Concurrency and Synchronization

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Slides are adapted from Brian Rogers (Duke)
Concurrency

- **Multiprogramming**
  - Supported by most all current operating systems
  - More than one “unit of execution” at a time

- **Uniprogramming**
  - A characteristic of early operating systems, e.g. MS/DOS
  - Easier to design; no concurrency

- What do we mean by a “unit of execution”?
• **Process** vs. Thread


- **Process** is –
  - Execution context
    - Program counter (PC)
    - Stack pointer (SP)
    - Registers
  - Code
  - Data
  - Stack
  - Separate memory views provided by virtual memory abstraction *(page table)*
Process vs. Thread

- **Process vs. Thread**

- A thread is –
  - Execution context
    - Program counter (PC)
    - Stack pointer (SP)
    - Registers
Process vs. Thread

- **Process**: unit of allocation
  - resources, privileges, etc.
- **Thread**: unit of execution
  - PC, SP, registers
- Thread is a unit of control within a process
- Every process has one or more threads
- Every thread belongs to one process
Process Execution

- When we execute a program
  - OS creates a process
  - Contains code, data
  - OS manages process until it terminates
    - We will talk more later about process management (e.g. scheduling, system calls, etc.)

- Every process contains certain information
  - Process ID number (PID)
  - Process state (‘ready’, ‘waiting for IO’, etc. – for scheduling purposes)
  - Program counter, stack pointer, CPU registers
  - Memory management info, files, I/O
Process Execution (2)

• A process is created by the OS via system calls
  • fork(): make exact copy of this process and run
    • Forms parent/child relationship between old/new process
    • Return value of fork indicates the difference
    • Child returns 0; parent returns child’s PID
  • exec(): can follow fork() to run a different program
    • Exec takes filename for program binary from disk
    • Loads new program into the current process’s memory

• A process may also create & start execution of threads
  • Many ways to do this
  • System call: clone(); Library call: pthread_create()
Back to Concurrency…

- We have multiple units of execution, but single resources
  - CPU, physical memory, IO devices
  - Developers write programs as if they have exclusive access

- OS provides illusion of isolated machine access
  - Coordinates access and activity on the resources
How Does the OS Manage?

- Illusion of multiple processors
  - Multiplex threads in time on the CPU
  - Each virtual “CPU” needs a structure to hold:
    - Program Counter (PC), Stack Pointer (SP)
    - Registers (Integer, Floating point, others...?)
- How switch from one CPU to the next?
  - Save PC, SP, and registers in current state block
  - Load PC, SP, and registers from new state block
- What triggers switch?
  - Timer, voluntary yield, I/O, other things
- We will talk about other management later in the course
  - Memory protection, IO, process scheduling
Concurrent Program

• Two or more threads execute concurrently
  • Many ways this may occur...
  • Multiple threads time-slice on 1 CPU with 1 hardware thread
  • Multiple threads at same time on 1 CPU with \( n \) HW threads
    • Simultaneous multi-threading (e.g. Intel “Hyperthreading”)
  • Multiple threads at same time on \( m \) CPUs with \( n \) HW threads
    • Chip multi-processor (CMP, commonly called “multicore”) or
      Symmetric multi-processor (SMP)

• Cooperate to perform a task

• How do threads communicate?
  • Recall they share a process context
    • Code, static data, heap
  • Can read and write the same memory
    • variables, arrays, structures, etc.
Motivation for a Problem

• What if two threads want to add 1 to shared variable?
  • x is initialized to 0

```c
x = x + 1;
```

May get compiled into:

(x is at mem location 0x8000)

```
lw r1, 0(0x8000)
addi r1, r1, 1
sw r1, 0(0x8000)
```

• A possible interleaving:

```
P1
lw r1, 0(0x8000)
addi r1, r1, 1
sw r1, 0(0x8000)
```

```
P2
lw r1, 0(0x8000)
addi r1, r1, 1
sw r1, 0(0x8000)
```

• At the end, x will have a value of 1 in memory!! 😞
Another Example – Linked List

