CSCE 313-201
Introduction to Computer Systems
Fall 2020

Synchronization V
Dmitri Loguinov
Texas A&M University

October 1, 2020
Updates

- Memory heaps
  - Normal new/delete ops go to the process heap
  - Internal mutex, slow delete
- Private heap doesn’t need to mutex
  - Benchmark with 12 threads on a 6-core system

```
#define ITER 1e7
DWORD __stdcall HeapThread (...) {
    DWORD **arr = new (DWORD *) [ITER];
    for (int i=0; i < ITER; i++)
        arr[i] = new DWORD [1];
    for (int i=0; i < ITER; i++)
        delete arr[i];
}
```

```
DWORD __stdcall HeapThread (...) {
    HANDLE heap = HeapCreate
        (HEAP_NO_SERIALIZE,
        4 * 1024 * sizeof(DWORD), 0);
    DWORD **arr = new (DWORD *) [ITER];
    for (int i = 0; i < ITER; i++)
        arr[i] = (DWORD*) HeapAlloc
            (heap, HEAP_NO_SERIALIZE,
            sizeof(DWORD));
    HeapDestroy (heap);
}
```

3.3M/s 12M/s 36M/s
Chapter 5: Roadmap

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

- Messages are discrete chunks of information exchanged between processes
  - This form of IPC is often used between different hosts
- Where used
  - Pipes (one-to-one)
  - Mailslots (one-to-many among hosts in the active directory domain)
  - Sockets (TCP/IP)

- In general form, message consists of fixed header and some payload
- Header may specify
  - Version and protocol 
  - Message length, type, various attributes
  - Status and error conditions
- Already studied enough in homework #1
Chapter 5: Roadmap

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5.6 Reader-Writer
Reader-Writer (RW)

• RW is another famous synchronization problem
• Assume a shared object that is accessed by M readers and K writers in parallel
• Example: suppose hw#1 restricted robot MOVE commands to only adjacent rooms
  – This requires construction of a global graph G as new edges are being discovered from the threads (writer portion)
  – To make a move, each thread has to plot a route to the new location along the shortest path in G (reader portion)
• Any number of readers may read concurrently
  – However, writers need exclusive access to the object (i.e., must mutex against all readers and other writers)
• **Q:** based on your intuition, do readers or writers usually access the object more frequently?

• First stab at the problem:
  - **RW 1.0**

```cpp
Reader::GoRead () {
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount == 0)
        semaW.Wait();
    readerCount ++;
    mutexRcount.Unlock();

    // read object
    mutexRcount.Lock();
    readerCount--; // last reader unblocks writers
    if (readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}
```

- Infinite stream of readers?
  - Writers never get access

- RW 1.0 gives readers priority and starves writers
Another policy is to let the OS load-balance the order in which readers and writers enter the critical section

- RW 1.1

```cpp
Reader::GoRead () {
    semaWriterPending.Wait();
    semaWriterPending.Release();
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount == 0)
        semaW.Wait();
    readerCount ++;
    mutexRcount.Unlock();
    // read object
    mutexRcount.Lock();
    readerCount--;
    // last reader unblocks writers
    if (readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}

Writer::GoWrite () {
    semaWriterPending.Wait();
    semaW.Wait();
    // write object
    semaW.Release();
    semaWriterPending.Release();
}
```

- Serves readers/writers in FIFO order if kernel mutex is fair
- What if 100x more readers than writers?

increasing writer thread priority may help against being starved
**Reader-Writer**

- Final policy: writers have absolute priority
  - Given a pending writer, no reader may enter
  - RW 1.2

```cpp
Reader::GoRead () {
    semaWriterPending.Wait();
    semaWriterPending.Release();
    mutexRcount.Lock();
    // first reader blocks writers
    if (readerCount++ == 0)
        semaW.Wait();
    mutexRcount.Unlock();
    // read object
    mutexRcount.Lock();
    // last reader unblocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}

Writer::GoWrite () {
    mutexWcount.Lock();
    if (writerCount++ == 0)
        semaW.Wait();
    mutexWcount.Unlock();
    semaW.Wait();
    // write object
    semaW.Release();
    mutexWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutexWcount.Unlock();
}
```

- Works fine except first writer still must compete

OS chooses between one writer and M readers
Reader-Writer

- To ensure priority for the first writer, need to prevent readers from competing for `semaWriterPending`
  - RW 1.3

```cpp
Reader::GoRead () {
    mutualDontCompete.Lock();
    semaWriterPending.Wait();
    mutualRcount.Lock();
    // first reader blocks writers
    if (readerCount++ == 0)
        semaW.Wait();
    mutualRcount.Unlock();
    semaWriterPending.Release();
    // pending writer gets unblocked here
    mutualDontCompete.Unlock();

    // read object
    mutualRcount.Lock();
    // last reader unlocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutualRcount.Unlock();
}

Writer::GoWrite () {
    mutualWcount.Lock();
    if (writerCount++ == 0)
        semaWriterPending.Wait();
    mutualWcount.Unlock();
    semaW.Wait();
    // write object
    semaW.Release();
    mutualWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutualWcount.Unlock();
}
```

