CS 242

Concurrency

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Announcements

- Last graded homework due November 24
  - May turn in Monday Nov 29, after Thanksgiving
  - Ungraded study questions instead of HW 8
- Schedule for rest of the quarter
  - Wed 11/24 – Java concurrency
  - Mon 11/29 – Interoperability
  - Wed 12/1 – HW and Sample solutions, Review
- Final exam – Wednesday, December 8
  - 8:30-11:30 AM in Gates B01, B03

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

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 an order of magnitude speedup (or more) 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

Why is concurrent programming hard?

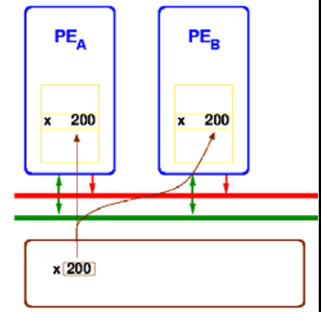
- Nondeterminism
  - *Deterministic*: two executions on the same input it always produce the same output
  - *Nondeterministic:* two executions on the same input may produce different output
- Why does this cause difficulty?
  - May be many possible executions of one system
  - Hard to think of all the possibilities
  - Hard to test program since some errors may occur infrequently

Example

- Cache coherence protocols in multiprocessors
  - A set of processors share memory
  - Access to memory is slow, can be bottleneck
  - Each processor maintains a memory cache
  - The job of the cache coherence protocol is to maintain the processor caches, and to guarantee that the values returned by every load/store sequence generated by the multiprocessor are consistent with the memory model.

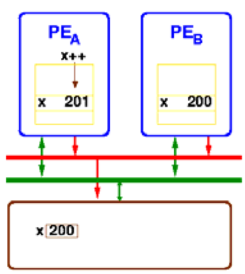
Cache filled by read

- PE_A reads loc x
  - Copy of x put in PE_A's cache.
- PE_B also reads x
  - Copy of x put in PE_B's cache too.

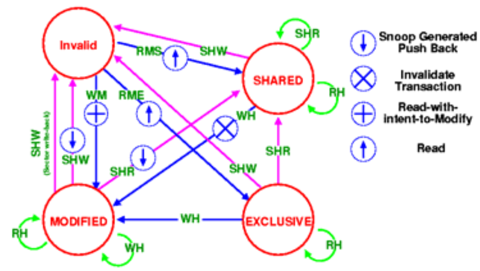


Cache modified by write

- PE_A adds 1 to x
  - x is in PE_A's cache, so there's a cache hit
- If PE_B reads x from cache, *may* be wrong
  - OK if program semantics allows PE_B read before PE_A write
- Need protocol to avoid using stale values



State diagram for cache protocol



- Necessary for multiprocessor; hard to get right.

Basic question for this course

- How can programming languages make concurrent and distributed programming easier?
  - Can do concurrent, distributed programming in C using system calls
  - Is there something better?

What could languages provide?

- Abstract model of system
  - abstract machine => abstract system
- Example high-level constructs
  - Process as the value of an expression
    - Pass processes to functions
    - Create processes at the result of function call
  - Communication abstractions
    - Synchronous communication
    - Buffered asynchronous channels that preserve msg order
  - Mutual exclusion, atomicity primitives
    - Most concurrent languages provide some form of locking
    - Atomicity is more complicated, less commonly provided

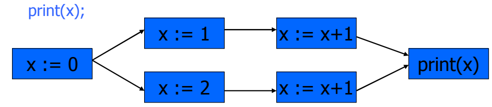
Basic issue: conflict between processes

- 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

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

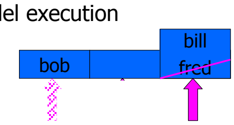
Mutual exclusion

- Sample action

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

- Problem with parallel execution

```
cobegin
  sign_up(fred);
  sign_up(bill);
end;
```



Locks and Waiting

```
<initialze concurrency control>
cobegin
   begin
        <wait>
        sign_up(fred);  // critical section
        <signal>
   end;
   begin
        <wait>
        sign_up(bill);    // critical section
        <signal>
    end;
end;
```

