Java™ Generics and Collections: Tools for Productivity

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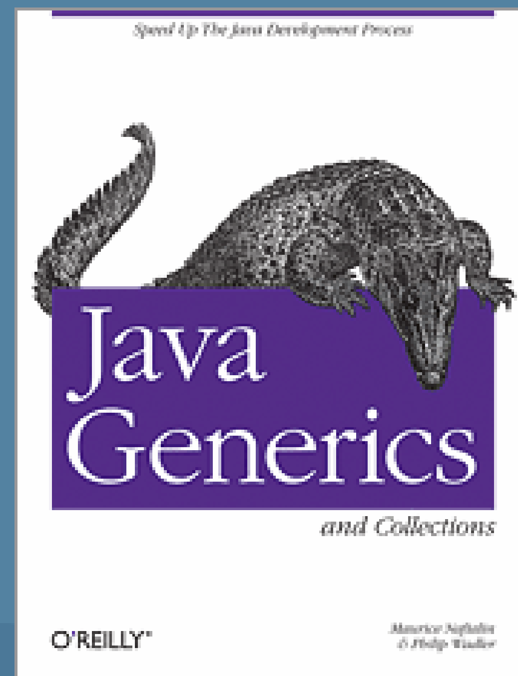

TS-2890

The Right Tools for the Job

What you can – and can't! – do with the Generics and Collections features introduced in Java 5 and Java 6

Agenda

- Generics
  - Why have them?
  - Implementation by erasure – benefits …
  - … and problems
  - What next?
- Collections
  - Trends in concurrency policy
  - Trends in API design
  - How to choose an implementation

Generics

- Generics
  - **Why have them?**
  - Implementation by erasure – benefits …
  - … and problems
  - What next?
- Collections
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Cleaner code

Before:

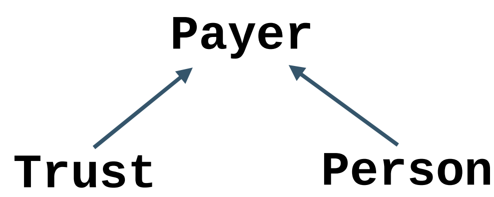
```
List ints = Arrays.asList(1,2,3);
int s = 0;
for (Iterator it = ints.iterator(); it.hasNext();){
   s += it.next();
}
```

After:

```
List<Integer> ints = Arrays.asList(1,2,3);
int s = 0;
for (int n : ints) { s += n; }
```

Detect more errors at compile-time

Strategy pattern for paying tax:




```
interface Strategy<P extends Payer>{ long computeTax(P p); }

class DefaultStrategy<P extends Payer>
   implements Strategy<P> { long computeTax(P p){…} }

class TrustTaxStrategy extends DefaultStrategy<Trust> {
   public long computeTax(Trust t) {
      return trust.isNonProfit ? 0 : super.computeTax(t);
   }
}
```

```
new TrustTaxStrategy().computeTax(person)
```

fails **at compile time** with generics

Detect more errors at compile-time

`ArrayStoreException`s become compile errors

- Arrays:

```
Integer[] ints = new Integer[]{1,2,3}
Number[] nums = ints;
nums[2] = 3.14;                    // run-time error
```

`Integer[]` is a subtype of `Number[]`

- Collections:

```
List<Integer> ints = Arrays.asList(1,2,3);
List<Number> nums = ints;  // compile-time error
nums.put(2, 3.14);
```

`List<Integer>` is not a subtype of `List<Number>`

More Expressive Interfaces

From **`javax.management.relation.Relation`**

- Before

```
interface Relation {
    public Map getReferencedMBeans()
    …
}
```

- After

```
interface Relation {
    public Map<ObjectName,List<String>>
                                  getReferencedMBeans()
    …
}
```

Explicit types in client code – much easier to maintain

Generics

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Migration Compatibility

Major design constraint for generics: *Binary for legacy client must link to generified library*

With erasure:

Generified library binary	=	Legacy library binary

Allows piecewise generification of libraries

Erasure Eases Evolution

From Legacy...

