CSCI-GA.3033-017

Special Topics:
Multicore Programming

Lecture 5

Threads and Pthreads II

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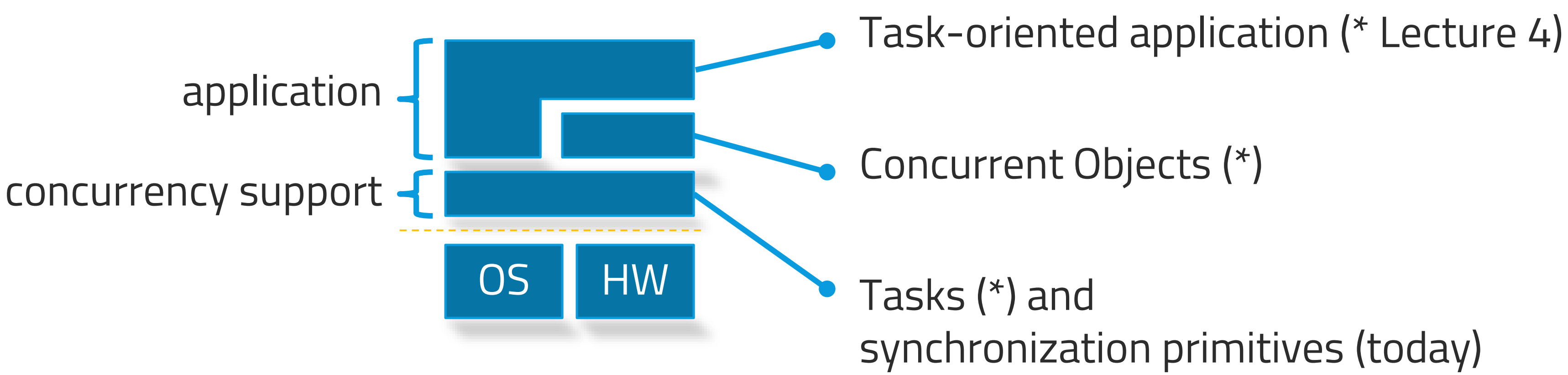
Context

- We’re exploring the layers of an application running on top of multicore hardware.



Mutices | Semaphores | Cond Vars

Today's Agenda

- Add the grader; email both of us your commit hashes
  - Github: Nitesh (Github account: nits3392)
  - Email: ns3664@nyu.edu
- Concrete Pthread Creation
- A Simple Mutual Exclusion Algorithm
- Semaphores and "Blocking" Mutices
- Condition Variables and the Wakeup Problem

Concrete Pthread Creation

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 4

void *printHello(void *thread_id) {
      size_t tid = (size_t)thread_id;
      printf("Hello World! It's me, thread #%ld!\n", tid);
      pthread_exit(NULL);
}

int main(int argc, char *argv[]) {
      pthread_t threads[NUM_THREADS];
      for(size_t t = 0; t < NUM_THREADS; t++) {
            printf("In main: creating thread %ld\n", t);
            int rval = 0;
            if (0 != (rval = pthread_create(&threads[t], NULL,
                  printHello, (void *)t))) {
                  fprintf(stderr, "ERROR; return code from pthread_create() is %d\n", rval);
                  break;
            }
            pthread_detach(threads[t]);
      }

      pthread_exit(NULL);
      return 0;
}
```

Understanding Mutices

- The literature on mutual exclusion algorithms is extensive
- In practice, mutual exclusion is implemented with some form of hardware and OS support (coming soon!)
- But we'll first develop our algorithmic and correctness evaluation skills by looking at some very elegant solutions that use only shared memory

Understanding Mutices: Review

- Mutual exclusion algorithms will provide two methods, `lock()` and `unlock()`, that allow us to mark the beginning and the end of critical sections in out code.
  - `lock()` will block the caller until there is no other thread in the critical section
  - `unlock()` would allow other thread in the critical section if there's one waiting

Peterson's Algorithm

- Mutual exclusion solution in "three" lines of code.

