VMs, Interpreters, JIT & Co

A First Introduction

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Overview

- Virtual Machines: How and Why
  - Bytecode
  - Garbage Collection (GC)
- Code Execution
  - Interpretation
  - Just-In-Time
  - Optimizing method lookup
  - Dynamic optimization

Caveat

- Virtual Machines are not trivial!
- This lecture can only give a very high-level overview
- You will not be a VM Hacker afterwards ;-)
- Many slides of this talk should be complete lectures (or even courses)

Virtual Machine: What's that?

- Software implementation of a machine

- Process VMs
  - Processor emulation (e.g. run PowerPC on Intel)
    - FX32!, MacOS 68k, powerPC
  - Optimization: HP Dynamo
  - High level language VMs

- System Virtual Machines
  - IBM z/OS
  - Virtual PC

High Level Language VM

- We focus on HLL VMs
- Examples: Java, Smalltalk, Python, Perl....

- Three parts:
  - The Processor
    - Simulated Instruction Set Architecture (ISA)
  - The Memory: Garbage Collection
  - Abstraction for other OS / Hardware (e.g, I/O)

- Very near to the implemented language
- Provides abstraction from OS

The Processor

- VM has an instruction set. (virtual ISA)
  - Stack machine
  - Bytecode
  - High level: models the language quite directly
    - e.g, "Send" bytecode in Smalltalk

- VM needs to run this Code
- Many designs possible:
  - Interpreter (simple)
  - Threaded code
  - Simple translation to machine code
  - Dynamic optimization ("HotSpot")

Garbage Collection

- Provides a high level model for memory
- No need to explicitly free memory
- Different implementations:
  - Reference counting
  - Mark and sweep
  - Generational GC

- A modern GC is *very* efficient
- It’s hard to do better

Other Hardware Abstraction

- We need a way to access Operating System APIs
  - Graphics
  - Networking (TCP/IP)
  - Disc / Keyboard....

- Simple solution:
  - Define an API for this Hardware
  - Implement this as part of the VM (“Primitives”)
  - Call OS library functions directly

Virtual Machine: Lessons learned

- VM: Simulated Machine
- Consists of
  - Virtual ISA
  - Memory Management
  - API for Hardware/OS
- Next: Bytecode

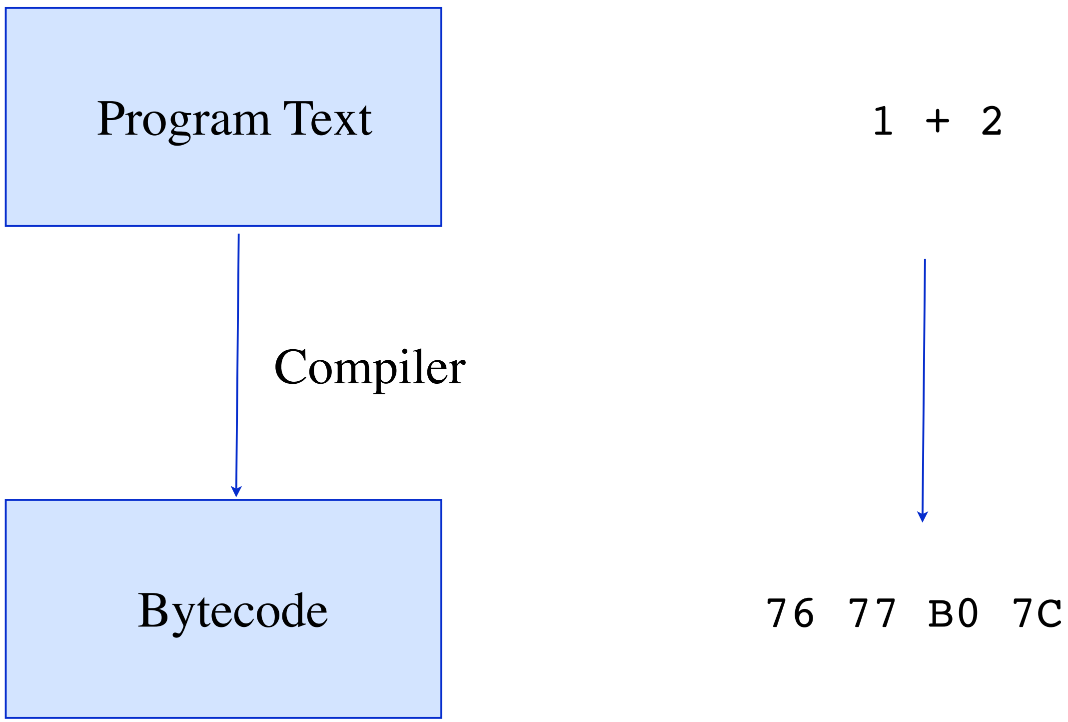
Bytecode

- Byte-encoded instruction set
- This means: 256 main instructions
- Stack based

- Positive:
  - Very compact
  - Easy to interpret

- Important: The ISA of a VM does not need to be Bytecode.

Compiling to Bytecode



Example: Number>>asInteger

- Smalltalk code:

```
^1 + 2
```

- Symbolic Bytecode

```
<76> pushConstant: 1
<77> pushConstant: 2
<B0> send: +
<7C> returnTop
```

Example: Java Bytecode

- From class Rectangle

```
public int perimeter()

0: iconst_2
1: aload_0          "push this"
2: getfield#2       "value of sides"
5: iconst_0
6: iaload
7: aload_0                                  2*(sides[0]+sides[1])
8: getfield#2
11: iconst_1
12: iaload
13: iadd
14: imul
15: ireturn
```

Difference Java and Squeak

- Instruction for arithmetic
  - Just method calls in Smalltalk
- Typed: special bytecode for int, long, float
- Bytecode for array access

- Not shown:
  - Jumps for loops and control structures
  - Exceptions (java)
  - ....

