JVM Backend and Optimizer in Scala 2.12

Lukas Rytz, Scala Team @ Typesafe

Scala 2.12 on one Slide

- Move to Java 8: enjoy new VM and library features
  - Interop for functions: source and bytecode
  - Make use of default methods
  - Interop with Java (parallel) streams
- New optimizer
  - Configurable, more reliable, better diagnostics
  - Fewer bugs (inline trait methods)

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Agenda

- Move to Java 8
  - Interop for functions: source and bytecode
  - Default methods for compiling traits
- New backend
  - Simplified compilation pipeline
  - New optimizer: capabilities and constraints

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Function Interoperability

- Source code: interoperability in both directions

```
// Scala code:
new Thread(() => println("hi!")).run()

// Java code:
scalaCollection.foreach(x -> println(x));
```

- Bytecode: generate the same as Java

Use Java APIs

- No explicit function types in Java 8
  - Lambda syntax for *functional (SAM) interfaces*

```
interface Runnable { void run(); }
class Thread { Thread(Runnable r) }
new Thread(() -> println("hi")).run();
```

Use Java APIs

- No explicit function types in Java 8
  - Lambda syntax for *functional (SAM) interfaces*

```
interface Runnable { void run(); }
class Thread { Thread(Runnable r) }
new Thread(() -> println("hi")).run();
```

- SAM support in Scala 2.12
  - Try it with 2.11.6 `-Xexperimental`

```
new Thread(() => println("hi!")).run()
```

SAMs in Scala

```
// Java example:
stream.filter(s -> s.startsWith("c"))
      .map(String::toUpperCase)
      .sorted()
      .forEach(System.out::println);
```

SAMs in Scala

@adriaanm

```
// Java example:
stream.filter(s -> s.startsWith("c"))
      .map(String::toUpperCase)
      .sorted()
      .forEach(System.out::println);
```

```
Welcome to Scala version 2.11.6 -Xexperimental
scala> import java.util.stream.Stream
scala> def s = Stream of ("a1","a2","b1","c2","c1")
scala> s.filter(s => s.startsWith("c"))
        .map(_.toUpperCase).sorted.forEach(println)
C1
C2
```

Write Java APIs

@retronym

- Scala 2.12: `FunctionN` are functional interfaces

```
// Java code:
scalaCollection.foreach(x -> println(x));
```

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Write Java APIs

@retronym

- Scala 2.12: `FunctionN` are functional interfaces

```
// Java code:
scalaCollection.foreach(x -> println(x));
```

- Scala 2.11: compatibility layer (*)
  - Defines `JFunctionN` functional interfaces

```
import static scala.compat.java8.JFunction.*;
scalaCollection.foreach(func(x -> println(x)));
```

(*) github.com/scala/scala-java8-compat

Bytecode: Scala 2.11

```
l.reduce((x, y) => x + y)
```

Bytecode: Scala 2.11

```
l.reduce((x, y) => x + y)
```

```
class anonfun$1 extends Function2 {
  def apply(x: Int, y: Int): Int = x + y
}

l.reduce(new anonfun$1())
```

Bytecode: Java 8

```
interface IIIFun { int apply(int x, int y); }
abstract class Test {
  abstract int reduce(IIIFun f);
  int test() { return reduce((x, y) -> x + y); }
}
```

Bytecode: Java 8

```
interface IIIFun { int apply(int x, int y); }
abstract class Test {
  abstract int reduce(IIIFun f);
  int test() { return reduce((x, y) -> x + y); }
}
```

```
private static int lambda$test$0(int x, int y) {
  return x + y;
}
return reduce(
  magicClosure("lambda$test$0", "IIIFun::apply"))
```

Bytecode: Java 8

```
interface IIIFun { int apply(int x, int y); }
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InvokeDynamic + LambdaMetaFactory

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Scala 2.11 with -Ydelambdafy:method

@Jameslry

```
l.reduce((x, y) => x + y)
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Scala 2.11 with -Ydelambdafy:method

@Jameslry

```
l.reduce((x, y) => x + y)
```

```
<static> def $anonfun$1(x: Int, y: Int): Int = x + y

class lambda$1 extends Function2 {
  def apply(x: Int, y: Int): Int = $anonfun$1(x, y)
}
l.reduce(new lambda$1())
```

Scala 2.11 with -Ydelambdafy:method

@Jamesilry

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l.reduce((x, y) => x + y)
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<static> def $anonfun$1(x: Int, y: Int): Int = x + y

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@retronym

2.12: InvokeDynamic + LambdaMetaFactory

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Why `InDy+LMF`

- No classfiles for functions – smaller JARs
- Let the JVM know what values are functions
    - Might lead to better optimizations
- Be a good JVM citizen

