Structured Ops in MLIR

Compiling Loops, Libraries and DSLs

MLIR Open Design Meeting - Dec 5th 2019

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Outline

MLIR Dialects for Codegen

Structured Ops Abstraction - Buffers

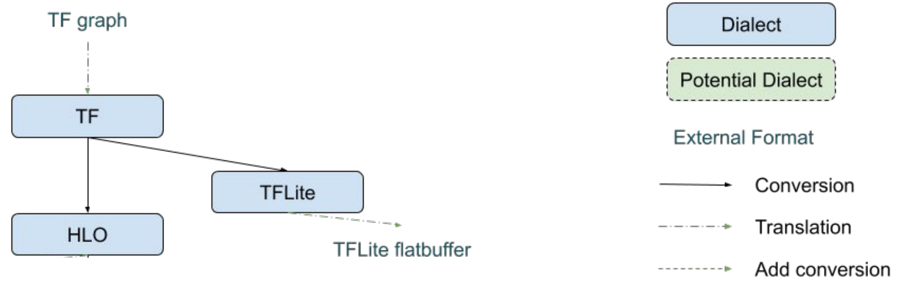
Structured Ops Abstraction - Vectors

Declarative Transformations with Composable Patterns

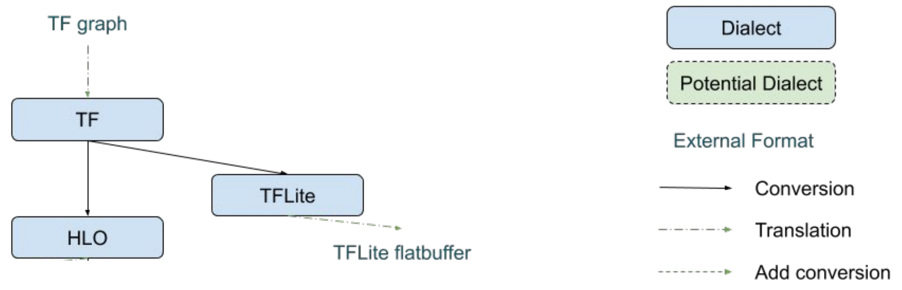
Conclusion

MLIR Dialects for Codegen

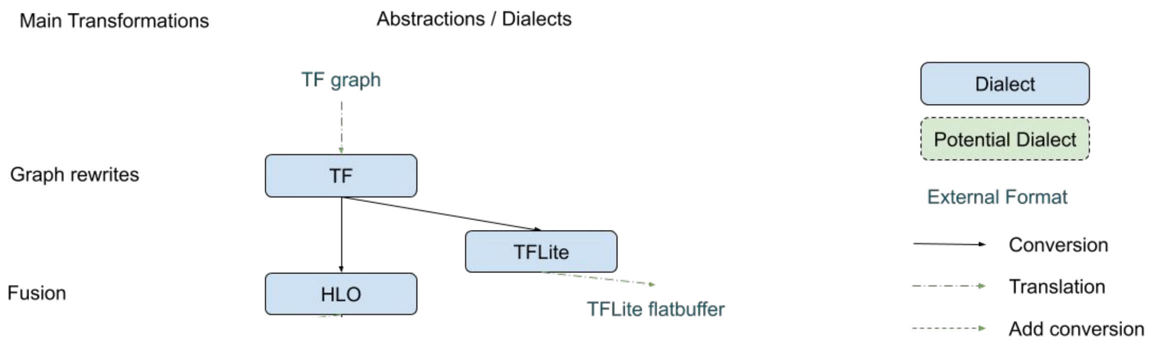
Abstractions / Dialects



Abstractions / Dialects




```