Library

```
interface Stack {
   void push(Object elt);
   Object pop();
}
class ArrayStack implements Stack {
   private List li = new ArrayList();
   public void push(Object elt) { li.add(elt); }
   public Object pop(){ return li.remove(li.size()-1); }
}
```

Client

```
Stack stack = new ArrayStack();
stack.push("first");
String top = (String)stack.pop();
```

...to Generic

Library

```
interface Stack<E> {
   void push(E elt);
   E pop();
}
class ArrayStack<E> implements Stack<E> {
   private List<E> li = new ArrayList<E>();
   public void push(E elt) { li.add(elt); }
   public E pop() { return li.remove(li.size()-1); }
}
```

Client

```
Stack<String> stack = new ArrayStack<String>();
stack.push("first");
String top = stack.pop();
```

Generic Library with Legacy Client

Library

```
interface Stack<E> {
   void push(E elt);
   E pop();
}
class ArrayStack<E> implements Stack<E> {
   private List<E> li = new ArrayList<E>();
   public void push(E elt) { li.add(elt); }
   public E pop() { return li.remove(li.size()-1); }
}
```

Client

```
Stack stack = new ArrayStack();
stack.push("first");       // unchecked call
String top = (String)stack.pop();
```

Legacy Library with Generic Client

Three options

- Minimal changes (surface generification)
- Stubs
- Wrappers - not recommended!

Minimal Changes

Library with "Surface Generification"

```
class ArrayStack<E> implements Stack<E> {
   private List li = new ArrayList();
   public void push(E elt){li.add(elt);} //unchecked call
   public E pop(){
      return (E)li.remove(li.size()-1);  //unchecked cast
   }
}
```

Stubs

Stubs

```
class ArrayStack<E> implements Stack<E> {
   public void push(E elt) { throw new StubException(); }
   public E pop() { throw new StubException(); }
   …
}
```

Compile with stubs, execute with legacy library

```
$ javac -classpath stubs Client.java
$ java -ea -classpath legacy Client
```

Wrappers (not recommended!)

Generified wrapper class

```
interface GenericStack<E> {
    void push(E elt);
    E pop();
   public Stack unwrap();
}
class StackWrapper<E> implements GenericStack<E> {
    private Stack st = new ArrayStack();
    public void push(E elt) { st.push(elt); }
    public E pop(){ return (E)st.pop(); } //unchecked cast
}
```

Generic client

```
GenericStack<String> stack = new StackWrapper<String>();
stack.push("first");
String top = stack.pop();
```

Problems With Wrappers

- Parallel class hierarchies
  - **`Stack/GenericStack`** etc
- Nested structures lead to multiple wrapper layers
  - E.g. a stack of stacks
- Library essentially in two versions
  - For generified and legacy clients

Wrappers recreate the problems that erasure solves

Generics

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Problems of Erasure

- Parameter types are not ***reified*** – they are not represented at run-time
- Constructs requiring run-time type information don't work well (or don't work)
  - Casts and **`instanceof`**
  - Parametric exceptions
  - Problems with arrays
    - array run-time typing doesn't play well with erasure

No Arrays Of Generic Types

Converting a collection to an array:

```
class ConversionAttemptOne {
   static <T> T[] toArray(Collection<T> c) {
      T[] a = new T[c.size()];   // compile error
      int i = 0;
      for (T x : c) {
         a[i++] = x;
      }
      return a;
   }
}
```

The Principle of Truth in Advertising

Converting a collection to an array:

```
class AttemptTwo {
    static <T> T[] toArray(Collection<T> c) {
        T[] a = (T[])new Object[c.size()]; // unchecked cast
        int i = 0;
        for (T x : c) {
            a[i++] = x;
        }
        return a;
    }
}
```

Is the return type from **`toArray`** an honest description?

JavaOne

The Principle of Truth in Advertising

An innocent client tries to use `AttemptTwo` :

```
public static void main (String[] args) {
   List<String> strings = Arrays.asList("one","two");
   String[] sa =
      AttemptTwo.toArray(strings); //ClassCastException!
}
```

What happened?

