Ten Things You Can Do With GraalVM

Hands-On Lab

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Live for the Code

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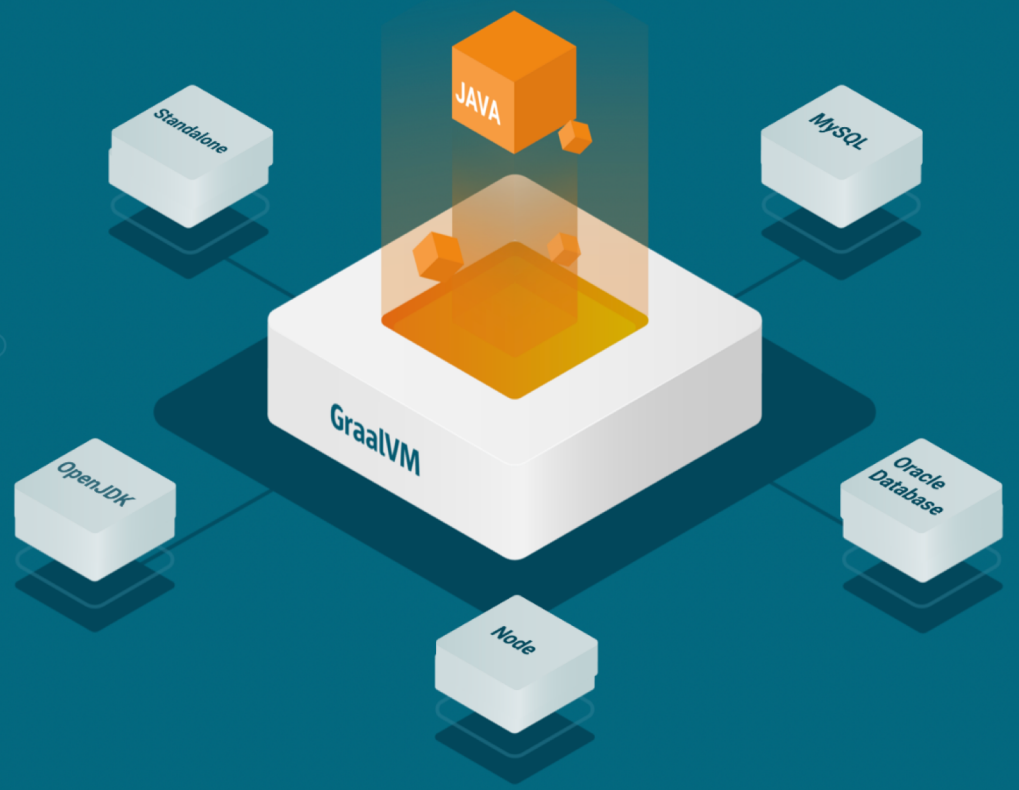
GraalVM™

Run Programs Faster Anywhere



- What, in concrete terms, is GraalVM?
- What can I practically do with it?
- What do all these things have to do with each other?
- What is the big idea?
- What kind of change is this going to enable?

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- Explain through demos
- We'll just dive in and figure out what it all means as we go
- Can follow on if you want, but can also just watch me
- Some demos easier to follow than others

What we need to get started

Files you'll need

- You'll need GraalVM to do anything – https://graalvm.org/
- Plus some source files to run on it
- Download everything:
  - https://www.dropbox.com/s/1t2ninff60ya4ni/ten-things-graalvm.tar.gz (https://goo.gl/K14jfa)
- Download just the sources to run:
  - https://www.dropbox.com/s/o7064h37wmdpbbs/ten-things-graalvm-sources.tar.gz (https://goo.gl/b3ncW4)
- I also have these on USB drives for an emergency

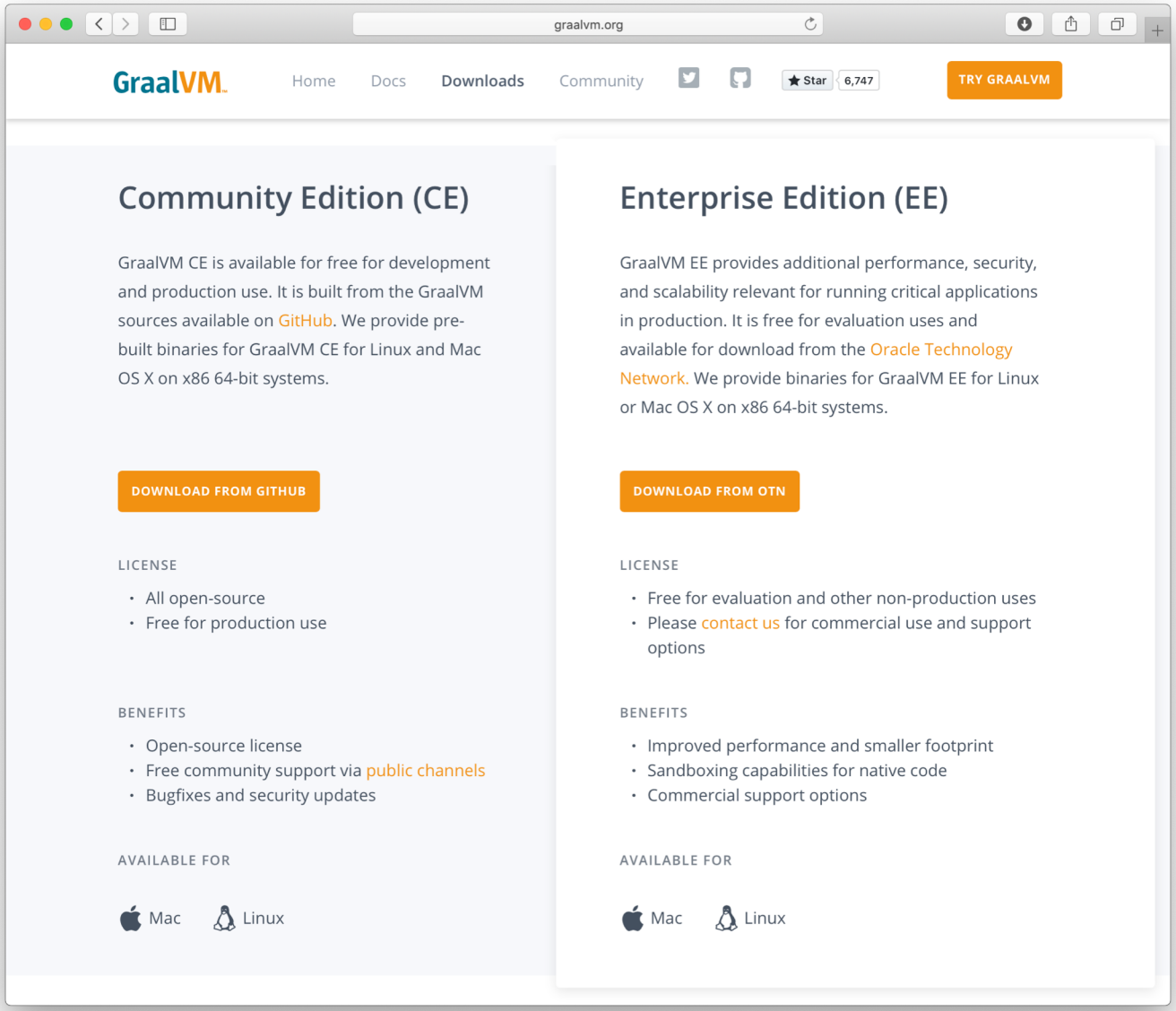
Files you'll need

- Some demos use some other common tools – Maven, Google Chrome
- Some use some more complex software – Docker, Oracle Database

- But feel free to just watch if you want! I'll run the demos myself

System you'll need

- AMD64
- macOS or Linux



High performance Java

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Using GraalVM as your JDK

- You can use GraalVM as a drop-in replacement for OpenJDK
- 1.8 at the moment, will be updated to the 11 LTS soon
- Includes all the same commands, flags, options and so on

Add it to your $PATH

```
$ export PATH=graalvm-ee-1.0.0-rc8/Contents/Home/bin:$PATH
```

```
public static void main(String[] args) {
    Arrays.stream(args)
            .flatMap(TopTen::fileLines)
            .flatMap(line -> Arrays.stream(line.split("\\b")))
            .map(word -> word.replaceAll("[^a-zA-Z]", ""))
            .filter(word -> word.length() > 0)
            .map(word -> word.toLowerCase())
            .collect(Collectors.groupingBy(Function.identity(), Collectors.counting()))
            .entrySet().stream()
            .sorted((a, b) -> -a.getValue().compareTo(b.getValue()))
            .limit(10)
            .forEach(e -> System.out.format("%s = %d%n", e.getKey(), e.getValue()));
}
```

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Compile and run as normal

```
$ javac TopTen.java
$ time java TopTen large.txt
…
real 0m18.905s
```

Compare to standard OpenJDK

```
$ time java -XX:-UseJVMCICompiler TopTen large.txt
…
real 0m23.102s
```

What is going on?

