Operating Systems
Lecture 11

lock and condition variables implementation

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Recap: Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible operations are!
- Atomic Operation (原子操作): an operation that always runs to completion or not at all
  - It is *indivisible:* it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  - Fundamental building block – if no atomic operations, then have no way for threads to work together
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
  - Consequently – weird example that produces "3" on previous slide can't happen
- Many instructions are not atomic
  - Double-precision floating point store often not atomic
  - VAX and IBM 360 had an instruction to copy a whole array

Motivation: "Too Much Milk"

- Great thing about OS's – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Recap: Definitions

- Synchronization (同步): using atomic operations to ensure cooperation between threads
  - For now, only loads and stores are atomic
  - We are going to show that its hard to build anything useful with only reads and writes
- Mutual Exclusion (互斥): ensuring that only one thread does a particular thing at a time
  - One thread *excludes* the other while doing its task
- Critical Section (临界区): piece of code that only one thread can execute at once.
  - Critical section is the result of mutual exclusion
  - Critical section and mutual exclusion are two ways of describing the same thing

Recap: Lock

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- 3 formal properties
  - Mutual exclusion: at most one thread holds the lock
  - Progress: if no thread holds the lock and any thread attempts to acquire the lock, then eventually some thread succeeds in acquiring the lock
  - Bounded waiting: if thread T attempts to acquire a lock, then there exists a bound on the number of times other threads can successfully acquire the lock before T does
    - Yet, it does not promise that waiting threads acquire the lock in FIFO order.

Some Advices

- Always acquire the lock at the beginning of a method and release it right before the return
  - Consistent behavior makes it easier to program
  - Also makes it easier to read and debug
- A case: double-checked locking

```
Singleton* Singleton::instance() {
    if (pInstance == NULL) {
        pInstance = new Instance();
    }
    return pInstance;
}
```

An unsafe solution

```
Singleton* Singleton::instance() {
    lock.acquire();
    if (pInstance == NULL) {
        pInstance = new Instance();
    }
    lock.release();
    return pInstance;
}
```

A safe solution

```
Singleton* Singleton::instance() {
    if (pInstance == NULL) {
        lock.acquire();
        if (pInstance == NULL) {
            pInstance = new Instance();
        }
        lock.release();
    }
    Return pInstance;
}
```

An ``optimized” solution.

Is it safe?

A Tricky (but Real) Case

```
Singleton* Singleton::instance() {
    if (pInstance == NULL) {
        lock.acquire();
        if (pInstance == NULL) {
            pInstance = new Instance();
        }
        lock.release();
    }
    Return pInstance;
}
```

Reordered by compiler

Thread A

```
if (pInstance == NULL) { // True
  lock.acquire();
  if (pInstance == NULL) {
    // malloc for pInstance;
    // point pInstance to the memory;


    // run new() function;
  }
  lock.release();
}
return pInstance;
```

Thread B

```
if (pInstance == NULL); // False
return pInstance; // uninitialized!
```

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level

How to Implement Locks?

- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - Important idea: all synchronization involves waiting
    - Should *sleep* if waiting for a long time
- Atomic Load/Store: get solution like Milk #3
  - Pretty complex and error prone
- Hardware Lock instruction
  - Is this a good idea?
  - What about putting a task to sleep?
    - How do you handle the interface between the hardware and scheduler?
  - Complexity?
    - Done in the Intel 432 – each feature makes HW more complex and slow

Naïve use of Interrupt Enable/Disable

How can we build multi-instruction atomic operations?

