Evolving the JVM: Principles and Directions

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JVM Vision, circa 1995

Theory: JVM is not just for the Java language

- “The Java virtual machine knows nothing about the Java programming language, only of a particular binary format, the class file format.”
- “Any language with functionality that can be expressed in terms of a valid class file can be hosted by the Java virtual machine.”
- “In the future, we will consider bounded extensions to the Java Virtual Machine to provide better support for other languages.”
  - *JVM Specification* First Edition (1997), preface and §1.2
  - also reaffirmed in the preface to the J2SE 7 Edition (2013)

JVM Status, circa 1995

Practice: Some instructions have fixed, Java-like semantics

- invoke* instructions
  - Linkage is static; once done, cannot be re-done
  - Single-dispatch, receiver-based selection
  - Single inheritance of implementation
  - No argument or return type adaptation
  - Limited return types (multiple values, but only via heap)
- Serious pain point for language implementors
  - Workarounds exist, with pain (reflective dispatch and/or adapters)

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JVM Vision, circa 2009

The down payment: JSR-292

- JSR-292 opened up method dispatch to arbitrary linkage semantics
  - invokedynamic: extensible invocation mode
  - MethodHandle: access to all previous invocation modes
  - guardWithTest, etc.: MethodHandle composition operators
  - (Mutable)CallSite, SwitchPoint: options to re-link calls

- Result: Less pain. Invocation sites can be shaped, not worked around.
  - *Caveat: Multiple return values are still a pain.*

JVM Status, circa 2013

- “In the future, we will consider bounded extensions to the Java Virtual Machine to provide better support for other languages.”
  - *JVM Specification* First Edition (1997), preface
- “The Java SE 7 platform in 2011 made good on [this] promise.”
  - *JVM Specification*, J2SE 7 Edition (2013)

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- Great start!
  - What's next?

JVM Vision, 2014

- Let's find some more pain points, where JVM semantics…

  … align too rigidly with Java language semantics,

  … fail to align closely with modern hardware,

  … or impose excessive costs in some other way.

- It appears we can relieve major pain points.
  - Improve simplicity and performance for new users
  - Retain compatibility and performance for present users

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JVM Pain Points (for language implementors)

Pain Point	Tools & Workarounds	Upgrade Possibilities
Names (method, type)	mangling to Java identifiers	unicode IDs ✓1.5/JSR-202, structured names
Invocation (mode, linkage)	reflection, intf. adapters	indy/MH/CS ✓1.7/JSR-292, tail-calls, basic blocks
Type definition	static gen., class loaders	specialization, value types
Application loading	JARs & classes, JIT compiler	Jigsaw, AOT compilation
Concurrency	threads, synchronized	Streams ✓1.8/JSR-335, Sumatra (GPU), fibers
(Im-)Mutability	final fields, array encap.	VarHandles, JMM, frozen data
Data layout	objects, arrays	Arrays 2.0, value types, FFI
Native code libraries	JNI	Panama

+ sun.misc.Unsafe

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(got all that?)

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Which language implementors?

…four letter word …starts with ‘J’

- Java is improving in each release
  - With great care and deliberation
  - Selective “sedimentation” of proven features (Reinhold)
  - The JVM evolves with the language
- The JVM also evolves with the underlying hardware
  - Sedimentation process is not just language-driven
- JVM design addresses a broad range of languages and hardware
- Wider applicability interests more people, applies more brainpower

When extending the JVM…

(some major principles)

- Never break old bytecodes
  - gate new behaviors on class file version number
  - new features must not interfere with old ones, even in new class files
- New mechanisms are supersets of old ones *(wherever applicable)*
  - e.g., invokedynamic provides complete access to old “bytecode behaviors”
  - overheads are collapsed by the compiler; no built-in “simulation overheads”
  - JVM users need not choose *clean* vs. *fast, expressive* vs. *compatible*
- Design to “categorical” language and machine capabilities

Some current JVM initiatives

- Project Valhalla http://openjdk.java.net/projects/valhalla/
  - Value Types – aggregates without identity
  - Specialization – templated types on demand
  - JMM Update – VarHandles
- Project Panama http://openjdk.java.net/projects/panama/
  - Arrays 2.0 – flexible array implementation and organization
  - Layouts – flexible object layout
  - FFI – better native code interop

What's in a value?

