Project Valhalla Update

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Project Valhalla

- Project Valhalla starts with a simple-seeming feature: *value types*
  - Pure data aggregates that (ideally) should have no ancillary overhead
  - This is the same reason Java has primitive types in the first place!
- But, features interact with other features
  - Adding one feature means adjusting many others
  - It's a long string…
- This will be a whirlwind tour of some of the areas we're investigating
  - The map is not fully drawn
  - Some parts are better filled in than others!

Project Valhalla

Why value types?

- The motivation for value types is simple

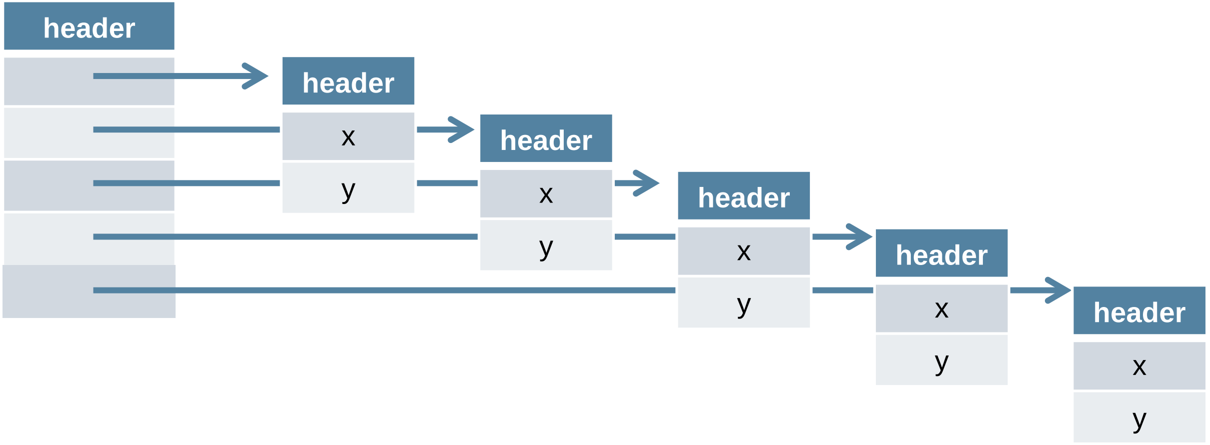
- Identity leads to pointers
- Pointers lead to indirection
- Indirection leads to suffering

Project Valhalla

The data layout we have

```
final class Point {
    final int x;
    final int y;
}
```

```
Point[] pts =
```



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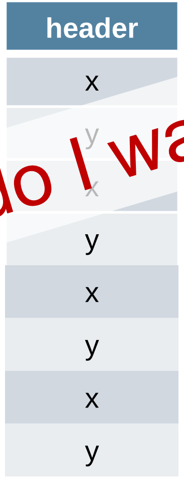
Project Valhalla

The data layout we want

```
value class Point {
    int x;
    int y;
}

Point[] pts =
```



What code do I want to write to get this layout?

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Valhalla: Goals

Performance goals

- Density and Flatness!
  - Get rid of extraneous headers and pointers (and heap allocation) when they don't add value
- *Stop making users choose between performance and abstraction*
  - Eliminate temptations to hand-unroll object abstractions into primitives
  - Eliminate need to hand-roll primitive specializations (like IntStream)
  - Generics should be the tool of choice for abstracting over types
- Value types, and specialized generics over values, eliminate these frictions

Valhalla: Goals

Expressiveness goals

- Caulk the seam between primitives and references
- Let generics abstract over references, primitives, values (and void!)
  - Write it once, not N+1 times
- Java 8 libraries illustrated the limitations here
  - Hand-written specializations like IntStream
  - Explosion of functional interfaces (Consumer<T>, ToIntFunction<T>, etc)
  - Streams of tuples are painful, inefficient
- Plus: *existing libraries* need help taking take advantage of new features
  - Just as Collections acquired lambda-friendly behavior via default methods

