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VMs
I Have Known
and/or
Loved

A subjective history

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Overview

- Aims of this talk: entertain, educate, stimulate
- How? By talking about the VMs I've worked on/with, and what I learned from them:
  - Smalltalk-80: **Blue Book**, **PS**, MUSHROOM (1984–1993)
  - **Self** (1993–'96)
  - JVMs: Exact VM, **HotSpot**, MaxineVM (1996–present)
  - **Truffle**, **Graal** and the **Alphabet Soup** (2010–)

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Caveats

- Not a scholarly treatise - a personal view of the landscape out my window
- Mostly not my work but that of those around me
  - Credit where it's due
  - Errors and omissions, are, of course, my own
- Intro and structure lifted from ICOOOLPS 2011 talk; one conclusion recanted

Personal history

Smalltalk interpreter

ParcPlace Smalltalk

Mushroom project (Smalltalk machine)

Optimizing ST80 compiler

GC

Prototypes

Adaptive optimization

Smalltalk in Self includes: self

PEP

Exact VM

HotSpot

KVM

HW for Java

HW performance monitoring

Klein VM

Maxine VM

Portmeirion - VM for ISA

Alphabet Soup

1981 '84 '87 1993 '96 '99 2000 '04 '11 2013

MANCHESTER 1824

Sun microsystems

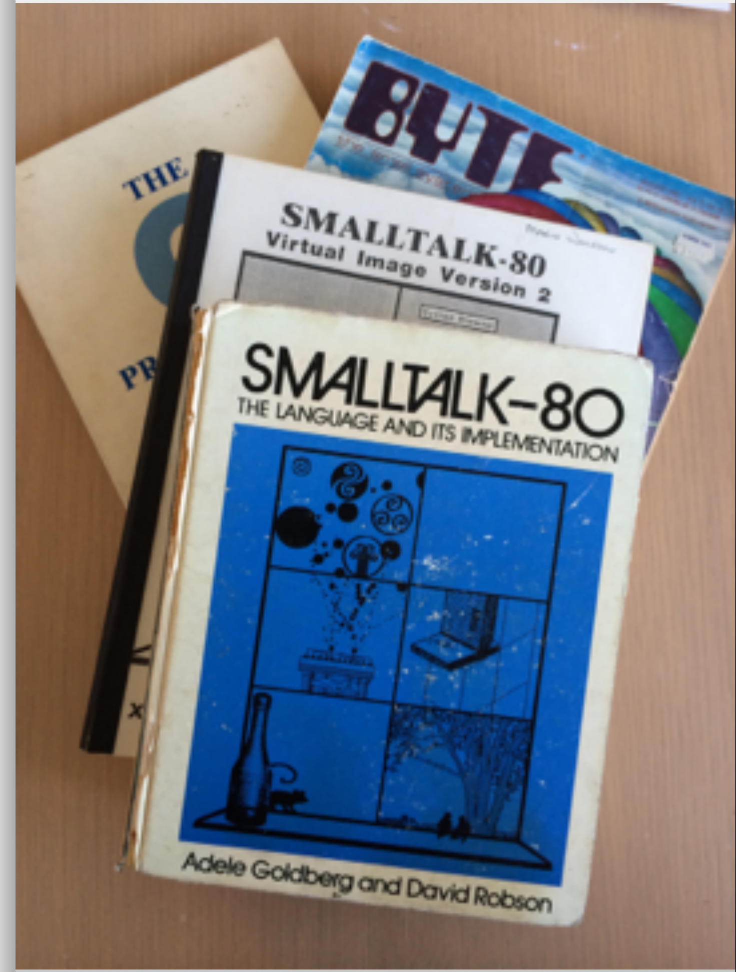
ORACLE

academia

industry

1984–1993

Smalltalk



1984: Implementing the Smalltalk Blue Book VM

Implementing Smalltalk-80 on the ICL PERQ

A dissertation submitted to the University of Manchester
for the degree of Master of Science
in the Faculty of Science.

October 1984

Mario I. Wolczko

Department of Computer Science

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- Demo
- In retrospect:
  - A nice project for a student
  - My C code was awful
  - No better demonstration of Moore’s Law over 30 years
    - Perq 1 was inadequate (only 1MB RAM)
    - Used VAX 11/750+remote graphics (over RS-232!), Apollo and finally Perq 2

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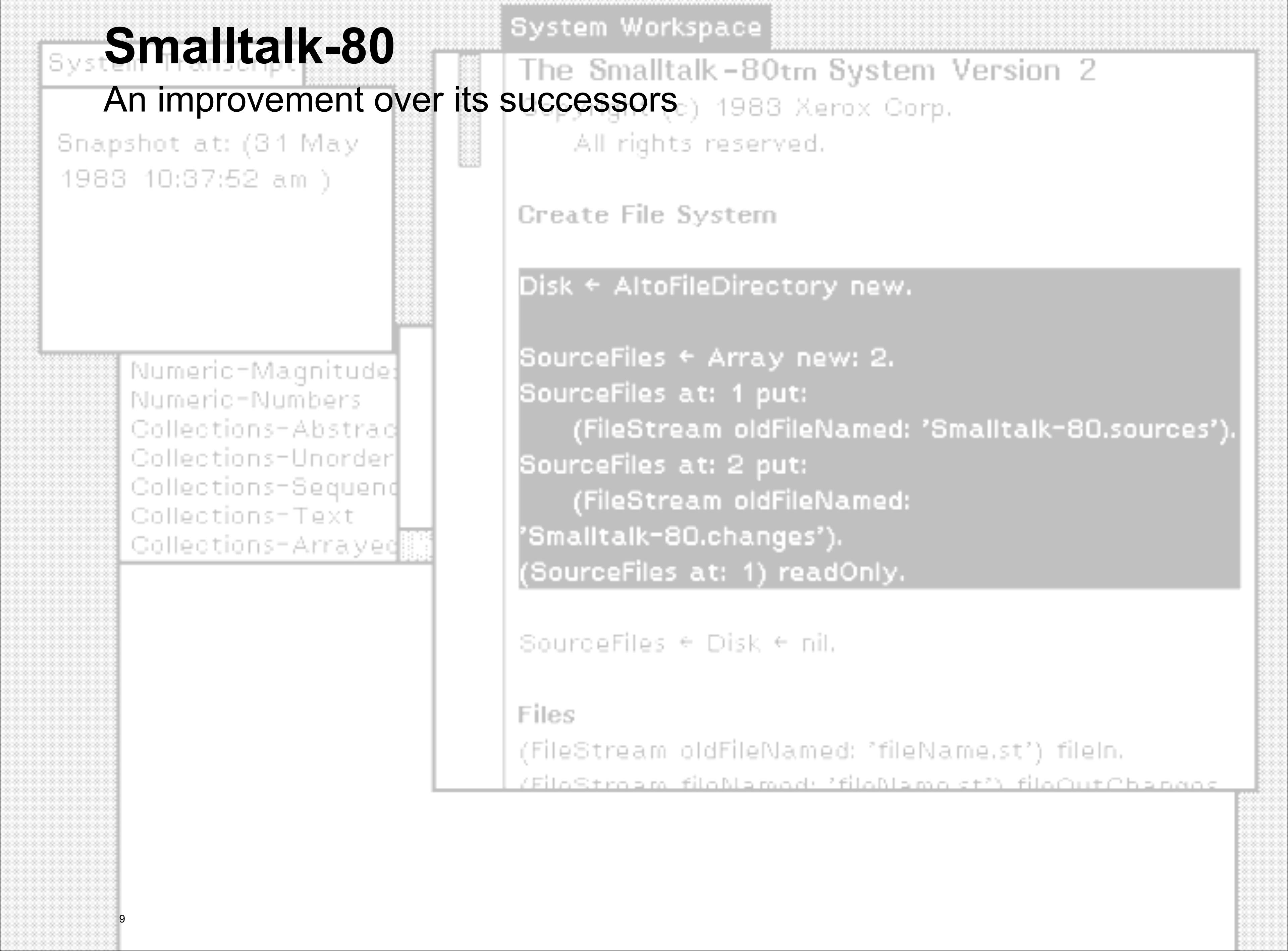
Smalltalk-80

An improvement over its successors



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- Smalltalk-80 was an artifact from the future
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- Demonstrated the power of virtualization
  - Implement a simple thing, get a complex thing
  - Virtual images transcend time and space
    - We see the same screen as someone at PARC on a spring morning in 1983

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  - Virtual images transcend time and space
    - We see the same screen as someone at PARC on a spring morning in 1983
- “Meta-circular” definition — precise, concise

Main Lesson: Bytecode interpretation is slow

- Simple, but slow—2500 bytecode/s
- Even in microcode
  - Perq projected speed: 50kbps (6MHz CPU, 1.5MHz RAM)
  - Dorado: 400kbps@16MHz

Why so slow? 1. Bytecode dispatch

- Interpreter loop overhead; unpredictable branches on modern h/w

```
for (;;) {
  BYTE b = getNextBytecode();
  switch (b) {
  case A: ...
  case B: ...
  ...
  }
}
```

- Various threading tricks can make it a few times faster
- But, still fundamentally inefficient

Why so slow?

