Lecture 6
Parallel Programming Primitives

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Lecture 6 Outline

➢ Thread execution model
➢ Parallel programming primitives
➢ A simple concurrent queue
➢ At last: Lab 1
Explicit Parallelism Review

• MIMD: Multiple Instruction, Multiple Data (Flynn’s taxonomy)

• Pipelining parallelism on the granularity of instructions, even in sequential code

• Programmers’ responsibility: task/thread/process parallelism
Review: Multicore Programming Tenets

• Keep all the cores busy
  • Break down a problem in **smaller tasks**
  • Perform tasks as independently as possible or with **little synchronization**
  • Always try to **reduce** the number and duration of **sequential** (non-parallelizable) **tasks**

• Your code would only go as fast as the duration of your sequential tasks

• Your code would scale with the number of cores to the proportion of its parallelizable tasks (Amdhal’s law)

Easier said than done... Let’s try it.
Making Programming Models Concrete

- Programming models should
  1. Start/stop tasks
  2. Allow tasks to communicate
  3. Synchronize tasks
  4. Schedule tasks
Starting/Stopping Tasks

• Language support to identify concurrent tasks
  • Processes
  • Fork/Join
  • Co-routines
  • *(Others too numerous to mention)*
Cobegin/Coend

- Marks a portion of where several "threads" of execution are allowed

- Example: OpenMP

```c
#pragma omp parallel for
for(int i = 0; i < n; i++) {
    c[i] = a[i] + b[i];
}
```
Coroutines

- For concurrency (and possibly parallelism)
- Execute part of a task
- Control transfer granularity

C++ (Boost) Example:

```cpp
#include <boost/coroutine/all.hpp>
using namespace boost::coroutines;

coro(coroutine<void>::yield_type &yield) {
    printf("Exec 1\n");
    yield();
    printf("Exec 3\n");
}

int main(int argc, char* argv[]) {
    coroutine<void>::yield_type routine{coro};
    printf("Exec 2\n");
    routine();
    printf("Exec 4\n");
}
```
Fork/Join

- Any task can start another task at any point
- Parent and child execute concurrently (and possibly in parallel)
- Parent may or may not wait for child to finish
- Examples
  - Unix processes
  - POSIX threads
Communication and Synchronization

• Synchronization goals
  • To delay processing until certain conditions hold
  • To guarantee that a block of code behaves as if it were executed atomically

• Message passing
  • Asynchronous communication

• Shared memory
  • Coordinating access...
Message Passing

- Asynchronous inter-task communication
- Channels: Go example (thanks to Prof. Lerner)

```go
func pump(ch chan int) {
    for i:=0; ; i++ {
        ch <- i
    }
}

ch1 := make(chan int)
go pump(ch1)
fmt.Println(<- ch1)  // prints 0

func sink(ch chan int) {
    for{ fmt.Println(<- ch) }
go sink(ch1)  // prints continuously
```
Shared Memory

- Communication via shared state
  - Same effective coordination as message passing, achieved differently
  - Main difference: multiple tasks can manipulate same state

- Synchronization primitives (coming momentarily)
Threads
Threads

- Fork/join, shared memory model
- No consensus on whether this is optimal abstraction
  - Writing correct threaded programs is hard
  - Current hardware actually “understands” threads
  - Arguably, this model is where other higher level abstractions would be layered
- This has been ongoing research (for a while) and we’ll have a chance to explore other models later in the course
Background: Hardware “Contexts”

- Context: thread’s current state
  - PC
  - Stack
  - Registers/flags
  - Memory map
- Threads share address space, but have local context
Sequential Execution Model

A single flow of instructions at any point in time. (This was not exactly always true, e.g., signals...)

```c
func() {
    ...
    foo(arg)
    ...
    bar(arg)
    ...
    return
}
```
Several flow of instructions at any point in time. How independent are they?

```c
func() {
  ...
  start thread foo
  ...
  start thread bar
  ...
  join threads
}
```

```
func()

foo()

bar()
```
• Each thread executes independently of the others
• Therefore, several threads could be executing the very same instruction of the code
• But each thread has its own stack (remember how functions call work?)

```c
void foo(int arg) {
    int a;
    if (arg < 10)
        a = 1;
    else
        a = arg;
    ...
    ... access a ...
    return
}
```
Thread Execution Model

But all threads share the same address space.

```
int b = 3;
bar(arg) {
    int a;
    ...
    a = b;
    ...
}
```
But all threads share the same address space.
Thread Execution Model: Data Races

• What if two threads want to change a process variable?

• Rule of thumb: if it is not a local variable, do assume others may change it

• Simultaneous accesses may occur and have unpredictable results

```c
int b = 3;
bar(arg) {
    int a;
    ...
    a = b;
    b += arg;
}
```
Critical Sections

- We need a **mutual exclusion** mechanism.