%0 = "xla_hlo.dot"(%arg0, %arg1) : (tensor<2x2xi32>, tensor<2x2xi32>) -> tensor<2x2xi32>
```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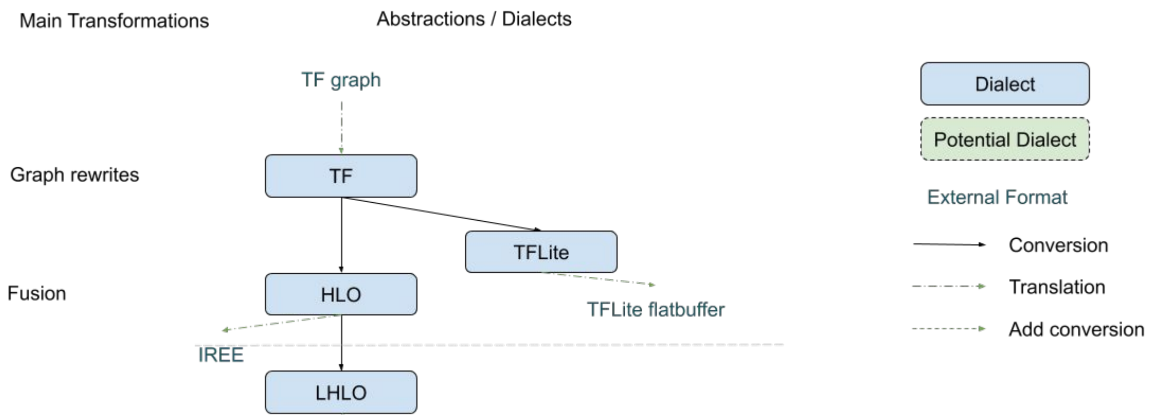
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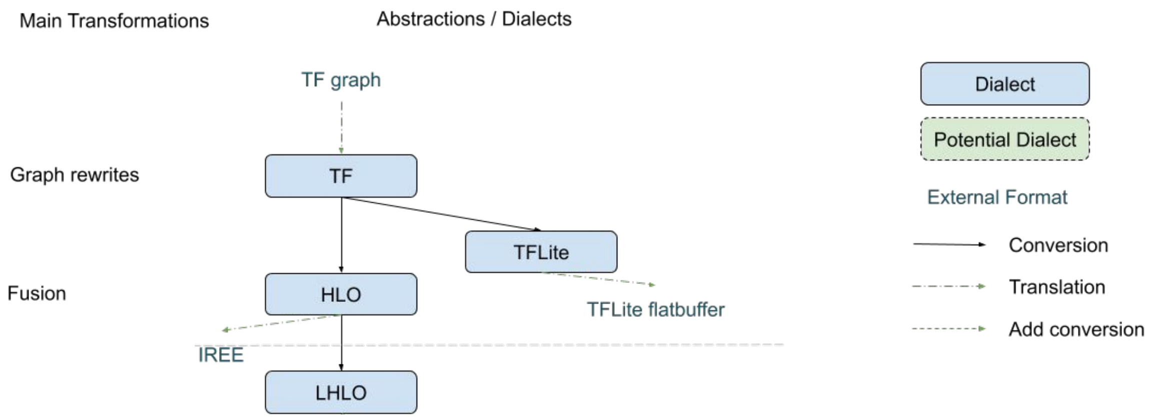
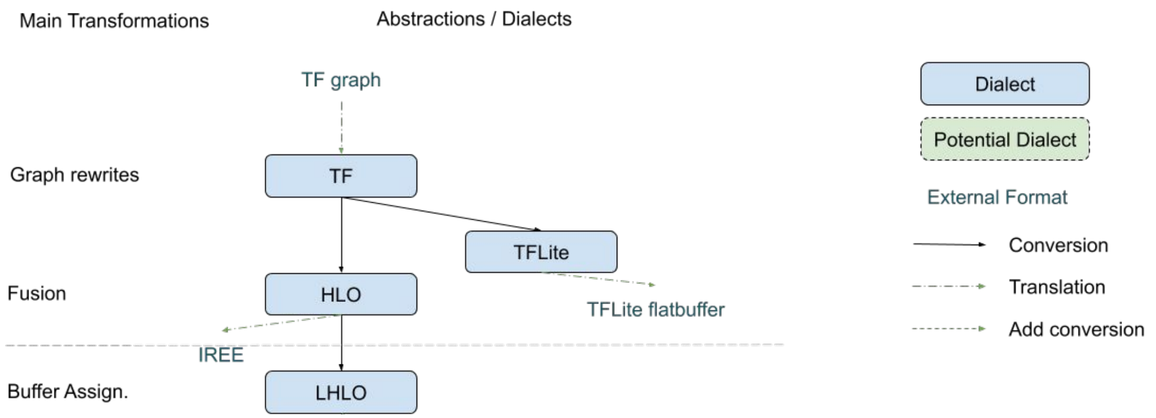
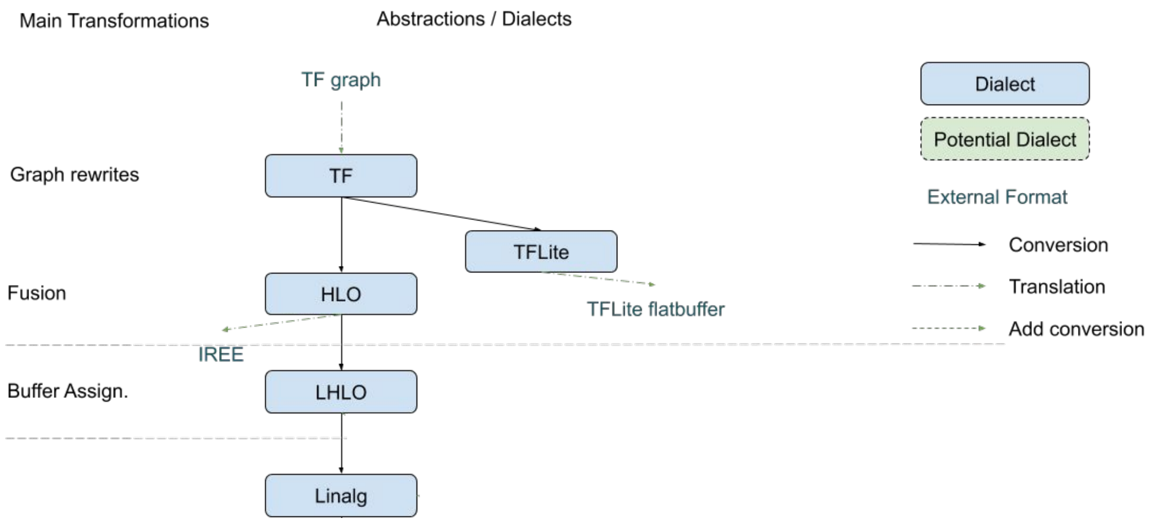



```
"xla_lhlo.mul"(%lhs, %rhs, %out) : (memref<10xf32>, memref<10xf32>, memref<10xf32>) -> ()
```

```
"xla_lhlo.fusion"() ( {
  %0 = tensor_load %input1 : memref<10xf32>
  %1 = tensor_load %input2 : memref<10xf32>