- To execute: c = a + b. *"a=2, b=2"*

```
b1 = getNextBytecode(); /* push a */
switch (b1) ...
  fetch variable a and push onto stack
b2 = getNextBytecode(); /* push b */
switch (b2) ...
  fetch variable b and push onto stack
b3 = getNextBytecode(); /* send + */
switch (b3) ...
  send + to a with arg b /* next slide */
b4 = getNextBytecode(); /* pop and store into c */
switch (b4) ...
  pop the top of stack and store in variable c
```

Why so slow? 2. Method dispatch

- Consider the execution of a simple expression, `a+b`, in a dynamic language:
  - Find out the type of `a`
  - Find out the type of `b`
  - Find out what + means
  - Check that the operation is applicable to the data types, throw error if not
  - Prepare the data (e.g, strip tags)
  - **Invoke the operation**
  - Convert the result to canonical form (add tags)

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C code for SmallInteger +

```
SIGNED intArg, intRcvr;
int intRes;
OOP argOop= popStack;
if (isInt(argOop)) {
    intArg= intVal(argOop);
    OOP rcvrOop= popStack;
    if (isInt(rcvrOop)) {
        intRcvr= intVal(rcvrOop);
        intRes= intRcvr + intArg;
        if (isIntVal(intRes)) {
            NRpush(intObj(intRes));
            return FALSE;
        }
    }
    unPop(2);
} else
    unPop(1);
return TRUE;
```

C code for SmallInteger +

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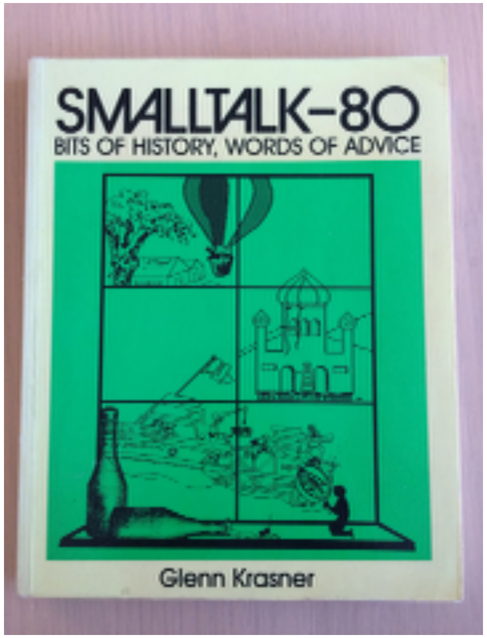
return TRUE;
```

