CMSC 330: Organization of Programming Languages

Multithreading

Multiprocessors

- Description
  - Multiple processing units (multiprocessor)
  - From single microprocessor to large compute clusters
  - Can perform multiple tasks in parallel simultaneously

Intel Core 2 Quad 6600
32 processor Pentium Xeon
106K processor IBM BlueGene/L
Concurrency

- Important & pervasive topic in CS
- Currently covered in
  - CMSC 132 – object-oriented programming II
    - Java threads, data races, synchronization
  - CMSC 216 – low level programming / computer systems
    - C threads
  - CMSC 411/430 – architectures / compilers
    - Instruction level parallelism
  - CMSC 412 – operating systems
    - Concurrent processes
  - CMSC 424 – database design
    - Concurrent transactions
  - CMSC 433 – programming language technologies
    - Advanced synchronization and parallelization
  - CMSC 451 – algorithms
    - Parallel algorithms

Parallelizable Applications of Interest

- Knowledge discovery: mine and analyze massive amounts of distributed data
  - Discovering social networks
  - Real-time, highly-accurate common operating picture, on small, power-constrained devices
- Simulations (games?)
- Data processing
  - NLP, vision, rendering, in real-time
- Commodity applications
  - Parallel testing, compilation, typesetting, …
Computation Abstractions

A computer

Processes vs. Threads

Processes do not share data

Threads share data within a process
Scheduling

The schedulers do most of the heavy lifting.

But they don’t know the semantics of what the threads are actually doing.

So, What Is a Thread?

- **Fundamental unit of execution**
  - All programs have at least one thread (main)

- **Implementation view**
  - A program counter and a stack
  - Heap and static area are shared among all threads
Implementation View

- Per-thread stack and instruction pointer
  - Saved in memory when thread suspended
  - Put in hardware esp/eip when thread resumes

Programming Processes

- Process creation is expensive
  - Stack, heap, PC, code, OS state

- Highly scalable
  - Virtually unlimited

- Processes may reside on separate processors
  - Sharing memory typically too expensive

- Message-passing programming paradigm
  - I/O streams, sockets, network, files
  - Cooperation key to communication (send/recv)
Programming Threads

- Thread creation is inexpensive
  - Stack, program counter, scheduler state
- Traditionally, they don’t scale well (10s of threads)
  - Multicore architectures relax this limitation
- Threads reside on same physical processor
  - So memory sharing is cheap
- Shared-memory programming paradigm
  - Everything except thread local variables are shared
  - Threads communicate via shared data
  - Synchronization used to avoid data races

What Is the Big Deal About Threads?

- Conventional wisdom: threads are hard
- Main reason: non-determinism
  - Different threads execute at different speeds
  - This leads to unpredictable results
  - When you program with threads, you have to be ready for unexpected results
- The goal of the PL designer is to make this easier
Programming Languages & Threads

- **Old: libraries**
  - pthreads
  - Could use different libraries for different properties

- **New: primitives**
  - Java, Ruby, Ocaml
  - Can utilize special keywords, syntax
  - Not dependent on operating system

Which is better?

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**Example**

- x = 0 initially. Then these threads are executed:

  \[
  \begin{align*}
  &T1 \quad y = x; \\
  &x = y+1; \\
  &T2 \quad z = x; \\
  &x = z+2;
  \end{align*}
  \]

- What is the value of x afterward

  \[
  \begin{array}{c|c|c}
  \text{T1} & \text{T2} & \text{Value of x} \\
  \hline
  y = x; & z = x; & 3 \\
  x = y+1; & x = z+2; & 1 \\
  \hline
  \end{array}
  \]

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Data Races

- That was an example of a data race
  - Threads are “racing” to read, write x
  - The value of x depends on who “wins” (3, 1, 2)

- Languages rarely specify who wins data races
  - The outcome is nondeterministic

- So programmers restrict certain outcomes
  - Synchronization with locks, condition variables

- And they often mess up
  - Deadlocks, bugs that are hard to track down…

Thread API Concepts

- Thread management
  - Creating, killing, joining (waiting for) threads
  - Sleeping, yielding, prioritizing

- Synchronization
  - Controlling order of execution, visibility, atomicity
  - Locks: Can prevent data races, but watch out for deadlock!
  - Condition variables: supports communication between threads

- Most languages have similar APIs, details differ
Java – Creating Threads

- Thread.create(Runnable r)
  - Or subclass the Thread class
  - Java makes it hard to create threads that access local variables (since it does not have closures)

- In practice, there are better ways
  - Use thread pools, to separate the idea of creating a thread from creating a (Runnable) task
    - May have N threads execute M > N jobs

- We’ll stick with the simple idea here

Thread Creation Example

```java
public class MyT implements Runnable {
    public void run() {
        ...
        // particular work for this thread
    }
}

Thread t = new Thread(new MyT()); // create thread
t.start(); // begin running thread
...
// thread executing in parallel

// waits for thread to exit
```