- Textbook solution
  - Works even if semaphore is unfair
Reader-Writer

• What about the next solution that eliminates one lock and rearranges some of the lines
  
  - RW 1.4

```cpp
Reader::GoRead () {
    mutexRcount.Lock();
    semaWriterPending.Wait();
    if (readerCount++ == 0)
        // first reader blocks writers
        semaW.Wait();
    semaWriterPending.Release();
    // pending writer gets unblocked here
    mutexRcount.Unlock();

    // read object
    mutexRcount.Lock();
    // last reader unblocks writers
    if (--readerCount == 0)
        semaW.Release();
    mutexRcount.Unlock();
}

Writer::GoWrite () {
    mutexWcount.Lock();
    if (writerCount++ == 0)
        semaWriterPending.Wait();
    mutexWcount.Unlock();

    semaW.Wait();
    // write object
    semaW.Release();

    mutexWcount.Lock();
    if (--writerCount == 0)
        semaWriterPending.Release();
    mutexWcount.Unlock();
}
```

• Find a problem at home
Chapter 5: Roadmap

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Performance
**Windows APIs**

- **GetCurrentProcess() and GetCurrentProcessId()**
  - Return a handle and PID, respectively
- **EnumProcesses(), OpenProcess()**
  - Enumerates PIDs in the system, opens access to them
- **TerminateProcess()** kills another process by its handle
  - ExitProcess() voluntarily quits (similar to C-style exit())
- **GetProcessTimes()**
  - Time spent on the CPU (both in kernel-mode and user-mode)
- **Available resources**
  - GlobalMemoryStatus(): physical RAM, virtual memory
  - GetActiveProcessorCount(): how many CPUs
- **CPU utilization**: see cpu.cpp in sample project
Performance

- WaitForSingleObject
  - Always makes a kernel-mode transition and is pretty slow
  - Mutexes, semaphores, events all rely on this API
- A faster mutex is CRITICAL_SECTION (CS)
  - Busy-spins in user mode on interlocked exchange for a fixed number of CPU cycles
  - If unsuccessful, gives up and locks a kernel mutex
- While kernel objects (i.e., mutexes, semaphores, events) can be used between processes, CS works only between threads within a process

```c
CRITICAL_SECTION cs;
InitializeCriticalSection (&cs);
// mutex.Lock()
EnterCriticalSection (&cs);
// mutex.Unlock()
LeaveCriticalSection (&cs);
```
Performance

- **Condition variables in Windows**
  - In performance, similar to CS (i.e., spins in user mode)
  - Secret (monitor) mutex is explicit pointer to some CS
- **PC 3.0 that actually works in Windows**

```cpp
pcQueue::push (Item x) {
    EnterCriticalSection (&cs);
    while ( Q.isFull () )
        SleepConditionVariable (&cvNotFull, &cs, ...);
    Q.add (x);
    LeaveCriticalSection (&cs);
    WakeConditionVariable (&cvNotEmpty);
}
```

- **Slim RW locks**
  - AcquireSRWLockShared (reader)
  - AcquireSRWLockExclusive (writer)
**Performance**

- **Example 1**: compute $\pi$ in a Monte Carlo simulation
  - Generate N random points in 1x1 square and compute the fraction of them that falls into unit circle at the origin
  - Probability to hit the red circle?
- This probability is the visible area of the circle divided by the area of the square (i.e., 1)
  - Quarter of a circle gives us $\pi/4$

```c
DWORD WINAPI ThreadPi (LONG *hitCircle) {
    for (int i=0; i < ITER; i++) {
        // uniform in [0,1]
        x = rand.Uniform(); y = rand.Uniform();
        if (x*x + y*y < 1)
            IncrementSync (hitCircle);
    }
}

main () {
    // run N ThreadPi() threads
    // wait to finish
    double pi =
        4*hitCircle/ITER/nThreads;
}
```
Performance

- Six-core AMD Phenom II X6, 2.8 GHz
- Two modes of operation
  - No affinity set (threads run on the next available core)
  - Each thread is permanently bound to one of the 6 cores
- Total k threads
- The basic kernel Mutex
  - \( \pi \approx 3.13 \)
  - CPU \( \approx 16\% \)
  - Requires 2 kernel-mode switches per increment
  - Runs almost twice as slow with 20K threads

```c
IncrementSync (LONG *hitCircle) {
    WaitForSingleObject (mutex, INFINITE);
    (*hitCircle) ++;
    ReleaseMutex (mutex);
}
```

