ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Scala *for* MULTICORE

PART 2: *Parallel Collections and Parallel DSLs*

Philipp HALLER, STANFORD UNIVERSITY AND EPFL

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BUT FIRST,

Let's pick up from where we left off yesterday...

Goal of Scala Actors

Programming system for Erlang-style actors that:

- offers high scalability on mainstream platforms;
- integrates with thread-based code;
- provides safe and efficient message passing.

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Safe and Efficient Message Passing.

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- Pass **a reference to a mutable object** in a message
- Two actors **accessing the same mutable object** can lead to data races

How do we prevent that?

- Make sure mutable objects are **unusable after they have been sent**
- Use a compiler plugin to **check whether a variable is unusable**

The Compiler Plugin.

The compiler plugin checks at which point a variable is transferred and becomes unusable.

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This check is done in two steps:

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This check is done in two steps:

1. MARK variables that we want to send in messages.
   - Add `@unique` annotation to their type.
2. Go through program and track which variables are USABLE/UNUSABLE.
   - Run additional type checking phase on program

Extending Type Checking.

An annotated variable

```
val buf: ArrayBuffer[Int] @unique
```

has a **type guarded with a capability:**

```
buf: ρ▻ArrayBuffer[Int]
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Extending Type Checking.

An annotated variable

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val buf: ArrayBuffer[Int] @unique
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has a **type guarded with a capability:**

```
buf: ρ▻ArrayBuffer[Int]
```

Key idea:

A variable with guarded type is **only usable when its capability is available**

Tracking Capabilities.

```
actor {
  var sum = 2 + 3
  val buf: Buffer[Int]@unique =
    new ArrayBuffer[Int]
  buf += sum
  someActor ! buf
  buf.remove(0)
}
```

Tracking Capabilities.

LOCAL VARIABLES: **CAPABILITIES:**

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Tracking Capabilities.

LOCAL VARIABLES:

`sum: Int`

CAPABILITIES:

∅

∅

∅

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THUS,
Uniqueness types can be used to ensure actors are isolated.

^

Implementation and Experience.

Plug in for Scala compiler

- Erases capabilities and `capturedBy` for code generation

Practical experience:

	size [LOC]	changes [LOC]	property checked
mutable collections	2046	60	collections self-contained
partest	4182	61	actor isolation
ray tracer	414	18	actor isolation

External vs. Separate Uniqueness

EXTERNAL UNIQUENESS

- No external aliases
- No unique method receivers
- Deep/full encapsulation

[*Clarke, Wrigstad 2003; Müller, Rudich 2007; Clarke et al. 2008*]

SEPARATE UNIQUENESS

THIS TALK.

- Local external aliases
- Unique method receivers (self transfer)
- Full encapsulation

Goal of Scala Actors?

REVISITED. (AGAIN)

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CAPABILITIES FOR UNIQUENESS

- Lightweight pluggable type system.
- Race-freedom through actor isolation.

[Haller and Odersky. **Capabilities for uniqueness and borrowing,** ***Proc. ECOOP, 2010***]

[Haller. **Isolated Actors for Race-Free Concurrent Programming,** ***PhD Thesis, 2010***]

Summary: Actors

- Scalable Erlang-style actors
- Integration of thread-based and event-based programming
- Used in large-scale production systems
- Lightweight uniqueness types for actor isolation

Parallel Collections

NEW!
in 2.9!

Collections?

THE COLLECTIONS MENTALITY:

Collections are literally collections of data elements, which you can perform operations on.

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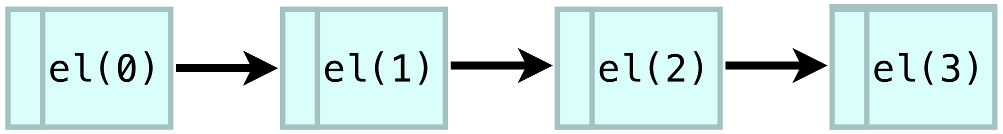
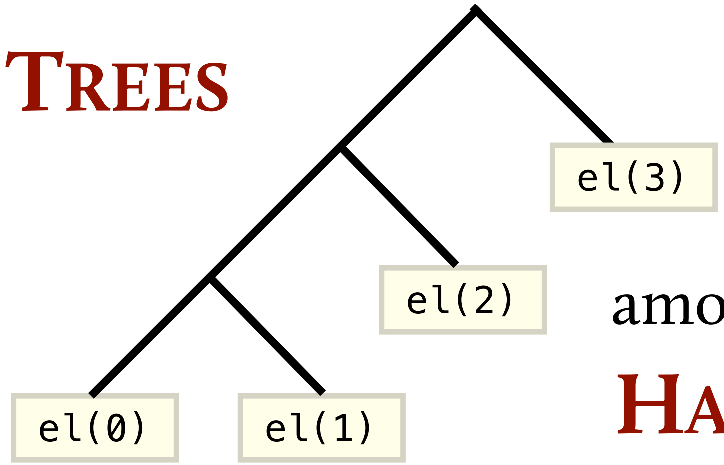
Collections are literally collections of data elements, which you can perform operations on.

A collection can be represented by
any data structure, like:

LINKED LISTS



TREES



amongst others...

HASH MAPS, RED-BLACK TREES, ETC.

Collections?

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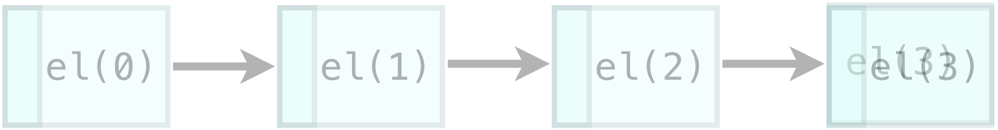

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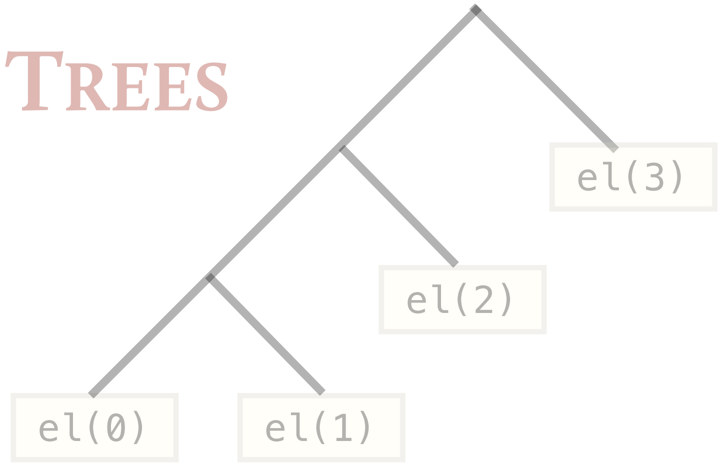

Each of which has a set of operations you can perform on it:

Menu

operations of the day:

`map`
`foreach`
`forall`
`groupBy`
`reduce`
`count`
`indexOf`
`sorted`

Collections?

Say you have *some* collection:

```
val myCollection: List[Int] = List(1,2,3,4,5)
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myCollection.foldLeft(0)((a,b) => a+b)
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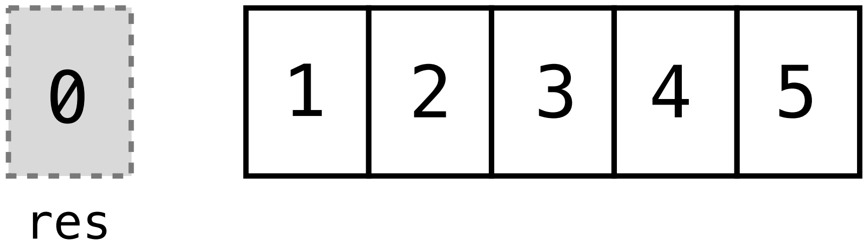

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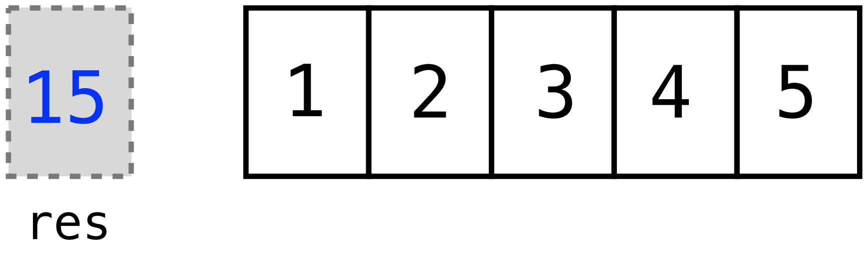

Collections Hierarchy.

