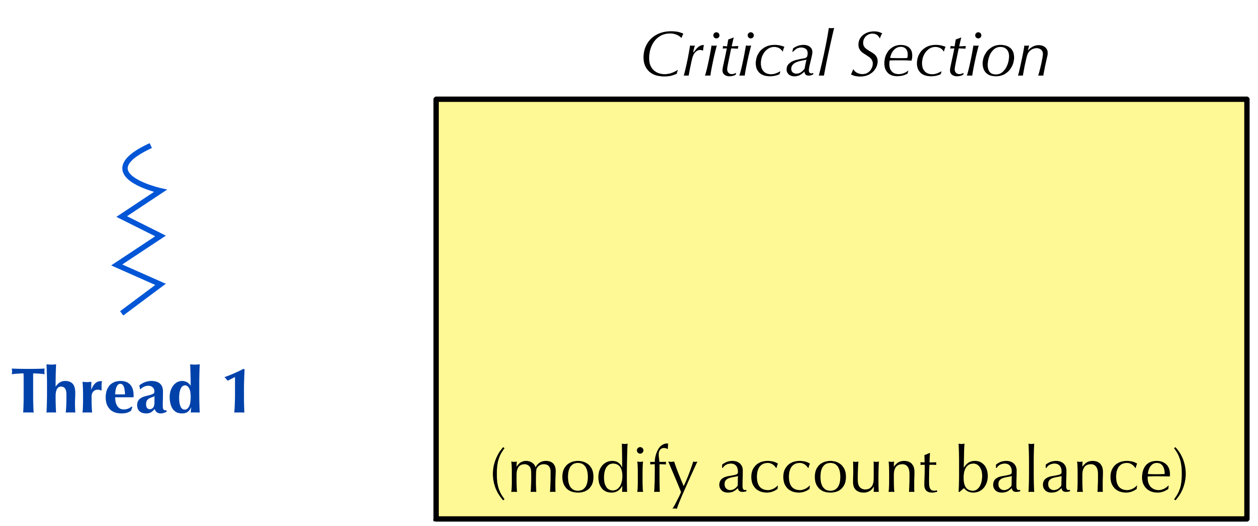
- Locks

  A simple mechanism to synchronize threads.

- Efficiently implementing locks
- Reading: 12.4

Mutual Exclusion

- We want to use **mutual exclusion** to synchronize access to shared resources
  - Mutual exclusion: only one thread can access a shared resource at a time.
- Code that uses mutual exclusion to synchronize its execution is called a **critical section**
  - Only one thread at a time can execute code in the critical section
  - All other threads are forced to wait on entry
  - When one thread leaves the critical section, another can enter



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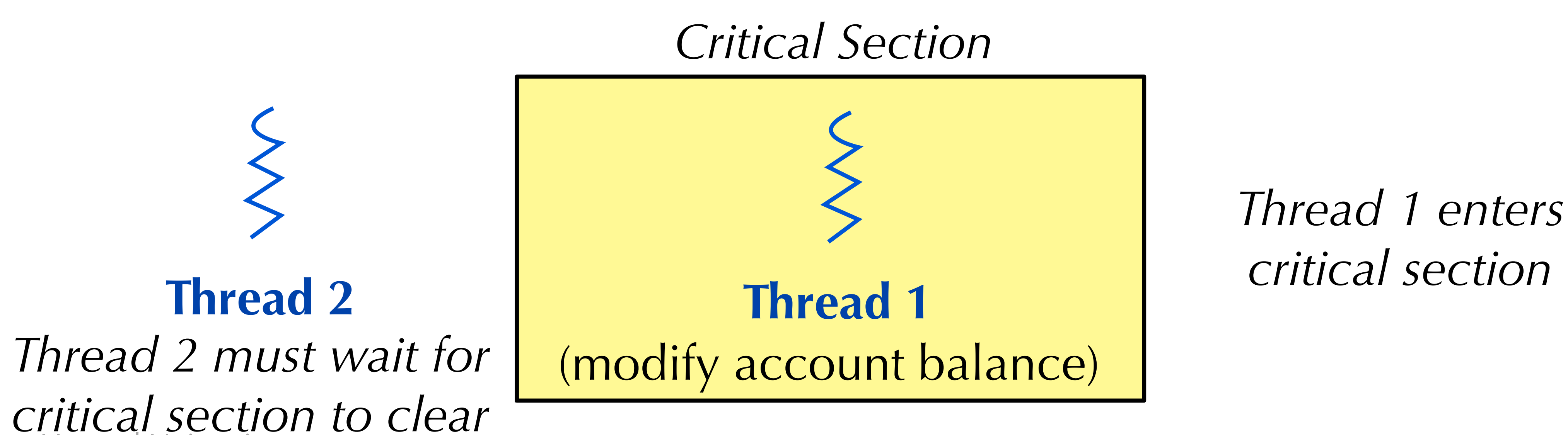

