your next JVM:
Panama, Valhalla, Metropolis

John Rose, JVM Architect

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Purpose of this talk:

- Outline major trends in the evolution of the Java Runtime (JVM)
- Show how we are pushing those trends forward in OpenJDK.

- *Warning: The future is complicated. Download in 3, 2, 1…*

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What should the JVM look like in ~~20~~ 18 years?

(eight not-so-modest goals, from JVMLS 2015)

- **Uniform** model: Objects, arrays, values, types, methods “feel similar”
- Memory efficient: tunable **data** layouts, naturally local, pointer-thrifty
- Optimizing: Shared **code** mechanically customized to each hot path
- Post-threaded: Confined/immutable data, granular **concurrency**
- **Interoperable**: Robust integration with non-managed languages
- Broadly useful: Safely and reliably runs most modern **languages**.
- **Compatible**: Runs 30-year-old dusty JARs.
- Performant: Gets the most out of major **CPUs** and systems.

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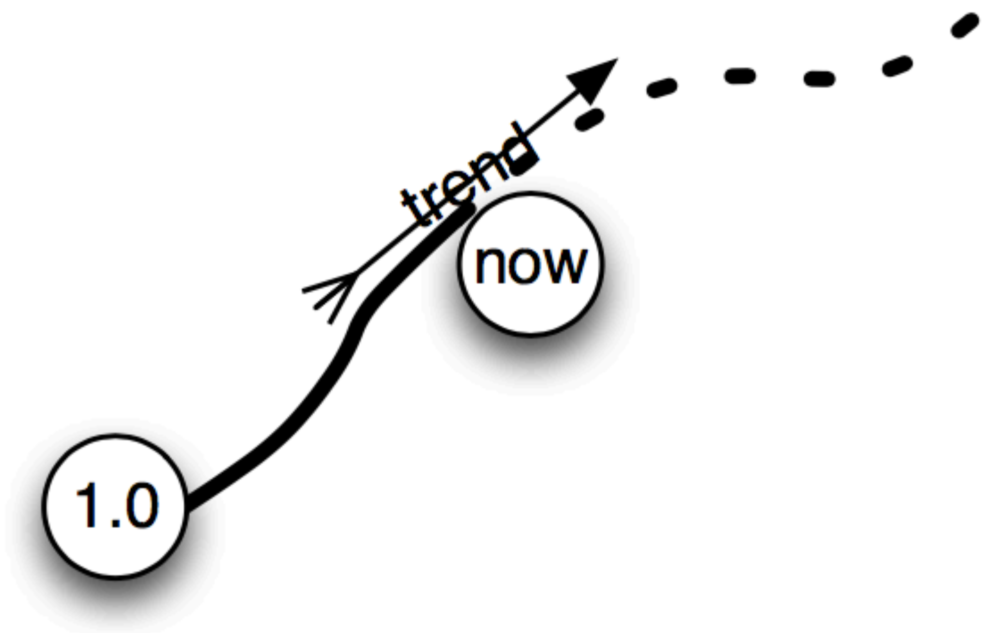
Forecasting is hard

(but sometimes you can draw a vector)



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Some trends

- Predictability / reliability / security
  - Manageable behavior: low-pause GCs, JVM provisioning
  - Ergonomics, metrics, monitoring: Flight Recorder, logging, telemetry
- Density / scaling
  - Data sharing, fast startup (AOT, Class Data Sharing), big heaps
  - Immutability (of native and AOT code now, data later)
- Polyglot / interoperability (more indy, Panama, machine code snippets)
- Layered implementations – strong abstractions + lowering
  - Macro-instructions (indy), simplified data model (value types)
  - Java-on-Java (JSR 292 v2, Panama, Graal, Metropolis)

Big Idea: Platform interoperability

- Idea: Make native code/data look more like Java code/data
  - A "heal the rift" move: abate invidious choices between on- and off-heap
- Depends partly on value types
  - To import native types (vectors, unsigned, complex) w/o boxing
  - To optimize "smart cursors" into foreign arrays and structs
- Depends on low-level bridges to non-Java ABIs and data layouts
  - The JIT makes a good code generator for this sort of thing
- Enables tight coupling with a wider range of data, APIs, ISAs
  - Both legacy (COBOL) and cutting edge (GPUs)
  - Low level punch-through to access ISA intrinsics directly ("Vector API")