The Principle of Truth in Advertising

This is **AttemptTwo** after erasure:

```
class AttemptTwo {
    static Object[] toArray(Collection c) {
            Object[] a = (Object[])new Object[c.size()];
            …
            return a;
    }
}
```

And this is the innocent client:

```
String[] sa = (String[])AttemptTwo.toArray(strings);
```

The Principle of Truth in Advertising

Static type of the array

Compiler inserts cast to static type

Reified (ie run-time) type is `Object[]`

```
String[] sa = (String[]) AttemptTwo.toArray(strings);
```

The reified type of an array must be a subtype of the erasure of its static type

(and here, it's not)

Converting A Collection To An Array

Get type information at run-time from array or class token

```
class SuccessfulConversion {
    static <T> T[] toArray(Collection<T> c, T[] a) {
        if (a.length < c.size())
                a = (T[])Array.newInstance( // unchecked cast
                a.getClass().getComponentType(),c.size());
        int i = 0; for (T x : c) a[i++] = x;
        if (i < a.length) a[i] = null;
        return a;
    }
    static <T> T[] toArray(Collection<T> c, Class<T> k) {
        T[] a = (T[])Array.              // unchecked cast
                    newInstance(k, c.size());
        int i = 0; for (T x : c) a[i++] = x;
        return a;
    }
}
```

Principle of Indecent Exposure

Don't ignore unchecked warnings!

```
class Cell<T> {
    private T value;
    Cell(T v) { value = v; }
    T getValue() { return value; }
}
class DeceptiveLibrary {
    static Cell<Integer>[] createIntCellArray(int size) {
        return (Cell<Integer>[])         // unchecked cast
                new Cell[size];
    }
}
class InnocentClient {
    Cell<Integer>[] intCellArray = createIntCellArray(3);
    Cell<? extends Number>[] numCellArray = intCellArray;
    numCellArray[0] = new Cell<Double>(1.0);
    int i = intCellArray[0].getValue(); //ClassCastException
}
```

Principle of Indecent Exposure

```
return (Cell<Integer>[])new Cell[size];
```

Don’t publicly expose an array whose components do not have a reifiable type

(and here, we have done)

Generics

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  - Why have them?
  - Implementation by erasure – benefits …
  - … and problems
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  - Trends in concurrency policy
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What Next For Generics?

- Reification?
  - The debate rages on…
  - Technically feasible?
  - Compatibility problems
  - One possible approach: distinguish reified type parameters with new syntax
    - ```
      interface NewCollection<class E> extends
                                  Collection<E> { ... }
      ```
  - Discussion on Java 7 still in early stages
      ```

Collections

- Generics
  - Why have them?
  - Implementation by erasure – benefits …
  - … and problems
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Collections concurrency policy

How has it changed?

- JDK 1.0
  - Synchronized collection methods
- JDK 1.2
  - Java Collections Framework – unsynchronized
    - Optional method synchronization with synchronized wrappers
- Java 5
  - java.util.concurrent (JSR166)
    - Thread-safe classes designed for efficient concurrent access

Many java.util Collections Aren't Thread-Safe (by design)

- From **`java.util.ArrayList`**

```
public boolean add(E e) {
    ensureCapacity(size + 1);
    elementData[size++] = e;
    return true;
}
```

- The value in **`elementData`** is set, then **`size`** is incremented

  Two threads could execute **`add`** concurrently, with **`size == 0`** initially:

  1. Thread A sets **`elementData[0]`**
  2. Thread B sets **`elementData[0]`**
  3. Thread A increments **`size`**
  4. Thread B increments **`size`**

- Unsynchronized method access leaves the **`ArrayList`** in an inconsistent state

Some java.util Collections Are Thread-Safe (at a cost)

From java.util.Vector (JDK 1.0)

```
public synchronized void addElement(E obj){
    ensureCapacityHelper(elementCount + 1)
    elementData[elementCount++] = obj;
}
```

From java.util.Collections (JDK 1.2)

```
static class SynchronizedList<E> implements List<E> {
    final List<E>; final Object mutex;
    SynchronizedList(List<E> list) {this.list = list;}
    public void add(int index, E element) {
        synchronized(mutex) {list.add(index, element);}
    }
    …
}
```