Collections are organized in two packages.

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scala.collection.**mutable**

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Methods that transform an immutable collection **return a new collection** and leave the old collection unchanged

Collections Hierarchy.

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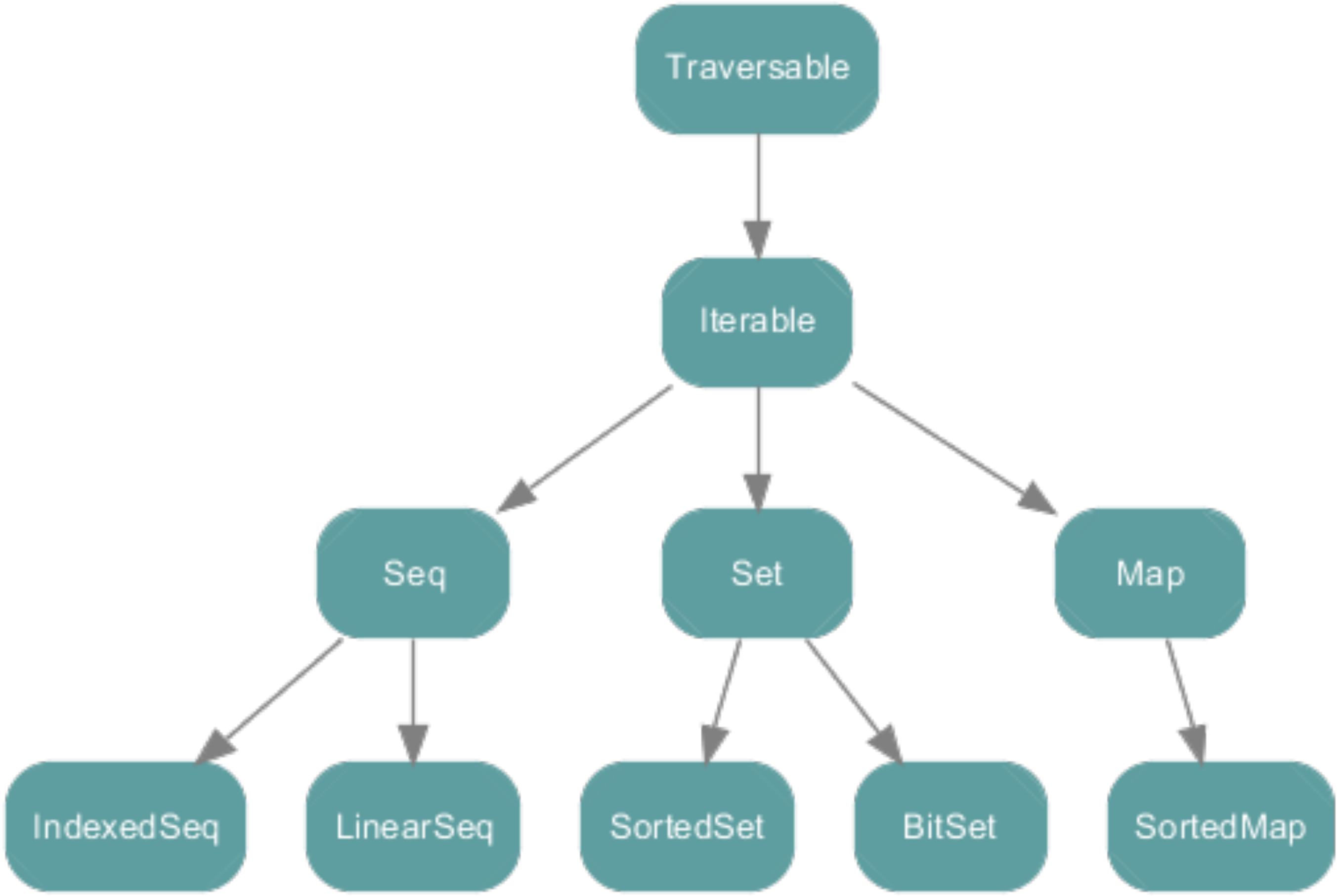
scala.collection.**mutable** scala.collection.**immutable**

Abstract classes in scala.**collection**



Parallel Collections

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Just add `.par`

And the same operation is performed in parallel:

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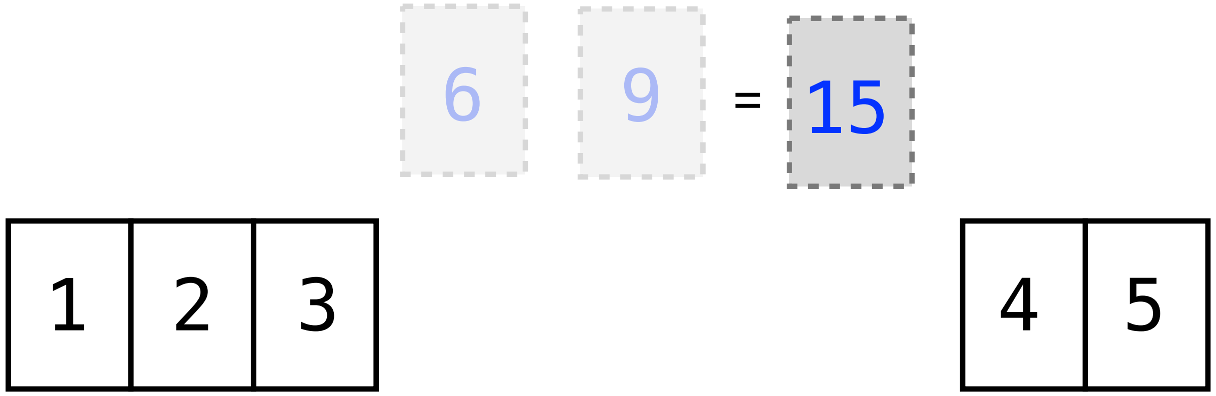
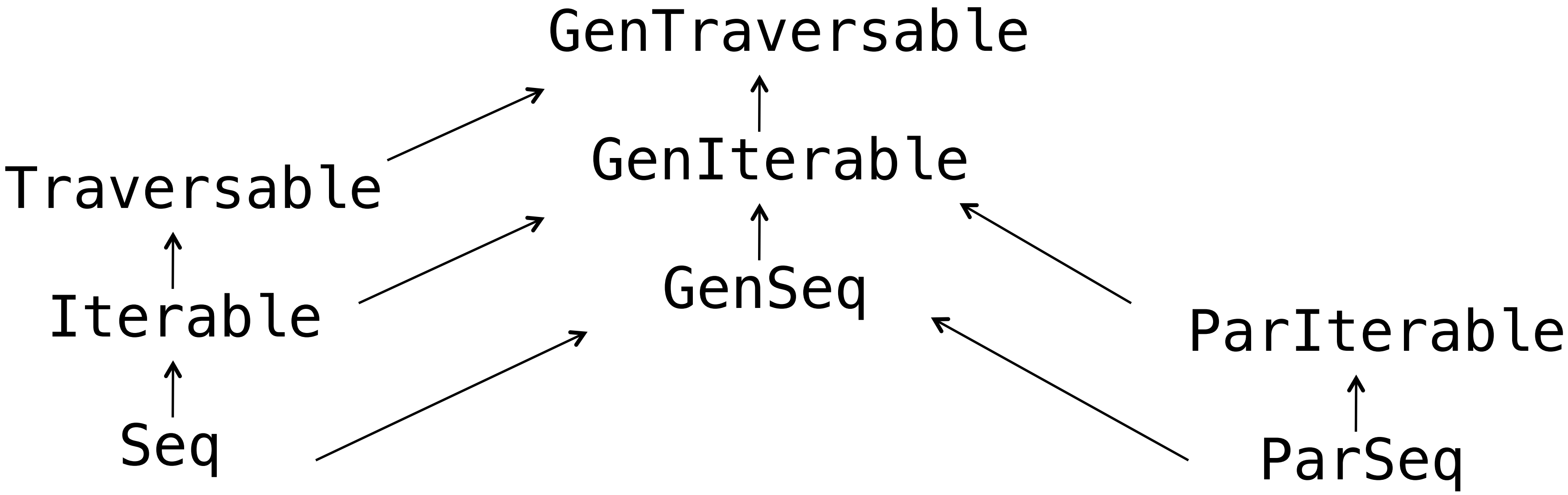


.`par`

- **New method** added to regular collections
- Returns a **parallel version of the collection** pointing to the same underlying data
- Use .`seq` to go back to the sequential collection
- Parallel sequences, maps, and sets defined in separate hierarchy