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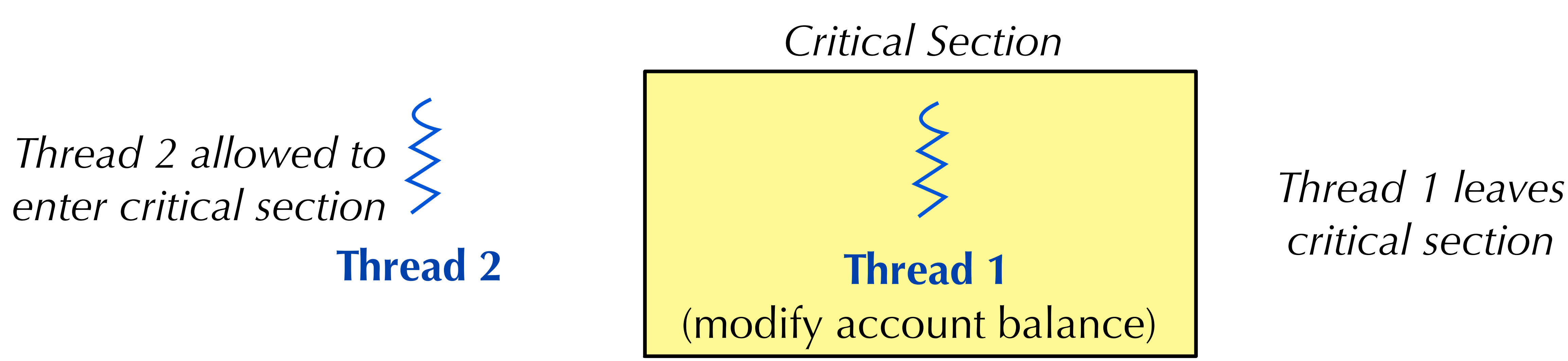

Critical Section Requirements

- Mutual exclusion
  - At most one thread is currently executing in the critical section
- Progress
  - If thread T1 is **outside** the critical section, then T1 cannot prevent T2 from entering the critical section
- Bounded waiting (no starvation)
  - If thread T1 is waiting on the critical section, then T1 will **eventually** enter the critical section
    - Requires threads eventually leave critical sections
- Performance
  - The overhead of entering and exiting the critical section is small with respect to the work being done within it

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Locks

- A lock is an object (in memory) that provides the following two operations:
  - `acquire( )`: a thread calls this before entering a critical section
    - May require waiting to enter the critical section
  - `release( )`: a thread calls this after leaving a critical section
    - Allows another thread to enter the critical section

- A call to `acquire( )` must have a corresponding call to `release( )`
  - Between `acquire( )` and `release( )`, the thread holds the lock
  - `acquire( )` does not return until the caller holds the lock
    - At most one thread can hold a lock at a time (usually!)
    - We'll talk about the exceptions later...
- What can happen if `acquire( )` and `release( )` calls are not paired?

Using Locks

```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  release(lock);
  return balance;
}
```

critical section

- Why is the `return` statement outside of the critical section?

Execution with Locks

Execution sequence as seen by CPU

```
acquire(lock);
balance = get_balance(account);
balance -= amount;
```

Thread 1 runs

```
acquire(lock);
```

Thread 2 waits on lock

```
put_balance(account, balance);
release(lock);
```

Thread 1 completes
Thread 2 resumes

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
release(lock);
```

Spinlocks

- Very simple way to implement a lock:

```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while (lock->held)
       ;
   lock->held = 1;
}
void release(lock) {
  lock->held = 0;
}
```

The caller **busy waits** for the lock to be released

Why doesn't this work?

Implementing Spinlocks

- Problem: internals of the lock acquire/release have critical sections too!

```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while (lock->held)
       ;
   lock->held = 1;
}
void release(lock) {
  lock->held = 0;
}
```

What can happen if there is a context switch here?

- The `acquire( )` and `release( )` actions must be **atomic**
- Atomic means that the code cannot be interrupted during execution
  - "All or nothing" execution

Implementing Spinlocks

- Problem: internals of the lock acquire/release have critical sections too!

```
struct lock {
  int held = 0;
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void acquire(lock) {
    while (lock->held)
        ;
    lock->held = 1;
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void release(lock) {
  lock->held = 0;
}
```

This sequence needs to be atomic!

- The `acquire( )` and `release( )` actions must be **atomic**
- Atomic means that the code cannot be interrupted during execution
  - "All or nothing" execution

Implementing Spinlocks

- Achieving atomicity requires hardware support
  - Disabling interrupts
    - Prevent context switches from occurring
    - Only works on uniprocessors. Why?
  - Atomic instructions – CPU guarantees entire action will execute atomically
    - Test-and-set
    - Compare-and-swap

Spinlocks using test-and-set

- CPU provides the following as one atomic instruction:

```
bool test_and_set(bool *flag) {
  bool old = *flag;
  *flag = True;
  return old;
}
```

- So to fix our broken spinlocks, we do this:

```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while(test_and_set(&lock->held));
}
void release(lock) {
  lock->held = 0;
}
```

What's wrong with spinlocks?

- So spinlocks work (if you implement them correctly), and are simple.
- What's the catch?

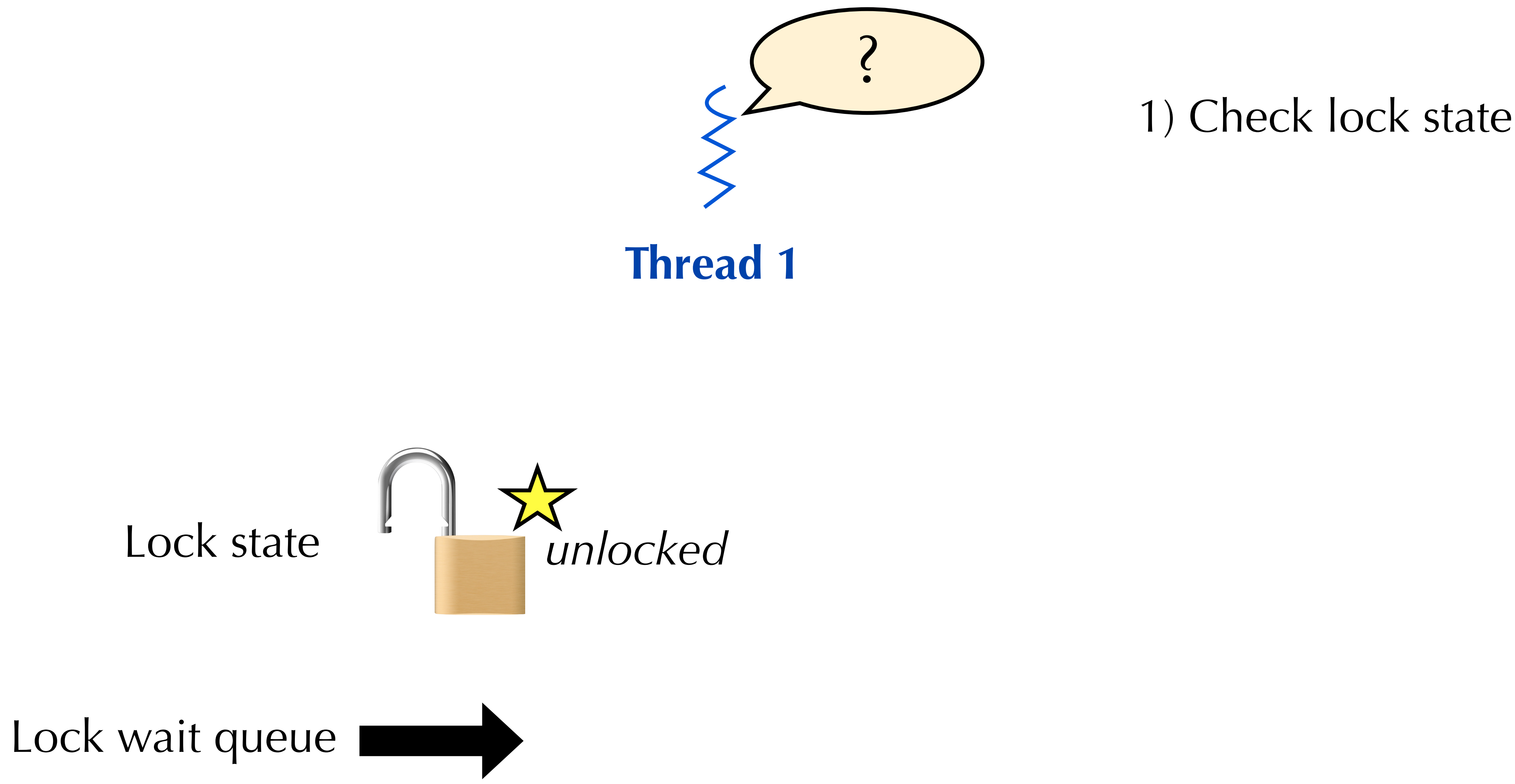
```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while(test_and_set(&lock->held));
}
void release(lock) {
  lock->held = 0;
}
```

Problems with spinlocks

- Inefficient!
  - Threads waiting to acquire locks spin on the CPU
  - Eats up lots of cycles, slows down progress of other threads
    - Note that other threads can still run ... how?