Project Panama — what comes after JNI

- Zero hand-written code
  - Header file “groveller” extracts metadata which drives binder
  - Example: Replace 10Kb of handwritten Java + C with 6Kb of metadata.
- Direct, optimizable native calls from JIT. (FFI intrinsic MethodHandles)
- Direct, optimizable access to off-heap, fewer copies to/from on-heap.
  - Smart, type-safe, storage-safe pointers, references, structs, arrays.
- Direct access to hardware, including jumbo primitives like uint256_t.
  - Vector API for direct coding with platform vector instructions.
  - JIT-integrated assembly-language snippet mechanisms.
- *Better use of native resources, data structures, and libraries.*

Big Idea: Java-on-Java

- Idea: Implement the Java runtime using Java itself (less C++/asm)
  - Another “heal the rift” move (see a pattern?)
  - Up-level and simplify critical technology components
- Depends partly on interoperability (Panama)
  - To integrate Java components (e.g., Graal) into HotSpot
- Depends partly on flat data (Valhalla)
  - Temporary IR spikes in JIT are limited (partly) by data density
- Reduces all costs: maintenance, innovation, security
- Current practice: the whole JDK, MH runtime, AOT (coming soon)
- Some current experiments: Graal, Substrate VM, Bifröst

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Project Metropolis: City of Tomorrow

- Experimental clone of JDK 10 (*not* for immediate release)
- Hosting work on AOT and the Graal compiler
- Definition of “System Java” for implementing HotSpot modules.
  - Experimentation with SVM-style deployment.
- Translation of discrete HotSpot modules into System Java.
  - Candidates: MethodLiveness, verifier, reflection, class file parser
- The Big One: Compilation of Graal as System Java for JIT
  - Replacement for C2, then C1, then stub and interpreter generators.
  - This will take a long time, but it’s a necessary technology refresh.
- *Tomorrow’s reference implementation!*

Big Idea: Post-thread concurrency

- Idea: work around “dinosaur threads”
  – Break the live bits into smaller parts
  – Leave behind the fossils
- “Fibers”
- Depends on:
  – Tricky cuts in JVM interpreter and JIT
  – Lots of library work; all blocking APIs need attention

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Fibers: Dinosaurs as draft animals, not pets

- Fibers = caller/callee snippets decoupled from threads
- A fiber ***mounts*** on a thread
  - can also ***dismount*** into the heap
- Current experiments:
  - better stack walking
  - flexible bytecode interpretation (more modes)
- Lots of library work needed; all **blocking** APIs need attention
- Tricky interactions with synchronization (VarHandles, transactions?)
- JVM is responsible for right-sizing a **frame object** (continuation)

Big Idea: Value types — Project Valhalla

- Idea: "heal the rift" ("caulk the seam") between classes and primitives
- Distinguish legacy, by-reference "L-types" from new, by-value "Q-types"
- Value proposition for Q-types: *"Codes like a class, works like an int."*
- Depends on parametric polymorphism (any-vars not limited to L-types)
  - Which depends on template-like classes and their "species"
- Requires deep cuts to JVM code and data model
  - Quintessential "big ticket item". These are the Last Types We Will Need.
- Enables pervasive changes throughout the stack
  - Comparable to the impact of generics or lambdas
- Extends the benefits of class-based encapsulation to all values.

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Big Idea: Parametric polymorphism

- Idea: Make generalizations across ***all*** values (reference/primitive)
  - A “generalization”, in Java code, is a generic class or method.
- Depends on templates
- Depended on by:
  - Stream cleanup (no more IntStream)
  - Values
  - New array types
  - Foreign/off-heap reference and pointer types
- This is also part of Valhalla! Type variable = universal value container.

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Parametric polymorphism is hard

- Challenge: Primitives look really, really different from references.
  - This is why today's generics only talk about object references.
  - But today's situation doesn't scale to value types. So let's solve primitives.
- Issues: Static typing, equality, data model, no methods on primitives.
- Possible solution
  - Build an efficient mapping to treat primitives as Q-types.
  - Then everything boils down to Q-types (values) and L-types (object refs)
  - Top it off with U-types (disjoint union of Q- and L-types) for generic code.
- (This is not the way we'd do it if we weren't already adding Q-types!)

