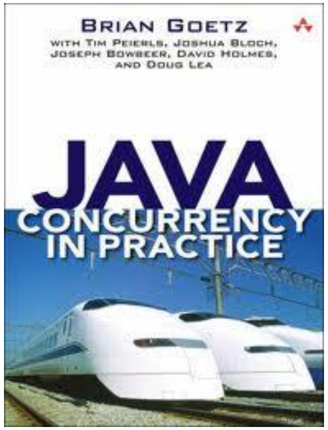

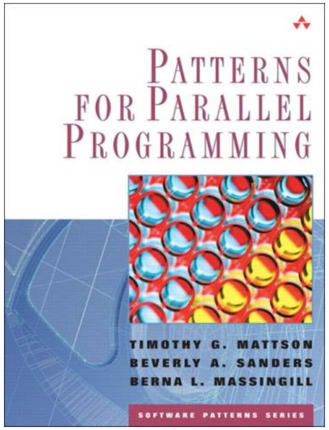

Parallel programming in Java

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Outline

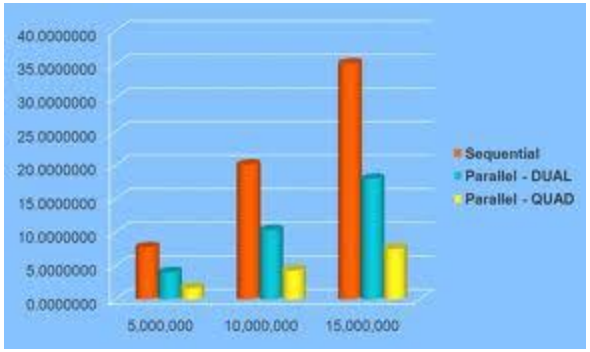
- Why is parallel programming so hard?
- Kinds of parallelism
- Implicit and explicit parallelism
- Most popular parallel model either
- Parallelism in the Java language
- java.util.concurrent

Why is parallel programming so hard?

- Human consciousness is sequential
- It is hard not only in programming
  - Doing two things simultaneously
  - Leading a team of co-workers
- Parallel programming is not just coding
  - In nontrivial cases it is the essence of program architecture
- To write complex parallel program programmer needs to think as multiple parallel entities
  - It can develop into a split personality

Kinds of parallelism

- Like sequential but faster
  - Do you need an explicit parallelism?
  - Sequential equivalence saves the day



- You cannot do without (aka Concurrency)
  - Be natural, OOP was invented for it
  - Smart Little Creature modeling (TRIZ)
    - Focused on single task at a time
    - Specialized
    - Minimal number
  - Add sequential arbiters (trafficlights)

Implicit parallelism

- Data parallelism
  - Chunks of data are processed independently by the same program
- Pipeline
  - One chunk of data is processed by multiple programs in same order
- Task parallelism
  - Independent branches in data flow are processed in parallel
- Transactional parallelism
  - Independent branches in control flow executed in parallel
  - Atomicity, Consistency, Isolation, Durability (ACID)
  - Like task parallelism but we don’t know data dependency beforehand

Explicit parallelism

- Passive objects – just data with operations
- Active objects (Actors) – act like real persons
  - Communicate by creating and processing events (messages)
  - Synchronous communication
    - Hoare's monitors, synchronous objects
    - Rendezvous (wait/notify), P1|{e}|P2, 0-queue
  - Asynchronous communication
    - Unbounded message queues
    - Joins, predicates on multiple events
      - Join-calculus, Join Java, HW Join Java, JOcaml, C++ Boost.Join, Cω

Most popular parallel model either

- If your system communicates with one external object or messages are independent from each other
  - No explicit parallelism is needed
- In case of multiple objects with communication sessions
  - Active Proxy object in the system for each
  - All shared data in DB (SQL, in-memory, NoSQL, whatever)
  - Synchronize data in DB using transactions
- Oops. Is it like a web service? Yes it is.
  - It is most popular parallel model in the world and in Java
  - It is easy, stable, scalable
  - Every web programmer can do it right