Thread-Safe != Concurrent

Even thread-safe java.util collections have *fail-fast iterators*

```
List<String> sl = new ArrayList<String>();
sl.addAll(Collections.nCopies(1000000,"x"));
```

- Thread A:

```
for( Iterator<String> itr = sl.iterator();
                                       itr.hasNext(); ) {
   System.out.println(itr.next());
}
```

- Thread B:

```
for( int i = 999999; i > 0; i-- ) {
   sl.remove(i);
}
```

Thread A throws **`ConcurrentModificationException`** immediately after thread B ***first*** modifies the List

Using java.util Collections Concurrently

Additional safeguards needed for concurrent access

- Use *client-side locking*
- Subclass or wrap the collection:

```
public class WrappedList<T> implements List<T> {
   private final List<T> list;
   public WrappedList<T> list){ this.list = list; }
   public synchronized void addIfAbsent(T x) {
      if (!list.contains(x))
         list.add(x);
      }
   }
   // delegate other methods
}
```

For concurrent use, **`java.util`** collections must often be locked for all operations, ***including iteration!***

Concurrent Collections

No safeguards needed for java.util.concurrent classes

Collections in **`java.util.concurrent`** don't require external locking:

- Atomic operators provided where necessary
  - **`ConcurrentMap`** operations
    - atomic test-then-act: **`putIfAbsent, remove, replace`**
  - **`Blocking{Queue|Deque`**} operations
    - blocking operations: **`take`**, **`put`**
    - operations from **`Queue`** or **`Deque`** now required to be atomic
- Iterators are *snapshot* or *weakly consistent*
  - Never throw **`ConcurrentModificationException`**

Concurrent Collections

Two kinds of iterator behavior

- Copy-on-write collections
  - **`CopyOnWriteArraySet,CopyOnWriteArrayList`**
  - *snapshot* iterators
  - underlying array is effectively immutable
  - iterators **do not** reflect changes in underlying collection
  - never fail with **`ConcurrentModificationException`**
- Other concurrent collections
  - *weakly consistent* (wc) iterators
  - Iterators **may** reflect changes in underlying collection
  - never fail with **`ConcurrentModificationException`**