- The Graal just-in-time compiler is one part of GraalVM
- It replaces (or runs as a tier above) the existing JIT compilers like C2
- It's written in Java, which we think lets us improve it more easily, so it achieves better performance than C2
- Here we're getting 20% faster performance on a benchmark
- Twitter see 18% faster in production on real Scala applications, using only the CE version – EE not needed for high performance
- Is it odd that a JIT compiler for Java is written in Java?

```
for (MonitorExitNode monitorExitNode : graph.getNodes(MonitorExitNode.TYPE)) {
    FixedNode next = monitorExitNode.next();
    if ((next instanceof MonitorEnterNode || next instanceof RawMonitorEnterNode)) {
        // should never happen, osr monitor enters are always direct successors of the graph
        // start
        assert !(next instanceof OSRMonitorEnterNode);
        AccessMonitorNode monitorEnterNode = (AccessMonitorNode) next;
        if (isCompatibleLock(monitorEnterNode, monitorExitNode)) {
            /*
             * We've coarsened the lock so use the same monitor id for the whole region,
             * otherwise the monitor operations appear to be unrelated.
             */
            MonitorIdNode enterId = monitorEnterNode.getMonitorId();
            MonitorIdNode exitId = monitorExitNode.getMonitorId();
            if (enterId != exitId) {
                enterId.replaceAndDelete(exitId);
            }
            GraphUtil.removeFixedWithUnusedInputs(monitorEnterNode);
            GraphUtil.removeFixedWithUnusedInputs(monitorExitNode);
        }
    }
}
```

JVMCI is the interface that lets you plug in a new JIT

```
$ time java -XX:-UseJVMCICompiler TopTen large.txt
…
real 0m23.102s
```

This is one way to use GraalVM

- Just using it as a faster version of the JDK
- Drop-in replacement gives you Graal by default, everything else is unmodified

High performance Java on OpenJDK 11

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Graal also works on standard OpenJDK 11

- Graal (the JIT compiler part) is also included in Graal
- As an experimental, unsupported option, hidden behind flags
- Older version, due to the release cycle
- We'd recommend using the GraalVM package to experiment with

Enable Graal in OpenJDK 11

On AMD64, on macOS and Linux

```
$ java -XX:+UnlockExperimentalVMOptions \
       -XX:+EnableJVMCI \
       -XX:+UseJVMCICompiler \
       …
```

Doesn’t mention Graal, does it? JVMCI does service discovery and automatically finds Graal as the only JVMCI compiler available

```
 * ...                                  and/or its affiliates. All rights reserved.
 */

package valhalla;

public value class Complex {

    private final double re;
    private final double im;

    Complex(double re, double im) {
        this.re =  re;
        this.im =  im;
    }

    public double re() { return re; }

    public double im() { return im; }

    public Complex add(Complex that) {
--  Complex.java  /demo/valhalla/src/main/java/valhalla/Complex.java  Top 26:28  (
Switch to buffer (default log): l
```

```java
public class Complex {
  private final double re;
  private final double im;

  public Complex(double re, double im) {
    this.re = re;
    this.im = im;
  }

  public double re() { return re; }
  public double im() { return im; }

  public Complex add(Complex that) {
    return new Complex(this.re + that.re, this.im + that.im);
  }

  public Complex mul(Complex that) {
    return new Complex(this.re * that.re - this.im * that.im,
                       this.re * that.im + this.im * that.re);
  }
}
```

```java
public Complex[][] multiply() {
  int size = A.length;
  Complex[][] R = new Complex[size][size];
  for (int i = 0; i < size; i++) {
    for (int j = 0; j < size; j++) {
      Complex s = new Complex(0, 0);
      for (int k = 0; k < size; k++) {
        s = s.add(A[i][k].mul(B[k][j]));
           }
           R[i][j] = s;
    }
  }
  return R;
}
```

Compile and run on OpenJDK 11

```
$ mvn package
$ java -jar target/benchmarks.jar -prof gc
```

Run on OpenJDK 11 with Graal enabled

```
$ java -XX:+UnlockExperimentalVMOptions \
       -XX:+EnableJVMCI \
       -XX:+UseJVMCICompiler \
       -jar target/benchmarks.jar -prof gc
```

2.4x faster by enabling Graal

```
valhallaBench.Multiply.multiply  9231.032 us/op
valhallaBench.Multiply.multiply  3774.706 us/op
```

This is a second way to use GraalVM

- Not using GraalVM, but using the key component from it, Graal
- Already present in OpenJDK 11
- Just need to enable it using some flags
- This is effectively what Twitter do (they probably build their own JDK and Graal, not sure, but it’s a detail)

Low footprint, fast startup Java

What about shorter running applications or functions?

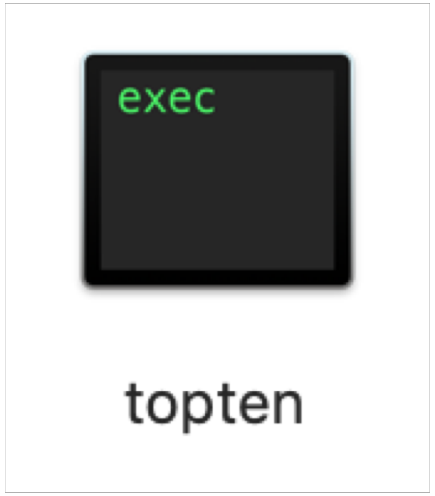
- The JVM typically has a relatively slow time to start
  - Compared to simpler VMs, like Python or Ruby
  - Compared to native executables like those produced from Go or Rust
  - JRuby ‘hello world’ startup time is an order of magnitude worse than standard Ruby
- The JVM typically takes up a relatively large amount of disk space
  - Can be helped with `jlink` – down to tens of MB
- The JVM typically takes up a relatively large amount of RAM
  - Interpreter, compiler, classfile parser, verifier etc all take up space

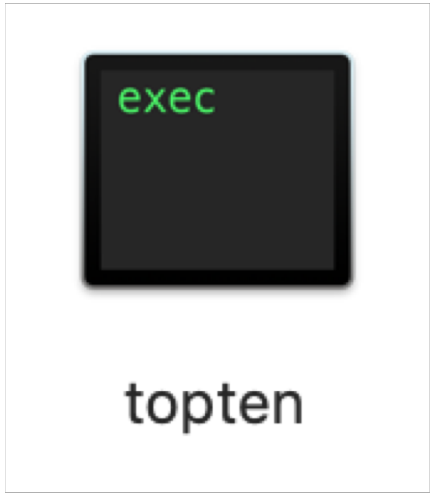
Run as normal

```
$ time java TopTen small.txt
…
real 0m0.408s
```

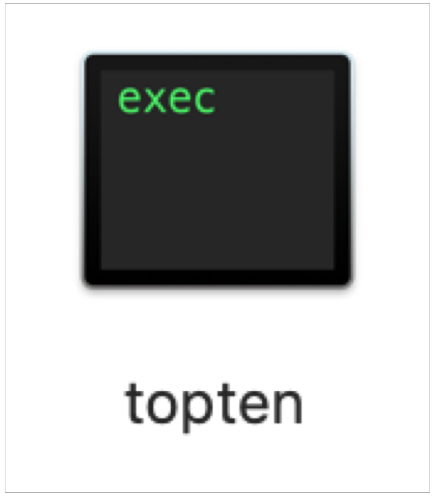
Compile to native using GraalVM

```
$ native-image TopTen
…
$ time ./topten small.txt
…
real 0m0.112s
```