Parallel facilities in Java

- Super High level (external libs)
  - Application server, Big Data platform: Tomcat, Glass Fish, Resin, Hadoop
  - Database: Java DB, H2, HSQLDB, HBase
- High level (java.util.concurrent)
  - ForkJoinTask (Java 7), Future, Task, Executor, ThreadPool
  - Copy on write collections
  - Concurrent collections
- Medium level (java.util.concurrent + java.lang.Thread)
  - Thread, BlockingQueue
- Low level (java.util.concurrent + java.lang.Thread + core language)
  - Thread, Monitor
  - Atomics
  - Synchronizers (Barriers, Semaphore)
  - Locks
  - park/unpark

Problem with treads

- Basic Thread programming model
  - Shared Memory, Rendezvous
  - Almost naive implementation of minimal models of parallelism (PRAM + CSP)
- Threads are like a parallel assembly language
  - You only really need them when developing frameworks
  - Parallel Random-Access Machine (PRAM)
    - Mathematical model of shared memory
    - Accesses are atomic, can be used for busy loop sync
  - Communicating Sequential Processes (CSP)
    - Term rewriting parallel formalization based on rendezvous
    - Rendezvous is (P1|{e}|P2), 0-queue

Parallelism in Java language

- Threads

```
new Thread(new Runnable() {
    public void run() {…}
}).start();
```

- Synchronized, maps to Monitor lock/unlock

```
synchronized void meth() {
    synchronized(other) {…}…
```

- Wait/notify

```
synchronized(other) {
    other.notifyAll();
    other.wait();…
```

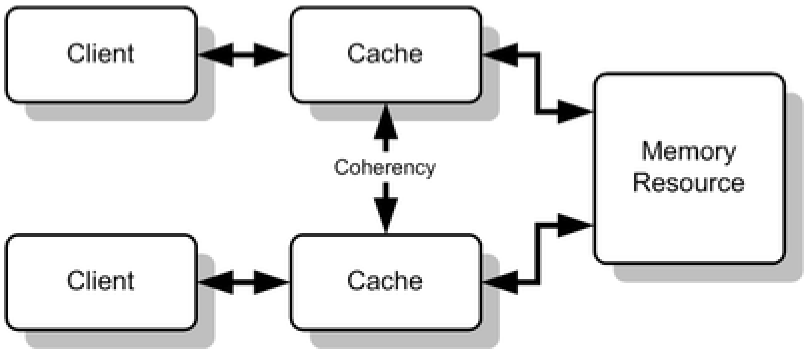
- volatile fields
- Causal memory model (JLS 3.0, 17.4)

Causal memory model in Java

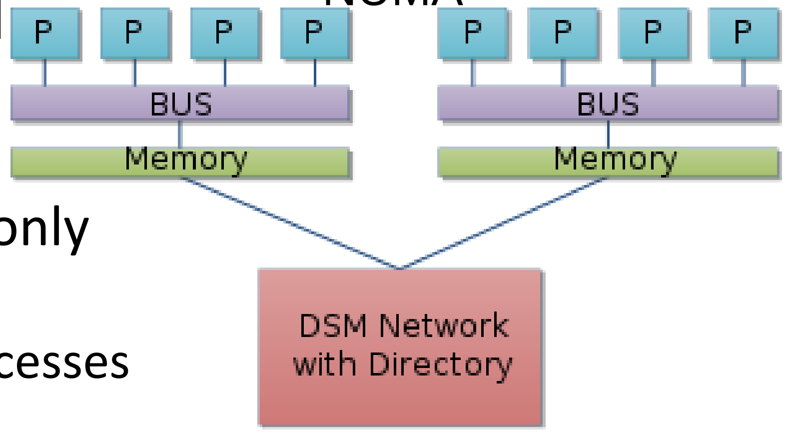
- Memory writes can be physically reordered by
  - Simultaneous execution on different processors
  - Superscalar processor
  - Memory caches
  - Optimizing compiler
- Only observable event order is important (Lamport's logical clock)
- Memory ops on one thread are observed in execution order on that thread
- Memory ops are atomic (except for long/double for embedded VM)
  UNDEFINED OBSERVABLE ORDER from other threads
- Before Java 1.5 only synchronized operations were ordered
  - Expected memory order implicitly resulted from cache coherence in CPU
- Causal memory model (JLS 3.0, 17.4) introduced in Java 1.5
  - Memory operations are observed in execution order by a synchronized observer
  - Specification was changed to accommodate NUMA memory model introduced in AMD Opteron used in Sun Enterprise Servers