(word history first, as found in http://etymonline.com)

- **value (n.)** c.1300, "price equal to the intrinsic worth of a thing;" late 14c., "degree to which something is useful or estimable,"
- … from Latin *valere* "be strong, be well; … worth"
- … from Proto-Indo-European root **wal-* "be strong"
- cognates: Old English *wealdan* "to rule," Old High German *-walt*, *-wald* "power" (in personal names), Old Norse *valdr* "ruler," Old Church Slavonic *vlasti* "to rule over," Lithuanian *valdyti* "to have power," Celtic **walos-* "ruler," Old Irish *flaith* "dominion," Welsh *gallu* "to be able"

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Blast from the past: Sumerian accounting

http://blogs.utexas.edu/dsb/tokens/the-evolution-of-writing/

- Mobile handheld
- Message based
- Token passing
- Polymorphic
- Secure envelope
- Linear (B) logic
- Silicate substrate
- Sub-cm process

…method and apparatus for symbolically transmitting objects of value…

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Subsequent refinements

http://magazine.uchicago.edu/1102/features/the_origins_of_writing.shtml

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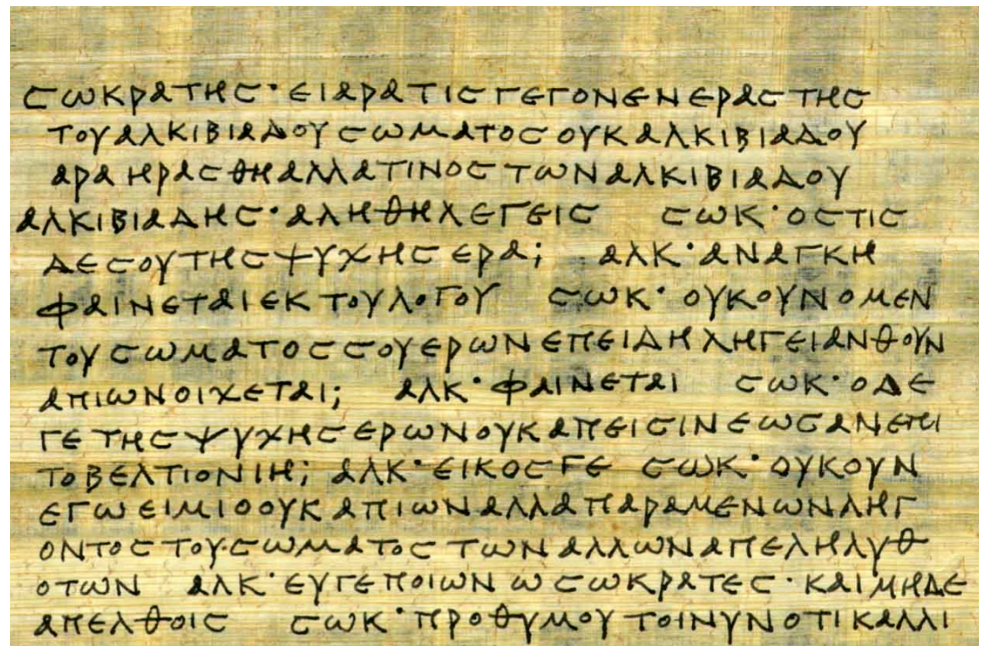
http://magazine.uchicago.edu/1102/features/the_origins_of_writing.shtml



images from commons.wikimedia.org

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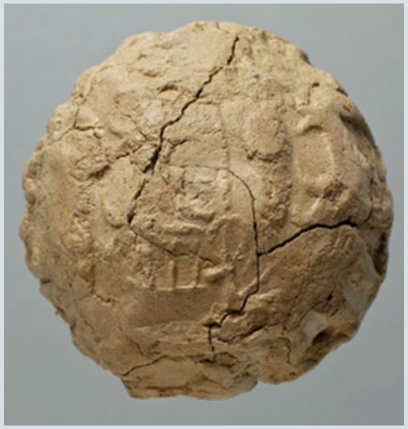
What is a value, for computers?

