Going meta to Panama & Valhalla

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http://cr.openjdk.java.net/~jrose/pres/201807-GoingMeta.pdf

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Meta…

How I learned to relax and generate my code on the fly…

OR

Many things worth doing are worth doing automatically.

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Demo first: Panama native library workflow

- New command:
  - `jextract` scans a header file into metadata JAR
- JARs to watch for:
  - **`stdio.jar`, `python.jar`**: C API's extracted as Java interfaces
- Types to watch for:
  - **`Library`**: a loaded native artifact
  - **`Pointer`**: cursor pointing into a native memory block
  - **`Scope`**: holder for native memory blocks and other resources
- Operations to watch for:
  - **`Libraries.bind`**: implement a set of extracted APIs

How to get Panama (1)

```
Projects$ hg clone http://hg.openjdk.java.net/panama/dev panama
http://hg.openjdk.java.net/panama/dev
pulling from http://hg.openjdk.java.net/panama/dev
…

Projects$ cd panama

panama$ hg config paths.default
http://hg.openjdk.java.net/panama/dev

panama$ hg log -b foreign -l1 --style compact
51692[tip]:51602,51687   9b3cc75708ea   2018-07-25 22:10 +0200   mcimadamore
  Automatic merge with nicl

panama$ hg co foreign
315 files updated, 0 files merged, 150 files removed, 0 files unresolved
```

How to get Panama (2)

```
panama$ vi README.foreign

panama$ CLANG=clang+llvm-6.0.0-x86_64-apple-darwin
panama$ open http://releases.llvm.org/6.0.0/$CLANG.tar.xz
panama$ (cd ~/Downloads; tar -xJf - < $CLANG.tar.xz)

panama$ (cd ~/Downloads/$CLANG; file lib/libclang.dylib)
lib/libclang.dylib: Mach-O 64-bit dynamically linked shared library x86_64

panama$ sh ./configure --with-sdk-name=MacOSX10.6 \
                 –with-boot-jdk=$HOME/env/JAVA11_HOME \
                 –with-libclang=$HOME/Downloads/$CLANG
configure: Configuration created at Wed Jul 25 16:26:13 PDT 2018.
…

panama$ make
Building target 'default (exploded-image)' in configuration 'macosx-x86_64-
normal-server-release'
…
```

How to get Panama (3)

```
panama$ ln -s build/macosx-x86_64-normal-server-release/jdk  JH

panama$ JH/bin/java -version
openjdk version "12-internal" 2019-03-19
OpenJDK Runtime Environment (build 12-internal+0-adhoc.jrose.panama)
OpenJDK 64-Bit Server VM (build 12-internal+0-adhoc.jrose.panama, mixed mode)

panama$ file JH/bin/jextract
JH/bin/jextract: Mach-O 64-bit executable x86_64

panama$ # make yourself an IDE project & open your favorite IDE

panama$ sh bin/idea.sh java.base

panama$ open -a 'IntelliJ IDEA 2018.2 EAP' IDE/java.foreign
```

How to kick the tires on Panama (1)

```
panama$ #ln -s build/macosx-x86_64-normal-server-release/jdk  JH

panama$ WRKARD='--exclude-symbols __.*|zopen /usr/include/i386/_types.h'
panama$ JH/bin/jextract -t nat /usr/include/stdio.h -o stdio.jar $WRKARD

panama$ zipinfo stdio.jar nat/stdio.class
-rw----     2.0 fat    21790 bl defN 18-Jul-30 17:06 nat/stdio.class

panama$ cat imports.jshell
import java.foreign.*
import java.foreign.memory.*
import java.foreign.layout.*
…

panama$ JH/bin/jshell JAVASE imports.jshell –class-path stdio.jar

jshell> <T> T bind(Class<T> api) {
                  return Libraries.bind(MethodHandles.lookup(), api); }

jshell> var stdio = bind(nat.stdio.class)
stdio ==> nat.stdio$Impl/0x0000000800168040@19d37183
```

How to kick the tires on Panama (2)

