GraalVM™

Java Ecosystem & GraalVM

Java

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  - ○ Java Releases
  - ○ Java Object Model
  - ○ JVM Multilanguage Environment
  - ○ JVM Languages
- ➢ GraalVM
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  - ○ JIT vs AOT
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Java

- High-level programming **environment**
    - Java Language (and compiler) + Java Virtual Machine (runtime) + standard libraries
- Created 1995 by James Gosling for Sun
- Major implementations:
    - Oracle
    - OpenJVM (GPL) - the reference
- Evolves following formal *Java Community Process* via *Java Enhancement Proposal* (JEP) and *Java Specification Requests* (JSR)
    - All standard features should have the reference implementation and the conformity test suit
- Two release per year (March, September)
    - Current release: 17 (18 should be released today)
    - We are mostly using: 8, sometimes 11
    - Early access already for: 19
- Yearly Java One Conference @ San Francisco
- Almost completely backward compatible (i.e. one can compile/run old programs in new Java), except for some newly introduced keywords (like `assert`)
- Very dynamic and flexible environment
    - Introspection, Memory Management, …
- Many monitoring and profiling tools (thanks to introspection)

Java Performance

- Performance:
  - As other languages: math, graphics,... (as they are all calling the same implementation behind)
  - Faster than other languages: OO features, memory management, parallelism, dynamic optimisation
  - Slower than other languages: matrix manipulations (as no native matrices), some numerical operations (a cost for exact reproducibility), startup (as should load VM and perform initial optimisation)
  - Needs more memory (to enable reflection, memory management and allow dynamical features and runtime optimisation)
- Comparing performance is very difficult
  - Startup vs warmup vs peak
  - Throughput vs latency vs memory
  - Min vs max vs mean
  - Environment may be tuned for a specific performance requirements
  - Should compare on **real** applications, but then comparing not only language
    - Should include aux functionality (memory management, at least some reflection, often parallelism,...)

Java Releases

Java 17

- JEP 306: Restore Always-Strict Floating-Point Semantics
- JEP 356: Enhanced Pseudo-Random Number Generators
- JEP 382: New macOS Rendering Pipeline
- JEP 391: macOS/AArch64 Port
- JEP 398: Deprecate the Applet API for Removal
- JEP 403: Strongly Encapsulate JDK Internals
- JEP 406: Pattern Matching for switch (Preview)
- JEP 407: Remove RMI Activation
- JEP 409: Sealed Classes
- JEP 410: Remove the Experimental AOT and JIT Compiler
- JEP 411: Deprecate the Security Manager for Removal
- JEP 412: Foreign Function & Memory API (Incubator)
- JEP 414: Vector API (Second Incubator)
- JEP 415: Context-Specific Deserialization Filters

Java 18

- JEP 400: UTF-8 by Default
- JEP 408: Simple Web Server
- JEP 413: Code Snippets in Java API Documentation
- JEP 416: Reimplement Core Reflection with Method Handles
- JEP 417: Vector API (Third Incubator)
- JEP 418: Internet-Address Resolution SPI
- JEP 419: Foreign Function & Memory API (Second Preview)
- JEP 420: Pattern Matching for switch (Second Preview)
- JEP 421: Deprecate Finalization for Removal

Java Object Model

- Very sophisticated mechanism for creating Objects from different sources via hierarchy of `ClassLoaders` (what 'new' does)
- Allows constructing Objects like Lego
  - System classes
  - From JAR files
  - From Network
  - As Java Beans (Web Service)
  - Via Serialisation, object databases (e.g. reading of Root files)
  - Using Aspects (= enhancing objects at runtime)

```
ClassLoader loader = new MyClassLoader(...);
Object o = loader.loadClass("MyNamespace.MyClass").newInstance();
```

- Full class name includes classloader namespace + class name
  - So we can have different classes with the same name in one program
    - Allows for object migration (= one object changes its class)
    - Allows for dynamic re-loading of classes
- Base for reflection, memory management,...
- May be tricky and non-intuitive to use (e.g. anti-inheritance pattern)
  - Sometimes misused (log4j ?)
  - Application developer rarely needs it
- Since Java 9 extended to Java Modules (which can explicitly import/export/hide components)
- Foundation for multi-language environment
  - Classloaders loading from different languages into the same runtime

