Principles of Software Construction: Objects, Design, and Concurrency

Part 5: Concurrency

Introduction to concurrency, part 3

Concurrency primitives, libraries, and design patterns

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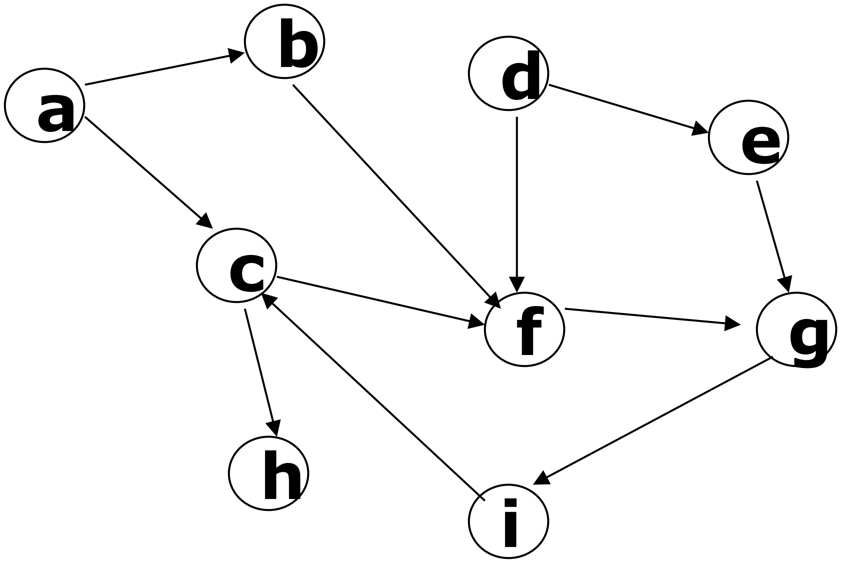
Administrivia

- Homework 5b due Tuesday 11:59 p.m.
  - Turn in by Wednesday 9 a.m. to be considered as a Best Framework
- 17-355/17-665/17-819: Program Analysis
  - http://www.cs.cmu.edu/~aldrich/courses/17-355/

Key concepts from Tuesday

Avoiding deadlock

- The *waits-for graph* represents dependencies between threads
  - Each node in the graph represents a thread
  - An edge T1->T2 represents that thread T1 is waiting for a lock T2 owns
- Deadlock has occurred iff the waits-for graph contains a cycle
- One way to avoid deadlock: locking protocols that avoid cycles



Encapsulating the synchronization implementation

```
public class BankAccount {
  private long balance;
  private final long id = SerialNumber.generateSerialNumber();
  private final Object lock = new Object();

  public BankAccount(long balance) {
    this.balance = balance;
  }

  static void transferFrom(BankAccount source,
                           BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first.lock) {
        synchronized (second.lock) {
            source.balance -= amount;
            dest.balance += amount;
        }
    }
  } …
```

An aside: Java Concurrency in Practice annotations

```
@ThreadSafe
public class BankAccount {
  @GuardedBy("lock")
  private long balance;
  private final long id = SerialNumber.generateSerialNumber();
  private final Object lock = new Object();

  public BankAccount(long balance) {
    this.balance = balance;
  }

  static void transferFrom(BankAccount source,
                           BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first.lock) {
        synchronized (second.lock) {
            source.balance -= amount;
            dest.balance += amount;
        } …
```

An aside: Java Concurrency in Practice annotations

- `@ThreadSafe`
- `@NotThreadSafe`
- `@GuardedBy`
- `@Immutable`

Today

- Strategies for safety
- Building thread-safe data structures
  - Java primitives for concurrent coordination
- Java libraries for concurrency
- Program structure for concurrency

Shared mutable state requires concurrency control

- Three basic choices:
  1. Don't mutate: share only immutable state
  2. Don't share: isolate mutable state in individual threads
  3. If you must share mutable state: *limit concurrency to achieve safety*

