Java 8

Lambda Expressions

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objective

- explain the new language feature of lambda expressions
- what is the intent?
- which problem do they solve?
- what are the syntax elements?
- how will they be used in the JDK?

speaker's relationship to topic

- independent trainer / consultant / author
  - teaching C++ and Java for 15+ years
  - curriculum of a couple of challenging courses
  - co-author of "Effective Java" column
  - co-author of "Java Core Programmierung"
  - author of Java Generics FAQ online
  - JCP member and Java champion since 2005

agenda

- **introduction**
- functional interfaces
- lambda expressions (the details)
- method references
- extension methods
- ‘lambdafication’ of the JDK

lambda expressions in Java

- *lambda expressions*
  - aka *lambdas;* formerly known as *closures*

- concept from functional programming
  - "anonymous method" / "code-as-data"
    - 'ad hoc' implementation of functionality
    - pass functionality around (parameter, return value)

  - similar to (anonymous) inner classes
    - advantage of lambda expressions: concise syntax + less code
    - "more functional"

history

- 2006 – 2009
  - several proposals for ‘closures in Java’
  - no convergence; none fully supported by Sun / Oracle

- since 2010
  - OpenJDK Project Lambda; tech lead Brian Goetz
  - JSR 335 (Nov. 2010)
    "Lambda Expressions for the Java Programming Language"
  - JEP 126 (Nov. 2011)
    "Lambda Expressions and Virtual Extension Methods"

Oracle’s design guideline

- aid usage of libraries that …
  - make use of parallelization on multi core platforms
  - special focus: JDK
- rules out
  - which features are relevant?
  - how complex can they be?
- general guideline: *"as simple as possible"*
  - several (previously discussed) features were dropped
  - e.g. function types, exception transparency, …

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key goal

- support JDK abstractions that …
  - make use of parallelization on multi core platforms
- collections shall have parallel bulk operations
  - based on fork-join-framework (Java 7)
  - execute functionality on a collection in parallel
    - i.e. access multiple elements simultaneously
  - specified as: JEP 107
    - details later

today

```
private static void checkBalance(List<Account> accList) {
   for (Account a : accList)
      if (a.balance() < threshold) a.alert();
}
```

- new **`for`**-loop style
  - actually an external **`iterator`** object is used:

```
Iterator iter = accList.iterator();
while (iter.hasNext()) {
  Account a = iter.next();
  if (a.balance() < threshold) a.alert();
}
```

- code is inherently serial
  - traversal logic is fixed
  - iterate from beginning to end

ParallelIterable.forEach() - definition

```
public interface ParallelIterable<T> ... {
     ...
  void forEach(Block<? super T> block) default ...
     ...
}
```

```
public interface Block<A> {
  void apply(A a);
}
```

- **forEach()**'s iteration is not inherently serial
  - traversal order is defined by **forEach()**'s implementation
  - burden of parallelization is put on the library developer
    - not on the library user

ParallelIterable.forEach() - example

```
ParallelIterable<Account> pAccs = accList.parallel();

// with anonymous inner class
pAccs.forEach(new Block<Account>() {
                 void apply(Account a) {
                    if (a.balance() < threshold) a.alert();
                 }
              });

// with lambda expression
pAccs.forEach( (Account a) ->
                 { if (a.balance() < threshold) a.alert(); } );
```

- lambda expression
  - less code (overhead)
  - only actual functionality
    - easier to read

lambda expression a `Block<Account>` ?

```
Block<Account> block =
    (Account a) -> { if (a.balance() < threshold) a.alert(); };
```

- right side: lambda expression
- intuitively
  - ‘something functional’
    - takes an **`Account`**
    - returns nothing (void)
    - throws no checked exception
- nothing in terms of the Java type system
  - just some code / functionality / implementation

functional interface = target type of a lambda

```
interface Block<A> { public void apply(A A); }

Block<Account> pAccs =
   (Account a) -> { if (a.balance() < threshold) a.alert(); };
```

- lambdas are converted to *functional interfaces*
  - function interface ≈ interface with one method
  - parameter type(s), return type, checked exception(s) must match
  - functional interface's name + method name are irrelevant
- conversion requires type inference
  - lambdas may only appear where target type can be inferred from enclosing context
  - e.g. variable declaration, assignment, method/constructor arguments, return statements, cast expression, …

idea behind functional interfaces

- interfaces with one method have been the ‘most functional things’ in Java already:

```
interface Runnable        { void run(); }
interface Callable<T>     { T call(); }
interface Comparator<T>  { boolean compare(T x, T y); }
...
```