Collections

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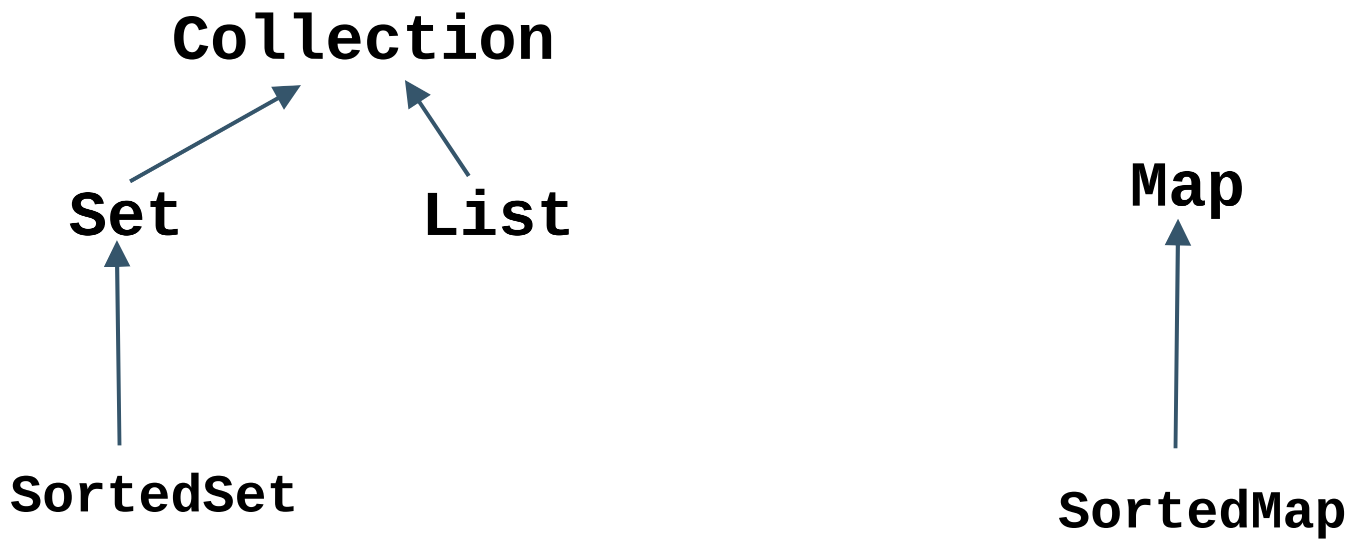
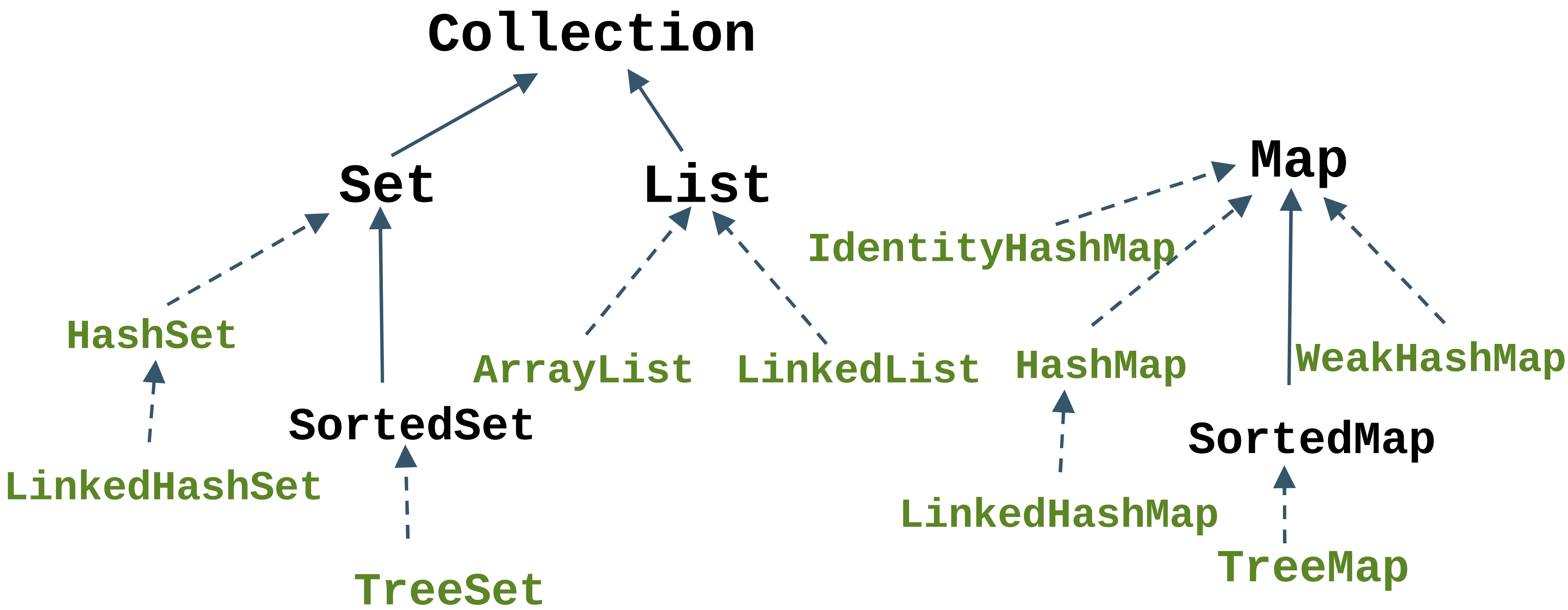
Java Collections Framework at Java 2

Interface-based API:



Implementations: JDK 1.2 – JDK 1.4

Increasing choice of implementations:



