Type-Safe Metaprogramming and Compilation Techniques for Optimizing High-Level Programs

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Type-Safe Metaprogramming and Compilation Techniques for Optimizing High-Level Programs

Clever Techniques for **Optimizing High-Level Programs**

High-Level Programming Example

What does this program do?

```
persons.filter(_.age > 7).groupBy(_.firstName)
```

Low-Level Programming Example

What does this program do?

```
var cur = persons
val groups = mutable.Map.empty[String, mutable.Buffer[Person]]
while (cur.nonEmpty) {
  val p = cur.head
  cur = cur.tail
  if (p.age > 7) {
    var gpeOpt = groups.get(p.firstName)
    val gpe = gpeOpt match {
      case None =>
        val buf = mutable.Buffer.empty[Person]
        groups(p.firstName) = buf
        buf
      case Some(buf) =>
        buf
    }
    buf += p
  }
}
groups
```

Dilemma of the Modern Programmer

- High-level code better for maintainability & correctness

  Important for productivity, flexibility
- Low-level code better for performance

⇒ Programmers often write lower level code;

harder to read, debug, evolve...

What if we did not have to choose?

compilers *should* do the rewriting for us automatically

But compilers are not smart enough

Making high-level programs efficient

Alternative 1:

Make compilers smarter, better at functional code

⇒ ***new compilation techniques***

Alternative 2:

Give users more control on how programs are compiled

safely teach the compiler how to optimize common patterns

⇒ ***new metaprogramming techniques***

Two Philosophies

Compilation techniques

not enough on their own

Metaprogramming techniques

not enough on their own

my work: synergy of **advances**

in both approaches

Metaprogramming

Metaprogramming – Definition + Motivation

Metaprogramming =

writing programs that manipulate programs

Manipulate = generate, analyse, transform, evaluate

Ubiquitous: code generation, DSL implementation, compile-time macros, program analysis, optimization and compilation, boilerplate generation, multi-stage programming...

Hard to get right — reserved for experts

→ bad user experience, security vulnerabilities, etc.

Metaprogramming – Problem

Metaprogramming is often **error-prone**

Example in the wild: Scala 2 macros

useful for optimizing a library; e.g., parser combinators

Very hard to make a macro robust & to debug it

```
[error] Workspace/scala-js-book/scalatexApi/src/main/scala/scalatex/stages/Parser.scala:16: type mismatch;
[error]  found   : shapeless.::[Int,shapeless.::[scalatex.stages.Ast.Block,shapeless.HNil]]
[error]  required: scalatex.stages.Ast.Block
[error]     new Parser(input, offset).Body.run().get
[error]                         ^
[error] Workspace/scala-js-book/scalatexApi/src/main/scala/scalatex/stages/Parser.scala:60: overloaded method value apply with alts:
[error]   [I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, RR](f: (I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, scalatex.stages.Ast.Block.Text, scalatex.stages.Ast.Chain, Int, scalatex.stages.Ast.Block) => RR)(implicit j: org.parboiled2.support.ActionOps.SJoin[shapeless.::[I,shapeless.::[J,shapeless.::[K,shapeless.::[L, ...
```

Metaprogramming errors are **not nice**

Squid:
Type-Safe Metaprogramming
& Compilation Framework

The Squid Framework

Squid – **Sc**ala **Qu**oted **D**SLs github.com/epfldata/squid ★ 154

Extension of Scala via compile-time macros

Type-safe metaprogramming via quasiquotes [POPL 2018]

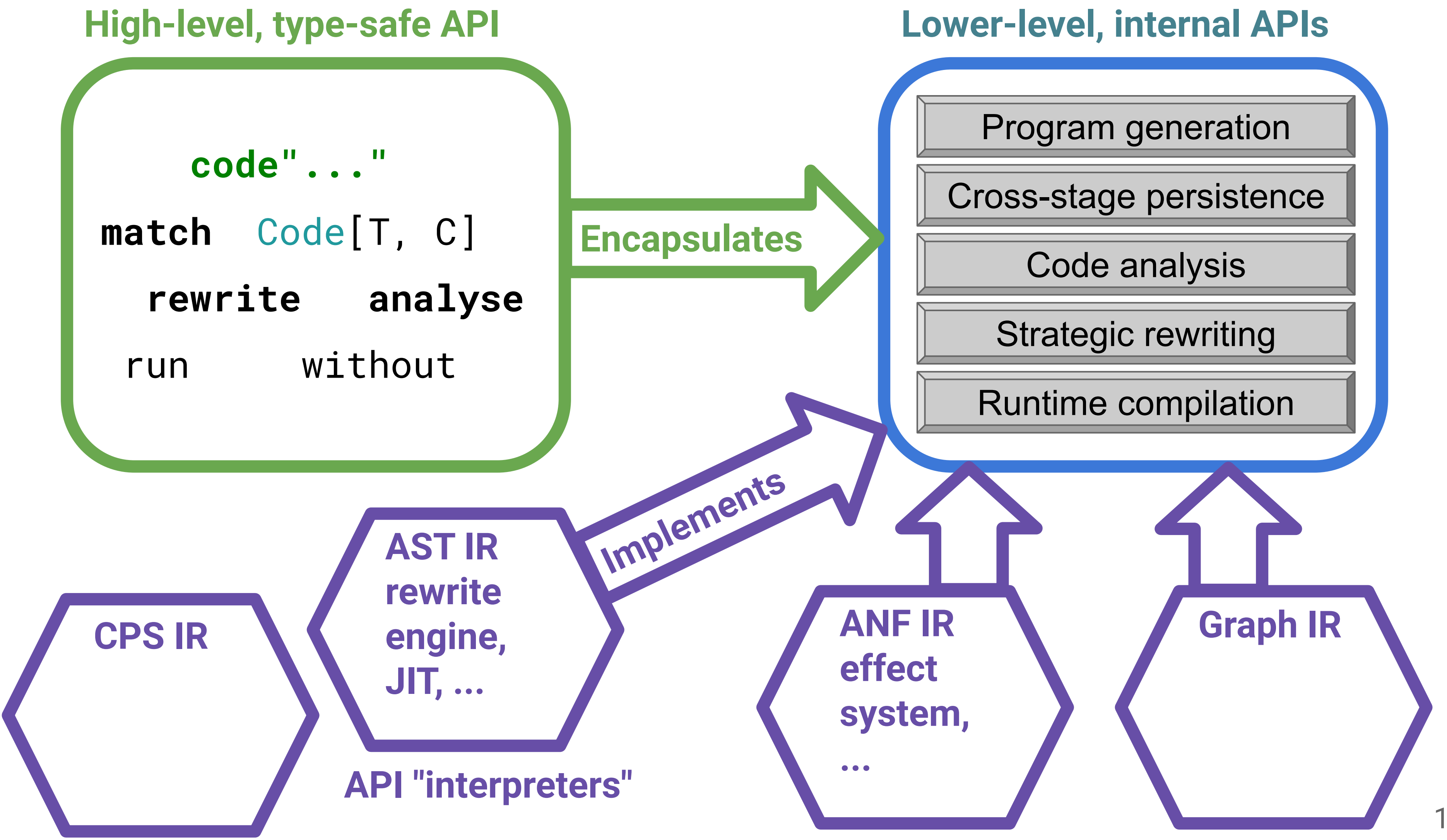
Ensures metaprograms are free of runtime type errors:

no type mismatches ; *no* unbound variables

Extensible optimizing compiler framework [Scala 2017]

⇒ both aspects work together [GPCE 2017, Best Paper]

The Squid Framework — Architecture



High-level, type-safe API

Lower-level, internal APIs

`code"..."`

match `Code[T, C]`

rewrite **analyse**

run without

Encapsulates

- Program generation
- Cross-stage persistence
- Code analysis
- Strategic rewriting
- Runtime compilation

Implements

CPS IR

AST IR rewrite engine, JIT, ...

ANF IR effect system, ...

Graph IR

API "interpreters"

Type-Safe Metaprogramming: Quasiquotation

Terminology

Quotation

“a group of words taken from a text”

Quasiquotation

“a group of *x* taken from a text” where *x* = “words”

Quasiquotation in programming (e.g. Scala, Haskell, ...)

```
val x = "words" ;  s"a group of $x taken from a text"
```

In this work: *code* quasiquotation for metaprogramming

```
val lsc = code"List(1,2,3)" ;  code"$lsc.map(x => x + 1)"
```

Two Flavors of (code) Quasiquotes

Analytic Quasiquotes Lisp, Scala, F#, Template Haskell…

Pioneered by Lisp – treat *code as data* and *data as code*

Limitation: metaprogramming is hard

code evaluation raises unbound variables errors; type mismatches…

```
code"max(x,true)".run  // runtime crash!
```

Statically-Typed Quasiquotes MetaOCaml, F#, Template Haskell…

Appeared in context of multi-stage programming (MSP, or *staging*)

Static guarantee: generated programs are well-typed

```
code"max(x,0)" // ill-typed      code"max(0,1)" : Code[Int]
  code"(x:Int) => ${ code"x".run; code"x" }"  : Code[Int => Int]
```

oops!

Limitation: *purely-generative* – generated code is a black box!

Squid Quasiquotes

Statically-typed quasiquotes, of type `Code[Type, Context]`

```
val c0 = code"(x: Int) => x * 2 + 1"
c0 : Code[Int => Int, Any]
```

Code evaluation

```
code"$c0(3)".run  →  7
```

First-class variables

```
val v = Variable[Int]  //  of type  Variable[Int]
val c1 = code"($v: Int) => $v * 2 + 1"  //  ==  c0
```

Free variables and contexts

Variable dependencies are statically tracked

```
val v = Variable[String]
val open = code"$v * 2 + 1" : Code[Int, v.Ctx]
open.run // type error: "Cannot prove that v.Ctx =:= Any"

( code"val $v = 3; $open" : Code[Int, Any] ).run  →  7
```

Multiple free variables

```
val w = Variable[Int]
val cde = code"$v * $w" : Code[String, v.Ctx & w.Ctx]
```

Quasiquotes for Pattern Matching

```
val p = code"Some(2 + 2)"
```

Pattern matching

```
p match {
  case code"Some($v)" =>  v
}
```

```
→ code"2 + 2"
```

Application Example:

Polymorphic but Efficient Linear Algebra Library

Application: polymorphic linear algebra library

Many data analytics tasks boil down to linear algebra

But different problems use different representations/types

$$f(x) = \begin{bmatrix} 0 & 0 & 1 & x+3 \\ 8 & 0 & 2x-1 & 6 \\ 0 & 3x+3 & 0 & 0 \\ 0 & 0 & x & 0 \end{bmatrix}^2 = \begin{bmatrix} 0 & 3x+3 & x^2+3x & 0 \\ 0 & 6x^2+3x-3 & 6x+8 & 8x+24 \\ 24x+24 & 0 & 6x^2+3x-3 & 18x+18 \\ 0 & 3x^2+3x & 0 & 0 \end{bmatrix}$$