  - What happens if you have a lot of threads trying to acquire the lock?
- Usually, spinlocks are only used as **primitives** to build higher-level, more efficient, synchronization constructs

Efficiently implementing locks

- Really want a thread waiting to enter a critical section to **block**
  - Put the thread to sleep until it can enter the critical section
  - Frees up the CPU for other threads to run



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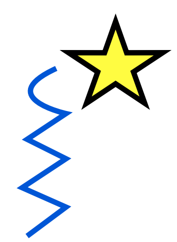

Thread 1

1) Check lock state
2) Set state to locked
3) Enter critical section

Lock state  *locked*

Lock wait queue →

Efficiently implementing locks

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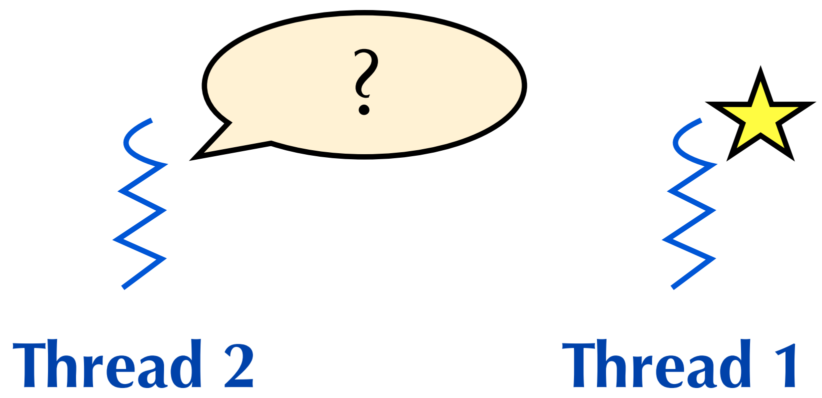