  %2 = "xla_hlo.add"(%0, %1) {name = "add"} : (tensor<10xf32>, tensor<10xf32>) -> tensor<10xf32>
  %3 = tensor_load %input3 : memref<10xf32>
  %4 = "xla_hlo.mul"(%2, %3) {name = "multiply"} : (tensor<10xf32>, tensor<10xf32>) -> tensor<10xf32>
  tensor_store %4, %out : memref<10xf32>
  "xla_lhlo.terminator"() : () -> ()
} ) : () -> ()
```




```
"xla_lhlo.mul"(%lhs, %rhs, %out) : (memref<10xf32>, memref<10xf32>, memref<10xf32>) -> ()
```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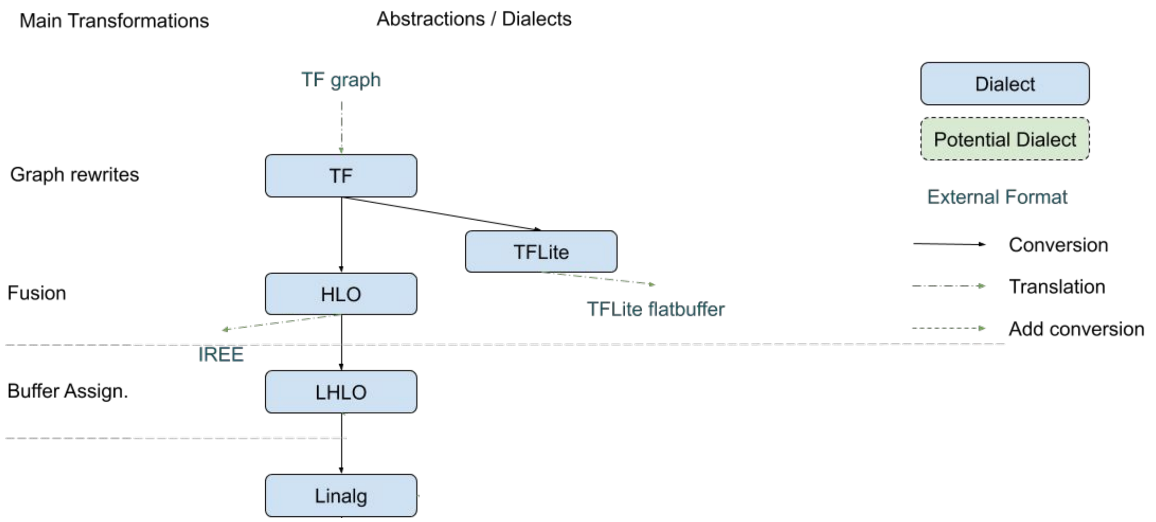