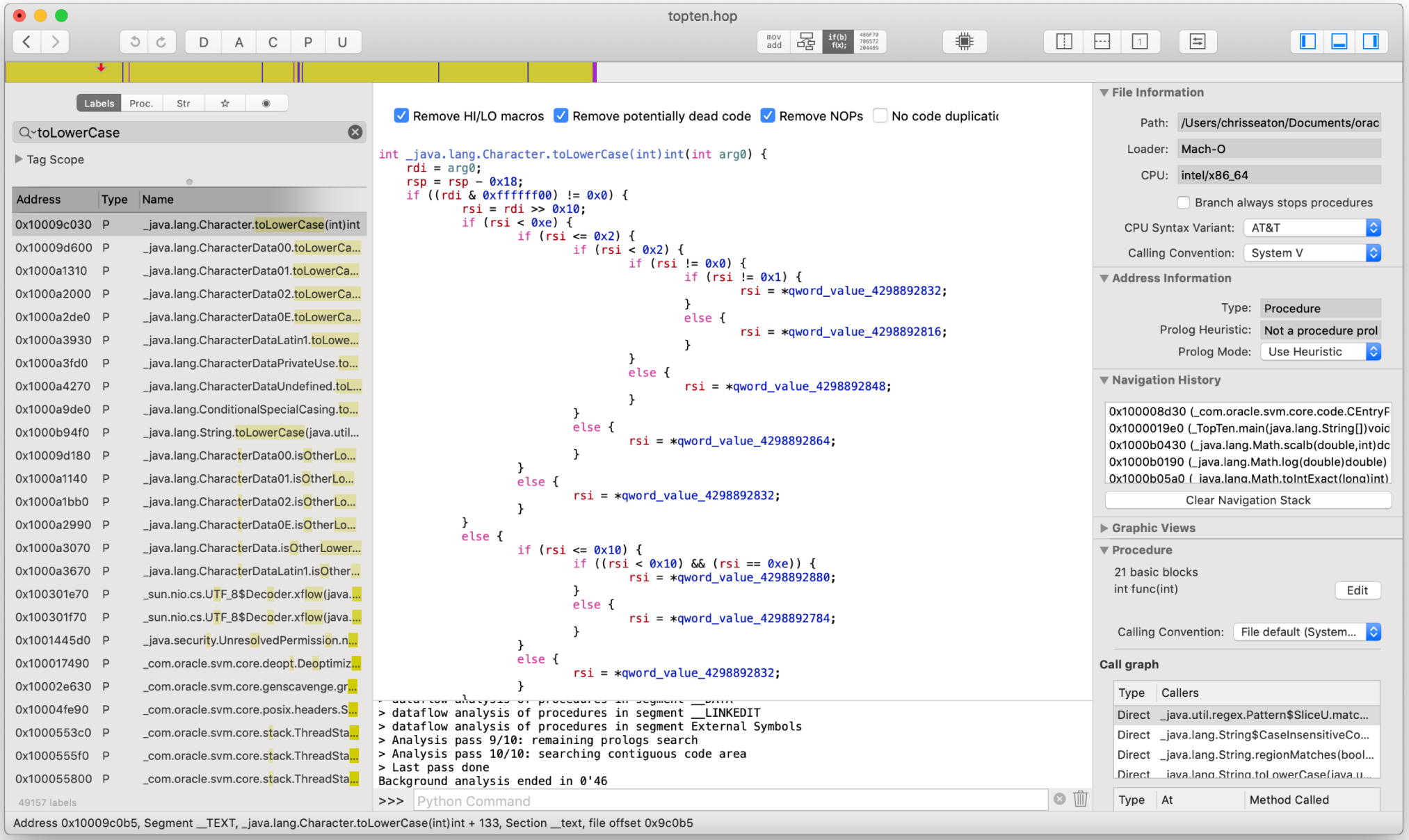





```
$ du -h topten
8.8M topten
```




```
$ otool -L topten
topten:
/usr/lib/libSystem.B.dylib
/usr/lib/libz.1.dylib
/System/Library/CoreFoundation
```



So what does this have to do with a JIT?

- Graal is written in Java
- So it can be used as a library from other Java code
- We realized that we could write a program to use it ahead-of-time, to build and ahead-of-time compiler
- This is what the `native-image` tool is – a Java application that uses Graal as a library

This is a third way to use GraalVM

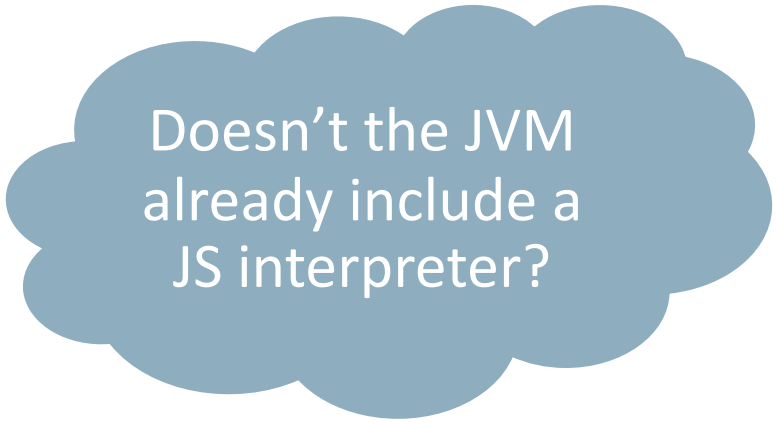
- Using the `native-image` tool to ahead-of-time compile your application to native code
- No dependency on the JVM
- Small executables – Docker deployments
- Starts quickly, has a low footprint

Run other languages

GraalVM includes a new JavaScript interpreter

```
$ js –version
Graal JavaScript 1.0 (GraalVM CE Native 1.0.0-rc8)

$ js
> print("hello");
hello
```



GraalVM also includes an implementation of Node.js

```
$ node --version
v10.9.0

$ npm --version
6.2.0
```

```
var express = require('express');
var app = express();

app.get('/', function (req, res) {
  res.send('<h1>Hello!</h1>');
});

app.listen(8080, function () {
  console.log('serving at http://localhost:8080')
});
```

```
$ npm install express

$ node hello-express.js
serving at http://localhost:8080
```

You can plug new languages into GraalVM

```
$ gu install ruby
$ gu install python
$ gu install R
```

This version works offline with the files on the USB drives

```
$ gu install --file ruby-installable-ce-1.0.0-rc8-macos-amd64.jar
$ gu install --file python-installable-ce-1.0.0-rc8-macos-amd64.jar
$ gu install --file r-installable-ce-1.0.0-rc8-macos-amd64.jar
```

```
$ gu rebuild-images polyglot libpolyglot js llvm python ruby
```

In reality you'd want to run this, but it takes a long time

You can plug new languages into GraalVM

```
$ ruby --version
truffleruby 1.0.0-rc8, like ruby 2.4.4, GraalVM CE Native [x86_64-darwin]

$ graalpython --version
Graal Python 3.7.0 (GraalVM CE Native 1.0.0-rc8)

$ R --version
R version 3.4.0 (FastR)
```

So what does this have to do with a JIT?

- We realized instead of writing languages that emit bytecode at runtime (JRuby) we could write languages that use the Graal JIT directly
- But that's hard, so we realized we could write a framework, Truffle, to do that automatically, based on a simple interpreter
- Faster, as they use a more powerful JIT more directly
- Simpler, because a framework does most of the hard work, so easy to implement lots of languages
- Interopable (polyglot) because they all use the same system
- Using `native-image` they start quickly

This is a fourth way to use GraalVM

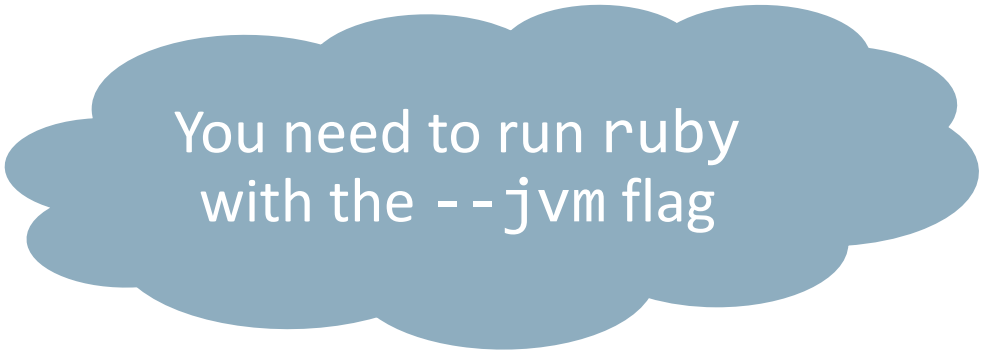
- As a multi language platform
- Use as a drop-in replacement for your existing language platform
- Faster than standard implementations

