CS 242

Concurrency 1

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Reading: Chapter 15

Course schedule

- This week
  - Two lectures on concurrency
  - Homework posted to web this week; due next Wed
  - Section on Friday (last Friday section)
- Next week
  - Monday – Logic programming
  - Wednesday – Review
- Following week
  - Final exam on Monday, Dec 10, 12:15-3:15 PM

Concurrency

Two or more sequences of events occur in parallel

- Multiprogramming
  - A single computer runs several programs at the same time
  - Each program proceeds sequentially
  - Actions of one program may occur between two steps of another
- Multiprocessors
  - Two or more processors may be connected
  - Programs on one processor communicate with programs on another
  - Actions may happen simultaneously

Process: sequential program running on a processor

Concurrency increasing: many cores on single chip

- From white papers and web sites of current projects:
  - "Conventional wisdom is now to double the number of cores on a chip with each silicon generation."
  - "The target should be 1000s of cores per chip, as this hardware is the most efficient in MIPS per watt, MIPS per area of silicon, and MIPS per development dollar."
  - "To maximize programmer productivity, programming models should be independent of the number of processors."
  - "To maximize application efficiency, programming models should support a wide range of data types and successful models of parallelism: data-level parallelism, independent task parallelism, and instruction-level parallelism."

see VIEW and RAMP projects (Berkeley, Stanford, MIT, CMU, UW, UT Austin, processor companies, …)

The promise of concurrency

- Speed
  - If a task takes time t on one processor, shouldn't it take time t/n on n processors?
- Availability
  - If one process is busy, another may be ready to help
- Distribution
  - Processors in different locations can collaborate to solve a problem or work together
- Humans do it so why can't computers?
  - Vision, cognition appear to be highly parallel activities

Challenges

- Concurrent programs are harder to get right
  - Folklore: Need at least an order of magnitude in speedup for concurrent prog to be worth the effort
- Some problems are inherently sequential
  - Theory – circuit evaluation is P-complete
  - Practice – many problems need coordination and communication among sub-problems
- Specific issues
  - Communication – send or receive information
  - Synchronization – wait for another process to act
  - Atomicity – do not stop in the middle and leave a mess

Basic question for this course

- How can programming languages make concurrent and distributed programming easier?

What could languages provide?

- Example high-level constructs
  - Thread as the value of an expression
    - Pass threads to functions
    - Create threads at the result of function call
  - Communication abstractions
    - Synchronous communication
    - Buffered asynchronous channels that preserve msg order
  - Concurrency control
    - Mutual exclusion
    - Most concurrent languages provide some form of locking
    - Atomicity is more abstract, less commonly provided

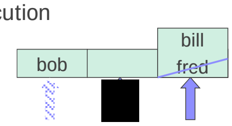
Basic issue: race conditions

- Sample action

```
procedure sign_up(person)
   begin
      number := number + 1;
      list[number] := person;
end;
```

- Problem with parallel execution

sign_up(fred) || sign_up(bill);



Resolving conflict between processes

- Critical section
  - Two processes may access shared resource
  - Inconsistent behavior if two actions are interleaved
  - Allow only one process in *critical section*
- Deadlock
  - Process may hold some locks while awaiting others
  - *Deadlock* occurs when no process can proceed

Locks and Waiting

```
<initialze concurrency control>

Thread 1:
      <wait>
      sign_up(fred);   // critical section
      <signal>

Thread 2:
      <wait>
      sign_up(bill);    // critical section
      <signal>
```

Need atomic operations to implement wait

Mutual exclusion primitives

- Atomic test-and-set
  - Instruction atomically reads and writes some location
  - Common hardware instruction
  - Combine with busy-waiting loop to implement mutex
- Semaphore
  - Avoid busy-waiting loop
  - Keep queue of waiting processes
  - Scheduler has access to semaphore; process sleeps
  - Disable interrupts during semaphore operations
    - OK since operations are short

State of the art

- Concurrent programming is difficult
  - Race conditions, deadlock are pervasive
- Languages should be able to help
  - Capture useful paradigms, patterns, abstractions
- Other tools are needed
  - Testing is difficult for multi-threaded programs
  - Many race-condition detectors being built today
    - Static detection: conservative, may be too restrictive
    - Run-time detection: may be more practical for now

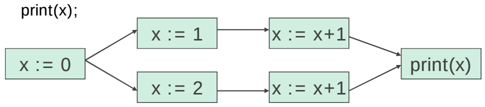
Concurrent language examples

- Language Examples
  - Cobegin/coend
  - Multilisp futures
  - Actors (C. Hewitt)
  - Concurrent ML
  - Java
- Some features to compare
  - Thread creation
  - Communication
  - Concurrency control (synchronization and locking)