- Any indication of quantity or quality, something like a symbol.
  - Chosen from a fixed set of alternatives (dynamic range, alphabet).
- Values can be recorded and copied at negligible cost.
  - Like written letters. Unlike clay tokens or coins.
- All such values (symbols) can be resolved to bits. (Shannon, 1948)
  - They also occupy channels: Clay, paper, media, ether, cache lines.
- In the setting of the JVM, a managed pointer, after “new”, is a value
  - **pre-existing managed pointer** = **special kind of bits**.

Values, objects, and immutability.

Object	Immutable Object	Value
		☺

(exaggerating to make a point here)

Values in the JVM

- So, we have value types already: Primitives and references
  - Yes, a reference is a value.
  - But (according to our working definitions) most **objects** are **not** values.
- The main problem with JVM values is composition (composite values)
  - Needed when the primitives are not quite right: BigInteger, Complex
  - JVM composites, **objects**, are expensive to construct
- Another problem is control of concurrent side effects (JMM)
- Simple answer: Make pointers optional

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Pointer-free programming in the JVM

The restrictions

- No locking
- No identity comparison (or, if forced, loose specification)
- No identity hash code
- No cloning
- No finalizer
- “null” is not a value
- No visible side effects
- No sub-**class**-ing (subtyping via extension)

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Example: a *value-based* class

(N.B. this is not a value type, yet)

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

    public Point(int x, int y) {
        this.x = x;
        this.y = y;
    }
}
```


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Value-based classes

- Let's just pretend the pointer isn't there!
  - And hope the optimizer gets the idea
  - (And the GC. And reflection. And…)
- A "value-based" class is defined as one whose pointer is negligible

  http://docs.oracle.com/javase/8/docs/api/java/lang/doc-files/ValueBased.html
- But we need a way to promise the JVM that it can always optimize
- This means new types, not new optimizations on old types

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Example: a value type

(same as the previous class, with a little more markup)

```
final __ByValue class Point {
    public final int x;
    public final int y;

    public Point(int x, int y) {
        this.x = x;
        this.y = y;
    }
}
```


Example: methods on a value type

```
final __ByValue class Point {
    ……
    public boolean equals(Point that) {
        return this.x == that.x && this.y == that.y;
    }
    private static String strValueOf(Point p) { … }
    public String toString() { return strValueOf(this); }
}
```


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Codes like a class, works like an int!

http://cr.openjdk.java.net/~jrose/values/values.html

Example: coding with values