```c
SIGNED intArg, intRcvr;
int intRes;
OOP argOop= *sp--;
if (argOop & 0x80000000) {
    intArg= argOop & 0x7fffffff;
    OOP rcvrOop= *sp;
    if (rcvrOop & 0x80000000) {
        intRcvr= rcvrOop & 0x7fffffff;
        intRes= intRcvr + intArg;
        if (intRes <= 0x3fffffff && intRes >= (-1<<30)) {
            *sp= intRes | 0x80000000;
            return FALSE;
        }
    }
    sp += 2;
} else
    sp++;
return TRUE;
```

...Confirmed many times...

- "there was little hope for performance high enough to lure users away from traditional programming systems"
  - Joseph R. Falcone,
    The Analysis of the Smalltalk-80 System at Hewlett-Packard



1986–1993: ParcPlace Smalltalk

- Landmark paper:

Efficient Implementation of the Smalltalk-80 System

L. Peter Deutsch
Xerox PARC, Software Concepts Group

Allan M. Schiffman
Fairchild Laboratory for Artificial Intelligence Research

  - Appeared in POPL 1984
  - Major contributions:
    - **Just-in-time compilation** for an OO language
    - **Inlining caching** of method invocation targets
  - and:
    - Change of representation of contexts
    - Deutsch-Bobrow reference counting

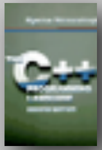
Using ParcPlace Smalltalk

- I used—practically lived in—ParcPlace Smalltalk for ~5 years.
  - Sun 3/50, SPARCstation 1
- Rock-solid—I never encountered a VM bug
- Predictably performant
  - 20x faster than the Blue Book VM
  - Typically 5x slower than C code
  - But I found Smalltalk perhaps 10x more productive for my research
- Large increase in implementation complexity
  - Beyond a student project
  - First version in 68000 assembler, later in C

1993–1996

Self

The complexity of speed



The Self VM

- Self: like Smalltalk, only more so
- *Even harder* to make fast:
  - Variable accesses are via messages
  - Every control structure is implemented using blocks (closures)
  - Prototypes, not classes
  - Minimalist bytecode set
- Generational GC (Ungar)—problem solved?
- Craig Chambers' compiler
  - Heroic efforts at optimization, but unpredictable
- Urs Hölzle's compiler
  - Observation beats speculation
  - Count activations, observe messages and gather type info
  - Compile (or recompile) when you have a hot loop
  - Used the profile info to guide the compiler
  - Speculate that the past is a good predictor of the future

My Self experiences

- I joined in mid-'93—project ended 2 years later
- System was already fast
  - How fast? 1/3-1/2 C, sometimes faster (eg inlined recursive calls)
  - But had rough edges (GC, code quality, bugs)
  - Debugging via C++ debugger (gdb) was painful - wrong level of abstraction for many tasks
  - Careful use of C++ was a big improvement on C, even absent a C++ IDE
    - oop/map hierarchy -- OO in the VM
  - Duplicated functionality in different forms
    - E.g., GC barrier in C++ code, in emitted code (2 compilers)

1996–

Java VMs

From research to production

Java features that changed the game

- Primitive types—no tagging
- Built-in control flow, lack of closures—easier to compile
- Dynamic class loading, but not reflective program change
  - Later: Misha Dmitriev's implementation of class redefinition
- Concurrency
- Awful bytecode design
- 1.0 VM: BlueBook-ish; conservative GC; "green" threads
- PEP - Java on Self (Agesen, with support from Ungar, me)
  - Demonstrated dynamic compilation and adaptive optimization for Java
  - Fast
- Considered—for a moment—converting the Self VM to Java
  - Didn't know about HotSpot

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1996–1999: The Exact VM

- Java 1.2 JVM for Solaris on SPARC and x86
- Derived from the "Classic" JVM (1.0, 1.1)
  - "Exactified" (Agesen, Detlefs)
- Initial goal was to provide PS-like performance, robustness for desktop and server workloads, for a limited lifetime (HotSpot acquisition in process)
  - Concurrency was important—Sun was selling lots of multiprocessor servers
  - Solaris thread support was good (!)
- Generational GC—but what about old space pauses?
- GC framework (Heller, White, Garthwaite, Flood)
  - Lots of GC research, leading to CMS, G1
  - Solaris threads were not so great after all — totally redone later by Roger Faulkner
- JIT compilation—awful bytecode design
- Later, basis of CVM (Sun's J2ME CDC JVM: Kindle v1, BluRay)

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1996–present: The HotSpot VM

- A start-up, Animorphic, founded in 1994 to build a high-performance Smalltalk VM starting from Self 3.0
  - Lars Bak and Urs Hölzle from the Self team, among others
- Neatly pivoted to Java
- Acquired by Sun
- Interpreter + compiler (rewritten later to become client compiler)
- Server compiler added
  - Much more **sophisticated** than predecessors
  - Click, Vick, Paleczny—the Rice compiler gurus—joined in 1997
- Still very much alive and in the lead
- Full-scale industrial development
  - Cast of >100 over the last 20 years?

2007–2013: The Maxine VM

- Started by Bernd Mathiske
- Influences from Klein (Self in Self), Jikes (Java in Java)
- Goal: make a fast but much more malleable VM
- Snippets—high-level description of intrinsic
- Inspector—VM-level abstractions for debugging and visualization
- Developed in Java IDE
- Compilers: CPS, C1X, **Graal**

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2011–present

Dynamic Languages
(again)

Recanting what I said at ICOOOLPS 2011

- VMs could be made fast, but at great effort and expense
- It didn't look there were any big new ideas to be found, just lots of work to be done
- Boy, was I wrong

> • Implementation, Compilation, Optimization of Object-Oriented Languages, Programs and Systems
> ➡ Solved Problem (mostly)

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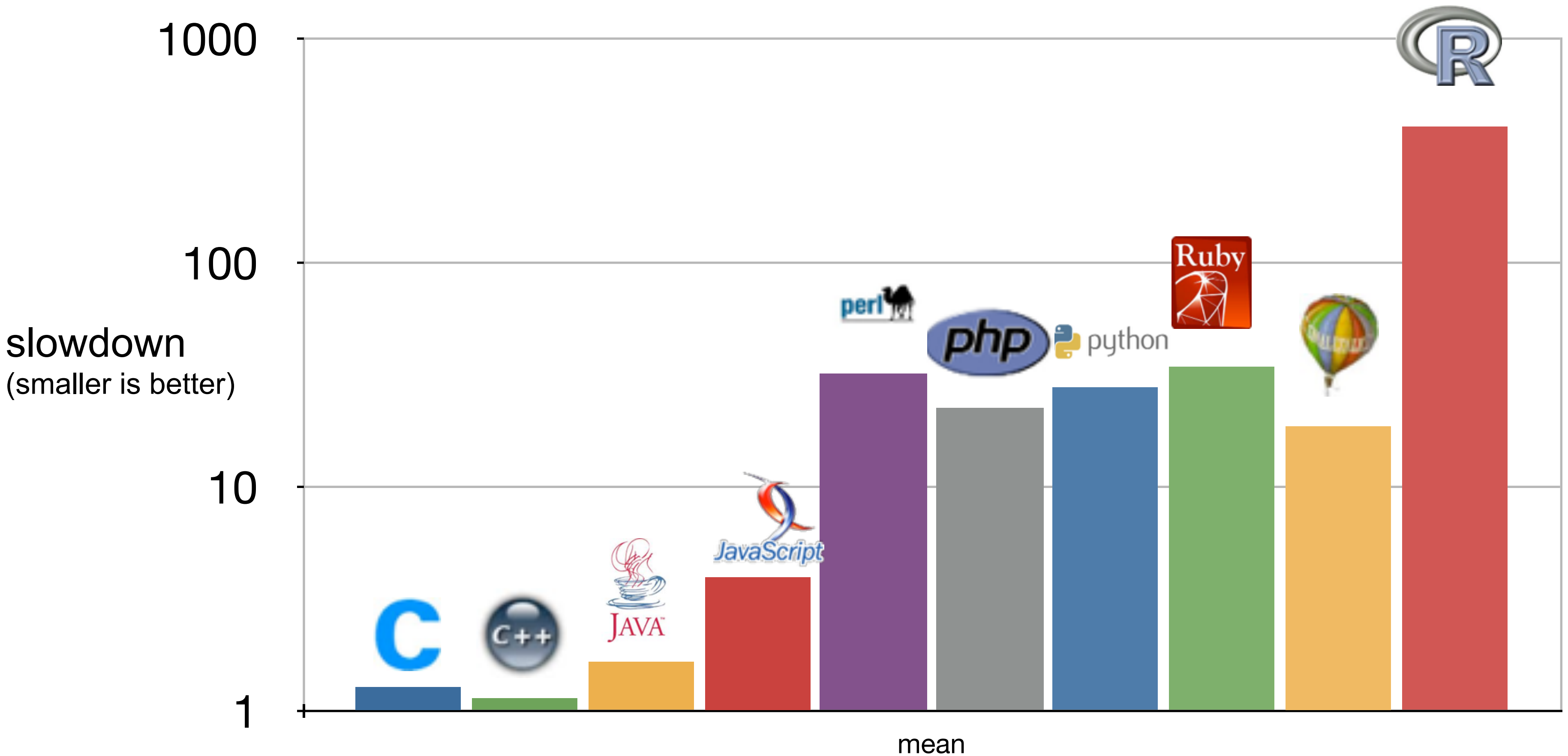
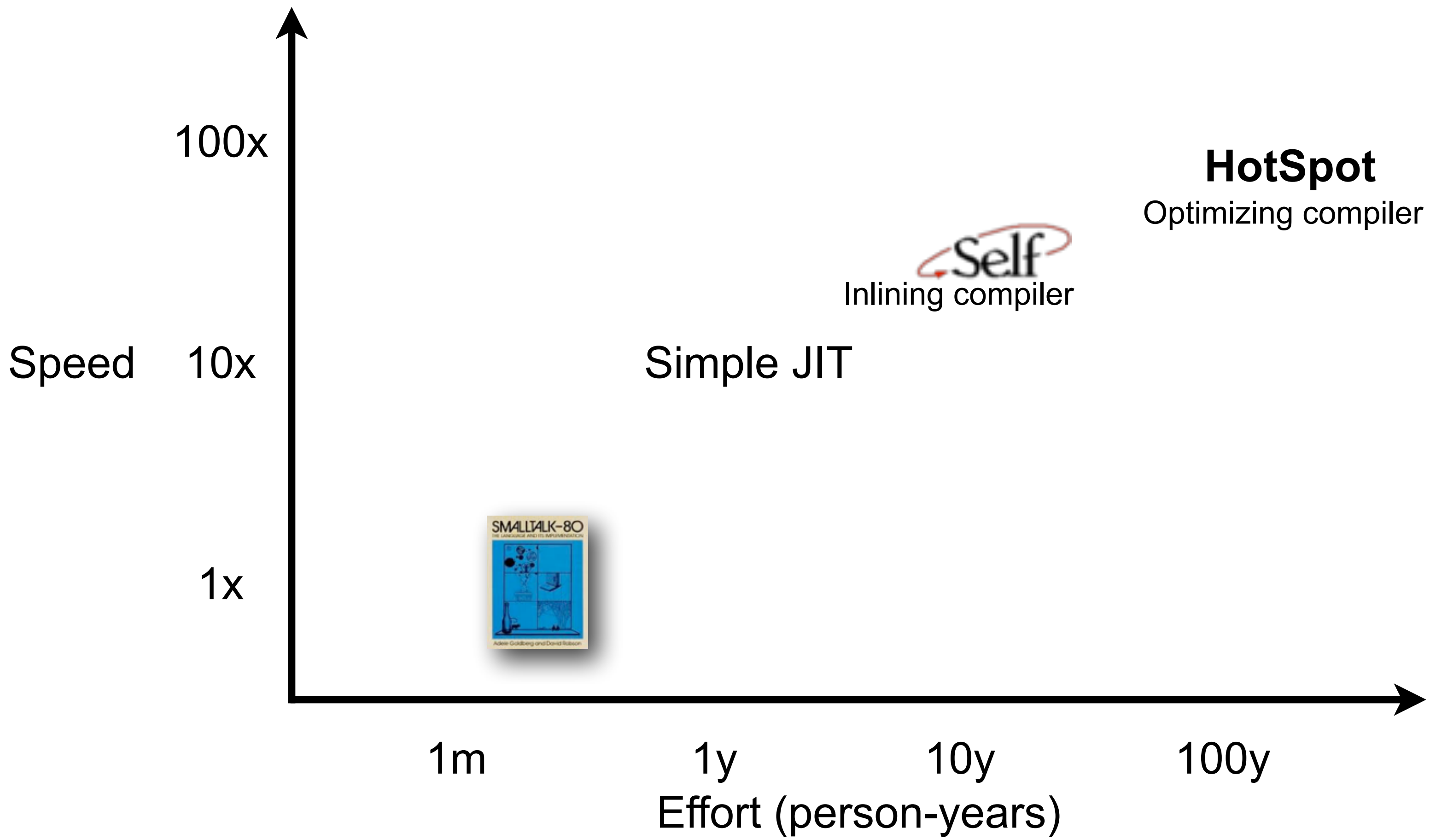
Relative speeds of various languages

(as measured by the Computer Language Benchmarks Game, ~1y ago)



Building fast VMs is a lot of work



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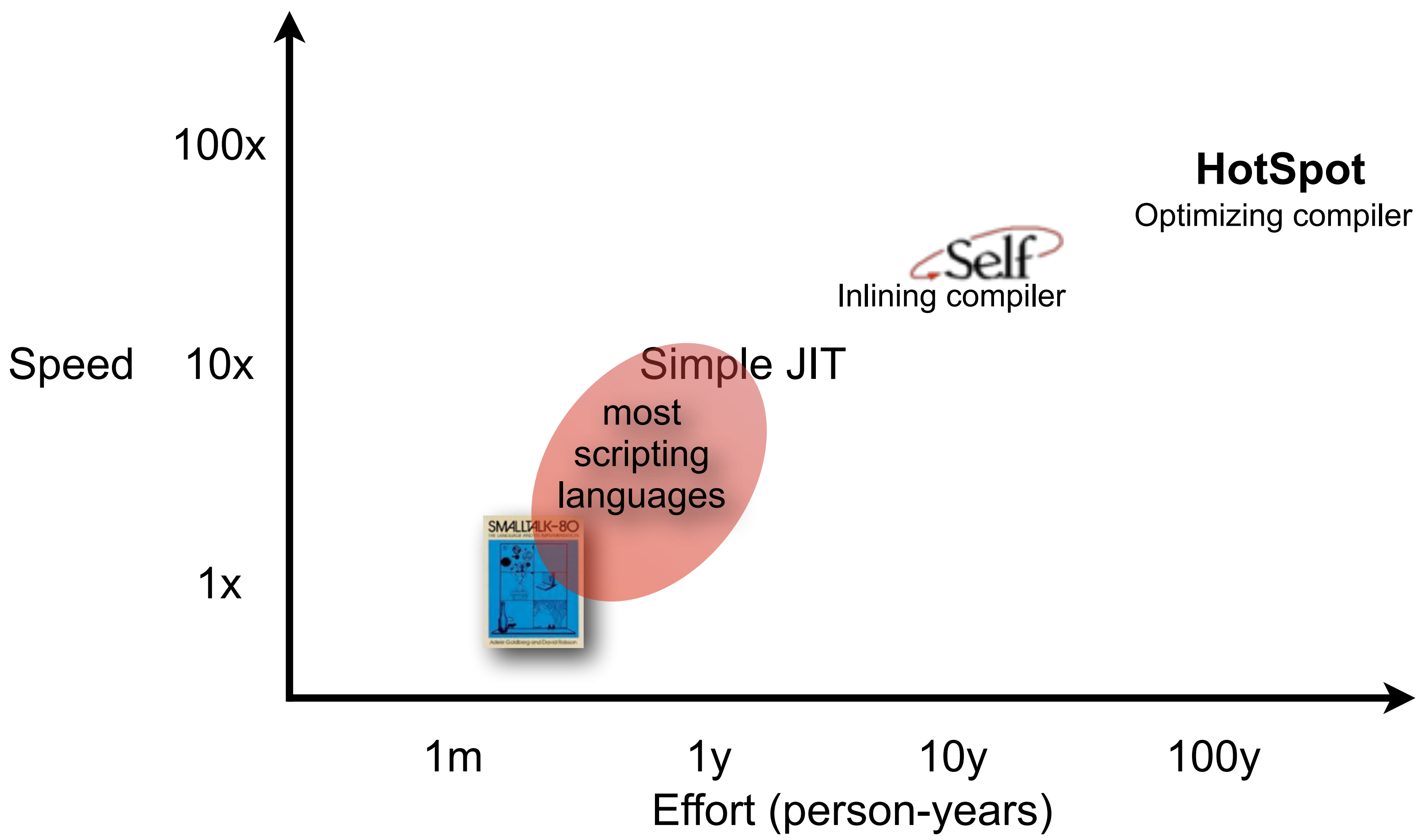

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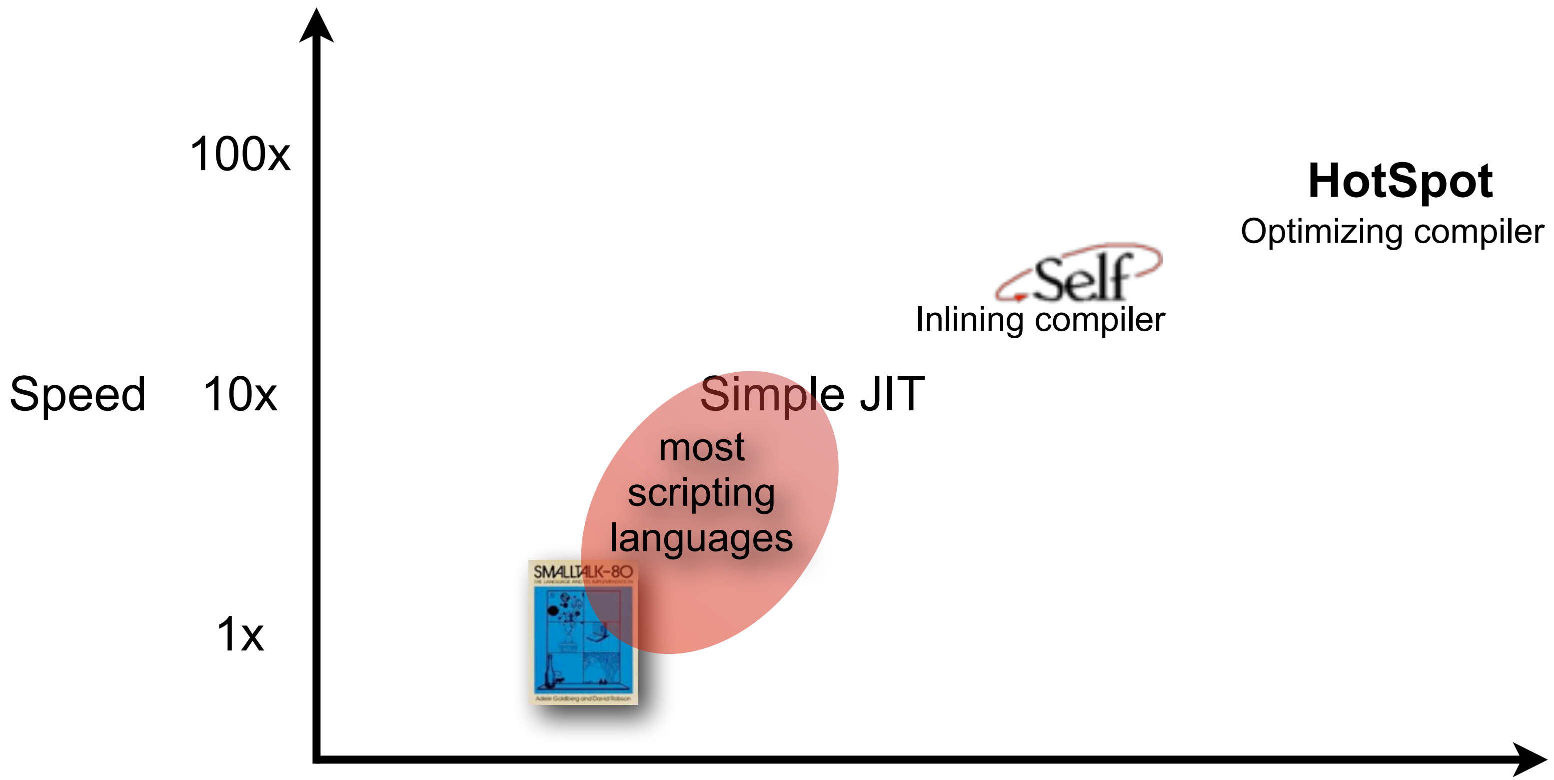

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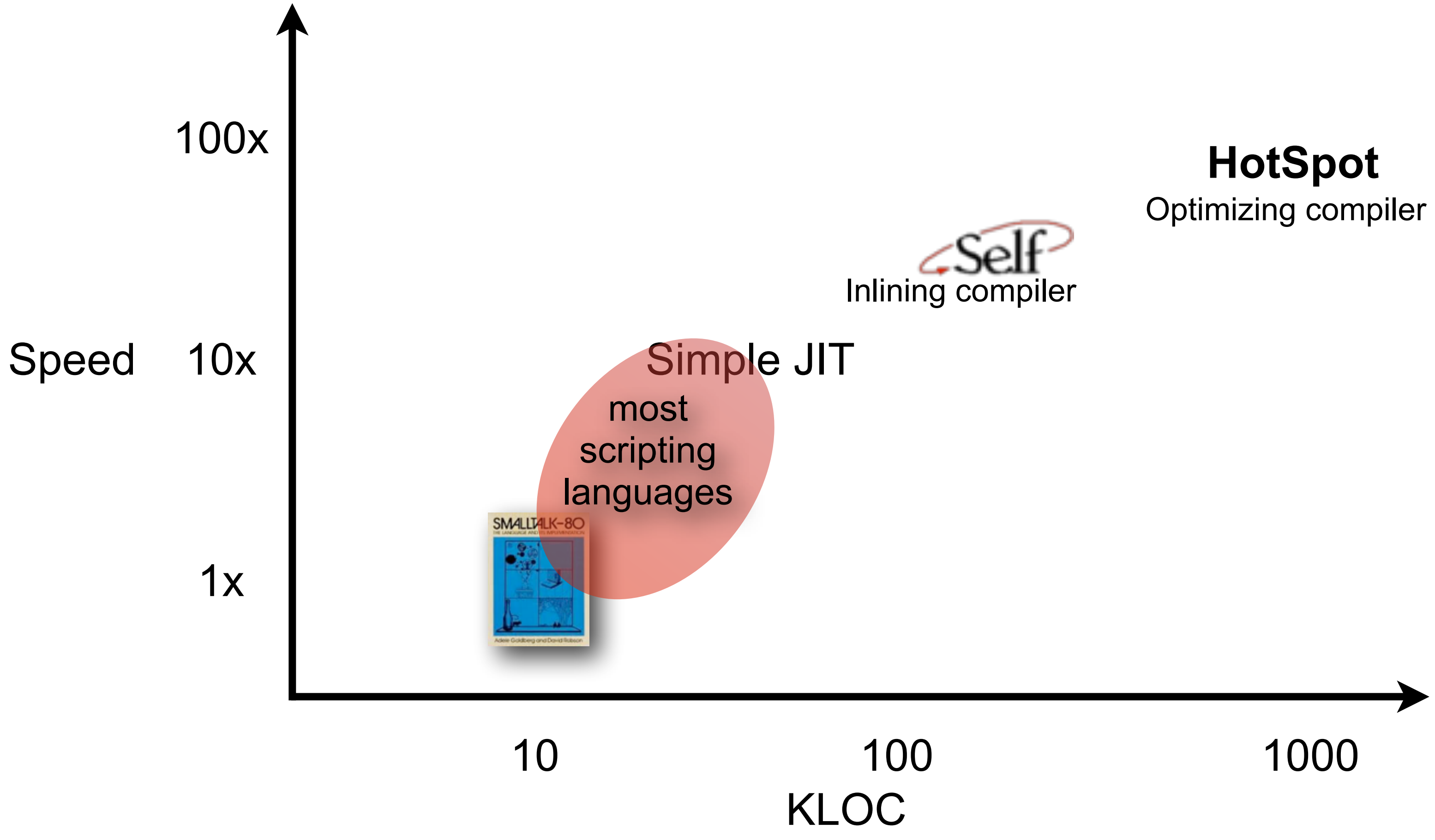

The language designer's dilemma

Current situation

Prototype a new language
- Parser and language work to build syntax tree (AST)
- Execute using AST interpreter

Write a "real" VM
- In C/C++
- Still using AST interpreter
- Spend a lot of time implementing runtime system, GC, …

People start using it

People complain about performance
- Define a bytecode format and write bytecode interpreter

Performance is still bad
- Write a JIT compiler
- Improve the garbage collector

Massive adoption
- Hire a big team of implementors to build an optimizing VM

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Most give up here

Why not reuse a compiler from another language?

- Glue on a different front end
  - PEP, Smalltalk in Self, Smalltalk-to-Eiffel, Smalltalk-to-Common Lisp
- Many languages translate to Java bytecode
  - But don’t seem to go much faster
  - Is Java bytecode the problem? Too Java-specific.
- Compiler already has to interoperate with garbage collection
  - Conservative GC is unacceptable
  - Static compiler are usually too slow to be used dynamically
  - Retrofitting GC to an optimizing compiler is usually unsuccessful
    - Large rewrites necessary to preserve info
- Even if this worked well, it’s still a lot of hard work

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A new approach: Truffle and Graal

Partial evaluation of self-specializing abstract syntax trees

Self-specializing interpreter nodes gather type and profile information

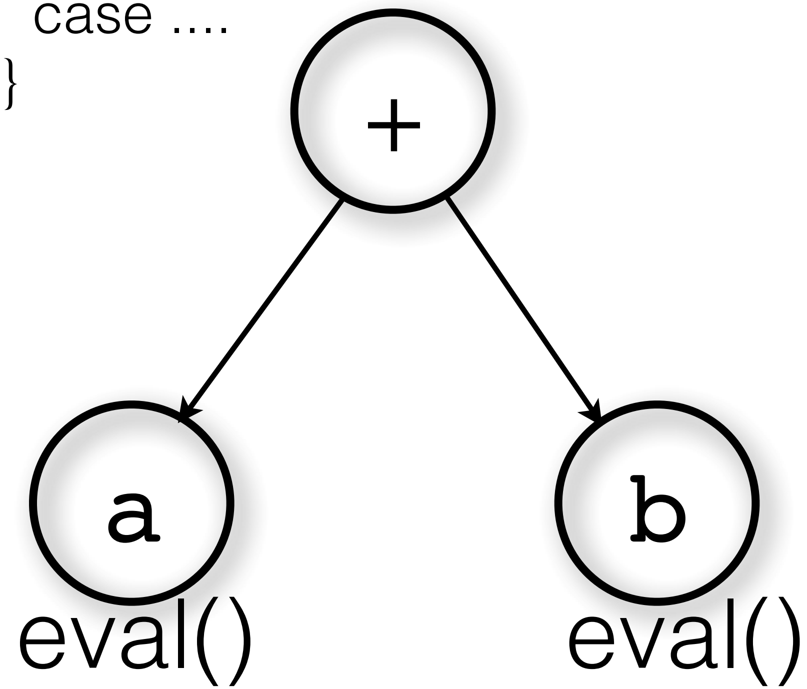
Optimizing compiler uses type, profile and AST structure to selectively inline and optimize

Conceived by Thomas Würthinger in 2011

Implementation by students and Oracle staff at Johannes Kepler University, Linz

Specializing interpreter nodes for the common case