Stack confinement

- Primitive local variables are never shared between threads

Thread confinement with `java.lang.ThreadLocal<T>`

- Sharable variable that confines state to each thread
  - Internally similar to a `Map<Thread,T>`

```
ThreadLocal<T>:
  T get();             // gets value for current thread
  void set(T value); // sets value for current thread
```

Defining thread-safe objects

- Identify variables that represent the object's state
- Identify invariants that constrain the state variables
- Establish a policy for maintaining invariants with concurrent access to state

Policies for thread safety

- Thread-confined
- Shared read-only
- Guarded
  - Objects that must be synchronized externally
- Shared thread-safe
  - Objects that perform internal synchronization

More Java primitives, for coordination

- Goal: *guarded suspension* without *spin-waiting*

```
volatile boolean ready = …;
while (!ready);  // loop until ready…
```

- `Object` methods for coordination:

```
void wait();
void wait(long timeout);
void notify();
void notifyAll();
```

A toy example: Read-write locks (a.k.a. *shared* locks)

Sample client code:

```
private final RwLock lock = new RwLock();

lock.readLock();
try {
    // Do stuff that requires read (shared) lock
} finally {
    lock.unlock();
}

lock.writeLock();
try {
    // Do stuff that requires write (exclusive) lock
} finally {
    lock.unlock();
}
```

A toy example: Read-write locks (implementation 1/2)

```
@ThreadSafe
public class RwLock {
    // State fields are protected by RwLock's intrinsic lock

    /** Num threads holding lock for read. */
    @GuardedBy("this")
    private int numReaders = 0;

    /** Whether lock is held for write. */
    @GuardedBy("this")
    private boolean writeLocked = false;

    public synchronized void readLock() throws InterruptedException {
        while (writeLocked) {
            wait();
        }
        numReaders++;
    }
```

A toy example: Read-write locks (implementation 2/2)

```
    public synchronized void writeLock() throws InterruptedException {
        while (numReaders != 0 || writeLocked) {
            wait();
        }
        writeLocked = true;
    }

    public synchronized void unlock() {
        if (numReaders > 0) {
            numReaders--;
        } else if (writeLocked) {
            writeLocked = false;
        } else {
            throw new IllegalStateException("Lock not held");
        }
        notifyAll(); // Wake any waiters
    }
}
```

Basic advice for building thread-safe objects

- Do as little as possible in synchronized region: get in, get out
  - Obtain lock
  - Examine shared data
  - Transform as necessary
  - Drop the lock
- If you must do something slow, move it outside the synchronized region

Documentation

- Document a class's thread safety guarantees for its clients
- Document a class's synchronization policy for its maintainers
- Use `@ThreadSafe`, `@GuardedBy` annotations

Summary of our `RwLock` example

- Generally, avoid `wait/notify`
- Never invoke `wait` outside a loop
  - Must check coordination condition after waking
- Generally use `notifyAll`, not `notify`
- Do not use our `RwLock` – it's just a toy
  - Instead, know the standard libraries…
    - Discuss: `sun.misc.Unsafe`

java.util.concurrent is BIG (1)

- Atomic variables: `java.util.concurrent.atomic`
  - Support various atomic read-modify-write ops
- Executor framework
  - Tasks, futures, thread pools, completion service, etc.
- Locks: `java.util.concurrent.locks`
  - Read-write locks, conditions, etc.
- Synchronizers
  - Semaphores, cyclic barriers, countdown latches, etc.

java.util.concurrent is BIG (2)

- Concurrent collections
  - Shared maps, sets, lists
- Data exchange collections
  - Blocking queues, deques, etc.
- Pre-packaged functionality: `java.util.Arrays`
  - Parallel sort, parallel prefix

The `java.util.concurrent.atomic` package

- Concrete classes supporting atomic operations, e.g.:
  - `AtomicLong`

```
long get();
void set(long newValue);
long getAndSet(long newValue);
long getAndAdd(long delta);
long getAndIncrement();
boolean compareAndSet(long expectedValue,
                      long newValue);
long getAndUpdate(LongUnaryOperator updateFunction);
long updateAndGet(LongUnaryOperator updateFunction);

…
```