$$f'(x) = \begin{bmatrix} 0 & 3 & 2x+3 & 0 \\ 0 & 12x+3 & 6 & 8 \\ 24 & 0 & 12x+3 & 18 \\ 0 & 6x+3 & 0 & 0 \end{bmatrix} \quad f(2) = \begin{bmatrix} 0 & 9 & 10 & 0 \\ 0 & 27 & 20 & 40 \\ 72 & 0 & 27 & 54 \\ 0 & 18 & 0 & 0 \end{bmatrix} \quad f'(2) = \begin{bmatrix} 0 & 3 & 7 & 0 \\ 0 & 27 & 6 & 8 \\ 24 & 0 & 27 & 18 \\ 0 & 15 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 \triangleright 0 & 0 \triangleright 0 & 1 \triangleright 0 & 5 \triangleright 1 \\ 8 \triangleright 0 & 0 \triangleright 0 & 3 \triangleright 2 & 6 \triangleright 0 \\ 0 \triangleright 0 & 9 \triangleright 3 & 0 \triangleright 0 & 0 \triangleright 0 \\ 0 \triangleright 0 & 0 \triangleright 0 & 2 \triangleright 1 & 0 \triangleright 0 \end{bmatrix} \otimes \begin{bmatrix} 0 \triangleright 0 & 0 \triangleright 0 & 1 \triangleright 0 & 5 \triangleright 1 \\ 8 \triangleright 0 & 0 \triangleright 0 & 3 \triangleright 2 & 6 \triangleright 0 \\ 0 \triangleright 0 & 9 \triangleright 3 & 0 \triangleright 0 & 0 \triangleright 0 \\ 0 \triangleright 0 & 0 \triangleright 0 & 2 \triangleright 1 & 0 \triangleright 0 \end{bmatrix} = \begin{bmatrix} 0 \triangleright 0 & 9 \triangleright 3 & 10 \triangleright 7 & 0 \triangleright 0 \\ 0 \triangleright 0 & 27 \triangleright 27 & 20 \triangleright 6 & 40 \triangleright 8 \\ 72 \triangleright 24 & 0 \triangleright 0 & 27 \triangleright 27 & 54 \triangleright 18 \\ 0 \triangleright 0 & 18 \triangleright 15 & 0 \triangleright 0 & 0 \triangleright 0 \end{bmatrix}$$

Application: polymorphic linear algebra library

In practice, each workload uses a specialized implementation

→ duplicated work

Idea: make a *maximally-polymorphic*, reusable library

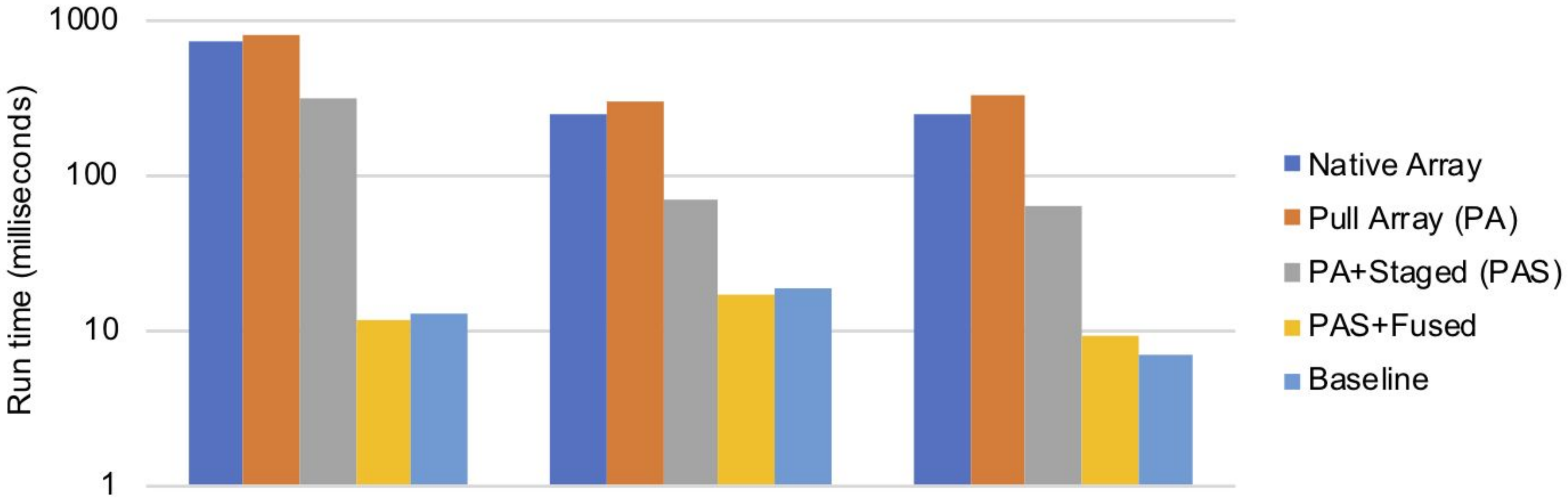
And remove overhead using Squid metaprogramming

tagless-final + quoted code matching

Application: polymorphic linear algebra library

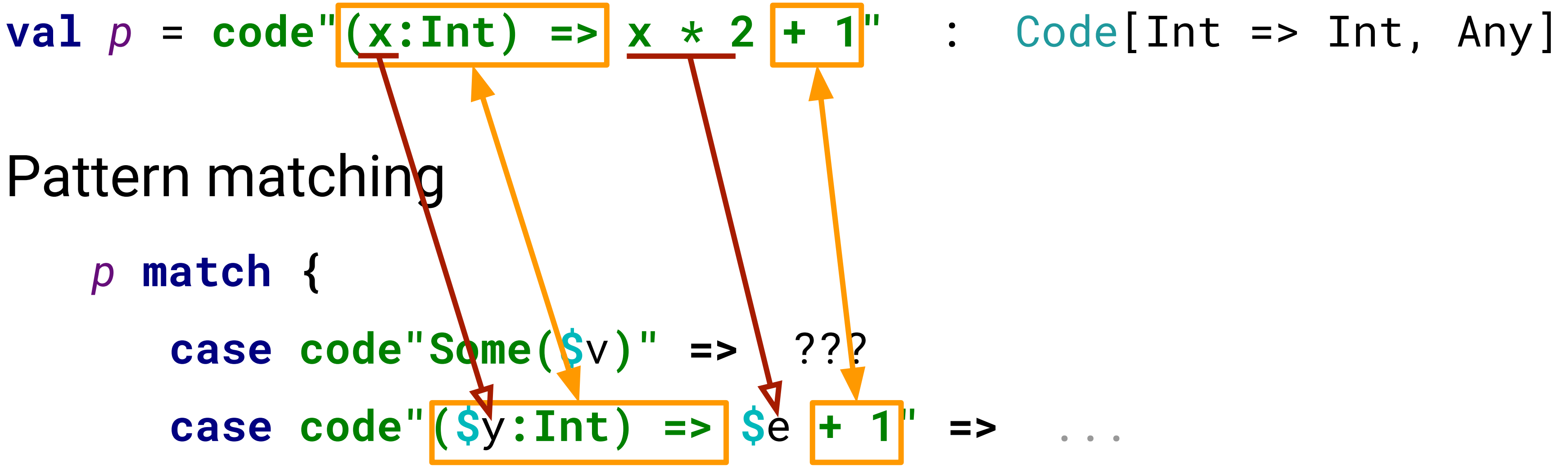
Polymorphism actually helps generate and optimize programs!