Value Types

Our starting point

- Value types are “pure data” aggregates
  - Just data, no identity
  - No representational polymorphism (no superclasses or subclasses)
  - Not mutable
  - Not nullable*
  - Equality comparison based on state (since there is no identity)
- By giving up on identity, mutability, polymorphism, we get…
  - Values routinely flattened into arrays, other values, objects
  - No object header needed
  - Aggregates (with behavior) that have runtime behavior of primitives

*Some possible relaxation may be needed here for migration compatibility

Value Types

- But, unlike primitives
  - Can have methods, fields
  - Can implement interfaces
  - Can use encapsulation to hide representation
  - Can be generic
- General rubric for answering “how would it work” questions
  - “What Would Int Do”

Codes like a class, works like an int

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Value Types

Who wants value types?

- Application writers
  – Can reason about locality and footprint of data-intensive code
- Library writers
  – Efficient and expressive implementations of smart pointers, alternate numerics, cursors, abstract data types
  – More efficient collections
- Compiler writers
  – Efficient substrate for language features like tuples, multiple return, built-in numeric types, wrapped native resources
- Everyone wants value types!

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Generics

- We can easily *express* everything we want with boxed generics
  - ArrayList<Integer> expresses what the user needs
- But each Integer in that list has the same problems as our Point class
  - Object header, indirection, allocation, GC overhead
- For all the same reasons we wanted values, we want ArrayList<int> instead of ArrayList<Integer>
  - Where the List is backed by a real int[]
  - (And same with generics over user-defined value types)
- Having value types, but no generics over values, would be terrible!
  - This is the string…

Value Types: Alternatives

Why not “just” do structs?

- The question suggests that structs are simpler than values
- But they aren’t simpler, they’re just more familiar!
  - A struct needs an identity
    - Sometimes the identity of the enclosing object
    - Sometimes an ad-hoc identity, if the struct is held in a local
  - Structs need both pass-by-value and pass-by-reference
    - Java only has pass-by-value – so this is new complexity surface
- Less optimizable
- Structs is really *more* work, and complexity, than values
  - Not “A OR B”, it’s “A OR (A AND B)”
- Conclusion: more cost, less safety

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Value Types: Alternatives

Why not “just” do tuples?

- We could easily denote “tuple of int and long” with the descriptor “(IJ)”
  - And provide opcodes for pushing, popping, and decomposing tuples
  - Semantics are very straightforward
  - Verification is easy
- But … almost as much new classfile surface area as values
- Would work for some value use cases
- What we’d lose is: encapsulation and nominality
  - Not suitable for secure representations (e.g., native pointers)
  - Point and IntRange would be the same type
- Conclusion: slightly less cost, measurably less benefit

Value Types

- What does it mean for the JVM to support value types?
  - How do we construct values?
  - How do we transfer values between stack and local variables?
  - How do we access fields of values?
  - How do we invoke methods of values?
  - How do we embed values as fields of objects?
  - How are values denoted in member descriptors?
  - How many stack slots does a value take?
  - How do we convert values to objects?
- Need new bytecodes, new type descriptors
  - Unlike refs or primitives, value types have **variable size**

Stack slots

- If a Point has two longs, how many slots should it take?
- Obvious (but wrong) answer is “4”
  - Would burn representation into client’s bytecode
  - Adding/removing fields would not be binary compatible
  - Might undermine encapsulation
- Reasonable answers include “1” and “2” (and other fixed numbers)
  - But both mean extra work for interpreter
- As we’ll see later, would like to get to all `xload` ops taking 1 slot – even dload/lload

Value Boxes

- Need a way to convert values to/from Object (and interfaces)
- Don't want ad-hoc, hand-written boxes like java.lang.Integer
  - Want to derive boxed projection from value classfile
- Do we need a way to separately denote boxed and unboxed values?
- Working theory:
  - **`LPoint;`** describes the boxed projection
  - **`QPoint;`** describes the unboxed projection