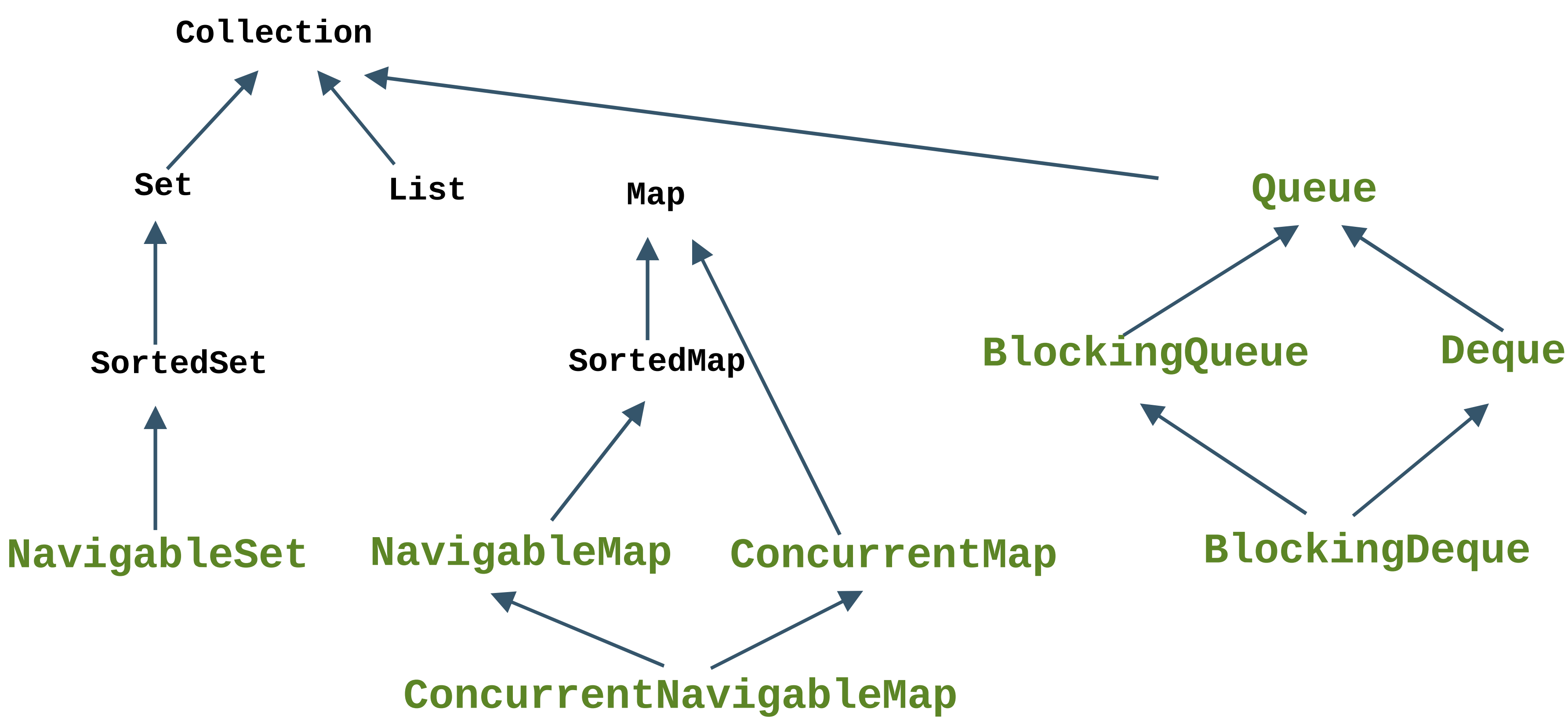
Collections in Java 5 and Java 6

Additions to the Collections Framework

- Top-level Interface
  - **`Queue`**
- Subinterfaces
  - **`Deque, NavigableMap, NavigableSet`**
- Concurrent interfaces in **`java.util.concurrent`**
  - **`BlockingQueue, BlockingDeque, ConcurrentMap, ConcurrentNavigableMap`**
- 18 implementation classes

Collections in Java 5 and Java 6

Eight new interfaces



Queue and Deque

- Queues hold elements prior to processing
  - yield them in order for processing
  - typically in producer-consumer problems
- **`java.util.Queue`**
  - **`offer/add, poll/remove, peek/element`**
  - implementations provide FIFO, delay, or priority ordering
- **`java.util.Deque`**
  - **`offerLast/addLast, pollFirst/removeFirst, peekFirst/elementFirst`**
  - FIFO or LIFO ordering