Systems Using Bytecode

- USCD Pascal (first, ~1970)
- Smalltalk
- Java
- PHP
- Python

- No bytecode:
  - Ruby: Interprets the AST

Bytecode: Lessons Learned

- Instruction set of a VM
- Stack based
- Fairly simple

- Next: Bytecode Execution

Running Bytecode

- Invented for Interpretation
- But there are faster ways to do it

- We will see
  - Interpreter
  - Threaded code
  - Translation to machine code (JIT, Hotspot)

Interpreter

- Just a big loop with a case statement

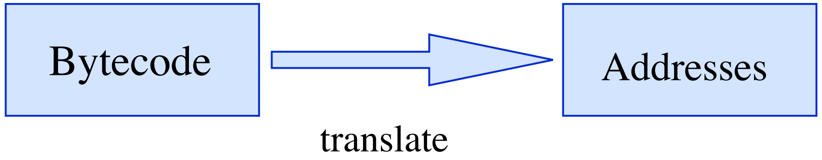
- Positive:
  - Memory efficient
  - Very simple
  - Easy to port to new machines

- Negative:
  - Slooooooow...

```
while (1) {
   bc = *ip++;
   switch (bc) {
      ...
      case 0x76:
         *++sp = ConstOne;
         break;
      ...
   }
}
```

Faster: Threaded Code

- Idea: Bytecode implementation in memory has Address

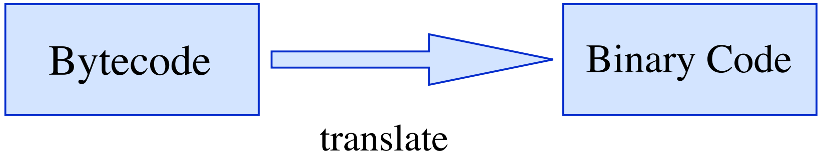



```
push1:
   *++sp = ConstOne
   goto *ip++;
push2:
   *++sp = ConstTwo
   goto *ip++;
```

- Pro:
  - Faster
  - Still fairly simple
  - Still portable
  - Used (and pioneered) in Forth.
  - Threaded code can be the ISA of the VM

Next Step: Translation

- Idea: Translate bytecode to machine code



- Pro:
  - Faster execution
  - Possible to do optimizations
  - Interesting tricks possible: Inline Caching (later)

- Negative
  - Complex
  - Not portable across processors
  - Memory

Simple JIT Compiler

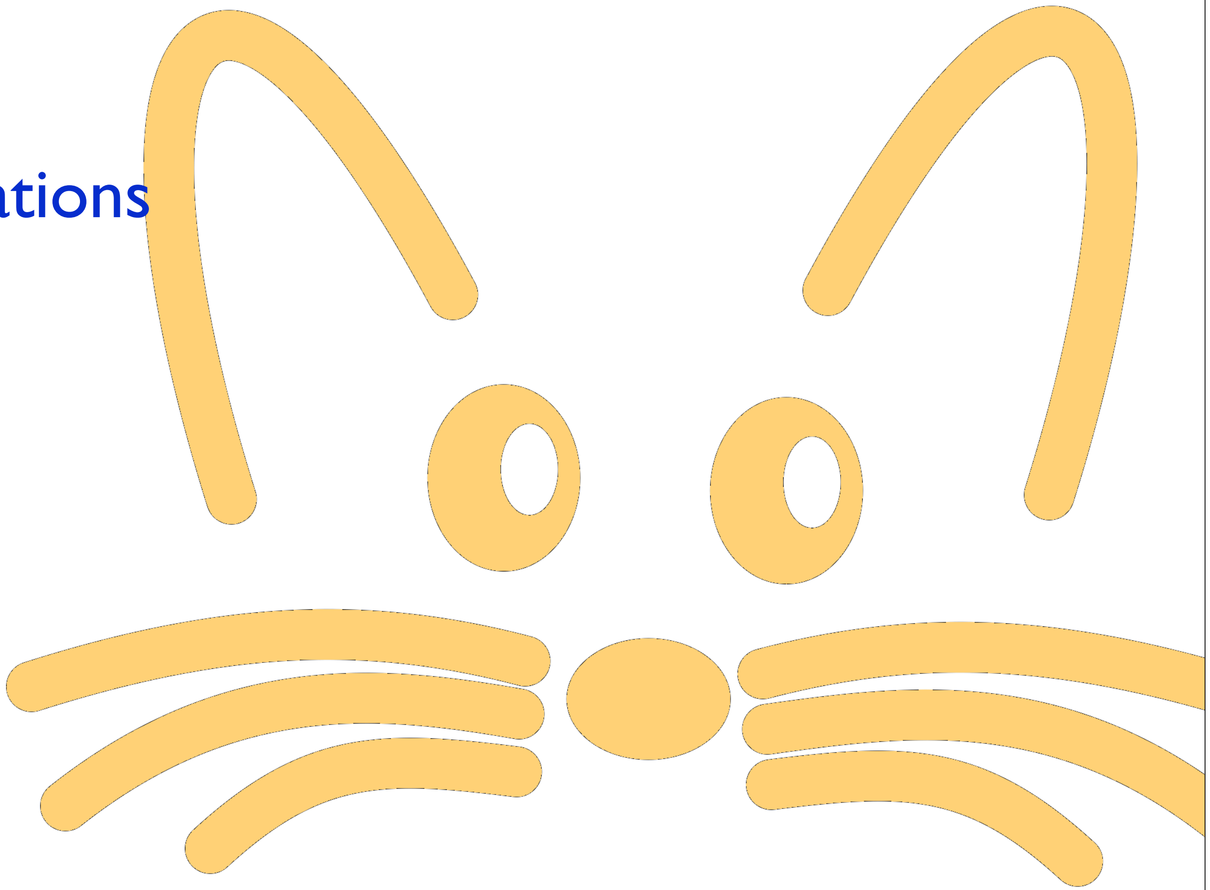
- JIT = “Just in Time”
- On first execution: Generate Code
- Need to be very fast
  - No time for many code optimizations
- Code is cached (LRU)