  – *"as simple as possible"*
  – reuse existing interface types as target types for lambda expressions

lambda expressions & functional interfaces

- functional interfaces

```
interface Block<A>    { void apply(A A); }
interface MyInterface { void doWithAccount(Account a); }
```

- conversions

```
Block<Account> block =
  (Account a) -> { if (a.balance() < threshold) a.alert(); };

MyInterface mi =
  (Account a) -> { if (a.balance() < threshold) a.alert(); };

mi = block;     <---- error: types are not compatible
```

- problems

```
Object o1 =     <---- error: cannot infer target type
  (Account a) -> { if (a.balance() < threshold) a.alert(); };

Object o2 = (Block<Account>)
  (Account a) -> { if (a.balance() < threshold) a.alert(); };
```

evaluation

- lambda expression
  - easy and convenient way to implement ad-hoc functionality
- functional interfaces
  - serve as target types for lambda expressions
  - integrate lambda expressions into Java type system
- advantages
  - simple: no new elements in Java type system
    - good for language designers and users
  - built-in backward compatibility
    - e.g. can provide a lambda where a `Runnable` (JDK 1.0) is needed

evaluation (cont.)

- down-side
  - must define `Block<A>` to describe parameter type:

```
public void forEach(Block<? super T> proc) ...

public interface Block<A> { void apply(A A); }
```

  - code overhead, no explicit function type: **`<T>->void`**

- justification: overhead is acceptable
  - explicit function types add many more complications
  - "we (the library providers) do it for you (the library users)"
  - may be added later
    - JSR 335 (lambda spec) mentions function types as potential future enhancement

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lambda expression syntax

- since September 2011:

```
(Account a) -> { if (a.balance() < threshold) a.altert(); }
```

- previously:

```
# { Account a -> if (a.balance() < threshold) a.alert(); }
```

- syntax: C#, with '`->`' instead of '`=>`'
  - proven concept
  - quite similar to Scala's closure syntax, too

  - '`->`' instead of '`=>`' to avoid *dueling arrows*

```
foo (x => x.size <= 0);
```

formal description

```
lambda = ArgList "->" Body

ArgList = Identifier
          | "(" Identifier [ "," Identifier ]* ")"
          | "(" Type Identifier [ "," Type Identifier ]* ")“

Body = Expression | "{" [ Statement ";" ]+ "}"
```

- options related to
  - argument list, and
  - body

argument list, pt. 1

```
ArgList = Identifier
        | "(" Identifier [ "," Identifier ]* ")"
        | "(" Type Identifier [ "," Type Identifier ]* ")“
```

```
a -> { if (a.balance() < threshold) a.alert(); }

(a) -> { if (a.balance() < threshold) a.alert(); }

(Account a) -> { if (a.balance() < threshold) a.alert(); }
```

- if possible, compiler infers parameter type
  - inference based on target type, not lambda body
- if not possible, parameter type must be specified
  - parameter type can always be specified
- multiple parameters
  - all parameters either declared or inferred (no mix possible)

argument list, pt. 2

```
ArgList = Identifier | ...
```

- omission of parentheses in case of one argument without type identifier possible

- examples:

```
a  -> { if (a.balance() < threshold) a.alert(); }

(int x) -> { return x+1; }
     x  -> { return x+1; }   // omit parentheses

(int x, int y) -> { return x+y; }
         (x,y) -> { return x+y; } // can't omit parentheses

// no special nilary syntax
() -> { System.out.println("I am a Runnable"); }
```

body

```
Body = Expression | "{" [ Statement ";" ]+ "}"
```

```
// single statement
a -> { if (a.balance() < threshold) a.alert(); }

// single expression
a -> (a.balance() < threshold) ? a.alert() : a.okay()

// list of statements
a -> {
       Account tmp = null;
       if (a.balance() < threshold) a.alert();
       else tmp = a;

       if (tmp != null) tmp.okay();
     }
```

return, pt. 1

```
()            -> { return 21; }         // returns  int

(Account a) -> { return a; }          // returns  Account

()            -> { return (long)21; }  // returns  long
```