- Recall: dispatcher gets control in two ways.
  - Internal: Thread does something to relinquish the CPU
  - External: Interrupts cause dispatcher to take CPU
- On a uniprocessor, can avoid context-switching by:
  - Avoiding internal events
  - Preventing external events by disabling interrupts

Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
LockRelease { enable Ints; }
```

Naïve use of Interrupt Enable/Disable: Problems

Can't let user do this! Consider following:

```
LockAcquire();
While(TRUE) {;}
```

Real-Time system—no guarantees on timing!

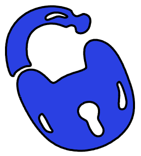
- Critical Sections might be arbitrarily long

What happens with I/O or other important events?

Better Implementation of Locks

Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
class Lock {
   int value = FREE;
   Queue wait_q;
}
```



```
Lock::Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait_q;
      next = readyList.pop();
      cur_thread->state = WAITING;
      thread_switch(current, next);
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Lock::Release() {
   disable interrupts;
   if (anyone on wait_q) {
      take thread off wait queue
      place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

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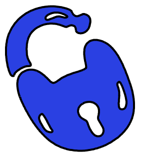

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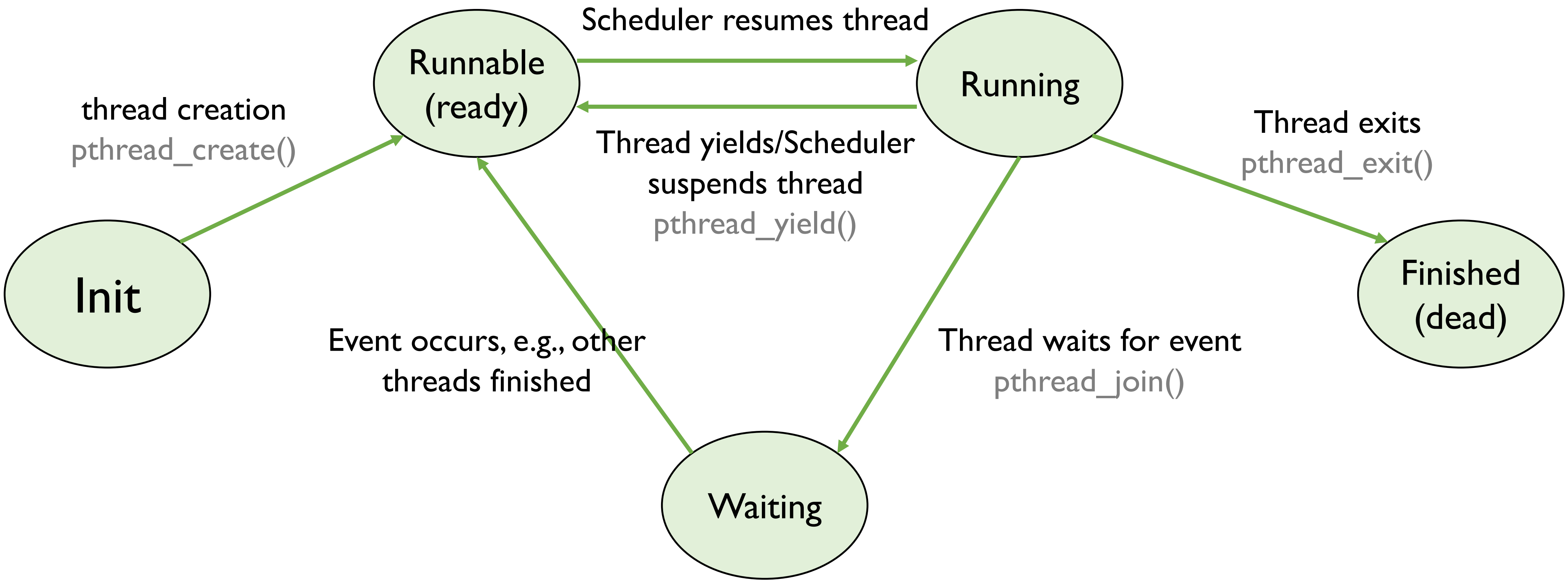
      thread_switch(current, next);
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

WHY??

```
Lock::Release() {
   disable interrupts;
   if (anyone on wait_q) {
      take thread off wait queue
      place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

Recall: Thread Lifecycle



Better Implementation of Locks

- Unlike previous solution, the critical section (inside **`Acquire()`**) is very short
  - User of lock can take as long as they like in their own critical section

```
Lock::Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait_q;
    next = readyList.pop();
    cur_thread->state = WAITING;
    thread_switch(current, next);
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

Better Implementation of Locks

- Unlike previous solution, the critical section (inside `Acquire()`) is very short
  - User of lock can take as long as they like in their own critical section
- Why do we need to disable interrupts at all?