Insert at head of linked list:
```
Node new_node = new Node();
new_node->data = rand();
new_node->next = head;
head = new_node;
```

- Two concurrent threads (A & B) want to add a new element to list
  1. A executes first three instructions & stalls for some reason (e.g. cache miss)
  2. B executes all 4 instructions
  3. A eventually continues and executes 4th instruction
     - Item added by thread B is lost!
Race Conditions

- These example problems occur due to race conditions.
- Race Condition
  - Result of computation by concurrent threads depends on the precise timing of the execution of an instruction sequence by one thread relative to another.
- Sometimes result may be correct, sometimes incorrect
  - Depends on execution timing
  - Non-deterministic result
- Need to avoid race conditions
  - Programmer must control possible execution interleaving of threads.
How to **NOT** fix race conditions

- Here’s what you should NOT do:
  - “If I just wait long enough, the other thread will finish, so I’ll add a sleep() call or some other delay”

- This doesn’t FIX the problem, it just HIDES the problem (worse!)

- Can mask the majority of timing delays, which are short, but the bug will just hide until an unlikely timing event occurs, and BAM! The bug kills someone.
Mutual Exclusion

- Previous examples show problem of multiple processes or threads performing read/write ops on shared data
  - Shared data = variables, array locations, objects
- Need mutual exclusion!
  - Enforce that only one thread at a time in a code section
  - This section is also called a *critical section*
  - Critical section is set of operations we want to execute *atomically*
- Provided by lock operations:
  
  ```
  lock(x_lock);
  x = x + 1;
  unlock(x_lock);
  ```
- Also note: this isn’t only an issue on parallel machines
  - Think about multiple threads time-sharing a single processor
  - What if a thread is interrupted after load/add but before store?
Mutual Exclusion

- Interleaving with proper use of locks (mutex)

P1

lock(x_lock)
ldw r1, 0(8000)
addi r1, r1, 1
stw r1, 0(8000)
unlock(x_lock)

P2

lock(x_lock)
ldw r1, 0(8000)
addi r1, r1, 1
stw r1, 0(8000)
unlock(x_lock)

- At the end, x will have a value of 2 in memory 😊
Global Event Synchronization

- BARRIER (name, nprocs)
  - Thread will wait at barrier call until nprocs threads arrive
  - Built using lower level primitives
  - Separate phases of computation

- Example use:
  - N threads are adding elements of an array into a sum
  - Main thread is to print sum
  - Barrier prevents main thread from printing sum too early

- Use barrier synchronization only as needed
  - Heavyweight operation from performance perspective
  - Exposes load imbalance in threads leading up to a barrier
Point-to-point Event Synchronization

- A thread notifies another thread so it can proceed
  - E.g. when some event has happened
  - Typical in producer-consumer behavior
  - Concurrent programming on uniprocessors: semaphores
  - Shared memory parallel programs: semaphores or monitors or variable flags

flag

<table>
<thead>
<tr>
<th>P0:</th>
<th>P1:</th>
</tr>
</thead>
</table>
| S1: datum = 5; | S3: while (!datumIsReady) {};
| S2: datumIsReady = 1; | S4: print datum

monitor

<table>
<thead>
<tr>
<th>P0:</th>
<th>P1:</th>
</tr>
</thead>
</table>
| S1: datum = 5; | S3: wait(ready);
| S2: signal(ready); | S4: print datum |
Lower Level Understanding

- How are these synchronization operations implemented?
  - Mutexes, monitors, barriers
- An attempt at mutex (lock) implementation

```c
void lock (int *lockvar) {
    while (*lockvar == 1) {} ;  // wait until released
    *lockvar = 1;               // acquire lock
}

void unlock (int *lockvar) {
    *lockvar = 0;
}
```

In machine language, it looks like this:

```asm
lock:  ld  R1, &lockvar       // R1 = lockvar
       bnz R1, lock          // jump to lock if R1 != 0
       st  &lockvar, #1     // lockvar = 1
       ret                   // return to caller

unlock: st  &lockvar, #0    // lockvar = 0
        ret                 // return to caller
```
Problem