⇒ PILATUS, Squid-based linear algebra library [ECOOP 2019]



Type-Safe Metaprogramming: Dealing with scopes/contexts

Quasiquotes for Pattern Matching



```
val p = code"(x:Int) => x * 2 + 1"   :  Code[Int => Int, Any]
```

Pattern matching

```
    p match {
        case code"Some($v)" => ???
        case code"($y:Int) => $e + 1" =>  ...
          e : Code[Int, y.Ctx]  ==   code"$y * 2"
          code"val $y = 3; $e"  :  Code[Int, Any]
                                ==  code"val x = 3; x * 2"
          val c = code"(x: Int, $y: Int) => $e"
          c → code"(x_0: Int, x_1: Int) => x_1 * 2"
    }
```

Context weakening and strengthening

Scala subtyping lattice: top is `Any`; bottom is `Nothing`

Context weakening

```
              C & D  <:  D  <:  Any
   Code[T, Any] <: Code[T, D] <: Code[T, C & D]
```

(Based on variance: `class Code[+T,-C]`)

Context strengthening: `c.without(v)` tests whether `v` free in `c`

```
val cde1: Code[String, v.Ctx & w.Ctx] = code"$v * $w"
cde1.without(w) : Option[Code[String, v.Ctx]]  →  None
val cde2: Code[String, v.Ctx & w.Ctx] = code"$v * 123"
cde2.without(w) : Option[Code[String, v.Ctx]]  →  Some(cde2)
```

Advanced example: binding order manipulation

```
reverseBindingsOrder(code"val a = 1; val b = 2; val c = 3; a + b + c")
                == Some(code"val c = 3; val b = 2; val a = 1; a + b + c")
```

Possible thanks to Scala's advanced type system:

```
def reverseBindingsOrder[T, C](p: Code[T, C]): Option[Code[T, C]] = {
 go(p, [A, B] => identity)
 def go[T, C](p: Code[T, C], k: [A, B] => Code[A, B & C] => Code[A, B & C])
   : Option[Code[T,C]]
   = p match {
        case code"val $v: Int = $init; $body" =>
          go(body, [S, D] => (cde: Code[S, D & C & v.Ctx]) =>
                        code"val $v = $init; ${ k[S, D & v.Ctx](cde) }"
          ).flatMap(b => b.without(v).toList)
        case expr => Some(k(expr)) }
}
```

Term rewriting

Rewrite entire program fragment bottom-up

```
pgrm rewrite {
  case code"($ls: List[$ta]).map($f).map($g)"
    => code"$ls.map($g.compose($f))" }
```

Primitive `abort()` for when rewriting turns out impossible

```
  pgrm rewrite { case code"..."  =>  ... abort() ... ... }
```

Still ensures context safety

Various transformation strategies
    (top-down, bottom-up, fixed-point, speculative)

Usage example: list maximum

Simple program – list maximum or default value

```
def maxOr(xs: List[Int], default: Int): Int =
  xs.foldLeft(None) {
    (acc, x) => Some( acc.fold(x)(y => max(x,y)) )
  }.getOrElse(default)
```

```
Some(a).fold(d)(f) == f(a)
None   .fold(d)(f) == d
List(1,2,3,4).foldLeft(z)(f) == f(f(f(f(z,1),2),3),4)
```

Usage example: list maximum

More efficient imperative version:

```
def maxOr(xs: List[Int], default: Int): Int = {
  var cur = xs
  var acc_val = 0
  var acc_isdef = false
  while (cur.nonEmpty) {
    val x = cur.head
    cur = cur.tail
    if (acc_isdef) { acc_val = max(x, acc_val) }
    else { acc_val = x }
    acc_isdef = true  }
  if (acc_isdef) acc_val else default  }
```

Usage example: flatten variable of option type

```
object Opt extends Transformer with BottomUp with FixedPoint {
 def apply[T,C](pgrm: Code[T,C]): Code[T,C] = pgrm match {
   case code"($ls: List[$t0]).foldLeft[$t1]($z)($f)" =>
     code""" var cur = $ls; var res = $z;
             while (cur.nonEmpty) { val e = cur.head;
               cur = cur.tail; res = $f(res, e) }
             res """
   case code"($opt:Option[$t0]).getOrElse($e)" =>
     code"$opt.fold($e)(identity)"
   case code"None.fold[$tr]($z)($e)" => z
   case code"Some[$t0]($v).fold[$tr]($z)($f)" => code"$f($v)"
```

Usage example: flatten variable of option type

```
object Opt extends Transformer with BottomUp with FixedPoint {
 def apply[T,C](pgrm: Code[T,C]): Code[T,C] = pgrm match {
   case code"($ls: List[$t0]).foldLeft[$t1]($z)($f)" =>
     code""" var
             whi
               cu
             res
   case code"($opt:Opt          t0]).getOrElse($e)" =>
     code"$opt.fold($e)(identity)"
   case code"None.fold[$tr]($z)($e)" => z
   case code"Some[$t0]($v).fold[$tr]($z)($f)" => code"$f($v)"
```

if mistake (eg: `fold(identity)($e)`)

→ type error at compile time

Usage example: flatten variable of option type

Tricky part of `def apply[T,C](pgrm: Code[T,C]): Code[T,C]`

```
 ...
 case code"var $r: Option[$t0] = $v0; $body" =>

   val r_isdef = Variable[Boolean]
   val r_value = Variable[t0.Typ]

   val b2 = body rewrite {
     case code"$$r.fold[$tr]($z)($f)" =>
       code"if ($r_isdef) $f($r_value) else $z"
     case code"$$r = $opt" =>
       code"$opt.fold(())(v => $r_value = v)" }

   code"""var $r_value = $v0.getOrElse(${t0.defaultValue});
         var $r_isdef = $v0.isDefined; $b2"""
     .without(r).getOrElse(abort())
```

Usage example: flatten variable of option type

Tricky part of `def apply[T,C](pgrm: Code[T,C]): Code[T,C]`

```
 ...
 case code"var $r: Option[$t0] = $v0; $body" =>
   val r_isdef = Variable[Boolean]
   val r_value = Variable[t0.Typ]
   val b2 = body rewrite {
     case code"$$r.fold[$tr]($z)($f)" =>
       c                                               $z"
     ca
                                                     )" }
   code"      va                               .defaultValue});
            va       r_isdef = $v0.isDefined; $b2"""
     .without(r).getOrElse(abort())
```

forget to capture or substitute FV?