```
Lock::Acquire() {
  disable interrupts;
  if (value == BUSY) {
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    thread_switch(current, next);
  } else {
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  enable interrupts;
}
```

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- Unlike previous solution, the critical section (inside **`Acquire()`**) is very short
  - User of lock can take as long as they like in their own critical section
- Why do we need to disable interrupts at all?
  - Avoid interruption between checking and setting lock value
  - Otherwise two threads could think that they both have lock

```
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  disable interrupts;
  if (value == BUSY) {
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  - Otherwise two threads could think that they both have lock
- Before putting thread on the wait queue?

Enable Position

```
Lock::Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait_q;
    next = readyList.pop();
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    thread_switch(current, next);
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

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- Before putting thread on the wait queue?
  - Release can check the queue and not wake up thread

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}
```

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  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue

Enable Position

```
Lock::Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait_q;
    next = readyList.pop();
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```

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- Why do we need to disable interrupts at all?
  - Avoid interruption between checking and setting lock value
  - Otherwise two threads could think that they both have lock
- Before putting thread on the wait queue?
  - Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  - Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  - Misses wakeup and still holds lock (deadlock!)
  - Note: the *value* is BUSY now!!!

Enable Position →

```
Lock::Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait_q;
    next = readyList.pop();
    cur_thread->state = WAITING;
    thread_switch(current, next);
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

How to Re-enable After thread_switch()?

- In scheduler, since interrupts are disabled when you call thread_switch():
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

Thread A	Thread B
.	
.	
disable ints	
thread_switch	
	thread_switch return
	enable ints
	.
	.
	.
	disable int
	thread_switch
thread_switch return	
enable ints	
.	
.	

Atomic Read-Modify-Write Instructions

- Can we extend the lock implementation to multi-processors?
  - Not good idea, as disabling interrupts on all processors requires messages and would be very time consuming
- Alternative: atomic instruction sequences
  - These instructions read a value and write a new value atomically
  - Hardware is responsible for implementing this correctly
    - ❑ on both uniprocessors (not too hard)
    - ❑ and multiprocessors (requires help from cache coherence protocol)
  - Unlike disabling interrupts, can be used on both uniprocessors and multiprocessors

Examples of Read-Modify-Write

- ```
  test&set (&address) {           /* most architectures */
      result = M[address];        /* return result from "address" and
      M[address] = 1;                  set value at "address" to 1 */
      return result;
  }
  ```

- ```
  swap (&address, register) {     /* x86 */
      temp = M[address];          /* swap register's value to
      M[address] = register;           value at "address" */
      register = temp;
  }
  ```

- ```
  compare&swap (&address, reg1, reg2) { /* 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
  ```
  ```

Implementing Locks with test&set

- Spinlock (自旋锁): another flawed, but simple solution:

```
int value = 0; // Free

Acquire() {
   while (test&set(value)); // while busy
}

Release() {
   value = 0;
}
```

- Simple explanation:
  - If lock is free, test&set reads 0 and sets value=1, so lock is now busy
    It returns 0 so while exits
  - If lock is busy, test&set reads 1 and sets value=1 (no change)
    It returns 1, so while loop continues
  - When we set value = 0, someone else can get lock
- Busy-Waiting: thread consumes cycles while waiting

Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock
  - Works on a multiprocessor
- Negatives
  - This is very inefficient as thread will consume cycles waiting
  - Waiting thread may take cycles away from thread holding lock (no one wins!)
  - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock ⇒ no progress!
- Priority Inversion problem with original Martian rover
- For semaphores, waiting thread may wait for an arbitrary long time!
  - Thus even if busy-waiting was OK for locks, definitely not ok for other primitives

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE;
Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      cur_thread->state = WAITING;
      thread_switch() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}
```

```
Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  - Can't entirely, but can minimize!
  - Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE;
Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      cur_thread->state = WAITING;
      thread_switch() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}
```

```
Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

Must be atomic! What if setting guard before or after thread_switch()? How to implement?

More details in Figure 5.17 (section 5.7 "Implementing Synchronization Objects") of our textbook

Locks using Interrupts vs. test&set

Compare to "disable interrupt" solution