- return type is always inferred
  - i.e. cannot be specified explicitly
  - you might consider to cast the return value

return, pt. 2

```
() -> { return 21; }

() -> return 21        <- error !!!

() -> 21
```

- no `return` with single expression
  - use of `return` is an error
- `return` used with list of statements
  - when using multiple `return`s:
    programmer responsible, that the return type can be inferred

local variable capture

```
int i = 16;

Runnable r = () -> { System.out.println("i is: " + i); };
```

- local variable capture
  - important feature
  - similar to anonymous inner classes
    - but no explicit **`final`**
    - but still only read access

local variable capture (cont.)

```
int i = 16;

Runnable r = () -> { System.out.println("i is: " + i); };

i++;
```

error because

- *effectively final* variables
  - same as with anonymous inner classes, but
    - you do not have to use the `final` identifier explicitly

effectively final

- local variable capture not much different from inner classes

- but caused a lot of discussion
  - *I want write access !*

- a look at the details
  - shows the limitations

reason for effectively final

```
int i = 0;

Runnable r =
  () -> { for (int j=0; j < 32; j++ ) i = j); };

// start Runnable r in another thread
...

while (i <= 16) ;

System.out.println("i is now greater than 16");
```

error

- problem: unsynchronized concurrent access
- no guaranties from the memory model

but the effectively final does not prevent …

… all evil in the world

- consider a mutable object referred to by an effectively final *reference*

```
int[] ia = new int[1];

Runnable r =
  () -> { for (int j==; j < 32; j++ ) ia[0] = j); };

// start Runnable r in another thread
...

while (ia[0] <= 16) ;

System.out.println("ia[0] is now greater than 16");
```

I want write access ! – idioms to come ?

```
File myDir = ....

int[] ia = new int[1];

File[] fs = myDir.listFiles( f -> {
               if (f.isFile() {
                  n = f.getName();
                  if (n.lastIndexOf(“.exe”) == n.length()-4)
                    ia[0]++;
                  return true;
               }
               return false;
             };);

System.out.println("contains " + fs.size + "files, " +
                                 ia[0] + "are exe-files");
```

- no problem, if everything is executed sequentially

no transparent parallelism !

```
int[] ia = new int[1];
pAccs.forEach( (Account a) -> {
                  if (a.balance() < threshold) {
                     a.alert();
                     ia[0]++;
                  }
                } );

System.out.println(ia[0] + " alerts !!!");
```

- need to know whether …
  - methods that take lambda uses multiple threads or not
  - `ParallelIterable.forEach()` vs. `File.list()`
- currently not expressed in Java syntax
  - JavaDoc, comment, …

lambda body lexically scoped, pt. 1

- lambda body scoped in enclosing method
  - like any inner code block enclosed in an outer scope
- effect on local variables:
  - capture works as shown before
  - no shadowing of lexical scope

lambda

```
int i = 16;
Runnable r = () -> { int i = 0;                          // error
                     System.out.println("i is: " + i); };
```

- different from inner classes
  - inner class body is a scope of its own

inner class

```
final int i = 16;
Runnable r = new Runnable() {
  public void run() { int i = 0;                         // fine
                      System.out.println("i is: " + i); }};
```

lambda body lexically scoped, pt. 2

- `this` refers to the enclosing object, not the lambda
  - due to lexical scope, unlike with inner classes

lambda

```
public class MyClass {
  private int i=100;

  public void foo() {
   ...
   Runnable r = () -> {System.out.println(“i is: “ + this.i);};
   ...
  }
}
```

inner class

```
public class MyClass {
  private int i=100;

  public void foo() {
   ...
   Runnable r = new Runnable() {
     private int i=100;
     public void run() {System.out.println(“i is: “ + this.i);}
   };
   ...
  }
}
```

lambda body lexically scoped, pt. 3

- what if …
  - you need to refer to lambda object from inside lambda body ?
  - like you can do via `this` in an inner class ?