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- New backend
    - Simplified compilation pipeline
    - New optimizer: capabilities and constraints

Trait Compilation

```
trait F1[-T, +R] {
  def apply(v: T): R
  def compose[A](g: A => T): A => R = ...
}
```

```
interface F1 {
  def apply(v: Object): Object
  def compose(g: F1): F1
}
```

```
class F1$class {
  <static> def compose($this: F1, g: F1): F1 = ...
}
```

Trait Compilation

```
trait F1[-T, +R] {
  def apply(v: T): R
  def compose[A](g: A => T): A => R = ...
}
```

```
interface F1 {
  def apply(v: Object): Object
  def compose(g: F1): F1
}
```

Not a SAM interface!

```
class F1$class {
  <static> def compose($this: F1, g: F1): F1 = ...
}
```

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SAM `FunctionN` interfaces

- Not possible in Scala 2.11
  - Targets Java 1.6, no default methods
- Options for Scala 2.12
  - Write `scala.FunctionN` in Java
  - Special treatment for `FunctionN`
  - Use default methods to compile traits

Default Methods for Traits

- Write SAM interfaces in Scala
  - Better Java APIs in written Scala
- Binary compatibility: allow some changes to traits
  - Add a method to a trait without recompiling subclasses
- Status: performed a few experiments (*)

(*) github.com/lrytz/traits-default-methods
github.com/scala/scala-java8-compat
github.com/lampepfl/dotty

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Default Methods for Traits

- Simple solution: forwarders to implementation class

```
interface F1 {
  def apply(v: Object): Object
  default def compose(g: F1): F1 =
    F1$class.compose(this, g)
}
```