Cobegin/coend

- Limited concurrency primitive
- Example

```
x := 0;
cobegin
   begin x := 1; x := x+1 end;  } execute sequential
   begin x := 2; x := x+1 end;  } blocks in parallel
coend;
print(x);
```



Atomicity at level of assignment statement

Properties of cobegin/coend

- Advantages
  - Create concurrent processes
  - Communication: shared variables
- Limitations
  - Mutual exclusion: none
  - Atomicity: none
  - Number of processes is fixed by program structure
  - Cannot abort processes
    - All must complete before parent process can go on

History: Concurrent Pascal, P. Brinch Hansen, Caltech, 1970's

Multilisp *future*

- Example

```
(define (split x) ...)
(define (merge x y) ... (car x) ...)
(define (mergesort x)
   (let ((y,z) (split x))
      (merge (mergesort y) (mergesort z))))
```

- How to rewrite as concurrent algorithm?

Slide credit: Michael Hicks (+ few slides)

Some general approaches

- Explicit concurrency
  - Fork or create threads explicitly
  - Explicit communication between threads
    - Producer computes useful value
    - Consumer requests or waits for producer
- Implicit concurrency
  - Rely on compiler to identify potential parallelism
  - Problems
    - Instruction-level and loop-level parallelism can be inferred, but inferring larger "subroutine"-level parallelism has had less success

Middle Ground: Futures

- Use future annotation [Halstead 85]
  - (future e) indicates e may run concurrently with parent
- Benefits
  - Notationally lightweight
    - Sequential algorithm still expressed in code
  - Concurrency determined by the run-time system
    - Can be based on system resources
  - Simple coordination between threads

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Where to annotate?

```
(define (split x) ...)
(define (merge x y) ... (car x) ...)
(define (mergesort x)
 (let ((y,z) (split x))
  (merge (mergesort y) (mergesort z))))
```

- No - result is used immediately in following call

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Where to annotate?

```
(define (split x) ...)
(define (merge x y) ... (car x) ...)
(define (mergesort x)
 (let ((y,z) (split x))
  (merge (mergesort y) (mergesort z) )))
```

- Yes - recursive calls can operate in parallel

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Multilisp Merge Sort

```
(define (split x) ...)
(define (merge x y) ... (car x) ...)
(define (mergesort x)
 (let ((y,z) (split x))
  (merge (future (mergesort y)
               (future (mergesort z)))))
```

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Basic Implementation Approach

- (future e)
  - fork a new thread T to evaluate e
  - return a proxy p to the parent
    - called a future or promise
- Producer
  - Thread T stores result of e into proxy p
- Consumer
  - Run-time system extracts result from p when accessed by the parent
  - Called a touch or claim

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Implementing Touches

- (define (merge x y) ... (car x) ...)

Could be a future...

- Futurized implementation of (car x)

```
(if (pair? (touch x))
  (get first elem of x)
  (error))
```

- Where (touch x) is

```
  (if (future? x) (get x) x)
```

Blocks until result has been computed

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Optimization I

- Forking a thread per future could be expensive and without advantage
  - Particularly if not many CPUs
- Idea: only use as many threads as there are processors [Mohr et al 91]
  - At a future call, use idle thread, if any
  - Otherwise, continue using current thread
    - Save continuation on a separate queue
  - When a thread would block, save the current continuation and grab one from the queue

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Optimization II

- Once a future computation completes, its result is immutable
  - Proxy and further touches redundant
- Thus
  - Use garbage collector to throw away the proxy and replace with the result [Halstead 85]
  - Avoid touching at all if static analysis can prove it's unnecessary [Flanagan & Felleisen 95]

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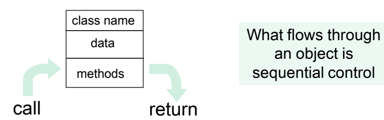
Actors [Hewitt, Agha, Tokoro, Yonezawa, ...]