→ type error at compile time

Usage example: final result

List maximum, reloaded: **high-level *and* efficient**

```
def maxOr(xs: List[Int], default: Int): Int = Opt.optimize {
  xs.foldLeft(None) {
    (acc, x) => Some( acc.fold(x)(y => max(x,y)) )
  }.getOrElse(default)
}
```

Can now change high-level code freely

optimization happens automatically

Type-Safe Metaprogramming: Limitations

Limitations of naive metaprogramming

Simple approach, many limitations

- function boundaries
- binding boundaries, side effects
- control-flow boundaries (join points)

Limitation: function boundaries

Rewrite rules are blind to escaping usages

```
var opt = ... ; ... myFunction(opt).fold(...)(...) ...
```

Usual solution: aggressive inlining

Problem: when to inline what?

eagerly inlining high-level constructs...

removes high-level optimization opportunities!

such as list fusion

```
case code"($ls: List[$ta]).map($f).map($g)" => ...
```

Solution: lowering + normalization phases

Lowering phases:

At each phase

- inline functions at the current level of abstraction
- normalize usages
- apply optimizing rewritings

Limitation: binding boundaries, side effects

Examples

```
val tmp = Some(expr); ... tmp.fold(...)(...) ...
val a = { val b = Some(expr); b }; a.fold(...)(...)
```

Need to commute and see through bindings

- But what if `expr` has side effects?
- What if `f` and `g` has side effects in `ls.map(f).map(g) ...` ?

Solution:

- rewrite engine needs to be side-effects-aware
- i.e., need internal effect system

Limitation: control-flow boundaries

Finally, consider — patterns that commonly arises:

`opt.fold(d)(f).fold(e)(g)` or `(if (…) … else …).fold(e)(g)`

Rewrite them to?

```
opt.fold(d.fold(e)(g))(x => f(x).fold(e)(g))
if (…) ….fold(e)(g) else ….fold(e)(g)
```

Does not scale: duplicates `e, g`

Solution: notion of join points

Requires smarter intermediate representation (CPS, ANF, CFG)

Squid supports user-defined IR!

Conclusion: rewriting needs compiler help

A practical optimizer needs:

- Progressive lowering + normalization phases
- Ability to look across and commute bindings
- Notion of side effects
- Practical representation of control-flow

These are what the "extensible compiler" part of Squid is about

Application Example:

Fusion for a Streaming Library

Application: Optimized streaming library

Expressive core constructs

```
type Stream[A] <: {
  def map[B](f: A => B): Stream[B]
  def flatMap[B](f: A => Stream[B]): Stream[B]
  def take(n: Int): Stream[A]
  def filter(p: A => Bool): Stream[A]
  def zipWith[B](that: Stream[B]): Stream [(A , B)]
  def fold[B](z: B)(f: (B , A) => B): B
  ...
}
def fromRange(from : Int, until: Int): Stream[Int]
def unfold[A, B](init: B)(next : B => Option[(A, B)]): Stream[A]
```

Streaming library

"Shorthand" constructs

```
@phase("Sugar") def fromArray[A](xs: Array[A]): Stream[A] =
  fromRange(0, xs.length).map(i => xs(i))
```

"Low-level" constructs

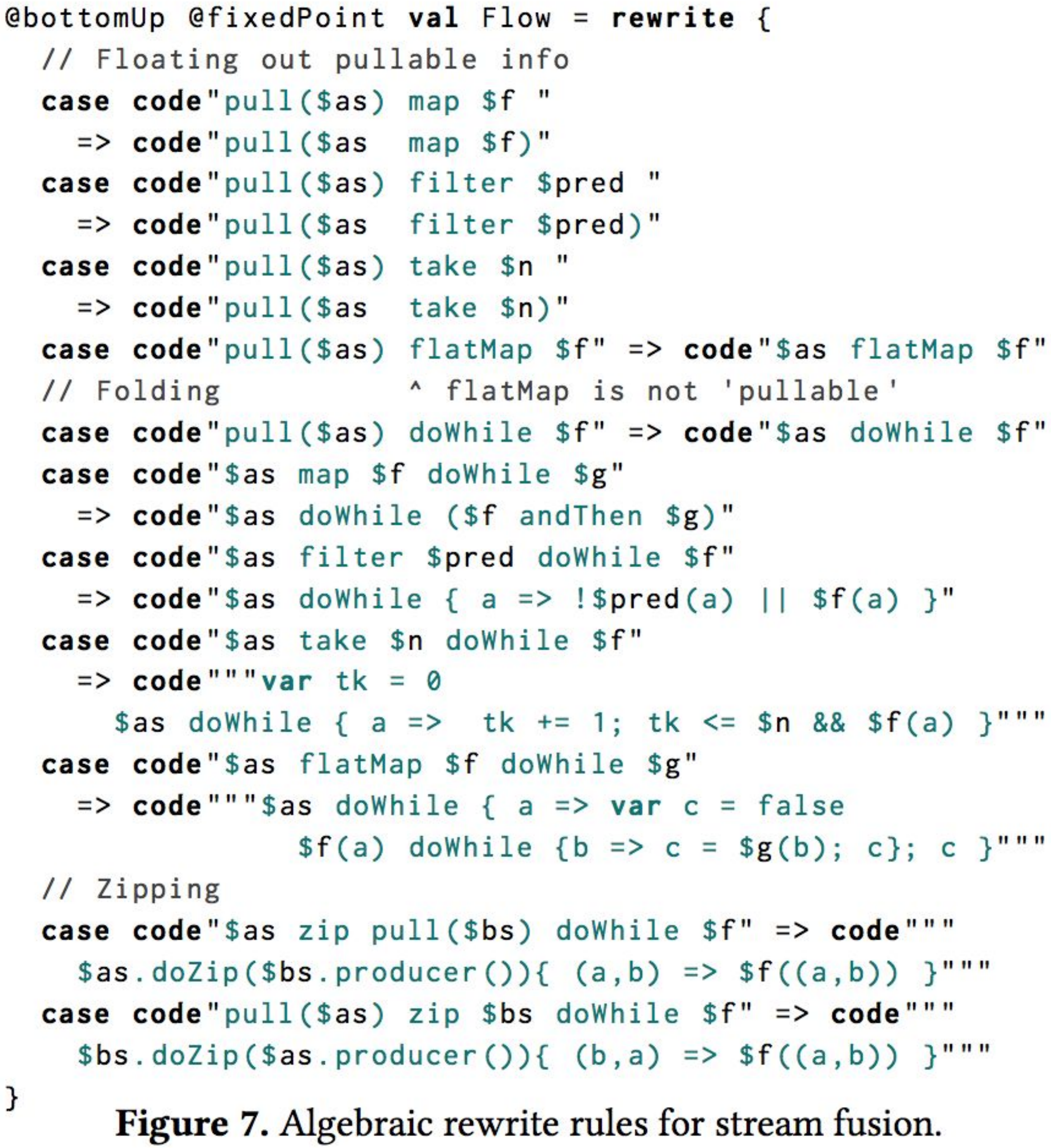
```
@phase("Low") def flatMap[B](f: A => Stream[B]): Stream[B]
```