- Ambitious solution: no more implementation classes, use only defaults

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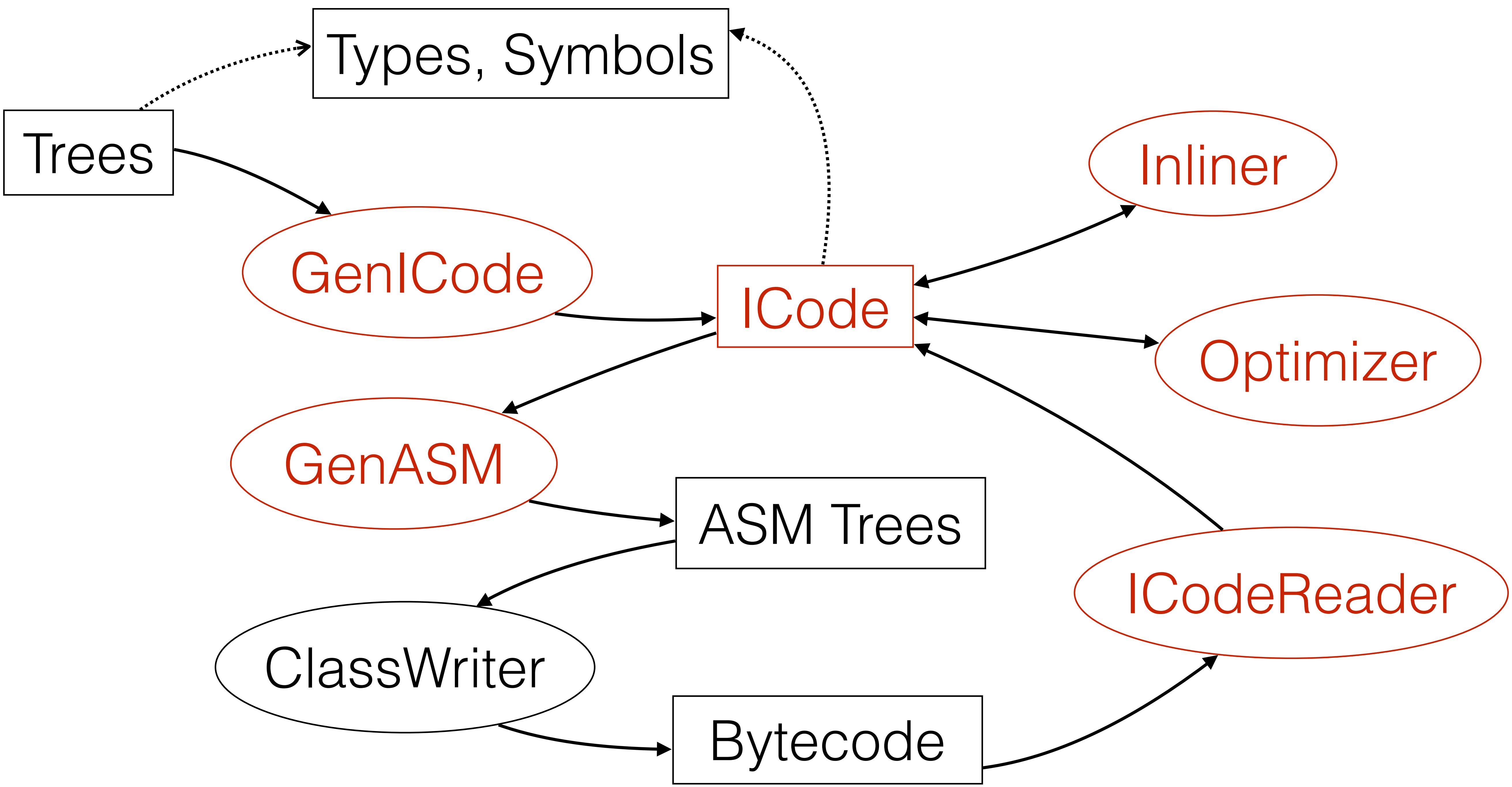
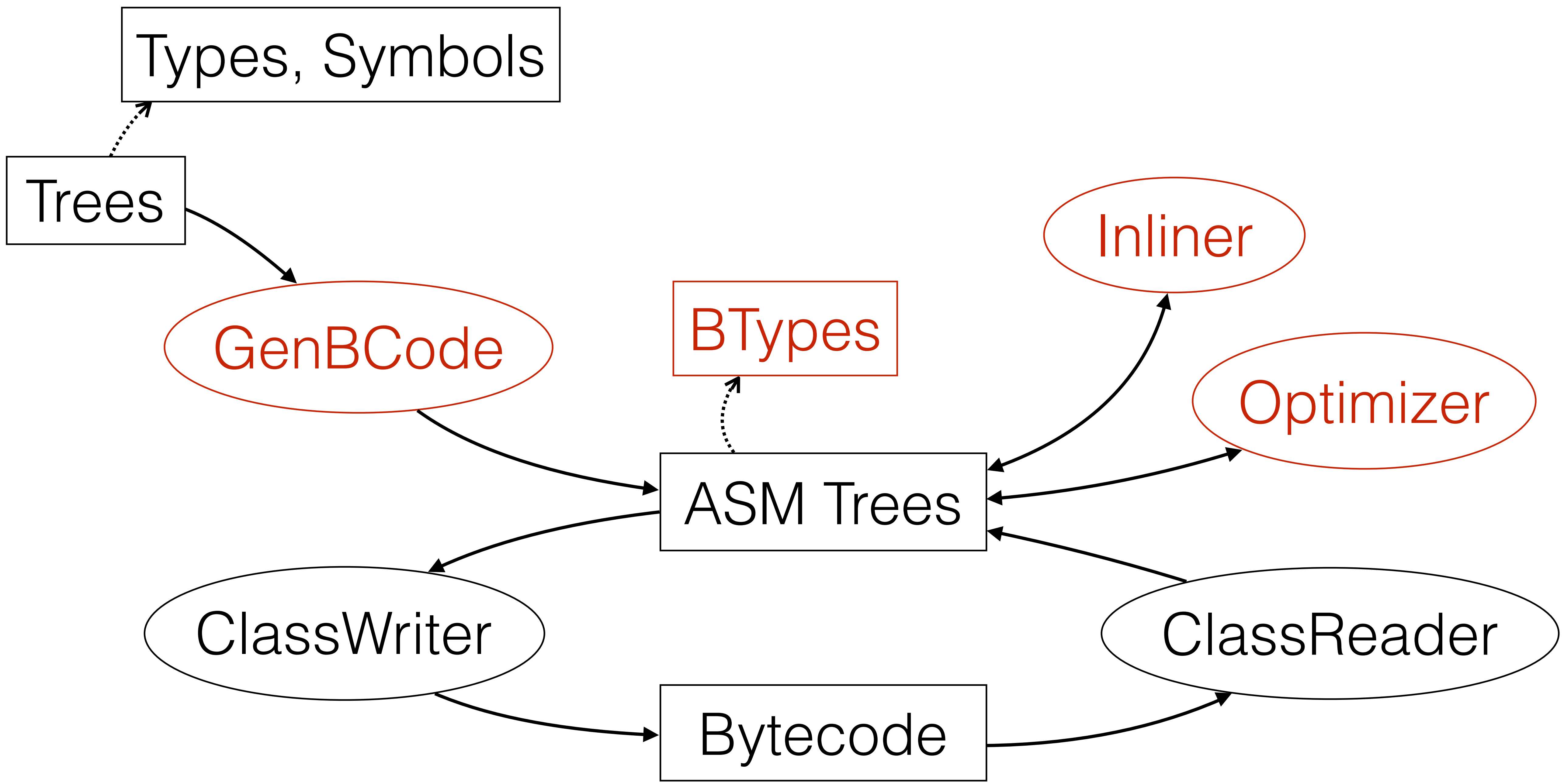
2.11 Backend: `GenASM`