=> use the variable that refers to the lambda !

```
public interface IntFunction { int apply(int i); }
```

```
IntFunction fact = in -> (n == 0) ? 1 : n * fact.apply(n-1);
```

  - deviation from 'define-before-use' rule

- drawback
  - cannot be used in context that does not introduce names
  - e.g. method/constructor argument

lambda body lexically scoped, pt. 4

- `break` and `continue` are illegal on top level of lambda body

```
for (…) {
  …
  myFunc mfi = ()->{ … break; … };
  mfi.invoke();
  …
}
```

error

- would allow implementation of user-defined control structures
  – top level `break` in a lambda invoked in a `for`-loop would transfer control flow to end of loop
  – i.e. from the (inner) lambda to the outer context

- maybe added after Java 8

lambdas vs. inner classes - differences

- *local variable capture*:
  - implicitly final vs. explicitly `final`
- *different scoping*:
  - `this` means different things
- *verbosity*:
  - concise lambda syntax vs. inner classes' syntax overhead
- *performance*:
  - lambdas slightly faster (use `MethodHandle` from JSR 292 ("invokedynamic"))

- bottom line:
  - lambdas better than inner classes for functional types
- but what if you add a second method to a functional interface
  - and turn it into a regular non-functional type ???

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an example

- want to sort a collection of `Person` objects
  - using the JDK's new function-style bulk operations and
  - a method from class `Person` for the sorting order

element type `Person`

```
class Person {
  private final String name;
  private final int age;
  …
  public static int compareByName(Person a, Person b) { … }
}
```

example (cont.)

- `ParallelIterable<T>` has a `sorted()` method

```
ParallelIterable<T> sorted(Comparator<? super T> comp)
```

- interface `Comparator` is a functional interface

```
public interface Comparator<T> {
  int compare(T o1, T o2);
  boolean equals(Object obj);
}
```

inherited from `Object`

- sort a `ParallelArray` of `Persons`

```
ParallelIterable<Person> piP = …
…
piP.sorted((Person a, Person b) -> Person.compareByName(a,b));
```

example (cont.)

- used a wrapper that invokes `compareByName()`

```
piP.sorted((Person a, Person b) -> Person.compareByName(a,b));
```

- specify `compareByName()` directly (*method reference*)

```
piP.sorted(Person::compareByName);
```

  - reuse existing implementation
  - less code

- syntax not final, but very likely: "::"

idea …

… behind method references

- take an existing method from some class, and make it the implementation of a functional interface
  - similar to lambda expressions
- need context that allows conversion to a target type
  - similar to lambda expressions
- method handles are included in JSR 335

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problem

- no (good) support for interface evolution in Java today

- interface evolution

  = add a new method to an existing interface

  – problem: all existing implementations of the interface break

- concrete situation
  – extend existing collection interfaces for functional programming
  – e.g. add to the interface `java.lang.Iterable<T>` the sequential method:

```
forEach(Block<? superT> block)
```

solution

- *extension method*

  – add a new method to an interface
  together with a default implementation

  – implementations of the interface are free to override it,
  but don’t have to

example

from package `java.lang`:

```
public interface Iterable<T> {

  ... everything as before ...

  public Iterable<T> forEach(Block<? super T> block)
  default {
    for (T each : this)
      block.apply(each);
    return this;
  }
  ...
}
```

alternative

- default implementation directly in the interface ?
  - long and intense discussion / compromise: both solutions possible

from package `java.lang`:

```
public interface Iterable<T> {
  ...
  public Iterable<T> forEach(Block<? super T> block)
  default Iterables::forEach;
  ...
}
```

from class `java.util.Iterables`:

```
public static <T> Iterable<T>
       forEach(Iterable<T> iterable, Block<? super T> block) {
   for (T each : iterable)
      block.apply(each);
   return iterable;
}
```

notes

- both solutions equivalent
  - no additional state / no instance fields
  - implementation based on the functionality of the other methods + the additional parameter(s) from the new method
- extension methods are included in JSR 335
- name:
  - also know as: *defender methods* and *default methods*
  - in JSR 335 called *virtual extension methods*
    - as opposed to C#'s (non-virtual) extension methods (which cannot be overridden)

Java's OO concepts change with e.m., pt. 1

- Java `interface`s are not really interfaces anymore
- they (can) provide implementation
- dilutes the concepts somewhat

Java's OO concepts change with e.m., pt. 2

- Java provides multiple inheritance of functionality now

```
class A extends B implements I, J, K, L {}
```

  - **A** inherits functionality from **B**
  - **A** might inherit functionality from **I**, **J**, **K**, **L**
    because these interfaces might provide extensions methods