JVM Multilanguage Environment

- Languages completely interoperable with Java (loaded into the same runtime or compiled into standard classfiles)
  - Groovy, Scala, Kotlin, Clojure, BeanShell,...
- Languages from different origin, made interoperable by re-implementation (or via specific bridges)
  - Go, Haskel, JavaScript, Lisp, OCaml, Pascal, PHP, Python, R, Rexx, Ruby, Scheme, Smalltalk, Tcl,...
- More than 100 languages available in some way
- Low-level languages (C,C++,...) can be only connected via direct JNI or JNA
  - As they are running in an **unmanaged environment**

JVM Languages

- **Groovy** (Apache): very high level scripting language, used in Graph DB
- **Scala** (Apache): functional language, used in Spark
- **Kotlin** (Google): for Android
- **Clojure**: Lisp-like
- **BeanShell**: interpreted/scripted Java

- We can freely mix code from all those languages (even via inheritance)
- Can be used in a scripting interpreted way or compiled
- Successful new features from those languages are being incorporated in Java itself (e.g. functional syntax from Scala)

```
#!/usr/bin/env groovy
// converting SQL into XML with Groovy
// either run as a shell script or compiled
// ---------------------------------------------------------
sql = Sql.newInstance("jdbc:mysql://localhost/Tuples",
                      "org.gjt.mm.mysql.Driver")
xml = new MarkupBuilder(new File("Tuples.xml"))
xml.tagSet() {
  sql.eachRow("select * from tuple where run > 2") {
    row -> xml.tag(Run:row.run, Event:row.event)
    }
  }
```

GraalVM

GraalVM™

- Polyglot (J)DK & (J)VM
- By Oracle
  - Big effort
  - Also included in OracleDB
  - Already used in industry (Twitter,...)
- CE (Community Edition): GPL licence (or less) - as Java
  - Components have the same licences as the original implementations (eg. Python as Python)
- EE (Enterprise Edition): better performance, security, support,...
- GraalVM JIT is included in OpenJDK: `java -XX:+UnlockExperimentalVMOptions -XX:+UseJVMCICompiler`
  - So trivial to try
- New release every 3 months
  - rel22 since Jan'22 supporting JDK 11,17
- Linux, MS, MacOSX
- Uses new Java modularity features (since Java 9)
  - As the pluggable JIT compiler
- Similar project in the past: NestedVM - failed in 2009

GraalVM

Major features

- **Universal VM**
  - Non-JVM languages are at the same level as JVM languages (=> full interoperability)
  - All languages running in the same VM (traditional multi-language environment runs multiple languages side-by-side with frequent conversions of data)
  - GraalVM is faster and smaller than OpenJVM (GraalVM is written in Java, OpenJVM is written in C++)
  - Full interoperability between OpenJVM and GraalVM (program compiled for one can be run in another)
  - Can be embedded in external applications (Oracle, Apache, MySQL,...)
- **Can build native executables and libraries** (using AOT (Ahead Of Time) compiler instead of JIT)
  - Fully interoperable with native applications
  - Smaller footprint, faster startup, sometimes faster execution
  - Losing some dynamical features

Supported Languages

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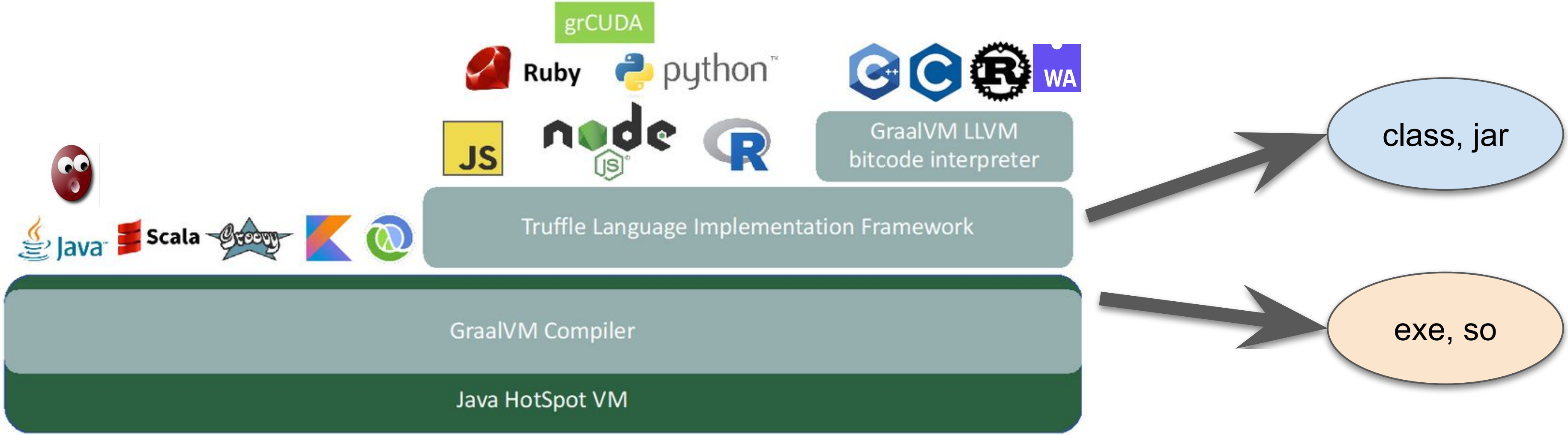
- ➢ <u>Growing number of supported languages (CUDA, WebAssembly,...)</u>
- ➢ New Tools (debuggers, profilers, monitors,...)
- ➢ Integration in other applications and toolkits