Need atomic operations to implement wait

Mutual exclusion primitives

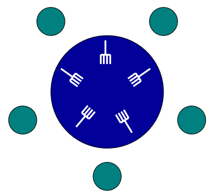
- Atomic test-and-set
  - Instruction atomically reads and writes some location
  - Common hardware instruction
  - Combine with busy-waiting loop to implement mutex
- Semaphore
  - Avoid busy-waiting loop
  - Keep queue of waiting processes
  - Scheduler has access to semaphore; process sleeps
  - Disable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

Monitor Brinch-Hansen, Dahl, Dijkstra, Hoare

- 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

Deadlock

- Possible with any mutual exclusion primitive
- Example
  - Dining philosophers
  - Each needs two forks to eat a plate of pasta
  - Each picks up fork to left, all at same time
  - None one can eat



Some entertaining Java animations on web

Reality

- Concurrent programming is difficult
  - Race conditions, deadlock are pervasive in Java libraries, etc.
- 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

Concurrent language examples

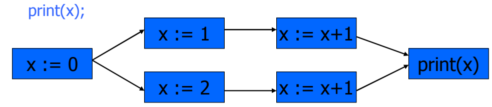
- Language Examples
  - Cobegin/coend
  - Actors (C. Hewitt)
  - Concurrent ML
  - Java
- Main features to compare
  - Threads
  - Communication
  - Synchronization
  - Atomicity

Cobegin/coend

- Limited concurrency primitive
- Example

```
x := 0;
cobegin
   begin x := 1; x := x+1 end;
   begin x := 2; x := x+1 end;
coend;
print(x);
```

execute sequential blocks in parallel



Atomicity at level of assignment statement

Properties of cobegin/coend

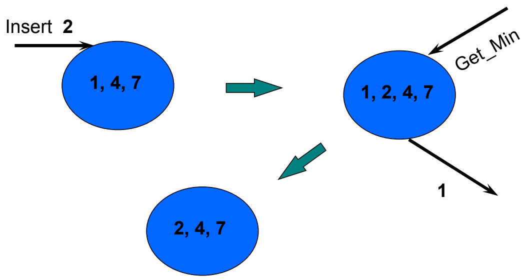
- Advantages
  - Create concurrent processes
  - Communication: shared variables
- Limitations
  - Mutual exclusion: none
  - Atomicity: none
  - Number of processes is fixed by program structure
  - Cannot abort processes
    - All must complete before parent process can go on

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

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

Example



Actor program

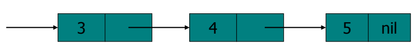
◆ Stack node   parameters

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

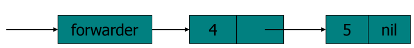
Hard to read but it does the "obvious" thing, except that the concept of *forwarder* is unusual….

Forwarder

◆ Stack before pop



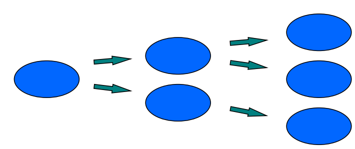
◆ Stack after pop



- 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 and Distribution

◆ Several actors may operate concurrently



◆ Concurrency not forced by program
- Depends on system scheduler

◆ Distribution not controlled by programmer

Attractive idealization, but too "loose" in practice

Concurrent ML   [Reppy, Gansner, …]

◆ Threads
- New type of entity

◆ Communication
- Synchronous channels

◆ Synchronization
- Channels
- Events

◆ Atomicity
- No specific language support

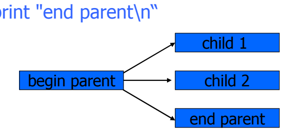
Threads

◆ Thread creation
- spawn : (unit → unit) → thread_id

◆ Example code

```
CIO.print  "begin parent\n";
    spawn (fn () => (CIO.print "child 1\n";));
    spawn (fn () => (CIO.print "child 2\n";));
CIO.print "end parent\n"
```