Polyglot

GraalVM is polyglot as well as multi-language

- Like many languages implemented on the JVM, our languages can use Java libraries
- Run `ruby-java.rb`

```
BigInteger = Java.type('java.math.BigInteger')
puts BigInteger.valueOf(2).pow(100).toString
```



GraalVM is polyglot as well as multi-language

- Run `python-java.rb`

```
import java
BigInteger = java.type('java.math.BigInteger')
print(BigInteger.valueOf(2).pow(100).toString())
```

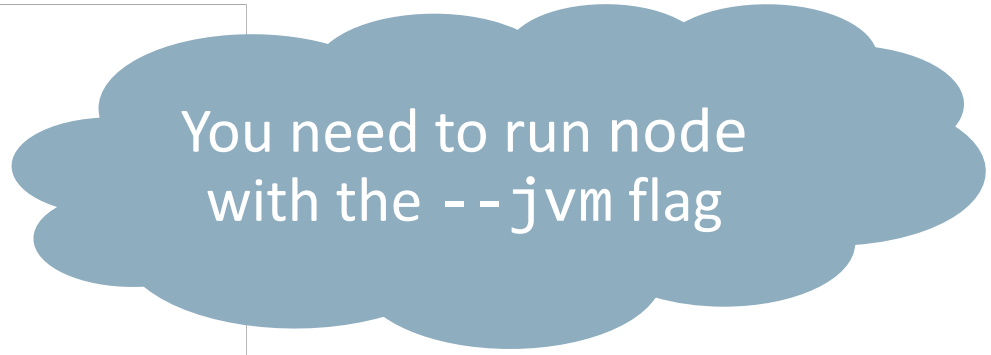
You need to run `graalpython` with the `--jvm` flag

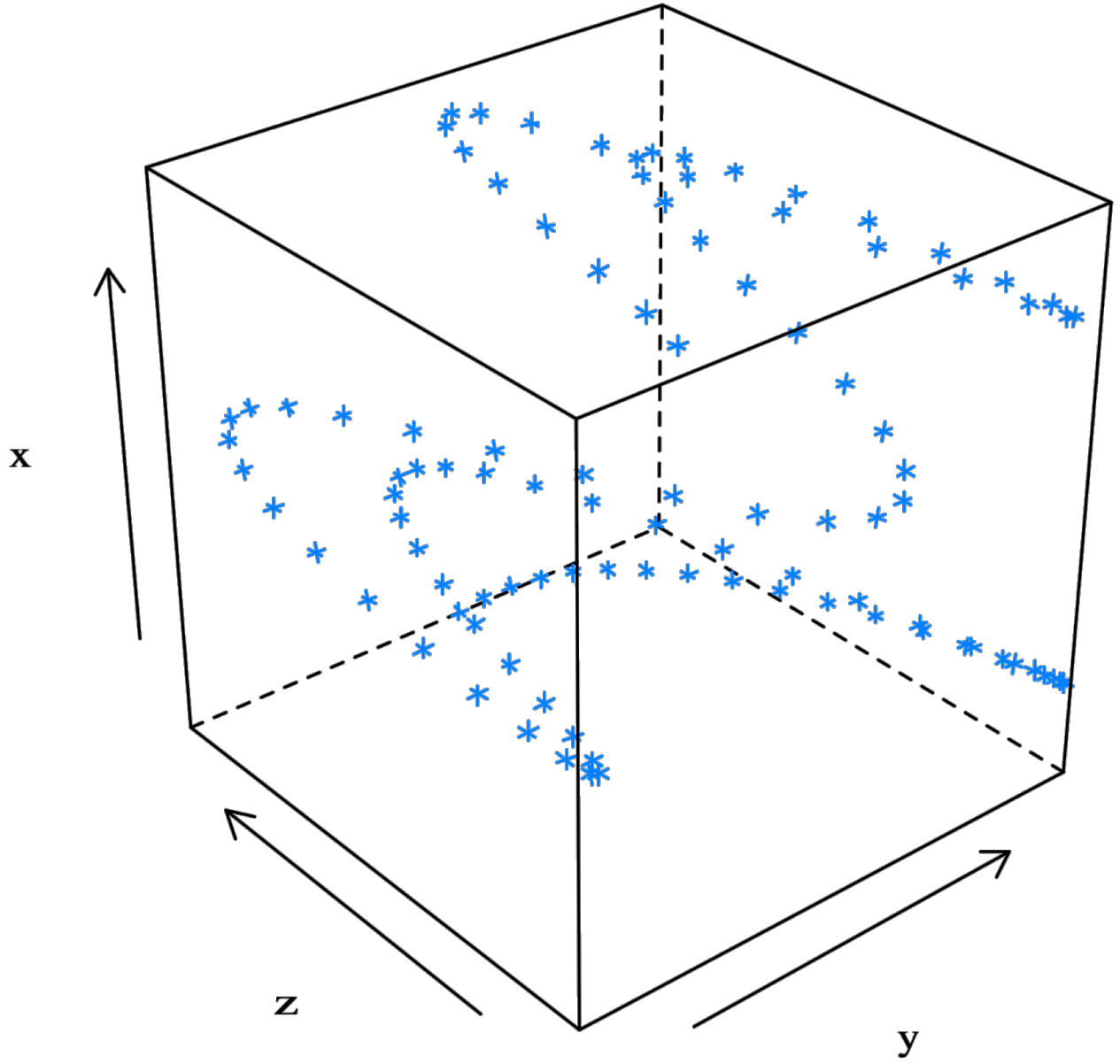
Java is just another language in this case

```
const express = require('express');
const app = express();

app.get('/', function (req, res) {
  res.send(Interop.eval('R',
    `svg();
     require(lattice);
     x <- 1:100
     y <- sin(x/10)
     z <- cos(x^1.3/(runif(1)*5+10))
     print(cloud(x~y*z, main="cloud plot"))
     grDevices:::svg.off()
    `));
})

app.listen(8080, function () {
  console.log('serving at http://localhost:8080');
});
```





So what does this have to do with a JIT?

- All the languages use the same JIT, and the same high-level implementation framework, so they can all work together
- Integration is at a higher level than with traditional bytecode implementation

This is our fifth way to use GraalVM

- As a polyglot language platform
- Java interop
- Poyglot interop

Native languages on the JVM

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Is our approach only suited to Java and dynamic languages?

- There's nothing special about native languages
- C has the same `if` statements and `while` loops Ruby does
- C has pointers and malloc, but so does Ruby in its `FFI` module

Is our approach only suited to Java and dynamic languages?

- Example – running `gzip` on the JVM
  - Not a clean piece of code
  - 8.6 k lines of C
  - Macros, pointer arithmetic, unions
  - We'll avoid the complexity of autotools and make by using a single-file version
  - http://people.csail.mit.edu/smcc/projects/single-file-programs/

```
if (more == (unsigned)EOF) {
    /* Very unlikely, but possible on 16 bit machine if strstart == 0
     * and lookahead == 1 (input done one byte at time)
     */
    more--;
} else if (strstart >= WSIZE+MAX_DIST) {
    /* By the IN assertion, the window is not empty so we can't confuse
     * more == 0 with more == 64K on a 16 bit machine.
     */
    Assert(window_size == (ulg)2*WSIZE, "no sliding with BIG_MEM");

    memcpy((char*)window, (char*)window+WSIZE, (unsigned)WSIZE);
    match_start -= WSIZE;
    strstart    -= WSIZE; /* we now have strstart >= MAX_DIST: */
   if (rsync_chunk_end != 0xFFFFFFFFUL)
       rsync_chunk_end -= WSIZE;

    block_start -= (long) WSIZE;

    for (n = 0; n < HASH_SIZE; n++) {
        m = head[n];
        head[n] = (Pos)(m >= WSIZE ? m-WSIZE : NIL);
    }
    for (n = 0; n < WSIZE; n++) {
        m = prev[n];
        prev[n] = (Pos)(m >= WSIZE ? m-WSIZE : NIL);
        /* If n is not on any hash chain, prev[n] is garbage but
         * its value will never be used.
         */
    }
    more += WSIZE;
}
```

```
$ clang -c -emit-llvm gzip.c
$ gzip small.txt
$ lli gzip.bc -d small.txt.gz
```

So what does this have to do with a JIT?