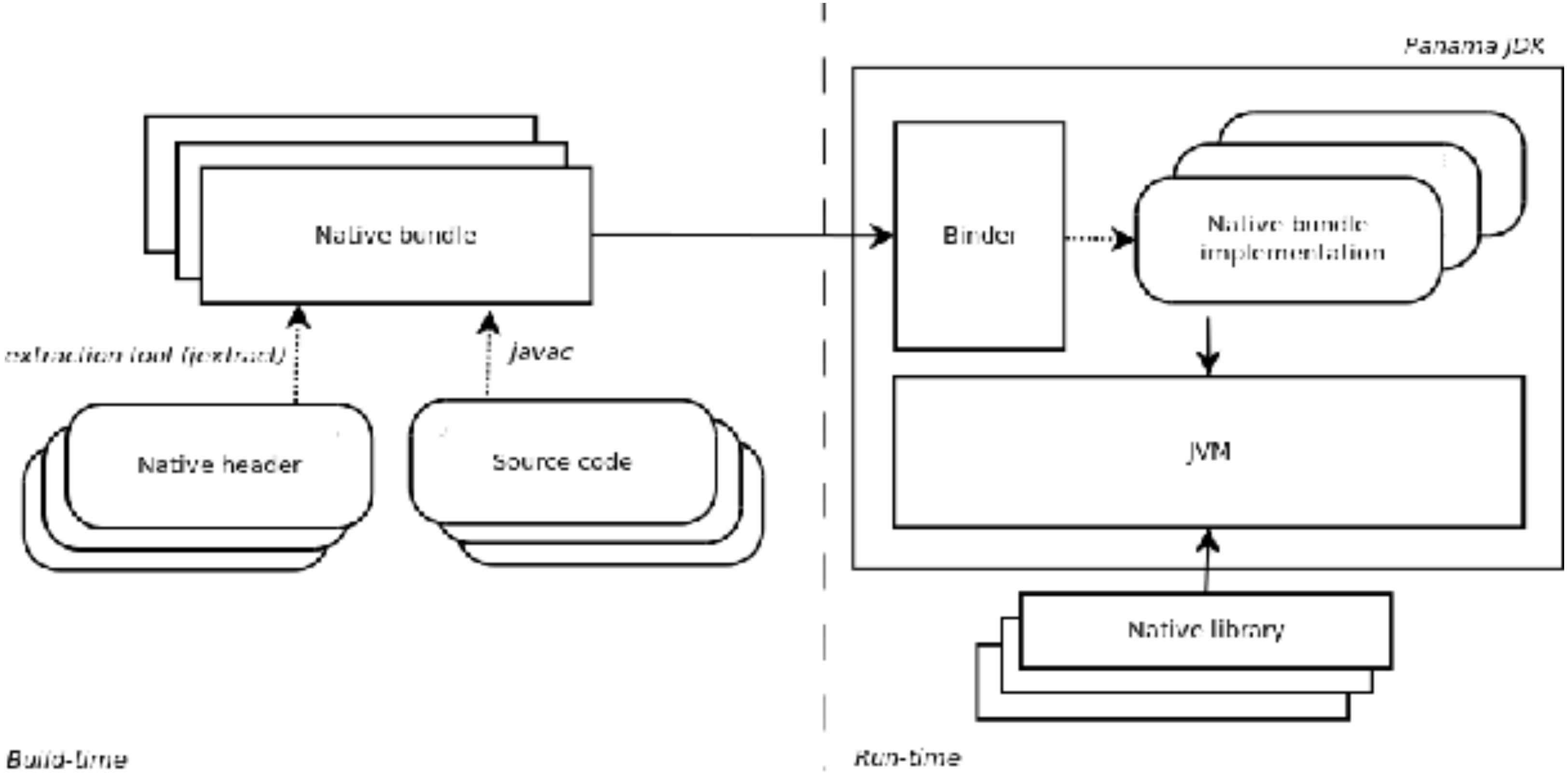
```
jshell> var globals = Scope.newNativeScope()
globals ==> jdk.internal.foreign.ScopeImpl$NativeScope@3bd40a57

jshell> Pointer<Byte> s(String s) { return globals.toCString(s); }
jshell> String s(Pointer<Byte> s) { return Pointer.toString(s); }

jshell> var buf = globals.allocate(NativeTypes.INT8, 100)
jshell> /var buf
|    Pointer<Byte> buf = { … }

jshell> var fmt = s("hello %s from #%d"); var world = s("world")
jshell> stdio.sprintf(buf, fmt, world, 42); s(buf)
$57 ==> "hello world from #42"

jshell> buf.offset(8).set((byte)0); s(buf)
$58 ==> “hello, w”
```