```
int value = FREE;

Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      thread_switch();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

Basically replace

- `disable interrupts` → `while (test&set(guard));`
- `enable interrupts` → `guard = 0;`

Implementing Condition Variables

- Recap the operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters

```
while (!testOnSharedState()) {
    cv.wait(&lock)
}
```

Synchronized Queue with Condition Variables

```
Lock lock;
Condition dataready;
Queue queue;


AddToQueue(item) {
   lock.Acquire();             // Get Lock
   queue.enqueue(item);        // Add item
   dataready.signal();         // Signal any waiters
   lock.Release();             // Release Lock
}


RemoveFromQueue() {
   lock.Acquire();             // Get Lock
   while (queue.isEmpty()) {
      dataready.wait(&lock); // If nothing, sleep
   }
   item = queue.dequeue();   // Get next item
   lock.Release();             // Release Lock
   return(item);
}
```

Implementing Condition Variables

- Recap the operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters

```
Class CV {
   Queue waiting;
   void wait(Lock *lock);
   void signal();
   void broadcast();
}

void CV::signal() {
   if (waiting.notEmpty()) {
      thread = waiting.remove();
      scheduler.makeReady(thread);
   }
}
```

```
void CV::wait(Lock *lock) {
   assert(lock.isHeld());
   waiting.add(currentTCB);
   // switch to new thread and release lock
in atomic manner
   scheduler.suspend(&lock);
   lock->acquire();
}
```

Mesa vs. Hoare monitors

- Need to be careful about precise definition of signal and wait. Consider a piece of our dequeue code:

```
while (queue.isEmpty()) {
  dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue();  // Get next item
```

  - Why didn't we do this?

```
if (queue.isEmpty()) {
  dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue();  // Get next item
```

- Answer: depends on the type of scheduling (管程模型)
  - Hoare-style
  - Mesa-style

Mesa monitors

- Signaler keeps lock and processor
- Waiter placed on ready queue with no special priority
- Practically, need to check condition again after wait
- Most real operating systems

```
…
lock.Acquire()
…
dataready.signal();
…
lock.Release();
```

Put waiting thread on ready queue

schedule waiting thread

```
lock.Acquire()
…
while (queue.isEmpty()) {
  dataready.wait(&lock);
}
…
lock.Release();
```

Mesa Monitor: Why "while()"?

- Why do we use "while()" instead of "if() with Mesa monitors?
  - Example illustrating what happens if we use "if()", e.g.,

```
if (queue.isEmpty()) {
   dataready.wait(&lock); // If nothing, sleep
}
```

- We'll use the synchronized (infinite) queue example

```
AddToQueue(item) {
   lock.Acquire();
   queue.enqueue(item);
   dataready.signal();
   lock.Release();
}
```

```
RemoveFromQueue() {
   lock.Acquire();
   if (queue.isEmpty()) {
      dataready.wait(&lock);
   }
   item = queue.dequeue();
   lock.Release();
   return(item);
}
```

Replace "while" with "if"

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: FREE

dataready queue → NULL

CPU State

Running: T1

Ready queue → NULL

…

T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why “while()”?

App. Shared State

queue

Monitor

lock: BUSY (T1)

dataready queue → NULL

CPU State

Running: T1

Ready queue → NULL

…

T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: FREE

dataready queue → T1

CPU State

Running:

Ready queue → NULL

wait(&lock) puts thread on dataready queue and releases lock

T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: FREE

dataready queue → T1

CPU State

Running: T2

Ready queue → NULL

…

T1 (Waiting)