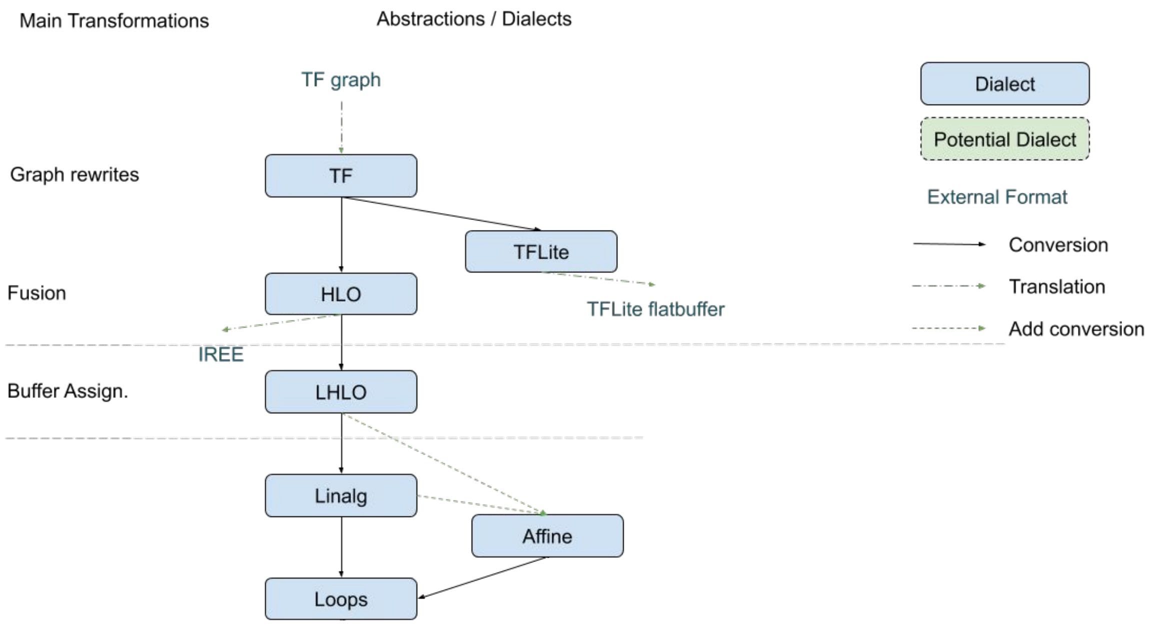

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  n_views = [2, 1],
  iterator_types = ["parallel", "parallel", "reduction"],
  indexing_maps = #matmul_accesses,
  library_call = "external_outerproduct_matmul"
}
```