How to kick the tires on Panama (3)

```
panama$ jextract -l=python2.7 -rpath=/System/Library/Frameworks/
Python.framework/Versions/2.7/lib/ /usr/include/stdio.h /usr/include/
stdlib.h /usr/include/python2.7/Python.h -t org.python -o python.jar
…
panama$ JH/bin/jshell imports.jshell --class-path python.jar

jshell> var Python = bind(org.python.Python.class)
Python ==> org.python.Python$Impl/0x0000000800142c40@6cc7b4de

jshell> var pythonrun = bind(org.python.pythonrun.class)
pythonrun ==> org.python.pythonrun$Impl/0x0000000800158040@3d299e3

jshell> pythonrun.Py_Initialize()
jshell> pythonrun.Py_AtExit(() -> System.out.println("Good bye!”))
jshell> pythonrun.PyRun_SimpleStringFlags(s("exit()"),Pointer.nullPointer())
Good bye!
… (jshell subprocess exits) …
```

What did we just see?

`http://cr.openjdk.java.net/~mcimadamore/panama/panama-binder-v3.html`



Wrapperless native programming

- Native resources:
  - `jextract -l=python2.7 -rpath=…/Python.framework/…`
  - the JVM itself
  - no JNI wrappers, no extra native methods for Python or stdio
- We saw methods in stdio; where did their bytecode come from?
  - ***not*** statically generated by jextract (interfaces only in stdio.jar)
  - the binder Libraries.bind implemented the native APIs
  - …using Unsafe-style native call generators (as trusted code)
  - …and Unsafe API points to peek-n-poke inside native structs

The “binder pattern”

Application specific schema (foo.h)

⇒ extract metadata (jextract) ⇒

JAR of annotated interfaces foo.jar

⇒ run binder (bind(foo.class)) ⇒

implemented interfaces plus loaded resources (var foo)

⇒ Java programmer ⇒

use implemented API points on the interfaces (foo.natfunc())

Advantages of the binder pattern

- Static configuration is metadata only, not executable.
  - Says “what we need”, not “how to get it”
  - Metadata JAR has multiple uses, not just for execution.
- The runtime has the final word on implementation
  - Can take into account exact hardware and class-path configuration
  - Can be trusted to deploy unsafe implementation techniques
  - Can be configured with more or less “debug mode” or “perf mode”
  - The binder is a JIT API creator
- General pattern, applies to C, C++, IDLs, parser generators, etc.

Drawbacks of the binder pattern

- Runtime generation of code might make apps. slow to start
  - (It cuts both ways: Meta-JARs are tiny compared to regular JARs.)
- No source code to single-step through
- Configuration failures are detected late

- It’s a work in progress.
- Idea: A bound API could be a compile-time or jlink-time constant!

meta-programs manage meta-data *about* programs

- The output of a meta-program is some part of a “normal” program
- javac and `URLClassLoader` are familiar meta-programs
- The JVM is a great honking monster metaprogram
- Over time, we are refactoring the JVM to allow more metaprogramming
  - key refactorings take the form of “hooks” like `invokedynamic`
  - bootstrap methods execute at “meta” level and then return control
- Are we done adding bootstraps? Probably not…