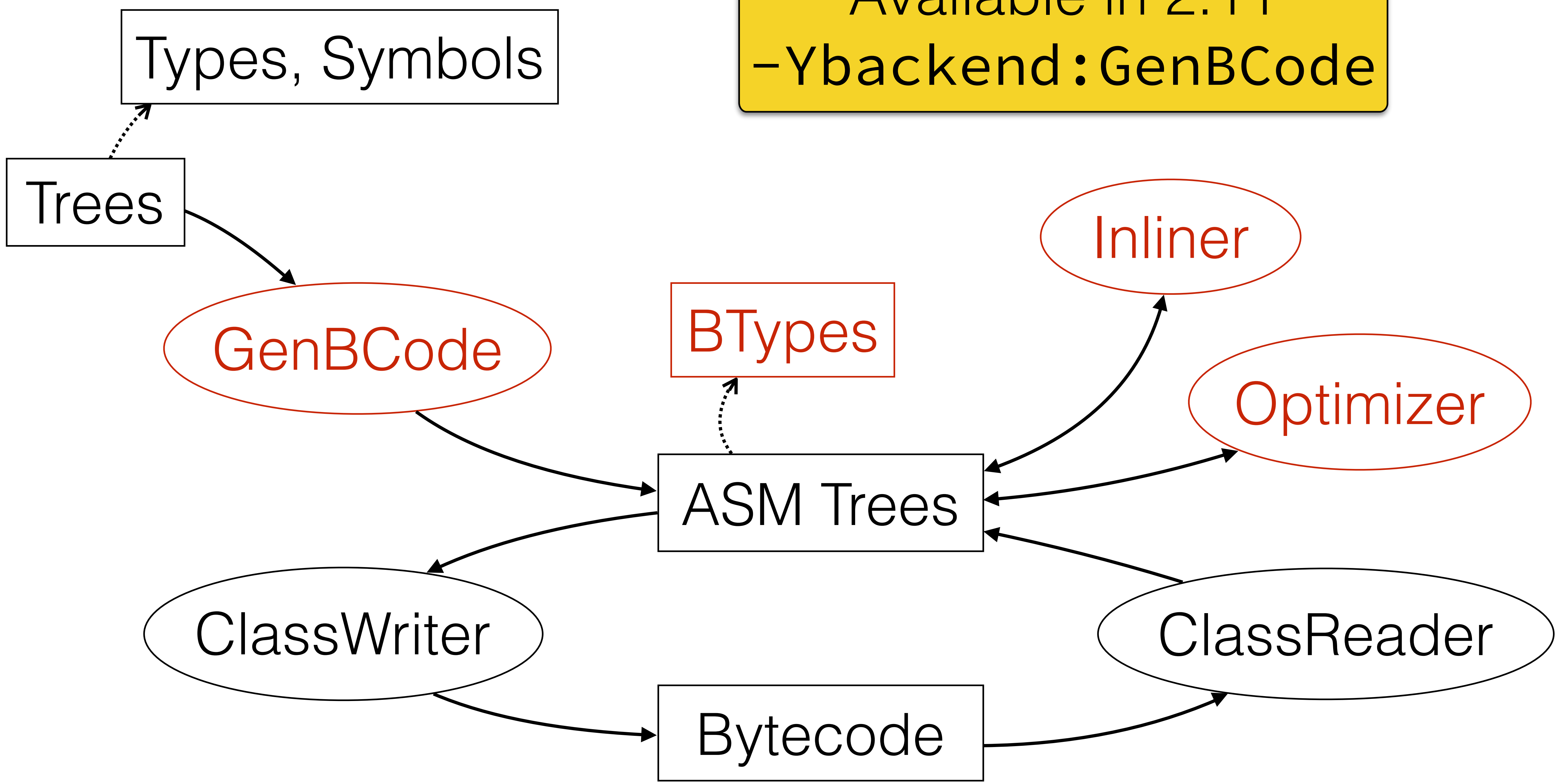
2.12 Backend: GenBCode

@magarciaEPFL



2.12 Backend: GenBCode

Available in 2.11
`-Ybackend:GenBCode`



New Backend

- Fewer components to maintain
- Thread-safe representation (ASM Trees + BTypes)
  - Parallelize classfile serialization, local optimizations
- Better platform to implement optimizations
  - ASM has built-in tools for code analysis
  - Fewer invariants (no explicit basic blocks)

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Optimizer in `GenBCode`

- Original prototype by @magarciaEPFL
- Work in progress
  - ↣ Optimizer being added to `GenBCode` backend under 2.11.x
  - ↣ Local optimizations in 2.11.6
  - ↣ Inliner in 2.11.7
  - ↣ Future: allocation elimination, heuristics, ...
- Thorough testing

Optimizer Sub-Agenda

- Why do we need a compile-time optimizer?
- Features and roadmap
- Inherent limitations
- Distant future: a whole-program optimizer?