```
VAL eval() {
  L=left.eval(); R=right.eval();
  switch (type(L)) {
  case INT: res= L+R;
    if (overflowed(L, R, res)) {...}
    else return BOX(res);
  case ....
}
```



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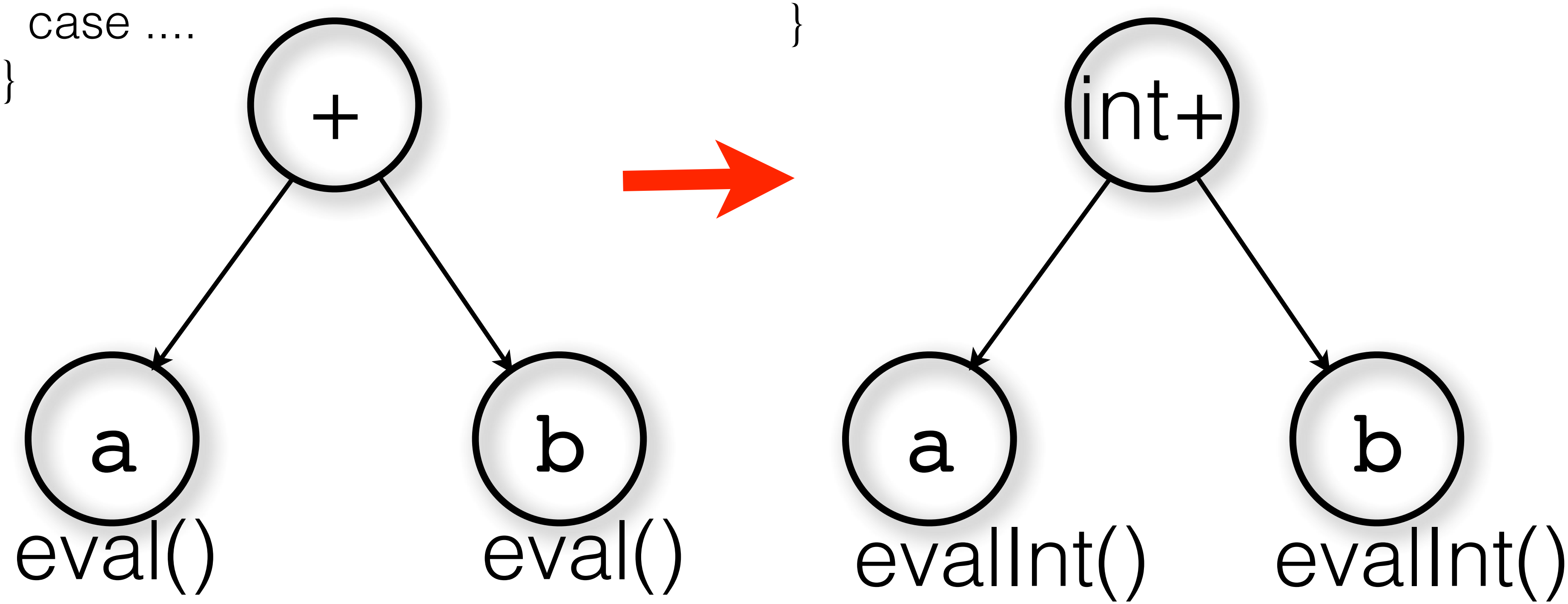
int evalInt() throws Unexpected {
  try {
     return left.evalInt()+right.evalInt();
  } catch (Unexpected u) {
     // revert to slow version }
}
```