◆ Result



Channels

- Channel creation
  - channel : unit → 'a chan
- Communication
  - recv : 'a chan → 'a
  - send : ('a chan * 'a) → unit
- Example

  ch = channel();
  spawn (fn()=> … <A> … send(ch,0); … <B> …);
  spawn (fn()=> … <C> … recv ch; … <D> …);
- Result

CML programming

- Functions
  - Can write functions : channels → threads
  - Build concurrent system by declaring channels and "wiring together" sets of threads
- Events
  - Delayed action that can be used for synchronization
  - Powerful concept for concurrent programming
- Sample Application
  - eXene – concurrent uniprocessor window system

Sample CML programming

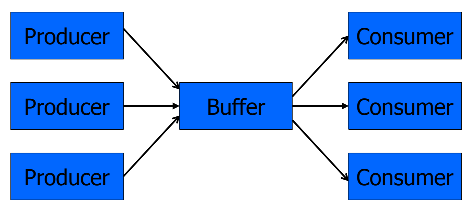
- Function to create squaring process

```
fun square (inCh, outCh) =
  forever () (fn () =>
    send (outCh, square(recv(inCh))));
```

- Put processes together

```
fun mkSquares () =
let
  val outCh = channel()
  and c1 = channel()
in
  numbers(c1);
  square(c1, outCh);
  outCh
end;
```

Problem: Producer-Consumer



- Easy with buffered asynchronous communication
- Requires buffer if synchronous communication

Synchronous consumer or buffer ???

- Code probably looks like this:

  for i = 1 to n
  receive(… producer[i] …)
- What's the problem?
  - Synchronous receive blocks waiting for sender
  - Deadlock if
    - Producer 1 is ready to send
    - Producer 2 is finished (nothing left to send)
    - Consumer or queue decides to receive from Producer 2
- How do we solve this problem?

Guarded Commands [Dijkstra]

- Select one available command; *non-blocking* test

```
do
  Condition ⇒ Command
  …
  Condition ⇒ Command
od
```

- Outline of producer-consumer buffer

```
do
  Producer ready and queue not full ⇒
      Receive from waiting producer and store in queue
  Consumer ready and queue not empty ⇒
      Send to waiting consumer and remove from queue
od
```

Expressiveness of CML

- How do we write choice of guarded commands?
  - Events and "choose" function
- CML Event = "delayed" action
  - 'a event
    - the type of actions that return an 'a when executed
  - sync : 'a event → 'a
    - Function that synchronizes on an 'a event and returns an 'a
  - fun recv(ch) = sync (recvEvt (ch));
- Choice
  - choose : 'a event list → 'a event

Does not seem possible to do producer-consumer in CML without choose

CML from continuations

- Continuation primitives
  - callcc : ('a cont → 'a) → 'a
    Call function argument with current continuation
  - throw : 'a cont -> 'a -> 'b
  - Curried function to invoke continuation with arg
- Example

```
fun f(x,k) = throw k(x+3);
fun g(y,k) = f(y+2,k) + 10;
fun h(z) = z + callcc(fn k => g(z+1,k));
h(1);
```

A CML implementation (simplified)

- Use queues with side-effecting functions

```
datatype 'a queue = Q of {front: 'a list ref, rear: 'a list ref}
fun queueIns  (Q(…))(…) =  (* insert into queue *)
fun queueRem (Q(…)) =  (* remove from queue *)
```

- And continuations

```
val enqueue = queueIns rdyQ
fun dispatch () = throw (queueRem rdyQ) ()
fun spawn f = callcc (fn parent_k =>
                  ( enqueue parent_k; f (); dispatch()))
```

Source: Appel, Reppy

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

Example subclass of Thread

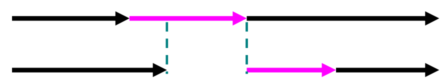
```
class PrintMany extends Thread {
    private String msg;
    public PrintMany (String m) {msg = m;}
    public void run() {
            try {   for (;;){ System.out.print(msg + " ");
                              sleep(10);
                    }
            } catch (InterruptedException e) {
                    return;
            }
    }                          (inherits start from Thread)
```