- At most one thread can execute inside each critical section at any point in time.

```c
int b = 3;
bar(arg) {
    int a;
    ...
    enter_crit_section
    a = b;
    b += arg
    leave_crit_section
}
```
Locks

- Used to implement critical sections

- Lock
  - If no other thread is in the critical section, proceed
  - Otherwise, wait

- Unlock
  - Leave critical section
  - Allow another thread to enter, if one is waiting.

int b = 3;
bar(arg) {
  int a;
  ...
  lock
  a = b;
  b += arg
  unlock
}
Threading and Synchronization Gotchas

• Simultaneous access & data races
  • Guard with locks if shared

• Single-instruction atomicity
  • \( x += 1; \)
  • Lock around anything that must look atomic

• Data atomicity
  • `struct Foo a = struct Foo b;`

• Data-race-free programs ONLY!
In this course: Pthreads (POSIX Threads) or C++ threads
- Shared memory, shared file pointers: need explicit synchronization

- Create: `pthread_create()` or `std::thread t()`
- Join or detach: `pthread_join()`, `pthread_detach()` or `t.join()`, `t.detach()`;
- Exit: `pthread_exit()` or delete `t`
[P]threads Concepts: Mutices

- Mutex ("Mutual Exclusion"): `pthread_mutex()` or `std::mutex m`
- Lock that can be used for exclusive access to any shared resource(s)
- Programmer defines what is protected
  - Programmer responsible for locking/unlocking around access to protected resource
[P]threads Concepts: Mutices

- Using a mutex
  - `pthread_mutex_lock(mutex)` or `m.lock()`
  - Use shared resources
  - `pthread_mutex_unlock(mutex)` or `m.unlock()`
  - *Do not* use shared resource until lock is re-acquired
thread Concepts:
Condition Variables

- `pthread_cond()` or `std::condition_variable cv`
- Synchronization based on data values
- Always used with mutex
- Replaces:
  1. Lock mutex
  2. Check value of data
  3. Unlock mutex, repeat.
[P]thread Concepts: Semaphores

- Counting mutex: `sem_init()` or n/a!
- Atomically increase or decrease
- Sample use: communication management
  - `sem_post()` (atomically increment) when sending new message to receiver
  - `sem_wait()` (atomically decrement) to receive (or wait for) new message from sender
Building a Concurrent Queue
Building a Concurrent Queue

element dequeue():
    element = head.data
    head = head.next
    return element

enqueue(element):
    n = new node(element)
    tail.next = n
    tail = n
Building a Concurrent Queue

**element dequeue():**
- `pthread_lock(queue_lock)`
- `element = head.data`
- `head = head.next`
- `pthread_unlock(queue_lock)`
- `return element`

**enqueue(element):**
- `pthread_lock(queue_lock)`
- `n = new node(element)`
- `tail.next = n`
- `tail = n`
- `pthread_unlock(queue_lock)`

![Diagram showing dequeue and enqueue operations on a concurrent queue](image-url)
Invariants

• A way to reason about correctness.

• Queue consistency
  • To be consistent, a queue has to maintain certain properties throughout its lifetime
  • If the properties hold during the queue operations, then the queue is consistent

• What are the invariants that guarantee our queue consistency?
Handling the Empty Queue Case: Invariants

element dequeue():
   pthread_lock(queue_lock)
   while (empty):
      pthread_cond_wait(cond, queue_lock)

   // Inv: queue is not empty
   element = head.data
   head = head.next

   // Inv: either head=tail=NULL or !empty
   if head is NULL:
      tail = NULL
      empty = true

   pthread_unlock(queue_lock)
   return element

enqueue(element):
   pthread_lock(queue_lock)
   n = new node(element)
   if tail != NULL:
      tail.next = n
      tail = n
   if head == NULL:
      head = tail

   // Inv: either !empty or head=tail=NULL
   empty = false
   pthread_cond_signal(cond)
   pthread_unlock(queue_lock)
Concurrent Queue Design Details

• Why do we wait with the lock held? How can the signal code execute if signal is inside the lock?
  • 
  • 

• Why do we signal inside the lock?
  • 
  •
Concurrent Queue Design Details

• Why do we wait with the lock held? How can the signal code execute if signal is inside the lock?
  • The wait code releases the lock if the thread goes to sleep and the wakeup only proceeds if it manages to reacquire the lock.
  • If the lock was not held, by the time we got outside the while loop, the predicate the condition is on may not be true any more.

• Why do we signal inside the lock?
  • We don’t have to but it’s strongly suggested you do
  • What we must do is never to change the predicate outside the lock (data-race-free, right?)
Concurrent Queue Design Details

• Why did we signal at every enqueue? Isn’t our condition based on the queue being non-empty?
  •

• Can we allow enqueue/dequeue in parallel (e.g., by using two locks instead of one)?
  •
  •
Concurrent Queue Design Details

• Why did we signal at every enqueue? Isn’t our condition based on the queue being non-empty?
  • We’re waiting on every dequeue. Signal/wait here cannot “peek into” our predicate. Our code needs to make the checking of the predicate itself because of the semantics of cond vars.

• Can we allow enqueue/dequeue in parallel (e.g., by using two locks instead of one)?
  • No, enqueue and dequeue are sharing state
  • Yes, if we made them not share state (hint: use a sentinel)
Lab 1

• Semester-long (2.25-month) lab: building a threaded server capable of executing genetic algorithms, on top of thread-safe primitives

• Will test your abilities with:
  • Threads
  • Concurrent data structures
Lab 1

• Due: Thursday, June 27\textsuperscript{th}

• Create a multithreaded $O(1)$ key-value data structure and $O(1)$ queue data structure
  1. Create the (thread-safe) data structures
  2. Create fixed number of workers to service requests

• Preview
  • Lab 2: Build a thread pool and connect to a trivial genetic algorithm
  • Lab 3: Measure performance
  • Lab 4: Complete the system: a non-toy algorithm