CSCE 313-201
Introduction to Computer Systems
Fall 2019

Synchronization IV
Dmitri Loguinov
Texas A&M University

October 3, 2019
Homework #2

• Previous version of search was slow
  – CPU utilization 14%, clearly system can handle more, but…
  – Lots of time spent on context switches, not doing useful work

• Delays in the CC are per command, not per room
  – Improvement #1: batching
    (multiple rooms per request)

• Next problem: STL set is a major bottleneck
  – Improvement #2: write a non-STL hash table

• Next problem: out of RAM on STL queue
  – Improvement #3: write a non-STL queue with batching

• Goal: caves w/4 billion rooms @ 10M rooms per sec
Homework #2

• **Suggestion**: develop incrementally from hw #1
  - 2a: Introduce CC 2.0 batching (push/pop up to 10K rooms, send them in one message), but keep the rest
  - Confirm correctness; run benchmarks for report question 2
  - 2b: Replace D with bit hash table; confirm result matches 2a
  - 2c: Replace U with custom queue (single push/pop); confirm result matches 2a-2b
  - 2d: Introduce batch-mode push/pop; confirm result
  - 2e: Optimize synchronization; confirm result

• **Make sure to print commas in large numbers**

--------- Switching to level 11 with 421,068,639 nodes
--------- Switching to level 12 with 471,263,881 nodes
*** Thread [1080]: found exit room 1C63A9F, distance 12, steps 619,225,089
Chapter 5: Roadmap

5.1 Concurrency
5.2 Hardware mutex
5.3 Semaphores
5.4 Monitors
5.5 Messages
5.6 Reader-Writer
Bounded Producer-Consumer

- Now assume the buffer has some fixed size B
  - Often the queue is a circular array of this size
- Classical version
  - PC 2.0

```java
Queue Q;
Mutex m;
Semaphore semaFullSlots = {0, B};
Semaphore semaEmptySlots = {B, B};
Producer() {
    while (true) {
        // make item x
        semaEmptySlots.Wait();
        m.Lock();
        Q.add (x); m.Unlock();
        semaFullSlots.Release(1);
    }
}
Consumer() {
    while (true) {
        semaFullSlots.Wait ();
        m.Lock();
        // no need to check Q.size
        x = Q.pop(); m.Unlock();
        semaEmptySlots.Release(1);
        // consume x outside
        // the critical section
    }
}
```

- What if bursty consumer or producer?
**Bounded Producer-Consumer**

- PC 2.0 requires two waits before item can be consumed or produced, potentially inefficient?
  - **PC 2.1**

```java
Queue Q;
Mutex m;
Semaphore semaFullSlots = {0, B};
Semaphore semaEmptySlots = {B, B};
Producer() {
  while (true) {
    // make item x
    WaitAll (semaEmptySlots, m);
    Q.add (x);
    m.Unlock();
    semaFullSlots.Release(1);
  }
}
```

- Drawback: does not work with eventQuit
  - Need a timeout in WaitAll to check for termination events
Bounded Producer-Consumer

- MSDN says STL objects can never be safely modified from multiple threads
  - Always need a mutex

- Can producer-consumer be implemented completely without synchronization?
  - Suppose we’re allowed to write our own circular queue

- Yes, but only if one thread of each type
  - Producer only modifies Q.tail, while consumer only Q.head

```c
void Q::push (Item x){
    newTail = (tail + 1) % B;
    do {
        if (newTail != head)  // not full
            break;
        Sleep (SOME_DELAY);
    } while (true);
    buf [tail] = x;
    tail = newTail;
}

Item Q::pop (void){
    do {
        if (tail != head)  // not empty
            break;
        Sleep (SOME_DELAY);
    } while (true);
    tmp = buf [head];
    head = (head + 1) % B;
    return tmp;
}
```
**Bounded Producer-Consumer**