```
static final Point ORIGIN = __MakeValue(0, 0);
static Point displace(Point p, int dx, int dy) {
    if (dx == 0 && dy == 0)
      return p;
    Point p2 = __MakeValue(p.x + dx, p.y + dy);
    assert(!p.equals(p2));
    return p2;
}
```


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Pointer-free *values* in the JVM

The permissions

- Customized boxes are available (at nominal cost)
- Whole values can be assigned
  - Structure tearing is controlled: Nothing halfway between ’A’ and ’B’.
- Methods and fields can be defined (public/package/private)
- Via the boxes, all the comforts of objects:
  - Object.toString etc.
  - Interfaces: Comparable, etc.
  - Reflection

Y U No Make Syntax Beauty?

- **__ByValue** and **__MakeValue** are calculated, blatant bad form
  - Lest anyone suppose we are proposing a source code notation
  - It is too early to define Java language syntax
- JVM folk need to define a bytecode syntax independently of JLS
  - Hey, JLS doesn’t define a syntax for the invokedynamic instruction either
- Lots of syntax choices involving ASCII and Unicode
  - JVM folks are deeply interested in syntax of UTF-8, u1, u2, u4, etc.

Selected details

(see values.html for many, many more)

- An array of values is not a subtype of an array of references
  - Works like an int, so like int[] or long[], flattening is expected.
- A value type is distinct from its (unique) box type
  - Auto(un)boxing rules apply to values as well as primitives
- Primitives are not exactly value types, but act like them
- A value field can be of almost any type, but must be final
  - Values should not have lots of fields, though limits are lax
  - No variable-length or recursive values. (Use a reference field.)

Some use cases

(see values.html for more)

- *Numerics:* complex, decimal, rarely-big-num, etc.
- *Native types:* int128_t, vectors, unsigned, safe native pointers
- *Algebraic data:* optional (no box), choice-of, unit (no bits)
- *Tuples:* multiple-value return! (requires specialization machinery also)
- *Cursors:* unboxed iterators, STL-style bounds
- *Flat data:* values naturally represent pointer-poor data structures
  - Caveat: values are not structs.

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Arrays 2.0 – degrees of design freedom

A million ways to roll an array

- Rank and size (dimensions)
- Index type (int, long, *other?*)
- Element storage (type)
- Locality design (row- or column-major, chunked, nested)
- Managed vs. native
- Loops (elemental ops, linear algebra, streams, for-loop, etc.)
- Element variability (read-only, single write, concurrent update)
- Structure variability (append, insert, delete, etc.)

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Sometimes freedom can slow you down!

For real freedom, define the ingredients, not the menu

- Remember that restaurant with the 20-page menu?
  - Better to select from a short list of fresh and healthy ingredients

- Use interfaces to create clean APIs (specialization will help also)
  - Use classes to cleanly layer implementations
- Supply a few low-level storage tactics, following hardware & GC design
- Let the library experts (JVM customers) invent the detailed recipes

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Needed: a well-appointed kitchen

- Classic arrays: Flat, 1-d, mutable (except frozen), non-concurrent
- A couple of internal chunking styles, optimized for flatness
  - Blocked array (all element types, including multi-field value types)
  - Low-arity B*-tree nodes
- A few concurrency strategies (includes struct-tearing protection)
  - Final/persistent, fenced/concurrent, divide-and-process
- Beyond that, classes & interfaces can build & defend new APIs
  - Syntax alert: Might want abstract array notations a[i] = x

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A note on scale

- N.B. Galaxy-sized contiguous arrays are an anti-pattern
  - 32 bits is almost large enough, for implementation blocks.
- Terabyte scale logical arrays should be segmented physically.
  - Segmentation should not appear to the user
  - Except perhaps via spliterators
- The most important locality is at the scale of a cache line (LSU)
  - Or perhaps a few hundred of them (HW/SW prefetch)

API notes

Standard operations (access)

- basic operations drawn from java.util.Arrays (binary search, sort, etc.)
  - sub-array, sub-matrix (aliased views, cf. List.subList)
  - element, row, column streams and/or collections
- array as matrix, matrix as array views (cf. APL reshape)
  - array and matrix gluing (aliased views, border creation)
- these can be defined as default methods
  - but can be specialized as needed

API Notes (2)

Standard operations (element processing)

- standard bulk (whole-array) arithmetic (cf. APL)
- transpose or reshape
  - as copy (not aliased)
  - as view (aliased)
  - in place (potentially overwrites representation)
- selected linear algebra operations on vectors, matrices

More JVM heap support for arrays

A few new tricks for managed memory

- Frozen arrays (safe immutability)
  - Requires a freeze() method to go with the clone() method
  - A few well-placed freeze() calls enable chains of copy-elimination