"Internal" constructs

```
@phase("Internal") def doWhile(f: A => Bool): Unit
```

QSR: Stream Fusion

Example optimization:

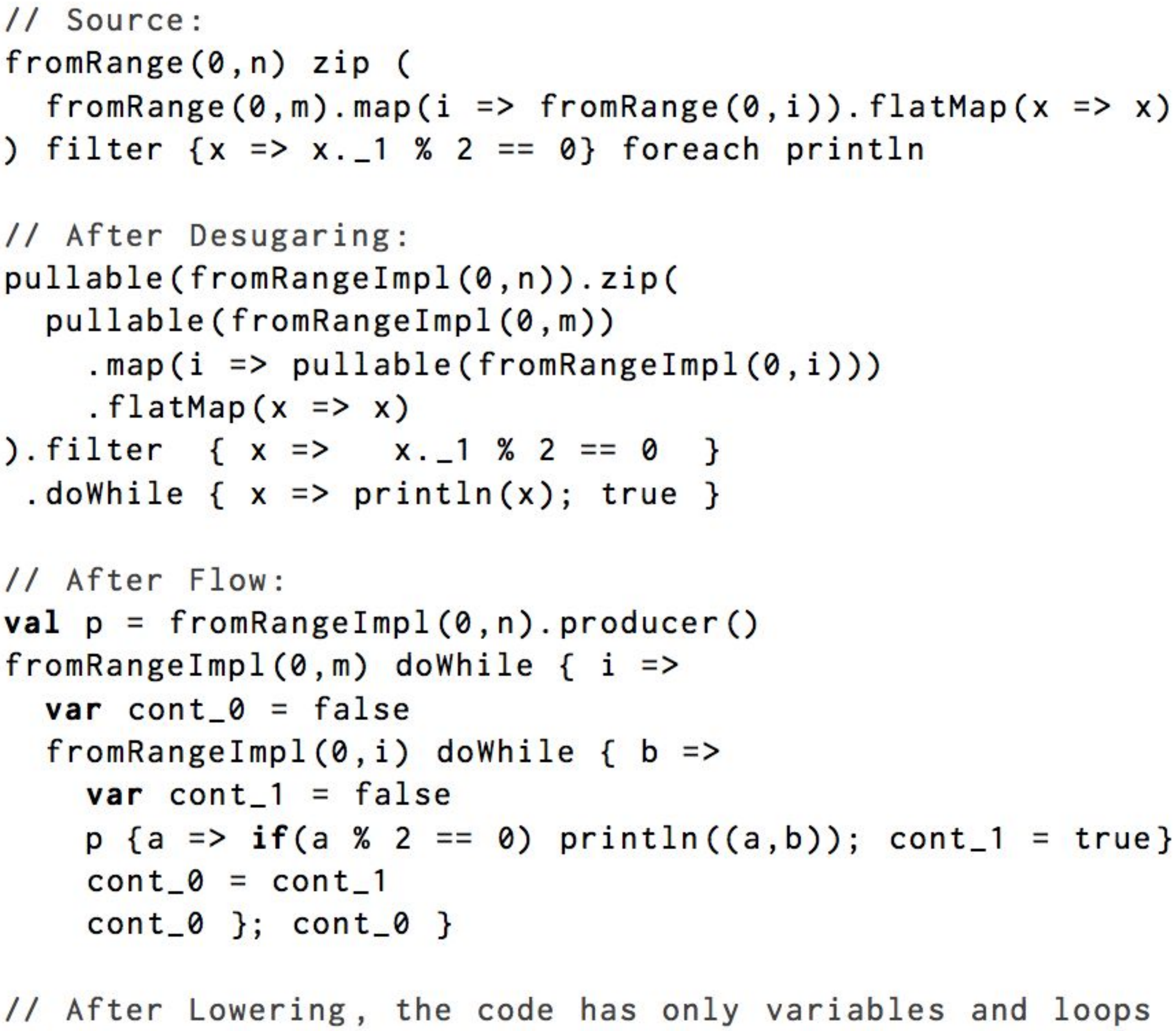


```
@bottomUp @fixedPoint val Flow = rewrite {
  // Floating out pullable info
  case code"pull($as) map $f "
    => code"pull($as  map $f)"
  case code"pull($as) filter $pred "
    => code"pull($as  filter $pred)"
  case code"pull($as) take $n "
    => code"pull($as  take $n)"
  case code"pull($as) flatMap $f" => code"$as flatMap $f"
  // Folding          ^ flatMap is not 'pullable'
  case code"pull($as) doWhile $f" => code"$as doWhile $f"
  case code"$as map $f doWhile $g"
    => code"$as doWhile ($f andThen $g)"
  case code"$as filter $pred doWhile $f"
    => code"$as doWhile { a => !$pred(a) || $f(a) }"
  case code"$as take $n doWhile $f"
    => code"""var tk = 0
      $as doWhile { a =>  tk += 1; tk <= $n && $f(a) }"""
  case code"$as flatMap $f doWhile $g"
    => code"""$as doWhile { a => var c = false
                $f(a) doWhile {b => c = $g(b); c}; c }"""
  // Zipping
  case code"$as zip pull($bs) doWhile $f" => code"""
    $as.doZip($bs.producer()){ (a,b) => $f((a,b)) }"""
  case code"pull($as) zip $bs doWhile $f" => code"""
    $bs.doZip($as.producer()){ (b,a) => $f((a,b)) }"""
}
```