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class file structure: the constant pool

```
ClassFile
  cp_info
  1: CONSTANT_Utf8 “Foo”
  2: CONSTANT_Class #1
  …
  41: CONSTANT_InvokeDynamic …
  …
```

class file structure: class/field/method schema

```
ClassFile

cp_info
1: CONSTANT_Utf8 “Foo”
2: CONSTANT_Class #1
…
41: CONSTANT_InvokeDynamic …
…

this_class = #2 “Foo”
super_class = #9 “Object”
interfaces[0] = #12 “Iterable”

field_info
name = “x”, desc = “LBar;”

method_info
name = “f”, desc = “()V”
```

class file structure: bytecode

```
ClassFile

cp_info
1: CONSTANT_Utf8 “Foo”
2: CONSTANT_Class #1
…
41: CONSTANT_InvokeDynamic …
…

this_class = #2 “Foo”
super_class = #9 “Object”
interfaces[0] = #12 “Iterable”

field_info
name = “x”, desc = “LBar;”

method_info
name = “f”, desc = “()V”

method_info
name = “g”, desc = “(I)I”

Code_attribute

0: iload 0 …
```

class file structure: indy

```
ClassFile
```

```
cp_info
1: CONSTANT_Utf8 “Foo”
2: CONSTANT_Class #1
…
41: CONSTANT_InvokeDynamic …
…
```

```
this_class = #2 “Foo”
super_class = #9 “Object”
interfaces[0] = #12 “Iterable”
```

```
field_info
name = “x”, desc = “LBar;”
```

```
method_info
name = “f”, desc = “()V”
```

```
method_info
name = “g”, desc = “(I)I”
```

```
Code_attribute

0: iload 0
3: invokedynamic #41
8: ldc #42
11: iadd
12: ireturn
```

indy

class file structure: indy, condy

ClassFile

```
cp_info
1: CONSTANT_Utf8 "Foo"
2: CONSTANT_Class #1
…
41: CONSTANT_InvokeDynamic …
42: CONSTANT_Dynamic …
…
```

condy

```
this_class = #2 "Foo"
super_class = #9 "Object"
interfaces[0] = #12 "Iterable"
```

```
field_info
name = "x", desc = "LBar;"
```

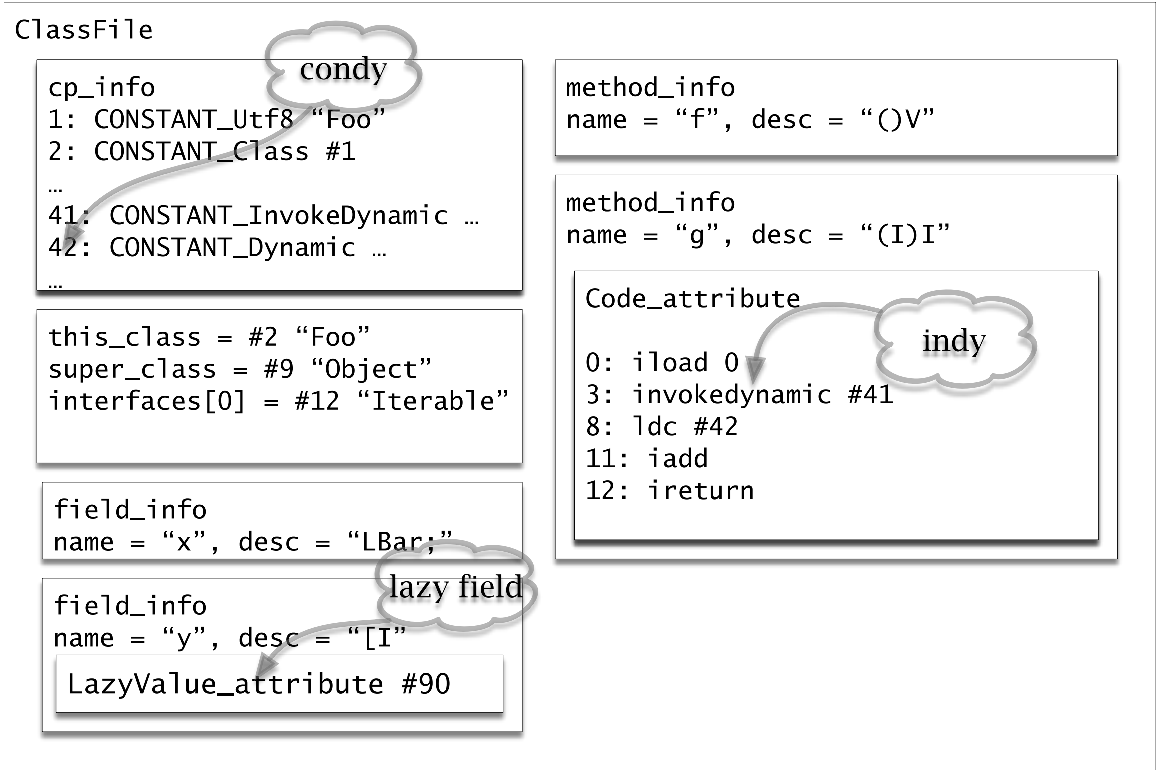
```
method_info
name = "f", desc = "()V"
```

```
method_info
name = "g", desc = "(I)I"
```