CMSC 330
Locks

Language designers limit non-determinism by introducing concurrency-control constructs
  • Make some parts deterministic = more predictable
  • Trade-off: reducing concurrency can reduce performance

Common concurrency-control feature: locks
  • They “guard” shared resources that shouldn’t be accessed by more than one thread at a time

The gist
  • At most one owner at a time
  • If someone else owns it, you block
  • When you’re done with it, release ownership

Java Locks (1.4)

Objects each have an associated lock

Use `synchronized` keyword to acquire lock
  - Code blocks – `synchronized (o) { ... }` // lock for Object o
  - Methods – `synchronized foo() { ... }` // lock for this

Thread blocks when lock held
  - Thread returns when lock is finally acquired
  - May deadlock if threads try to acquire each other’s lock

Locks sometimes referred to as mutexes
Why Locks?

- #1 concern: prevent data races
- Patterns of use:
  - Enforce atomicity of shared data
    - Rule of thumb 1: You must hold a lock when accessing shared data
    - Rule of thumb 2: You must not release a lock until shared data is in a valid state
  - Overuse use of synchronization can create deadlock
    - Rule of thumb: No deadlock if only one lock
- Synchronization also used to ensure ordering and visibility
  - The last is due to memory models in modern arch’s

Synchronization Example (Java 1.4)

```java
public class Example extends Thread {
    private static int cnt = 0;
    static Object value = new Object();
    public void run() {
        synchronized (value) {
            int y = cnt;
            cnt = y + 1;
        }
    }
}
```

- **Value**, any Java object
- **Acquires** the lock associated w/ value; only succeeds if not held by another thread, otherwise blocks
- **Releases** the lock
**Producer / Consumer Problem**

- Suppose we are communicating with a shared variable
  - E.g., a fixed size buffer holding messages

- One thread **produces** input to the buffer
- One thread **consumes** data from the buffer

**Rules**
- Producer can’t add input to the buffer if it’s full
- Consumer can’t take input from the buffer if it’s empty

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**Producer / Consumer Idea**

- If buffer is partially full, producer or consumer can run
  
  producer  

  c   b   a  

  consumer

- If buffer is empty, only producer can run
  
  producer  

- If buffer is full, only consumer can run
  
  e   d   c   b   a  

  consumer
Broken Producer/Consumer Example

```java
boolean valueReady = false;
Object value;

void produce(object o) {
    synchronized (value) {
        while (valueReady)
            ;
        value = o;
        valueReady = true;
    }
}

Object consume() {
    synchronized (value) {
        while (!valueReady)
            ;
        Object o = value;
        valueReady = false;
return o;
    }
}

Threads wait with lock held – no way to make progress
```

Broken Producer/Consumer Example

```java
boolean valueReady = false;
Object value;

void produce(object o) {
    while (valueReady)
        ;
    synchronized (value) {
        value = o;
        valueReady = true;
    }
}

Object consume() {
    while (!valueReady)
        ;
    synchronized (value) {
        Object o = value;
        valueReady = false;
        return o;
    }
}

valueReady accessed without a lock held – data race
```
Inefficient Producer/Consumer Example

```java
boolean valueReady = false;
Object value;

void produce(Object o) {
    boolean done = false;
    while (!done) {
        synchronized (value) {
            if (!valueReady) {
                value = o;
                valueReady = true;
                done = true;
            }
        }
    }
}

Object consume() {
    Object o = null;
    boolean done = false;
    while (!done) {
        synchronized (value) {
            if (valueReady) {
                o = value;
                valueReady = false;
                done = true;
            }
        }
    }
    return o;
}
```

Constantly acquiring / releasing lock — busy wait

Solving Producer / Consumer Problem

- Difficult to use locks directly
  - Very hard to get correct (or efficient) solution
  - Problems often very subtle
- Proper approach – use signaling
- Common signaling scenario
  1. You get the lock
  2. You realize it’s no good to you yet (buffer is empty)
  3. Go to sleep: “wake me up when there’s work to do”
- Virtually every threading model supports this
  - Condition variables
  - Wait / notify
**Condition Variables**

- Each condition variable represents those threads waiting for a condition to become true
  - Implemented, at least conceptually, as a wait set associated with the condition variable

- Since different threads access the variable at once, we must protect the wait set contents with a lock

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**Condition Variables in Java 1.4**

- Use `synchronize` on object to get associated lock

  ![Diagram of object o and its lock and wait set]

- Objects also have an associated condition variable (and thus a wait set)
Wait and NotifyAll

- `o.wait()`
  - Must hold lock associated with o
  - Release that lock
    - And no other locks
  - Adds this thread to wait set for lock
  - Blocks the thread

- `o.notifyAll()`
  - Must hold lock associated with o
  - Resumes all threads on lock’s wait set
  - Those threads must reacquire lock before continuing
    - This is part of the function; you don’t need to do it explicitly