Navigable Collections

- **Navigable{Set|Map}** improve on **Sorted{Set|Map}**
  - **NavigableXXX** extends and replaces **SortedXXX**
  - **TreeSet** and **TreeMap** retrofitted to implement new interfaces
  - Concurrent implementations: **ConcurrentSkipListSet, ConcurrentSkipListMap**
- Operations on **NavigableSet**
  - **ceiling/floor, higher/lower, pollFirst/pollLast**
  - **headSet,tailSet,subSet** overloaded to allow choice of inclusive or exclusive limits (unlike **SortedSet** operations)

Example Use of NavigableSet

- A set of dates suitable for use in an events calendar
- A date is in the set if there is an event on that date
- We use **`org.joda.time.LocalDate`** to represent dates

```
NavigableSet<LocalDate> calendar = new TreeSet<LocalDate>();
LocalDate today = new LocalDate();
calendar.ceiling(today); // the next date, starting with
                         // today, that is in the calendar
calendar.higher(today);  // the first date in the future
                         // that is in the calendar
calendar.pollFirst();    // the first date in the calendar
calendar.tailSet(today,false);
                         // all future dates in the calendar
```

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  - **How to choose an implementation**

Choosing a Collection Implementation

- Choose on the basis of
  - Functional behavior
  - Performance characteristics
  - Concurrency policies
- Not all combinations available
  - Like buying a car – if you want VXR trim, you have to have the 2.8i engine
  - Some customization
    - Synchronized wrappers

Choosing a Set Implementation

- Special-purpose implementations:
  - **`EnumSet`** – for sets of enum – not thread-safe; wc iterators
  - **`CopyOnWriteArraySet`** – thread-safe, snapshot iterators, used when there are more reads than writes and set is small
- General-purpose implementations:
  - **`HashSet`**, **`LinkedHashSet`** – not thread-safe; fail-fast iterators
    - **`LinkedHashSet`** faster for iteration, provides access ordering

	add	**contains**	**next**
HashSet	O(1)	O(1)	O(n/h)
LinkedHashSet	O(1)	O(1)	O(1)

  - **`TreeSet`**, **`ConcurrentSkipListSet`** – provide ordering
    - **`ConcurrentSkipListSet`** thread-safe, slower for large sets

Choosing a List Implementation

- Special-purpose implementation:
  - **`CopyOnWriteArrayList`** – thread-safe, snapshot iterators, used when there are more reads than writes and list is small
- General-purpose implementations:
  - **`LinkedList`** – not thread-safe; fail-fast iterators
    - May be faster for insertion and removal using iterators
  - **`ArrayList`** – not thread-safe; fail-fast iterators
    - Still the best general-purpose implementation (until Java 7?)

	get	**add(e)**	**add(i,e)**	**iterator. remove**
`ArrayList`	O(1)	O(1)	O(n)	O(n)
`LinkedList`	O(n)	O(1)	O(1)	O(1)

Choosing a Queue Implementation

- Don't need thread safety?
  - FIFO ordering – use **`ArrayDeque`** (not **`LinkedList`**!)
  - Priority ordering – **`PriorityQueue`**
- Thread-safe queues:
  - Specialised orderings:
    - **`PriorityBlockingQueue`**, **`DelayQueue`**
  - Best general purpose non-blocking thread-safe queue:
    - **`ConcurrentLinkedQueue`**
  - Blocking queue without buffering
    - **`SynchronousQueue`**
  - Bounded blocking queues, FIFO ordering:
    - **`LinkedBlocking{Queue|Deque}, ArrayBlockingQueue`**
    - **`LinkedBlockingQueue`** typically performs better with many threads