  - Must be a dynamic property of classic arrays, not a new kind of array
- Mixed arrays (It’s an object! No, it’s an array!)
  - Objects with inlined private arrays; **not** a subtype of classic arrays
  - Safe version of the C trick of a struct with trailing zero-length array
  - Requires special factory-style constructors (new;<init> consider harmful)
- Maybe, something with a more programmable mix of bits and refs.

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Native interconnect

- Native access between the JVM and native APIs
  - Native code via FFIs (JNR is starting point)
  - Native data via safely-wrapped access functions
  - Tooling for header file API extraction and API metadata storage
- Wrapper interposition mechanisms, based on JVM interfaces
  - add (or delete) wrappers for specialized safety invariants
  - value and view transformation
- Basic bindings for selected native APIs

Foreign layouts

- Native data requires special address arithmetic
  - Native layouts should not be built into the JVM (sorry, no native classes)
  - Native types are unsafe (hello, C!), so trusted code must manage the bits
- Solution: A metadata-driven Layout API
- As a bonus, layouts other than C and Java are naturally supported
  - Network protocols, specialized in-memory data stores, mapped files, etc.

Synergy with other JVM initiatives

- *Arrays 2.0:* Native arrays can be presented using array APIs
- *Value Types:* Can efficiently carry native types: complex, int128
- *Specialization:* Native type management, but not built into the JVM
- *Invokedynamic:* Native linking rules, but not built into the JVM
- *Sumatra:* Effective binding to fast moving GPU-related APIs.

To GC or not to GC?

- Some high-end customers need “wired” buffers in native heap
  - Native interconnect can help place this data where it’s needed.
  - Arrays 2.0 APIs make it look clean.
- Low-level access methods (based on Unsafe) can reach both sides
  - Allows some temporary quasi-values to be buffered on the managed heap
  - Allows code to be written without a native/managed committment
- Thread-scoped temporaries will need new mechanisms
  - There are good options available using try-with-resources

There's lots more on the distant horizon

- More hooks to vary hardwired JVM behaviors (see specialization!)
- Bytecode design cleanups (many small ones)
  - But, we are trying to avoid a complete classfile format overhaul
- New tools for statically processing code and data (jlink)
- Lighter alternatives to threads (coro and/or fibers and/or GPU SIMD)
  - (J. Rose is still looking for a compelling design for the JVM.)
- Tail-call, plus reification of basic block states as MHs for tail-calling

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Java Language-VM co-evolution

Where to put new features?

- When we implement a language feature, we could…
  - Do it all in the front-end compiler
    - Generics, checked exceptions, autoboxing
  - Do it mostly in the VM
    - New bytecodes, constant types, classfile attributes, privileged runtime, Unsafe
    - Front-end compiler is just syntax for VM features
  - Mix and match
    - VM provides sensible low-level building blocks
    - Front-end compiler uses building blocks to implement feature
- The trick is finding the right balance
  - Minimize impedance mismatch between language and VM
  - …without exporting “language problems” onto the VM

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Language-VM co-evolution

The balancing act

- Try to balance
  - Keeping Java language complexity from impinging on VM complexity
  - Avoiding impedance mismatch between language and VM
- How to win: find key language-agnostic VM/JDK improvements
  - Example: Lambda metafactory
  - Other compilers are free to use – or not
- What not to do: push Java’s wildcards into VM type system
  - A naïve version of reification would do this

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Java Language Initiatives

- Specialized generics (generics over primitives and value types)
  - On-the-fly adaptation of classes and methods
  - Motivates some new general-purpose VM features
    - classdynamic – programmatic class generation
    - Possibly “method missing” support
- Value types (and tuples)
  - Builds on VM support
- Atomic and fenced data access
  - VarHandle

Generic Specialization

Motivation

- Refresher: why value types?
  - Smaller footprint (no object header)
  - Better locality (no dereference)
  - Simpler semantics (no identity, no aliasing worries)
  - Lower operational impact (no allocation and GC)
- *Don't make user choose between abstraction and performance*

Generic Specialization

Motivation

- The same reasoning applies to generics
- Consider ArrayList<Integer>
  - Lots of boxing, extra footprint, loss of locality, possible aliasing
  - Yuck!
- User really wants ArrayList<int>
  - And have it backed by a real int[]
- Its bad enough we have eight types that don’t play nicely with generics
  - When we have value types, more than half our types wouldn’t
  - Would undermine the usefulness of value types

Generic Specialization

Basic Idea

- Given a class Box<T>
  - Currently, erase T to Object
    - And insert casts at use site