- More complex designs are possible
  - One internal mutex for \( K \) producers (modifying \( Q.\text{tail} \)) and another for \( M \) consumers (modifying \( Q.\text{head} \))
- What if the buffer gets reallocated periodically?
  - Then, whoever is allocating the new buffer needs to obtain both mutexes simultaneously

```c
void Q::push (Item x) {
    producerMutex.Lock();
    if (buffer too small)
        consumerMutex.Lock();
        // change buffer to be bigger
        consumerMutex.Unlock();
    deposit x, modify tail
    producerMutex.Unlock();
}
```

```c
Item Q::pop (void){
    consumerMutex.Lock();
    if (buffer too large)
        producerMutex.Lock();
        // change buffer to be smaller
        producerMutex.Unlock();
    remove x, modify head
    consumerMutex.Unlock();
}
```

potential for a deadlock
Chapter 5: Roadmap

5.1 Concurrency
5.2 Hardware mutex
5.3 Semaphores
5.4 Monitors
5.5 Messages
5.6 Reader-Writer
Monitors

• The concept, invented in 1974, is now used in certain programming languages
  – Concurrent Pascal, Modula-2/3, Java, Ada, Ruby
• **Definition**: monitor is a class with two properties
  – No external access to internal objects (all data is private)
  – Each member function is protected by compiler to ensure that only one thread can execute inside
• Compiler locks some hidden class-specific mutex on entry and unlocks it on exit
• Mutex is not accessible directly in the code, so a wait for another event inside the monitor may deadlock the whole program
Monitors

- **Example**: producer-consumer queue as a monitor
  - How about this:

```cpp
pcQueue::push(Item x) mutex.Lock(); {
  semaEmptySlots.Wait();
  Q.add(x);
  semaFullSlots.Release (1);
}  mutex.Unlock();
```

We want this, but can’t have it because the mutex is invisible to the programmer

- Obviously a problem
- To fix this, a new type of synchronization primitive was invented that is similar to an event
  - When blocked waiting on this primitive, the compiler secretly unlocks the mutex and when the event is signaled, the compiler secretly locks it again
• **Definition:** condition variable is a class with two ops:
  - Sleep: unlocks the secret mutex of the monitor and blocks on the event; then tries to acquire mutex when event is signaled
  - Wake: signals the event if threads are sleeping; otherwise, does nothing

```cpp
CondVar::Sleep () {
    UnlockWaitLock (mutex, waitEvent);
}
```

```cpp
CondVar::Wake () {
    if (threads are blocked)
        waitEvent.Signal();
    // if nobody is blocked,
    // the wake-up is lost
}
```

• **Function UnlockWaitLock():**
  - *Atomically* unlocks compiler mutex and blocks on event
  - Once event is signaled, it *atomically* blocks on mutex
• Wake is guaranteed to unblock one thread
Monitors

• Producer-consumer with monitors
  - PC 3.0

```cpp
class pcQueue {
private:
    queue<Item> Q;
    CondVar cvNotEmpty, cvNotFull;
public:
    push (Item x); Item pop ();
};
```

```cpp
pcQueue::push (Item x) mutex.Lock (); {
    while ( Q.isFull () )
        cvNotFull.Sleep ();
    Q.add (x);
    cvNotEmpty.Wake ();
} mutex.Unlock();
```

```cpp
Item pcQueue::pop () mutex.Lock (); {
    while ( Q.isEmpty () )
        cvNotEmpty.Sleep ();
    x = Q.remove ();
    cvNotFull.Wake (); return x;
} mutex.Unlock();
```

• When pop() finishes, producers compete for mutex
  - New threads wanting to enter push() and those asleep

• Why is there a while loop around Q.isFull()? 
  - In certain monitor implementations, Sleep() allows new threads to enter the monitor and steal a wake-up
  - Thus, awakened thread must check if the queue is still not full before attempting to add to it
Back to Semaphores

• Version 3.0 with auto events / binary semaphores
  – PC 3.1

// all events are AUTO (binary semaphore)
pcQueue::push (Item x) {
  mutex.Lock();
  while ( Q.isFull() )
    mutex.Unlock();
    eventNotFull.Wait();
  mutex.Lock();
  Q.add (x);
  if ( !Q.isFull() )
    eventNotFull.Signal();
  eventNotEmpty.Signal();
  mutex.Unlock();
}