Parallel Collections Hierarchy


GenTraversable

GenIterable

GenSeq

Traversable

Iterable

Seq

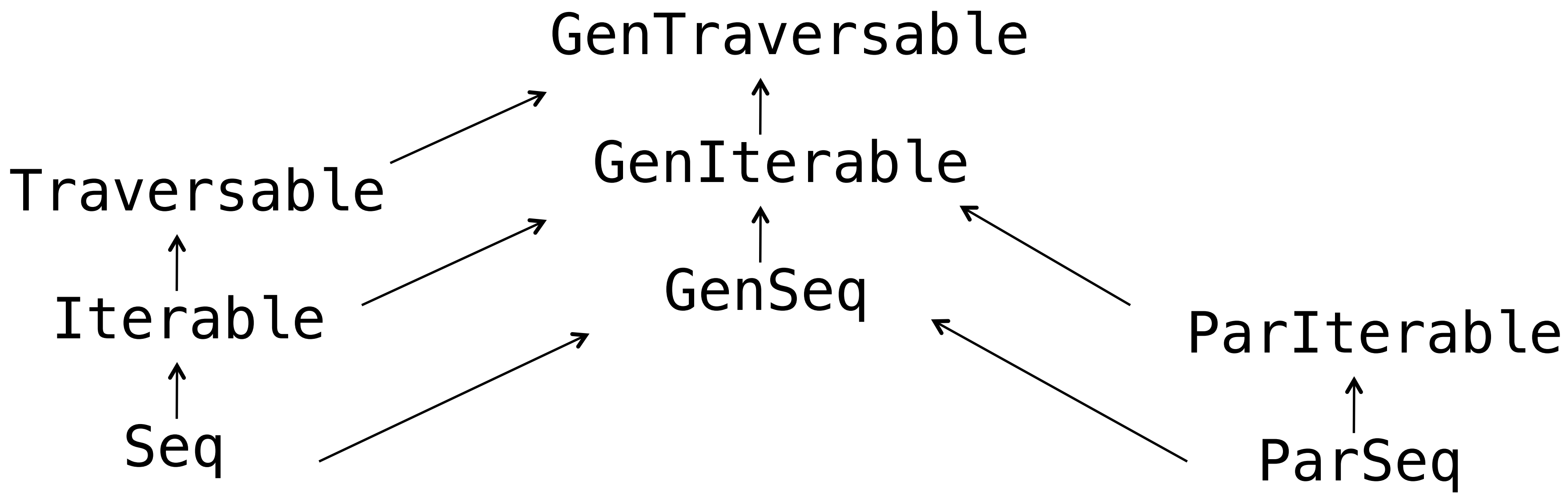
ParIterable

ParSeq

Parallel Collections Hierarchy

Immutable parallel collections:

`ParRange`
`ParVector`
`ParHashMap`
`ParHashSet`



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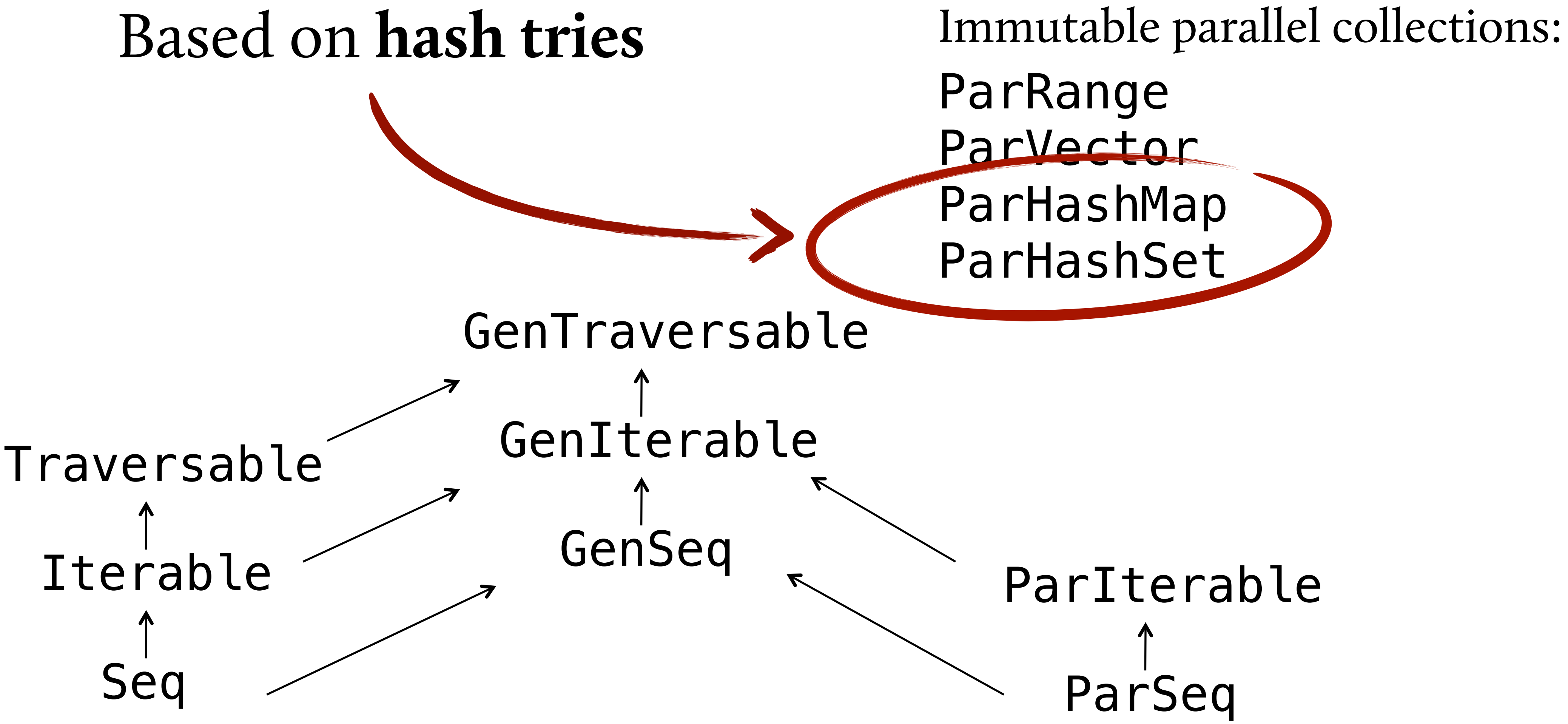
Parallel Collections Hierarchy



Based on **hash tries**

Immutable parallel collections:

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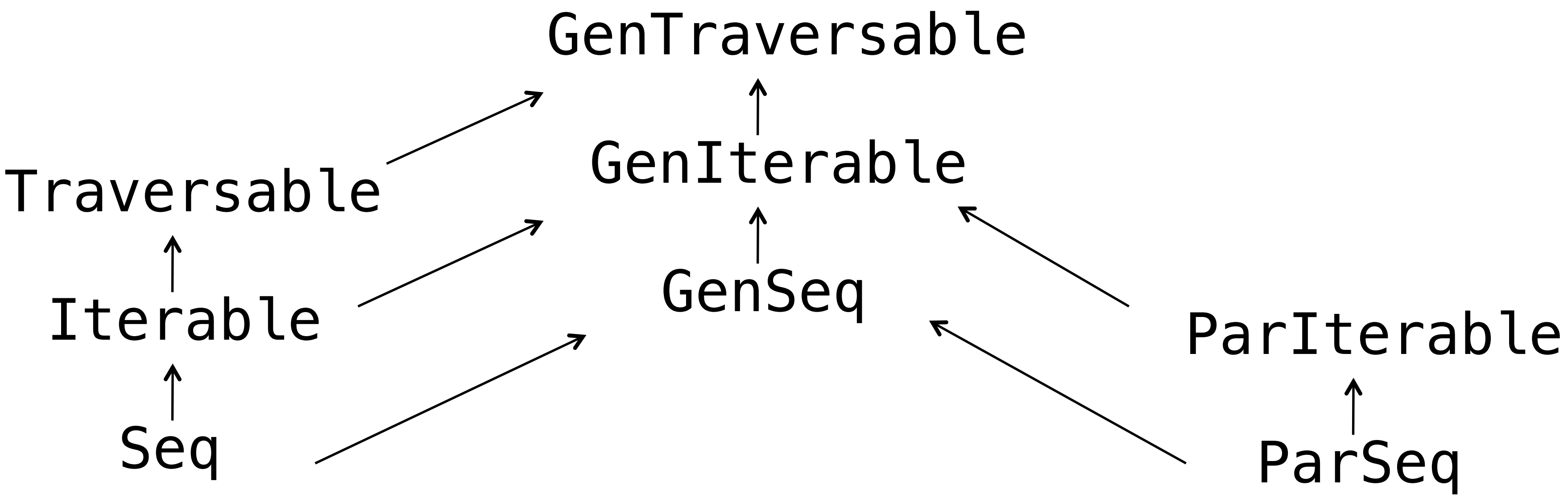
Parallel Collections Hierarchy