Optimizing compilation driven by specialized ASTs

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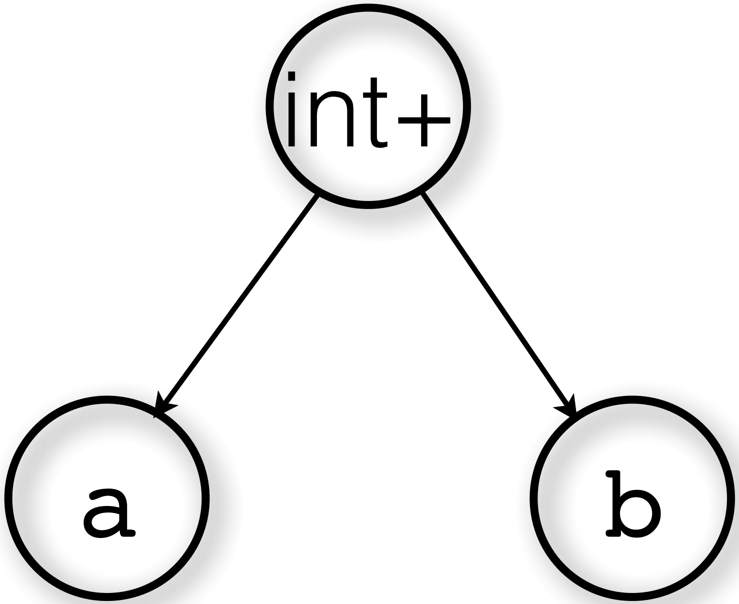


```
evalInt() {
  return val(“a”);}
```

```
evalInt() {
  return val(“b”);}
```

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Optimizing compilation driven by specialized ASTs

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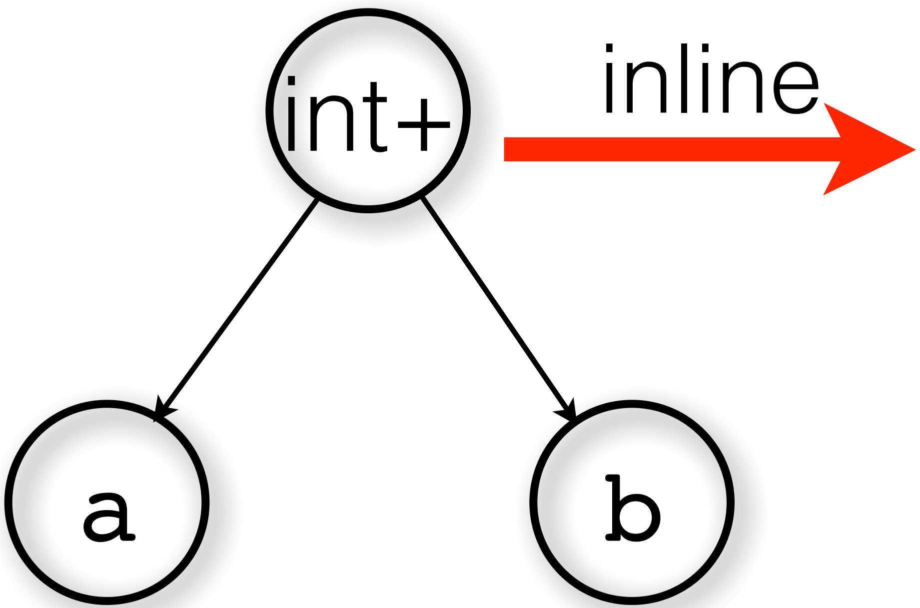


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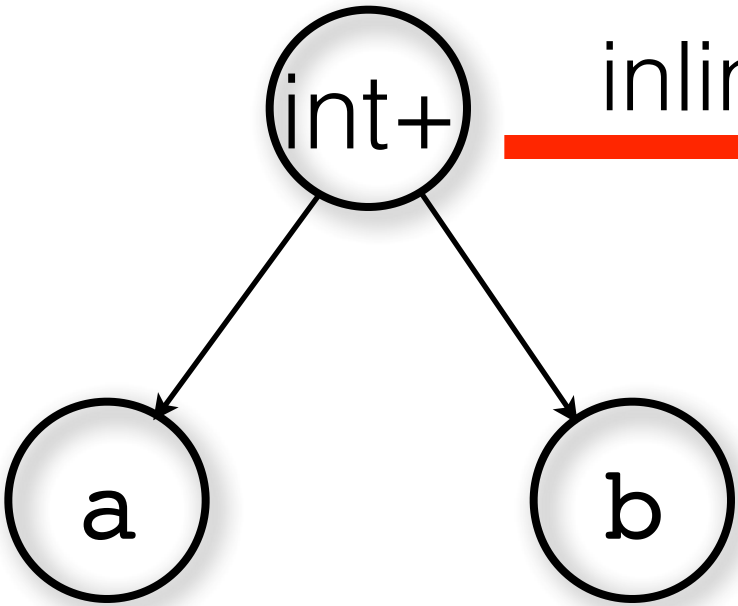


```
evalInt() {
  return val("a");}
```

```
evalInt() {
  return val("b");}
```