<u>Multiple languages are running in the same space/environment.</u>

X

Traditional multi-language pgms run multiple languages side-by-side.



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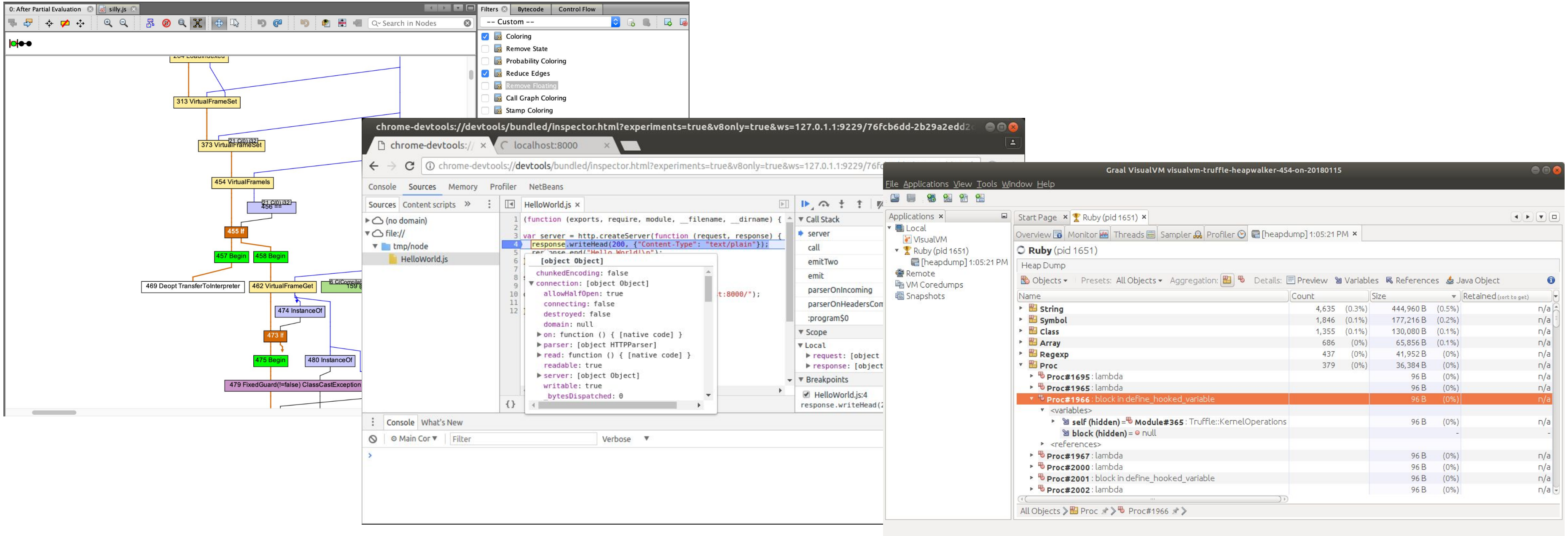
Tools

- ➢ Growing number of supported languages (CUDA, WebAssembly,...)
- ➢ New Tools (debuggers, profilers, monitors,...)
- ➢ Integration in other applications and toolkits

Tools understand your language.

Unlike tools for pre-compiled languages.