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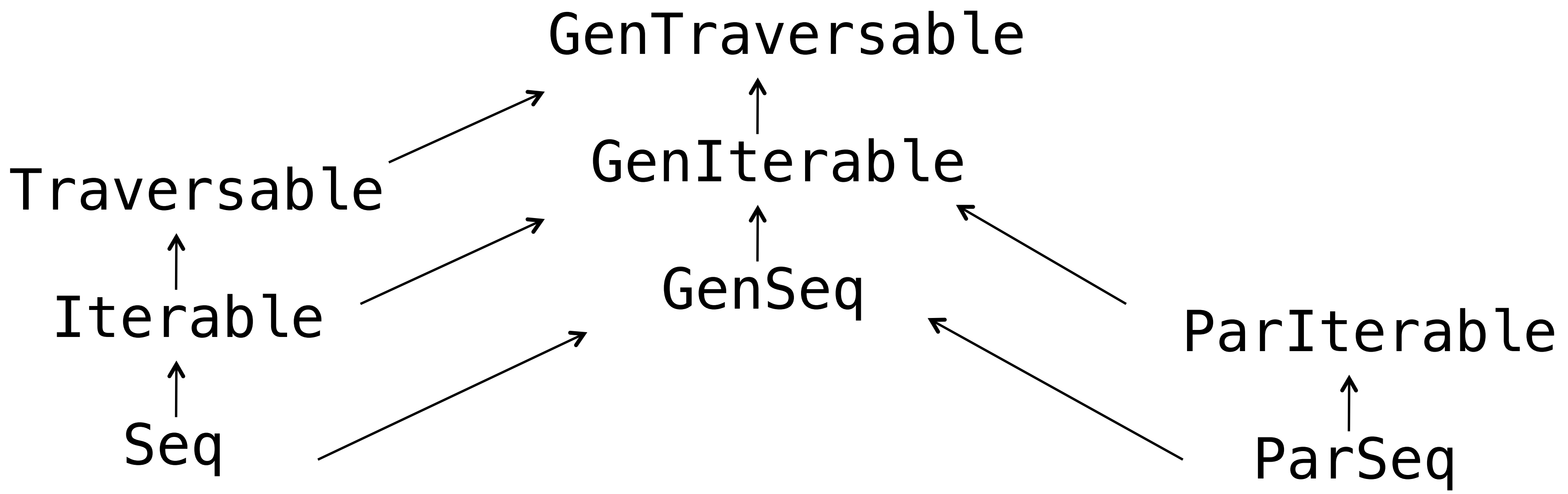
Parallel Collections Hierarchy

Mutable parallel collections:

`ParArray`
`ParHashMap`



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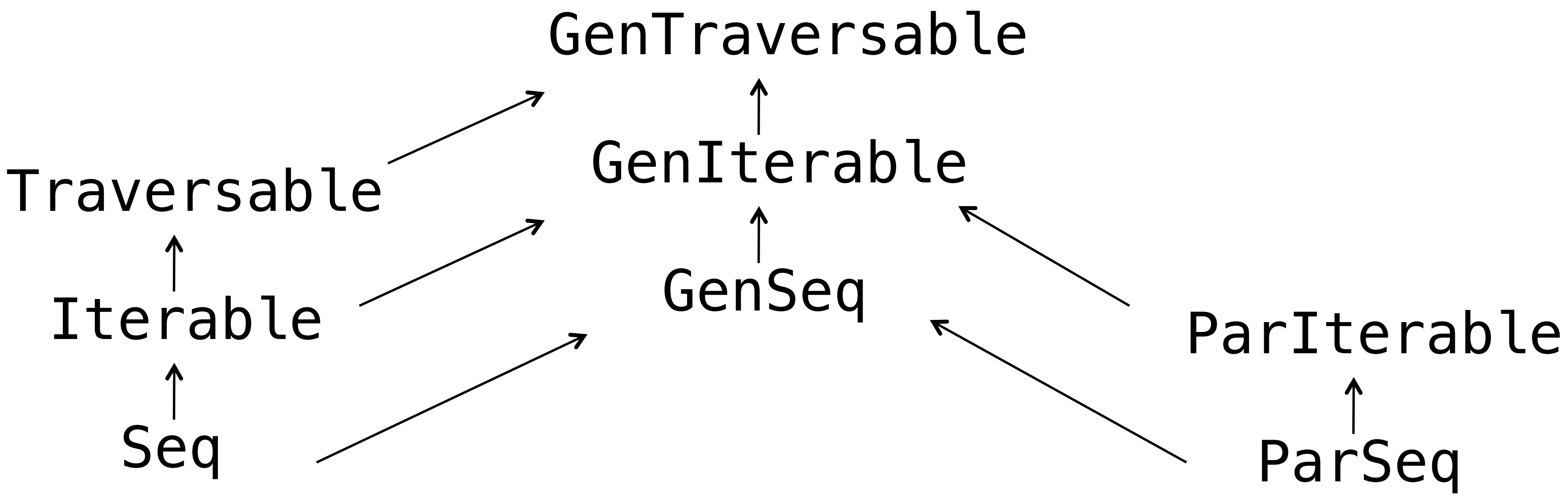
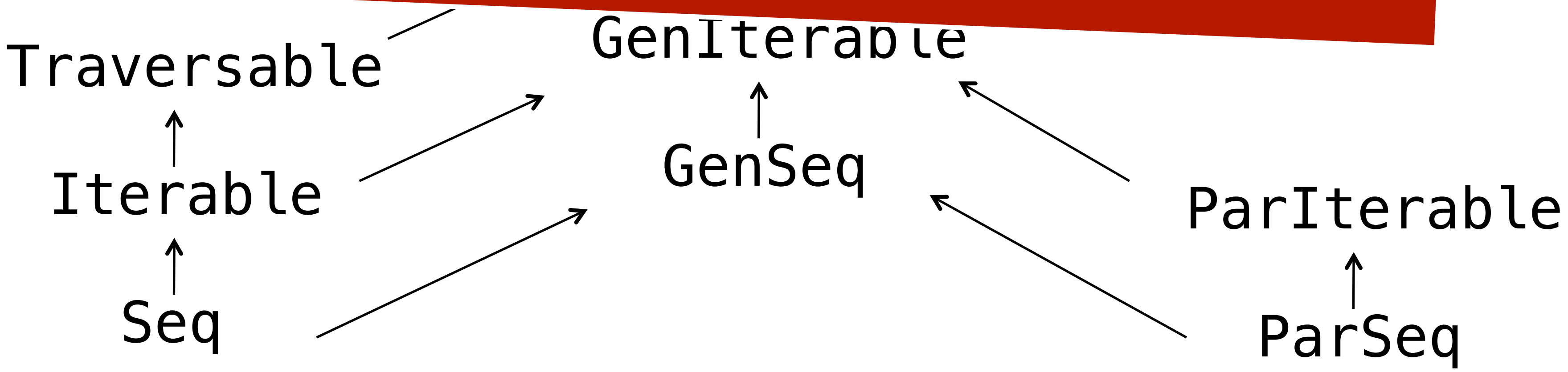


Parallel Collections Hierarchy

Why isn't a `ParSeq` a `Seq`?



`Traversable`

`Iterable`

`Seq`

`GenIterable`

`GenSeq`

`ParIterable`

`ParSeq`

Seq vs. ParSeq

```
def nonEmpty(sq: Seq[String]) = {
  val res = new mutable.ArrayBuffer[String]()
  for (s <- sq) {
    if (s.nonEmpty) res += s
  }
  res
}
```

Seq vs. ParSeq

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def nonEmpty(sq: ParSeq[String]) = {
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Side effect!
ArrayBuffer's += is not atomic!

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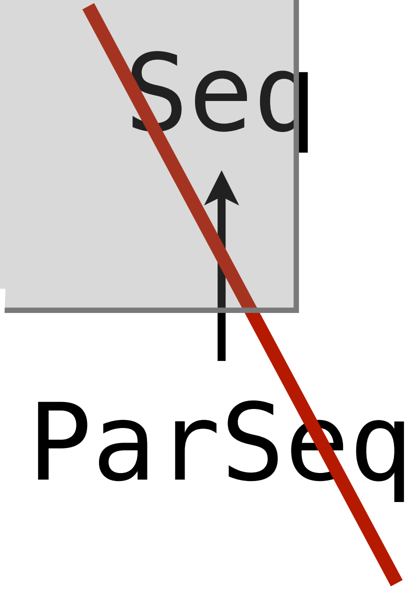

~~Seq~~

~~ParSeq~~

Implementing Parallel Collections.