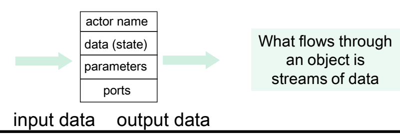
- Each actor (object) has a script
- In response to input, actor may atomically
  - create new actors
  - initiate communication
  - change internal state
- Communication is
  - Buffered, so no message is lost
  - Guaranteed to arrive, but not in sending order
    - Order-preserving communication is harder to implement
    - Programmer can build ordered primitive from unordered
    - Inefficient to have ordered communication when not needed

Actor-Oriented Programs

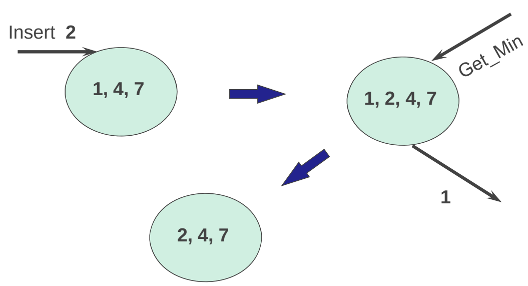
Object orientation:



Actor orientation:



Example



Actor program

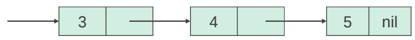
- Stack node (parameters)

  a stack_node with acquaintances content and link
  if operation requested is a pop and content != nil then
  become forwarder to link
  send content to customer
  if operation requested is push(new_content) then
  let P=new stack_node with current acquaintances (a clone)
  become stack_node with acquaintances new_content and P

Hard to read but it does the "obvious" thing, except that the concept of *forwarder* is unusual....

Forwarder

- Stack before pop

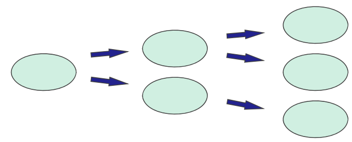


- Stack after pop

  - Node “disappears” by becoming a forwarder node. The system manages forwarded nodes in a way that makes them invisible to the program. (Exact mechanism doesn’t really matter since we’re not that interested in Actors.)

Concurrency

- Several actors may operate concurrently



- Concurrency not controlled explicitly by program
  - Messages sent by one actor can be received and processed by others sequentially or concurrently

Pros and Cons of Actor model

- High-level programming language
  - Communication by messages
  - Mutual exclusion: if two msgs sent, actor reacts atomically to first one received before seeing second
  - Concurrency is implicit; no explicit fork or wait
- Possibly too abstract for some situations?
  - How do you fork several processes to do speculative computation, then kill them all when one succeeds?
    - Seems to require many msgs to actor that tells all others whether to proceed; this “coordinator” becomes a bottleneck

Concurrent ML [Reppy, Gansner, ...]

- Threads
  - New *type* of entity
- Communication
  - Synchronous channels
- Synchronization
  - Channels
  - Events
- Atomicity
  - No specific language support

Brinch-Hansen, Dahl, Dijkstra, Hoare

Pre-Java Concept: Monitor

- Synchronized access to private data
- Combines
  - private data
  - set of procedures (methods)
  - synchronization policy
    - At most one process may execute a monitor procedure at a time; this process is said to be *in* the monitor
    - If one process is in the monitor, any other process that calls a monitor procedure will be delayed
- Modern terminology: synchronized object

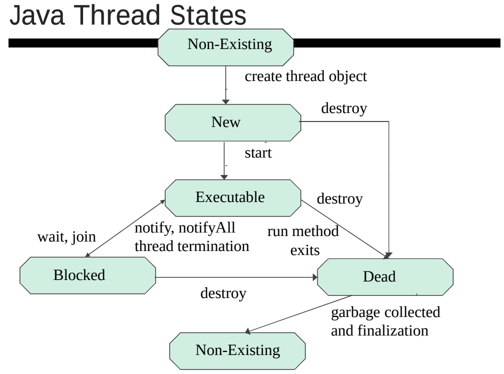
Java Concurrency

- Threads
  - Create process by creating thread object
- Communication
  - Shared variables
  - Method calls
- Mutual exclusion and synchronization
  - Every object has a lock (inherited from class Object)
    - synchronized methods and blocks
  - Synchronization operations (inherited from class Object)
    - wait : pause current thread until another thread calls notify
    - notify : wake up waiting threads

Java Threads

- ◆Thread
  - Set of instructions to be executed one at a time, in a specified order
- ◆Java thread objects
  - Object of class Thread
  - Methods inherited from Thread:
    - start : method called to spawn a new thread of control; causes VM to call run method
    - suspend : freeze execution
    - interrupt : freeze execution and throw exception to thread
    - stop : forcibly cause thread to halt

Java Thread States



Allen Holub, *Taming Java Threads*

Problem with language specification

- ◆Java Lang Spec allows access to partial objects

```
class Broken {
   private long x;
   Broken() {
      new Thread() {
            public void run() { x = -1; }
      }.start();
      x = 0;
} }
```

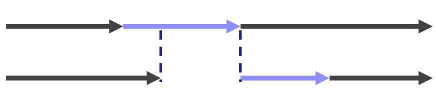
Thread created within constructor can access the object not fully constructed