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Can we beat the JVM?

- The JVM is a powerful optimizing runtime
    - ↣ Run-time statistics available (counts, types)
- Fails to optimize certain common Scala patterns
- Goal: help out the JVM to do a great job
    - ↣ Avoid blind, premature "optimization"
        - ↣ Example: slowdown when inlining too much

Virtual Calls

```
class Range {
  def foreach(f: Int => Unit) = {
    while(..) { .. f.apply(i) .. }
  }
}




(1 to 10) foreach (x => foo)
(2 to 20) foreach (x => bar)
(3 to 30) foreach (x => baz)
```

Virtual Calls

```scala
class Range {
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Virtual call:

- Run-time type of `f` defines which code to run

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Virtual Calls

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}
```

Virtual call:

- Run-time type of `f` defines which code to run
- VM statistics: what types for `f` get here?
- JIT: skip lookup (with guard) if monomorphic

```
(1 to 10) foreach (x => foo)
(2 to 20) foreach (x => bar)
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```

Megamorphic Callsites

"The Inlining Problem" – coined by Cliff Click ①

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class Range {
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}
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① www.azulsystems.com/blog/cliff/2011-04-04-fixing-the-inlining-problem
See also: shipilev.net/blog/2015/black-magic-method-dispatch

Megamorphic Callsites

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class Range {
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- `f.apply` is hot, but megamorphic → not inlined by VM

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- `f.apply` is hot, but megamorphic → not inlined by VM
- Fix: inline `foreach` → copy of `f.apply` is monomorphic

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Megamorphic Callsites

"The Inlining Problem" – coined by Cliff Click ①

```
class Range {
  def foreach(f: Int => Unit) = {
    while(..) { .. f.apply(i) .. }
  }
}
```

- `f.apply` is hot, but megamorphic → not inlined by VM
- Fix: inline `foreach` → copy of `f.apply` is monomorphic
- Call to `foreach` typically not hot → not inlined by VM

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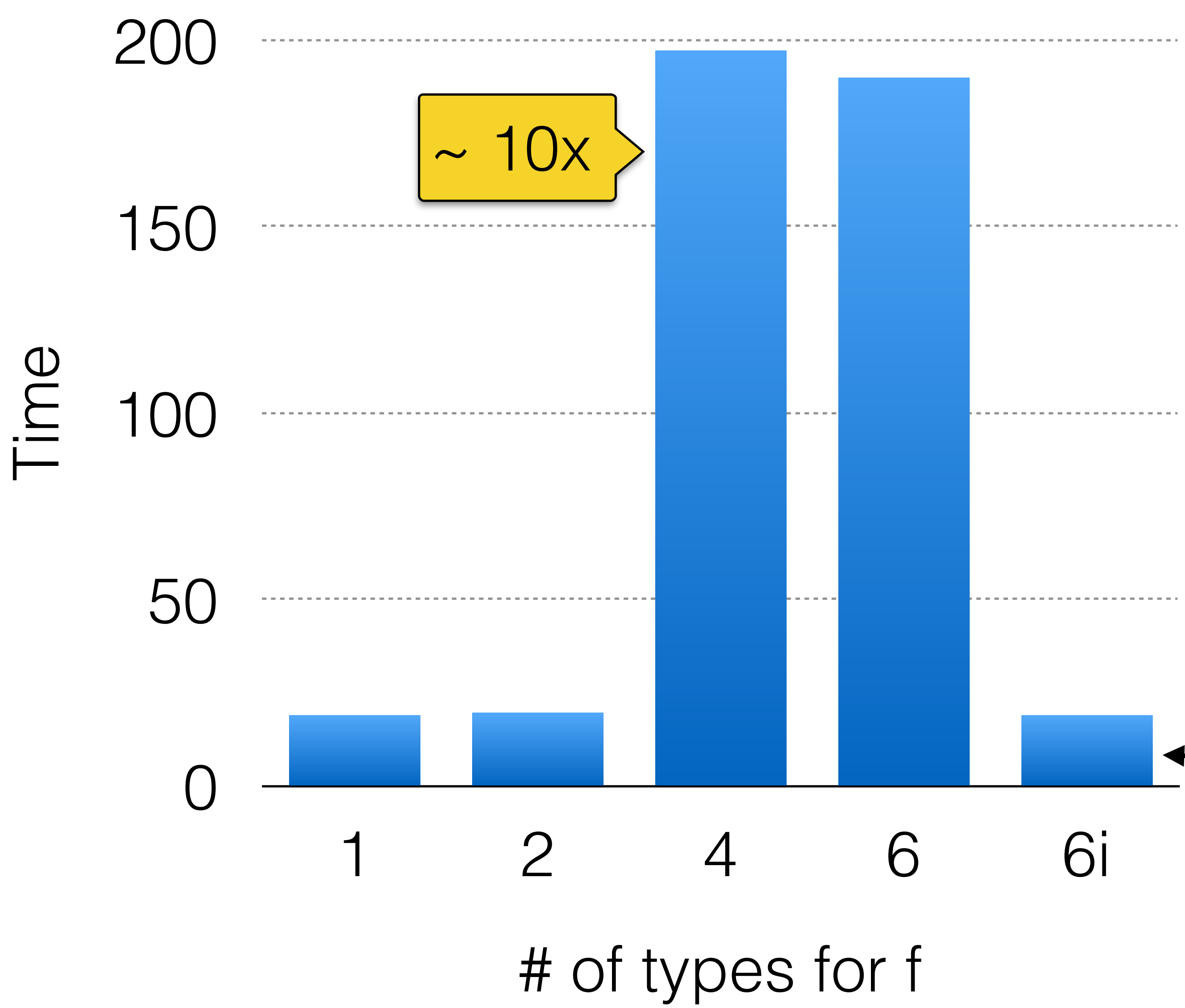
Megamorphic Callsites