Value Bytecodes

- Bytecode design has many constituents
  - Verifier – can we guarantee type safety (especially pointer safety)?
  - GC – can we find all the pointers?
  - Compiler writers / code generators
  - Tools – can we easily extract and optimize data and control flow?
- Various bytecode schemes possible
  - Tradeoff between number of new bytecodes, footprint, and complexity
  - Some cases (e.g., getfield) could be retrofitted onto existing bytecodes
  - Could model most v* bytecodes with a prefix (**`typed QFoo; aload`**)
- We'll err on the side of simplicity now, and optimize later

Value Bytecodes

```
Point point = __make Point(3, 4);
int x = point.x;
int y = point.y;
```

```
 0: iconst_3
 1: iconst_4
 2: vnew          #19 // <vinit>:(II)QPoint;
 5: vstore        1 QPoint;
 7: vload         1 QPoint;
 9: vgetfield     #12 // Field x:I
12: istore_2
13: vload         1
15: vgetfield     #15 // Field y:I
18: istore_3
```

How many slots?

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Object Model

Lots of new questions

- Should Object be the top type?
  - Seems like “has identity” should be reflected in the type system
- Should there be a new “Any” type?
  - What would its in-memory representation be?
- Should there be a top type for values?
- Where should common methods (equals, hashCode) be defined?
- Should primitives become more like values?
  - Have methods, implement interfaces?

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Generics

- Generics embed an uneasy compromise: cannot generify over primitives
- Why?
  - No common top type between Object and int
  - No bytecode that can move both a ref and an int
- Assuming away primitives solved a lot of problems
  - But leaves us with lousy performance with boxed primitives
  - More allocation, less locality
- Library writers compensate with tricks like IntStream
  - Usually by cut and paste duplication
  - More footprint, more bugs
  - Less abstraction!

Generics

Erasure

- Erasure gets a bad rap, but was a *pragmatic compromise*
  - Enabled Java to acquire generics with no VM changes
  - Significant additional type safety, ZERO additional runtime cost
  - No additional runtime code footprint
- Permitted *gradual migration compatibility*
  - Libraries could be generified independently from clients
  - Clients could generify immediately, later, or never
  - No “flag days”
- Libraries are often in different maintenance domains than their clients (e.g., java.util.ArrayList)
  - Dynamic linkage is the norm, not the exception

Specialized Generics

- What does the bytecode look like for this class?
  - What are the method and field descriptors?
  - What bytecode pushes a T? aload? Something else?

```
class Box<any T> {
    T t;                                         // LBox;

    T get() { return t; }                        // ()LObject;
    void reset() { this.t = T.default; }         // ()V
    void set(T t) { this.t = t; }                // (LObject;)V
    Box<T> dup() { return new Box<T>(t); }       // ()LBox;
}
```


Specialized Generics

Model 1

- Our first attempt ("Model 1") annotated the classfile with type-variable metadata and specialized at runtime
- An aload bytecode that moved a \`T\` would get annotated as such
  - Specializer would rewrite appropriately to iload, dload, etc
- Amazingly, this worked!
  - All done with compiler and classloader trickery – no VM involvement
  - But … messy, intrusive and complex
- No commonality between List<int> and List<long>
  - No wildcards!

Specialized Generics

The prime directive: compatibility

- Just as with the first time around, we need gradual migration compatibility for enhanced generics
  - Anyfying an existing type variable must be source- and binary-compatible (for clients and subclasses)
  - Generifying an enclosing scope must be source/binary compatible
  - Alpha-renaming a type variable must be source/binary compatible
  - Adding a new type var at the end should be binary compatible
- Hierarchies anyfied from the top down
  - Clients/subclasses should have choice of anyfying immediately, later, or never
  - No flag days!