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GOAL: define operations in terms of *a few common abstractions*

- Typically, in terms of a foreach method or iterators
- However, their sequential nature makes these approaches **ill-suited for parallel execution!**

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INSTEAD: **abstractions for splitting and combining**

- Split collection into non-trivial partition
- Iterate over disjunct subsets in parallel
- Combine partial results computed in parallel

Splitters and Combiners.

Splitters and Combiners.

- A splitter is an iterator that can be recursively split into disjoint iterators:

```
trait Splitter[T] extends Iterator[T] {
  def split: Seq[Splitter[T]]
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- A combiner combines partial results
  - The combine method returns a combiner containing the union of its argument elements
  - Results from different tasks are combined in a tree-like manner

```
trait Combiner[T, Coll] extends Builder[T, Coll] {
  def combine(other: Combiner[T, Coll]): Combiner[T, Coll]
}
```

Implementing ParArray.

SPLITTERS

- Hold a reference to the array and iteration bounds
- Divide the iteration range into two equal parts

Implementing ParArray.

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```
class ArraySplitter[T](a: Array[T], start: Int, end: Int)
  extends Splitter[T] {

  def split = Seq(
    new ArraySplitter(a, start, (start + end) / 2),
    new ArraySplitter(a, (start + end) / 2, end))
}
```

Implementing ParArray.

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- Maintain elements in linked list of buffers
- The result method allocates the array, and copies the chunks into the array in parallel

```
class ArrayCombiner[T] extends Combiner[T, ParArray[T]] {
  val chunks = LinkedList[Buffer[T]]() += Buffer[T]()
  def +=(elem: T) = chunks.last += elem
  def combine(that: ArrayCombiner[T]) = chunks append that.chunks
  def result = exec(new Copy(chunks,
                    new Array[T](chunks.fold(0)(_+_.size))))
}
```

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- Simple transition from regular collections to parallel collections (“just add .`par`!”)
  - If access patterns aren’t inherently sequential

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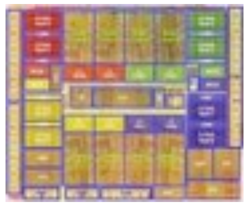
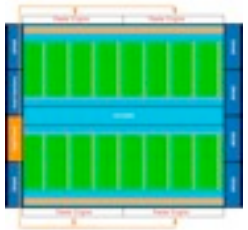
- Simple transition from regular collections to parallel collections ("just add `.par`!")
  - If access patterns aren't inherently sequential
- Parallel collection types do not extend sequential collection types
  - To avoid breaking existing code with side effects
- Parallel collections are implemented in terms of **splitters and combiners**
  - Parallel collections must provide efficient implementations of those

Heterogeneous Parallel DSLs

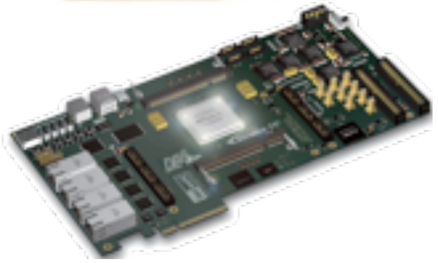
Heterogeneous Parallel Programming

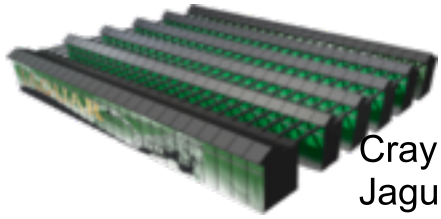


Sun
T2



Nvidia
Fermi

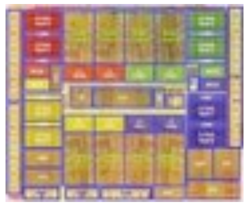




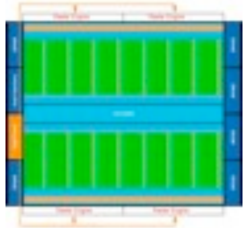
Cray
Jaguar

Heterogeneous Parallel Programming

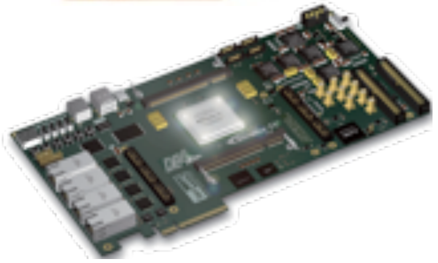
Pthreads
OpenMP

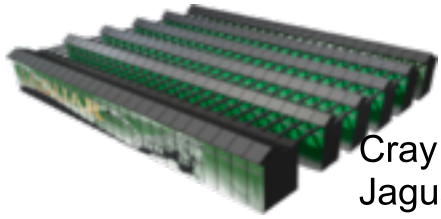


Sun
T2



Nvidia
Fermi





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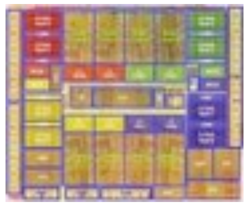

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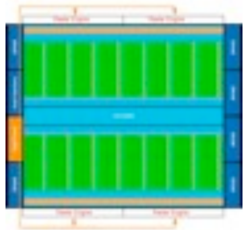
CUDA
OpenCL



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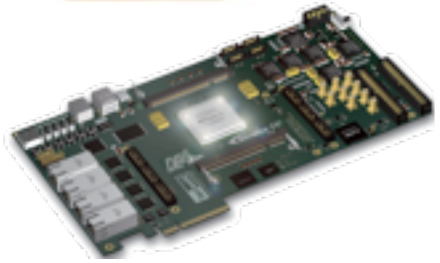

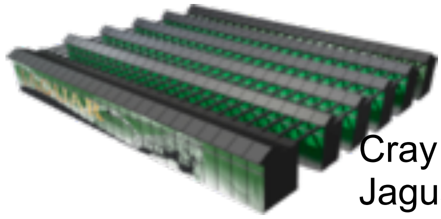

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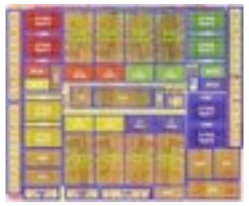

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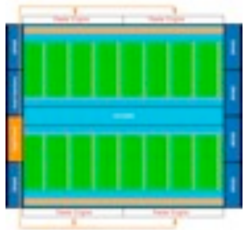

Nvidia
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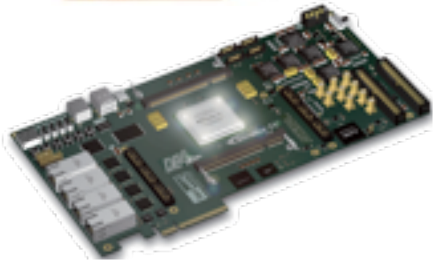
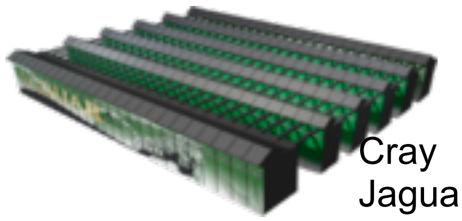
Verilog
VHDL





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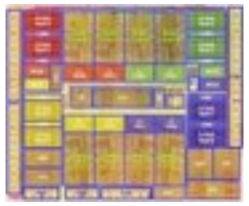

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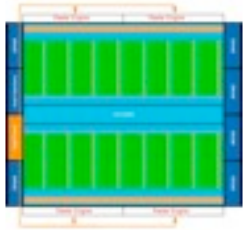

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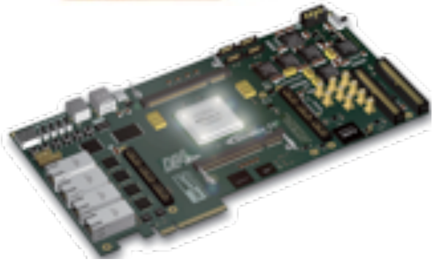
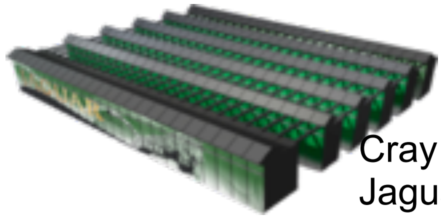


MPI



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Heterogeneous Parallel Programming

Applications

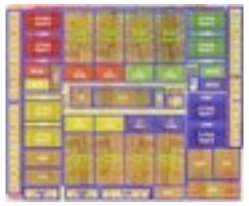
Scientific Engineering

Virtual Worlds

Personal Robotics

Data informatics

Pthreads
OpenMP



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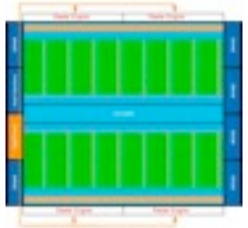

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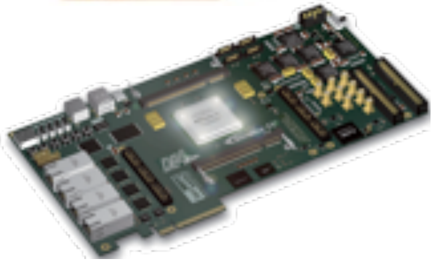

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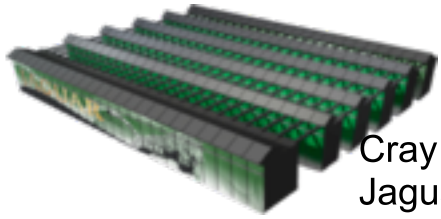

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Too many different programming models

Hypothesis and New Problem

Q: Is it possible to write one program and run it on all these targets?

