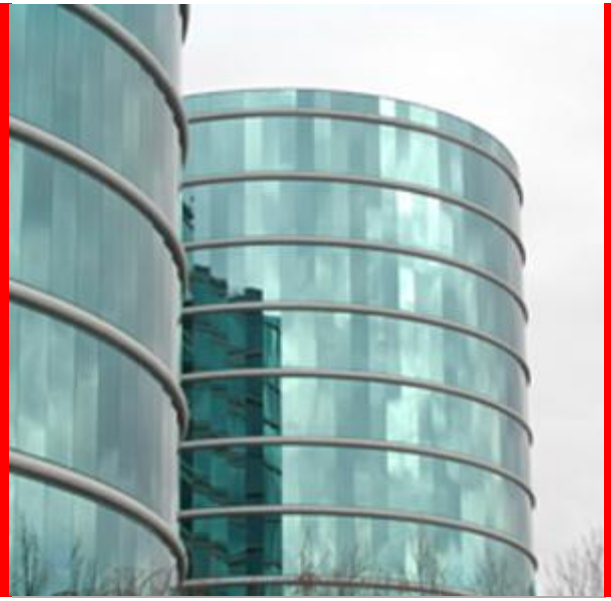

ORACLE

Virtual Extension Methods for Java

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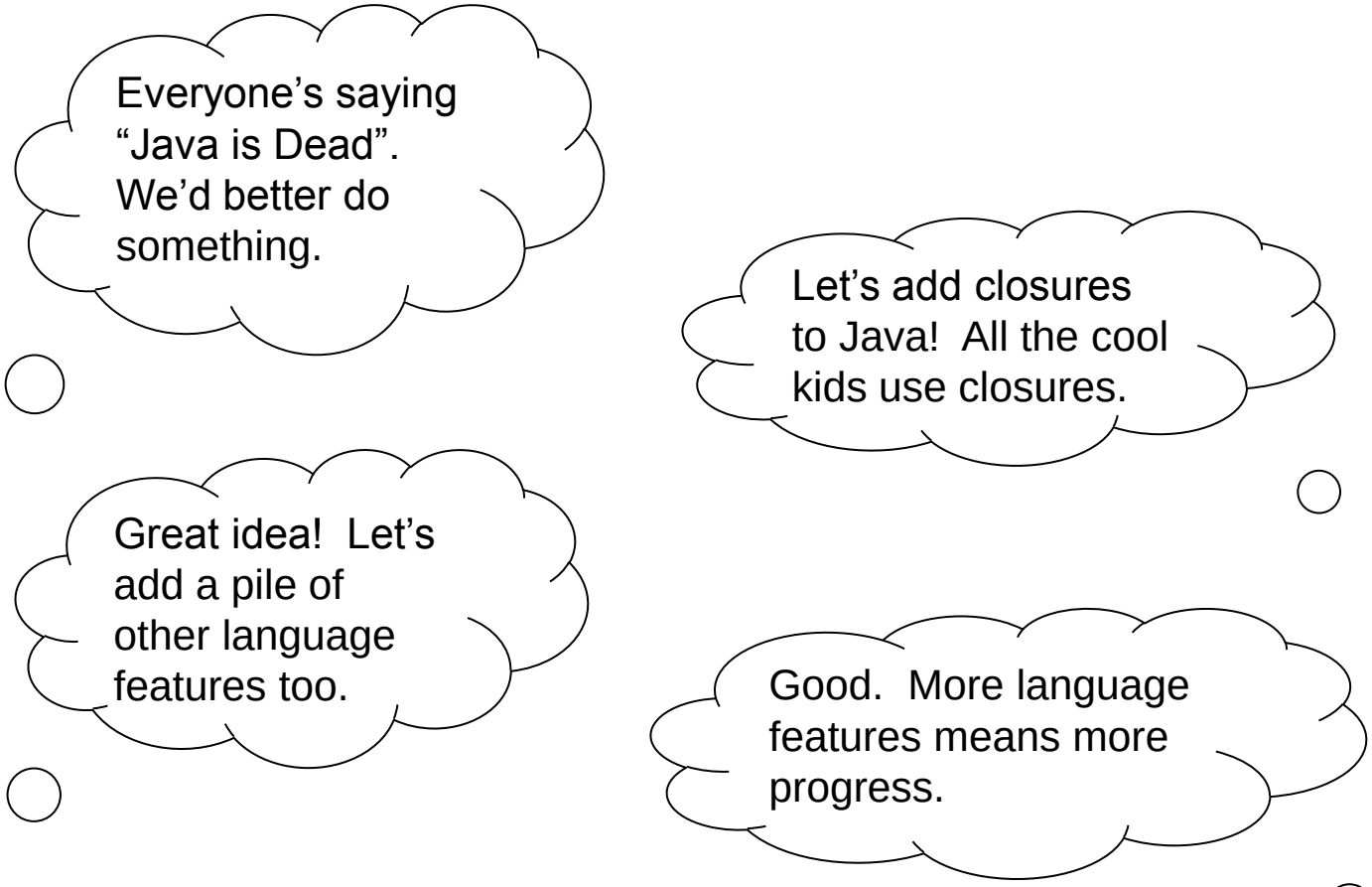
BACKGROUND

