Virtual Extension Methods
(or, wedging multiple inheritance into the JVM)

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New language features for Java SE 8

• Lambda expressions (closures)
  
  \{ String x -> x.length() == 0 \}

• SAM conversion
  
  Predicate<String> p = \{ String x -> x.length() == 0 \}

• More type inference, e.g. lambda formals
  
  Predicate<String> p = \{ x -> x.length() == 0 \}

• Method references
  
  Predicate<> p = String->isEmpty

• Exception transparency (maybe)

• Virtual extension methods (aka defender methods)
Why *these* features?

- It’s about time!
  - Java is the lone holdout among mainstream OO languages at this point
- Provide libraries a path to multicore
  - Internal iteration needed to make data structures parallel-friendly
  - Today, developer’s primary tool for computing over aggregates is the (fundamentally serial) for loop
- Empower library developers
  - Easier to evolve the programming model through libraries than through language
  - Enable developers to evolve interface-based APIs over time
Goals

- Encourage the creation of more abstract, high-performance libraries
  - Secondary goal: encourage a more side-effect-free programming model
- Simplify the consumption of such libraries through a concise code-as-data mechanism
- Provide for better library evolution and migration
  - Collections are looking long in the tooth
  - Lambdas without broad library support would be disappointing
- Secondary goal: keep doors open
  - Function types (but requires reification)
  - Control abstraction (but lots of work needed to get there)
Why extension methods?

- Adding closures is a big language change
- If Java had closures from day 1, our APIs would definitely look different
  - So adding closures now makes our APIs show their age!
  - 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 `collection.forEach(lambda)`?
- Therefore we need a mechanism for *interface evolution*
Static extension methods

- C# has *static extension methods*
- A static extension method is a tuple \((T, n, D, m)\)
  - Calls to \(t.n(\text{args})\) rewritten at compile time as \(D.m(t, \text{args})\)
- **Advantages**
  - Simple to implement
  - No VM changes
- **Limitations**
  - Brittle – if default changes, clients have to be recompiled
  - No covariant overrides
  - Not reflectively discoverable
  - Poor interaction with existing instance methods of same name
  - Extended class cannot provide a “better” implementation
  - Not very object-oriented
Solution: *virtual* extension methods

- Virtual extension methods specified in the interface
  ```java
  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.”
Virtual extension methods

- Within I, extension methods are a tuple \((n, D, m)\)
  - Calls to \(i.m(\text{args})\) are rewritten \textit{at run time} to \(D.m(i, \text{args})\)
- Gack, is this multiple inheritance in Java?
  - Yes, but Java already has multiple inheritance of \textit{types}
  - This adds multiple inheritance of \textit{behavior} too
    - But not state!
    - Abstract classes still relevant for representation
  - Multiple inheritance still a source of complexity due to separate compilation and dynamic linking
- API evolution may be the primary motivator, but useful as an inheritance mechanism in itself
Method resolution

- The rules treat inheritance of behavior from classes and interfaces separately
- Declarations in classes always win over interfaces
  - Follow the implementation hierarchy upwards
  - If you find a concrete body, OR a declaration that the method is abstract, stop
  - Only then consider defaults provided by interfaces
- Declarations in more-specific (under subtyping) interfaces win over less-specific interfaces
- 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

    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> { … }

• Here, the fact that C<T> declares Collection<T> as an immediate supertype is irrelevant
  • Set is more specific and also provides a default, so it wins over Collection
Method resolution
Handling diamonds

• We track not the identity of the default, but the interface that provides it

```java
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)
  • Diamonds are a problem for state inheritance, not behavior
But wait, there’s math

The type checking and method resolution rules are specified by a formal model (excerpts here)
Compatibility goals

• The whole point of this feature is being able to *compatibly* evolve APIs

• Compatibility has multiple faces
  • Source compatibility
  • Binary compatibility

• The key operation we care about is *adding new methods with defaults* to existing interfaces
  • 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 goals

- How to achieve source and binary compatibility for addition of extension methods is not fully solved
  - Almost there – solved for programs that are globally consistent (i.e., would compile if recompiled from scratch)
  - Damn that pesky separate compilation!
- Currently several vectors through which an “innocent” change to an interface can break code
  - Add an extension method whose signature matches that of another method but whose return type is not compatible
    - This problem existed before, but went untriggered because changes to interfaces in standalone libraries were rare
  - Add an extension method which is identical to an extension method in another interface, and classes exist that implement both interfaces
Compatibility goals

• The solutions to each of these problems involve tradeoffs between complexity of method resolution, and the set of incompatible changes
  • Three kinds of solutions
    • Storing additional as-compiled state in the classfile
    • Using properties of the call site (e.g., interface through which invokeinterface is invoked)
    • Imposing a linearization order on candidate interfaces that could be used to resolve incompatibilities

• We care more about avoiding binary incompatibilities than source incompatibilities
  • After-the-fact source incompatibilities can be mitigated by module dependencies
How to implement?

- There are many possible 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
- Big question: is this a language or VM feature?
  - Reality: everything else about inheritance is a VM feature
  - Trying to implement otherwise would cause visible seams
Bridge methods rear their ugly head

• In Java 5, we added generics and covariant overrides
  • These broke the 1:1 correspondence between methods in Java source code and methods in classfiles
  • Compiler needs to generate “bridge methods” to make up for differences between the language and VM type systems
  • This happens with both covariant overrides and with generic type substitution

• The compiler knows that the two signatures are the same method, but the VM does not
  • Arguably this should have been a VM feature, but we took the easy route and did it in the compiler
Bridge methods

• Example:
  
  ```java
  interface A<T> { void m(T t); }
  interface B { void m(String s); }
  class C implements A<String>, B {
      public void m(String s) { ... }
  }
  ```

• Here, instances of C must respond to both signatures: `m(Ljava/lang/String;)` and `m(java/lang/Object;)`
  • Compiler generates the Object version which redirects to the String version
  • We need to be prepared to resolve defaults for both
  • Need to know at runtime these are really the same method!
    • “A simple matter of programming”
  • In the long run should probably push bridges into the VM
    • This problem also shows up with SAM conversion
Consequences for non-Java languages

• By making this a VM feature, non-Java languages can remain mostly ignorant of extension methods
   • Can invoke extension methods through invokeinterface without having to know that they are extension methods or how they are resolved
   • Can generate classes that implements an interface, and if new methods are added to the interface after compilation, defaults still work
   • Can generate interfaces with default implementations and use as a composition mechanism
   • Can package language-specific runtime functionality into interfaces that Java classes can “mix in”
Summary

• Virtual extension methods are an upgrade to existing interface inheritance, where classes can inherit behavior from interfaces
• Goal is to allow interfaces to be evolved without breaking existing implementations
  • Though also presents new options for composing functionality
• Implementation is as a VM feature, reducing impact on classfile consumers