<table>
<thead>
<tr>
<th></th>
<th>k = 60</th>
<th>k = 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>No affinity</td>
<td>384K/s</td>
<td>278K/s</td>
</tr>
<tr>
<td>Affinity</td>
<td>447K/s</td>
<td>220K/s</td>
</tr>
</tbody>
</table>
Performance

- AtomicSwap
  - $\pi \approx 3.1405$
  - CPU = 100% (locks up the computer)
  - Unable to start more than 7K threads since the CPU is constantly busy
- AtomicSwap and yield
  - When cannot obtain mutex, yield to other threads if they are ready to run
  - $\pi \approx 3.1412$
  - CPU = 100%, but computer much more responsive

```c
LONG taken = 0; // shared flag
IncrementSync (LONG *hitCircle) {
    while (InterlockedExchange (&taken, 1) == 1) {
        SwitchToThread();
        (*hitCircle) ++;
        taken = 0;
    }
}
```

<table>
<thead>
<tr>
<th>k = 60</th>
<th>k = 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>No affinity</td>
<td>Affinity</td>
</tr>
<tr>
<td>448K/s</td>
<td>485K/s</td>
</tr>
</tbody>
</table>

```c
LONG taken = 0; // shared flag
IncrementSync (LONG *hitCircle) {
    while (InterlockedExchange (&taken, 1) == 1) {
        SwitchToThread();
        (*hitCircle) ++;
        taken = 0;
    }
}
```

<table>
<thead>
<tr>
<th>k = 60</th>
<th>k = 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>No affinity</td>
<td>Affinity</td>
</tr>
<tr>
<td>6.8M/s</td>
<td>6.8M/s</td>
</tr>
</tbody>
</table>
Performance

- **CRITICAL_SECTION**
  - \( \pi \approx 3.1417 \)
  - CPU = 36%
- Interlocked increment
  - \( \pi \approx 3.1416 \)
  - CPU = 100%
  - Fastest method so far
- No sync (dumb approach)
  - CPU = 100%
  - Some of the concurrent updates are lost due to cache sync problems

```c
CRITICAL_SECTION cs;
IncrementSync (LONG *hitCircle) {
EnterCriticalSection (&cs);
(*hitCircle) ++;
LeaveCriticalSection(&cs);
}
k = 60
k = 20k
<table>
<thead>
<tr>
<th>No affinity</th>
<th>Affinity</th>
<th>No affinity</th>
<th>Affinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.9M/s</td>
<td>15.9M/s</td>
<td>7.3M/s</td>
<td>12.8M/s</td>
</tr>
</tbody>
</table>
```

```c
IncrementSync (LONG *hitCircle) {
    InterLockedIncrement (hitCircle);
}
k = 60
k = 20k
<table>
<thead>
<tr>
<th>No affinity</th>
<th>Affinity</th>
<th>No affinity</th>
<th>Affinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.4M/s</td>
<td>19.2M/s</td>
<td>19.1M/s</td>
<td>19.0M/s</td>
</tr>
</tbody>
</table>
```

```c
IncrementSync (LONG *hitCircle) {
    (*hitCircle)++;
}
k = 60
k = 20k
<table>
<thead>
<tr>
<th>No affinity</th>
<th>Affinity</th>
<th>No affinity</th>
<th>Affinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5M/s</td>
<td>19.9M/s</td>
<td>20.6M/s</td>
<td>20.2M/s</td>
</tr>
<tr>
<td>( \pi \approx 1.21 )</td>
<td>( \pi \approx 1.03 )</td>
<td>( \pi \approx 0.96 )</td>
<td>( \pi \approx 1.33 )</td>
</tr>
</tbody>
</table>
Performance

- No sync (correct approach)
  - $\pi \approx 3.1415$
  - 202M/s, 100% CPU, bottlenecked by `rand.Uniform()`

- Lessons
  - Kernel mutex is slow, should be avoided
  - `CRITICAL_SECTION` is the best general mutex
  - Interlocked operations are best for 1-line critical sections
  - Affinity mask makes a big difference in some cases

- If you can write code only using local variables and synchronize rarely, it can be 1000x faster than kernel mutex and 10x faster than `InterlockedAdd`
**Performance**

- **Example 2**: unbounded producer-consumer
  - Producer batch = 1
    - $Q.size() \leq 1$
  - Producer batch = 10
    - $Q.size() \to \infty$
- **PC 1.1**
  - Busy spins to enter
  - CPU is high, mostly spent in the kernel
  - Worst method in our comparison