inline

```
evalInt() {
 return val("a")+val("b");}
```

compile

```
add Ra,Rb,Result
```

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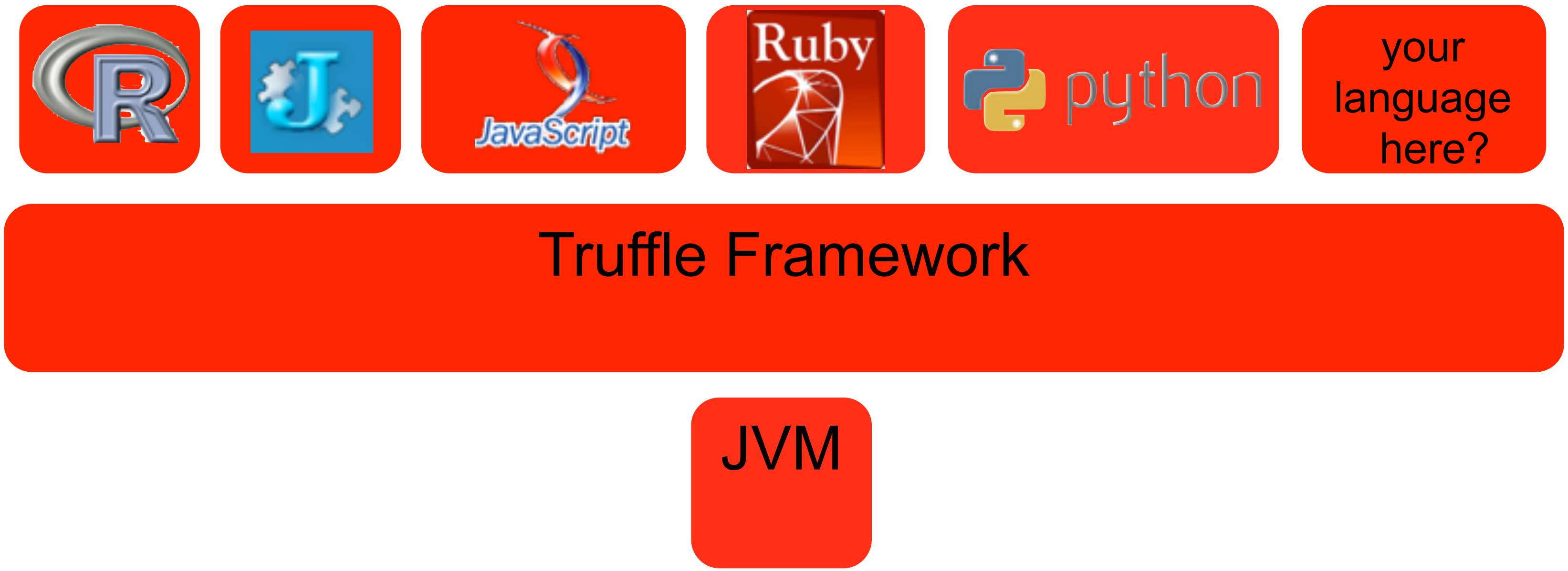
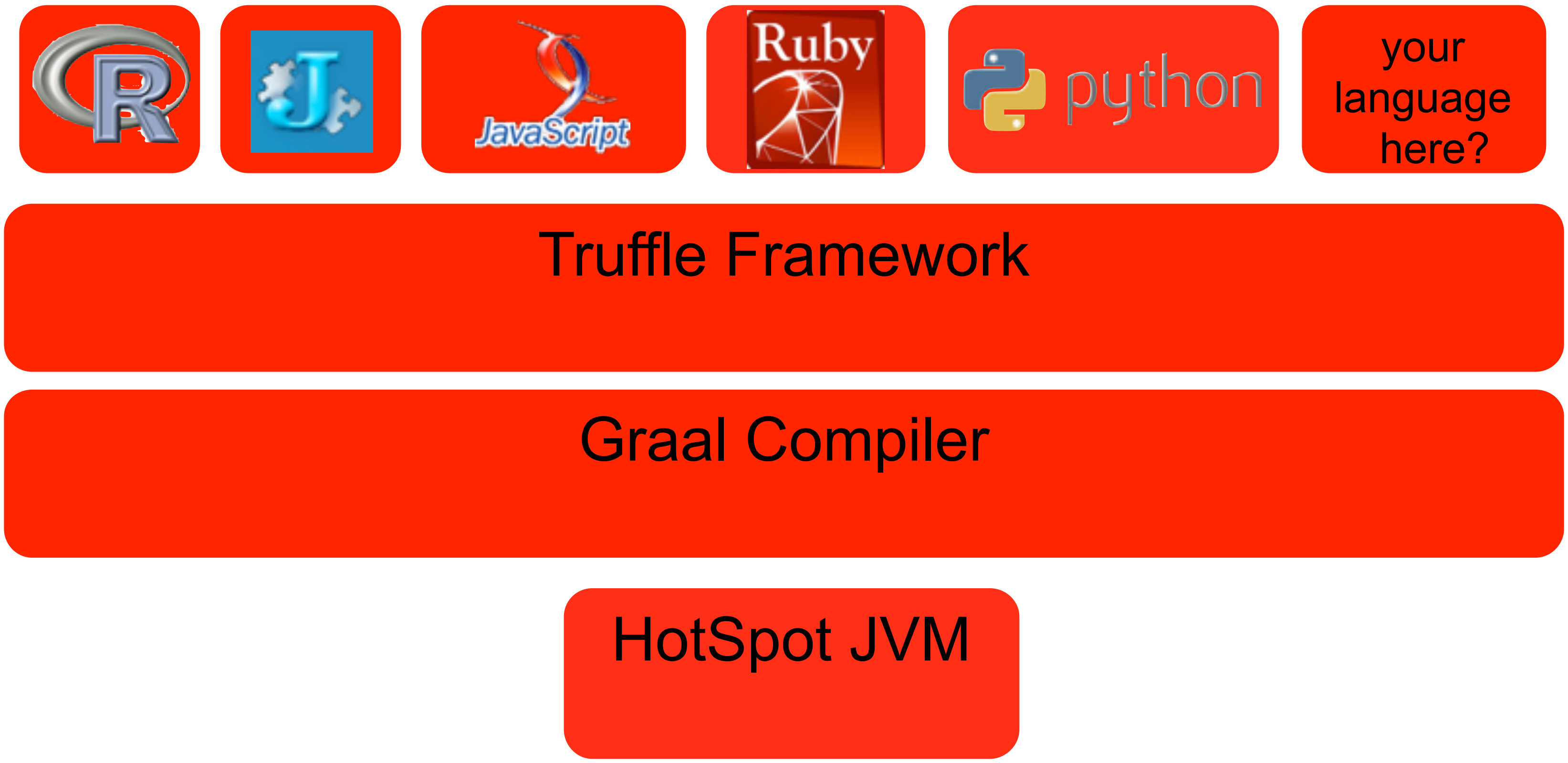
System architecture



System architecture



System architecture

your language here?

Truffle Framework

Graal Compiler

Standalone Substrate VM

or

HotSpot JVM

System architecture

Ruby

python

your language here?

Truffle Framework

Graal Compiler

Standalone Substrate VM

or

HotSpot JVM

or

Substrate VM embedded

System architecture

your language here?

Truffle Framework

Graal Compiler

Standalone Substrate VM

or

HotSpot JVM

or

Substrate VM embedded

GPU backend for Graal

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The language designer's dilemma—resolved?

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How it should be

Prototype a new language in Java
- Parser and language work to build syntax tree (AST)
- Execute using AST interpreter and optimizing compiler

People start using it
- And it is already fast

Tag elimination for dynamically-typed languages

- Chambers and Ungar came up with method customization for Self
  - Don't have to inherit machine code for a machine; can customize and optimize for local behavior (e.g., variable overrides abstract method)
- Idea: customized methods for objects whose fields contain primitives (int, float)
  - Due to Thomas Würthinger (2010)
  - Eliminates need for tagging
    - although could be a halfway between unboxed and boxed representations

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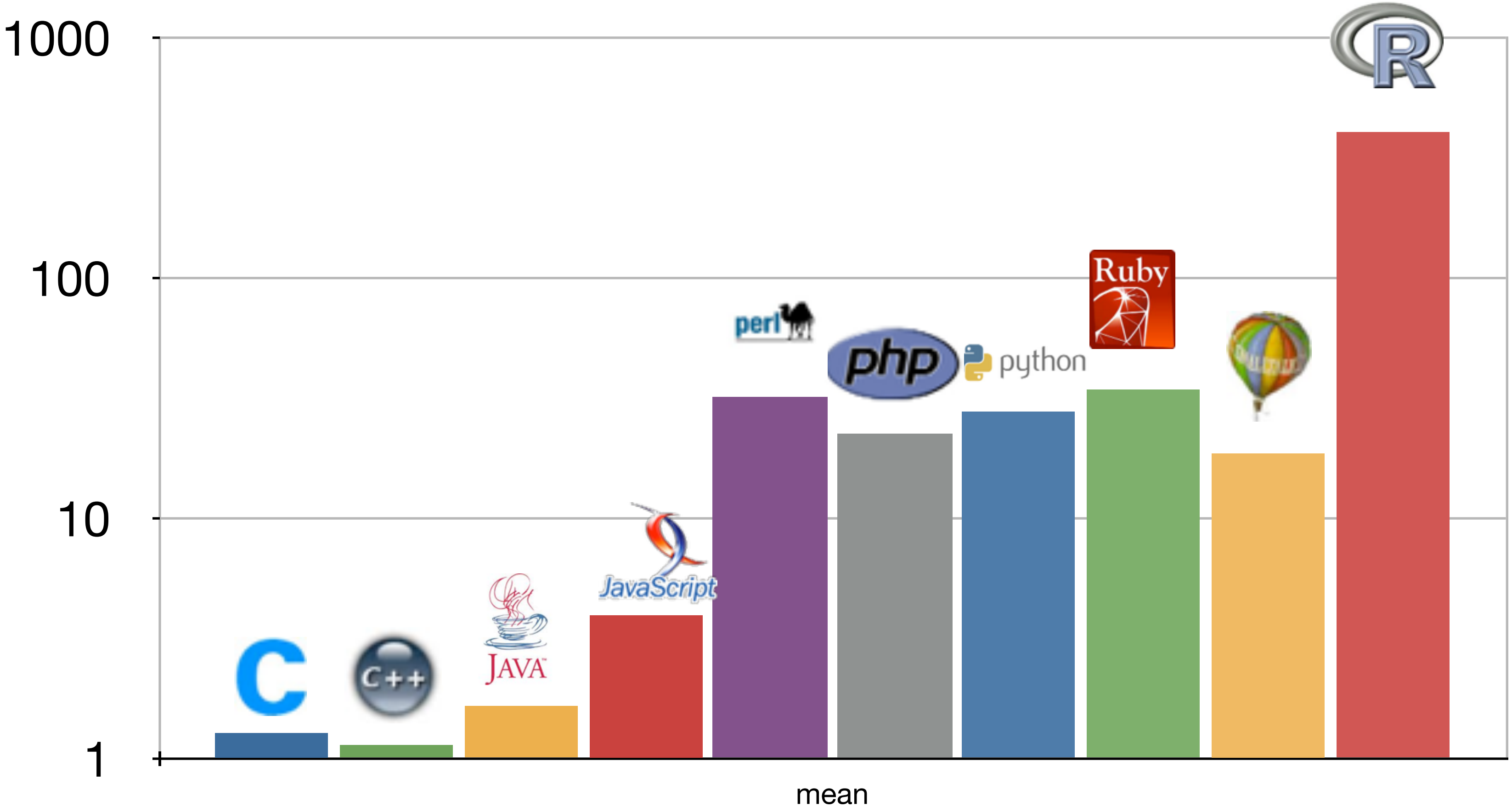
Relative speeds of various languages

(as measured by the Computer Language Benchmarks Game, ~1y ago)