Specialized Generics

Bytecode set is hostile to parametric polymorphism

- The bytecode set has various annoying non-orthogonalities
- Some data types take one slot, some take two
  - How many LVT slots should we allow for a T in List<T>?
- Some instructions are not symmetric across types
  - Compare and branch: if_acmpeq for refs, dcmp + if for doubles
  - Array creation: anewarray for refs; newarray for primitives
  - Default values; aconst_null for refs; iconst_0 for int, etc
- These make it hard to represent a generic class in a classfile
  - Also made the specialization transform in Model 1 highly intrusive

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Specialized Generics

Model 3

- Our 3rd attempt lightly refactors the classfile format to move all specializable metadata to the constant pool
- Declarations and uses of generic types captured in the classfile
  - Attributes to capture generic class declaration
  - Constants to describe uses of type variables, parameterized types
  - Bytecodes / bytecode modifiers to describe moving tvar-valued quantities, boxing conversions
- End result – specializing a class becomes specializing the constant pool!
- Still needs some help with long/double taking two slots

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Specialized Generics

GenericClass attribute

- An any-generic class has a GenericClass attribute
- "Table of contents" for type variables for this class *and enclosing classes*
  - Type variables from enclosing classes are implicitly part of a class declaration!
- Then refer to type variables by *number*

```
class Outer<any T> {
    class Inner<any U> { ... }
}
```

```
GenericClass {
    u2 name_index;
    u4 length;
    u1 classCount;
    struct {
        u2 clazz;
        u1 tvarCount;
        struct {
            u2 name;
            u1 isAny;
            u2 bound;
        } tvars[tvarCount];
    } classes[classCount];
}
```

Specialized Generics

ParameterizedType constant

- We need a way to denote List<int> in a descriptor
  - Where List is a generic class
- We describe a class with a Constant_Class_info
  - So how about describing a parameterized class with a similar constant?
- Needs to capture
  - Parameterization of enclosing class, if any
  - Name of the generic class to be parameterized
  - The type parameters

Specialized Generics

ParameterizedType constant

- Can denote **`List<int>`** as ***`ParamType[List, I]`***
- Type params can refer to “type entries” in constant pool
  - Including other parameterized types
  - Preserves structure of type description
- Can denote **`List<Optional<int>>`** as ***`ParamType[List, ParamType[Optional, I]]`***

```
CONSTANT_ParameterizedType_info {
        u1 tag;
        u2 enclosing;            // ParamType of enclosing class
        u2 templateClassName;    // Generic class
        u1 count;                // # of tvars
        u2 params[count];        // type parameters
}
```


Specialized Generics

Incorporating erasure

- We also need a way to describe an *erased* parameterization
  - At the very least, need this for compatibility with existing generics
  - Existing classfiles only know about erased parameterizations
- Use a special type parameter token (we use _) to denote “erased”
  - List of int : ***`ParamType[List, I]`***
  - List of reified String : ***`ParamType[List, Class[String]]`***
  - List of erased String : ***`ParamType[List, _]`***

Specialized Generics

MethodDescriptor constant

- How do we put a parameterized type in a method descriptor?
  - Currently, method descriptors just concatenate nominal descriptors of parameter types
  - But parameterized types don't have a nominalization…
- Need a structural descriptor for method descriptors!
  - Return type, arg types can refer to other types in CP

```
CONSTANT_MethodDescriptor_info {
    u1 tag;
    u1 argCount;
    u2 returnType;
    u2[argCount] argTypes;
}
```

Specialized Generics

ArrayType constant

- How do we refer to an array of a parameterized type?
  - Same trick – make a structural descriptor for array types
- Can denote **`List<int>[]`** as
  `ArrayType[1, ParamType[List, I]]`
- Type entries in ParamType, MethodDescriptor can also refer to arrays

```
CONSTANT_ArrayType_info {
   u1 tag;
   u1 arrayDepth;
   u2 componentType;
}
```