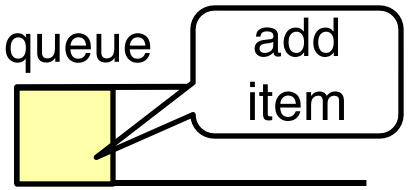
```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

Mesa Monitor: Why “while()”?

App. Shared State



Monitor

lock: BUSY (T2)

dataready queue → T1

CPU State

Running: T2
Ready queue → NULL
…

T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: BUSY (T2)

dataready queue → NULL

CPU State

Running: T2

Ready queue → T1

…

signal() wakes up T1 and moves it on ready queue

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

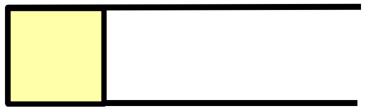
T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue



Monitor

lock: BUSY (T2)

dataready queue → NULL

CPU State

Running: T2

Ready queue → T1, T3

…

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

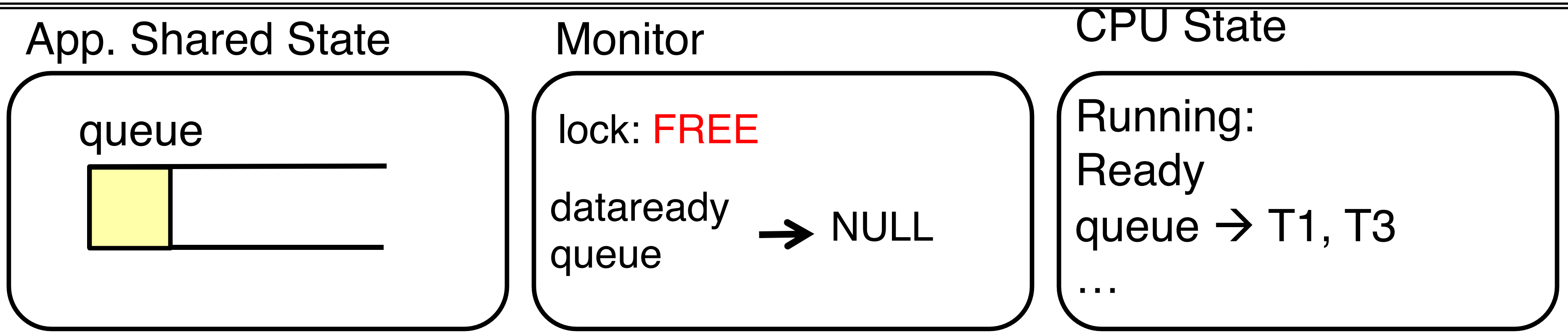
T2 (Running)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

T3 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why “while()”?



T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T2 (Terminate)

```
AddToQueue(item) {
  lock.Acquire();
  queue.enqueue(item);
  dataready.signal();
  lock.Release();
}
```

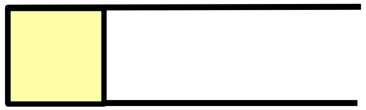
T3 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue



Monitor

lock: FREE

dataready queue → NULL

CPU State

Running: T3

Ready queue → T1

T3 scheduled first!

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

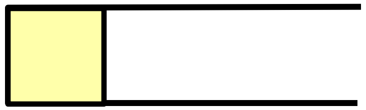
T3 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue



Monitor

lock: BUSY (T3)

dataready queue → NULL

CPU State

Running: T3
Ready queue → T1
…

T1 (Ready)

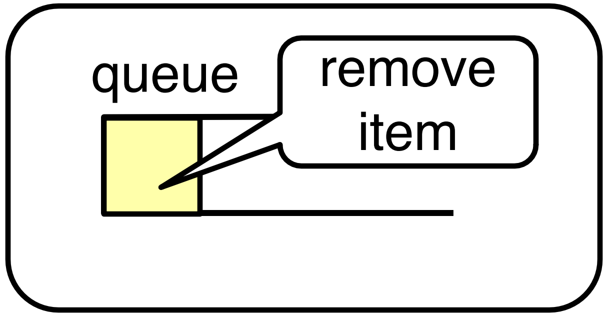
```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T3 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why “while()”?