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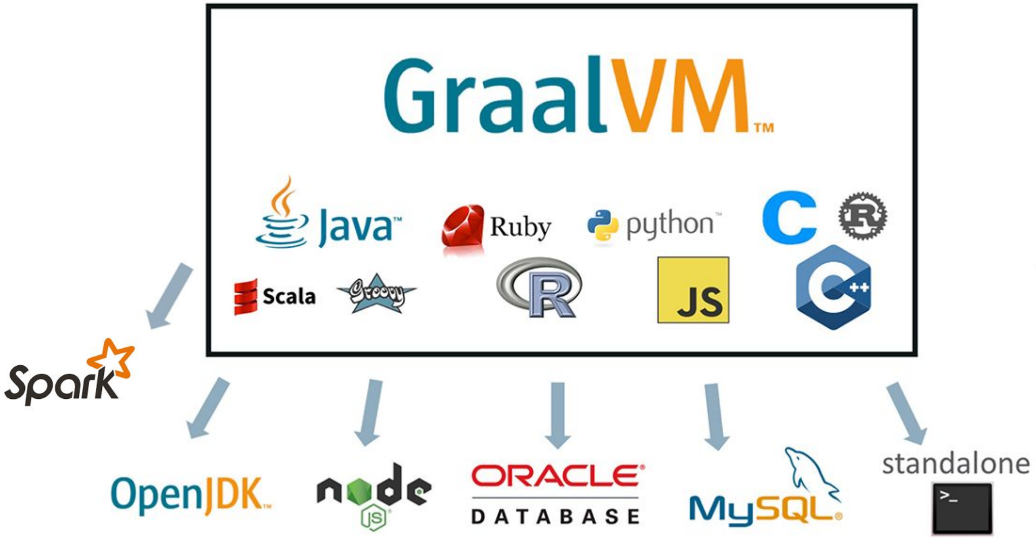
Integration

- Growing number of supported languages (CUDA, WebAssembly,...)
- New Tools (debuggers, profilers, monitors,...)
- Integration in other applications and toolkits

Allows, for example, using MySQL with Python instead of SQL.



Generating GraalVM native image is better than re-writing Java/Python/... in C/C++/Go,..

JIT vs AOT

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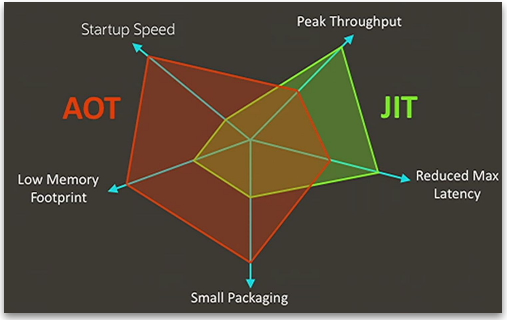
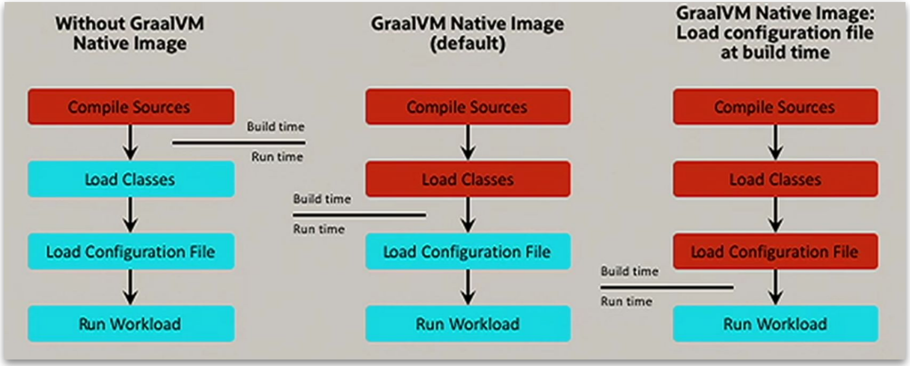
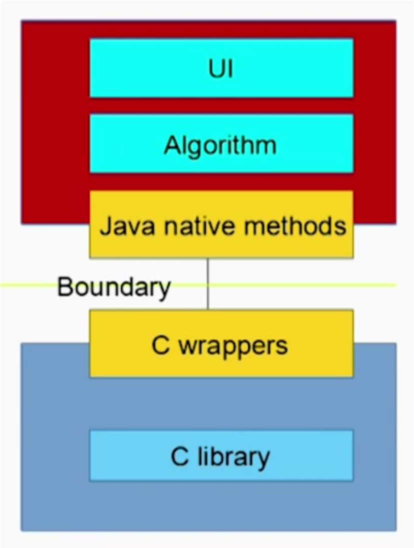
- ➢ JIT = Just In Time Compiler: compiling into bytecode (jar), dynamically re-compiling at runtime by JVM (HotSpot)
- ➢ AOT = Ahead Of Time Compiler: compiling into native binary (exe, so)
  - Very complex due to extremely dynamic nature of Java - tries to guess what is going on during runtime
  - Runs initialisation and creates initial heap during compilation
  - *Close World Assumption*: All dependencies should be available at compile time (not true for JIT), no dynamic loading
  - May have to provide hints about dynamic usage (reflection operations, class initialisation, lambdas, annotations, service loaders,...)
    - Can use **Tracing Agent** for that
    - Can put this configuration in jar `META-IN/native-image`
  - Can configure to tune the image (memory vs speed,...)
  - May need JVM at runtime (*fallback image*) to handle some dynamical operations
- ➢ Can compile jar into exe, so