Cache coherency and NUMA

- Cache coherency provides consistency of data stored in local caches of a shared resource
- Older multiprocessor systems were symmetric (SMP) with single shared memory
- Older coherency protocols provided sequential consistency
- Multiprocessors with distributed memory provide weak consistency only to reduce performance overhead
  - Consistency is guaranteed only at accesses to synchronization variables



NUMA



Synchronized operations

- *Volatile read/write*
- *Monitor lock/unlock*
- Synthetic first and last thread operations
- Thread start and termination
- Thread.interrupt() and it's detection
- There is a total order of synchronized operations
  - It is consistent with execution order in each thread

Synchronizes-with

- M.unlock with following M.lock
- V.write following V.read
- Thread.start() with first thread operation
- Default value init (0) with first operation of every thread
- Last thread operation with thread termination detection (Thread.isAlive(), Thread.Join())
- Thread.interrupt() with interrupt detection (InterruptedException, Thread.interrupted(), Thread.isInterrupted())

Happens-before

- Let *x, y* be operations. *hb*(*x*, *y*) means that *x* happens before *y.*
- *hb* is partial order of operations
- *hb(x, y)* if
  - *x, y* are executed on the same thread and *x* is executed before *y*
  - x is last operation of object constructor, and y is the first operation of Object.finalize() of the same object
  - *x synchronizes-with y*
  - *hb(x, z) and hb(z, y)* – transitivity
  - x (write) precedes y (read) by *final* field semantics (JLS 3.0, 17.5)
- ATTENTION! If z is unordered relative to x and y, then z doesn't know the order of x and y

Examples of operation order

```
synchronized void m() {
    notifyAll();
    wait();
}
```

- notifyAll() does not awake the following wait

```
class A {
    final B b;
    A() {
        b = new B();
    }
}
```

- b contains the reference to fully initialized object

Example (lazy init)

Incorrect

```
class A {
  private R r;
  R getR() {
    R result = r;
    if (result == null) {
      synchronized {
        if (r == null) {
          result = r = new R();
    }}}
    return result;
}}
```

Correct

```
class A {
  private volatile R r;
  R getR() {
    R result = r;
    if (result == null) {
      synchronized {
        if (r == null){
          result = r = new R();
    }}}
    return result;
}}
```

Better version for singleton (works due to lazy class loading required by JVM spec.)

```
class A {
  static R getR() { return RHolder.INSTANCE;}

  static class RHolder {
     static final R INSTANCE = new R();
}}
```

java.util.concurrent

- ForkJoinTask, Future, Task, Executor, ThreadPool

```
class Fibonacci extends RecursiveTask<Integer> {
  final int n;
  Fibonacci(int n) { this.n = n; }
  public Integer compute() {
    if (n <= 1) { return n; }
    ForkJoinTask<Integer> f1 = new Fibonacci(n - 1).fork();
    ForkJoinTask<Integer> f2 = new Fibonacci(n - 2);
    return f2.invoke() + f1.join();
}}
public class JUCTest {
  static final ForkJoinPool mainPool = new ForkJoinPool();

  public static void main(String[] args) {
    int res = mainPool.invoke(new Fibonacci(10));
    System.out.println(res);
}}
```

java.util.concurrent

- ForkJoin and memory consistency Example

```
class SortTask extends RecursiveAction {
  final long[] array;
  final int lo;
  final int hi;
  SortTask(long[] array, int lo, int hi) {…}
  protected void compute() {
    if (hi - lo < THRESHOLD)
      sequentiallySort(array, lo, hi);
    else {
      int mid = (lo + hi) >>> 1;
      invokeAll(new SortTask(array, lo, mid),
        new SortTask(array, mid, hi));
      merge(array, lo, hi);
}}}
```

java.util.concurrent

- Dynamic load balancing (sum)

```
class Sum extends RecursiveTask<Double> {
  final double[] array; final int lo, hi;
  Sum next; // keeps track of right-hand-side tasks
  Sum(double[] array, int lo, int hi, Sum next) {…}
  double sumAtLeaf(int l, int h) {…}
  protected Double compute() {
    int l = lo; int h = hi; Sum right = null;
    while (h - l > 1 && getSurplusQueuedTaskCount() <= 3) {
      int mid = (l + h) >>> 1;
      right = new Sum(array, mid, h, right);
      right.fork();
      h = mid;
    }
    double sum = sumAtLeaf(l, h);
    while (right != null) {
      if (right.tryUnfork()) { // directly calculate if not stolen
        sum += right.sumAtLeaf(right.lo, right.hi);
      } else { sum += right.join(); }
      right = right.next;
    }
    return sum;
}}
```