```
!vector_type_A = type vector<4xf32>
!vector_type_B = type vector<4xf32>
!vector_type_C = type vector<4x4xf32>

!matrix_type_A = type memref<?x?x!vector_type_A>
!matrix_type_B = type memref<?x?x!vector_type_B>
!matrix_type_C = type memref<?x?x!vector_type_C>

func @matmul_vec_impl(%A: !matrix_type_A, %B: !matrix_type_B, %C: !matrix_type_C) {
  linalg.generic #matmul_trait %A, %B, %C {
    ^bb0(%a: !vector_type_A, %b: !vector_type_B, %c: !vector_type_C):
      %d = vector.outerproduct %a, %b, %c: !vector_type_A, !vector_type_B
      linalg.yield %d: !vector_type_C
  } : !matrix_type_A, !matrix_type_B, !matrix_type_C

  return
}
```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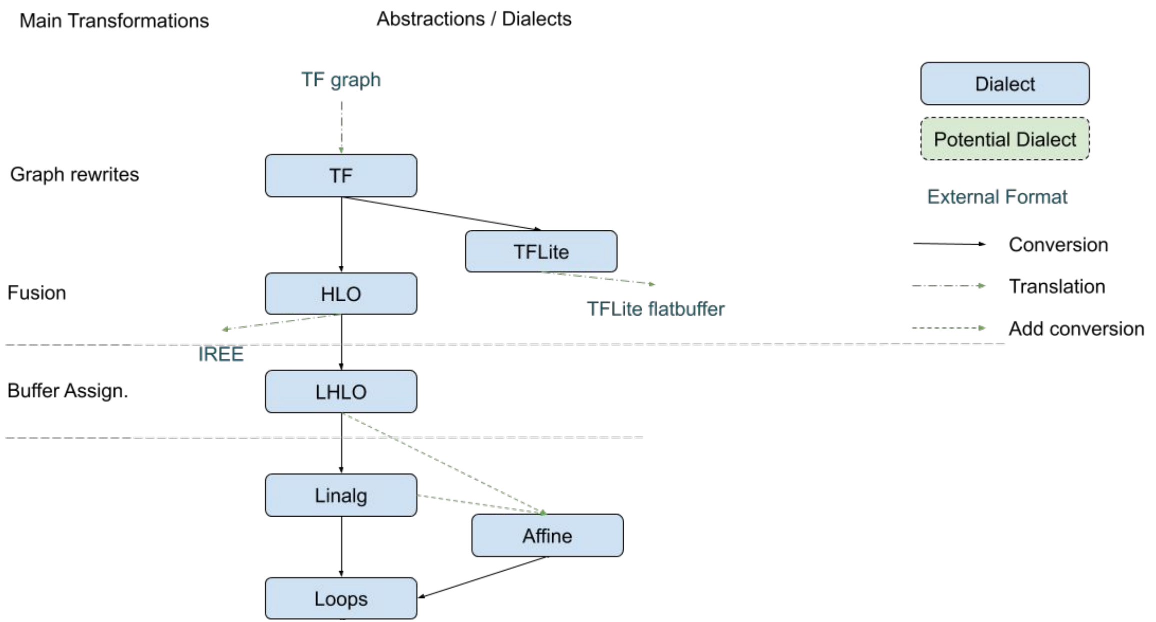
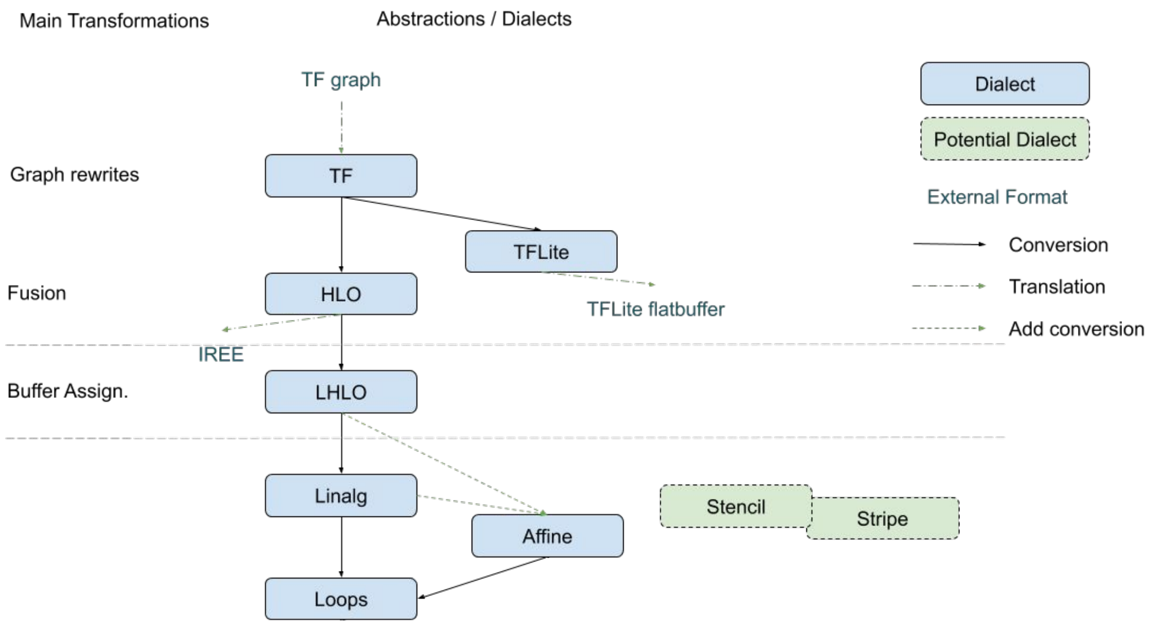