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 example

- Objects may have *synchronized* methods
- Can be used for mutual exclusion
  - Two threads may share an 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]

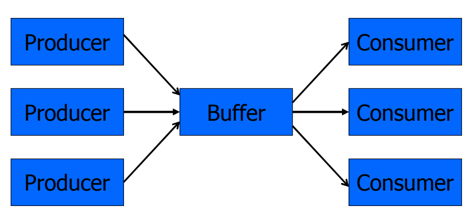
```
class LinkedCell {           // Lisp-style cons cell containing
  protected double value;  // value and link to next cell
  protected LinkedCell next;
  public LinkedCell (double v, LinkedCell t) {
          value = v; next = t;
  }
  public synchronized double getValue() {
          return value;
  }
  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?

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;
}
```

Aspects of Java Threads

- Portable since part of language
  - Easier to use in basic libraries than C system calls
  - Example: garbage collector is separate thread
- General difficulty combining serial/concur code
  - Serial to concurrent
    - Code for serial execution may not work in concurrent sys
  - Concurrent to serial
    - Code with synchronization may be inefficient in serial programs (10-20% unnecessary overhead)
- Abstract memory model
  - Shared variables can be problematic on some implementations

Priorities

- Each thread has a priority
  - Between Thread.MIN_PRIORITY and Thread.MAX_PRIORITY
    - These are 1 and 10, respectively
    - Main has default priority Thread.NORM_PRIORITY (=5)
  - New thread has same priority as thread created it
  - Current priority accessed via method getPriority
  - Priority can be dynamically changed by setPriority
- Schedule gives preference to higher priority

ThreadGroup

- Every Thread is a member of a ThreadGroup
  - Default: same group as creating thread
  - ThreadGroups nest in a tree-like fashion
- ThreadGroup support security policies
  - Illegal to interrupt thread not in your group
  - Prevents applet from killing main screen display update thread
- ThreadGroups not normally used directly
  - collection classes (for example java.util.Vector) are better choices for tracking groups of Thread objects
- ThreadGroup provides method uncaughtException
  - invoked when thread terminates due to uncaught unchecked exception (for example a NullPointerException)

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

Nested Monitor Lockout Problem

```
class Stack {
    LinkedList list = new LinkedList();
    public synchronized void push(Object x) {
            synchronized(list) {
                    list.addLast( x ); notify();
    } }
    public synchronized Object pop() {
            synchronized(list) {
                    if( list.size() <= 0 ) wait();
                    return list.removeLast();
    } }
}
```

Releases lock on Stack object but not lock on list; a push from another thread will deadlock

Immutable objects

- What is an immutable object?
  - State does not change
- Immutable objects useful in programming
  - Simple to construct, test, and use
  - Always thread-safe; no synchronization issues
  - Do not need a copy constructor
  - Do not need an implementation of clone
  - Do not need to be copied defensively when used as a field
  - Good Map keys and Set elements (objects must not change state while in the collection)
  - Class invariant is established by construction, does not need to be checked as state changes (since it doesn't)

Concurrent garbage collector

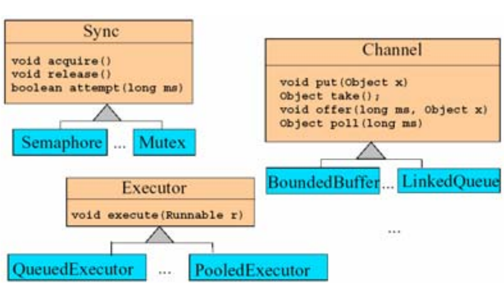
- How much concurrency?
  - Need to stop thread while mark and sweep
  - Other GC: may not need to stop all program threads
- Problem
  - Program thread may change objects during collection
- Solution
  - Prevent read/write to memory area
  - Details are subtle; generational, copying GC
    - Modern 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