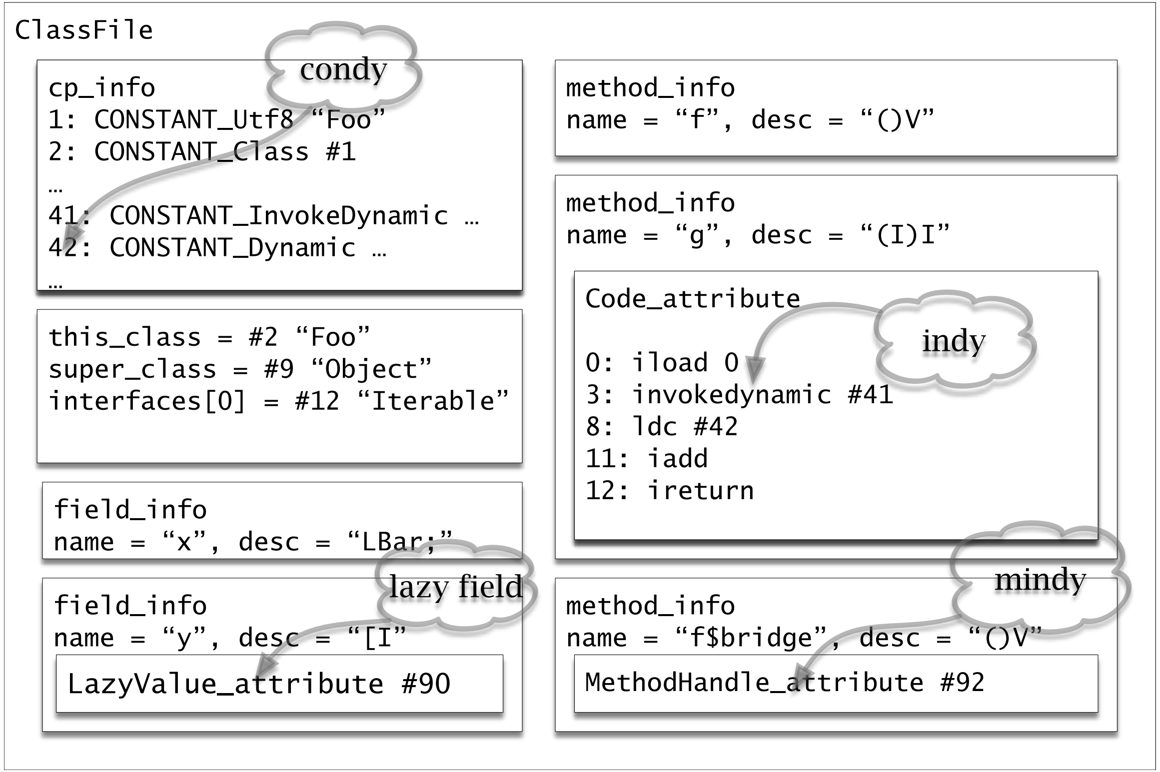
```
Code_attribute

0: iload 0
3: invokedynamic #41
8: ldc #42
11: iadd
12: ireturn
```

indy

class file structure: field impl. (“findy” ?)