1) Check lock state

2) Add self to wait queue (sleep)

Lock state  *locked*

Lock wait queue

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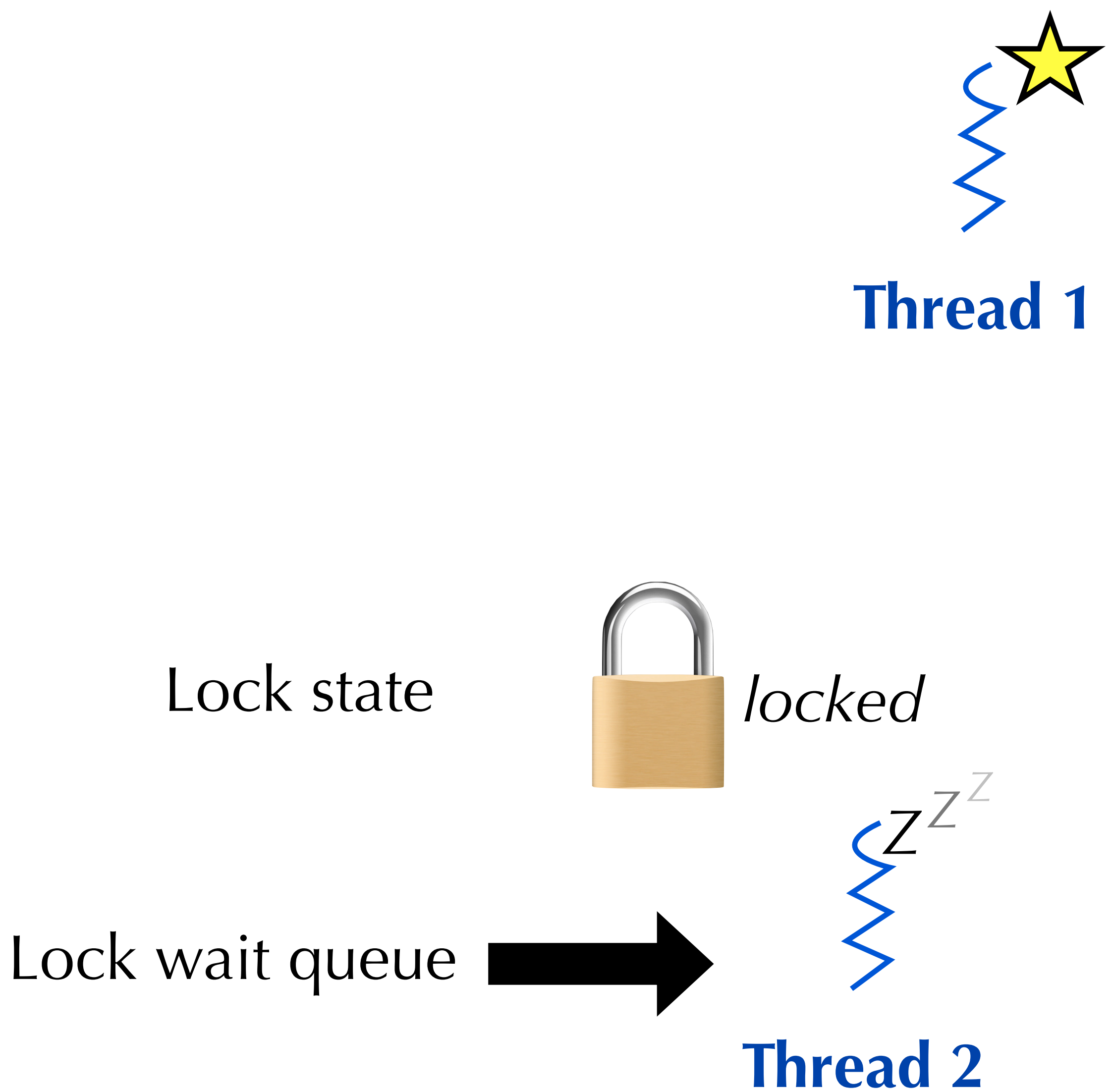

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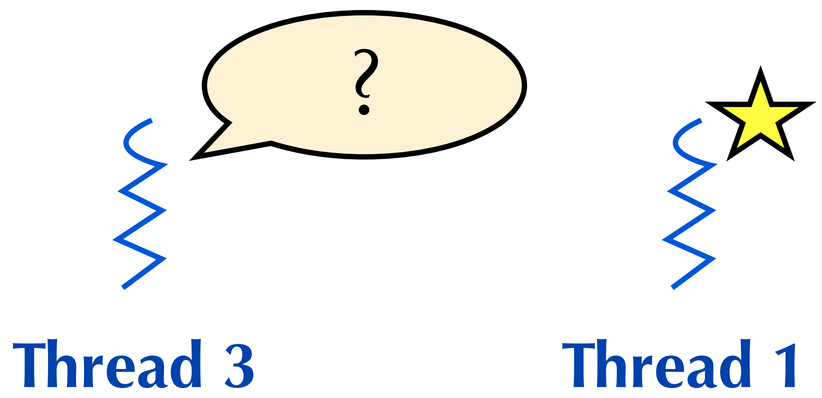

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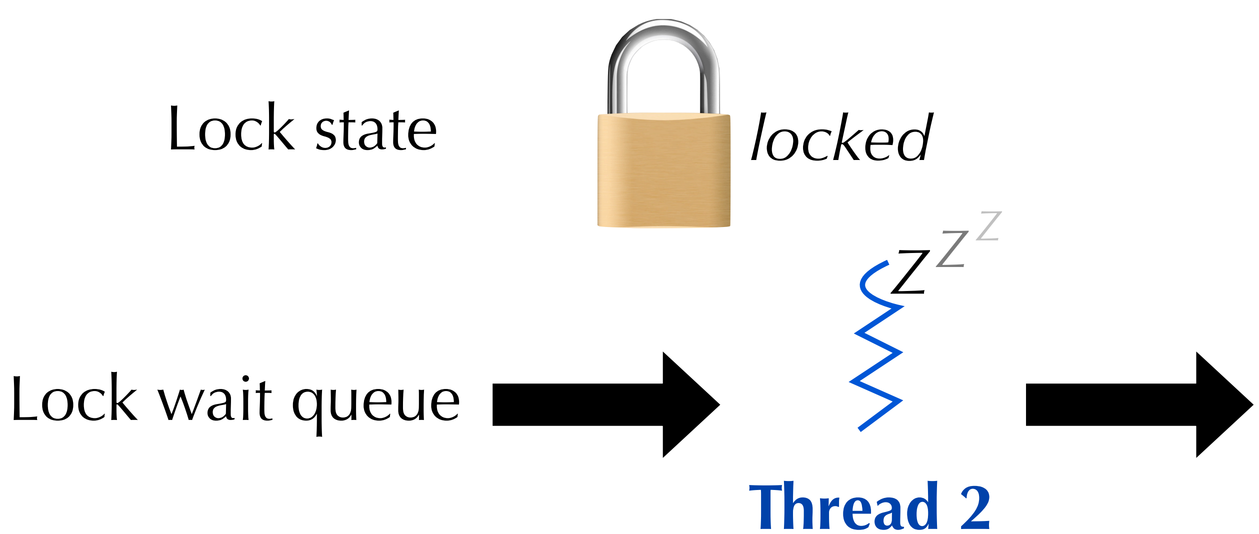

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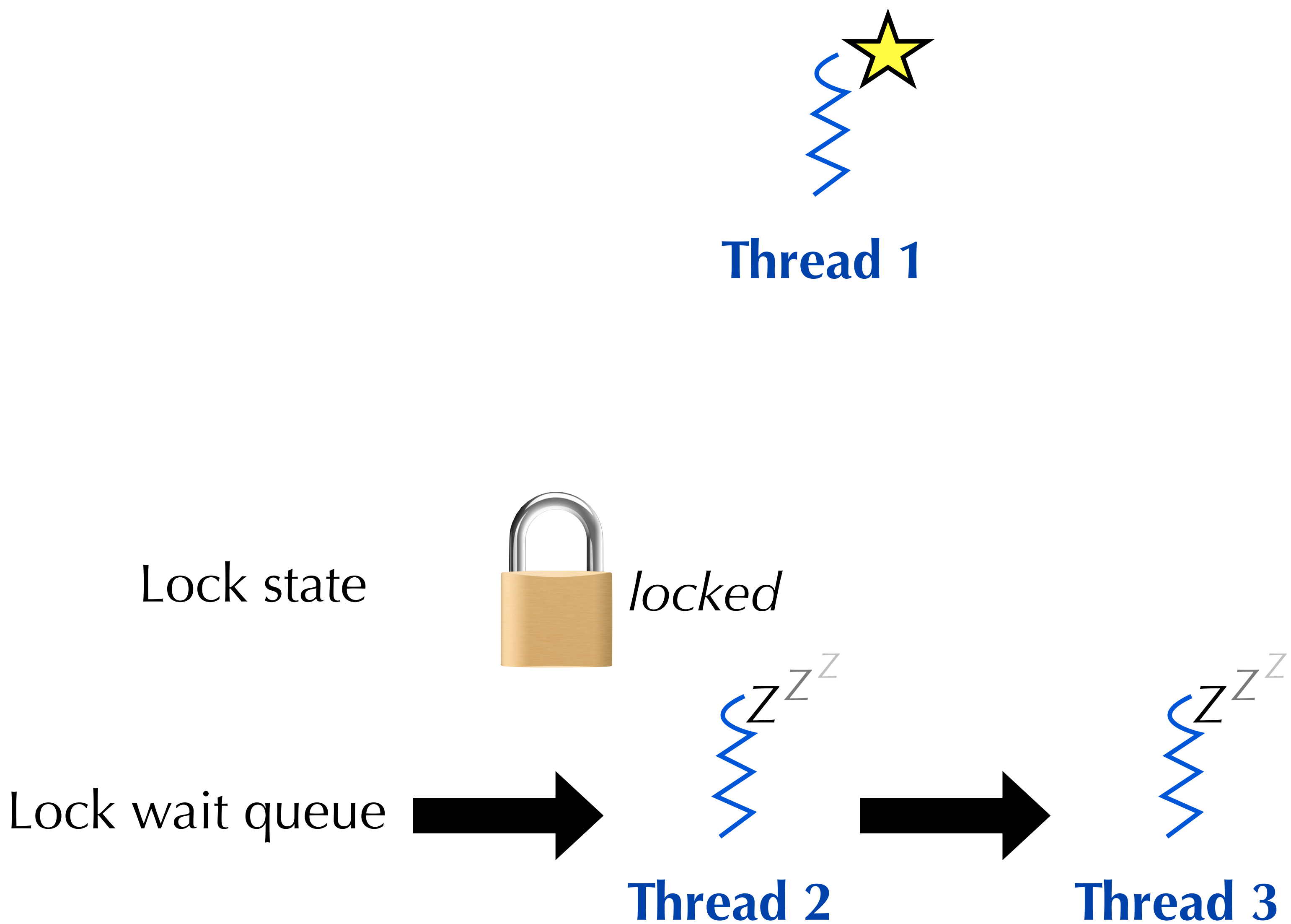

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Efficiently implementing locks

- Really want a thread waiting to enter a critical section to **block**