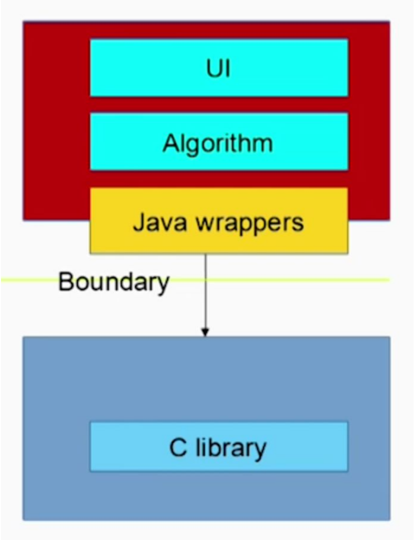


Java calling C

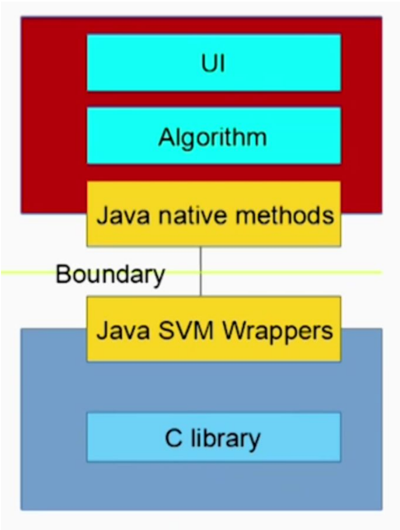
GraalVM



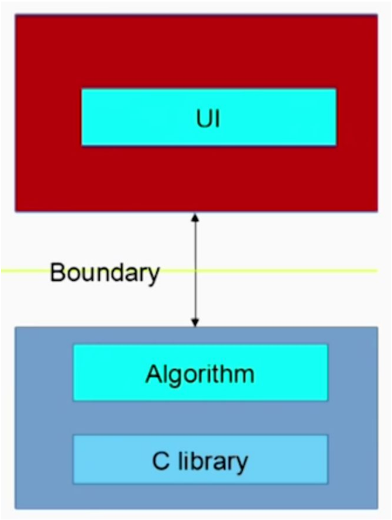
Traditional JNI
slow, complex



Traditional JNA
faster, complex



JNI via Native Image
fast, simpler



Native Image
fast, simple

Native Image Example

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Basic Example

```
$ javac Hello.java
$ time java Hello
Hello !
0,10s user 0,03s system 131% cpu 0,097 total
$ native-image Hello
========================================================================================
GraalVM Native Image: Generating 'hello'...
========================================================================================
[1/7] Initializing...                                                   (4.1s @ 0.21GB)
 Version info: 'GraalVM 22.0.0.2 Java 11 CE'
[2/7] Performing analysis...  [*******]                                (12.7s @ 0.47GB)
   2,563 (82.60%) of  3,103 classes reachable
   3,211 (60.36%) of  5,320 fields reachable
  11,648 (72.43%) of 16,082 methods reachable
      27 classes,     0 fields, and   135 methods registered for reflection
      57 classes,    58 fields, and    51 methods registered for JNI access
[3/7] Building universe...                                              (0.8s @ 0.62GB)
[4/7] Parsing methods...      [*]                                       (0.8s @ 0.84GB)
[5/7] Inlining methods...     [****]                                    (1.2s @ 0.75GB)
[6/7] Compiling methods...    [***]                                     (9.3s @ 1.19GB)
[7/7] Creating image...                                                 (1.1s @ 1.45GB)
   3.69MB (35.06%) for code area:    6,949 compilation units
   5.86MB (55.66%) for image heap:   1,543 classes and 80,509 objects
 999.26KB ( 9.28%) for other data
  10.52MB in total
------------------------------------------------------------------------------------------
Top 10 packages in code area:                              Top 10 object types in image heap:
 606.25KB java.util                                           1.64MB byte[] for general heap data
 282.31KB java.lang                                         715.44KB java.lang.String
 222.52KB java.util.regex                                   548.99KB java.lang.Class
 219.55KB java.text                                         451.55KB byte[] for java.lang.String
 193.17KB com.oracle.svm.jni                                363.75KB java.util.HashMap$Node
 149.73KB java.util.concurrent                              192.00KB java.util.HashMap$Node[]
 117.92KB java.math                                         139.81KB java.lang.String[]
 103.60KB com.oracle.svm.core.reflect                       139.04KB char[]
  97.83KB sun.text.normalizer                               130.59KB java.util.concurrent.ConcurrentHashMap$Node
  88.78KB com.oracle.svm.core.genscavenge                   103.92KB sun.util.locale.LocaleObjectCache$CacheEntry