Figure 7. Algebraic rewrite rules for stream fusion.

Stream Fusion

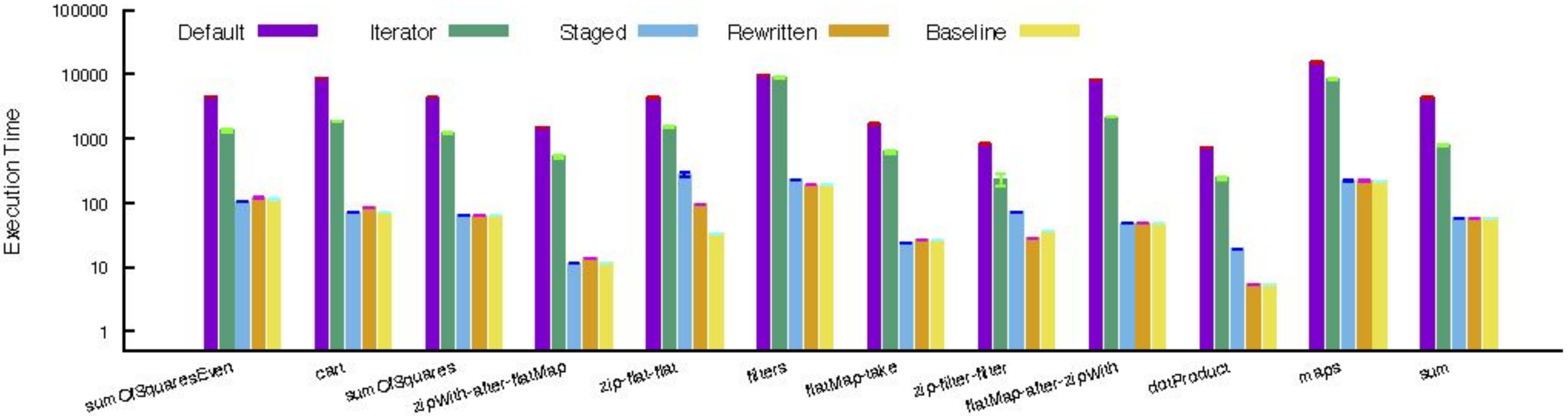
Example optimized program:



```
// Source:
fromRange(0,n) zip (
  fromRange(0,m).map(i => fromRange(0,i)).flatMap(x => x)
) filter {x => x._1 % 2 == 0} foreach println

// After Desugaring:
pullable(fromRangeImpl(0,n)).zip(
  pullable(fromRangeImpl(0,m))
    .map(i => pullable(fromRangeImpl(0,i)))
    .flatMap(x => x)
).filter  { x =>   x._1 % 2 == 0  }
 .doWhile { x => println(x); true }

// After Flow:
val p = fromRangeImpl(0,n).producer()
fromRangeImpl(0,m) doWhile { i =>
  var cont_0 = false
  fromRangeImpl(0,i) doWhile { b =>
    var cont_1 = false
    p {a => if(a % 2 == 0) println((a,b)); cont_1 = true}
    cont_0 = cont_1
    cont_0 }; cont_0 }

// After Lowering, the code has only variables and loops
```

QSR: Stream Fusion Results

Microbenchmarks for functional stream pipelines



- 1–2 **orders of magnitude faster** vs. unstaged/iterators
- As fast as **hand-written loops** and staged code
  (but much more **user-friendly** than both)

Metaprogramming beyond expressions

Metaprogramming beyond expressions

Squid so far: powerful manipulation of *expressions*

(composition, matching, rewriting, execution…)

Great for:

- static targeted optimization with `optimize { ... }`
- generation of specialized computation kernels
- on-the-fly compilation of small components

What about definitions? Want to generate full programs?

Squid's solution: ***first-class classes***

Basic first-class class example

Normal Scala class:

```
class Vector(val x: Int, val y: Int, val z: Int)
val v = new Vector(0,1,2)  →  Vector(0,1,2)
val f = (u: Vector) => u.x + u.y
f(v)  →  1
```

Squid-virtualized representation of same class:

```
object Vector extends Class { val x, y, z = param[Int] }
val v = Vector(c"0", c"1", c"2")  →  c"new Vector(0,1,2)"
val f = c"(u: Vector.T) => ${Vector.x}(u) + ${Vector.y}(u)"
val f = c"(v: Vector.T) => v.x + v.y" // syntax sugar
c"$f($v)"  →  c"0 + 1" // automatically reduce pure classes
```

Language-integrated database system compiler

Application: I'm working on ***dbStage***

- Users define their integrated database with Scala constructs
- Users define queries using a Scala DSL
- dbStage generates efficient implementations

```
class TableClass(name: String) extends Class("Row_"+name)
  { val params: Array[Param[_]] }
val rowClasses = schema.tables.map { tbl => new TableClass(tbl.name) {
   val params = tbl.columns.map {
     case (cname, ctyp) => param[ctyp.Typ]("col_"+cname) } } }
// generates:
class Row_Person(val col_name: String, col_age: Int)
...
```

Conclusions

Metaprogramming made **type- and scope-safe** without pain:

- quoted program fragments `code"..."`
- contextual types made of intersections `C & v.Ctx`
- hygienic, first-class variables `Variable[T]`
- automatic weakening based on variance `Code[+T,-C]`

Optimizations enabled by **synergy** with **compiler technology**

- strategic rewriting `rewrite`, `abort`
- advanced intermediate representations: ANF, Graph, …
- effect system
- progressive lowering phases to remove abstraction

Squid: open-source implementation for Scala 2, **soon Scala 3**

Thank you!