- Memory:
  - Cache + implementation JIT in RAM.
  - We trade memory for performance.

Bytecode Execution: Lessons Learned

- We have seen
  - Interpreter
  - Threaded Code
  - Simple JIT

- Next: Optimizations



Optimizing Method Lookup

- What is slow in OO virtual machines?
- Overhead of Bytecode Interpretation
  - Solved with JIT
- Method Lookup
  - Java: Polymorph
  - Smalltalk: Polymorph and dynamically typed
  - Method to call can only be looked up at runtime

Example Method Lookup

- A simple example:

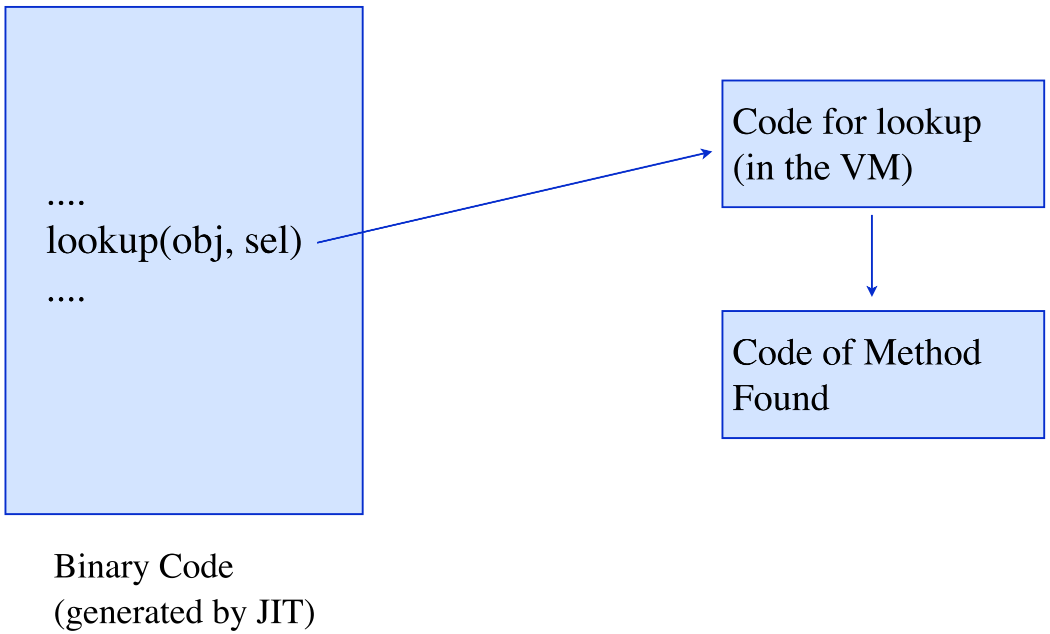
```
array := #(0 1 2 2.5).

array collect: [:each | each + 1]
```

- The method “+” executed depends on the receiving object

Method Lookup

- Need to look this up at runtime:
  - Get class of the receiver
  - if method not found, look in superclass



Observation: Yesterday’s Weather

- Predict the weather of tomorrow: Same as today
- Is right in over 80%

- Similar for method lookup:
  - Look up method on first execution of a send
  - The next lookup would likely get the same method