Hypothesis and New Problem

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HYPOTHESIS: Yes, but need domain-specific languages

THOUGH, IT'S QUITE DIFFICULT TO CREATE DSLS USING CURRENT METHODS.

Current DSL Development Approaches

Stand-alone DSLs

- Can include extensive optimizations
- Enormous effort to develop to a sufficient degree of maturity
  - Compiler, optimizations
  - Tooling (IDEs, debuggers, ...)
- Interoperation between multiple DSLs very difficult
- Examples: MATLAB, SQL

Current DSL Development Approaches

Purely embedded DSLs (“just a library”)

- Easy to develop (can reuse full host language)
- Easier to learn DSL
- Can combine multiple DSLs in one program
- Can share DSL infrastructure among several DSLs
- **Hard to optimize using domain knowledge**

We need to do better.

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GOAL:

Develop embedded DSLs that perform as well as stand-alone ones.

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Develop embedded DSLs that perform as well as stand-alone ones.

INTUITION: General-purpose languages should be designed with DSL embedding in mind.

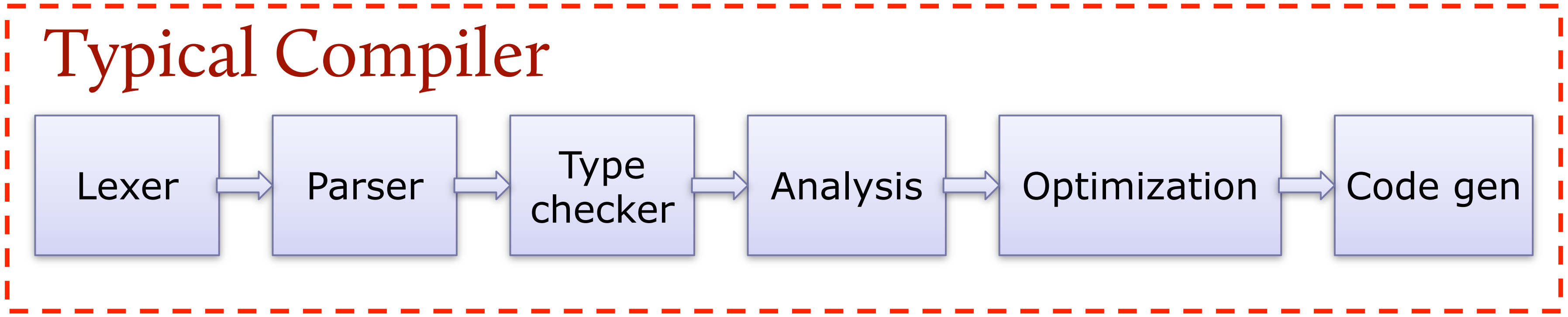
Lightweight Modular Staging.

Typical Compiler

Lexer → Parser → Type checker → Analysis → Optimization → Code gen

Lightweight Modular Staging.

Embedded DSL gets it all for free,
but can't change any of it



Typical Compiler

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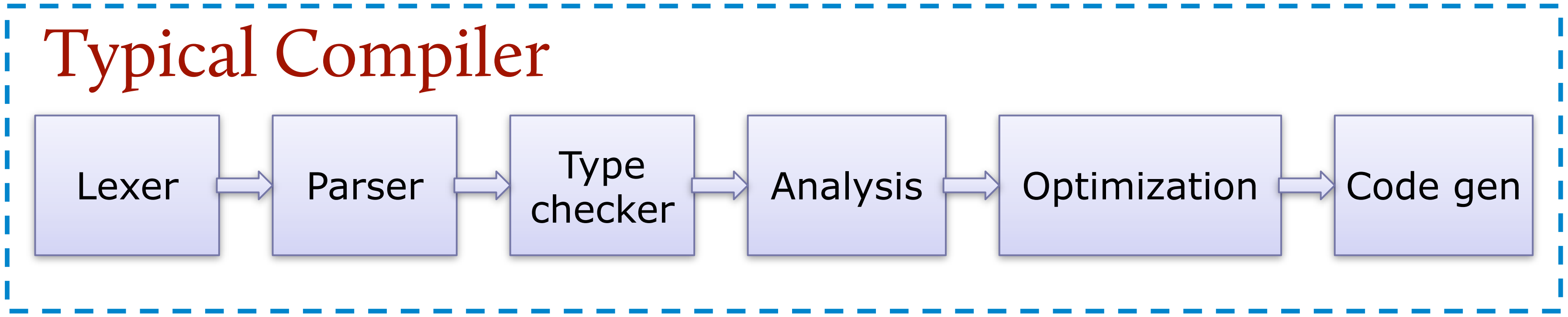
Lightweight Modular Staging.

Stand-alone DSL
implements everything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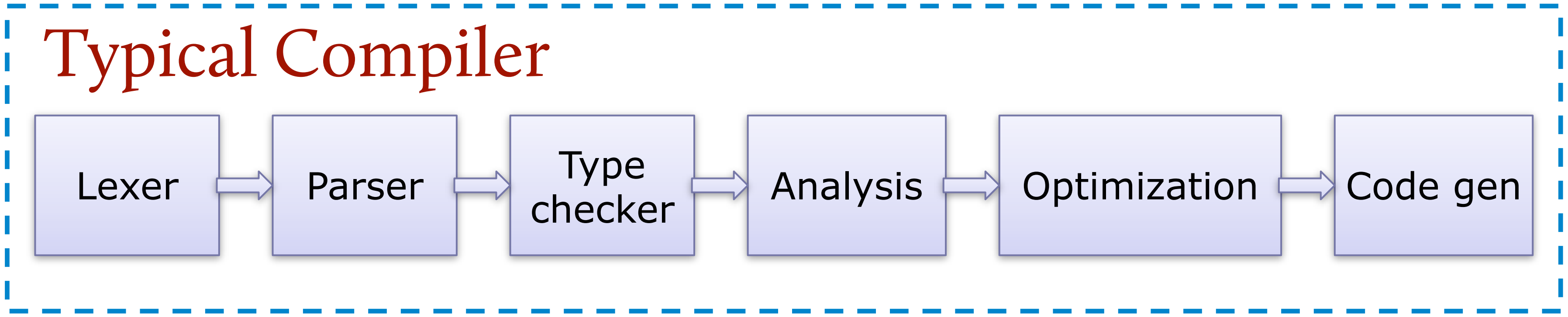
Lightweight Modular Staging.