(Not) heard in a hallway in Santa Clara



Why closures for Java?

- It's about time!
  - Java is the lone holdout among mainstream OO languages at this point to not have closures
- Provide libraries a path to multicore
  - Today, a developer's primary tool for computing over aggregates is the for loop – which is *fundamentally serial*
  - Internal iteration needed to make data structures parallel-friendly
- Empower library developers
  - Easier to evolve the programming model through libraries than through language
- Hidden motivation: give developers a gentle push away from a side-effect-centric programming model

New language features for Java SE 8
Pulling on the string called closures

- Lambda expressions (closures)

```
(String x) -> x.length() == 0
```

- Functional interface conversion

```
Predicate<String> p = (String x) -> x.length() == 0;
```

- Type inference of lambda formal parameters

```
Predicate<String> p = x -> x.length() == 0;
```

- Method references

```
Predicate<String> p = String::isEmpty;
```

- Virtual extension methods

The real problem: interface evolution

- Adding closures is a big language change
  - If Java had closures from day 1, APIs would look different
  - Adding closures now makes aging APIs show their age even more
  - Most important APIs (Collections) are based on interfaces
  - Can’t add to interfaces without breaking source compatibility
- Adding closures, but not upgrading the APIs to use them effectively, would be silly
  - “What do you mean, I can’t say coll.forEach(lambda)? “

Know your inner poster child

- Most language evolution stories have a “poster child”
  - A canonical use case that can’t be supported in the “old” language
- For lambda: filter/map/reduce on collections

```
List<Student> students = ...
double highestScore =
  students.filter(s -> s.gradYear == 2011)
          .map(Student::getScore)
          .reduce(Integer::max);
```

- We need a mechanism for *library evolution*

LIBRARY EVOLUTION

Library-based evolution options

1. Don’t evolve existing collections, but add some new parallel implementation classes
   - Doesn’t do anything for serial programming model
   - Far removed from existing collections
2. Build “Collections 2”
   - Unrealistic – the Collections types infect the entire library
   - Huge design space
   - Still stuck with VM limitations (32-bit arrays, erasure)
3. Add aggregate operations to concrete classes
   - Hurts everyone who follows best-practice style advice
   - Code riddled with casts
   - Ties users to implementation instead of interface contracts
4. Add new interfaces (BetterList) with aggregate ops
   - More casts
   - Where does this lead to? NewBetterImprovedList2?

Language-based evolution options

1. Static extension methods
   - What appears to be an instance method call is really a static method call
   - Suppose static method `Collections.map(List, Mapper)` is available, and imported as a static extension – then `ls.map(…)` would compile to `Collections.map(ls, …)`
   - Simple to implement, and "proven" in C#
   - Programmer must reason about extensions in scope for each call
   - Subclass cannot provide a better implementation or covariant return
   - Poor interaction with instance methods of same name
   - Invisible to reflection

Language-based evolution options

2. Expanders, Classboxes
   - Unproven, risky
   - Expanders can't be applied to interfaces ☹ because a class might implement multiple interfaces and a client might "use" multiple expanders → call-site ambiguity.
3. Modularity-based solutions
   - Components in Jiazzi and Fortress
   - Information hiding techniques in Jigsaw and OSGi
   - Complex, risky
4. Traits
   - Too big a change

API evolution is a cross-cutting concern

- Library changes alone don’t help
- Nor do simple-minded language changes

- The fundamental problem is that we can’t evolve interface-based APIs
- This burden should fall to implementors, not users
  - Relatively fewer implementors
  - New methods often have an “obvious” implementation
  - Let the implementor provide a mostly reasonable default
  - Subclasses can override it at their leisure

Solution: virtual extension methods

- A virtual extension method is specified in the interface

```
interface Collection<T> {
    // existing methods, plus
    void forEach(Block<T> block) default Collections.<T>forEach;
}
```

- The forEach method is an extension method
  - From caller's perspective, an ordinary virtual method
- Collection provides a default implementation
  - Default is only used when implementation classes do not provide a body for the extension method
  - "If you cannot afford an implementation of forEach, one will be provided for you at no charge."