Specialized Generics

TypeVar constant

- How do we refer to a type variable, or a parameterization that includes a type variable?
  - Same trick – a TypeVar constant
  - Refers to a type var (by number), and carries (contextual) erasure with it
    - “In case of erasure, break glass”
  - Can denote **`List<T>`** as
    `ParamType[List, TypeVar[0, “LObject;” ]]`

```
CONSTANT_TypeVar_info {
   u1 tag;
   u1 tvarNumber;  // index into tvar table
   u2 ifErased;    // type to use for erasure
}
```


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Specialized Generics

Structural descriptions of types

- Parameterized types (and array types) are fundamentally structural
  - Method descriptors are structural too
- New CP forms retain this structure, rather than flattening it
  - Leaves of tree are ground types (classes, primitives)
- “Type entry” fields can refer to a ground type, or to a ArrayType, ParamType, or TypeVar constant

Specialized Generics

Constant pool reduction

- Strategy: consolidate all type information in the constant pool
  - Much of the type information is already there (e.g., method sigs)
  - There should be *one* place where the binding T=int is recorded
  - Turn specialization of *classes* into specialization of the *constant pool*
- There is a simple, mechanical transformation on the CP for a generic class to produce a CP for any given specialization
  - Storing the erasure with each type variable use means that erasure computation is owned entirely by the language compiler
- VM is free to share rest of the class

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Specialized Generics

Specialization example

```
class Example<any T, any U> {
    Example<T,U> example;
    Example<int, int> ii;
    Example<int, String> is;

    void m(Example<T, U> e) { }
}
```

```
 #2 = Utf8                 _              // erased
 #3 = TypeVar              0/#2           // T
 #7 = Utf8                 V
#11 = Utf8                 Example
#12 = TypeVar              1/#2           // U
#13 = ParameterizedType    #11<#3,#12>    // Example<T,U>
#23 = Utf8                 I
#24 = ParameterizedType    #11<#23,#23>   // Example<I,I>
#27 = ParameterizedType    #11<#23,#2>    // Example<I,_>
#32 = MethodDescriptor     (#13)#7
```

```
               T=_, U=_
 #2 = Utf8     _
 #3 = Utf8     Object
 #7 = Utf8     V
#11 = Utf8     Example
#12 = Utf8     Object
#13 = Utf8     Example
#23 = Utf8     I
#24 = Utf8     Example${II}
#27 = Utf8     Example${I_}
#32 = Utf8     (LExample;)V
```

```
               T=int, U=_
 #2 = Utf8     _
 #3 = Utf8     I
 #7 = Utf8     V
#11 = Utf8     Example
#12 = Utf8     Object
#13 = Utf8     Example${I_}
#23 = Utf8     I
#24 = Utf8     Example${II}
#27 = Utf8     Example${I_}
#32 = Utf8     (LExample${I_};)V
```

```
               T=int, U=int
 #2 = Utf8     _
 #3 = Utf8     I
 #7 = Utf8     V
#11 = Utf8     Example
#12 = Utf8     I
#13 = Utf8     Example${II}
#23 = Utf8     I
#24 = Utf8     Example${II}
#27 = Utf8     Example${I_}
#32 = Utf8     (LExample${II};)V
```

Specialized Generics

New bytecodes

- Wait, what about bytecodes?
  - Bytecodes operands point into the CP too!
  - So if we modify a bytecode with a “typed” prefix…

```
typed operand  aload_0
```

  - Operand points to a type entry in the CP (like a TypeVar constant)
- Theoretically only need a “typed” prefix, and a conversion bytecode (for boxing and unboxing)

```
a2b from-operand to-operand
```

  - Alternately could define family of uload/etc which take a type operand

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Specialized Generics

Runtime representation

- Historically, there was a (mostly) 1:1 relationship between source files, classfiles, and runtime types
  - Not for values: classfile describes at least two types, the value and the box
  - Not for generics: classfile describes a *parametric family* of runtime types
- We've been using the term *species* to describe deriving multiple related runtime types from a single classfile
  - The *class* of **`List<int>`** is still List, but the *species* is **`List<int>`**
  - **`Object.getClass()`** will still return the class
  - Something else (TBD) will have to return the species