- True polymorphic sends are seldom

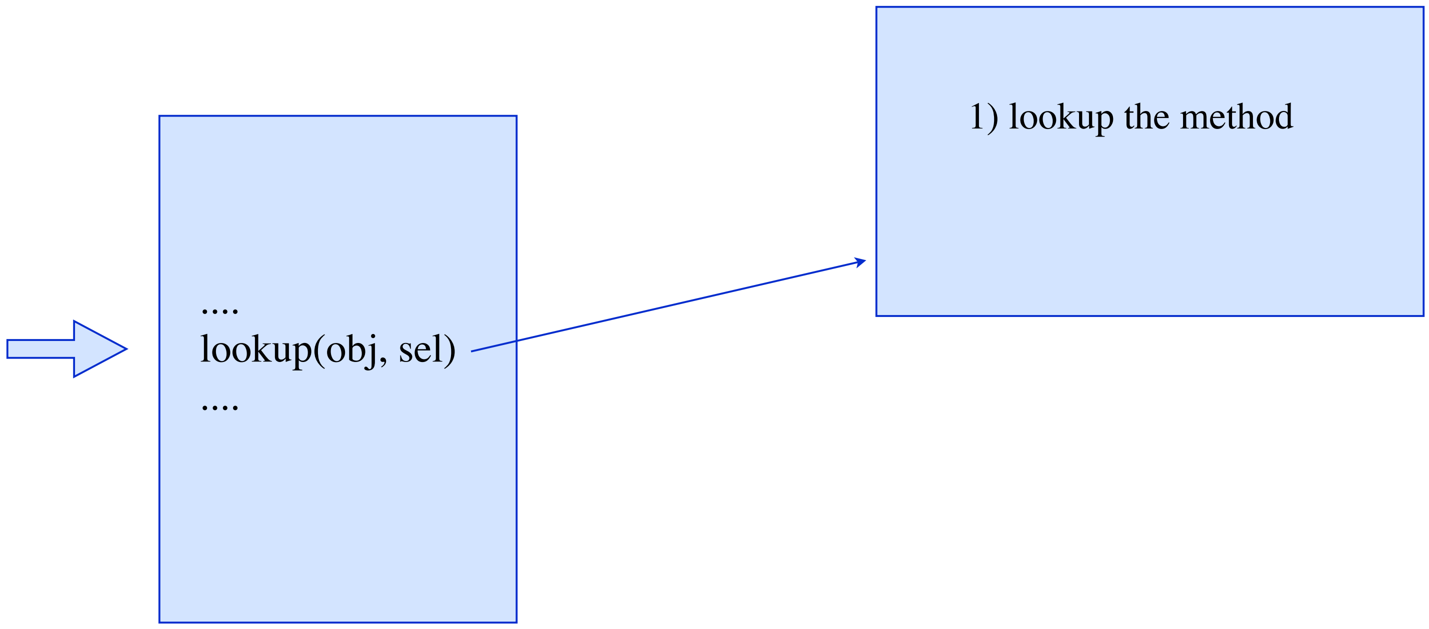
Inline Cache

- Goal: Make sends faster in many cases
- Solution: remember the last lookup

- Trick:
  - Inline cache (IC)
  - In the binary code of the sender

Inline Cache: First Execution

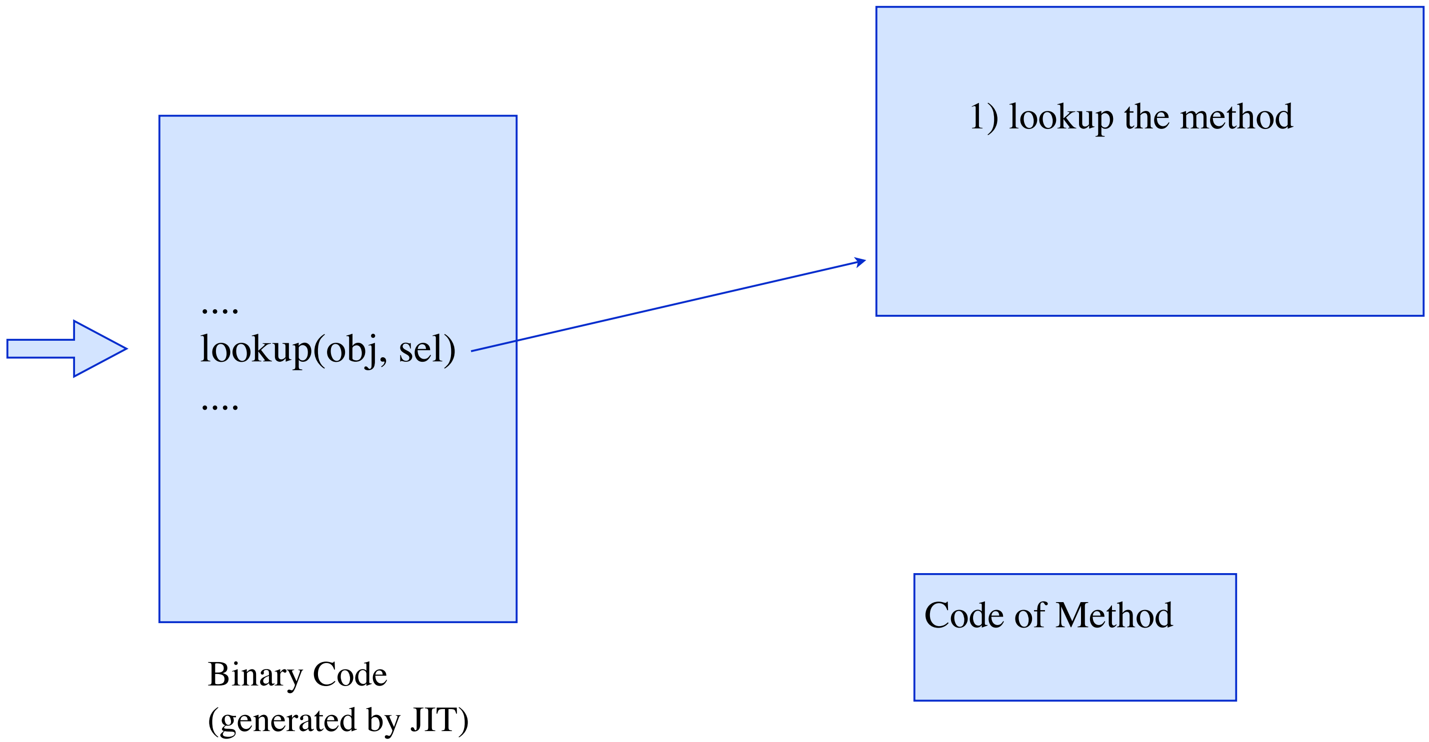
First Call:



Binary Code
(generated by JIT)

Inline Cache: First Execution

First Call:



Inline Cache: First Execution

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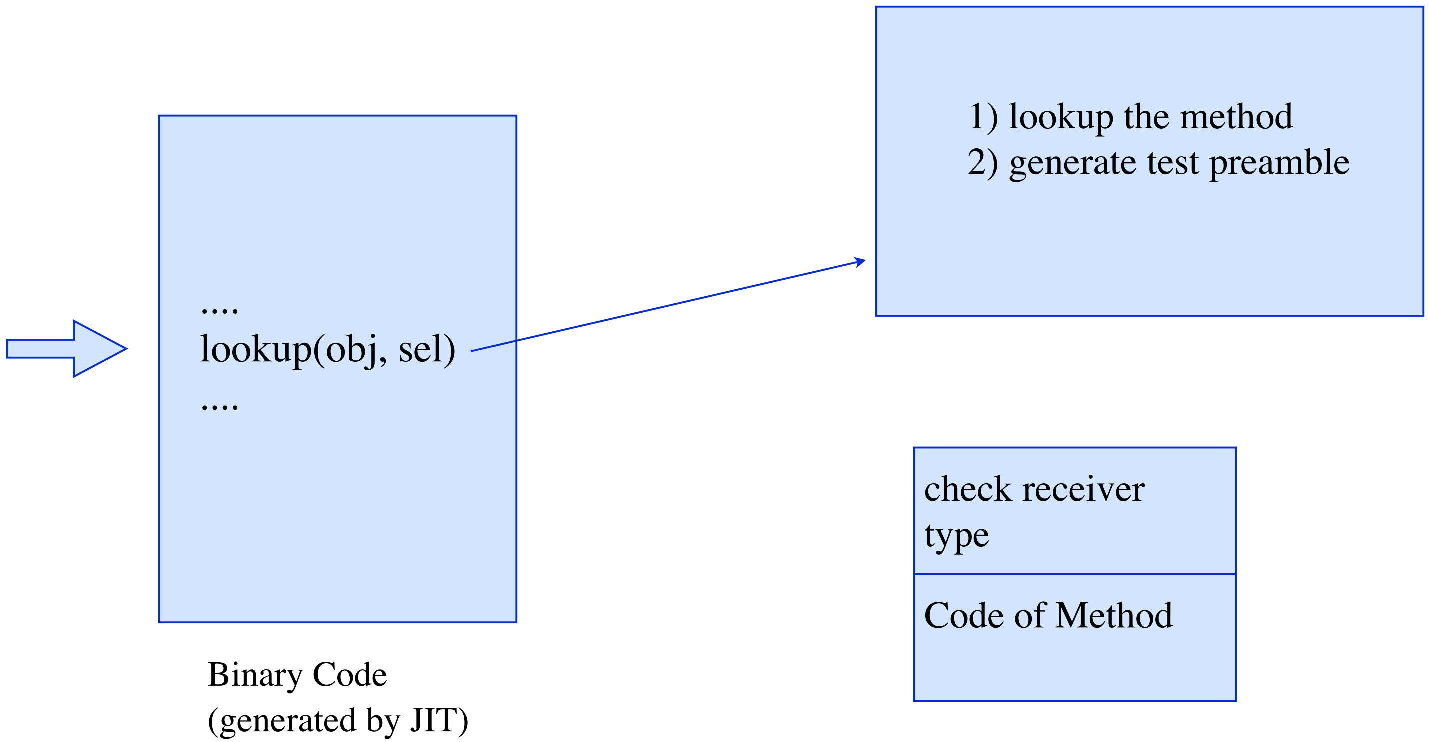

Inline Cache: First Execution

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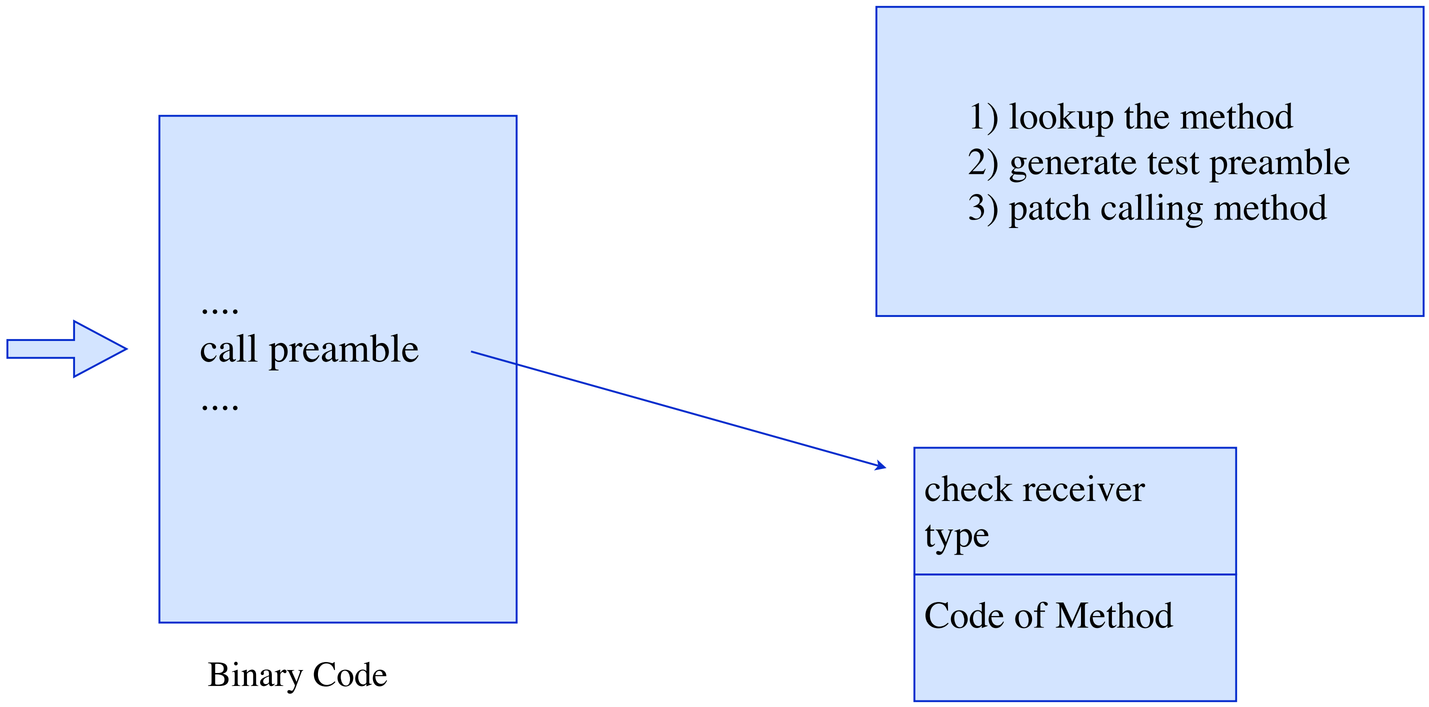