Choosing a Map Implementation

- Special-purpose implementations:
  - **`EnumMap`** – mapping from enums – non-thread-safe, wc iterators
  - **`IdentityHashMap`** – keys on identity instead of equality
  - **`WeakHashMap`** – allows garbage collection of “abandoned” entries
- General-purpose implementations:
  - **`HashMap`, `LinkedHashMap`** – non-thread-safe, fail-fast iterators
    - **`LinkedHashMap`** faster for iteration, provides access ordering, useful for cache implementations
  - **`TreeMap`**, **`ConcurrentSkipListMap`** – provide ordering
    - **`ConcurrentSkipListMap`** thread-safe, slower for large maps
  - **`ConcurrentMap`** – thread-safe, uses *lock striping*
    - Map divided into separately locked segments (not locked for reads)

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Summary

- Generics and new Collections major step in Java Platform evolution
- Generics are a quick win in client code
  - Primary use-case: collections
  - Understand the corner cases for API design
- Collections Framework evolution
  - Fixing many deficiencies
  - **`java.util.concurrent`** – great new toolset for the Java programmer

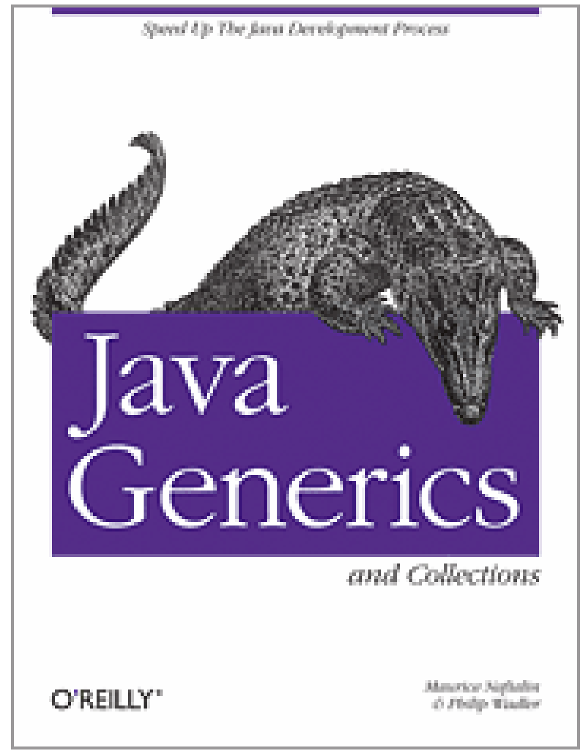
For More Information

- Angelika Langer's Generics FAQ
    - http://www.angelikalanger.com/GenericsFAQ/JavaGenericsFAQ.html
- Java Concurrency in Practice (Goetz, et al) Addison-Wesley, 2006
- JavaDoc for **`java.util, java.util.concurrent`**
- Concurrency-interest mailing list
    - http://gee.cs.oswego.edu/dl/concurrency-interest/index.html

For Much More Information

Java Generics and Collections
(Naftalin and Wadler)
O'Reilly, 2006

- Everything discussed today, plus
  - Subtyping and Wildcards
  - Reflection
  - Effective Generics
  - Design Patterns
  - Collection Implementations
  - The Collections class
- And lots more!



Q&A

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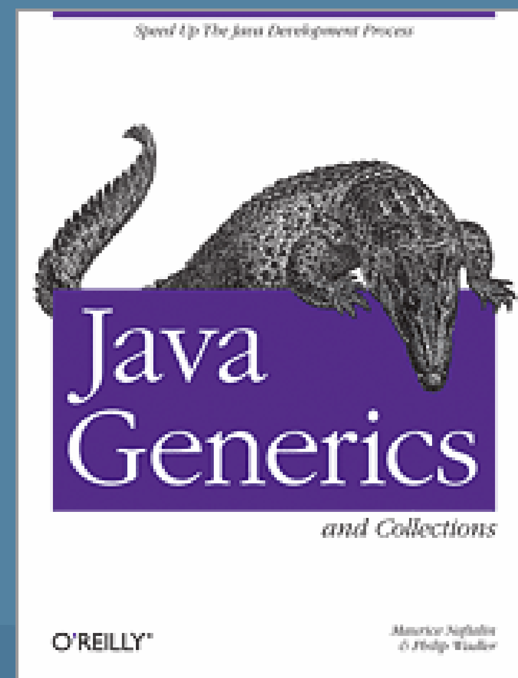

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