A bit about the type system

Typing judgement $\Gamma \vdash t : T \dashv \Gamma$

context of current term **context outside current quote**

No need for stack of context: only unquote variables

```
code""" foo(code"bar(${f($x)})") """ // nested quote/unquote
 ⇔ code""" val u = f($x); foo(code"bar($u)") """
```

T-Quote

$$\frac{C \vdash t : T \dashv \Gamma}{\Gamma \vdash \texttt{code"}t\texttt{"} : \mathtt{Code}[T, C] \dashv \Gamma'}$$

T-Unquote

$$\frac{(x : \mathtt{Code}[T, C]) \in \Gamma'}{\Gamma \vdash \$x : T \dashv \Gamma'}$$

Usage example: split array of pairs

```
def optimize[T,C](pgrm: Code[T,C]): Code[T,C] = pgrm rewrite {
 case code"val arr = new Array[($ta,$tb)]($size); $body" =>
   val a = code"?a:Array[$ta]"; val b = code"?b:Array[$tb]"
   val body2 = body rewrite {
     case code"${body.arr}($i)._1" => code"$a($i)"
     case code"${body.arr}($i)._2" => code"$b($i)"
     case code"${body.arr}.size"   => code"$a.size"    }
   val body3 = body2.arr ~> abort()
   code"""val a = new Array[$ta]($size)
          val b = new Array[$tb]($size)
          $body3                                 """ }
```

Advanced example: Scala 2 version (verbose)

```
reverseBindingsOrder(code"val a = 1; val b = 2; val c = 3; a + b + c")
             == Some(code"val b = 2; val a = 1; val c = 3; a + b + c")
```

Possible thanks to Scala's advanced type system:

```
/** Safely reverse the order of val bindings, if possible. */
def reverseBindingsOrder[T: CodeType, C](p: Code[T, C]): Option[Code[T, C]] = {
 class K[C] { def apply[A: CodeType, B](cde: Code[A, B & C]): Code[A, B & C] = cde }
 def go[T: CodeType, C](p: Code[T,C], k: K[C]): Option[Code[T,C]] = p match {
   case code"val $v: Int = $init; $body" =>
     go(body, new K[C & v.Ctx] {
       override def apply[S: CodeType, D](cde: Code[S, D & C & v.Ctx]) =
         code"val $v = $init; ${ k[S, D & v.Ctx](cde) }"
     }).flatMap(b => b.without(v))
   case expr => Some(k(expr)) }
 go(p, new K[C]) }
```

Publications

- Amir Shaikhha and **Lionel Parreaux**. (2019). **Finally, a Polymorphic Linear Algebra Lan- guage.** In 33rd European Conference on Object-Oriented Programming (**ECOOP 2019**). DOI: https://doi.org/10.4230/LIPIcs.ECOOP.2019.25

- **Lionel Parreaux**, Aleksander Boruch-Gruszecki, and Paolo G. Giarrusso. 2019. **Towards improved GADT reasoning in Scala.** In Proceedings of the Tenth ACM SIGPLAN Symposium on Scala (**SCALA 2019**). ACM, New York, NY, USA, 12-16. DOI: https://doi.org/10.1145/3337932.3338813

- **Lionel Parreaux**, Antoine Voizard, Amir Shaikhha, and Christoph E. Koch. 2018. **Unifying Analytic and Statically-Typed Quasiquotes.** Proc. ACM Program. Lang. 2, (**POPL 2018**), Article 13 (January 2018), 33 pages. DOI: https://doi.org/10.1145/3158101

- **Lionel Parreaux**, Amir Shaikhha, and Christoph E. Koch. 2017. **Quoted staged rewriting: a practical approach to library-defined optimizations.** In Proceedings of the 16th ACM SIGPLAN International Conference on Generative Programming: Concepts and Experiences (**GPCE 2017, Best Paper**). ACM, New York, NY, USA, 131-145. DOI: https://doi.org/10.1145/3136040.3136043

- **Lionel Parreaux**, Amir Shaikhha, and Christoph E. Koch. 2017. **Squid: type-safe, hygienic, and reusable quasiquotes.** In Proceedings of the 8th ACM SIGPLAN International Symposium on Scala (**SCALA 2017**). ACM, New York, NY, USA, 56-66. DOI: https://doi.org/10.1145/3136000.3136005

- Amir Shaikhha, Yannis Klonatos, **Lionel Parreaux**, Lewis Brown, Mohammad Dashti, and Christoph Koch. 2016. **How to Architect a Query Compiler.** In Proceedings of the 2016 International Conference on Management of Data (**SIGMOD 2016**). ACM, New York, NY, USA, 1907-1922. DOI: https://doi.org/10.1145/2882903.2915244

Multi-Stage Programming (a.k.a., Staging)

Squid features allow multi-stage programming (staging)

i.e., separate execution of program into **code-generation phases**

Each stage **executes parts** of program **known** at this stage;

    delays execution of rest by emitting code

Last stage: much simpler/**more efficient** program,

    where most **abstractions have been removed**

Canonical example of MSP: power function

Start from normal implementation; add staging annotations

Limitations of Pure Staging

Traditional staging: purely generative

But Squid also supports rewriting… can be combined!

i.e., ***Quoted Staged Rewriting*** (QSR)

/Backup slides