Binary Code
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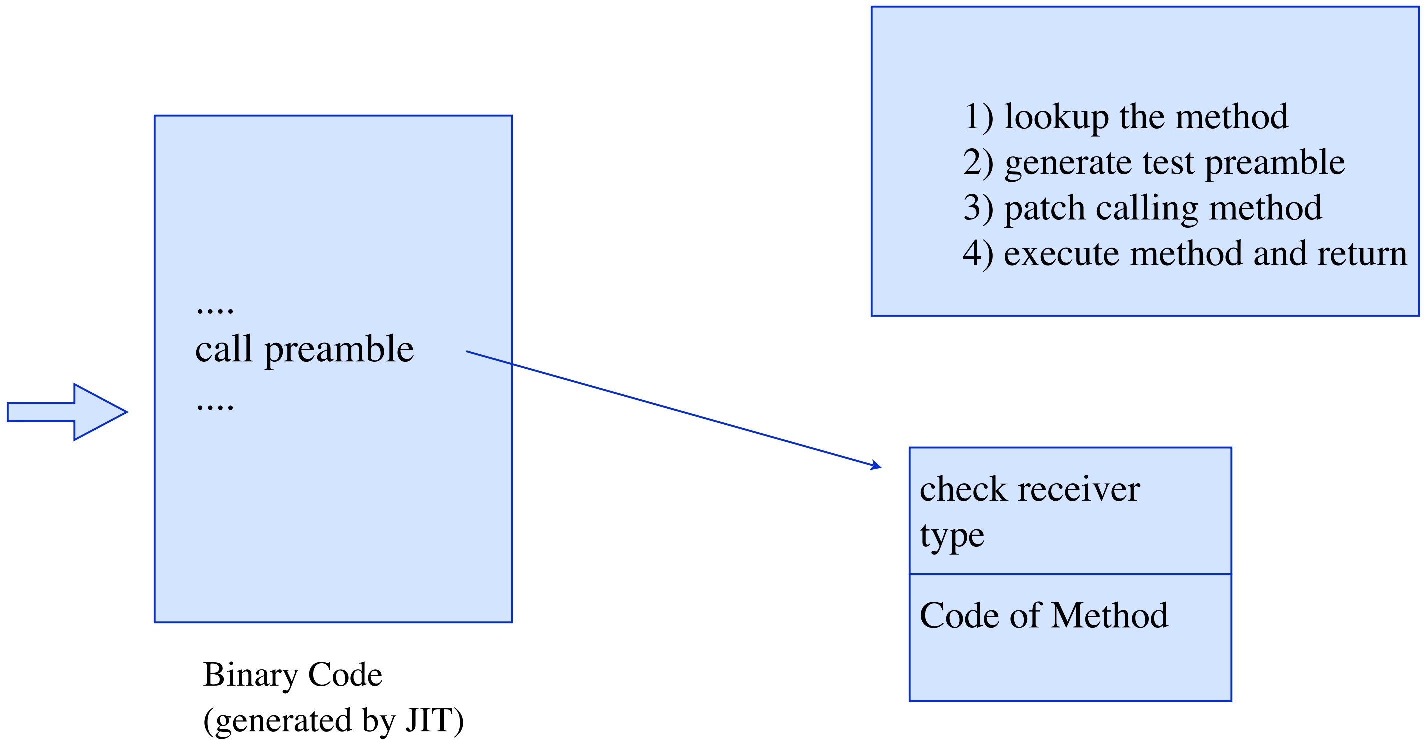
Inline Cache: First Execution