```
while(..) {
  .. (x => foo).apply() ..
}
while(..) {
  .. (x => bar).apply() ..
}
...
```

github.com/lrytz/benchmarks

Captured Local

```scala
var r = 0
(1 to 10000) foreach { x => r += x }
```

```scala
val r = IntRef(0)
val f = new anonfun(r)
(1 to 10000) foreach f
```

```scala
class anonfun(r: IntRef) {
  def apply(x: Int) {
    r.elem += x
  }
}
```

Captured Local

```scala
var r = 0
(1 to 10000) foreach { x => r += x }
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```scala
val r = IntRef(0)
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(1 to 10000) foreach f
```

```scala
class anonfun(r: IntRef) {
  def apply(x: Int) {
    r.elem += x
  }
}
```

Slow

- Why? Not obvious..

Inlining

```
val r = IntRef(0)
val f = new anonfun(r)
(1 to 10000) foreach f
```

Inline `foreach` and function body

```
val r = IntRef(0)
val f = new anonfun(r)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Inlining

```
val r = IntRef(0)
val f = new anonfun(r)
(1 to 10000) foreach f
```

Inline `foreach` and function body

```
val r = IntRef(0)
val f = new anonfun(r)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Still slow (same as before)!

- Why? `IntRef`
- Escape analysis fails..

Help Out the JVM

```
val r = IntRef(0)
val f = new anonfun(r)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Eliminate the closure allocation

```
val r = IntRef(0)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

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Help Out the JVM

```
val r = IntRef(0)
val f = new anonfun(r)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Eliminate the closure allocation

```
val r = IntRef(0)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Fast! JVM escape analysis kicks in.

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Eliminate the IntRef?

```
val r = IntRef(0)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Local `var` instead of `IntRef`

```
var r = 0
var x = 0
while (x < 10000) {
  r += x
}
```

Eliminate the IntRef?