- We can use the JIT that we use for Java, JavaScript, Ruby, Python, R and so on, for C as well
- Actually – any language that can target LLVM
- C, C++, Objective C, Swift, Fortran, Rust, etc
- Genuine potential for dynamic optimization
- Potential for sandboxing as well

This is our sixth way to use GraalVM

- To run native applications on the JVM
- Our demo showed a full application
- More probably use-case is running native libraries from Java or other managed languages

Debugging

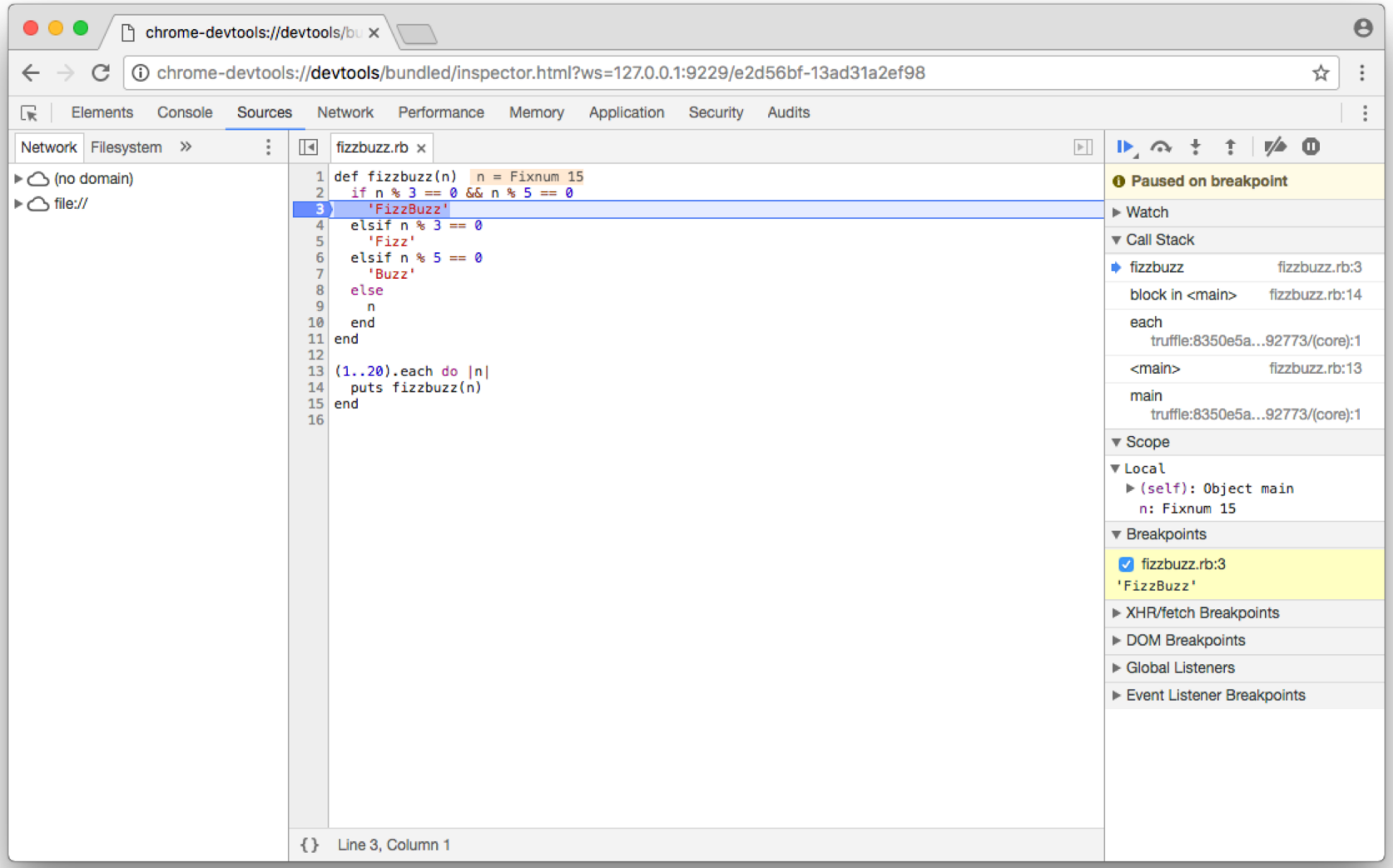
Tooling for these extra languages

- With other languages on the JVM you usually have to use a Java debugger
- Perhaps with source information in the bytecode for the guest language
- Some custom debuggers, but not for all languages

```ruby
def fizzbuzz(n)
  if n % 3 == 0 && n % 5 == 0
    'FizzBuzz'
  elsif n % 3 == 0
    'Fizz'
  elsif n % 5 == 0
    'Buzz'
  else
    n
  end
end

(1..20).each do |n|
  puts fizzbuzz(n)
end
```

```
$ ruby fizzbuzz.rb
…
$ ruby --inspect fizzbuzz.rb
Debugger listening on port 9229.
To start debugging, open the following URL in Chrome:
    chrome-devtools://devtools/bundled/…
```



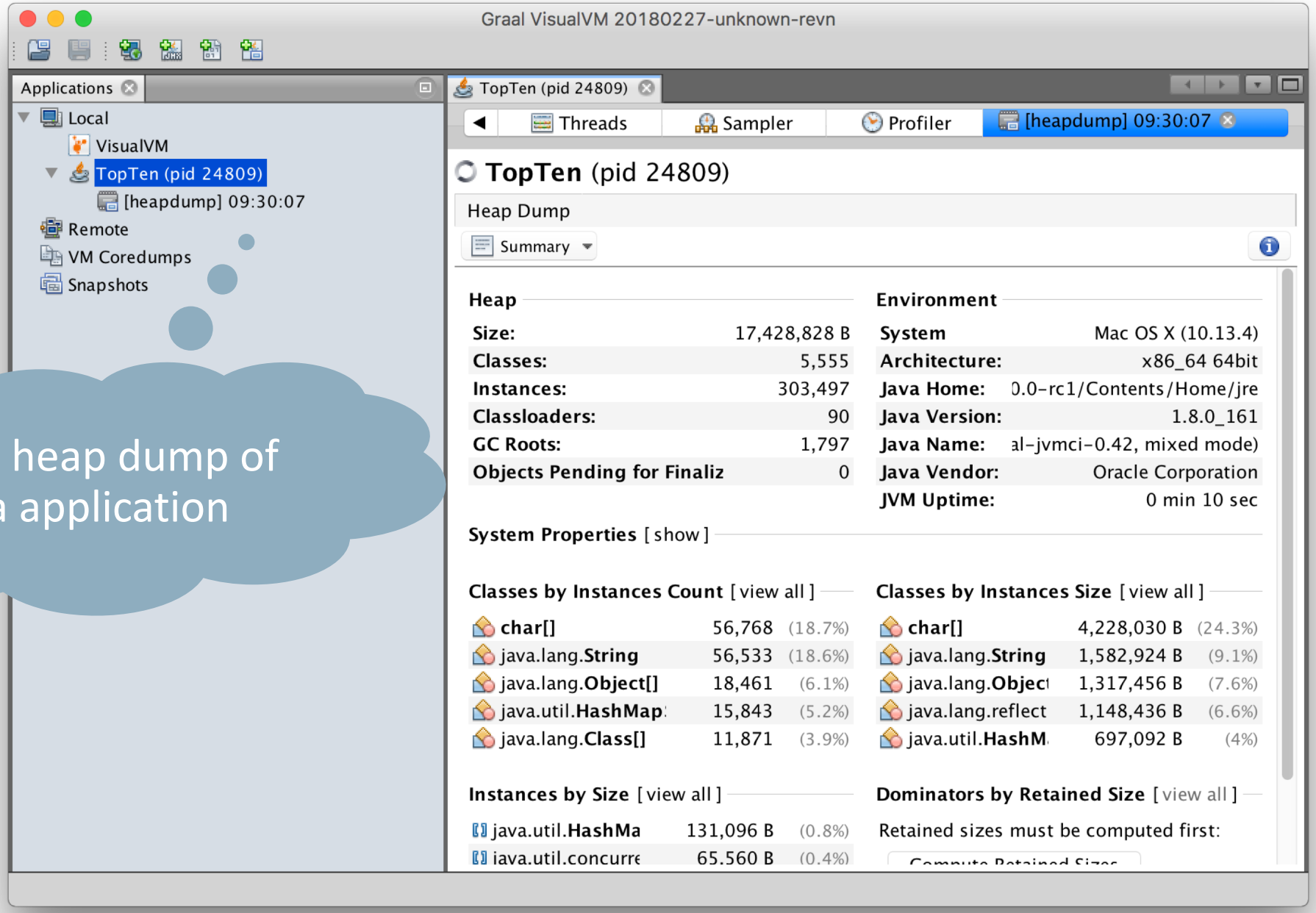
So what does this have to do with a JIT?