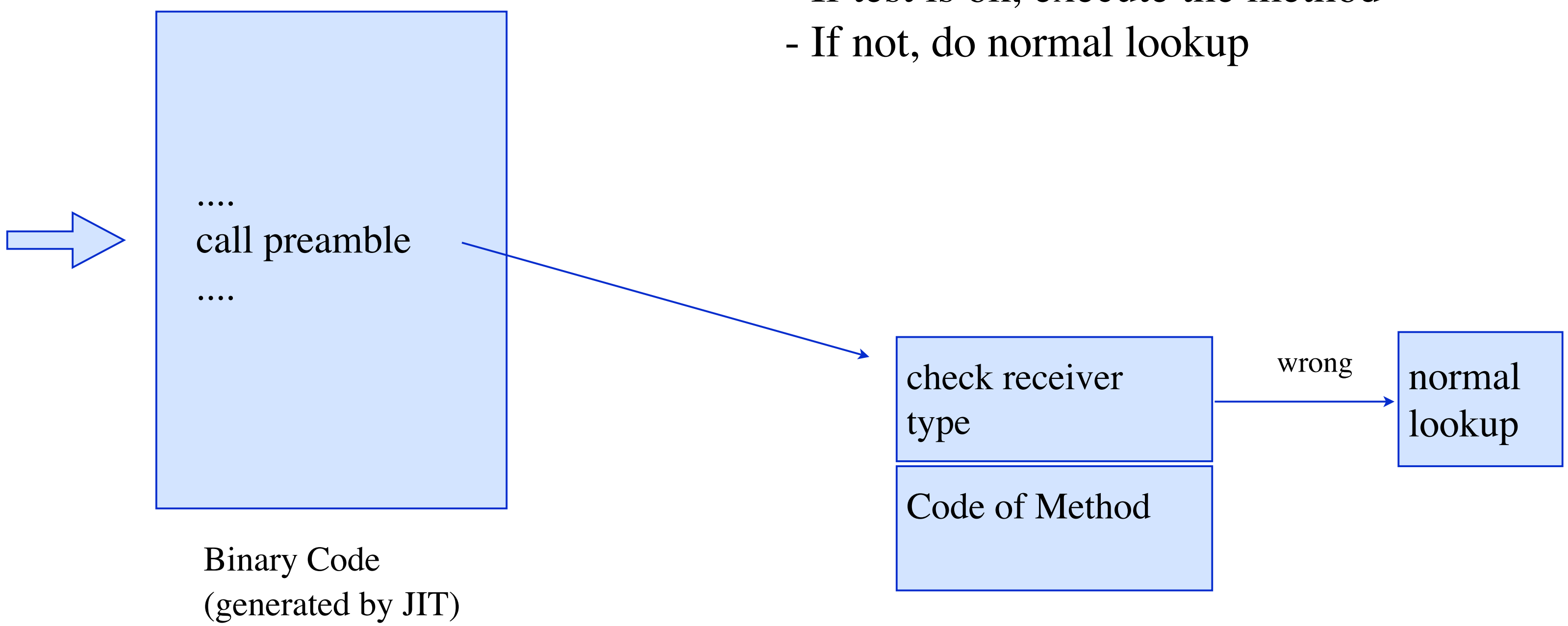
First Call:



Inline Cache: Second Execution

Second Call:

- we jump directly to the test
- If test is ok, execute the method
- If not, do normal lookup



Limitation of Simple Inline Caches

- Works nicely at places were only one method is called. "Monomorphic sends". >80%

- How to solve it for the rest?

- Polymorphic sends (<15%)
  - <10 different classes

- Megamophic sends (<5%)
  - >10 different classes

Example Polymorphic Send

- This example is Polymorphic.

```
array := #(1 1.5 2 2.5 3 3.5).

array collect: [:each | each + 1]
```

- Two classes: Integer and Float

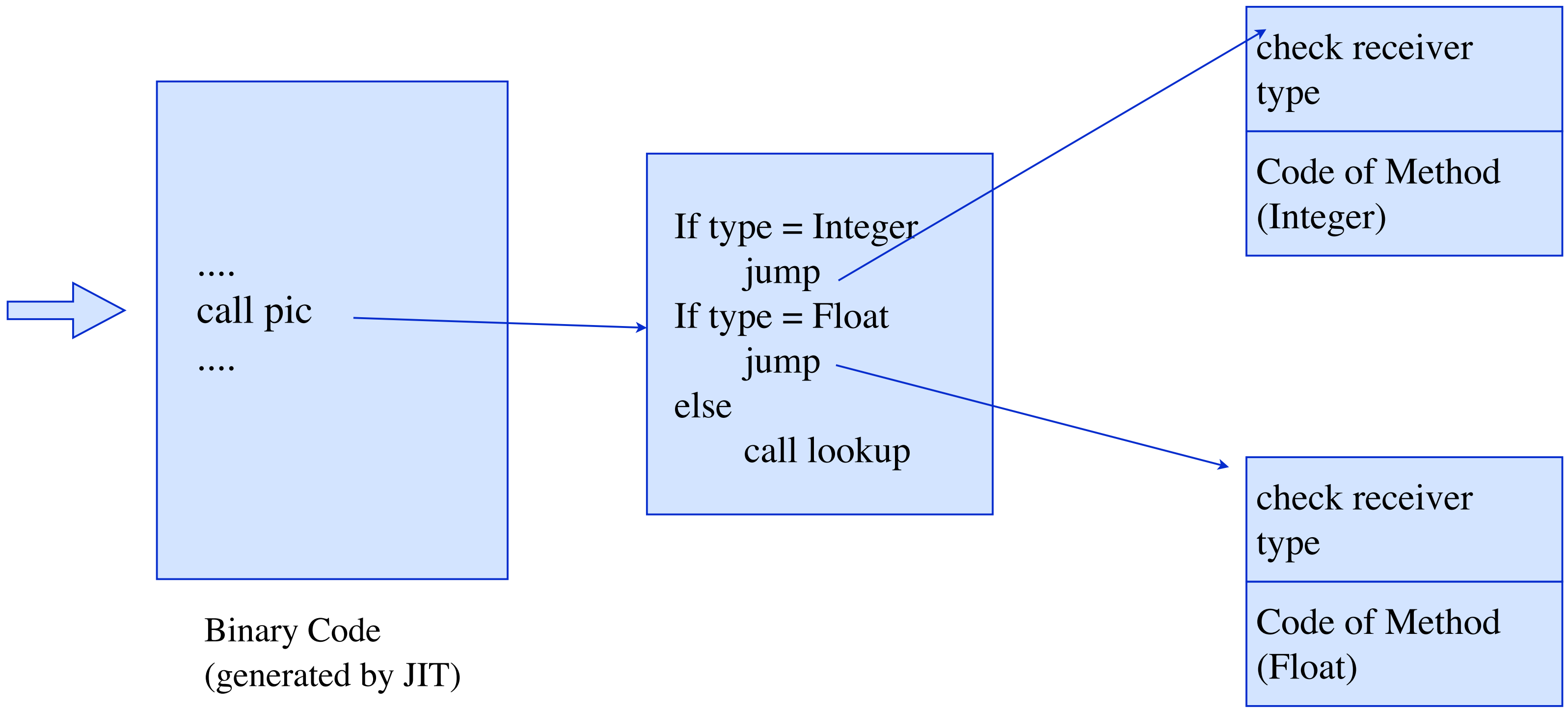
- Inline cache will fail at every send
- It will be slower than doing just a lookup!