Some rough spots in Java concurrency

- Class may have synchronized, unsynch methods
  - No notion of a class that is a monitor
  - Not preserved by inheritance (bug or feature?)
- Immutable objects
  - If declared in program, could minimize locking
- Fairness is not guaranteed
  - Chose arbitrarily among equal priority threads
- Wait set is not a FIFO queue
  - notifyAll notifies all waiting threads, not necessarily highest priority, one waiting longest, etc.
- Condition rechecks essential
  - use loop (previous slide)

Java progress: util.concurrent

- Doug Lea's utility classes, basis for JSR 166
  - A few general-purpose interfaces
  - Implementations tested over several years
- Principal interfaces and implementations
  - Sync: acquire/release protocols
  - Channel: put/take protocols
  - Executor: executing Runnable tasks



Sync

- Main interface for acquire/release protocols
  - Used for custom locks, resource management, other common synchronization idioms
  - Coarse-grained interface
    - Doesn't distinguish different lock semantics
- Implementations
  - Mutex, ReentrantLock, Latch, CountDown, Semaphore, WaiterPreferenceSemaphore, FIFOSemaphore, PrioritySemaphore
    - Also, utility implementations such as ObservableSync, LayeredSync that simplifycomposition and instrumentation

Channel

- Main interface for buffers, queues, etc.

- Implementations
  - LinkedQueue, BoundedLinkedQueue, BoundedBuffer, BoundedPriorityQueue, SynchronousChannel, Slot

Executor

- Main interface for Thread-like classes
  - Pools
  - Lightweight execution frameworks
  - Custom scheduling
- Need only support execute(Runnable r)
  - Analogous to Thread.start
- Implementations
  - PooledExecutor, ThreadedExecutor, QueuedExecutor, FJTaskRunnerGroup
  - Related ThreadFactory class allows most Executors to use threads with custom attributes

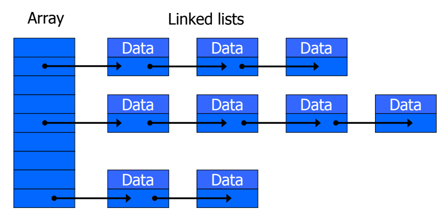
Example: Concurrent Hash Map

- Implements a hash table
  - Insert and retrieve data elements by key
  - Two items in same bucket placed in linked list
  - Allow read/write with minimal locking
- Tricky

  "ConcurrentHashMap is both a very useful class for many concurrent applications and a fine example of a class that understands and exploits the subtle details of the Java Memory Model (JMM) to achieve higher performance. … Use it, learn from it, enjoy it – but unless you're an expert on Java concurrency, you probably shouldn't try this on your own."

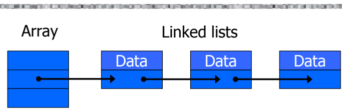
See http://www-106.ibm.com/developerworks/java/library/j-jtp08223

ConcurrentHashMap



- Concurrent operations
  - read: no problem
  - read/write: OK if different lists
  - read/write to same list: clever tricks sometimes avoid locking

ConcurrentHashMap Tricks



- Immutability
  - List cells are immutable, except for data field

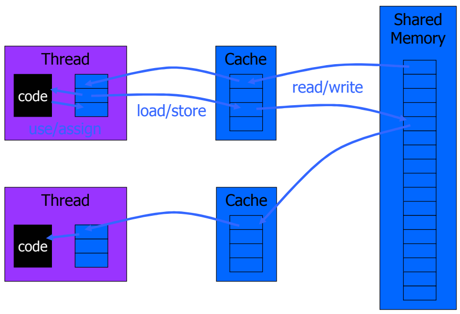
    ⇒ read thread sees linked list, even if write in progress
- Add to list
  - Can cons to head of list, like Lisp lists
- Remove from list
  - Set data field to null, rebuild list to skip this cell
  - Unreachable cells eventually garbage collected