- All the languages are implemented in the same framework, so the debugger can understand them all via that framework
- The Graal JIT has support for deoptimization, so can debug optimized code running in production

This is our seventh way to use GraalVM

- As a way to get a debugger for multiple languages
- Not all languages have a community large enough to support a high quality debugger
- Few have a user interface as nice as Chrome
- The debugger works cross-language as well
- If you implement your own language on our framework, you get this debugger for free

Monitoring



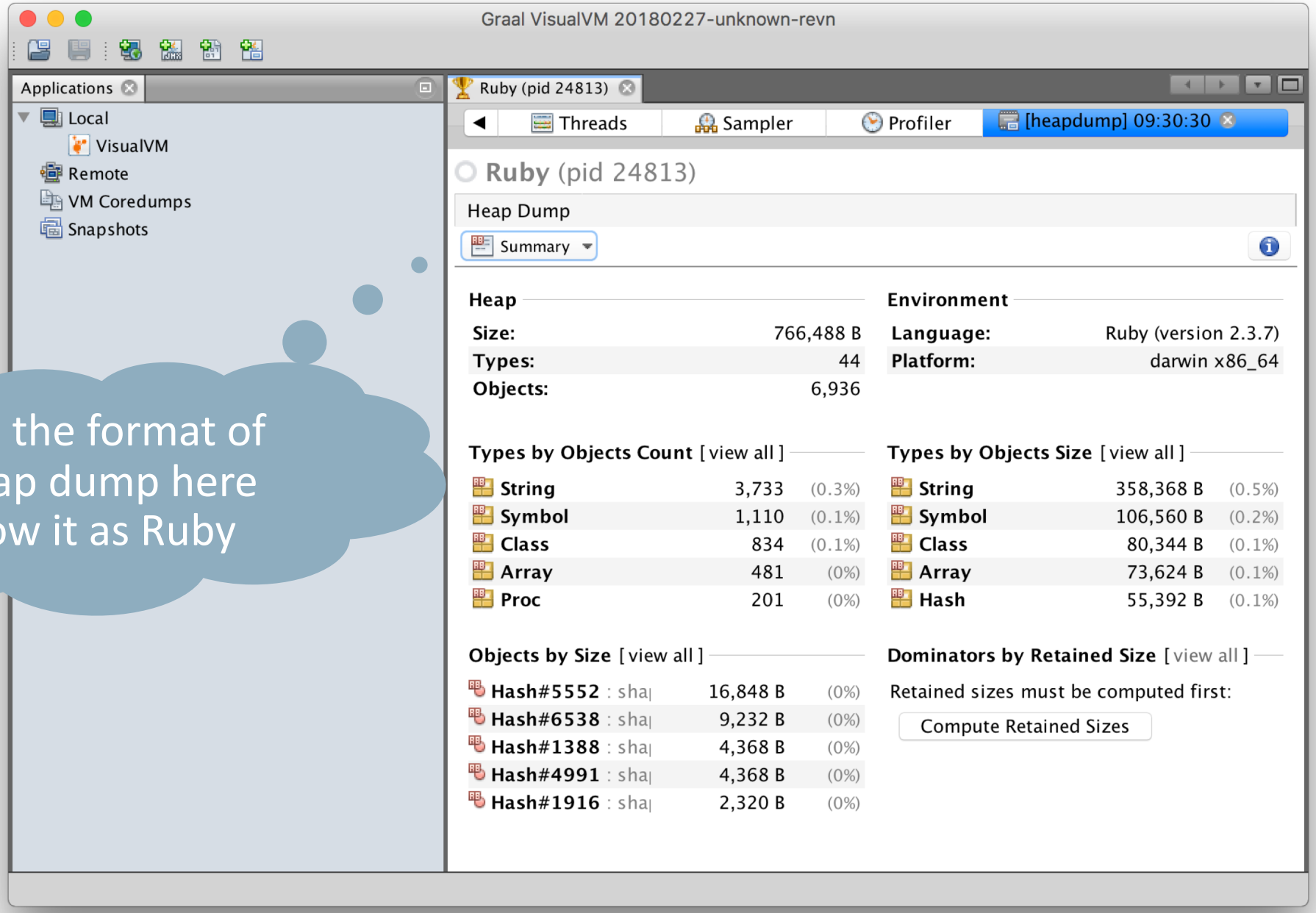
Taking a heap dump of a Java application

Monitoring for these extra languages

- VisualVM and other similar tools let you monitor the JVM
- Non-JVM languages often don’t have this kind of tool
- With other languages on the JVM, then often show the underlying Java objects, rather than the guest language objects

```
$ ruby render.rb

$ jvisualvm
```



Change the format of the heap dump here to show it as Ruby

So what does this have to do with a JIT?

- Like the debugger, all languages use the same framework so VisualVM can understand them all
- All the languages use the same system to implement their objects on top of Java objects

This is our eighth way to use GraalVM

- Like the debugger, to get high quality tooling for other languages

Java as a native library

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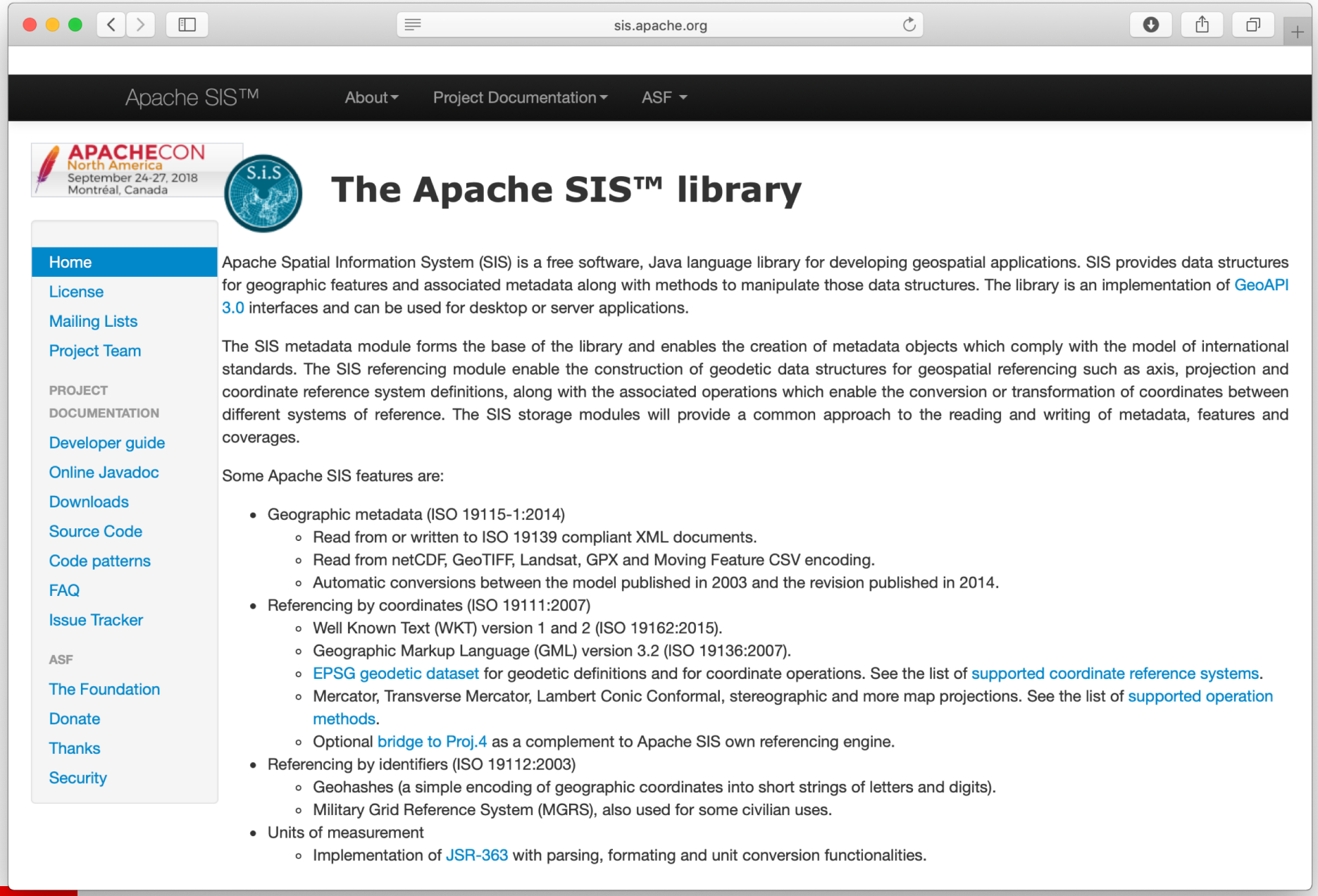
Java code as a native library