AtomicLong example

```
public class SerialNumber {
    private static AtomicLong nextSerialNumber = new AtomicLong();

    public static long generateSerialNumber() {
        return nextSerialNumber.getAndIncrement();
    }
}
```

Overview of `java.util.concurrent.atomic`

- `Atomic{Boolean,Integer,Long}`
  - Boxed primitives that can be updated atomically
- `AtomicReference<T>`
  - Object reference that can be updated atomically
- `Atomic{Integer,Long,Reference}Array`
  - Array whose elements may be updated atomically
- `Atomic{Integer,Long,Reference}FieldUpdater`
  - Reflection-based utility enabling atomic updates to volatile fields
- `LongAdder`, `DoubleAdder`
  - Highly concurrent sums
- `LongAccumulator`, `DoubleAccumulator`
  - Generalization of `adder` to arbitrary functions (`max`, `min`, etc.)

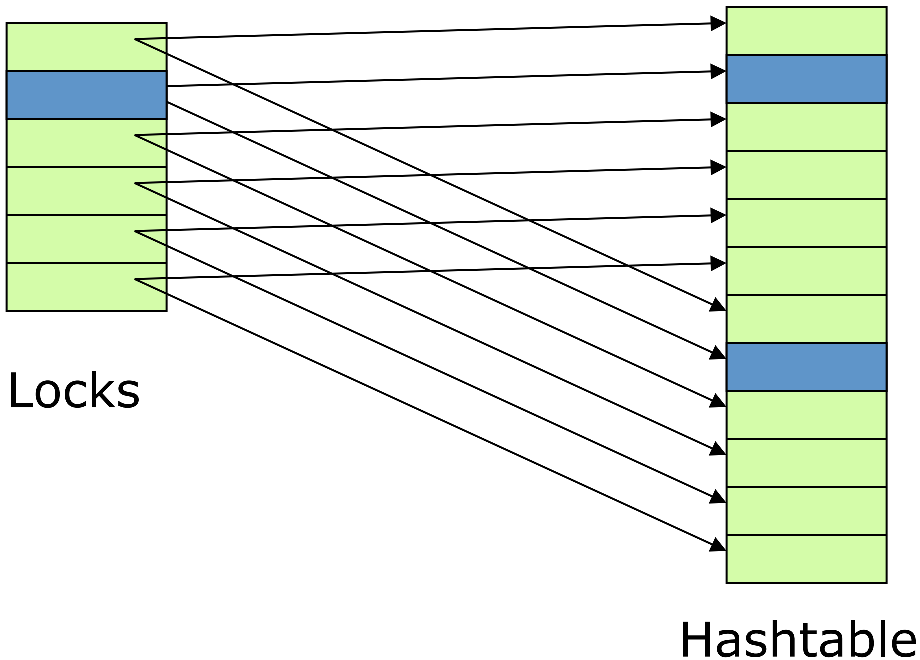
Concurrent collections

- Provide high performance and scalability

Unsynchronized	Concurrent
`HashMap`	`ConcurrentHashMap`
`HashSet`	`ConcurrentHashSet`
`TreeMap`	`ConcurrentSkipListMap`
`TreeSet`	`ConcurrentSkipListSet`

`java.util.concurrent.ConcurrentHashMap`

- Implements `java.util.Map<K,V>`
  - High concurrency lock striping
    - Internally uses multiple locks, each dedicated to a region of hash table
  - Externally, can use `ConcurrentHashMap` like any other map…



Atomic read-modify-write methods

- `V putIfAbsent(K key, V value);`
- `boolean remove,(Object key, Object value);`
- `V replace(K key, V value);`
- `boolean replace(K key, V oldValue, V newValue);`
- `V compute(K key, BiFunction<...> remappingFn);`
- `V computeIfAbsent(K key, Function<...> mappingFn);`
- `V computeIfPresent (K key, BiFunction<...> remapFn);`
- `V merge(K key, V value, BiFunction<...> remapFn);`