Specialized Generics

Generic methods

- Generic methods pose a new challenge
  - VM has a notion of class, but no first-class notion of method
  - But code can refer to type variables defined in enclosing generic methods
- Need to include enclosing generic methods in GenericClass “table of contents”

```
class Outer<any T> {
    class Inner<any U> {
        <any V> void m() {
            class Local<any W> {
                void m(T t, U u, V v, W w) { ... }
            }
        }
    }
}
```


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Specialized Generics

Generic methods

- Current strategy is to desugar generic methods into nested classes
  - Reduces method specialization to class specialization
  - Invoke specialized via invokedynamic – bootstrap takes specialization params (statically known at compile time)

```
class Foo<any T> {
    <any U> void m(T t, U v) { ... }
}
```

```
class Foo<any T> {
    bridge void m(Object t, Object u) { ... } // erased bridge

    synthetic class Foo$m<any U> {
        species-static void m(T t, U v) { ... }
    }
}
```

Specialized Generics

These are not the reified generics you're looking for…

- A specialized class List<int> *is* reified
  - But List<String> (probably) won't be
  - M3 classfiles can express both List<String> and List<_>
  - Choice of when, and how, to erase becomes language's prerogative
- Reified generics are harder to program with
  - Real-world code resorts to tricks that implicitly assume erasure
  - Casting through raw, unchecked ops
- Many potential compatibility, performance pitfalls
  - We still want gradual migration compatibility for anyfying a library
- So erasure is *still* (probably) a pragmatic compromise here

Specialized Generics

Species statics

- There are currently two “places” to put state / behavior
  - Static members – associated with a class
  - Instance members – associated with an instance
- Is it useful to associate members with a species too?
- Yes! This is the natural placement for
  - Cached instances (e.g., empty list)
  - Instantiation tracking (e.g., counters, interning)
  - Reified type variables (e.g., List<T> has a species-specific field T)
  - Static factories
  - Cached associations (e.g., preferred box type of X in Y)

Specialized Generics

Species statics

```
interface List<any T> {
    // new way
    private species-static List<T> empty = new EmptyList<>();

    public species-static <T> List<T> emptyList() {
        return empty; // no cast needed
    }

}
```

Specialized Generics

Species statics

```
class Foo<any T> {
    public synthetic final species-static ReflectiveThingie T;
}

Foo<int> fi = ...
... fi.T ...  // reflective mirror for int
Foo<String> fs = ...
... fs.T ...  // reflective mirror for “erased”
```

Specialized Generics

Nestmates

- There's a mismatch between the language-level rules for accessibility and the VM rules
  - In Java language, private means "accessible from anywhere in my top-most enclosing class"
  - In VM, it means "only from within this classfile"
  - Compiler emits access bridges (access$000) and downgrades private to package to make up difference
- With species, the set of runtime types that derive from a single top-level source class gets bigger (and more complicated)
  - We introduce the concept of *nest-mate,* which eliminates the need for bridges / encapsulation downgrades

Specialized Generics

Nestmates

- Nests form a partition over classes
  - Each class belongs to exactly one nest
  - What constitutes a nest is defined by language compiler
  - All specializations of a class C belong to C’s nest
  - All inner classes of C belong to C’s nest
  - Private becomes “accessible from within my nest”
- This is *not* “friends”
  - Simply a generalization of “common compilation unit”
  - Fixing some age-old technical debt

Specialized Generics

Partial methods

- As the domain of generics broadens to include things like numerics…
  - We start to want to condition behavior on receiver type parameters

```
interface Stream<any T> {
    <where T implements Arithmetic>
    T sum();
}
```

  - Here, sum() would be a member of Stream<int> but not Stream<Shoe>
  - Represented in classfile as a ConditionalMethod attribute on the method
- Both an expressivity feature *and* a migration compatibility feature

Specialized Generics

Wildcards

- Model 1 had no wildcards
  - This was “wildly” unpopular
  - Very difficult to port existing generic libraries without them

```
class Foo<any T> extends Bar<T> { ... }
```