```cpp
int batch; // PC 1.1
while (true) {
  while (true) {
    WaitForSingleObject(mutex, INFINITE);
    if (Q.size() > 0) {
      x = Q.pop();
      break;
    }
    ReleaseMutex (mutex);
  }
  ReleaseMutex (mutex);
  // now produce
  while (true) {
    WaitForSingleObject(mutex, INFINITE);
    for (int i=0; i < batch; i++)
      Q.add (i+x);
    ReleaseMutex (mutex);
  }
}
```

<table>
<thead>
<tr>
<th>k</th>
<th>batch=1</th>
<th>batch=10</th>
<th>batch=1</th>
<th>batch=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>660/sec</td>
<td>187K/sec</td>
<td>worse</td>
<td>worse</td>
</tr>
</tbody>
</table>
Performance

- PC 1.2 sleeps on semaphore
  - CPU = 20%
- PC 1.4 releases semaphore in bulk
  - Speed-up by 40% over PC 1.2 with batch=10
  - CPU = 20%

<table>
<thead>
<tr>
<th></th>
<th>k = 600</th>
<th>k = 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>batch=1</td>
<td>275K/s</td>
<td>130K/s</td>
</tr>
<tr>
<td>batch=10</td>
<td>223K/s</td>
<td>112K/s</td>
</tr>
</tbody>
</table>

PC 1.2

```c
int batch; // PC 1.2
while (true) {
    WaitForSingleObject(sema, INFINITE);
    WaitForSingleObject(mutex, INFINITE);
    x = Q.pop ();
    ReleaseMutex (mutex);
    WaitForSingleObject(mutex, INFINITE);
    for (int i=0; i < batch; i++) {
        Q.add (i+x);
        ReleaseSemaphore(sema,1,NULL);
    }
    ReleaseMutex (mutex);
}
```

PC 1.4 (hw1)

```c
int batch; // PC 1.4
while (true) {
    WaitForSingleObject(sema, INFINITE);
    WaitForSingleObject(mutex, INFINITE);
    x = Q.pop ();
    ReleaseMutex (mutex);
    WaitForSingleObject(mutex, INFINITE);
    for (int i=0; i < batch; i++)
        Q.add (i+x);
    ReleaseMutex (mutex);
    ReleaseSemaphore(sema,batch,NULL);
}
```
Performance

- **PC 2.1**
  - Adds WaitAll
  - CPU = 100%
  - Horrible performance
  - PC 3.2-3.3 similar

- **Back to 1.4**
  - Over 450% faster than 1.4 for batch=10
  - CPU = 100%

<table>
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</thead>
<tbody>
<tr>
<td>batch=1</td>
<td>batch=10</td>
</tr>
<tr>
<td>27K/s</td>
<td>27K/s</td>
</tr>
<tr>
<td>worse</td>
<td>worse</td>
</tr>
</tbody>
</table>

PC 1.4 w/CS

<table>
<thead>
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<th>k = 600</th>
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</tr>
</thead>
<tbody>
<tr>
<td>batch=1</td>
<td>batch=10</td>
</tr>
<tr>
<td>361K/s</td>
<td>850K/s</td>
</tr>
<tr>
<td>worse</td>
<td>worse</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>batch=1</th>
<th>batch=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>280K/s</td>
<td>1.1M/s</td>
</tr>
</tbody>
</table>

HANDLE arr[] = {sema, mutex};  // PC 2.1
while (true) {
    WaitForMultipleObjects(2, arr, true, INFINITE);
    x = Q.pop();
    ReleaseMutex (mutex);

    WaitForSingleObject(mutex, INFINITE);
    for (int i=0; i < batch; i++)
        Q.add (i+x);
    ReleaseMutex (mutex);
    ReleaseSemaphore(sema,batch,NULL);
}

int batch;  // PC 1.4 with CS
while (true) {
    WaitForSingleObject(sema, INFINITE);
    EnterCriticalSection (&cs);
    x = Q.pop();
    LeaveCriticalSection (&cs);

    EnterCriticalSection (&cs);
    for (int i=0; i < batch; i++)
        Q.add (i+x);
    LeaveCriticalSection (&cs);
    ReleaseSemaphore(sema,batch,NULL);
}
Wrap-up

- **PC 3.0**
  - CPU = 100%
  - Breaks down when Q is persistently small
- **PC 3.1**
  - Uses kernel events, runs at 450K/s
- **PC 3.4**
  - CPU = 30%

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</thead>
<tbody>
<tr>
<td>batch=1</td>
<td>205K/s</td>
<td>5.9M/s</td>
</tr>
<tr>
<td></td>
<td>78K/s</td>
<td>7.1M/sec</td>
</tr>
</tbody>
</table>

<table>
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<th>k = 600</th>
<th>k = 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>batch=1</td>
<td>22M/s</td>
<td>5.9M/s</td>
</tr>
<tr>
<td></td>
<td>16.5M/s</td>
<td>7.5M/sec</td>
</tr>
</tbody>
</table>