// all events are AUTO (binary semaphore)
Item pcQueue::pop () {
  mutex.Lock();
  while ( Q.isEmpty() )
    mutex.Unlock();
    eventNotEmpty.Wait();
  mutex.Lock();
  x = Q.remove();
  if ( !Q.isEmpty() )
    eventNotEmpty.Signal();
  eventNotFull.Signal();
  mutex.Unlock();
  return x;
}

• Increments past max, stolen wake-ups are possible
• What if events were manual in the above?
  – Major performance hit: all threads wake up and busy spin on their while loops
Back to Semaphores

- If `WaitAll` is available, work “theft” can be avoided
  - PC 3.2

```cpp
// all events are AUTO (binary semaphore)
pcQueue::push (Item x) {
    WaitAll (eventNotFull, mutex);
    Q.add (x);
    if ( !Q.isFull () )
        eventNotFull.Signal();
    eventNotEmpty.Signal();
    mutex.Unlock();
}
```

```cpp
// both events are AUTO (binary semaphore)
Item pcQueue::pop () {
    WaitAll (eventNotEmpty, mutex);
    x = Q.remove ();
    if ( !Q.isEmpty() )
        eventNotEmpty.Signal();
    eventNotFull.Signal();
    mutex.Unlock(); return x;
}
```

- Now the same with manual-reset events
  - PC 3.3

```cpp
// all events are MANUAL
pcQueue::push (Item x) {
    WaitAll (eventNotFull, mutex);
    Q.add (x);
    if ( Q.isFull () )
        eventNotFull.Reset();
    eventNotEmpty.Signal();
    mutex.Unlock();
}
```

```cpp
// both events are MANUAL
Item pcQueue::pop () {
    WaitAll (eventNotEmpty, mutex);
    x = Q.remove ();
    if ( Q.isEmpty() )
        eventNotEmpty.Reset();
    eventNotFull.Signal();
    mutex.Unlock(); return x;
}
```
Back to Semaphores

• One more version to consider:
  - PC 3.4

```cpp
pcQueue::push (Item x) {
    mutex.Lock();
    while ( Q.isFull() )
        mutex.Unlock();
        Sleep(DELAY);
    mutex.Lock();
    Q.add (x);
    mutex.Unlock();
}
```

```cpp
Item Queue::pop () {
    mutex.Lock();
    while ( Q.isEmpty() )
        mutex.Unlock();
        Sleep(DELAY);
        mutex.Lock();
    x = Q.pop ();
    mutex.Unlock();
    return x;
}
```

• Probably the simplest approach
  - Arguably inefficient due to sleep-looping
  - May cause starvation for certain threads
Summary

All methods need at least a mutex, but additionally:

• PC 2.0 requires a counting semaphore
  – Ideal textbook solution since it’s elegant and simple
  – Does not handle bursty push/pop

• PC 2.1 similar to 2.0, but further requires WaitAll
  – Even more elegant, but same drawbacks as 2.0
  – Does not work with eventQuit

• PC 3.0 requires monitors and condition variables
  – Possible in C++, but not optimal speed

• PC 3.1 requires just a binary semaphore
  – Allows stolen wake-ups, but can handle bursty data easily
Wrap-up

- PC 3.2 requires *binary semaphore* and *WaitAll*
  - Handles bursty data well, but more elegant than 3.1 and prevents stolen wake-ups
  - Signals unnecessarily if queue is rarely full or empty
- PC 3.3 requires *manual events* and *WaitAll*
  - Similar to 3.2, but less signaling when there is work to do
- PC 3.4 requires nothing beyond a mutex
  - Most flexible as threads can perform useful checks (e.g., the quit flag) while being awake
  - Sleep-spinning is seemingly bad, or … is it?
- Ultimately, *performance* is what really matters
  - We’ll consider a few benchmarks next time