Impact of parametric polymorphism

- There are fewer “kinds” of types.
  - Everything has methods, and (maybe) has interfaces.
  - Everything has the same levels of equality (Lisp EQ, EQV, EQUAL).
- Introduction of templated classes
  - Pointer polymorphism isn’t enough; we need representation polymorphism
  - This implies some new distinctions; ArrayList<int> ≠ ArrayList<byte>
  - C++ templates do this statically; the JVM can do this dynamically.
- Dangerous Opportunity (not to be confused with “crisis” 危劫)
  - Maybe the expression “x * y” is generic?
  - A type-ful solution would amount to restricted operator overloading.

JVM “template classes” and “species”

- In JVM, template-ness is “really” constant-polymorphism.
  - I.e., a template class has holes in its constant pool.
- Holes are type-variables for parametric polymorphism.
  - Maybe holes could be numbers, strings, functions, etc.? (Cf. C++)
- Requires deep thinking about “what’s a constant pool”.
- Hardest problem: Avoid premature “code splitting”
  - Execute cold code from one set of bytecodes shared by species
  - The JIT inlines and customizes hot code, in the usual way.
  - Result: No footprint cost for seldom-used template instances.

Let’s look at some smaller ideas

(perhaps more self-contained – or maybe just more distant)

- Stack introspection
- Length-polymorphism
- Bootstrap methods everywhere
- Immutability & montonicity

VM design, like language design, is complicated like a Chinese puzzle.

When it’s finished it should look simple, from the outside.

Stack reification (introspecting the thread)

(backtraces 2.0)

- Walk “live” stack frames.
- See classes & methods, not just their names.
- Observe full frame states (locals, stack, monitors, BCI)
- ***Edit*** the stack
  - Replace ongoing computations with “better” ones
- Application: Dismount a blocking call from a thread onto a fiber
- Application: Generator coroutines
- Application: Replace a serial algorithm by a parallel one.

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Length polymorphism

(fused arrays)

- Poster child: String sub-object costs 16-24 bytes
  - String.value pointer = 4, 2nd header = 8, 2nd klass = 4, 2nd frag = 0..8
  - Matches or betters “bytewise string” tactic for String.length ≤ 24
- Generalization: Mark a private array as fused.
  - To the JVM, it looks like an array with an object jammed on the front.
- Requires array-like proxies to implement “baload”, etc.
- Requires GC cooperation to interpret embedded length field.
- Requires deep refactoring of new/invoke<init> ⇒ invoke<new>
  - ~~Constructor~~ Factory must be reponsible for object sizing & allocation.
- Bonus: Multiple fused sub-arrays?

Bootstrap methods everywhere

(works in progress)

- Embrace and double down on dynamicity of indy BSMs
- Use them wherever the JVM already has a “hook” for resolution
  – ldc of CONSTANT_foo
  – invoke of CONSTANT_Methodref or field ref
  – creation of a method or class

- Three examples:
  - Constants
  - Lazy Boilerplate Methods
  - BSMs in source code

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Bootstrap methods everywhere

- **Constants**
- Lazy Boilerplate Methods
- BSMs in source code

What’s in a constant?

(in the current JVM)

- Primitives: CONSTANT_{Int,Long,Float,Double}
- Strings, type names: CONSTANT_{String,Class}
- API points: field and method references (w/ nameAndType)
- Indy and MHs: CONSTANT_{InvokeDynamic,Method{Handle,Type}}

What’s in a constant?

(possible future use cases)

- Containers: arrays, Lists, Sets, Maps
- Value types: enums, BigInteger, Complex<F>, Point, Line, Color
- DSL snippet, compiled AST: RE Pattern, *(insert Linq-like feature here)*
- Support for ***templates*** for most of the above
  - "foo" + bar+(++barCount) + "baz" — *DONE!*
  - #"foobar{++barCount}baz" — *maybe?*
  - List#("foo", bar+(++barCount), "baz”)
- Key constraint: They can be internally mutable, but their value must persist reliably. Just like java.lang.String.
  - They are “materialized” lazily, perhaps interned, at resolution time.