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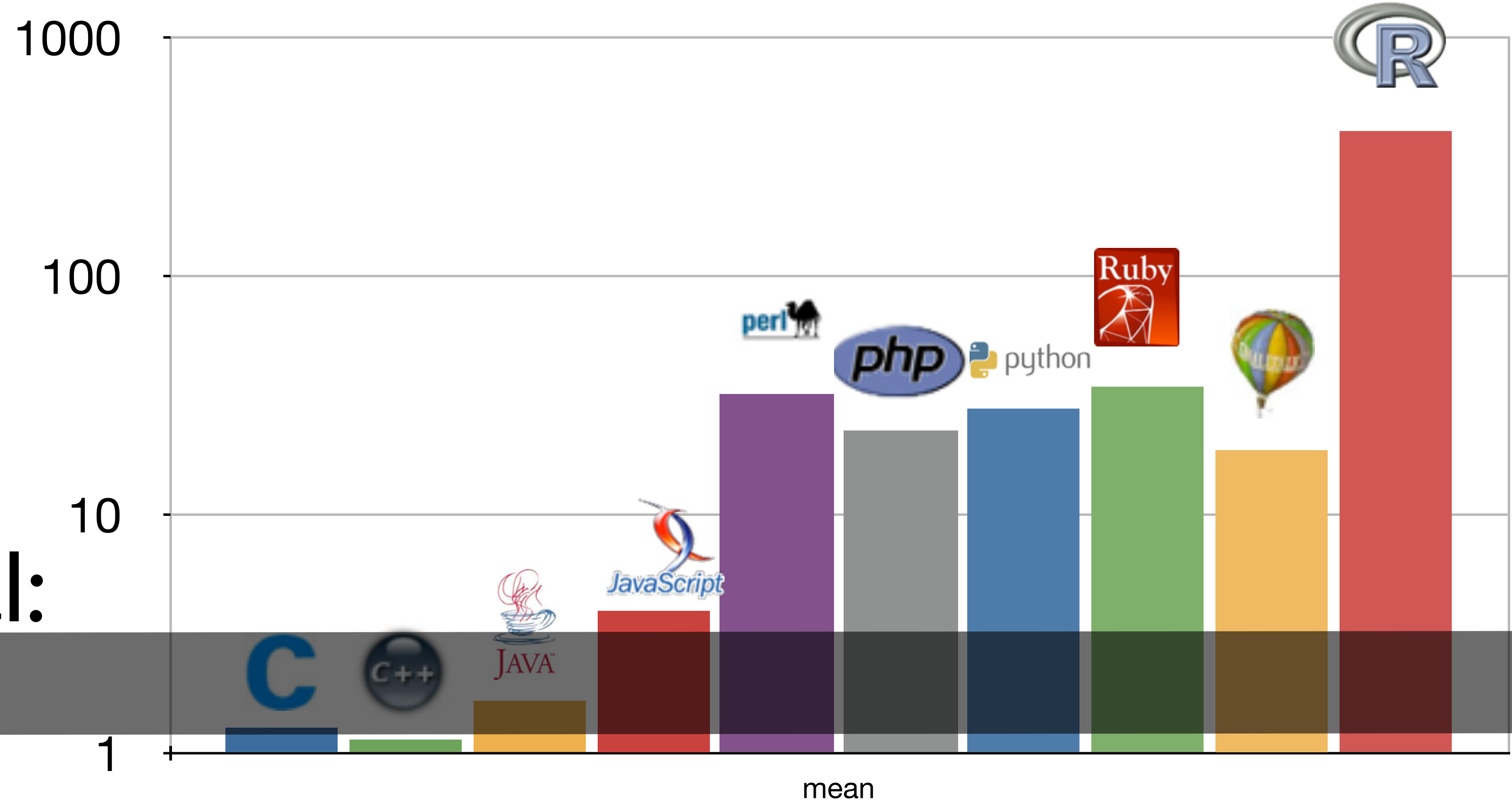
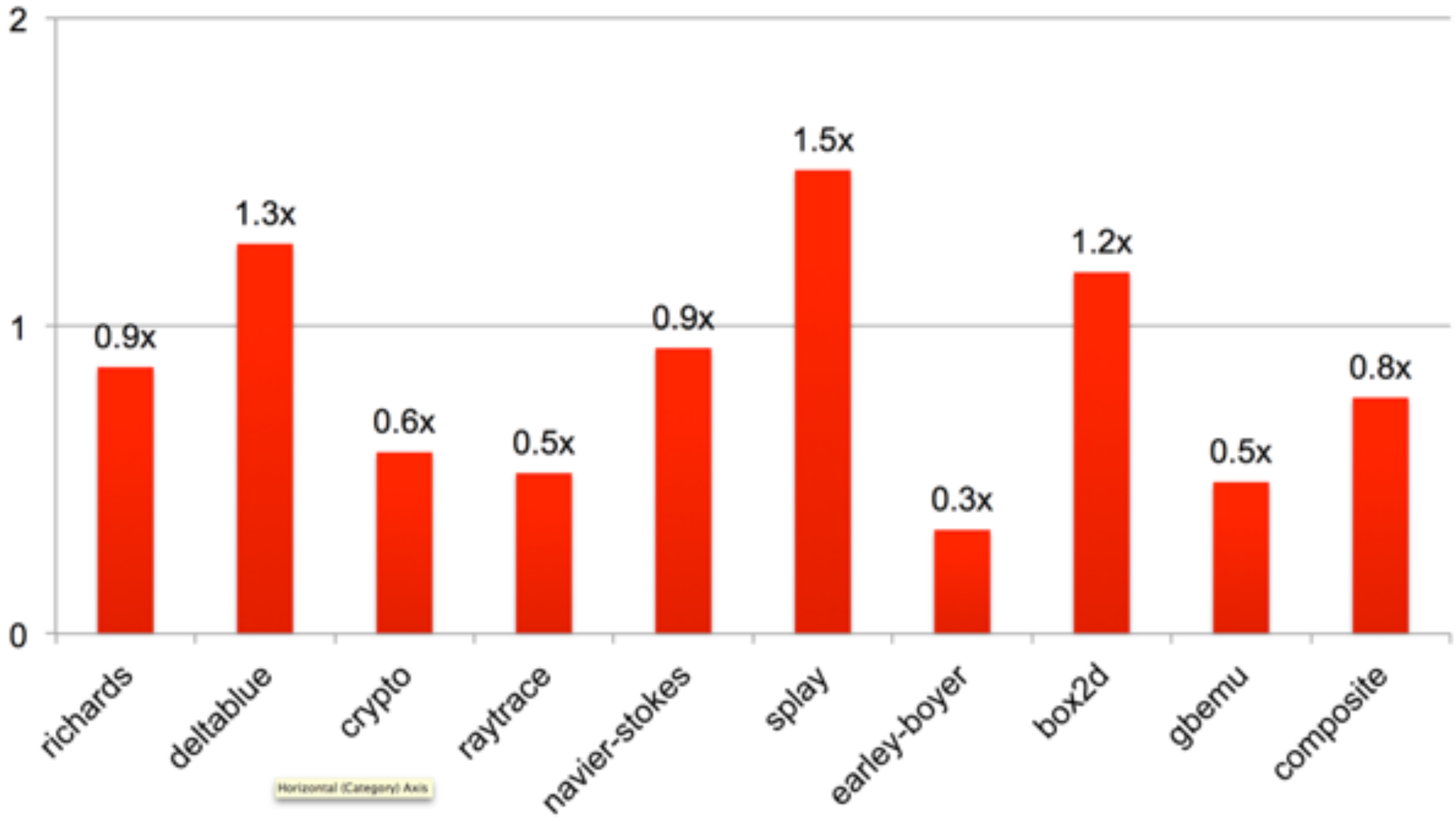


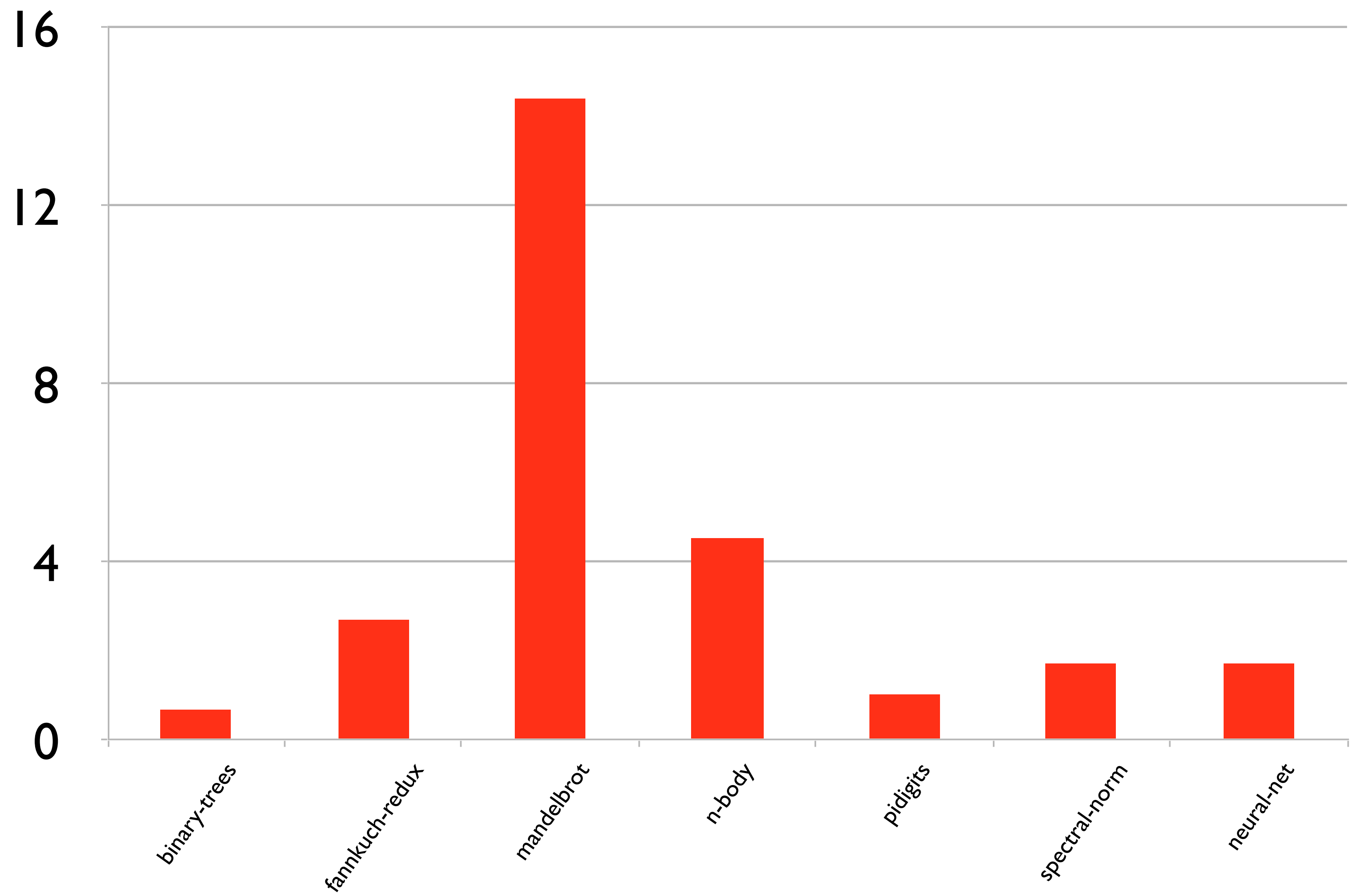
Goal:

Peak Performance: Truffle/JavaScript versus V8



Benchmarks from Octane v.1 suite, Hardware: Intel Core i7-3770, 16 GB RAM, V8 version 3.22.1 from 25-Sep-2013, Truffle/JavaScript: Running on Graal/OpenJDK changeset 63c378b7c1c3 from 26-Oct-2013

Peak Performance: Truffle/Ruby versus JRuby 1.7.5



Evidence that it can be done with modest effort

Slide from Chris Seaton, JVM Lang Summit 2013, describing his Ruby implementation on Truffle

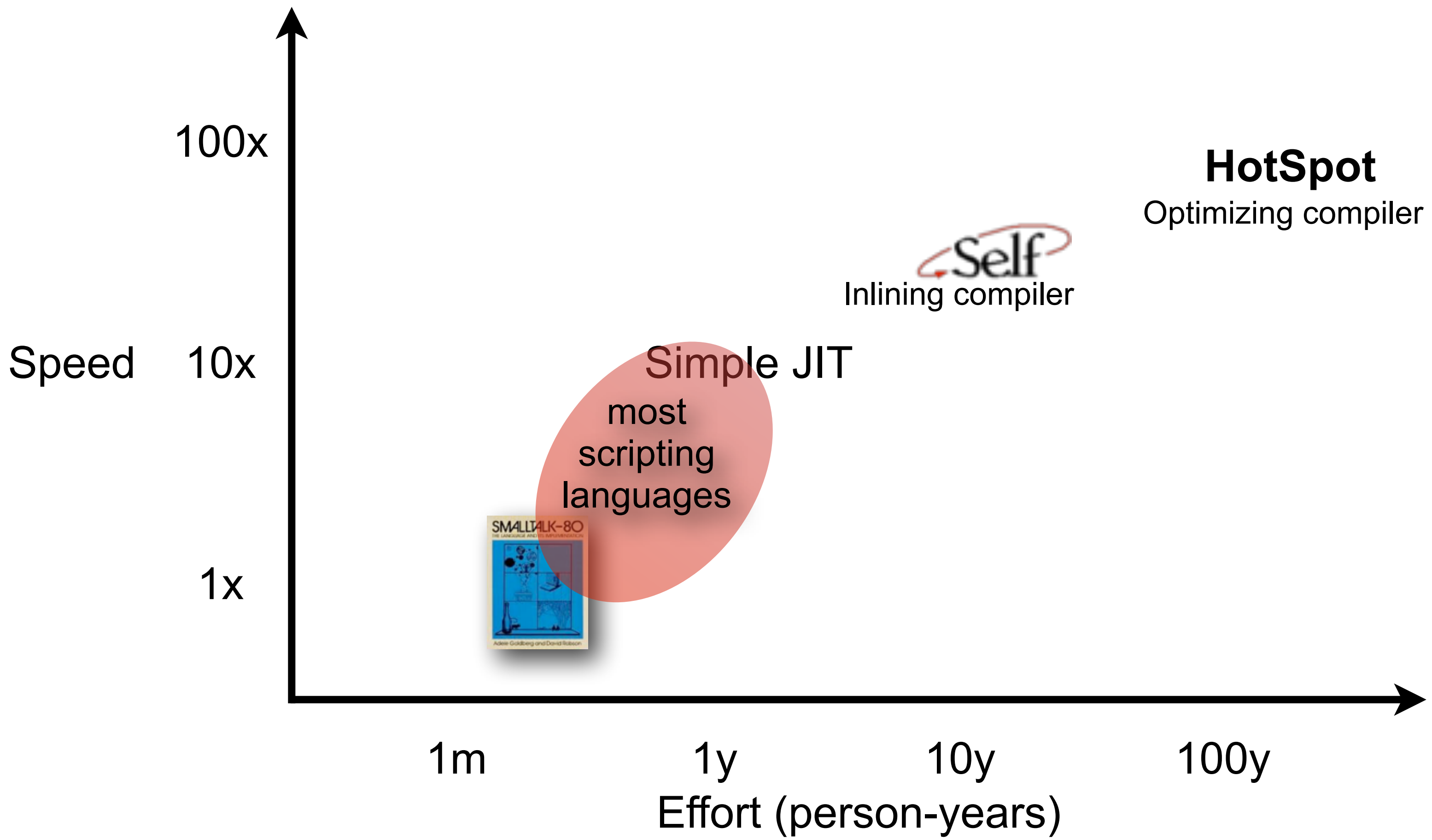
Simplicity

- One intern working for five months on the Ruby implementation
- New to Truffle, Graal and Ruby

- Written using Eclipse
- Debugged as a normal Java program using the server compiler
- Run using Graal for testing and performance numbers

- No mention in the implementation of bytecode, classloaders, assembly, system calls, OSR
- One very minor use of Unsafe, one very minor use of reflection

Summary: reuse our stack, get a fast VM without a ton of work



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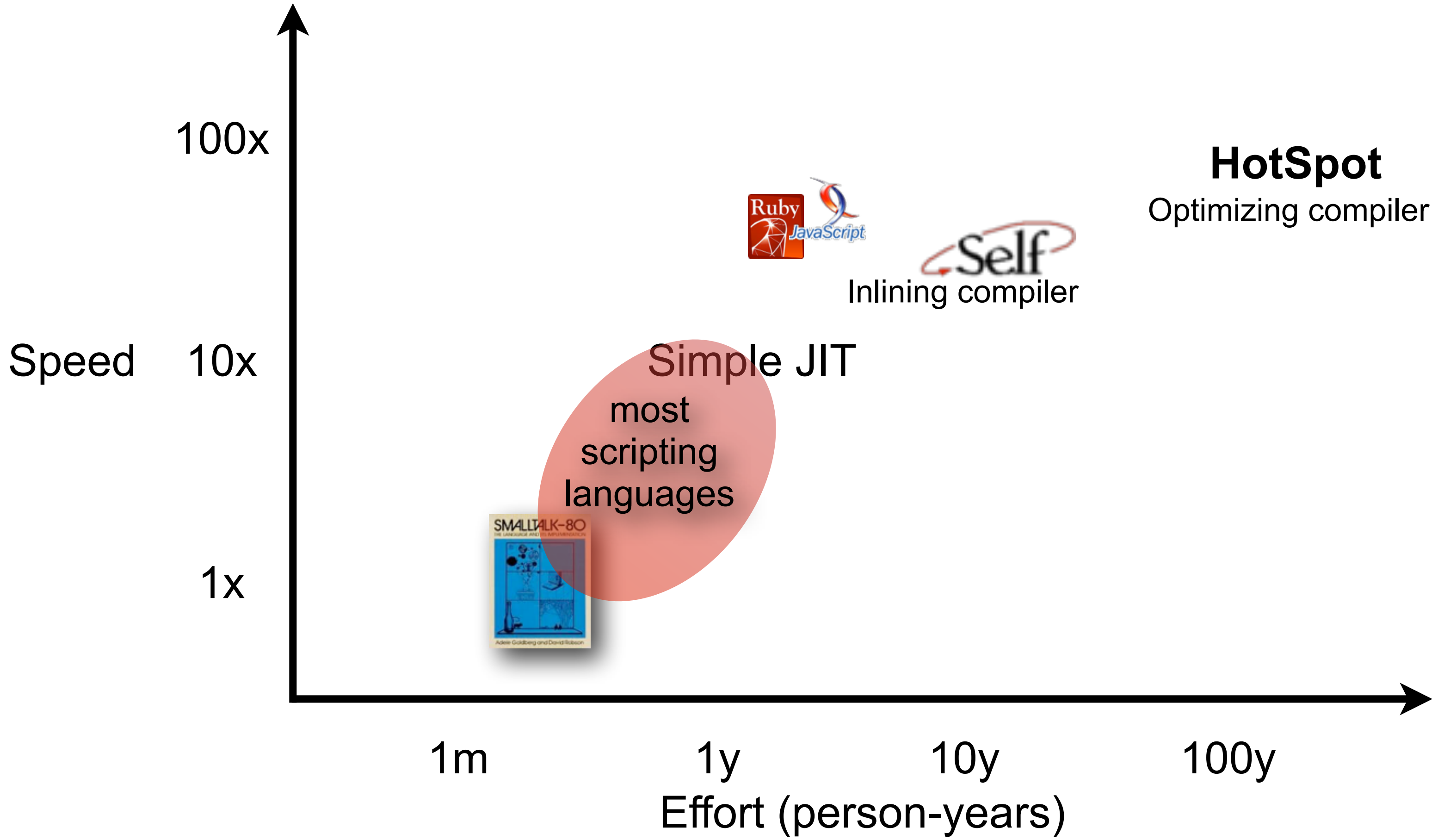

For more information

An Intermediate Representation for Speculative Optimizations in a Dynamic Compiler, Mon@4.00, "Regency B" (VMIL workshop)

How the Graal IR is good for optimizing Java code

ZipPy on Truffle: A Fast and Simple Implementation of Python, Demo, Wed@11.15, “Vision” room

A Truffle deep dive

One VM to Rule Them All — Onward! paper, Thu @ 10.30, Cosmopolitan B

Full paper on Truffle: http://dx.doi.org/10.1145/2509578.2509581

So you want to be an industrial researcher? SPLASH-I, Tue @ 1pm

http://openjdk.java.net/projects/graal/

https://wiki.openjdk.java.net/display/Graal/Publications+and+Presentations

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