  - Put the thread to sleep until it can enter the critical section
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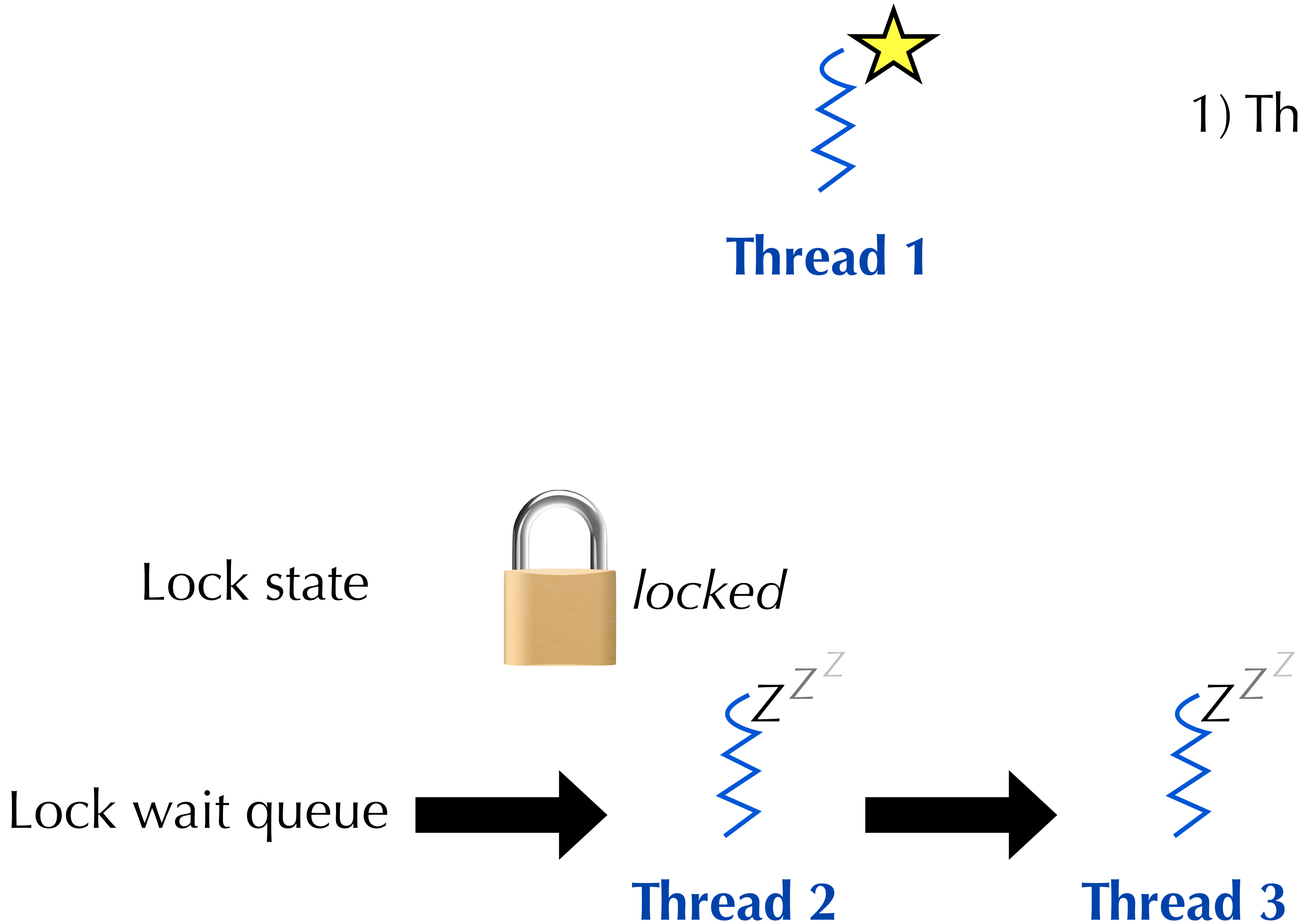
1) Thread 1 finishes critical section



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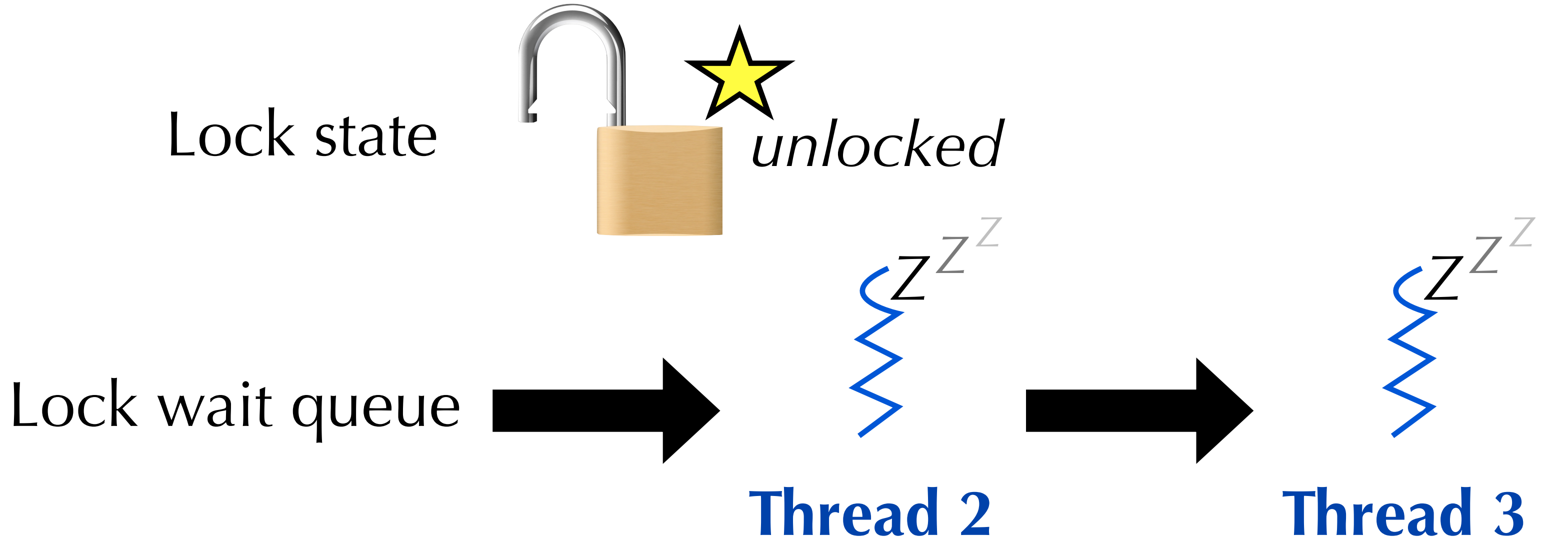
A blocked thread can now acquire lock



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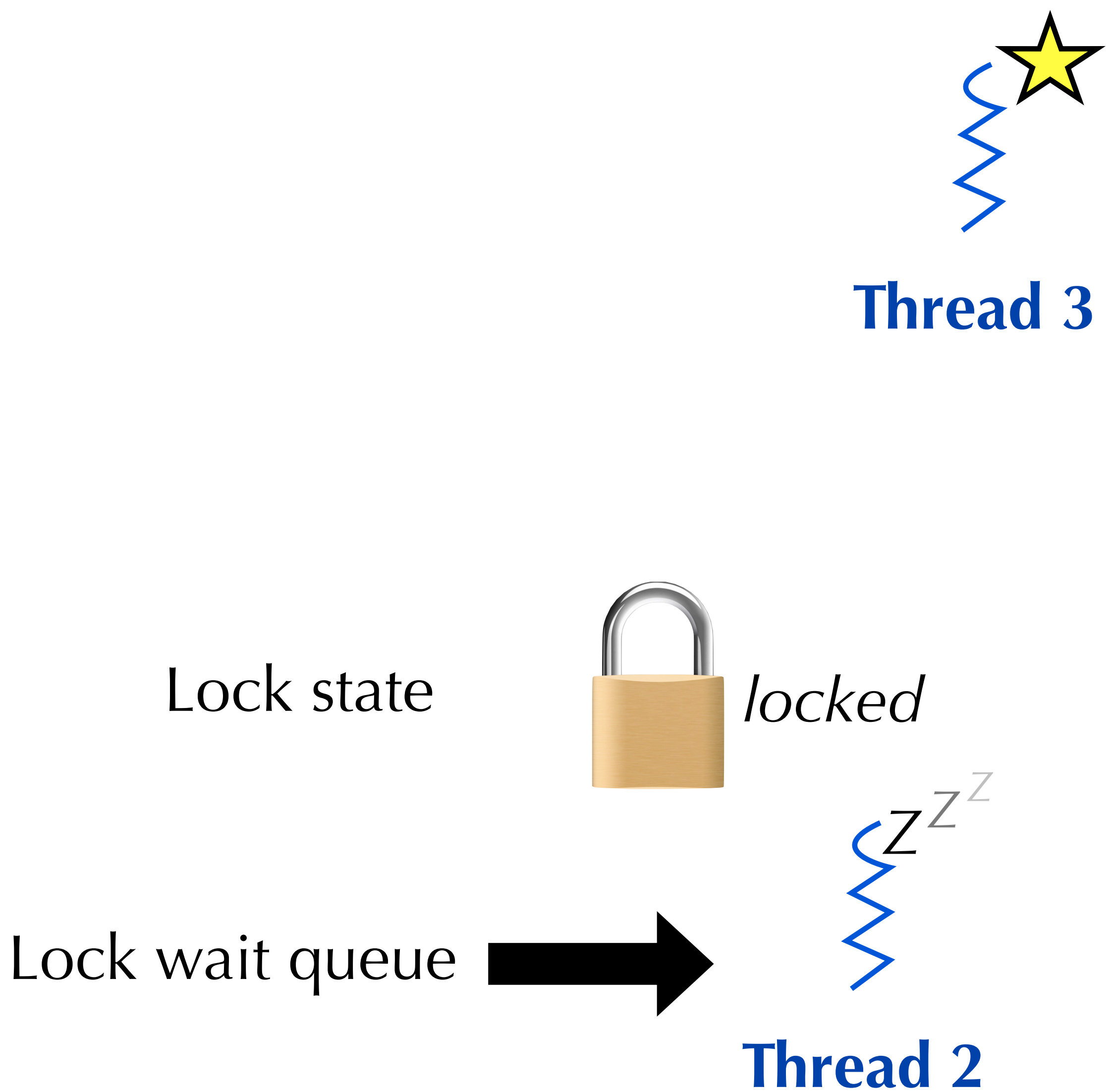

A blocked thread can now acquire lock

No guarantee on which blocked thread will get the lock!!!

Locks in PThreads

- Pthreads provides a `pthread_mutex_t` to represent a lock for mutual exclusion, a **mutex**.
  - Threads using the mutex must have access to the `pthread_mutex_t` object.
  - Usually, this means declaring it as a global variable.

```
pthread_mutex_t myLock; /* Must be global so all
                         * threads using the lock
                         * can access this variable. */

/* Initialize it. */
/* Only one thread has to do this. */
pthread_mutex_init(&myLock, NULL);

void *mythread(void *arg) {
  /* Do something with the lock */
  pthread_mutex_lock(&myLock);

  /* Do stuff... */

  pthread_mutex_unlock(&myLock);
}
```

Lock granularity

- Locks are great, and simple, but have limitations
- What if you have a more complex resource than a single location?
- What if you want to protect access to two (or more) data structures at a time?
  - e.g., Transferring money from one bank account to another.
  - Simple approach: Use a separate lock for each.
  - What happens if you have transfer from account A → account B, at the same time as transfer from account B → account A?
    - Hmmmmm ... tricky.
    - We will get into this next time.

Next Lecture

- Higher level synchronization primitives:
  How do to fancier stuff than just locks
- Semaphores, monitors, and condition variables
  - Implemented using basic locks as a primitive
- Allow applications to perform more complicated coordination schemes

- (Note: next class is a guest lecture on analyzing executable files)