- is it a problem ? - NO !
  - relatively safe, no additional state from `interfaces`

language evolution

C++:

- multiple inheritance of functionality+ data
  - considered dangerous

classic Java:

- single inheritance of functionality + multiple inheritance only for interfaces
  - problem: interface evolution => where to provide new functionality ?

recent languages:

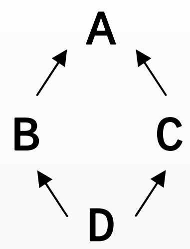
- mixins (Ruby) / traits (Scala)
  - to solve the problem

Java 8:

- extension methods
  - fit into existing language
  - not too different from ‘stateless’ traits in Scala (but without linearization to resolve defaults)

problem with multiple inheritance

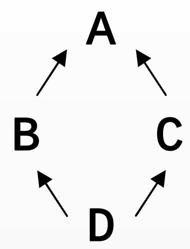
the diamond:



- how is `A`'s state inherited to `D` ?
  - once, or
  - twice (via `B` and via `C`)

- there is no 'right' answer to this question
  - C++ gives you the option: virtual / non-virtual inheritance
  - makes it more complicated

the diamond:

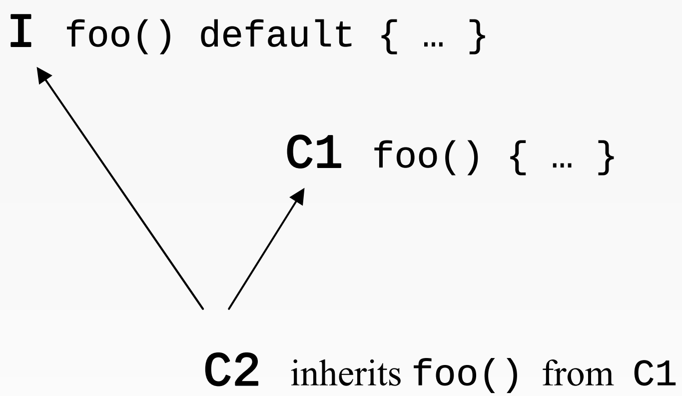


- `A` can only be an `interface` (not a `class`)
  - can have an implementation, but
  - no state (no instance fields)

- no state means no (diamond) problem !
  - no issue regarding "how many `A` parts does `D` have ?"

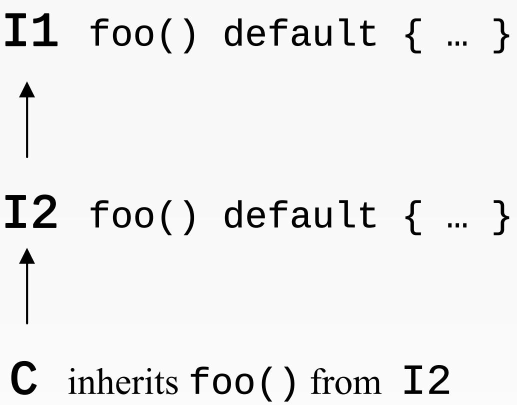
still conflicts – ambiguity #1

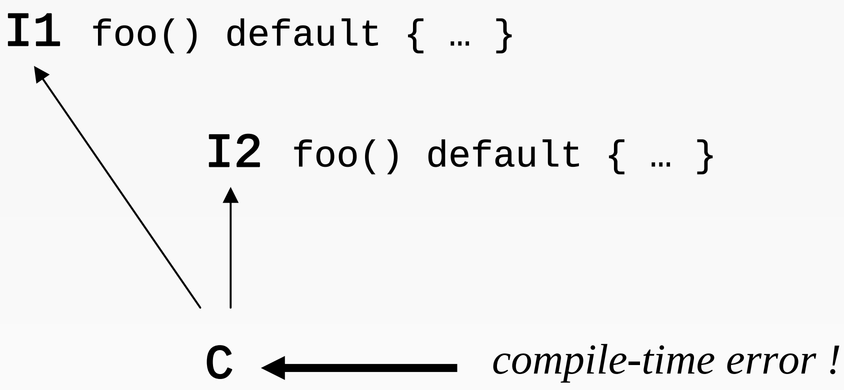
- inherit the same method from
  a `class` and an **`interfaces`**
  - `extends` dominates `implements`
  - sub-class inherits super-class's method (not interface's method)