`java.util.concurrent.BlockingQueue`

- Implements `java.util.Queue<E>`
- `java.util.concurrent.SynchronousQueue`
  - Each `put` directly waits for a corresponding `poll`
- `java.util.concurrent.ArrayBlockingQueue`
  - `put` blocks if the queue is full
  - `poll` blocks if the queue is empty

The `CopyOnWriteArrayList`

- Implements `java.util.List<E>`
- All writes to the list copy the array storing the list elements

Example: adding concurrency to the observer pattern

```java
// Not thread safe. Contains a subtle bug.

private final List<Observer<E>> observers = new ArrayList<>();
public void addObserver(Observer<E> observer) {
   synchronized(observers) { observers.add(observer); }
}
public boolean removeObserver(Observer<E> observer) {
   synchronized(observers) { return observers.remove(observer); }
}
private void notifyOf(E element) {
   synchronized(observers) {
       for (Observer<E> observer : observers)
           observer.notify(this, element);
   }
}
```

Example: adding concurrency to the observer pattern

```
private final List<Observer<E>> observers = new ArrayList<>();
public void addObserver(Observer<E> observer) {
   synchronized(observers) { observers.add(observer); }
}
public boolean removeObserver(Observer<E> observer) {
   synchronized(observers) { return observers.remove(observer); }
}
private void notifyOf(E element) {
   synchronized(observers) {
      for (Observer<E> observer : observers)
         observer.notify(this, element);  // Risks liveness and
   }                                      // safety failures!
}
```

One solution: *snapshot iteration*

```
private void notifyOf(E element) {
    List<Observer<E>> snapshot = null;

    synchronized(observers) {
        snapshot = new ArrayList<>(observers);
    }

    for (Observer<E> observer : snapshot) {
        observer.notify(this, element); // Safe
    }
}
```

A better solution: `CopyOnWriteArrayList`

```
private final List<Observer<E>> observers =
       new CopyOnWriteArrayList<>();

public void addObserver(Observer<E> observer) {
   observers.add(observer);
}
public boolean removeObserver(Observer<E> observer) {
   return observers.remove(observer);
}
private void notifyOf(E element) {
   for (Observer<E> observer : observers)
       observer.notify(this, element);
}
```

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Producer-consumer design pattern

- Goal: Decouple the producer and the consumer of some data
- Consequences:
  - Removes code dependency between producers and consumers
  - Producers and consumers can produce and consume at different rates

`java.util.concurrent.BlockingQueue`

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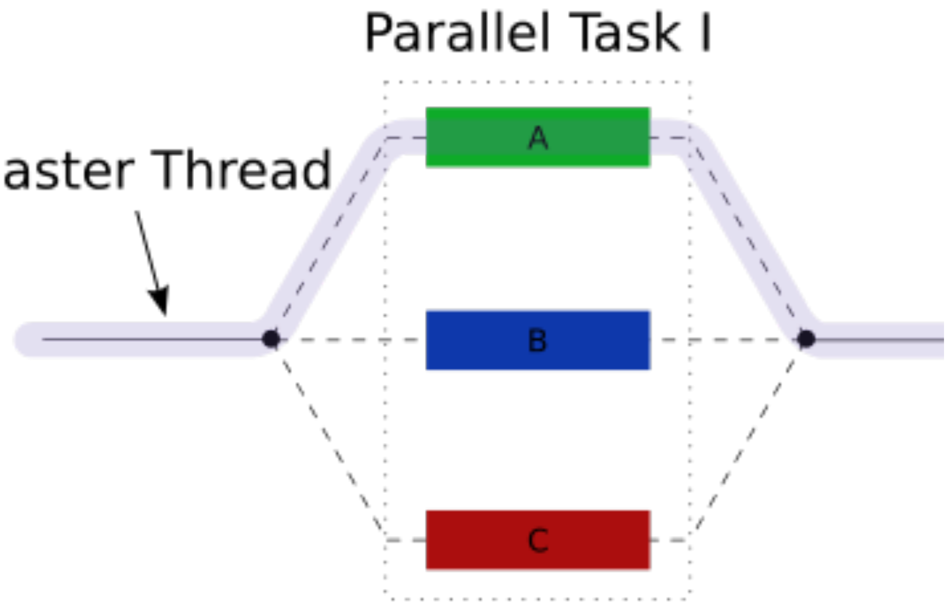
The fork-join pattern




```
if (my portion of the work is small)
    do the work directly
else
    split my work into pieces
    invoke the pieces and wait for the results
```