More info: see study questions

Java memory model

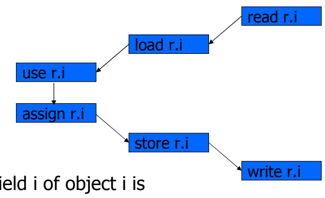
- Main ideas
  - Threads have local memory (cache)
  - Threads fill/flush from main memory
- Interaction restricted by constraints on actions
  - Use/assign are local thread memory actions
  - Load/store fill or flush local memory
  - Read/write are main memory actions

Memory Hierarchy



Example

- Program
  r.i = r.i+1



- The value of field i of object i is
  - *read* from main memory
  - *load*ed into the local cache of the thread
  - *use*d in the addition r.i+1
- Similar steps to place the value of r.i in shared memory

Java Memory Model [Java Lang Spec]

- Example constraints on use, assign, load, store:
  - *use* and *assign* actions by thread must occur in the order specified by the program
  - Thread is not permitted to lose its most recent assign
  - Thread is not permitted to write data from its working memory to main memory for no reason
  - New thread starts with an empty working memory
  - New variable created only in main memory, not thread working memory
- "Provided that all the constraints are obeyed, a *load* or *store* action may be issued at any time by any thread on any variable, at the whim of the implementation."

Access to Main Memory

- Constraints on load, store, read ,write
  - For every *load*, must be a preceding *read* action
  - For every *store*, must be a following *write* action
  - Actions on master copy of a variable are performed by the main memory in order requested by thread

Prescient stores

- Under certain conditions …
  - Store actions (from cache to shared memory) may occur earlier than you would otherwise expect
  - Purpose:
    - Allow optimizations that make properly synchronized programs run faster
    - These optimizations may allow out-of-order operations for programs that are not properly synchronized

Details are complicated. Main point: there's more to designing a good memory model than you might think!

Criticism [Pugh]

- Model is hard to interpret and poorly understood
- Constraints
  - prohibit common compiler optimizations
  - expensive to implement on existing hardware
- Not commonly followed
  - Java Programs
    - Sun Java Development Kit not guaranteed valid by the existing Java memory model
  - Implementations not compliant
    - Sun Classic Wintel JVM, Sun Hotspot Wintel JVM, IBM 1.1.7b Wintel JVM, Sun production Sparc Solaris JVM, Microsoft JVM

Prescient stores anomaly [Pugh]

- Program
  - x = 0; y = 0;
  - Thread 1: a = x; y = 1;
  - Thread 2: b = y; x = 1;
- Without prescient stores
  - Either a=b=0, or a=0 and b=1, or a=1 and b=0
- With prescient stores
  - Write actions for x,y may occur before either read
  - Threads can finish with a=b=1

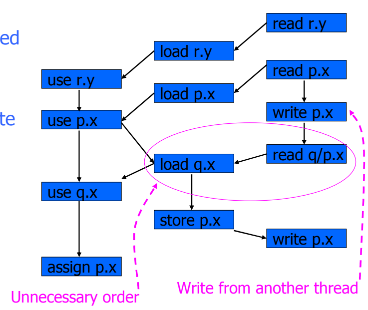
Homework: draw out ordering on memory operations

Over-constrained actions [Pugh]

- Program
  - // p & q are aliased
  - i = r.y;
  - j = p.x;
  - // concurrent write to p.x from another thread
  - k = q.x;
  - p.x = 42;
- Problem
  - Memory model is too constrained
    - Programmer will be happy if j, k get same value
    - Memory model *prevents* this

Constraints on memory actions

// p & q are aliased
i = r.y;
j = p.x;
// concurrent write
k = q.x;
p.x = 42;



Summary

- Concurrency
  - Powerful computing idea
  - Requires time and effort to use effectively
- Actors
  - High-level object-oriented form of concurrency
- Concurrent ML
  - Threads and synchronous events
- Java concurrency
  - Combines thread and object-oriented approaches
  - Some good features, some rough spots
  - Experience leads to programming methods, libraries
    Example: ConcurrentHashMap