class file structure: method impl. (mindy)



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class file structure: class impl.

```
ClassFile

cp_info
1: CONSTANT_Utf8 “Foo”
2: CONSTANT_Class #1
…
41: CONSTANT_InvokeDynamic …
42: CONSTANT_Dynamic …
…

this_class = #2 “Foo”
super_class = #9 “Object”
interfaces[0] = #12 “Iterable”
interfaces[1] = #43 “List<int>”

field_info
name = “x”, desc = “LBar;”

field_info
name = “y”, desc = “[I”
  LazyValue_attribute #90

method_info
name = “f”, desc = “()V”

method_info
name = “g”, desc = “(I)I”
  Code_attribute
  0: iload 0
  3: invokedynamic #41
  8: ldc #42
  11: iadd
  12: ireturn

method_info
name = “f$bridge”, desc = “()V”
  MethodHandle_attribute #92
```

condy

cindy

lazy field

indy

mindy

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meta programming with bootstrap methods

- Key question: What's in a name?
  - The JVM names classes, supers, fields, methods, descriptor types
  - Names are interpreted in the course of constant pool resolution
  - Can we add our own BSMs to enhance such resolution?
- invokedynamic on an arbitrary name
- ldc or getstatic on a lazy constant
- method resolution can use a BSM: "mindy" aka. "bridge-o-matic"
- class resolution uses `ClassLoader` API but can also use a BSM
- "Bootstrap methods everywhere!"

mindy (bridge-o-matic)

- Given: JVM needs to resolve a method (from `invokevirtual`, say)
- Step 1: JVM performs hardwired method lookup, and fails.
- Step 2: JVM notices one or more related classes with mindy BSMs.
- Step 3: JVM goes meta, hands request to each BSM in turn.
- Step 4: A BSM returns a valid MH for the method descriptor
- Step 5: JVM saves the resolution result, and uses it.
- Result: User request links to just-in-time special delivery code.
  - The code is generated using accurate information; no ICCE.

mindy (bridge-o-matic): today and tomorrow

- We are using automatic method generation today for values & records
- Idea: Pre-generate the method; body is a single `invokedynamic`
- Followup #1: No bytecodes, swap out `Code` for `MethodHandle` attribute
- Followup #2: Inherit specialized methods from the super
  - No methods at all in the class-file, just sugary supers
- Followup #3: ***import*** specialized methods from supplier classes.
  - The supplier would be privately declared inside the class.
  - This decouples inheritance from reuse, a very powerful move.
  - (Did you ever notice that `AbstractList` smells a little bit bad?)

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cindy (class-o-matic)

- Given: JVM needs to resolve a class (from `invokestatic`, say)
- Step 1: JVM performs hardwired class lookup, and fails.
- Step 2: JVM notices one or more related classes with cindy BSMs.
- Step 3: JVM goes meta, hands request to each BSM in turn.
- Step 4: A BSM returns a meta-class object for the class descriptor
- Step 5: JVM saves the resolution result, and uses it.
- Result: User request links to just-in-time special delivery code.

- Hang on! What's that "meta-class object"? Did we spin bytecodes?

going meta on classes

- A `MethodHandle` is reflected new behavior, not just a plain method
- So, what’s a reflected new type?

  ```
  jl.Class : jlr.Method  ::  ??? : jli.MethodHandle
  ```
- Idea: A type is a bundle of the same “stuff” as in a classfile
  - So a new reflected type is a bundle of reflected “classfile stuff”
- Operations on a reflected type (not just a `jl.Class`):
  - Resolve a static field, method, or constructor.
  - Test an object for membership in the type, or cast it.
  - Ask about related types, supers, etc.   (Also make an array?)
- If we can do “mindy”, then “cindy” becomes a bunch of “mindy” points.