```
int  victim;
bool flag[2] = { false, false };
```

Current State

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 – me
  1 flag[me] = true
  2 victim = me
  3 while (flag[other] &&
             victim == me) {
        no-op;
    }
}
```

```
void unlock(void) {
    int me = my_tid % 2
    flag[me] = false
}
```

Uncontested Case

- Solved in two simple tests and no wait.

```
int  victim = 0;
bool flag[2] = { true, false };
```

Current State

Thread 0

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 - me
    flag[me] = true
    victim = me
    while (flag[other] &&
           victim == me) {
        no-op;
    }
}
```

```
void unlock(void) {
    int me = my_tid % 2
    flag[me] = false
}
```

Contested Case

- Thread 1 will busy-wait until Thread 0 executes unlock

```
int  victim  = 1;
bool flag[2] = { true, true };
```

Current State

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 – me
    flag[me] = true
    victim = me
    while (flag[other] &&
           victim == me) {
        no-op;
    }
}
```

Thread 1

loop

```
void unlock(void) {
    int me = my_tid % 2
    flag[me] = false
}
```

Thread 0

Simultaneous Case

- Assumes both cannot write to same mem addr at once.

```
int  victim  = ?;
bool flag[2] = { true, true };
```

Current State

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 - me
    flag[me] = true
    victim = me
    while (flag[other] &&
           victim == me) {
        no-op;
    }
}
```

```
void unlock(void) {
    int me = my_tid % 2
    flag[me] = false
}
```

Analyzing Peterson's Algorithm

- Three criteria
  1. Mutual exclusion
  2. Progress (no deadlock)
  3. Bounded waiting (fairness)

Analyzing Peterson's Algorithm

- Does Peterson's Algorithm guarantee mutual exclusion?
- Assume that both threads could pass the tests:

```
while (flag[other] && victim == me)
```

- This would have meant that each would have set the victim to be itself and each would have seen the victim as the other thread
- Is this possible?

Analyzing Peterson's Algorithm

- Is it starvation free? Fair?
- If a thread `unlock()`s then it would set victim to be itself
- The contenting thread would have the chance to pass `lock()` then.
- Now, nothing prevents the `unlock()` thread from going ahead and trying a `lock()` again.
  - But in that case, that thread changes the victim to be itself before getting in the loop.

Deadlock on Simultaneous Case

- Using flag[] alone doesn't work
- Could it be simpler? Instead of flag[] and victim, let's have one or the other

```
bool flag[2] = { true, true };
```

Current State

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 - me
    flag[me] = true
    while (flag[other]) {
        no-op;
    }
}
```

```
void unlock(void) {
    int me = my_tid % 2
    flag[me] = false
}
```

Deadlock on the Uncontested Case

- Peterson’ s is as simple as it gets.
- Now with ‘victim’ only

```
int victim;
```

Current State

```
void lock(void) {
    int me = my_tid % 2
    int other = 1 - me
    victim = true
    while (flag[other]) {
        no-op;
    }
}
```

```
void unlock(void)
```

Observations

- We'll be using the reasoning we developed here in other algorithms.
- Peterson's lock is important because it was arguably the first one to show 2-thread mutual exclusion can be solved in a simple way
- It makes several assumptions, though, and these turn out not to be so in practice
  - Number of threads is known *a priori*
  - Program execution is strictly sequential and each instruction is atomic
- The algorithm uses busy waiting

Semaphores

- Invented by Edsger Dijkstra in 1968.
- A synchronization primitive that enables waiting without busy-wait
- A semaphore has an initial value, usually 1 (binary semaphore), and two operations: `up()` and `down()`
- There are some differences on that interface in practice (and some flavors of interface)
  - We'll reason using up/down

Semaphores

- `down()`
  - Atomically check that value is greater than 0 and decrement it, allowing the thread to continue
  - Otherwise, suspend the thread, waiting on the counter value to be greater than 0
- `up()`
  - Atomically increment the counter.

Exercise: Semaphor-Based Mutex

- Required methods: `lock()` and `unlock()`
- Assume unlocking an unlocked mutex is okay
  - ie, handle this case properly
  - Without needing to handle this, we can use a single semaphore initially set to 1 as a mutex!
- Semaphores are powerful!

Semaphore-Based "Blocking" Mutex

```
S: private semaphore, initial count 1
locked: Boolean, initially false
holder: thread ID
M: private semaphore, initial count 1
```

```
void lock(void) {
    M.down();
    S.down(); // Critical v
    locked = true;
    holder = self();
    S.up();   // Critical ^
}
```

```
void unlock(void) {
    S.down(); // Critical v
    if (!locked ||
        holder != self()) {
        S.up();
        return;
    }
    locked = false;
    S.up();   // Critical ^
    M.up();
}
```