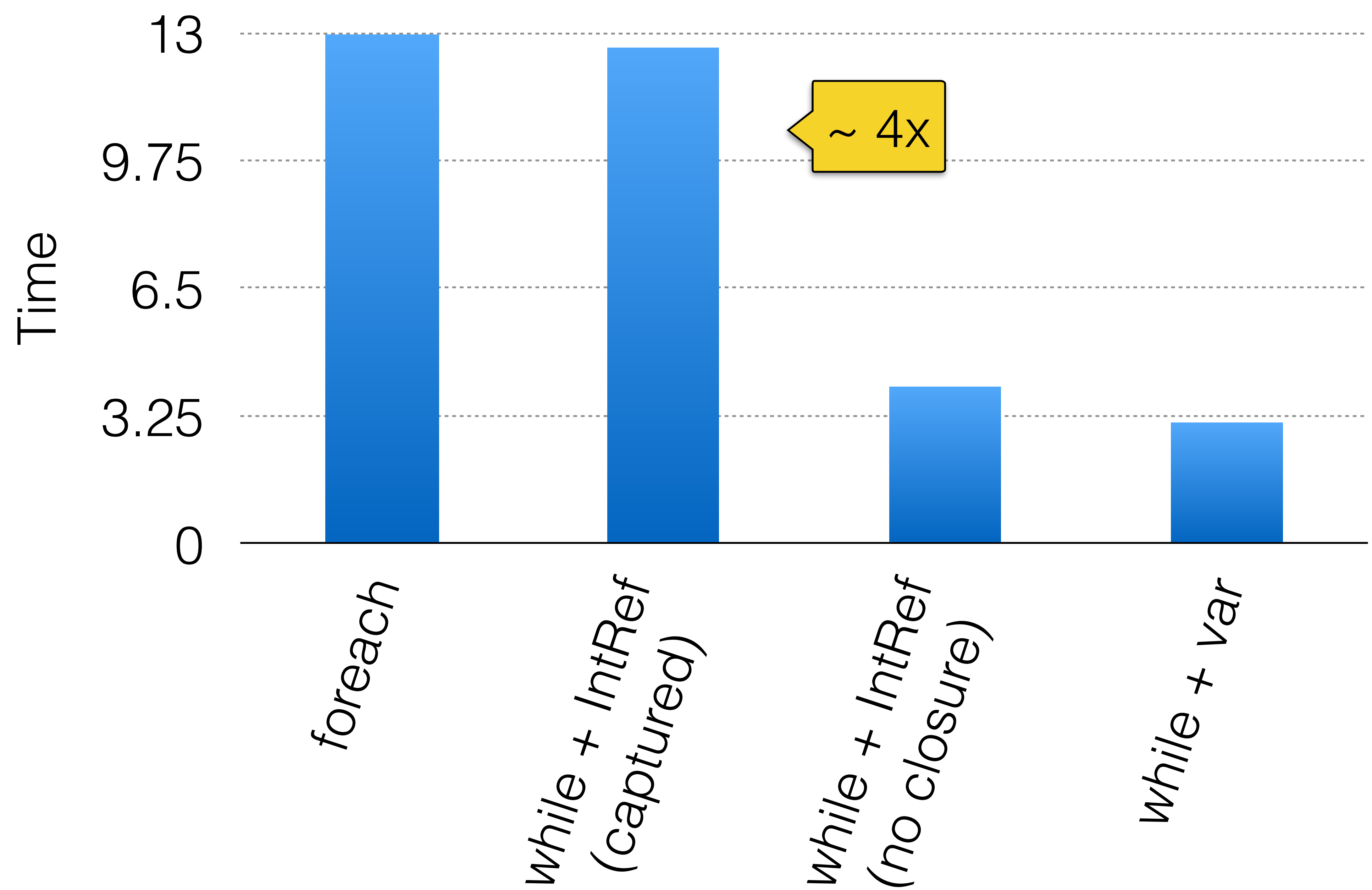
```
val r = IntRef(0)
var x = 0
while (x < 10000) {
  r.elem += x
}
```

Local `var` instead of `IntRef`

```
var r = 0
var x = 0
while (x < 10000) {
  r += x
}
```

Same as before!
JVM optimizes the IntRef just fine.

En Graphe



13
9.75
6.5
3.25
0
Time
~ 4x
foreach
while + IntRef (captured)
while + IntRef (no closure)
while + var

Summary

- Scala compiler can fix some known performance issues
    - New optimizer provides better abstractions to implement heuristics
- Need to be prudent and benchmark-driven

Optimizer Sub-Agenda

- Why do we need a compile-time optimizer?
- Features and roadmap
- Inherent limitations
- Distant future: a whole-program optimizer?

Features

- Some local optimizations in 2.11.6
  - Dead code elimination, simplify jumps
  - More to come. Goal: generate clean code
- Inliner in 2.11.7 (work is almost done)
- Thereafter
  - Eliminate allocations: closures, tuples, boxes
  - Testing, benchmarking, tuning heuristics

Inliner

- Transformation from bytecode to bytecode
- Clean call graph representation
  - ↣ Future-proof: experiment with heuristics
- Reliable and configurable error reporting
- Well tested
  - ↣ Community build
  - ↣ "Insane" mode: all-you-can-inline

Collaboration

- GitHub repo and issue tracker: scala-opt/scala
  - Keep track of plans and tasks
  - Plenty available: from "rewrite x efficiently" to "implement type analysis"
  - File new issues for bugs in the optimizer
- Questions and discussions
  - Compiler hacker's Gitter channel: scala/scala

Optimizer Sub-Agenda

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Binary Compatibility

- Inlining from a library enforces a specific version
  - ↣ All bets are off if the runtime classpath has a different version
- Problematic for library authors: forces specific versions for dependencies