      ... 111 additional packages                                ... 723 additional object types
                                           (use GraalVM Dashboard to see all)
------------------------------------------------------------------------------------------
                        1.6s (5.1% of total time) in 17 GCs | Peak RSS: 2.54GB | CPU load: 3.33
------------------------------------------------------------------------------------------
Produced artifacts:
 hello (executable)
 hello.build_artifacts.txt
========================================================================================
Finished generating 'hello' in 31.1s.
$ time hello
Hello !
0,00s user 0,00s system 89% cpu 0,002 total
```

Real-life Example

```
${graalvm_dir}/bin/native-image \
--delay-class-initialization-to-runtime=\
io.grpc.netty.shaded.io.netty.handler.ssl.OpenSsl \
--initialize-at-build-time=\
org.apache.log4j.Level,\
org.apache.log4j.Layout,\
org.apache.log4j.PatternLayout,\
org.apache.log4j.Logger,\
org.apache.log4j.helpers.LogLoorg.apache.log4j.Level,\
org.apache.log4j.Priority,\
org.apache.log4j.LogManager,\
org.apache.log4j.helpers.Loader,\
org.apache.log4j.helpers.LogLog,\
org.apache.log4j.Category,\
org.apache.log4j.spi.RootLogger,\
org.apache.log4j.spi.LoggingEvent,\
org.slf4j.LoggerFactory,\
org.slf4j.impl.Log4jLoggerAdapter,\
org.slf4j.impl.StaticLoggerBinder,\
java.beans.Introspector,\
com.sun.beans.Introspector,\
com.sun.beans.introspect.ClassInfo \
--report-unsupported-elements-at-runtime \
-H:Name=GroovyEL.exe \
-H:Path=../bin \
-jar ../lib/GroovyEL.exe.jar
```

Polyglot Examples (1)

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- ➢ Objects are never copied
- ➢ Conversion (into client physical format) at the latest possible time
- ➢ All tools are available for all languages
- ➢ **Several ways of calling foreign language:**
    - **Load as a script and execute**
    - **Compile as a class and use**
    - **Generate Native Image and call**

```
// Java calling C
Context context = Context.create();
File file = new File("polyglot"); // c-pgm compiled with GraalVM
Source source = Source.newBuilder("llvm", file).build();
Value cpart = polyglot.eval(source);
cpart.execute();
```

```
// Java calling Python
Value clazz = context.eval(Source.newBuilder("python", new File("mycode.py")).build());
Value instance = clazz.newInstance(1234);
System.out.println(instance.invokeMember("pyMethod", new int[]{1, 2, 3}));
```

```
// C calling JS
poly_create_context(thd, &ctx);
poly_context_eval(thd, ctx, "js", "foo", "function() {return 42;}", &func);
poly_value_execute(thd, func, NULL, 0, &answer);
poly_value_fits_in_int32(thd, answer, &fits);
poly_value_as_int32(thd, answer, &result);
return result;
```

```
// Java calling JS
Context context = Context.create();
Value v = context.eval("js", "function() {return 42;}");
Value answer = v.execute();
return answer.asInt();
```

