Lift: The Language, The IR and Code Generation

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Based on (Steuwer, Remmelg, Dubach, 2017)

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LIFT – An Intermediate Language

Algorithmic Patterns

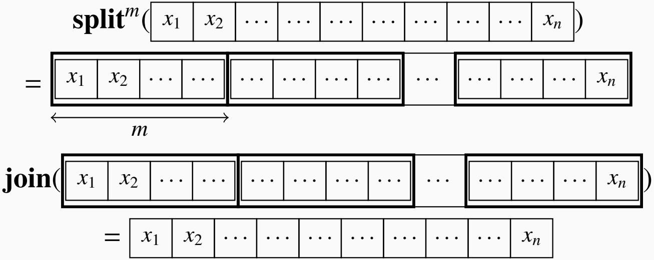
$$\textbf{mapSeq}(f, \boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1}) = \boxed{f(x_1)}\boxed{f(x_2)}\boxed{\cdots}\boxed{f(x_n)}$$

$$\textbf{reduceSeq}(z, f, \boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1}) = \boxed{f(\cdots(f(f(z, x_1), x_2)\cdots), x_n)}$$

$$\textbf{id}(\boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1}) = \boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1}$$

$$\textbf{iterate}^m(f, \boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1}) = \underbrace{f(\cdots(f(}_{m \text{ times}}\boxed{x_n}\boxed{\cdots}\boxed{x_2}\boxed{x_1})))$$

Data Layout Patterns



- Do not perform any computation
- Reorganize the data layout (**`View`**)

Data Layout Patterns

$$\textbf{gather}(f, \boxed{x_{f(1)}}\boxed{x_{f(2)}}\boxed{\cdots}\boxed{x_{f(n)}}) = \boxed{x_1}\boxed{x_2}\boxed{\cdots}\boxed{x_n}$$

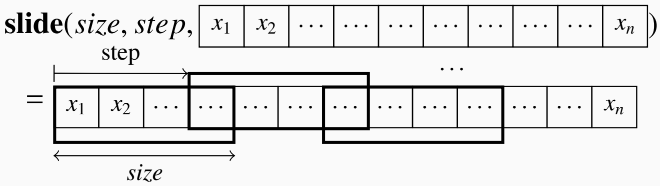
$$\textbf{scatter}(f, \boxed{x_1}\boxed{x_2}\boxed{\cdots}\boxed{x_n}) = \boxed{x_{f(1)}}\boxed{x_{f(2)}}\boxed{\cdots}\boxed{x_{f(n)}}$$

```
val transposeFunction = (outerSize: ArithExpr, innerSize: ArithExpr) =>
(i: ArithExpr, t: Type) => {
  val col = (i % innerSize) * outerSize
  val row = i / innerSize

  row + col
}

val Transpose = Split(N) o Gather(IndexFunction.transposeFunction(M, N)) o Join()
```

For examples of **`Gather`** and **`Scatter`** indexing functions, see *src/main/ir/ast/package.scala*

$$\mathbf{zip}(\boxed{x_1 \mid x_2 \mid \cdots \mid x_n}, \boxed{y_1 \mid y_2 \mid \cdots \mid y_n}) = \boxed{(x_1,y_1) \mid (x_2,y_2) \mid \cdots \mid (x_n,y_n)}$$

$$\mathbf{get}_i((x_1, x_2, \ldots, x_n)) = x_i$$



Parallel Patterns

- `mapWrg`^{0,1,2}
- `mapLcl`^{0,1,2}
- `mapGlb`^{0,1,2}

- `mapWarp`
- `mapLane`

- `mapAtomWrg`
- `mapAtomLcl`

Address Space Patterns

toGlobal **toLocal** **toPrivate**

```
MapWrg(MapLcl(toLocal(MapSeq(id))) $ X
```

- These primitives decouple the decision of *where* to store data from the decision of *how* the data is produced.