- The Java ecosystem is phenomenal
- Often more and better libraries than available in other languages
- In the examples so far, it's always been the Java code that has owned the process
- Can we run Java code inside another application that we already have?



```java
import org.apache.sis.distance.DistanceUtils;

public class Distance {

    public static void main(String[] args) {
        final double aLat   = Double.parseDouble(args[0]);
        final double aLong  = Double.parseDouble(args[1]);
        final double bLat   = Double.parseDouble(args[2]);
        final double bLong  = Double.parseDouble(args[3]);
        System.out.printf("%f km%n", DistanceUtils.getHaversineDistance(aLat, aLong, bLat, bLong));
    }

}
```

```
$ javac -cp sis.jar -parameters Distance.java
$ java -cp sis.jar:. Distance \
      51.507222 -0.1275 40.7127 -74.0059
5570.25 km
```

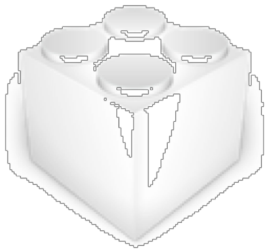
```
$ native-image -cp sis.jar:. Distance
...
$ ./distance 51.507222 -0.1275 40.7127 -74.0059
5570.25 km
```

```
...
import org.graalvm.nativeimage.IsolateThread;
import org.graalvm.nativeimage.c.function.CEntryPoint;

public class Distance {

    ...

    @CEntryPoint(name = "distance")
    public static double distance(IsolateThread thread,
          double a_lat, double a_long,
          double b_lat, double b_long) {
        return DistanceUtils.getHaversineDistance(a_lat, a_long, b_lat, b_long);
    }

    ...

}
```

```
$ native-image -cp sis.jar:. -H:Kind=SHARED_LIBRARY \
       -H:Name=libdistance
```

```c
#include <stdlib.h>
#include <stdio.h>

#include <libdistance.h>

int main(int argc, char **argv) {
  graal_isolate_t *isolate = NULL;
  graal_isolatethread_t *thread = NULL;

  if (graal_create_isolate(NULL, &isolate) != 0 || (thread = graal_current_thread(isolate)) == NULL) {
    fprintf(stderr, "initialization error\n");
    return 1;
  }

  double a_lat   = strtod(argv[1], NULL);
  double a_long  = strtod(argv[2], NULL);
  double b_lat   = strtod(argv[3], NULL);
  double b_long  = strtod(argv[4], NULL);

  printf("%f km\n", distance(thread, a_lat, a_long, b_lat, b_long));

  return 0;
}
```

```
$ clang -I. -L. -ldistance distance.c -o distance
$ otool -L distance
distance:
	libdistance.dylib
	/usr/lib/libSystem.B.dylib
$ ./distance 51.507222 -0.1275 40.7127 -74.0059
5570.25 km
```



libdistance.dylib

This is our ninth way to use GraalVM

- To compile Java code to native libraries
- Can then embed in a native application
- Or any language with a native FFI (Ruby, Python, Rust, Haskell, Go, etc)

Polyglot in the database

Demo using the Oracle Database MLE

- Multi-lingual (polyglot) edition
- Available as a Docker image
- Subject to the Oracle Technology Network license agreement, so you need to accept that and download it yourself

https://oracle.github.io/oracle-db-mle/releases/0.2.7/docker/

```
$ docker load --input mle-docker-0.2.7.tar.gz # takes a while

$ docker run mle-docker-0.2.7 # takes a while
$ docker ps
$ docker exec -ti <container_id> bash -li
```

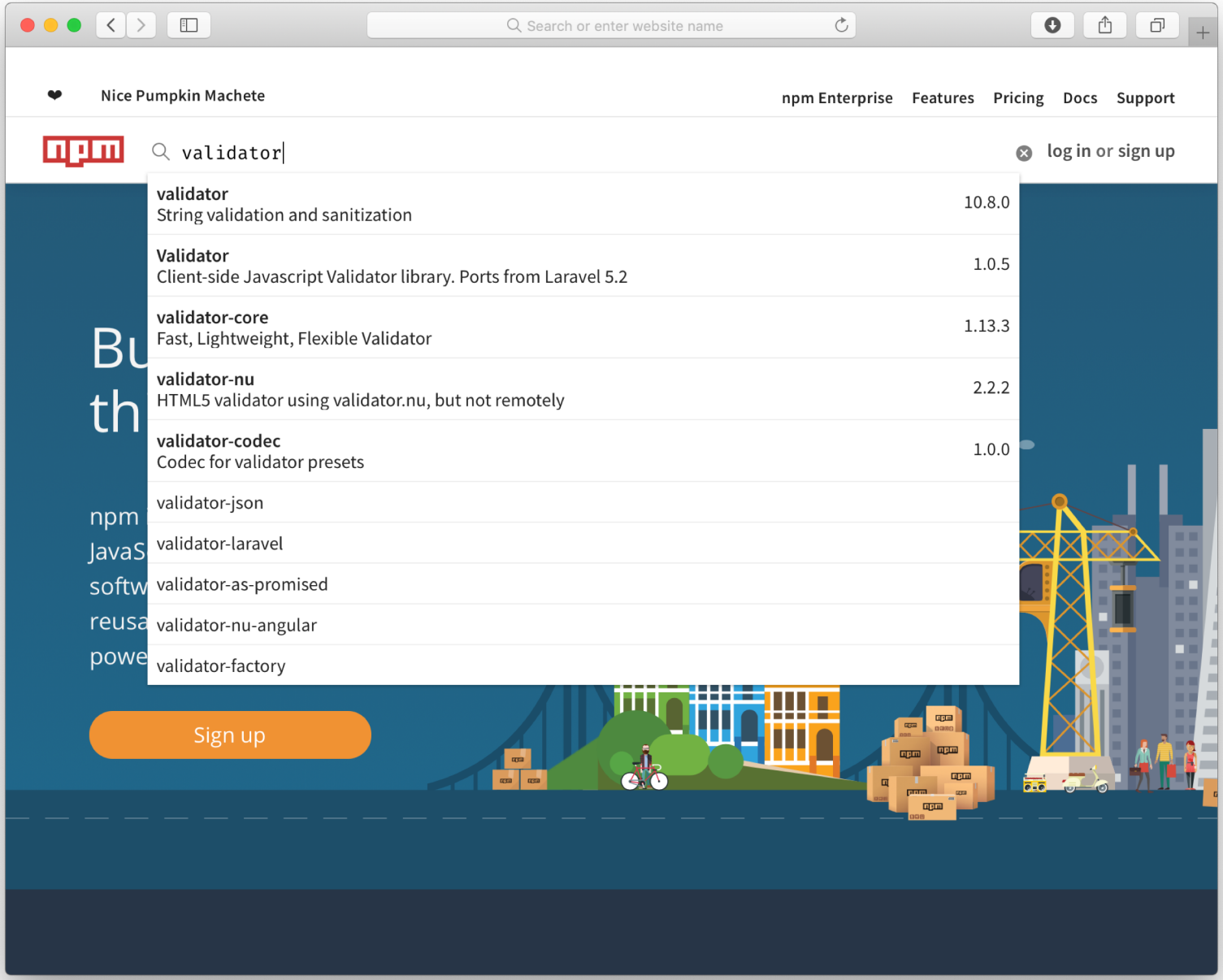
JavaScript in the client and frontend, Oracle in the backend