java.util.concurrent

- Copy on write collections
  - CopyOnWriteArrayList<E>
    A thread-safe variant of ArrayList in which all mutative operations (add, set) are implemented by making a fresh copy of the underlying array
  - CopyOnWriteArraySet<E>
    A Set that uses an internal CopyOnWriteArrayList for all of its operations
- Concurrent collections
  - ConcurrentHashMap<K,V>
    A hash table supporting full concurrency of retrievals and adjustable expected concurrency for updates
  - ConcurrentLinkedDeque<E>
    An unbounded concurrent deque based on linked nodes
  - ConcurrentLinkedQueue<E>
    An unbounded thread-safe queue based on linked nodes
  - ConcurrentSkipListMap<K,V>
    A scalable concurrent ConcurrentNavigableMap implementation
  - ConcurrentSkipListSet<E>
    A scalable concurrent NavigableSet implementation based on a ConcurrentSkipListMap.

java.util.concurrent

- BlockingQueue
  - ArrayBlockingQueue<E>
    A bounded blocking queue backed by an array
  - DelayQueue<E extends Delayed>
    An unbounded blocking queue of Delayed elements, in which an element can only be taken when its delay has expired
  - LinkedBlockingDeque<E>
    An optionally-bounded blocking deque based on linked nodes
  - LinkedBlockingQueue<E>
    An optionally-bounded blocking queue based on linked nodes
  - LinkedTransferQueue<E>
    An unbounded TransferQueue based on linked nodes
  - PriorityBlockingQueue<E>
    An unbounded blocking queue that uses the same ordering rules as class PriorityQueue and supplies blocking retrieval operations
  - SynchronousQueue<E>
    A blocking queue in which each insert operation must wait for a corresponding remove operation by another thread, and vice versa

java.util.concurrent

- Atomics
  - AtomicBoolean, AtomicInteger, AtomicLong, AtomicReference<V> Atomic scalar variable wrapper
  - AtomicIntegerArray, AtomicLongArray, AtomicReferenceArray<E> Array with atomic entries
  - AtomicMarkableReference<V> Atomic reference+boolean
  - AtomicStampedReference<V> Atomic reference+int
- Example

```
class Sequencer {
  private final AtomicLong sequenceNumber = new AtomicLong(0);
  public long next() {
    return sequenceNumber.getAndIncrement();
}}
```

java.util.concurrent

- Synchronizers
  - Semaphore is a classic concurrency tool.
  - CountDownLatch is a common utility for blocking until a given number of signals, events, or conditions hold
  - CyclicBarrier is a resettable multiway synchronization point useful in some styles of parallel programming
  - Phaser provides a more flexible form of barrier that may be used to control phased computation among multiple threads
  - Exchanger<V> allows two threads to exchange objects at a rendezvous point, and is useful in several pipeline designs.

java.util.concurrent

- Locks
  - ReentrantLock A reentrant mutual exclusion Lock with the same basic behavior and semantics as the implicit monitor lock accessed using synchronized methods and statements, but with extended capabilities
  - ReentrantReadWriteLock An implementation of ReadWriteLock supporting similar semantics to ReentrantLock

java.util.concurrent

- LockSupport.park() Disables the current thread for thread scheduling purposes unless the permit is available
- LockSupport.unpark() Makes available the permit for the given thread, if it was not already available
- Along with Atomics it is the foundation and only non-Java part of java.util.concurrent
- Can be used to build your own types of locks

java.util.concurrent

- Example of custom lock

```
class FIFOMutex {
  private final AtomicBoolean locked = new AtomicBoolean(false);
  private final Queue<Thread> waiters = new ConcurrentLinkedQueue<Thread>();
  public void lock() {
    Thread current = Thread.currentThread();
    waiters.add(current);
    // Block while not first in queue or cannot acquire lock
    while (waiters.peek() != current || !locked.compareAndSet(false, true)) {
      LockSupport.park(this);
    }
    waiters.remove();
  }
  public void unlock() {
    locked.set(false);
    LockSupport.unpark(waiters.peek());
  }
}
```