Interaction between threads

- ◆Shared variables
  - Two threads may assign/read the same variable
  - Programmer responsibility
    - Avoid race conditions by explicit synchronization !!
- ◆Method calls
  - Two threads may call methods on the same object
- ◆Synchronization primitives
  - Each object has internal lock, inherited from Object
  - Synchronization primitives based on object locking

Synchronization

- ◆Provides mutual exclusion
  - Two threads may have access to some object
  - If one calls a synchronized method, this locks object
  - If the other calls a synchronized method on same object, this thread blocks until object is unlocked



Synchronized methods

- ◆Marked by keyword
  - public synchronized void commitTransaction(...) {...}
- ◆Provides mutual exclusion
  - At most one synchronized method can be active
  - Unsynchronized methods can still be called
    - Programmer must be careful
- ◆Not part of method signature
  - sync method equivalent to unsync method with body consisting of a *synchronized block*
  - subclass may replace a synchronized method with unsynchronized method

Example [Lea]

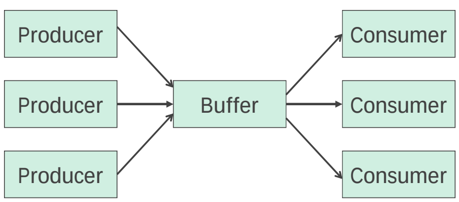
```
class LinkedCell {            // Lisp-style cons cell containing
   protected double value;   // value and link to next cell
   protected final LinkedCell next;
   public LinkedCell (double v, LinkedCell t) {
           value = v; next = t;
   }
   public synchronized double getValue() {
           return value;
   }
   public synchronized void setValue(double v) {
           value = v;   // assignment not atomic
   }
   public LinkedCell next() {   // no synch needed
           return next;
   }
```

Join, another form of synchronization

- Wait for thread to terminate

```
class Future extends Thread {
     private int result;
     public void run() {  result = f(…); }
     public int getResult() { return result;}
}
…
Future t = new future;
t.start()                         // start new thread
…
t.join(); x = t.getResult(); // wait and get result
```

Producer-Consumer?



- Method call is synchronous
- How do we do this in Java?

Solution to producer-consumer

- Cannot be solved with locks alone
  - Use wait and notify methods of Object
- Basic idea
  - Consumer must wait until something is in the buffer
  - Producer must inform waiting consumers when item available
- More details
  - Consumer waits
    - While waiting, must *sleep*
    - This is accomplished with the wait method
    - Need condition recheck loop
  - Producer notifies
    - Must *wake up* at least one consumer
    - This is accomplished with the notify method

Stack<T>: produce, consume methods

```
public synchronized void produce (T object) {
   stack.add(object); notify();
}

public synchronized T consume () {
   while (stack.isEmpty()) {
     try {
              wait();
     } catch (InterruptedException e) { }
   }
   Int lastElement = stack.size() - 1;
   T object = stack.get(lastElement);
   stack.remove(lastElement);
   return object; }
```

Why is loop needed here?

See: http://www1.coe.neu.edu/~jsmith/tutorial.html (also cartoon)

Concurrent garbage collector

- How much concurrency?
  - Need to stop thread while mark and sweep
  - Other GC: may not need to stop all program threads
- Problem
  - Program thread may change objects during collection
- Solution
  - Prevent read/write to memory area
  - Details are subtle; generational, copying GC
    - Modern GC distinguishes short-lived from long-lived objects
    - Copying allows read to old area if writes are blocked …
    - Relatively efficient methods for read barrier, write barrier

Limitations of Java 1.4 primitives

- No way to back off from an attempt to acquire a lock
  - Cannot give up after waiting for a specified period of time
  - Cannot cancel a lock attempt after an interrupt
- No way to alter the semantics of a lock
  - Reentrancy, read versus write protection, fairness, …
- No access control for synchronization
  - Any method can perform synchronized(obj) for any object
- Synchronization is done within methods and blocks
  - Limited to block-structured locking
  - Cannot acquire a lock in one method and release it in another

See http://java.sun.com/developer/technicalArticles/J2SE/concurrency/

Continue next time …

Condition rechecks

- Want to wait until condition is true

```
public synchronized void lock() throws InterruptedException {
        if ( isLocked )  wait();
        isLocked = true;
}
public synchronized void unLock() {
        isLocked = false;
        notify();
}
```

- But need loop since another process may run

```
public synchronized void lock() throws InterruptedException {
        while ( isLocked ) wait();
        isLocked = true;
}
```