Modular Staging provides a hybrid approach



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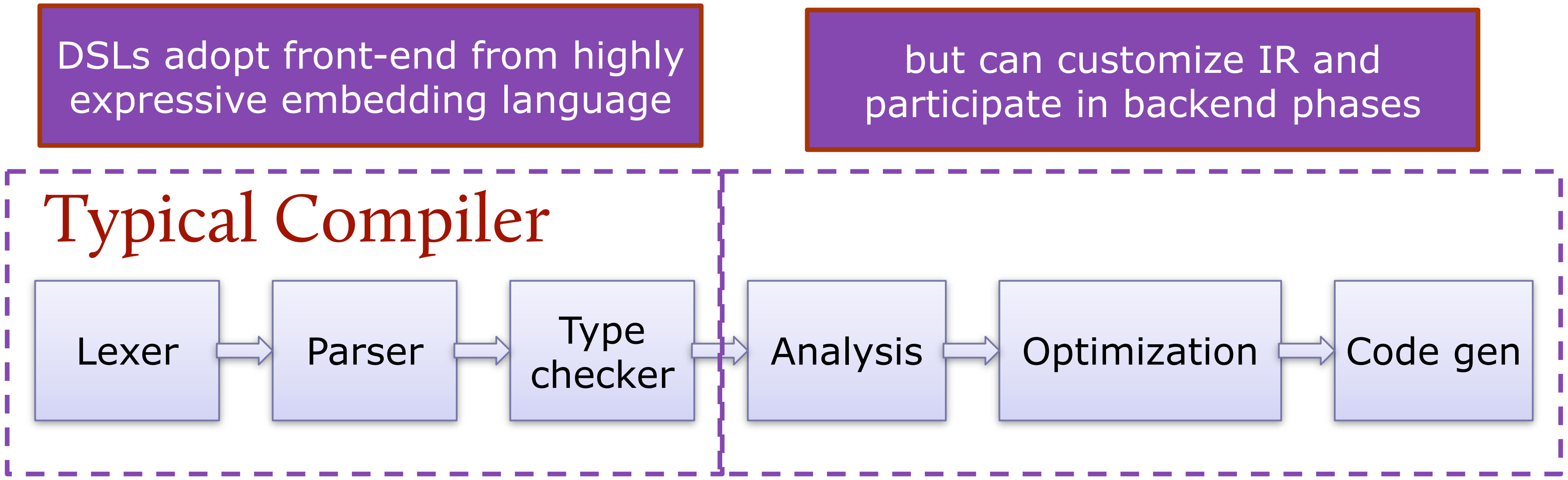

DSLs adopt front-end from highly expressive embedding language

but can customize IR and participate in backend phases

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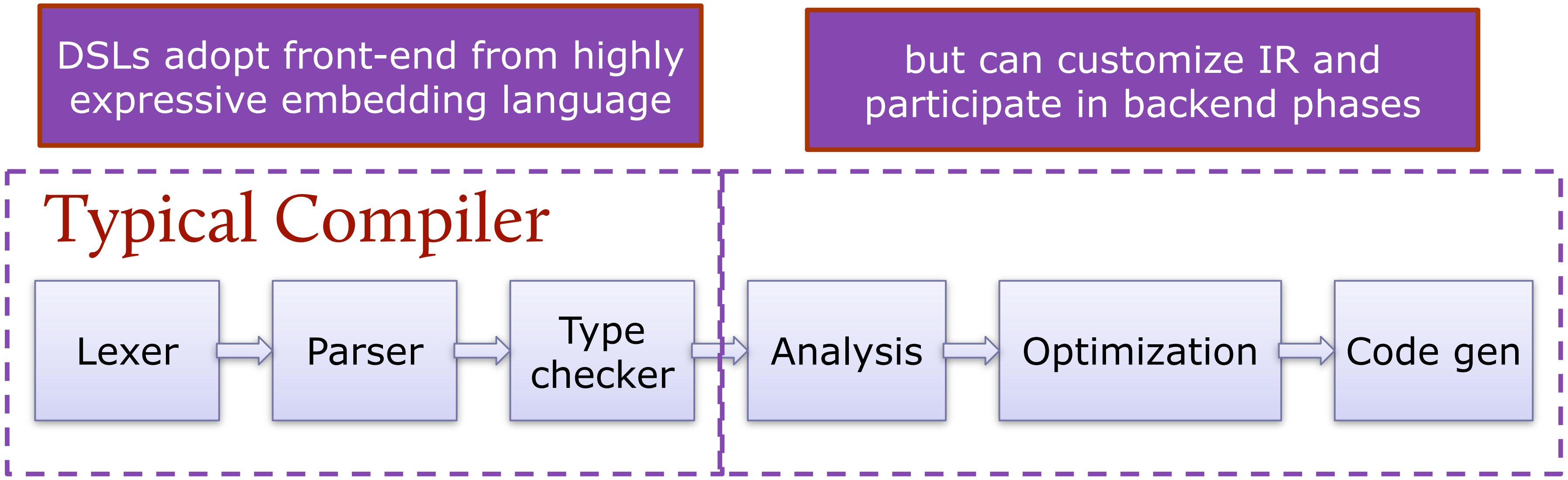
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GPCE'10: Lightweight modular staging: a pragmatic approach to runtime code generation and compiled DSLs

Linear Algebra Example.

```
object TestMatrix {

  def example(a: Matrix, b: Matrix, c: Matrix, d: Matrix) = {
    val x = a*b + a*c
    val y = a*c + a*d
    println(x+y)
  }
}
```

Targeting heterogeneous HW requires changing

- how data is represented
- how operations are implemented

Abstracting Matrices

Use abstract type constructor

- Do not fix a specific implementation, yet
- Operations work on abstract matrices

```
  type Rep[T]

  def infix_+(x: Rep[Matrix], y: Rep[Matrix]): Rep[Matrix]

  def example(a: Rep[Matrix], b: Rep[Matrix], c: Rep[Matrix],
d: Rep[Matrix]) = {
    val x = a*b + a*c
    val y = a*c + a*d
    println(x+y)
  }
```

IMPLEMENTATION DOESN’T CHANGE!

Lifting Scala Constants

Want to reuse Scala constants when operating on abstract data types:

```
val v: Rep[Vector[Double]]
v * 2
```

Possible approach: `v * intConst(2)`

- where `def intConst(x: Int): Rep[Int]`
- adds noise
- would be required also for more complex constants

Lifting Scala Constants

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Demands parameters of type `Rep[Vector[Int]]` and `Rep[Int]`!

Lifting Scala Constants.

- **OUR APPROACH:** introduce:

  `implicit def intToRep(x: Int): Rep[Int]`
- Implicitly applied by compiler if `Rep[Int]` required, but `Int` found, and `intToRep` in scope
- No syntactic noise added to user programs
- Works not only for primitives

Staging.

Programming using only `Rep[Matrix]`, `Rep[Vector]` etc. allows different implementations for `Rep`

EXAMPLE: expression trees

```
abstract class Exp[T]
case class Const[T](x: T) extends Exp[T]
case class Symbol[T](id: Int) extends Exp[T]
abstract class Op[T]
```

Matrix implementation:

```
type Rep[T] = Exp[T]

def infix_+(x: Exp[Matrix], y: Exp[Matrix]) =
    new PlusOp(x, y)

class PlusOp(x: Exp[Matrix], y: Exp[Matrix])
      extends DeliteOpZip[Matrix]
```

Staging.