Polymorphic Inline Caches

- Solution: When inline cache fails, build up a PIC

- Basic idea:
  - For each receiver, remember the method found
  - Generate stub to call the correct method

PIC



....
call pic
....
Binary Code
(generated by JIT)
If type = Integer
jump
If type = Float
jump
else
call lookup
check receiver
type
Code of Method
(Integer)
check receiver
type
Code of Method
(Float)

PIC

- PICs solve the problem of Polymorphic sends
- Three steps:
  - Normal Lookup / generate IC
  - IC lookup, if fail: build PIC
  - PIC lookup
- PICs grow to a fixed size (~10)
- After that: replace entries

- Megamorphic sends:
  - Will be slow
  - Some systems detect them and disable caching

Optimizations: Lessons Learned

- We have seen
  - Inline Caches
  - Polymorphic Inline Caches

- Next: Beyond Just-In-Time

Beyond JIT: Dynamic Optimization

- Just-In-Time == Not-Enough-Time
  - No complex optimization possible
  - No whole-program-optimization

- We want to do real optimizations!

Excursion: Optimizations

- Or: Why is a modern compiler so slow?

- There is a lot to do to generate good code!
  - Transformation in a good intermediate form (SSA)
  - Many different optimization passes
    - Constant subexpression elimination (CSE)
    - Dead code elimination
    - Inlining
  - Register allocation
  - Instruction selection

State of the Art: HotSpot et. al.

- Pioneered in Self
- Use multiple compilers
  - Fast but bad code
  - Slow but good code

- Only invest time were it really pays off
- Here we can invest some more

- Problem: Very complicated, huge warmup, lots of Memory
- Examples: Self, Java Hotspot, Jikes

PIC Data for Inlining

- Use type information from PIC for specialisation
- Example: Class Point

```
...
lookup(rec, sel)
....
```

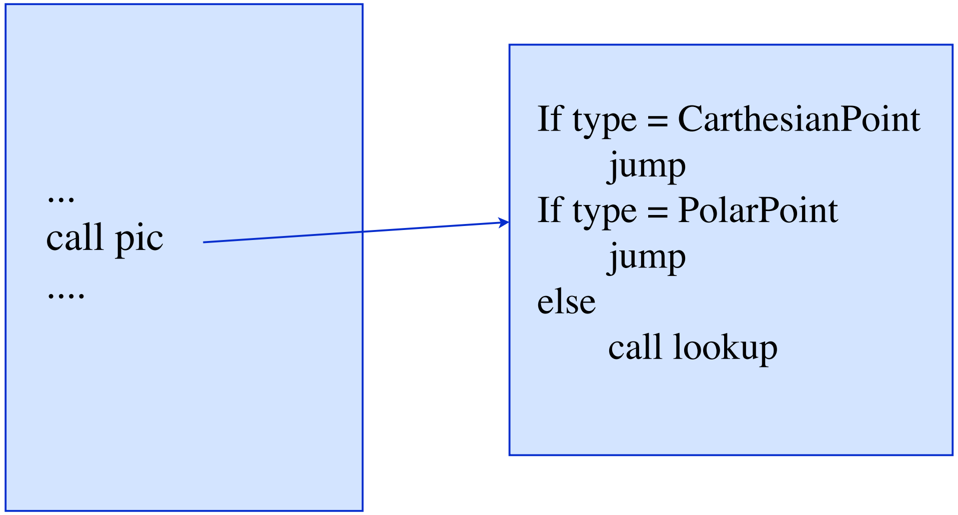
Binary Code
(generated by JIT)

```
CarthesianPoint>>x
   ^x
```

```
PolarPoint>>x
   “compute x from rho and theta”
```

Example Inlining

- The PIC will be build



Binary Code
(generated by JIT)

The PIC contains
type Information!

Example Inlining

- We can inline code for all known cases

```
...
if type = cartesian point
     result ← receiver.x
else if type = polar point
     result ← receiver.rho * cos(receiver.theta)
else call lookup
...
```

Binary Code
(generated by JIT)

End

- What is a VM
- Overview about bytecode interpreter / compiler
- Inline Caching / PICs
- Dynamic Optimization

- Questions?

Literature

- Smith/Nair: Virtual Machines (Morgan Kaufman August 2005). Looks quite good!

- For PICs:
  - Urs Hölzle, Craig Chambers, David Ungar: Optimizing Dynamically-Typed Object-Oriented Languages With Polymorphic Inline Caches
  - Urs Hoelzle. "Adaptive Optimization for Self: Reconciling High Performance with Exploratory Programming." Ph.D. thesis, Computer Science Department, Stanford University, August 1994.