Advances in Programming Languages

APL13: Concurrency Abstractions

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Techniques for concurrency

This is the second of a block of lectures looking at programming-language techniques for managing concurrency.

- Introduction, basic Java concurrency
- Concurrency abstractions in Java
- Concurrency in some other languages
- Guest lecture(s) TBC

Outline

Thread safety

To avoid consistency problems with racy code, the programmer should explain which classes are considered **thread safe**, especially for library classes used for storing data that is likely to be shared between threads.

Informally, a class is thread safe if its methods may be invoked from different threads at the same time. A precise definition is *much* more tricky.

- a good idea to document this, e.g. with an *annotation* `@ThreadSafe`.

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A very naive approach to concurrency problems is to fix concurrency bugs by successively adding more uses of synchronize. Just like deleting statements that cause runtime errors, this rarely succeeds (why not?).

A better approach is to make objects *immutable* when feasible. Once constructed, such an object cannot be modified, so is inherently thread safe. A precise definition is suprisingly tricky.

- good idea to document this, e.g., writing `@Immutable`.

Managing atomicity

If an object cannot be made immutable, then accesses to it can be made *atomic* to avoid race conditions. **Even `x++` is not an atomic operation!**

A non thread-safe hit counter

```
@NotThreadSafe
public class BadHitCounter {
    private int hits = 0;

    public int getHits() { return hits.get(); }

    public String fetchPage() {
      String page = ... ; page = page + hits++; ...
      return page;
    }
}
```

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A thread-safe hit counter

```
@ThreadSafe
public class GoodHitCounter {
    private int hits = 0;

    public synchronized int getHits() { return hits; }

    public synchronized String fetchPage() {
      String page = ... ; page = page + hits++; ...
      return page;
    }
}
```

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A thread-safe hit counter using **AtomicInteger**

```
import java.util.concurrent.atomic.AtomicInteger;
@ThreadSafe
public class GoodHitCounter2 {
    private final AtomicInteger hits = new AtomicInteger(0);

    public integer getHits() { return hits.get(); }

    public String fetchPage() {
      String page = ... ;  page = page + hits.incrementAndGet(); ...
      return page;
    }
}
```

Synchronizing many objects

How do we manage synchronization across compound objects in a system?

A *synchronization policy* is necessary to describe which locks protect which pieces of shared data, who is responsible for obtaining the locks, and in which order they are obtained.

Deadlock 101

Thread A:

```
synchronized (o1) {
  ...
  synchronized (o2) {
    ...
  }
}
```

Thread B:

```
synchronized (o2) {
  ...
  synchronized (o1) {
    ...
  }
}
```

Thread safe collections

Some basic Java collection classes are not thread safe, but convenient wrapper methods can add synchronization around accessor methods.

```
List<Customer> customerList =
        Collections.synchronizedList(new ArrayList<Customer>());

addCustomers(customerList);

for (Customer c : customerList) {
    processCustomer(c);
}
```

Despite using a synchronized list, it is still possible for this code to throw ConcurrentModificationException. Why? How could it be avoided?

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The addCustomers call *leaks* the reference to the customer list. It's possible that another thread retains this and manipulates the list after return.

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The implicit iteration in the **for** loop may interact with another thread that is modifying the list. We must lock the whole list while iterating.