```
class Box {
    Object val;

    public Box(Object val) { this.val = val; }

    public Object get() { return val; }
}
```

- To specialize Box<int>, we would need different signatures
- Conclusion: we can cheat by using one class for ref types, but this trick does not scale well to non-reference types
  - Two choices: try to unify, or admit reality

```
class Box<int> {
    int val;

    public Box(int val) { this.val = val; }

    public int get() { return val; }
}
```

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Generic Specialization

Basic Idea

- Converting Box.class for T=int is not just mangling signatures
  - Mangle the bytecodes too!
  - Also, Box<int> does not extend Box
- Classfile representation annotated to reflect which signatures and bytecodes need adjustment for specialization

```
class Box extends Object {
private final Object*T t;

public Box(Object);
  Code:
   0:   aload_0
   1:   invokespecial   #1; //Method Object."<init>":()V
   4:   aload_0
   5:   aload_1*T
   6:   putfield    #2; //Field t;
   9:   return

Public Object*T get();
  Code:
   0:   aload_0
   1:   getfield    #2; //Field t;
   4:   areturn*T
}
```


Generic Specialization

Classfile representation

- Specializations should be generated on the fly, as needed
- Classfile serves double-duty
  - Directly loadable as erased class
  - Can be used as a template for generating specializations
- Need a way to write “Box<int>” in a classfile
  - But don’t want to impart semantics to naming convention like Box${T=int}
- Box<int> really means “The result of applying the specialization transform, with parameters T=int, to class Box”
  - Can we somehow write that in the classfile?

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Classdynamic

Invokedynamic for class generation

- The previous description sounds a lot like an indy callsite!
  - Bootstrap = specialization transform
  - Static args = class to specialize plus type substitutions
  - Together, these compose a *structural description* of a class
  - Type uses are compared structurally: the same if bootstrap and static args are the same
- Classdynamic = structural description of a dynamically generated class

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Classdynamic

Invokedynamic for class generation

- Strawman: create a new constant pool type, *dynamic class*
  - Whose structure looks like a bootstrap + static args
  - Allow dynamic class wherever nominal type uses are allowed
    - (Actual classfile representation is TBD)
  - Expository notation: **`classdyn { bootstrap(args) }`**
  - So List<int> would be written as
    `classdyn { JavaSpecializer(List, int) }`
- VM knows nothing about semantics of any given bootstrap
  - But there may be agreement between compiler and bootstrap

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Classdynamic

- Classdynamic can represent any mechanical class transform
  - Generic specialization (if the underlying class is suitably annotated)
  - Dynamic proxies
  - Synchronized wrappers
  - Forwarding proxies
  - Unreflectors
  - Tuples (*)
  - Function types (*)
- Moves code generation from compile time to runtime

*Even better if classdynamic can generate value types

Specialization of Generic Methods

- Java also supports generic methods
  – Need a mechanism for specialization of them too
  – Example: `<T> T identity(T t) { return t; }`
- Same challenges as class specialization, and then some
  – Adding new methods to existing classes is painful
  – We *could* statically generate specializations for all primitives
    - But this would fall apart for value types
  – So need a mechanism for hooking into nominal method linkage

Specialization of Generic Methods

“Method Missing” handlers?

- Many systems have a mechanism for providing last-ditch nominal linkage when traditional resolution fails
  - Generic method specialization can be implemented with a traditional “method missing” handler
  - Method-missing handler would be associated with a class, would consume a signature and produce a MethodHandle
  - Search order would follow usual inheritance order
  - Interaction with reflection … TBD
- Alternately, specialized generic methods could be invoked with indy
  - Much simpler, but less flexible

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Specialization Challenges

- Suppose I write a generic class ArrayList<any T>
  – Can I provide a hand-written replacement for ArrayList<boolean> ?
  – Can I do the same for a single method (e.g., hand-written version of ArrayList.contains() for T=int?)
  – Can I do the same for a specific instantiation of a generic method?
  – Can I add a sum() method to ArrayList<int>, that is not a member of other instantiations of ArrayList?
- Not being able to do these things would be a big limitation
  – Sometimes generic code is *too* generic

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Specialization Challenges

- Extending generics to primitives/values brings new challenges
  - Can’t assume “T extends Object”
  - Can’t assume “T[] extends Object[]”
    - But ArrayList still need *some* means of expressing “new T[]”
  - Can’t assume `null` is a valid value for T
    - Bad news for Map.get()
  - Can no longer overload remove(T) with remove(int)

Conditional Methods