ambiguity #2

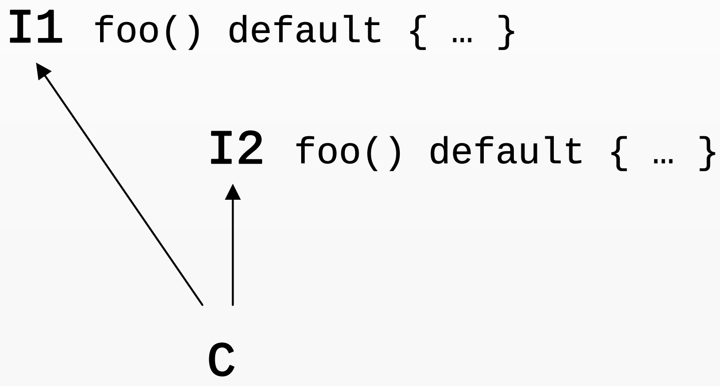
- inherit the same method from different `interfaces`
  - sub-interfaces shadow super-interfaces
  - if the interfaces are unrelated **`->`** no default at all
    - results in a compile error





ambiguity #2 (cont.)

- can address ambiguity explicitly when implementing class `C`

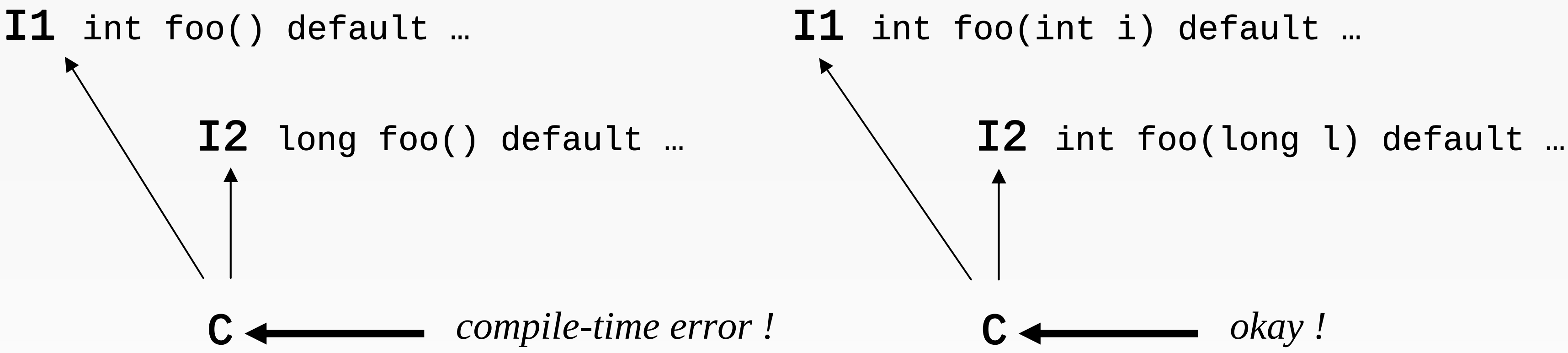



```
class C implements I1, I2 {
   public void foo() { I1.super.foo(); }
}
```