“Is this multiple inheritance in Java?!”

- Yes, but Java already has multiple inheritance of *types*
- This adds multiple inheritance of *behavior*, not state
- Multiple inheritance still a problem due to high complexity of separate compilation and dynamic linking

- Library evolution may be the primary motivator, but useful as an inheritance mechanism in itself
  - Almost all the way to stateless traits

METHOD RESOLUTION

Compatibility goals

- The point of this feature is being able to *compatibly* evolve APIs
- Compatibility has multiple faces
  - Source compatibility: Implementation class recompiles successfully
  - Binary compatibility: Callers continue to link correctly
- The key operation we care about is *adding new methods with defaults* to existing interfaces
  - *Without* necessarily recompiling the implementation class
- Also care about adding defaults to existing methods, and changing defaults on existing extension methods
  - Removals of most kinds are unlikely to be compatible

Compatibility is hard because of separate compilation

- Most interfaces are defined in libraries and consumed in applications
- Cannot count on application being recompiled
  - No guarantee that the same classes or symbols that were present at compile time will be there at runtime
- Compatibility means tolerating changes to interfaces without recompiling implementations and/or clients
  - Assumptions of uniqueness at compile-time must be verified at runtime, and if untrue, mitigated

Method resolution

- Key choice: treat inheritance of behavior from classes and interfaces separately
  - If there is an inheritance conflict between a superclass and a superinterface, the superclass takes priority
  - Defaults only come into play if there is no declaration for that method in the superclass chain
- Conflicts between superinterfaces may be resolved using subtyping
  - More specific interfaces take priority over less
- Invocation is resolved to a default if there is a *unique*, *most-specific default-providing interface*

Method resolution
Pruning less specific interfaces

- If interface B extends A, then B is *more specific* than A
  - If both A and B provide a default, we remove A from consideration because B is more specific
- Below, the fact that C<T> declares Collection<T> as an immediate supertype is irrelevant
  - Set is more specific and it provides a default, so it beats Collection

```
interface Collection<T> {
    public Collection<T> filter(Predicate<T> p) default …;
}
interface Set<T> extends Collection<T> {
    public Set<T> filter(Predicate<T> p) default …;
}
class D<T> implements Set<T> { ... }
class C<T> extends D<T> implements Collection<T> { … }
```

Method resolution
Handling diamonds

- We care about the identity of the interface providing the default, not the default itself

```
interface A { void m() default X.a; }
interface B extends A { }
interface C extends A { }
class D implements B, C { ... }
```

- When analyzing D, it is A that is the provider of the default, and it is unique
  - Therefore d.m(args) resolves to X.a(d, args)

Method resolution
Explicit disambiguation

- If ambiguous multiple inheritance is detected at compile-time, the programmer must provide a non-abstract method

```
interface A { void m() default X; }
interface B { void m() default Y; }

class C implements A, B {
  /* Required */ public void m() { A.super.m(); }
}
```

- New syntax *X*.super.*m*() to invoke the default in superinterface *X*

Modelling compilation and linking of virtual extension methods

- The type checking and method resolution rules are specified by a formal model
- Separated into type rules and resolution rules
  - Compiler would implement both
  - Runtime implements only resolution rules

Formal model: candidate computation

- We compute a set of candidate interfaces to provide a default for method m()
  - Pruning out less-specific candidates

$$\text{R-IntDef}\ \frac{\texttt{interface}\ I\ \texttt{extends}\ I_1, ..., I_n\ \{\ T\ m()\ \texttt{default}\ \langle\ k \mid \texttt{none}\ \rangle\ \}}{dcand(I) = \{\ I\ \}}$$

$$\text{R-IntInh}\ \frac{\begin{array}{c}\texttt{interface}\ I\ \texttt{extends}\ I_1, ..., I_n\ \{\ [\ T\ m()\ ]\ \} \\ S = \bigcup_i\ dcand(I_i)\end{array}}{dcand(I) = \{\ W \in S\ :\ \forall_{V \in S}\ V <: W\ \Rightarrow\ V = W\ \}}$$

$$\text{R-ClassInh}\ \frac{\begin{array}{c}\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ \} \\ S = \bigcup_{U \in \{\ D, I_1, ..., I_n\ \}} dcand(U)\end{array}}{dcand(C) = \{\ W \in S\ :\ \forall_{V \in S}\ V <: W\ \Rightarrow\ V = W\ \}}$$