- Unfortunately, this attempted solution is incorrect
- The sequence of \texttt{ld}, \texttt{bnz}, and \texttt{sti} are not atomic
  - Several threads may be executing it at the same time
- It allows several threads to enter the critical section simultaneously
Software-only Solutions

• Peterson’s Algorithm (mutual exclusion for 2 threads)

```c
int turn;
int interested[n]; // initialized to 0

void lock (int process, int lvar) {     // process is 0 or 1
    int other = 1 - process;
    interested[process] = TRUE;
    turn = process;
    while (turn == process && interested[other] == TRUE) {};
}

void unlock (int process, int lvar) {
    interested[process] = FALSE;
}
```

• Exit from lock() happens only if:
  • interested[other] == FALSE: either the other process has not competed for the lock, or it has just called unlock()
  • turn != process: the other process is competing, has set the turn to itself, and will be blocked in the while() loop

NOTE: This is more of a curiosity than a commonly deployed technique. We use hardware support (see next slide). This technique can be useful if hardware support isn’t available (rare).
Help From Hardware

• Software-only solutions have drawbacks
  • Tricky to implement – think about more than 2 threads
  • Need to consider different solutions for different memory consistency models

• Most processors provide atomic operations
  • E.g. Test-and-set, compare-and-swap, fetch-and-increment
  • Provide atomic processing for a set of steps, such as
    • Read a location, capture its value, write a new value
  • Test-and-set
    • Instruction supported by HW
    • Write to a memory location and return its old value as a single atomic operation
Multi-threaded Programming

• How can we create multiple threads within a program?
  • Multiple ways across programming languages
  • E.g. C: pthreads,  C++: std::thread or boost::thread

• What will the threads execute?
  • Typically spawned to execute a specific function

• What is shared vs. private per thread?
  • Recall address space
  • Thread-local storage
Programming with Pthreads

- POSIX pthreads
  - Found on most all modern POSIX-compliant OS
  - Also Windows implementations
  - Allows a process to create, spawn, and manage threads

- How to use it:
  - Add `#include <pthread.h>` to your C source code
  - When compiling with gcc, add `-lthreads` to your list of libraries
    - `gcc -o p_test p_test.c -lpthread`
  - Instrument the code with pthread function calls to:
    - Create threads
    - Wait for threads to complete
    - Destroy threads
    - Synchronize across threads
    - Protect critical sections
Pthread Thread Creation

• Create a pthread:

```c
int pthread_create(
    pthread_t* thread,
    pthread_attr_t* attr,
    void *(*start_routine)(void *),
    void* arg);
```

• Arguments:
  • `pthread_t *thread_name` – thread object (contains thread ID)
  • `pthread_attr_t *attr` – attributes to apply to this thread
  • `void *(*start_routine)(void *)` – pointer to function to execute
  • `void *arg` – arguments to pass to above function

Example:

```c
pthread_t *thrd;
pthread_create(thrd, NULL, &do_work_fcn, NULL);
```
Pthread Destruction

\texttt{pthread_join}(\texttt{pthread_t} \texttt{thread}, \texttt{void**} \texttt{value_ptr})

- Suspends the calling thread
- Waits for successful termination of the specified thread
- \texttt{value_ptr} is optional data passed from terminating thread’s exit

\texttt{pthread_exit}(\texttt{void \*value_ptr})

- Terminates a thread
- Provides \texttt{value_ptr} to any pending \texttt{pthread_join()} call
Pthread Mutex

```
pthread_mutex_t lock;
```

- **Initialize a mutex; 2 ways:**
  - `int pthread_mutex_init(
    pthread_mutex_t* mutex,
    const pthread_mutexattr_t* mutex_attr);
  - `pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;`
    - Initialized with default pthread mutex attributes
    - This is typically good enough

- **Operate on the lock:**
  - `int pthread_mutex_lock(pthread_mutex_t* mutex);`
  - `int pthread_mutex_trylock(pthread_mutex_t* mutex);`
  - `int pthread_mutex_unlock(pthread_mutex_t* mutex);`
Read/Write Locks

