CSCE 313-200
Introduction to Computer Systems
Spring 2022

Synchronization
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Chapter 5: Roadmap

5.1 Concurrency
   Appendix A.1
5.2 Hardware mutex
5.3 Semaphores
5.4 Monitors
5.5 Messages
5.6 Reader-Writer
Inter-Process Communication (IPC)

- IPC enables exchange of information between threads/processes
- Two main approaches
  - Shared memory
  - Messages
- Shared memory
  - Primary method to pass data between threads
  - Much faster than messages
  - However, requires protection against concurrent modification to shared data
- Messages
  - Data copied through a kernel buffer
  - OS provides exclusion
  - Can be used between hosts in distributed applications (e.g., pipes, network sockets)
- Pipes already covered, now deal with shared-memory IPC
Motivation

- Most examples will be in C++ style pseudocode
  - See MSDN for detailed usage of functions
- Start with two threads
  - Shared class passed to each thread
  - Thread1 computes a+b and saves into a
  - Thread2 does the same, but saves into b
- What is the outcome?

```c
class Shared {
    int a;
    int b;
};

Shared::Thread1 () {
    a += b
}

Shared::Thread2 () {
    b += a
}

main () {
    Shared st;
    st.a = 1
    st.b = 2
    CreateThread (st.Thread1)
    CreateThread (st.Thread2)
    print (st.a, st.b)
}
```

- Prints (1,2) and quits
  - Need to wait for threads
  - Assuming this problem is fixed, what is the result?
Motivation

• Analyze the various execution paths
  - Two threads concurrently execute this:

  thread 1
  
  Shared::Thread1 ()
  1)  a += b

  thread 2
  
  Shared::Thread2 ()
  2)    b += a

• CPU trace:

  ver 1
  
  1)  a = 3, b = 2
  2)  a = 3, b = 5
  main prints (3,5)

  ver 2
  
  1)  a = 4, b = 3
  2)  a = 1, b = 3
  main prints (4,3)

  ver 3
  
  1) reads a,b into registers
  2) reads a,b into registers
  1) computes sum, saves a = 3
  2) computes sum, saves b = 3
  main prints (3,3)

  non-deterministic result that depends on who gets there first (race condition)

  unintended result (depends on compiler)

// initial state
st.a = 1
st.b = 2
Motivation

• How about the next example
  – Now both variables are modified, threads print their values

<table>
<thead>
<tr>
<th>thread 1</th>
<th>thread 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared::Thread1 ()</td>
<td>Shared::Thread2 ()</td>
</tr>
<tr>
<td>1) ( a += b )</td>
<td>4) ( a = 2*a + b )</td>
</tr>
<tr>
<td>2) ( b += a )</td>
<td>5) ( b = a + 2*b )</td>
</tr>
<tr>
<td>3) print ((a, b))</td>
<td>6) print ((a, b))</td>
</tr>
</tbody>
</table>

• CPU trace:

<table>
<thead>
<tr>
<th>ver 1</th>
<th>ver 2</th>
<th>ver 3</th>
<th>ver 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ( a = 3, b = 2 )</td>
<td>1) ( a = 3, b = 2 )</td>
<td>1) ( a = 3, b = 2 )</td>
<td>1) ( a = 3, b = 2 )</td>
</tr>
<tr>
<td>2) ( a = 3, b = 5 )</td>
<td>4) ( a = 8, b = 2 )</td>
<td>2) ( a = 3, b = 5 )</td>
<td>4) ( a = 8, b = 2 )</td>
</tr>
<tr>
<td>3) prints ((3,5))</td>
<td>2) ( a = 8, b = 10 )</td>
<td>4) ( a = 11, b = 5 )</td>
<td>2) ( a = 8, b = 10 )</td>
</tr>
<tr>
<td>4) ( a = 11, b = 5 )</td>
<td>5) ( a = 8, b = 28 )</td>
<td>5) ( a = 11, b = 21 )</td>
<td>3) prints ((8,10))</td>
</tr>
<tr>
<td>5) ( a = 11, b = 21 )</td>
<td>3) prints ((8,28))</td>
<td>3) prints ((11,21))</td>
<td>5) ( a = 8, b = 28 )</td>
</tr>
<tr>
<td>6) prints ((11,21))</td>
<td>6) prints ((8,28))</td>
<td>6) prints ((11,21))</td>
<td>6) prints ((8,28))</td>
</tr>
</tbody>
</table>
Motivation

- Example (cont’d)
  - How many possible execution traces?
  - Build an execution tree:

Generalization: for two threads with \( m \) and \( n \) instructions respectively, the number of possible ways to interleave them:

\[
\binom{m + n}{m}
\]

For \( m = n = 100 \), this is \( 10^{59} \)

symmetric subtree omitted

ver1

ver2

ver3

ver4
Motivation

• Actual tree is deeper since we have to consider each assembler-level instruction
  – Even most basic \( c = a + b \) may be implemented as 4 CPU instructions: load (reg1, a), load(reg2, b), add(reg1, reg2), store (c, reg1)
  – Also could be load(reg, a), add(reg, b), store (c, reg)

• Because of this, synchronization bugs may be compiler-specific
  – Some may only appear in debug or release mode

• Conclusion: proper synchronization is mandatory for access to shared memory

• However, not all access needs protection
  – Required only if data is modified by at least one thread
**Terminology**

- **Critical section**
  - Piece of code that is sensitive to concurrent events in other threads

- **Critical sections require synchronization to exclude other threads from damaging data**

- **Atomic operation**
  - Set of instructions that cannot be interrupted by another thread

- **Single CPU instruction is always atomic**
  - Is the code above safe?

- **Nope, L2/L3 cache coherency problems on multi-core platforms**
  - Result unpredictable

- **Also, compiler may split this into multiple instructions**
  - Possible in debug mode

- **Deadlock**
  - Infinite wait for events or some conditions
Deadlock Illustrated
**Terminology**

- **Livelock**
  - Non-stop activity that typically changes *shared state*, but makes no progress
  - Unlike deadlock, which makes no change to shared variables
- **Elevator example:**
  - Every time a button is pressed, elevator responds by moving towards the floor where it was pressed
  - New button commands *preempt* old ones
  - Selfish customers
Terminology

• Mutual exclusion (mutex)
  - Data structure that allows only one thread in its critical section at one time

• Multiple critical sections within a thread possible

• Race condition
  - Situation where the outcome depends on the order of thread execution
  - Hw1-part3: robots race to find the exit; found solution is non-deterministic
  - Sometimes acceptable

• Busy-spinning
  - A while loop that tests variable(s) until some condition is reached
  - Not used often in user space, but parts of the kernel rely on it

• Work starvation
  - Certain threads are under-utilized (ready to run, but no work)
Terminology

- **Work starvation (cont’d)**
  - Caused by unbalanced job partitioning or OS scheduler giving less CPU time to certain threads
- **Assuming the OS is well-designed, only the former issue is of concern**
- **Examples**
  - Hw1-part3: one thread deposits new rooms in the queue, then immediately grabs them all back for exploration

- Threads sort keys concurrently, where thread i gets keys whose upper k bits are i
- **Does this search loop require a mutex:**
  ```
  while (exit not found)
  x = U.pop();
  Explore(x);
  ```
- **Yes since U.pop() modifies the underlying data structure**
- **Should Explore(x) be inside a mutex?**