Formal model: method resolution

- For each class, calculate:
  - Do I have or inherit a declaration for m() (C HasDefn)
    - If so, what class provides this (mprov(C))
  - Do I have a concrete body for m() (T HasBody)

$$\text{R-ClassBody}\ \frac{\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ T\ m()\ \langle\ b \mid\ \texttt{abstract}\ \rangle\ \}}{mprov(C) = C \qquad C\ \texttt{HasDefn}}$$

$$\text{R-ClassInhBody}\ \frac{\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ \}\quad D\ \texttt{HasDefn}}{mprov(C) = mprov(D) \qquad C\ \texttt{HasDefn}}$$

$$\text{R-HasBody}\ \frac{\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ T\ m()\ b\ \}}{C\ \texttt{HasBody}}$$

$$\text{R-HasDef}\ \frac{\texttt{interface}\ I\ \texttt{extends}\ I_1, ..., I_n\ \{\ T\ m()\ \ \texttt{default}\ k\ \}}{I\ \texttt{HasBody}}$$

Formal model: method resolution

- If the class or superclass has a declaration for m(), that wins
  - If that declaration is abstract, then there is no resolution
- Otherwise, if there is a unique most-specific default-providing interface, use that
  - If that interface has an “abstract default”, also no resolution

$$\text{R-ResolveImpl}\ \frac{\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ ...\ \} \quad C\ \texttt{HasDefn} \quad T = mprov(C) \quad T\ \texttt{HasBody}}{mres(C) = T}$$

$$\text{R-ResolveDef}\ \frac{\texttt{class}\ C\ \texttt{extends}\ D\ \texttt{implements}\ I_1, ..., I_n\ \{\ ...\ \} \quad \neg C\ \texttt{HasDefn} \quad |\ dcand(C)\ | = 1 \quad \exists_{J \in dcand(C)} \quad J\ \texttt{HasBody}}{mres(C) = J}$$

Formal model: limitations

- No method overloading (not really needed)
- No resolution of super invocations (can be added)
- No bridge methods
  - Irrelevant to general understanding
  - Big problem for implementation

Bridge methods: an inconvenient truth

- Java 5 added generics and covariant overrides
- These broke the 1:1 correspondence between methods in Java source and methods in class files
- Compiler generates “bridge methods” to make up for differences in the language and VM type systems
- Compiler knows that the two signatures are the “same” method, but the VM does not
  - A “semantic gap” in compile-time v. runtime resolution
  - Arguably bridges should have been a VM feature

Bridge methods

```
interface A<T> { void m(T t); }
interface B    { void m(String s); }
class C implements A<String>, B {
    public void m(String s) { … }
}
```

- Because of erasure, a variable of class C must respond to two signatures: m(String) and m(Object)
  - Compiler emits both methods
  - Object version “redirects” (with a cast) to the String version
- We need to defend (i.e. resolve defaults for) both
  - Need to know at runtime these are really the same method!
  - Compiler can’t generate the bridges for us, because methods with defaults might be added to superinterfaces *after C is compiled*

Compatibility: the good news

- The operations we care about are:
  - add-meth – add a method with a default to an interface
  - add-def – add a default to an existing interface method
  - mod-def – change the default of an existing method
- mod-def: Always source and binary compatible
- add-meth, add-def: Binary compatible if:
  - (Easy case) The resulting program is globally consistent (recompiling all sources would succeed)
  - (Hard case) The new interface method does not create conflicting defaults or invalid overridings

Compatibility: the hard cases

- Conflicting defaults: Add an extension method which is identical to an extension method in another interface, and classes exist that implement both interfaces

```
// red code added later with separate compilation
interface A { void m() default X.a; }
interface B { void m() default Y.b; }
class C implements A, B { }
```

- Invalid overriding: add an extension method whose signature matches one from a subclass, but whose return type is not compatible
  - This problem exists already in Java, where a new method is added to a superclass

Compatibility: further work needed

- Solutions to each of these problems involve tradeoffs against complexity of method resolution
  - Could impose a linearization order on candidate interfaces that could be used to resolve incompatibilities
  - Could use properties of the call site (e.g., the interface name referred to by an invokeinterface instruction)
  - Could store additional compile-time state in the class file
- We care more about avoiding binary incompatibilities than source incompatibilities
  - After-the-fact source incompatibilities can be mitigated by module dependencies or by explicit disambiguation (***`intf`*`.super.`*`m`*`()`**)