App. Shared State



Monitor

lock: BUSY (T3)

dataready queue → NULL

CPU State

Running: T3

Ready queue → T1

…

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T3 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: FREE

dataready queue → NULL

CPU State

Running:

Ready queue → T1

…

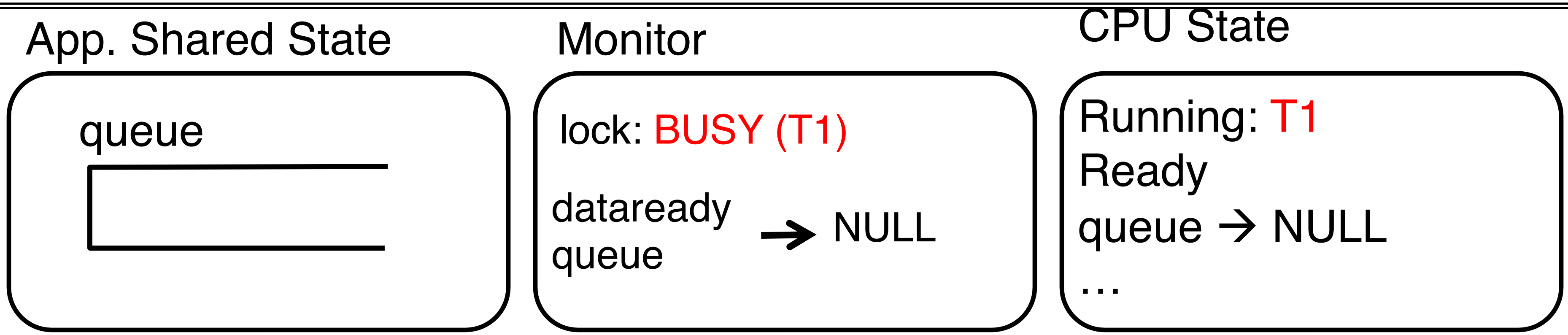
T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

T3 (Finished)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?



T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: BUSY (T1)

dataready queue → NULL

CPU State

Running: T1

Ready queue → NULL

…

T1 (Running)

```
RemoveFromQueue() {
  lock.Acquire();
  if (queue.isEmpty()) {
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

ERROR: Nothing in the queue!

Mesa Monitor: Why “while()”?

App. Shared State

queue

Monitor

lock: BUSY (T1)

dataready queue → NULL

CPU State

Running: T1

Ready queue → NULL

…

T1 (Running)

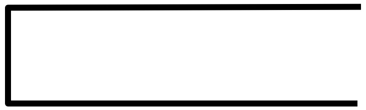
```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
{
   dataready.  it(&lock);
  }
  item = que
  lock.Relea
  return(item
}
```

Replace “if” with “while”

Mesa Monitor: Why "while()"?

App. Shared State

queue



Monitor

lock: BUSY (T1)

dataready queue → NULL

CPU State

Running: T1
Ready queue → NULL
…

T1 (Ready)

```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
{
   dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Check again if empty!

Mesa Monitor: Why "while()"?

App. Shared State

queue

Monitor

lock: FREE

dataready queue → T1

CPU State

Running: T1

Ready queue → NULL

…

T1 (Waiting)

```
RemoveFromQueue() {
  lock.Acquire();
  while (queue.isEmpty())
{
    dataready.wait(&lock);
  }
  item = queue.dequeue();
  lock.Release();
  return(item);
}
```

Hoare monitors

- Signaler gives up lock, CPU to waiter; waiter runs immediately
- Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
- Most textbooks

```
…
lock.Acquire()
…
dataready.signal();
…
lock.Release();
```

Lock, CPU →

← Lock, CPU

```
lock.Acquire()
…
if (queue.isEmpty()) {
  dataready.wait(&lock);
}
…
lock.Release();
```

Quick Questions

- Do lock.Acquire() and lock.Release() always trap into kernel?
- Interrupt handlers must use spinlocks instead of queueing locks. Why?
  - Note: interrupt handlers are not supposed to sleep

Homework

- Search for how Java synchronization works.
  - Key words: "synchronized", "wait", "notify", "notifyAll".
  - Is it based on Hoare or Mesa model?

- Implement semaphores with test&set in pseudo code.