```
class ArrayList<any T> {
    ...
    <where T=int>  int sum() { ... }
    <where T=long> long sum() { ... }
}
```

- Most of these challenges can be met with *conditional methods*
  - These are methods that only appear in some instantiations
  - They can be new methods or override existing methods
- Methods marked by special attributes
  - Ignored during ordinary class loading
  - Acted on by specializer (include the method or not, depending on T)
- Can be conditional on T=primitive, “T is a reference”, “T is a value”
  - Maybe on “T extends bound”, maybe not

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Value Types

- Value types are heterogeneous aggregates, like classes
  - Borrow many concepts from classes – methods, fields, etc
  - Declared like classes – with restrictions
    - No inheritance
    - No mutation
    - No cyclic containment
- Syntax still TBD!

```
__value__ class Box<any T> {
    T val;

    public Box(T val) { this.val = val; }

    public T get() { return val; }
}
```


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Value Types

- The sweet spot for value types are those aggregates that benefit from being passed … by value
  - Small tuples
  - Alternate numerics (complex, unsigned int)
  - Algebraic data types (Optional<T>, Choice<T,U>)
  - Cursors
- Motivation: don’t force users to choose between safety/abstraction and performance
  - Optional<T> provides a lot of type safety – but shouldn’t cost anything

Open question: value polymorphism

- In the current design, value types are not polymorphic
  - This may well be too limiting
- Considering a limited form of value polymorphism
  - Something like interfaces for values
  - But without boxing, identity, or heap allocation
- Example: Arrays 2.0
  - Many kinds of array representation
  - Would be nice if we could treat them all as Array<T>
    - While still allowing an array reference to be a value

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Challenge: Migration Compatibility

- Some classes today, like Optional<T>, should have been values
  – Will we be able to migrate these to be real values in the future?
    - If the answer is “no”, that would be sad
  – These classes already disclaim use in an identity-sensitive fashion
  – Can we migrate `Ljava/util/Optional;` to `Qjava/util/Optional;` compatibly?

Tuples

Really just classdynamic + value types!

- Tuples are an obvious application for value types
  - Tuple of T,U can be represented by `classdyn { Tuple(T, U) }`
  - Tuple bootstrap spins a simple value class with fields of the given types
  - Two tuple classes are the same if their component types are the same
- To represent in the Java language, “all” we need is:
  - Means of denoting type “tuple of T,U” (e.g., `[T,U]`, `Tuple<T,U>`, etc)
  - Means of constructing a tuple value from components (e.g., `[e1, e2]`)
  - Means of destructuring a tuple into its components (e.g., `[ a, b ] = aTuple`)

Tuples

Not just for the Java language!

- Recall central challenges of language-VM co-evolution
  - Minimize impedance mismatch between Java language and VM
  - When we evolve the VM for Java, make sure others can play too
- These tuples build trivially on general-purpose VM building blocks
  - Value types and classdynamic
  - (Exact same trick can be used to generate function (arrow) types)
- We can put java.lang.Tuple bootstrap into the platform runtime
  - Others are free to use or ignore it
  - If they use it for their tuples, cross-language interop comes for free

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VarHandles

Method handles for data

- Currently, support for atomicity and fencing is limited
  - Accesses to volatile fields automatically fenced, others not
  - Fenced operations and atomic operations (CAS) available through Unsafe
  - Is it time to bring these into the programming model “for reals”?
- VarHandle is like method handles for data
  - Abstracts over location – static fields, instance fields, array elts, off heap
  - Supports explicit fenced and atomic operations
- Safer than Unsafe, as fast as MethodHandle
  - Maybe will add language support, maybe VarHandle API is enough

Summary

- Common theme: more flexible access to data
  - Value types – aggregation without indirection
  - Arrays 2.0 – flexible data layout
  - FFI – access to off-heap data
  - Generic specialization – bring the benefits of value types to generics
  - VarHandle – more flexible, high-performance access to variables
- Time to stop making programmers choose between expressiveness/ abstraction/safety and performance