Polyglot Examples (2)

GraalVM™

- ➢ Interaction with LLVM languages requires more boiler-plate code
- ➢ It's simpler to compile JVM code into Native Image than to interface JVM with LLVM
- ➢ C++ calling Java is simpler than Java calling C++

```
// JS calls CUDA
const DeviceArray = Polyglot.eval('grcuda', string='DeviceArray')
const in_arr = DeviceArray('float', 1000)
const out_arr = DeviceArray('float', 1000)
// set arrays ...
const code = '__global__ void inc_kernel(...) ...'
const buildkernel = Polyglot.eval('grcuda', string='buildkernel')
const incKernel = buildkernel(code, 'inc_kernel', 'pointer, pointer, uint64')
incKernel(160, 256)(out_arr, in_arr, N)
```

```
// C++ calls Java

// C++
int main() {
  graal_isolate_t *isolate = NULL;
  graal_isolatethread_t *thread = NULL;
  graal_create_isolate(NULL, &isolate, &thread);
  printf("Result> %d\n",ceilingPowerOfTwo(thread, 14));
  }

// Java
public class MyMath {
  @CEntryPoint (name = "ceilingPowerOfTwo")
  public static int ceilingPowerOfTwo(IsolateThread thread, int x) {
    return IntMath.ceilingPowerOfTwo(x);
    }
  }
```

```
// JS calls C++

// JS
loadSource("llvm", "cpppart");
Value getSumOfArrayFn = polyglotCtx.getBindings("llvm").getMember("getSumOfArray");
int sum = getSumOfArrayFn.execute(sqrNumbers, sqrNumbers.length).asInt();

// C++
extern "C" getSumOfArray(int array[], int size) {
  int i, sum = 0;
  for (i = 0; i < size; i++) {
    sum += array[i];
    }
  return sum;
  }
```

How it works

GraalVM™

- ➢ Good news: **It really works and it works well**
  - I was able to process big & complex applications (Java, Scala, Groovy)
- ➢ It may be complicated to use (configuration), there are **so many possibilities**
  - It many cases, native image generation should be configured/tuned
  - One can/should configure/tune for performance
- ➢ Some (Java) applications may need JVM even when compiled into native executable
  - When they (mis)use reflection and construct classes at run-time
    - For example log4J
  - But after all, we may consider JVM just as another native library (which it is)
- ➢ We may gain speed for small applications, not so often for large complex ones
  - Not surprising, Java is often fast for real-life applications
- ➢ By compiling into native executable, we lose flexibility and portability
- ➢ Truffle languages (Python, Ruby, JS,...) are at the same level of inter-operability as direct JVM languages
- ➢ Co-existence of LLVM languages (C, C++, Rust) with JVM languages is not as straightforward as between two JVM languages
  - Different memory & object models
  - Values, objects, names should be converted
  - Heavy communication across LLVM-JVM border may slow down execution
  - In that case, it may be more useful to compile JVM languages into native image

Where to use it

GraalVM™

- For Java languages:
  - Just using GraalVM JIT (included in OpenJVM) makes it faster (it can optimise more than the standard Java compiler)
  - Compiling with GraalVM compiler may help
  - Creating Native Image may improve performance (and connection to C/C++)
  - Allows better integration with other languages
  - For Scala:
    - It looks like GraalVM JIT is able to optimize Scala much more than OpenJVM JIT (factor > 2)
- For Python:
  - Interoperability with Java
  - Speed, especially when compiled to Native Image
  - Better interoperability with C/C++ when compiled to Native Image
- For C/C++:
  - Can replace C/C++ code with code in better languages or integrate existing components written in better languages
    - By compiling them into Native Image or connecting with Truffle multi-language environment
  - Integration in frameworks written in other languages
  - Possibility to run in *Managed Environment*
  - Sometimes performance gain just by re-building using GraalVM

Can rewrite just one part of the system in another (more suitable) language,
And compile into native executable.

References

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Some use C++ because they don't know Java
Others use Java because they know C++

Rene Brun has claimed that
a multi-language environment can't work because
it would require n*m interfaces.
GraalVM has proven him wrong, once again.

- https://www.graalvm.org
- https://github.com/graalvm
- https://app.slack.com/client/TN37RDLPK/CNBFR78F9
- @graalvm
- r/graalvm

It would be interesting to try it on some big C++ project too.