Vectorize Pattern

$$\textbf{asVector}(\begin{array}{|c|c|c|c|}\hline x_1 & x_2 & \cdots & x_n \\ \hline\end{array}) = \overrightarrow{x_1, x_2, \ldots, x_n},\ x_i \text{ is scalar}$$

$$\textbf{asScalar}(\overrightarrow{x_1, x_2, \ldots, x_n}) = \begin{array}{|c|c|c|c|}\hline x_1 & x_2 & \cdots & x_n \\ \hline\end{array}$$

$$\textbf{mapVec}(f, \overrightarrow{x_1, x_2, \ldots, x_n}) = \overrightarrow{f(x_1), f(x_2), \ldots, f(x_n)}$$

- During code generation, the LIFT compiler transforms f into a vectorized form using OpenCL built-in vectorized arithmetic operations whenever possible.
    - In other cases, f is applied to each scalar in the vector.

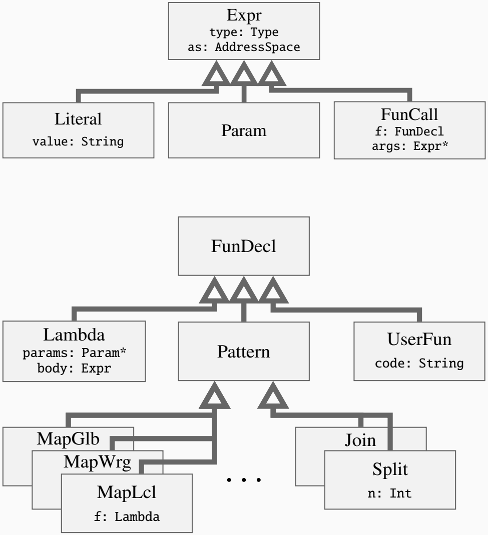
Low-level IRs

All LIFT primitives are either:

- High-level, capturing rich information about the algorithmic structure of programs
- Low-level and platform-specific (OpenCL, OpenCL for FPGAs, OpenMP, etc)

LIFT intermediate representation

Class diagram



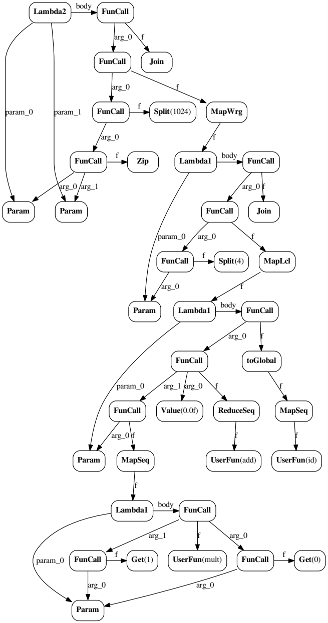
- **Expressions** represent values and have a type associated with.
- **Function declarations** represent callable entities: lambdas, patterns and user functions.

Dot product example

```
val dotProductLift = fun(
  ArrayTypeWSWC(Float, N),
  ArrayTypeWSWC(Float, N),
  (left, right) => {
    Join() o MapWrg(
      Join() o
      MapLcl(
        toGlobal(MapSeq(id)) o
        ReduceSeq(add, 0.0f) o
        MapSeq(mult)) o
      Split(4)
    ) o Split(1024) $ Zip(left, right)
  })
```

For more dot product variations, see
src/test/tutorial/applications/DotProduct.scala

Corresponding AST

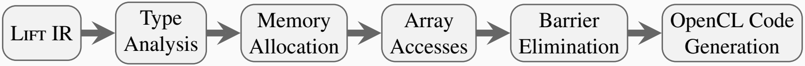


LIFT type system

- Scalar types: **`int`**, **`float`**, etc
- Vector types corresponding to OpenCL types **`int2`**, **`float4`**, etc
- Tuples
    - *Represented as* **`structs`** *in the generated OpenCL code*
- Arrays
    - Can be nested
    - Carry information about the size and capacity of each dimension in their type
    - This information is represented by arithmetic expressions (more on this later)