other JVM work required: Species

- The JVM works very hard to efficiently implement class instances.
- It can help us implement abstract reflected types.
  - Even if they are not just dynamically spun classfiles.
- When is a type not a class? When it is a template species.
  - A class which can be specialized has one or more “holes”.
  - It is therefore a template which must be filled out.
  - Each specialization (“species”) fills the holes in a different way.
  - `List<int>` and `List<Point>` are species of template `List<·>`
- Conjecture: the JVM can spin up species more quickly than classes.

template classes in the JVM

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

- Idea: Punch some holes in a constant pool.
- Mark them (with metadata) describing how they must be filled.
  - Many holes will be types, as with reified generics
  - Conjecture: Other holes could be behaviors or arities or signatures
- Every time a template is filled in, a new species is created.
  - Implementor responsibility: Choose names and/or registries.
  - Filling in a template is like running a `ClassLoader`
- Generic methods can be localized templates inside a template class.
- Appropriate BSMs can perform ad hoc template expansion
  - For example: `FooList<T>` is comparable if `T` is comparable

what’s in a name, take #2

- Objects are nifty; we can model behaviors and types with them.
- When an object models meta-thing, it’s a meta-object.
- BSMs and binders are good ways to answer meta-questions.

- But what’s the ***name*** of a meta-object? Can a name be “meta”?
- Idea: Expand the JVM’s naming of classes and descriptors.
  - Add annotation-like decorations to existing type names.
  - Give useful rules for how to process annotated types.
  - Annotations trigger BSM invocation at link-time (resolution).
  - The verifier treats annotations conservatively (no BSM upcalls).

type operators in the JVM

https://bugs.openjdk.java.net/browse/JDK-8204937

- A type name can be followed by one or more type operators.
- Type operators have a syntax distinct from class names or descriptors.
- An appropriate BSM protocol (TBD) dispatches resolution requests.
- The verifier ensures
- Key semantic rule: A type operator ***always narrows*** its type operand.
  - Thus `Ljava/util/Map;/[ID]` is a subtype of `Ljava/util/Map;`
  - The prefix always names a less constrained type.
  - The undecorated type is the ***carrier type*** known to the JVM

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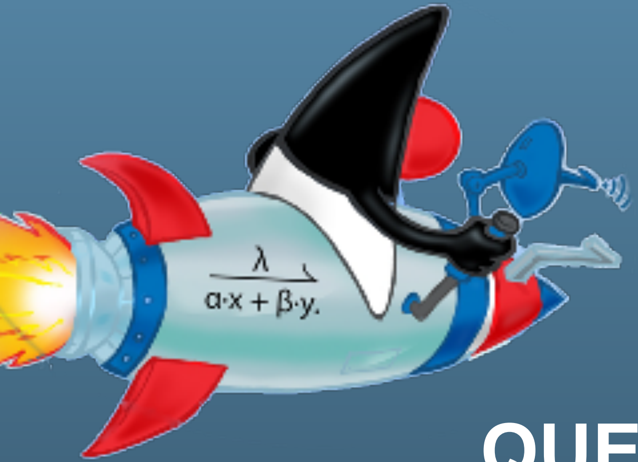
hypothetical type operator examples

- `Ljava/util/Map;/[ID]` denotes `Map<int,double>`
- `Ljava/util/List;/[$wild;]` denotes the wildcard species of `List`
- `I/$interval[$ge;0;]` denotes an int whose value is non-negative
- `Ljava/lang/String;/$N;` denotes `the` "`N`" variant of `String`
- `(Ljava/lang/String;)Ljava/lang/String;/$N;`
  … describes a method wrapping a String as an N-String
- `L/$union[LFoo;LBar;]` denotes a union of `Foo` and `Bar`
- `LFoo;/$and[LBar;]` denotes a `Foo` which must also be a `Bar`
- `L/$nullable[LPoint;]`
  … denotes a nullable reference further constrained to `Point`

meta-programs everywhere

- API bundles (Panama binder)
- method bundles (value type hashCode, datum toString)
- linkable instructions (indy, ldc/condy)
- template classes (reified generics)
- names (type operators)



QUESTIONS?

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