What’s in a constant?

(a future-proof design)

- Should require only a handful of new CONSTANT_Foo types.
- Should be programmable via meta-factories (a la indy).
- Should enable but not mandate compression schemes.
- Should allow a generous amount of constant “payload bits”.
- Should clearly work for arrays, collections, and something value-like.

What's in a constant?

(ConDy, and more)

- CONSTANT_Dynamic (puts a BSM in a constant)
  - Equipped with BSM+args and type *(cf. indy = {{BSM+args},{name+type}})*
  - Resolved by executing BSM.invoke(lookup, type.class, static arg…)
  - Same rules as indy for dealing with exceptions, races, etc.
- CONSTANT_Group (overcomes the arity limit to BSMs)
  - Arbitrary group of constants, with 16-bit count.
  - Each constant can refer to main constant pool or can be inline.
  - Can nest, so can act like an S-Expression (for ASTs).
- CONSTANT_Bytes (delivers maximum sharing and density)
  - Up to Integer.MAX_VALUE bytes, reified as zero-copy ByteSequence.

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What’s in a constant?

(application to arrays)

- CONSTANT_Dynamic[ArrayFactory::constArray, int[].class, theBits]
- Where theBits = CONSTANT_Bytes[…bit image of desired array...]
- Where constArray(int[].class, theBits) makes and fills the array.
- What’s in the bits? Private agreement between javac and constArray.
  - Probably fodder for DataInput. (Big-endian by tradition.)
  - Could be var-ints (UNSIGNED5) or some other compression method.
- KEY CONSTRAINT: The array must be immutable (like a string).
  - Dependency: Support for frozen arrays.
- Alternative to frozen arrays: Only support CharSequence and similar.

Bootstrap methods everywhere

- Constants
- **Lazy Boilerplate Methods**
- BSMs in source code

Boilerplate reduction (aka. “bridge-o-matic”)

(use cases)

- Signature adjustment bridges
  - Adjust arguments: compareTo(String) ≡ compareTo(T<:Comparable)
  - Adjust returns: clone():Object ≡ clone():EnumSet
  - Bridges must be generated statically by javac
  - Sometimes this is too early to know critical class hierarchy info.
- Boilerplate methods
  - For Amber data classes: constructor, toString, hashCode, equals
  - Other method builders, such as Comparable.compareTo (lexicographic
- Panama binder (metadata-driven accessor creation)
- Valhalla per-species code (unclear if this is needed, though)

JVMs have boilerplate problems too!

- Amber might reduce your data-class source code to a single line.
- But if your class file is 100x larger your app. is still fat.
- Solution: Generate only the bytecodes you actually use.
- Pretty toString is there when you want it, but has no static cost.

- We must eagerly generate boilerplate when circumstances require.
  - AOT of shared, provisioned application runtime.
  - Bootstrap cycle breaking in the JDK itself.

Lazy boilerplate methods

(details)

- Allow a method to be equipped with its own bootstrap method (+args).
- Method is resolved on first execution (as if it contains an indy)
- Resolved by executing BSM.invoke(lookup, name, type, static arg…)

- Trivia question: What kind of method, *today*, has no bytecodes but is executable?
  – I.e., it is not ACC_ABSTRACT, yet it lacks a Code attribute.
- Answer: A native method.
  – Perhaps ACC_NATIVE+ACC_BRIDGE is the marker for a bridge-o-matic.

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Lazy boilerplate methods

(more variations)

- Existing bridges correspond to MH::asType transforms.
  - Actual as-loaded class hierarchy can be queried and validated.
- Type-polymorphism: A class declares a BSM for all types on a name.
  - Callers can avoid boxing primitives and varargs arrays.
- Name-polymorphism: A class declares a BSM for all names.
  - Aka. the “doesNotUnderstand” hook. (The original “invokedynamic”.)
- Inherited boilerplate
  - Interface “PrettyToStringForDataClasses” defines a default method
  - Default method is lazy boilerplate, instantiated *in each concrete subtype*

Bootstrap methods everywhere

- Constants
- Lazy Boilerplate Methods
- **BSMs in source code**

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BSMs in source code

(Const-able types, method builder recipes)

- Project Amber is exploring source-code syntaxes for BSM constructs
- Programmable “ConDy” constants using special javac intrinsics
- Programmable declarative method builders using InDy
- Result: Wider adoption of BSM-based mechanisms
- The JVM will be ready.