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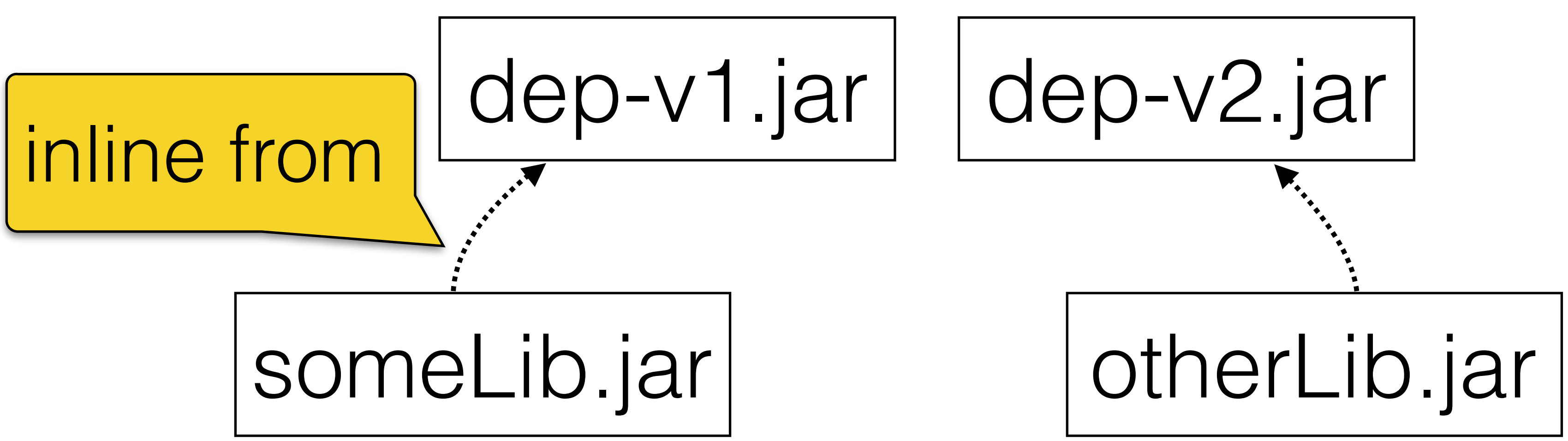

Binary Compatibility

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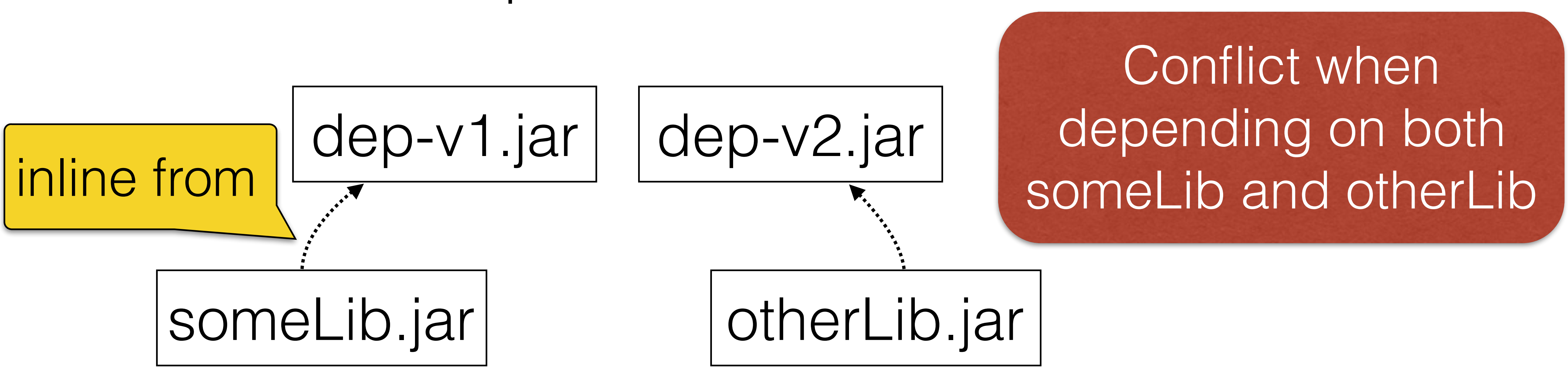

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Binary Compatibility

- Library authors: don't inline from the classpath
  - Harsh limitation: `Range.foreach` stays slow
- Deployed applications: optimize freely
  - Ensure same classpath at runtime
  - Consider building dependencies from source
- Future: safe but restricted cross-library inlining?

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Outlook: Global Optimizer

- Would solve the binary compatibility issues
  - Libraries are compiled without optimizations
  - Final program compilation optimizes everything
- Approach works successfully in Scala.js

Outlook: Global Optimizer

- More liberty under closed-world assumption
  - ↣ Eliminate unused (public) code
  - ↣ Global data flow analyses
  - ↣ Assume closed type hierarchies
- Challenges
  - ↣ Just classfiles? New IR (like Scala.js, TASTY)?
  - ↣ Support run-time reflection?

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Thank You!