  – new syntax to qualify the super-interface

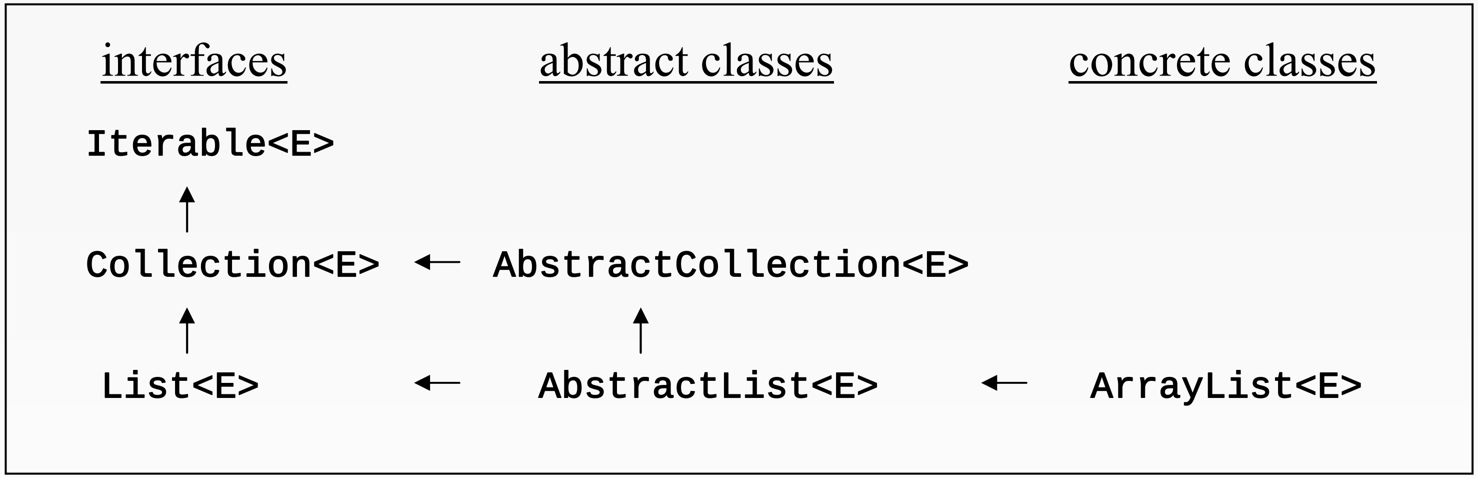
ambiguity #3

- inherit conflicting methods from different **`interfaces`**
  - same name, parameters, different return type
  - results in a compile time error



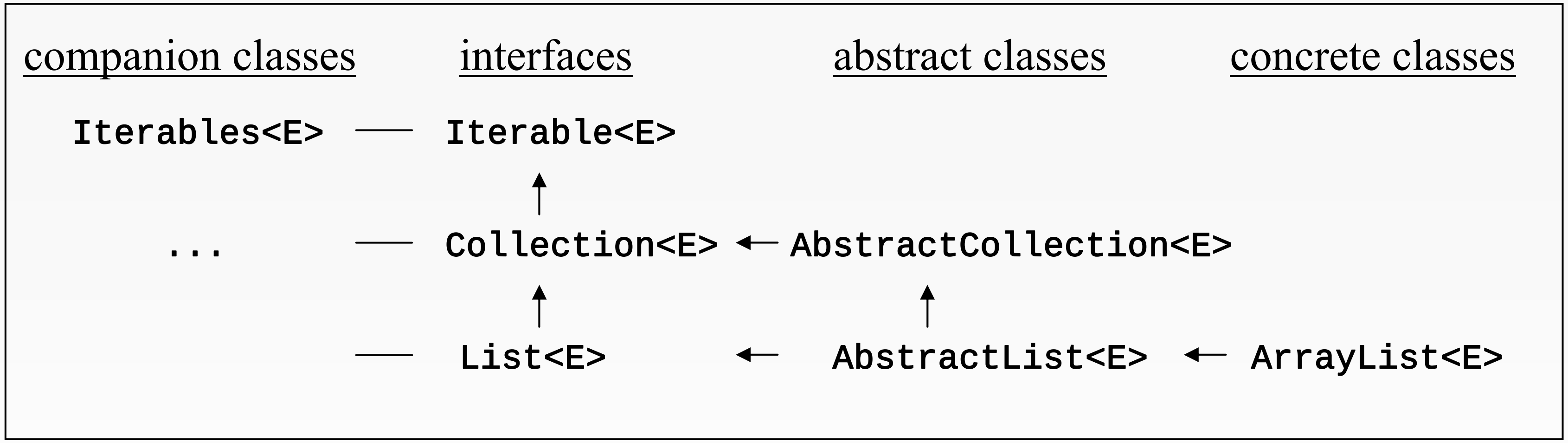
implementation techniques in collection framework

- until now:
  - interfaces for types
  - skeletal behavior with abstract classes



implementation techniques (cont.)