Semaphore-Based "Blocking" Mutex

- Starvation free!
  - `lock()` can block at `M.down()`, but only until `unlock()`
  - Nothing can prevent `unlock()`

```
void lock(void) {
    M.down();
    S.down(); // Critical v
    locked = true;
    holder = self();
    S.up();   // Critical ^
}
```

```
void unlock(void) {
    S.down(); // Critical v
    if (!locked ||
        holder != self()) {
        S.up();
        return;
    }
    locked = false;
    S.up();   // Critical ^
    M.up();
}
```

Semaphore-Based "Blocking" Mutex

- Deadlock free!
  - S protects the critical sections, never left locked.
  - No cycles

```
void lock(void) {
    M.down();
    S.down(); // Critical v
    locked = true;
    holder = self();
    S.up();   // Critical ^
}
```

```
void unlock(void) {
    S.down(); // Critical v
    if (!locked ||
        holder != self()) {
        S.up();
        return;
    }
    locked = false;
    S.up();   // Critical ^
    M.up();
}
```

Semaphore Considerations

- In order to sleep instead of busy wait, need to call the OS
  - But if at each semaphore operation we incur one system call, doing synchronization may be expensive
  - “Ideal” mutex (“blocking”)
    - Use shared memory to store the state of the lock
    - Uncontended case requires access to memory only
    - In contended case, ask OS to sleep until value of shared memory changes
- Reasoning about semaphore algorithms can be daunting.

Condition Variable Semantics

- Allows a thread to wait on a given predicate to change
- Associated with a mutex that protects the predicate state
- Operations
  - `wait()` – atomatically suspends the execution of the thread and unlock the associated mutex
  - `signal()` – if there's at least one thread suspended on the cond var, then dequeue it and resume execution, again, atomically
  - `broadcast()` – if there are any threads suspended on the cond var, resume execution for all of them. They'll contend for the associated lock.

Implementing wait() and signal()

- `wait()` is always inside a loop that checks the predicate
  - Easier to implement in terms of thread scheduling
  - Allows signal on every predicate change
- `signal()` should be done inside the lock (although it might be correct to do so outside)

```
element dequeue()
    pthread_muex_lock(queue_lock)
    …
    while (empty) {
        pthread_cond_wait(cond, queue_lock)
    }
    // !empty
    …
```

```
enqueue(element)
    pthread_mutex_lock(queue_lock)
    …
    empty = false
    pthread_cond_signal(cond)
    …
```

Fair Condition Variables Using Semaphores

- Reported by Andrew Birrell in 1993[1]

```
cond has: a queue of waiters and a semaphore
thread has: a private semaphore with initial count 0
```

```
wait(cond, mutex) {
    // assumes mutex held
    // assumes cond is false
    Thread self = Thread.self()
    cond.sem.down()
    enqueue(self) on cond's queue
    cond.sem.up()
    release mutex
    self.sem.down()
    acquire mutex
}
```

```
signal(cond) {
    // assumes mutex held
    cond.sem.down()
    if a thread t is waiting {
        dequeue(t)
        t.sem.up()
    }
    cond.sem.up()
}
```

[1] https://birrell.org/andrew/papers/ImplementingCVs.pdf

Fair Condition Variables Using Semaphores

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```
cond has: a queue of waiters and a semaphore
thread has: a private semaphore with initial count 0
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wait(cond, mutex) {
    // assumes mutex held
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    Thread self = Thread.self()
    cond.sem.down()
    enqueue(self) on cond's queue
    cond.sem.up()
    release mutex
    self.sem.down()
    acquire mutex
}
```

```
signal(cond) {
    // assumes mutex held
    cond.sem.down()
    if a thread t is waiting {
        dequeue(t)
        t.sem.up()
    }
    cond.sem.up()
}
```

Equivalent to atomically releasing the lock and going to sleep. What if t.sem.up() runs before self.sem.down()? What could happen if we released the mutex lock earlier?

Lost Wakeup Race Condition

- A deadly (and common) mistake

```
wait(cond, mutex)
    // assumes mutex held
    // assumes cond is false
    release mutex
    Thread self = Thread.self()
    cond.sem.down()
    enqueue(self) on cond's queue
    cond.sem.up()
    self.sem.down()
    acquire mutex
```

```
signal(cond)
    // assumes mutex held
    cond.sem.down()
    if a thread t is waiting
        dequeue(t)
        t.sem.up()
    cond.sem.up()
```

Conclusion

- Mutices: How can we build our own?
- Semaphores: Making mutices, working with the OS
- Cond Vars: Implementation gotchas

- Lab 1: Questions? Problems?