LIFT compilation

Compilation stages



- Compile: *src/main/opencl/executor/Compile.scala:44*
  - Type checking: *src/main/ir/TypeChecker.scala:39*
    - Example Pattern.checkType(): *src/main/opencl/ir/pattern/ReduceSeq.scala:11*
  - Generate: *src/main/opencl/generator/OpenCLGenerator.scala:176*
    - Memory address space inference: *src/main/opencl/ir/InferOpenCLAddressSpace.scala:18*
    - Domain-specific range inference: *src/main/opencl/generator/RangesAndCounts.scala:26*
    - Memory allocation: *src/main/ir/Type.scala:559*
    - Loop unrolling: *src/main/opencl/generator/ShouldUnroll.scala:50*
    - Barrier elimination: *src/main/opencl/generator/BarrierElimination.scala:41*
    - Views (array Accesses): *src/main/ir/view/View.scala:585*

Memory allocation

- The naive approach would be to allocate a new output buffer for every **`FunCall`** AST node
- We only allocate memory to the nodes where the called function contains a **`UserFun`**
- The size of the memory to allocate is inferred from the array length (or the associated **`View`**)
- The address space is inferred from **`FunCall`**

Memory allocation

```
input   : Lambda expression representing a program
output  : Expressions annotated with address space information

inferAddressSpaceProg(lambda)
foreach param in lambda.params do
    if param.type is ScalarType then param.as = PrivateMemory;
    else param.as = GlobalMemory;
inferASExpr(lambda.body, null)

inferASExpr(expr, writeTo)
switch expr.type do
    case Literal expr.as = PrivateMemory;
    case Param assert (expr.as != null);
    case FunCall
        foreach arg in expr.args do
            inferASExpr(arg, writeTo)
        switch expr.f.type do
            case is UserFun
                if writeTo != null then expr.as = writeTo;
                else expr.as = inferASFromArgs(expr.args);
            case is Lambda inferASFunCall(expr.f, expr.args, writeTo);
            case is toPrivate
             inferASFunCall(expr.f.lambda, expr.args, PrivateMemory);
            case is toLocal
             inferASFunCall(expr.f.lambda, expr.args, LocalMemory);
            case is toGlobal
             inferASFunCall(expr.f.lambda, expr.args, GlobalMemory);
            case is Reduce
             inferASFunCall(expr.f.f, expr.args, expr.f.init.as);
            case is Iterate or Map
             inferASFunCall(expr.f.f, expr.args, writeTo);
            otherwise do  expr.as = expr.args.as;

inferASFunCall(lambda, args, writeTo)
foreach p in lambda.params and a in args do p.as = a.as;
inferASExpr(lambda.body, writeTo)
```

Algorithm 1: Recursive address space inference algorithm

Array accesses

- In LIFT IR, arrays are accessed implicitly based on the patterns
- This eliminates arbitrary memory accesses and the associated problems
- However, expressing (efficient) pattern-transformed accesses is not obvious
- …which is where **`Views`** come to the rescue (but more on that later)

Barrier elimination

- We start by synchronizing after each occurrence of a parallel `Map`
- Then we remove barriers one by one in cases when it can be inferred that they are not required
    - When the data is not shared (i.e. `Split`, `Join`, `Gather` and `Scatter` are not used)
    - When the two parallel `Maps` are executed independently in separate branches of `Zip`

OpenCL code generation

- The AST is traversed recursively
- No OpenCL code is generated for the patterns that only affect `View`
- Low-level optimizations such as loop unrolling are applied to simplify the control flow using the information on *ranges* inferred from the patterns such as `mapLcl`

References

- Steuwer, Michel, Toomas Remmelg, and Christophe Dubach. "Lift: a functional data-parallel IR for high-performance GPU code generation." Code Generation and Optimization (CGO), 2017 IEEE/ACM International Symposium on. IEEE, 2017.
- Steuwer, Michel, Toomas Remmelg, and Christophe Dubach. "Matrix multiplication beyond auto-tuning: Rewrite-based GPU code generation." Compliers, Architectures, and Sythesis of Embedded Systems (CASES), 2016 International Conference on. IEEE, 2016.

http://www.lift-project.org/