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    processCustomer(c);
}
```

Confusingly, even single-threaded code can throw ConcurrentModificationException, when the API contract of call sequences is violated by modifying during iteration; Java chooses a *fail fast* policy to detect this between calls and abort.

Concurrent collections

The drawback with synchronized compound objects is that further locking may be required when executing compound operations, so we haven't automatically solved consistency problems.

More crucially, they may become a *serialization bottleneck* as serialising accesses prevents concurrency.

The *concurrent collections* introduced in Java 5.0 allow a remedy.

Interfaces:

- Queue
- List
- ConcurrentMap
- BlockingQueue

Classes:

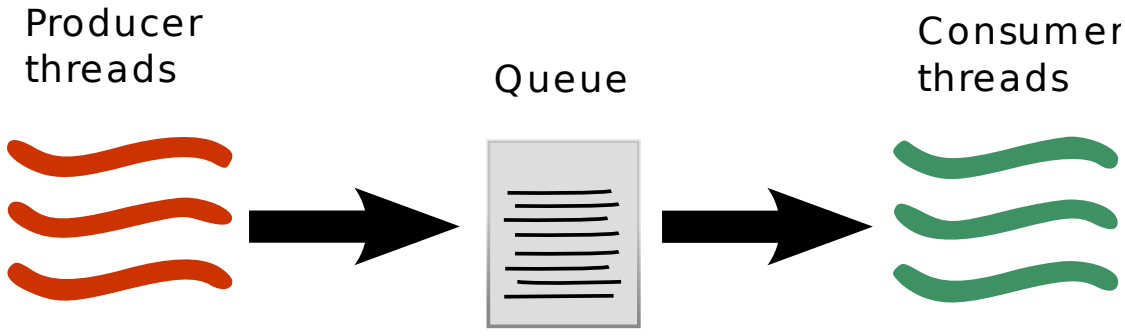
- ConcurrentLinkedQueue
- CopyOnWriteArrayList
- ConcurrentHashMap
- ArrayBlockingQueue

These live in the package java.util.concurrent alongside other utilities. They use various mechanisms to give thread safe results, including *non-blocking* algorithms and lower-level features such as **volatile** variables.

Queues and producer-consumer patterns

The producer-consumer pattern is a common way to decouple jobs and achieve scalable parallelism.

A queue acts as thread-safe "glue" which allows independent tasks to proceed on each side without interfering. Consumers block when the queue is empty; producers block when the queue full.



BlockingQueue access methods

	Throws ex'n	Special value	Blocks	Times out
Insert	add(e)	offer(e)	put(e)	offer(e, time, unit)
Remove	remove()	poll()	take()	poll(time, unit)
Examine	element()	peek()	–	–

Outline

Application frameworks

Application frameworks separate duties and isolate subparts of a system by using different threads for different tasks. For example:

- The Java Virtual Machine runs a thread for executing the program's main() method, which may start further threads; it also runs *daemon* threads for housekeeping tasks such as garbage collection.
- Swing applications create a GUI thread which uses an input event queue; all GUI operations are confined to the GUI thread.
- JEE application servers use a *thread pool* to use for container tasks.

To manage finer grained concurrency in a system, some form of additional management on top of threads is often desirable, for example, to manage *work queues* and *tasks* effectively.

Finer granularity allows applications to avoid excessive overhead, by reducing the amount of context switching and the load on a single system level scheduler (which may have hard limits).

Tasks and executors

Effective concurrent programs subdivide work into *tasks*, which are as independent as possible. Some types of tasks may have to be executed in a given sequence, one at a time. Others may be executed concurrently in multiple threads.

Java provides **executors** as an abstraction for work queues which execute tasks. An executor encapsulates one or more threads.

```
public interface Runnable {
  void run();
}

public interface Executor {
  // execute command at some time
  void execute(Runnable command);
}
```

```
Executor workerExecutor =
        Executors.newFixedThreadPool(5);

// schedule 20 jobs immediately
for (int i = 0; i<20; i++) {
   WorkerJob job = new WorkerJob();
   workerExecutor.execute(job);
}
```

Executor Strategies

Executors can encode particular strategies for managing the execution of tasks between different threads.

Standard executors include:

Fixed thread pool
: tasks are run by a fixed number of threads;

Cached thread pool
: the pool of threads grows and shrinks dynamically;

Single thread
: tasks are executed in order in one thread;

Scheduled thread pool
: a thread pool for executing tasks periodically.

Futures

Simple Runnable tasks do something and then finish. To communicate a result, Java uses *futures*, which are an abstraction of asynchronous result-returning computations. Futures can also be managed by executors.

```
public interface Callable<V> {
  V call() throws Exception;
}

public interface Future<V> {
  V get();
// maybe blocking
  void cancel();
  boolean isCancelled();
  boolean isDone();
}
```

```
FutureTask<Integer> searchFuture =
new FutureTask<String>(new Callable<String>() {
  public String call() {
    return searcher.findMatch(target);
}});

// search while we do something else
executor.execute(searchFuture);
...
if (searchFuture.isDone()) {
  result = searchFuture.get();
} else {
  result = "not found";
  searchFuture.cancel();
}
```

Outline

Homework

Before the next lecture:

- Write a program which demonstrates the race condition in `BadHitCounter`.
- Explore the deficiencies of Java intrinsic locking by describing programs which demonstrate when:
  - it might be desirable to back-off from an attempt to acquire a lock;
  - it might be desirable for a lock *not* to be reentrant;
  - it would be useful to have non-block structured locking.
- Investigate some of the facilities included in `java.util.concurrent`. Specifically, use them to:
  - re-implement your pigeon fancier program using executors;
  - modify the program to allow the pigeon coop to be rerranged (by inserting or removing pigeon holes) while in use, but with minimal disruption.

Summary

Java concurrency abstractions

Java provides concurrency extensions in the library java.util.concurrent. These include:

- **concurrent collections** which include scalable thread-safe classes for lists, maps and queues;
- **task management** at a finer granularity than threads, using *executors* which provide a range of thread pooling and (simple) scheduling strategies.
  - Java 7 will have a *fork-join* library for managing tasks which subdivide themselves, and executors which schedule tasks with *work stealing*.
- **futures** which are asynchronous tasks that return results.

Similar abstractions are available in other languages and libraries.

References

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- Doug Lea. *Concurrent Programming in Java. Second Edition. Design Principles and Patterns.* Addison-Wesley, 2000.
  - the original standard text, describing many of the patterns now implemented inside `java.util.concurrent`, and some of the horrors of the Java Memory Model.
- Christian Haack, Erik Poll, Jan Schäfer and Aleksy Schubert. *Immutable Objects for a Java-Like Language*, Proc. European Symposium On Programming 2007, Springer Lecture Notes in Computer Science 4421, pages 347–362, 2007.
  - a precise formalisation of immutability for a simplifed version of Java.