Implementation strategies

- Compiler techniques
  - Compile-time injection of default bodies into classes
    - Brittle, contradicts dynamic linking imperative
  - Translate invocations of extension methods using invokedynamic, and let bootstrap resolve default
    - Creates yet another way to invoke methods
    - Creates binary incompatibilities
- VM techniques
  - Classload-time injection of default bodies into classes
  - Integrated with vtable building
- Are virtual extension methods a language or VM feature?
  - Reality: everything else about inheritance is a VM feature
  - Trying to implement otherwise would cause visible seams

EVOLVING COLLECTIONS

Remember what we wanted to write?

```
List<Student> students = ...
double highestScore =
  students.filter(s -> s.gradYear == 2011)
          .map(Student::getScore)
          .reduce(Integer::max);
```

Need to add new methods to Collection / List

Lots of design choices here

- Eager vs lazy
- In-place vs create-new
- Serial vs parallel
- Where in the hierarchy to put new methods

Attractive target: Iterable

Add higher-order, streaming operations to Iterable

- All collections get these for free
- Default easily implemented in terms of iterator()

```
public interface Iterable<T> {
  Iterator<T>     iterator();
  boolean         isEmpty() default ...;
  void            forEach(Block<? super T> block)            default ...;
  Iterable<T>     filter(Predicate<? super T> predicate)     default ...;
  <U> Iterable<U> map(Mapper<? super T, ? extends U> mapper) default ...;
  T               reduce(T base, Operator<T> reducer)        default ...;
  Iterable<T>     sorted(Comparator<? super T> comp)         default ...;
  <C extends Collection<? super T>> C into(C collection)     default ...;
  // and more...
}
```

Eager v. lazy

- New methods are a mix of lazy and eager
  - Naturally lazy operations: filter, map, cumulate
  - Naturally eager operations: reduce, forEach, into
- Many useful operations can be represented as pipelines of source-lazy-lazy-eager
  - collection-filter-map-reduce
  - array-map-sorted-foreach
- In which case the laziness is mostly invisible
  - No new abstractions for LazyCollection, LazyList, etc

Going parallel

- A collection knows how to iterate itself
  - By augmenting Iterable, all Collections types now expose bulk data operations
  - Without changing the Collections implementations!
  - Individual classes can always override default implementations
- Can we do the same for parallel algorithms?
  - What is the parallel equivalent of Iterable?

Parallel Iterable is … Spliterable

A Spliterable can decomposed into two smaller chunks

- Small chunks can be iterated sequentially

Most data structures (arrays, trees, maps) admit a natural means of subdividing themselves

- Default implementations work in terms of Spliterable
- Add parallel() method to collections to dispense a Spliterable

```
public interface Iterable<T> {
  Iterator<T>     iterator();
  Spliterable<T>  parallel();
  // … Lots of extension methods follow …
}
```

Methods on Spliterable are analogous to Iterable

```
public interface Spliterable<T> {
  Iterator<T>     iterator();
  Spliterable<T>  left();
  Spliterable<T>  right();
  boolean            isEmpty() default ...;
  void               forEach(Block<? super T> block)            default ...;
  Spliterable<T>     filter(Predicate<? super T> predicate)     default ...;
  <U> Spliterable<U> map(Mapper<? super T, ? extends U> mapper) default ...;
  T                  reduce(T base, Operator<T> reducer)        default ...;
  Spliterable<T>     sorted(Comparator<? super T> comp)         default ...;
  <C extends Collection<? super T>> C into(C collection)        default ...;
  // and more...
}
```

Individual collection classes can always override default implementation

Explicit but unobtrusive parallelism

```
List<Student> students = ...
double highestScore =
  students.parallel()
          .filter(s -> s.gradYear == 2011)
          .map(Student::getScore)
          .reduce(Integer::max);
```

- More readable
- Better abstraction
- No reliance on mutable state
- Runs in parallel

- Implementation fuses three operations into one parallel pass
- Big win for data locality
- Works on any data structure that knows how to subdivide itself

Summary

- Java SE 8 will have closures for many reasons
  - Fundamental need to upgrade (not replace) libraries
  - No way to compatibly evolve interface-based APIs
- Java SE 8 adds virtual extension methods, a mechanism for compatible interface evolution
  - An upgrade to existing interface inheritance, so that classes may inherit behavior from interfaces
  - Looks like a language feature, but mplementation is in the JVM, reducing impact on class file consumers
- Java SE 8 evolves the language, libraries, and VM together