The membrane pattern

- Multiple rounds of fork-join, each round waiting for the previous round to complete

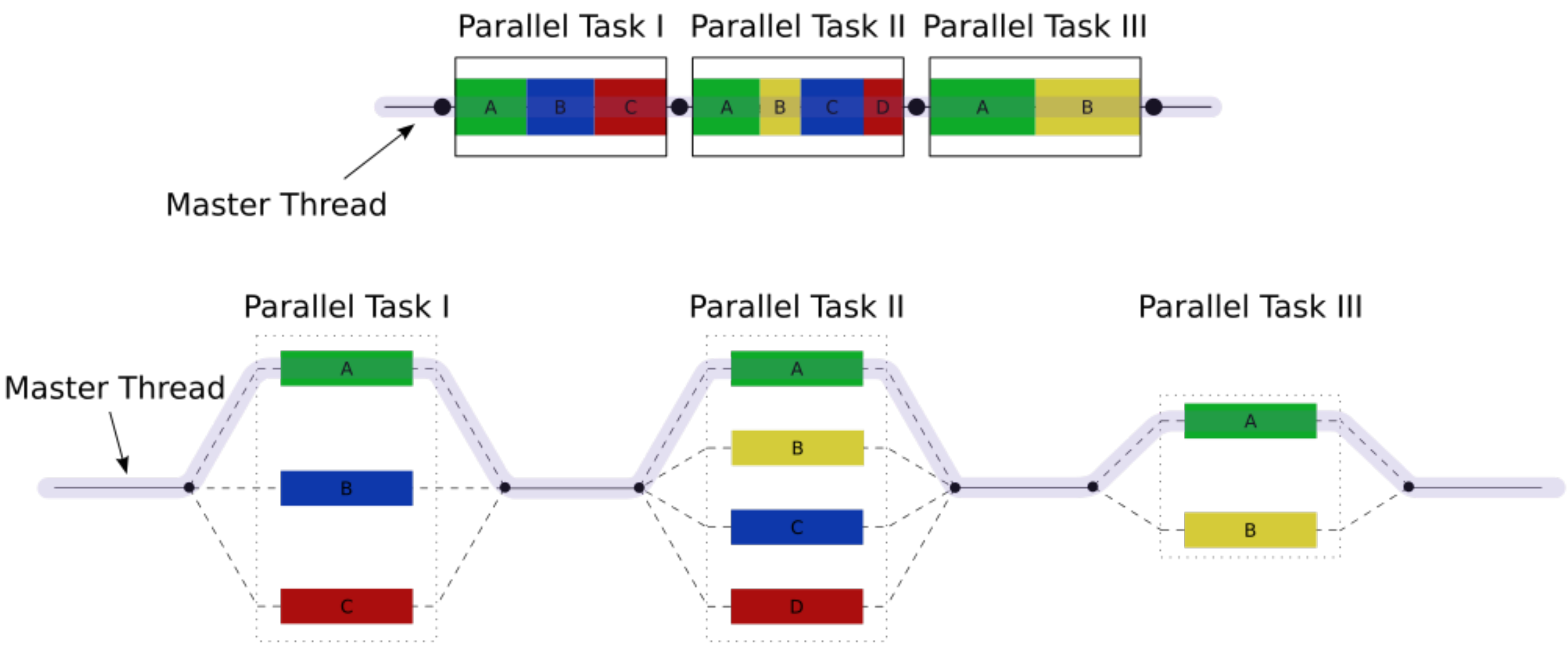


Image from: Wikipedia

Summary

- Reuse, don't build: know the j.u.c. libraries
- Use common patterns for program structure
  - Decompose work into independent tasks