- new with Java 8:
  - interfaces for types + default behavior (without state)
    - implemented as static methods in companion classes (most likely for JDK)
  - example: `forEach()`



beyond interface evolution

- interface evolution is primary motivation,
  but extension methods are useful in themselves

- approach:
  - define interface as always
  - provide default implementation for those methods that …
    - don’t need state, but
    - can be based on functionality of other (really abstract) methods
  - provide implementation of (really abstract) methods
    - by abstract classes (if functionality can be factored out)
    - by concrete classes

extension methods and retrofits

- JDK 1.0 introduced `Enumeration`
- JDK 1.2 replaced it with `Iterator`
- conceivable in Java 8

```
interface Enumeration<E> extends Iterator<E> {
  boolean hasMoreElements();
  E nextElement();

  boolean hasNext() default { return hasMoreElements(); }
  E next()          default { return nextElement(); }
  void remove()     default {
               throw new UnsupportedOperationException();
  }
}
```

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JEP 107: Bulk Data Operations for Collections

- JEP = JDK enhancement proposal, for Java 8
- also know as: for-each/filter/map/reduce for Java
  - for-each
    apply a certain functionality to each element of the collection

```
accountCol.forEach(a -> a.addInterest());
```

  - filter
    build a new collection that is the result of a filter applied to each element in the original collection

```
Iterable<Account> result =
   accountCol.filter(a -> a.balance() > 1000000 ? true:false);
```

JEP 107 (cont.)

– map
  build a new collection, where each element is the result of a mapping from an element of the original collection

```
ParallelIterable<Integer> result =
                   accountCol.map(a -> a.balance());
```

– reduce
  produce a single result from all elements of the collection

```
accountCol.map(a -> a.balance())
          .reduce(new Integer(0),
       (b1, b2) -> new Integer(b1.intValue()+b2.intValue()));
```

JEP 107 (cont.)

… additional methods

- combinations for optimizations
  - e.g. map-reduce

```
accountCol.mapReduce(a -> a.balance(), 0, (b1, b2) -> b1+b2);
```

- `sorted()`, `anyMatch()`, …
  - see JavaDoc for yourself

JEP 107 (cont.)

- provides
  - serial version, i.e. operation performed by the calling thread
  - parallel version, i.e. using multiple parallel threads

- provides
  - eager mode
  - lazy mode

- four types:

serial + eager	serial + lazy
parallel + eager	parallel + lazy

eager vs. lazy - example

- consider a sequence of operations
  - filter with a predicate, map to long value, and apply printing

```
myCol.filter((Account a) -> a.balance() > 1000000)

     .map((Account a) -> a.balance())

     .forEach((long l) -> System.out.format("%d\t",l));
```

- eager
  - each operation is executed when it is applied
- lazy
  - execute everything after the last operation has been applied
  - optimize this execution
    - e.g. call `a.balance()` only once for each account and print it directly without any intermediate collection of balances

prototype available of implementation …

… of the serial versions

- `java.lang.Iterable<T>`
  - extended with foreach/filter/map/reduce operations
  - serial default extension methods provided in `java.util.Iterables`
- similar extensions for `java.util.Iterator<T>`

prototype available of implementation …

… of the parallel versions

- `java.util.ParallelIterable<T>`
  - interface for parallel foreach/filter/map/reduce operations
  - default extension methods provided in companion class `java.util.ParallelIterables<T>`
- note: no transparent parallelism
  - parallel functionality must be explicitly requested
  - collection has a method `parallel()` that returns a `ParallelIterable<T>`
  - concrete class is a private type
- and similarly for arrays ...

"lambdafication" beyond collections

- JEP 109: Enhance Core Libraries with Lambdas
- survey in the OpenJDK discussion group
  - upgrade core JDK to take advantage of lambda expressions
- result:
  - 17 places in JDK that could benefit from lambda expressions
  - http://mail.openjdk.java.net/pipermail/lambda-dev/2011-September/004013.html
- `java.util.concurrent.Lock: withLock(block)`
  - run block with lock held, release lock in finally-clause
  - variations with timeout, tryLock
  - the classic, already used in Neal Gafter's closure proposal

JEP 109 (cont.)

- `java.util.Collections: toMap(keyGen)`
  - for each element in a coll., generate a key, store both into a map
  - could be a static utility method or an extension method
- `java.lang.Throwable: visitCauses(block)`
  - run block for each `Throwable` in the chain of causes
- … plus 14 more …

wrap-up

- lambda expressions
  - new functional elements for Java
  - similarities with anonymous inner classes
    - advantages: less code, ‘more functional’, most likely faster

- additionally in JSR 335 / JEP 126
  - method handles
  - extension methods

- JDK changes
  - JEP 107: for-each, filter, map, reduce for collections
  - JEP 109: additional smaller changes

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Q & A