Bootstrap methods everywhere

(THE DOWNSIDE!)

The smarter your bytecode instructions become, the smarter your compiler has to be.

- JIT compilers usually work after resolution (including BSM calls)
- But AOT compilers cannot do this, in general.
  - Must be able to leave “holes” for non-AOT resolution logic (slow)
  - Or, must be able to simulate or predict the action of the BSM (tricky)
- Solution: Allow programmers to code BSMs directly when needed.
- Solution: Teach jlink and AOT to “expand” BSMs when needed.
  - BSMs must somehow support partial evaluation at AOT time (WIP!)

Immutability

(motivations)

- Simpler Semantics: Fewer program states to reason about.
  - Surprising or non-local side effects lead to bugs and races.
- Better sharing (better system density)
  - Between mutually untrusting actors. (Race condition = security vuln.)
  - Between JVM instances (if bits are in mapped file or shared memory)
- No more defensive copying.
  - If identity is suppressed, “expansive copying” can improve memory locality.
- Semantic simplicity enables ahead-of-time execution.
  - AOT of bootstrap methods or constant expressions, for example.

Immutability

(a quick observation for us Java programmers)

Imagine a version of Java where “final” is the default, and you need a keyword “nonfinal” to get variable mutability, method overridability, or class extensibility.

You would have to opt-in to those power features. Simpler-looking codes would have simpler semantics.

From that POV, today’s Java gets the defaults backwards.

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Immutability
(concrete cases)

- Frozen arrays or “array values”
  - array constants, secure array sharing
- Boxes that really work: Immutable final fields.
  - May require stronger guarantees on final field semantics.
  - We need to tame setAccessible(true) and deserialization.
- Frozen objects: Immutable ***non-final*** fields. (Cf. C++ const structs.)
  - Requires final-polymorphic classes, and/or a lock-bit in object headers.
  - Builder packs a private “larval” mutable, delivers a frozen result.

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Immutability

(the connection with identity)

- Headers can carry state if we don't watch out.
  – Monitor entry must be forbidden on frozen objects. (Check the lock bit.)
- More subtly, object identity can cause bugs similar to mutation-bugs.
  – Imagine if List.contains "forgot" to use equals and just used op==
- Current thinking: Leave identity as-is, but *only for legacy L-types*
- Add new Q-types for identity-hostile values
  - Some legacy L-type classes can "divest" identity by conversion to Q-types
  - Add U-types (union of L- and Q-) for code paths which must mix kinds.

Fit and finish: Small polishes to the JVM

- Nestmates
- Sealed interfaces
- Sealed fields

Nestmates: Smaller circles of trust

- In Java, all nested classes under one top-level class trust each other.
- This is not true in the JVM.
  - Javac generates package-private bridge methods for side-channels.
  - This makes bridged privates accessible throughout the package!
- Better solution: Clearly define “nestmates” at JVM level.
  - Use a new attribute, rather than parsing InnerClasses attribute.
  - Hardwire this attribute into the JVM’s access checking logic.
  - Result: No more package-private bridges into nest privates.
- Will also help clarify the status of runtime injected code (“host class”).
- Clean concentric circles: nest < package < module < everywhere

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Sealed interfaces: Better information hiding

- Interfaces, combined with private implementations, hide information
- Problem: They can be spoofed by untrusted code.
  - Root cause: Interfaces don’t have constructors.
  - Workaround: Recode as abstract class with private constructor.
- Better solution: Allow interfaces to be declared “sealed”.
  - In effect, it is as if the interface declared a private constructor.
  - Interface-specific contracts can be rigorously imposed—no spoofing.
- Possible “seal” granularity is nest, package, and/or module.
  - Nest is the most useful: Only nest mates may implement.