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```

The Delite DSL Framework

- Provides IR with parallel execution patterns

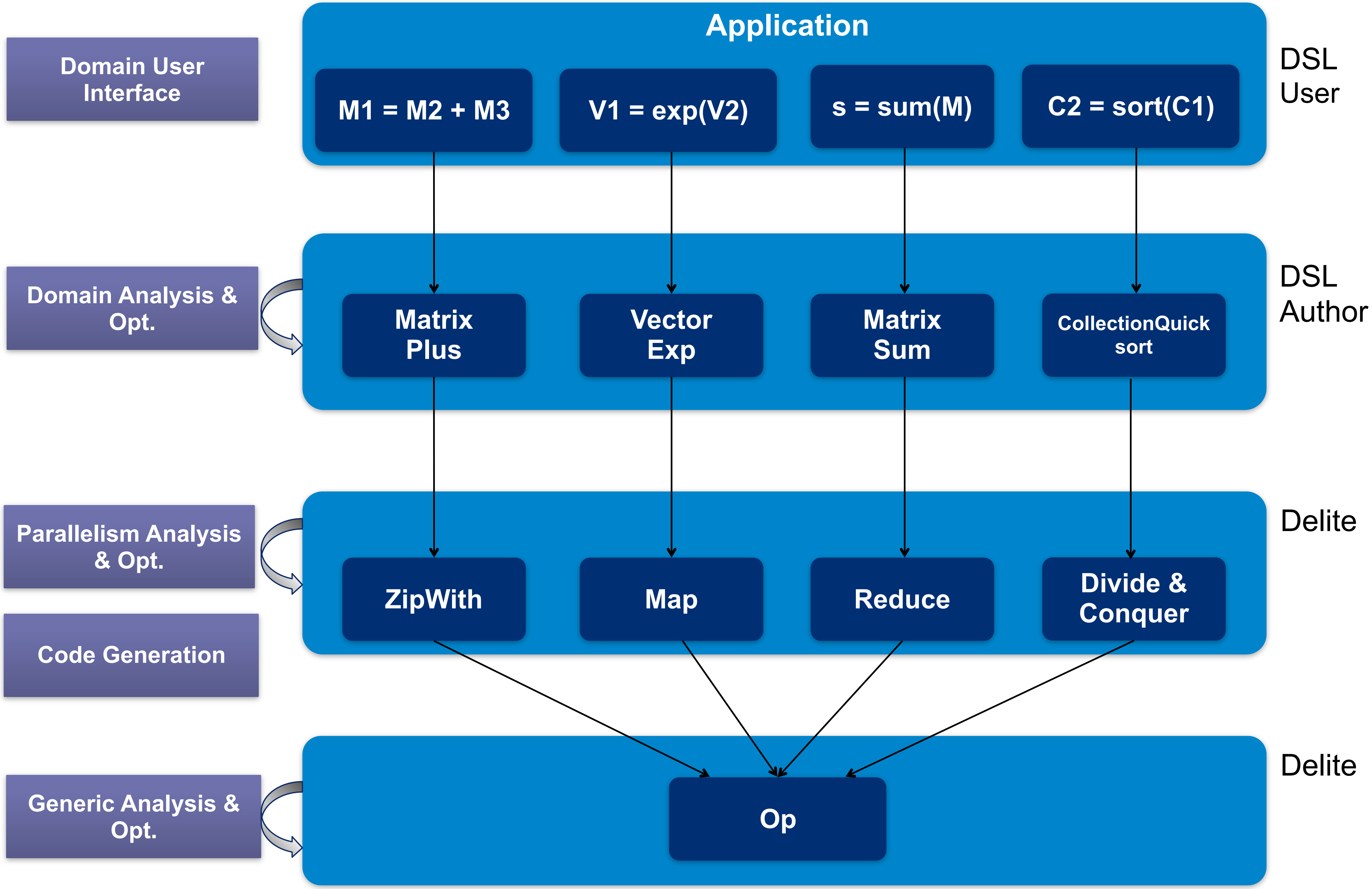
  EXAMPLE: `DeliteOpZip[T]`

- Parallel optimization of IR graph
- Compiler framework with support for heterogeneous hardware platforms
- DSL extends parallel operations

  EXAMPLE: `class Plus extends DeliteOpZip[Matrix]`

- Domain-specific analysis and optimization

The Delite IR Hierarchy



Domain User Interface

Application

M1 = M2 + M3

V1 = exp(V2)

s = sum(M)

C2 = sort(C1)

DSL User

Domain Analysis & Opt.

Matrix Plus

Vector Exp

Matrix Sum

CollectionQuicksort

DSL Author

Parallelism Analysis & Opt.

Code Generation

ZipWith

Map

Reduce

Divide & Conquer

Delite

Generic Analysis & Opt.

Op

Delite

Delite Ops

- Encode parallel execution patterns
  - **EXAMPLE:** data-parallel: map, reduce, zip, ...
- Delite provides implementations of these patterns for multiple hardware targets
  - **EXAMPLE:** multicore, GPU
- DSL developer maps each domain operation to the appropriate pattern

Optimization: Loop Fusion

Reduces loop overhead and improves locality

- Elimination of temporary data structures
- Communication through registers

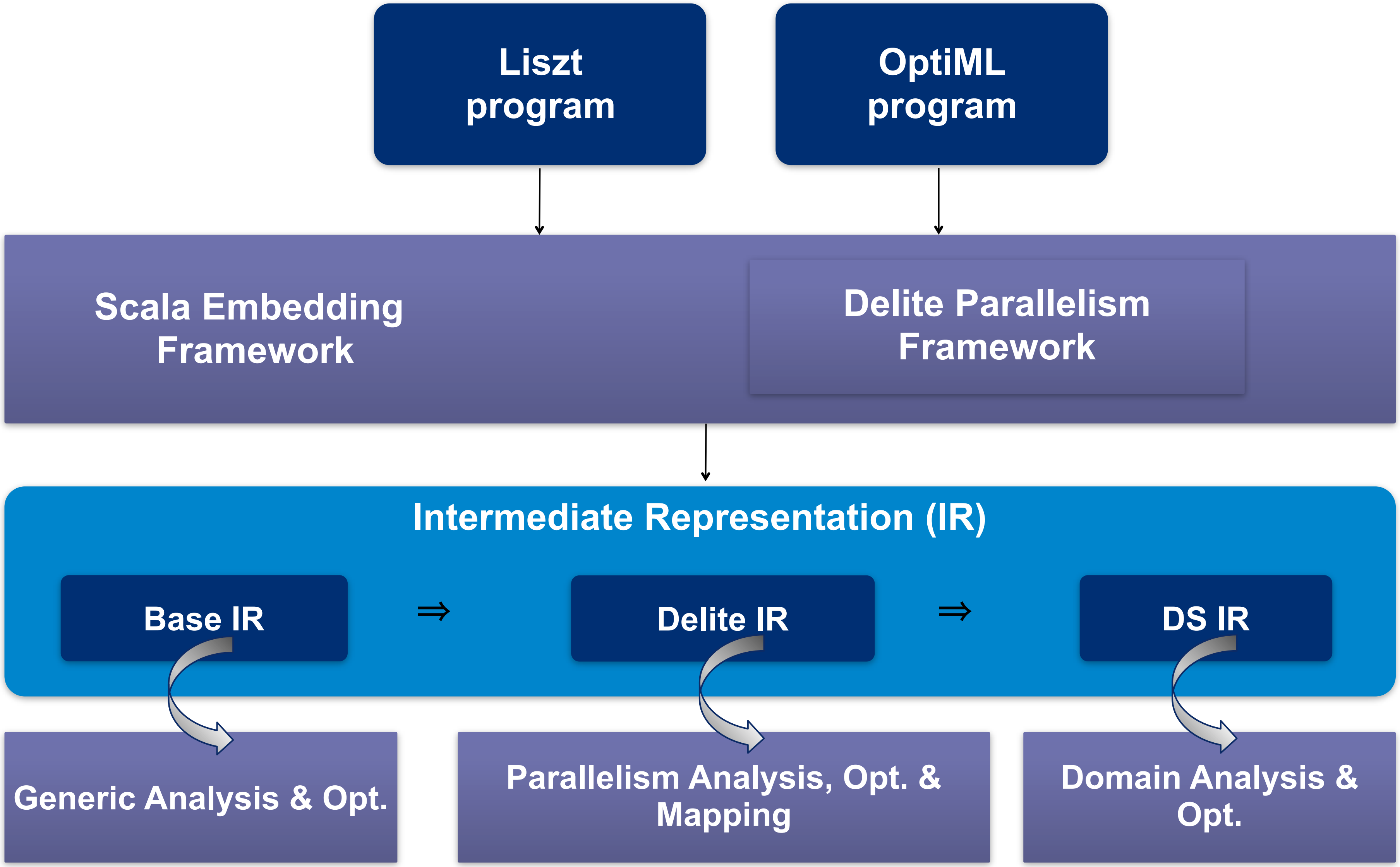
Fuse both dependent and side-by-side operations

- Fused operations can have multiple outputs

ALGORITHM: Fuse two loops if,

- `size(loop1) == size(loop2)`
- No dependencies exist that would require an impossible schedule when fused (e.g., C depends on B depends on A => cannot fuse C and A)

Delite DSL Compilers.



Liszt program

OptiML program

Scala Embedding Framework

Delite Parallelism Framework

Intermediate Representation (IR)

Base IR ⇒ Delite IR ⇒ DS IR

Generic Analysis & Opt.

Parallelism Analysis, Opt. & Mapping

Domain Analysis & Opt.

Delite: Conclusions.

- Need to simplify the process of developing DSLs for parallelism.
- Need programming languages to be designed for flexible embedding.
- Lightweight modular staging allows for powerful embedded DSLs.
- Delite provides a framework for adding parallelism.

THANK YOU.

Questions?

PhD Tips: Writing Papers

- Best help to earn you a PhD
  - But can earn PhD without a conference paper if practical contribution is worthwhile (in Europe)
- Follow Simon Peyton-Jones' advice on how to write a paper (it's motivating, too: write paper about any idea, no matter how small)

Submitting to a Conference

- Paper(s) accepted at conferences (as opposed to workshops) are best way to ensure you graduate soon
  - Acceptance at big conference (PLDI, POPL, OOPSLA, ECOOP) will earn PhD without any doubt (if you and advisor are authors)
  - But, second tier conference fine places to publish papers, too: actors paper with most impact appeared at a second class conference
  - Use deadlines to drive work (to some extent)

Doing Research

- Worst mistake: **Not** spending **1 hour per day** thinking really hard about your most important problem
    - Without **any** distractions
    - While working on an implementation, hard to make room for 1 hour **not at the computer**
    - Important to have deep thinking time that is not required to produce immediate result
- Balance between reading papers and thinking/programming yourself
    - Reading **the right papers** carefully most important