  - Foo<int> is a subtype of Bar<int>
  - And also a subtype of Foo<?>
- Foo<?> can be neither a class nor an interface
  - Needs to be something new
  - Need VM help here

Reflection

- How do we reflect over specialized classes?
  - Can we get a Class for List<int>?
  - Can we reflect over an abstract template List<T>?
  - How do we reflect over generic methods?
  - How do we model erasure in reflection?
- See “One Mirror To Rule Them All”, later today…

Arrays

- The lack of a common useful supertype between int[] and Object[] becomes a bigger problem
  – What happens when a method returns T[]?
- Some subset of Arrays 2.0 is needed here
  – Common supertype Array<any T> for all array types?
- For migration compatibility, some way to migrate an Object[]-bearing method to a T[]-bearing method is needed

Migration

- Phew, that was a lot
  - … and we're not done
  - … actually we're just getting started!
- What we've outlined so far might be OK if this was a NEW language
- What about migrating existing APIs, clients, and implementations?
  - Some APIs won't anyfy cleanly
  - Anyfying core libraries *must* be compatible – for clients *and* subclasses
  - Can we migrate existing reference types to value (like Optional?)
  - Can we consolidate IntStream into Stream<int>?
  - Can we consolidate the nine version of Arrays.fill() into one method?

Migration

Anyfying existing libraries

- Just as generifying libraries not designed for generics posed challenges…
- … Anyfying APIs not designed for values also poses challenges
  – Some signatures use Object instead of T, or Foo<?> instead of Foo<? {extends,super} T>
  – Some overloads become questionable (e.g., remove(T) vs remove(int))
  – Some methods use null to signal “no answer” (e.g., Map.get())
- Anyfying implementations also requires code adjustments
  – Assignment to / comparison with null
  – Array creation – new T[n]
  – Instanceof / cast

Migration

Migrating classes to values

- Some classes, like Optional, LocalDateTime, and BigInteger are semantically values already
  - We'd like to migrate their implementation to be values too!
- L/Q descriptor split was motivated by enabling binary compatibility via bridge methods
  - Good story, but doesn't get us 100% of the way there
  - LOptional is nullable and QOptional is not, means there are source compatibility issues to be worked out

Migration

Signature migration

- There are many kinds of signature migrations we'd like to make compatible
  - Migrate off of deprecated types: m(Date) -> m(LocalDateTime)
  - Widen returns: migrate Collection.size() to return long
  - Convert value types to reference types
  - Squeeze IntStream to implement Stream<int>
- The older our libraries get, the more important it is that we be able to flexibly and compatibly evolve them
- As we add language features, we'd like for existing libraries to have a migration path, rather than making them "instant legacy"

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Migration

Signature migration

- Investigating features to enable library authors to provide metadata for "this method migrated from …"
  - Old signature, conversion functions for argument/return
  - Box/Unbox, Date <-> LocalDateTime, etc
- Binary compatibility for clients can be handled by bridges
- Binary compatibility for subclasses is harder … working on this
- Source compatibility is another story…

Summary

- We started out with a simple performance goal – dense/flat aggregates
  - This led to value types
- In order for values to be useful, must address interaction with arrays, generics, reflection, core libraries, …
  - It's a long string!
- In order for new language features to be useful, must be possible to bring old libraries up to date
  - So migration tools are a big part of the story too
- Some areas well understood … some areas still research

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Summary

Current status

- 3rd-generation prototype of anyfied generics (works over primitives) in Valhalla repo
  - More limited prototype of value types
- For further reference:
  - Model 3: http://cr.openjdk.java.net/~briangoetz/valhalla/eg-attachments/model3-01.html
  - State of the Values: http://cr.openjdk.java.net/~jrose/values/values-0.html

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Project Valhalla Update

Brian Goetz, Java Language Architect

JVM Language Summit, Santa Clara, August 2016

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