• Declaration
  • `pthread_rwlock_t x = PTHREAD_RWLOCK_INITIALIZER;`

• Operations
  • Acquire Read Lock: `pthread_rwlock_rdlock(&x);`
  • Acquire Write Lock: `pthread_rwlock_wrlock(&x);`
  • Unlock Read/Write Lock: `pthread_rwlock_unlock(&x);`
  • Destroy: `pthread_rwlock_destroy(&x);`
Read/Write Lock Behavior

• Lock has 3 states: unlocked, read locked, write locked

`pthread_rwlock_rdlock(&x)`

• If state = unlocked: thread proceeds & state becomes read locked
• If state = read locked: thread proceeds & state remains read locked
  • Internally a counter increments to track # of readers
• If state = write locked: thread blocks until state becomes unlocked
  • Then state becomes read locked

`pthread_rwlock_wrlock(&x)`

• If state = unlocked: thread proceeds & state becomes wr locked
• If state = read locked or state = write locked
  • Thread blocks until state becomes unlocked
  • State becomes write locked
Common read/write lock pattern

- A common need:
  - Find a thing X, then modify X
  - Want to allow multiple threads to do their own searches for X, then modify

- Possible approaches that are bad:

  - Solution:

    ```c
    while (1) {
      rdlock()
      x = do_search()
      unlock()
      wrlock()
      if (*x has become 'wrong') continue;
      modify(&x)
      unlock()
      break;
    }
    ```

    FIX: Re-check once we have the write lock, re-do the search if our X got messed with (rare)
Pthread Barrier

```c
pthread_barrier_t barrier;

• Initialize a barrier; 2 ways:
  • int pthread_barrier_init(
      pthread_barrier_t* barrier,
      const pthread_barrierattr_t* barrier_attr,
      unsigned int count);

  • pthread_barrier_t barrier = PTHREAD_BARRIER_INITIALIZER(count);
    • Initialized with default pthread barrier attributes
    • This is typically good enough

• Operation on a barrier:
  int pthread_barrier_wait(pthread_barrier_t* barrier);
```
double **a, **b, **c;
int numThreads, matrixSize;

int main(int argc, char *argv[]) {
    int i, j;
    int *p;
    pthread_t *threads;

    // Initialize numThreads, matrixSize; allocate and init a/b/c matrices
    // ...

    // Allocate thread handles
    threads = (pthread_t *) malloc(numThreads * sizeof(pthread_t));

    // Create threads
    for (i = 0; i < numThreads; i++) {
        p = (int *) malloc(sizeof(int));
        *p = i;
        
        pthread_create(&threads[i], NULL, worker, (void *)(p));
    }

    for (i = 0; i < numThreads; i++) {
        pthread_join(threads[i], NULL);
    }

    printMatrix(c);
}
void mm(int myId) {
    int i, j, k;
    double sum;
    // compute bounds for this thread
    int startrow = myId * matrixSize/numThreads;
    int endrow = (myId+1) * (matrixSize/numThreads) - 1;

    // matrix mult over the strip of rows for this thread
    for (i = startrow; i <= endrow; i++) {
        for (j = 0; j < matrixSize; j++) {
            sum = 0.0;
            for (k = 0; k < matrixSize; k++) {
                sum = sum + a[i][k] * b[k][j];
            }
            c[i][j] = sum;
        }
    }
}

void* worker(void* arg) {
    int id = *((int*) arg);
    mm(id);
    return NULL;
}
C++ Threads

-Introduced in C++11
-Support for similar features as pthreads
  -Create threads
  -Wait for threads to complete
  -Various synchronization

-Look at in-class example code
Thread Local Storage

- Mechanism to allocate variables such that there is 1 per thread
  - Can be applied to variable declarations that would normally be shared
    - E.g. global data, static data members, etc.
  - Indicated with the __thread keyword:
    - E.g. __thread int x = 0;
C++ Synchronization

- **Mutex locks for enforcing critical sections**

```cpp
#include <mutex>

std::mutex mtx;

mtx.lock();  // also mtx.try_lock() is available
//critical section
mtx.unlock();
```

- **Barriers: use** `boost::barrier`