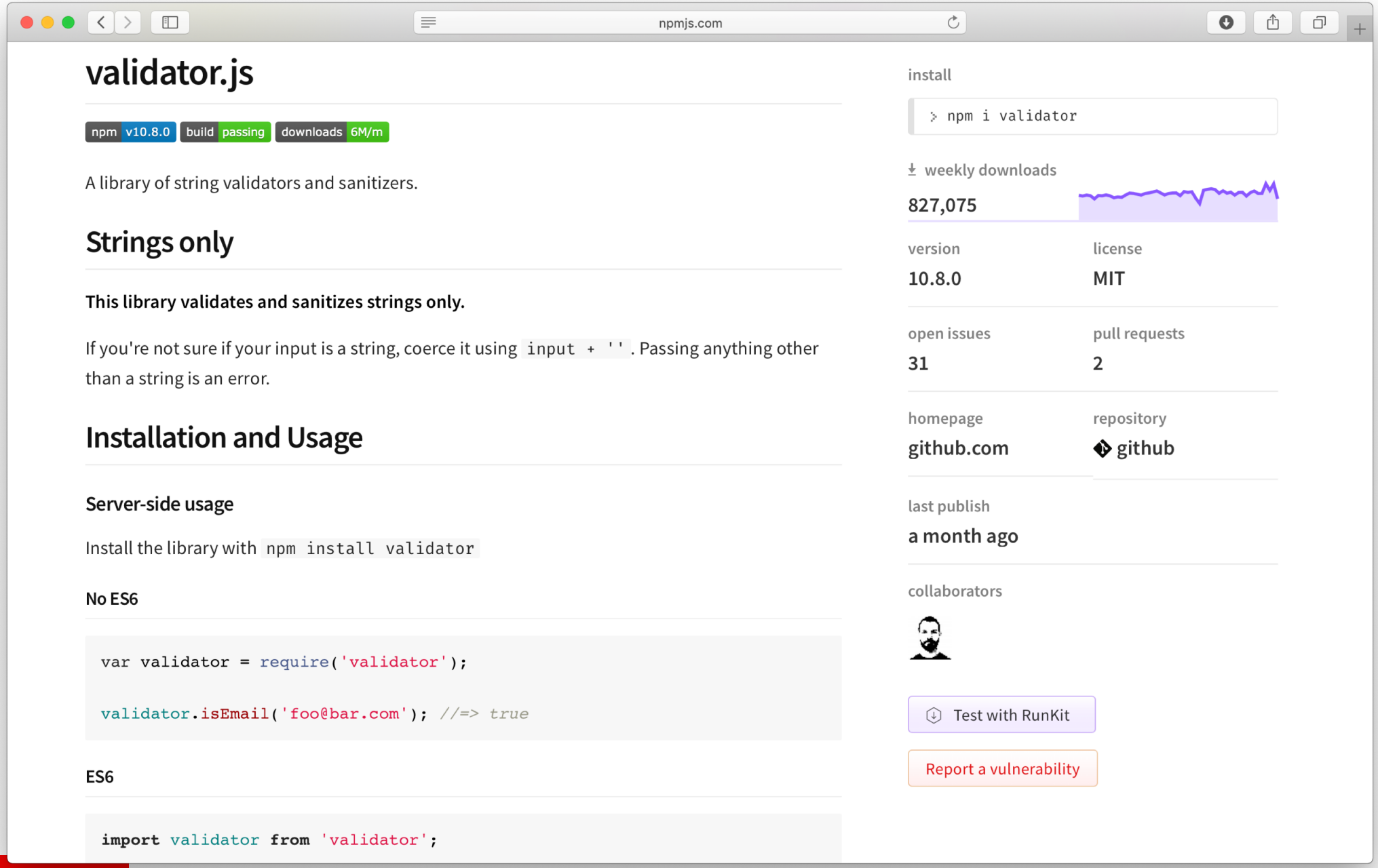
JS

JS

ORACLE DATABASE

ORACLE





```
$ echo "{}" > package.json
$ npm install validator
$ npm install @types/validator

$ dbjs deploy -u scott -p tiger -c localhost:1521/ORCLCDB validator

$ sqlplus scott/tiger@localhost:1521/ORCLCDB
```

```
SQL> select validator.isEmail('oleg.selaev@oracle.com') from dual;
SQL> select validator.isEmail('oleg.selaev') from dual;
```

This is our tenth and final way to use GraalVM

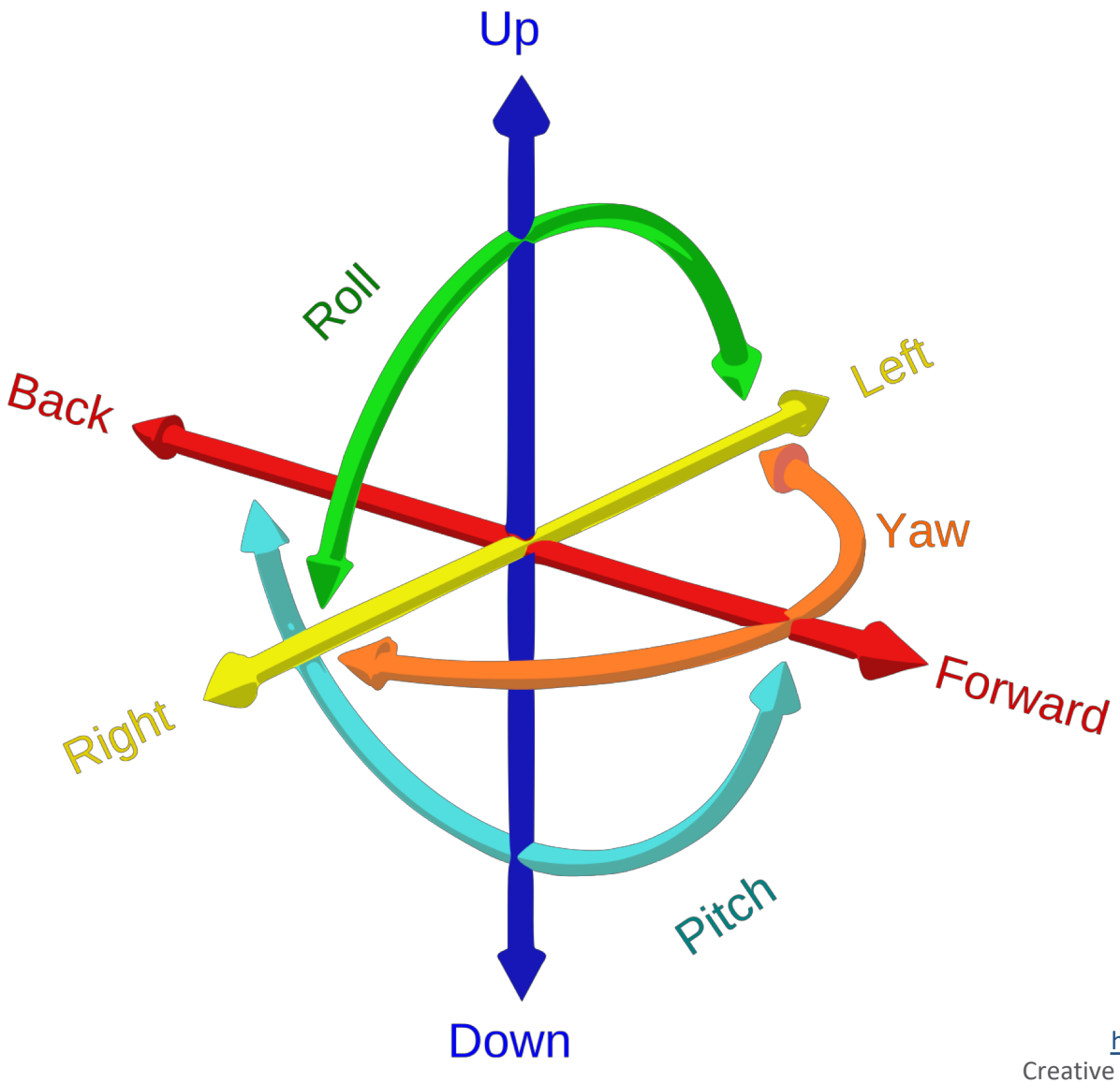
- To run user functions (stored procedures) in the Oracle Database
- JavaScript at the moment, but Python soon, can also demo Ruby and R
- The same idea works in MySQL

- Note this functionality isn't part of GraalVM

How does this bring it all together?

- This is a…
  - JavaScript interpreter, implemented in Java, using our framework
  - Using the polyglot interface to talk to the query language
  - Compiled ahead-of-time using Graal into a native library
  - Which can be linked into the database
  - Including Graal as a JIT within that library for high performance

Wrap up



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I think it’s about giving people degrees of freedom

- Let people run the language they want
- With the ecosystem of libraries they want
- On the JVM or on native
- Embedded or embedding
- With the tooling they want
- With the performance they want
- ‘One compiler to rule them all’

Get in touch with us

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- https://twitter.com/ChrisGSeaton
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