Producer/Consumer Example

```java
boolean valueReady = false;
Object value;

void produce(Object o) {
    synchronized (value) {
        while (valueReady)
            wait();
        value = o;
        valueReady = true;
        notifyAll();
    }
}

Object consume() {
    synchronized (value) {
        while (!valueReady)
            wait();
        Object o = value;
        valueReady = false;
        notifyAll();
        return o;
    }
}
```
Using Conditions Correctly

- **wait() must** be called in a while loop
  - Conditions may not be met when await returns
  - Some other thread may have awoken first
    - And changed condition (e.g., consumed item in buffer)

- Avoid holding other locks when waiting
  - **wait()** only gives up lock on object you are waiting on
  - Reduces possibility of deadlock

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Broken Producer/Consumer Example

```java
boolean valueReady = false;
Object value;

void produce(Object o) {
    synchronized (value) {
        if (valueReady)
            wait();
        value = o;
        valueReady = true;
        notifyAll();
    }
}

Object consume() {
    synchronized (value) {
        if (!valueReady)
            wait();
        Object o = value;
        valueReady = false;
        notifyAll();
        return o;
    }
}

- Illegal access if multiple producers or consumers
```
Lock Interface (Java 1.5)

Interface Lock

```java
interface Lock {
    void lock();
    void unlock();
    ... /* Some more stuff, also */
}
```

class ReentrantLock implements Lock {
    ...
}

- **Explicit Lock objects**
  - Same as implicit lock used by synchronized keyword

- **Only one thread can hold a lock at once**
  - `lock()` causes thread to block (become suspended) until lock can be acquired
  - `unlock()` allows lock to be acquired by different thread

Synchronization Example (Java 1.5)

```java
public class Example extends Thread {
    private static int cnt = 0;
    static Lock lock = new ReentrantLock();
    public void run() {
        lock.lock();
        int y = cnt;
        cnt = y + 1;
        lock.unlock();
    }
}
```

**Lock**, for protecting the shared state

**Acquires** the lock; only succeeds if not held by another thread, otherwise blocks

**Releases** the lock
ReentrantLock Class (Java 1.5)

- Reentrant lock
  - Can be reacquired by same thread by invoking `lock()`
    - Up to 2147483648 times
  - To release lock, must invoke `unlock()`
    - The same number of times `lock()` was invoked

Reentrancy is useful
- Each method can acquire/release locks as necessary
  - No need to worry about whether callers already have locks
- Discourages complicated coding practices
  - To determine whether lock has already been acquired

```java
class ReentrantLock implements Lock {
    ...
}
```

Reentrant Lock Example

```java
static int count = 0;
static Lock l =
    new ReentrantLock();

void inc() {
    l.lock();
    count++;
    l.unlock();
}

void returnAndInc() {
    int temp;
    l.lock();
    temp = count;
    inc();
    l.unlock();
}
```

Example
- `returnAndInc()` can acquire lock and invoke `inc()`
- `inc()` can acquire lock without having to worry about whether thread already has lock
Condition Interface (Java 1.5)

```java
interface Lock {
    Condition newCondition();
    // ... other methods
}

interface Condition {
    void await();
    void signalAll();
    // ... other methods
}
```

- **Explicit condition variable objects**
  - Condition variable $C$ is created from a Lock object $L$ by calling $L$.newCondition()
  - Condition variable $C$ is then associated with $L$

- **Multiple condition objects per lock**
  - Allows different wait sets to be created for lock
  - Can wake up different threads depending on condition

**Condition – await() and signalAll()**

- **Calling await( ) w/ lock held**
  - Releases the lock
    - But not any other locks held by this thread
  - Adds this thread to **wait set** for condition
  - Blocks the thread

- **Calling signalAll( ) w/ lock held**
  - Resumes all threads in condition’s wait set
  - Threads must reacquire lock
    - Before continuing (returning from await)
    - Enforced automatically; you don’t have to do it
Producer / Consumer Solution (Java 1.5)

```java
Lock lock = new ReentrantLock();
Condition ready = lock.newCondition();
boolean bufferReady = false;
Object buffer;

void produce(Object o) {
    lock.lock();
    while (bufferReady) ready.await();
    buffer = o;
    bufferReady = true;
    ready.signalAll();
    lock.unlock();
}

Object consume() {
    lock.lock();
    while (!bufferReady) ready.await();
    Object o = buffer;
    bufferReady = false;
    ready.signalAll();
    lock.unlock();
}
```

- Uses single condition per lock (as in Java 1.4)

Producer / Consumer Solution (Java 1.5)

```java
Lock lock = new ReentrantLock();
Condition producers = lock.newCondition();
Condition consumers = lock.newCondition();
boolean bufferReady = false;
Object buffer;

void produce(Object o) {
    lock.lock();
    while (bufferReady) producers.await();
    buffer = o;
    bufferReady = true;
    consumers.signalAll();
    lock.unlock();
}

Object consume() {
    lock.lock();
    while (!bufferReady) consumers.await();
    Object o = buffer;
    bufferReady = false;
    producers.signalAll();
    lock.unlock();
}
```

- Uses 2 conditions per lock for greater efficiency