Sealed fields: Better mutability

- Many objects have public getters and private setters (or no setters)
- Problem: The most natural notation would be public fields
  - But that would allow untrusted parties to scribble non-final fields
- Cover this case by adding *asymmetric* field accessibility
- A “sealed field” looks mutable inside the class, and final outside.
- Important usability tweak for mutable data classes (if we do those)

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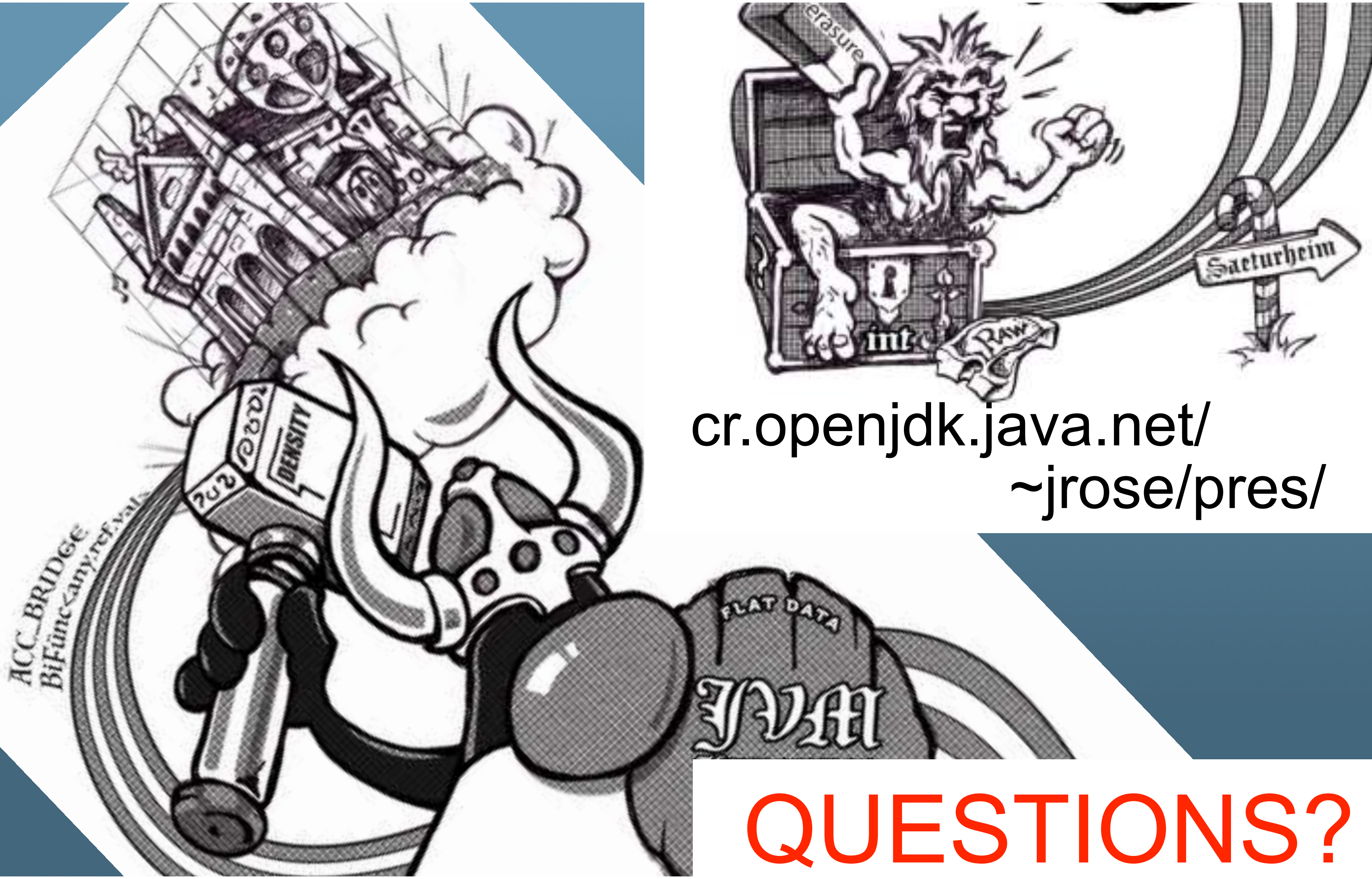

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QUESTIONS?