```
loop.for %i0 = %arg0 to %arg1 step %arg2 {
  loop.for %i1 = %arg0 to %arg1 step %arg2 {
    %min_cmp = cmpi "slt", %i0, %i1 : index
    %min = select %min_cmp, %i0, %i1 : index
    %max_cmp = cmpi "sge", %i0, %i1 : index
    %max = select %max_cmp, %i0, %i1 : index
    loop.for %i2 = %min to %max step %i1 {
    }
  }
```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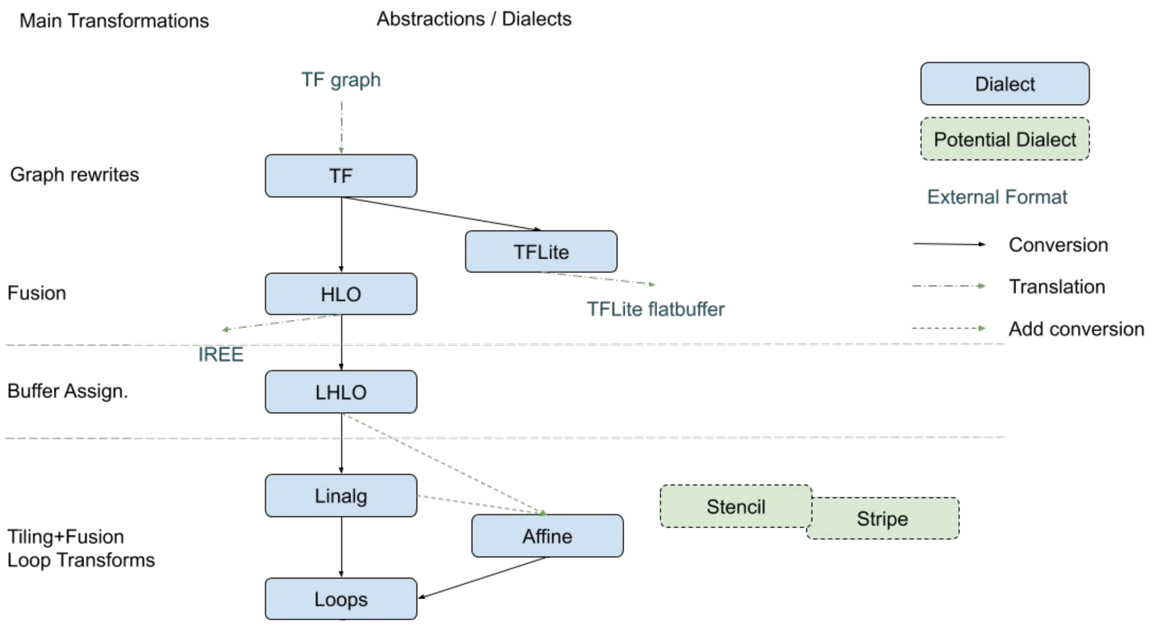
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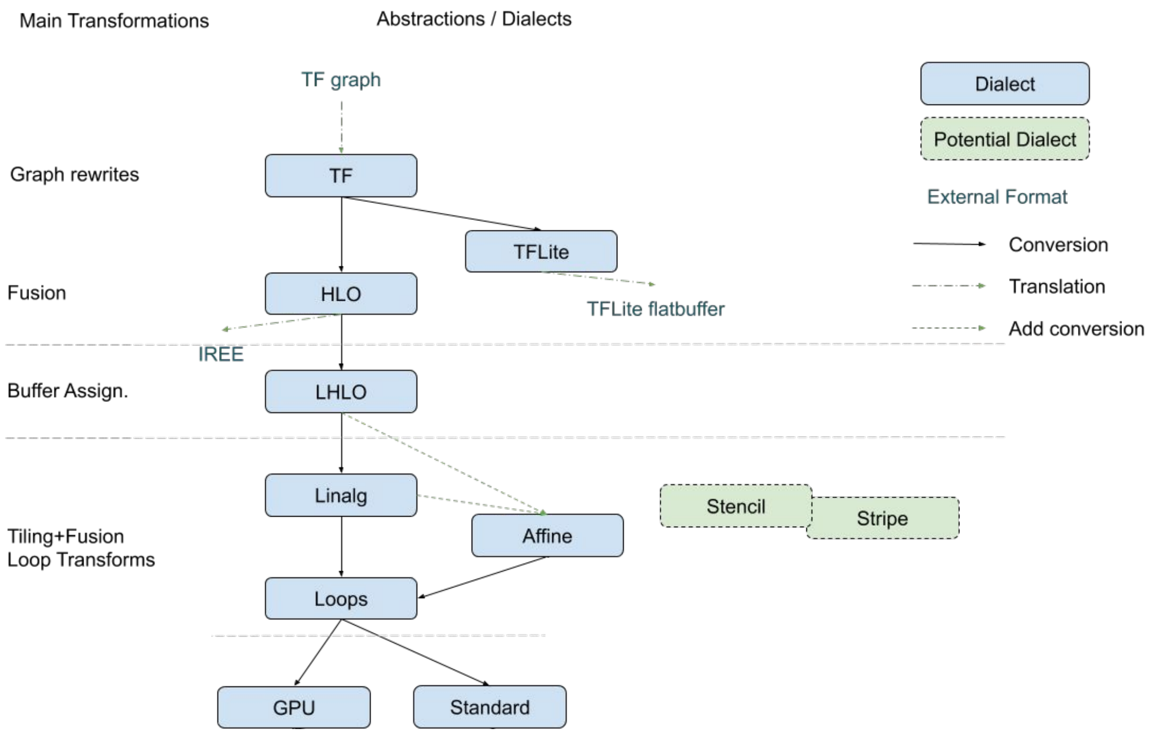
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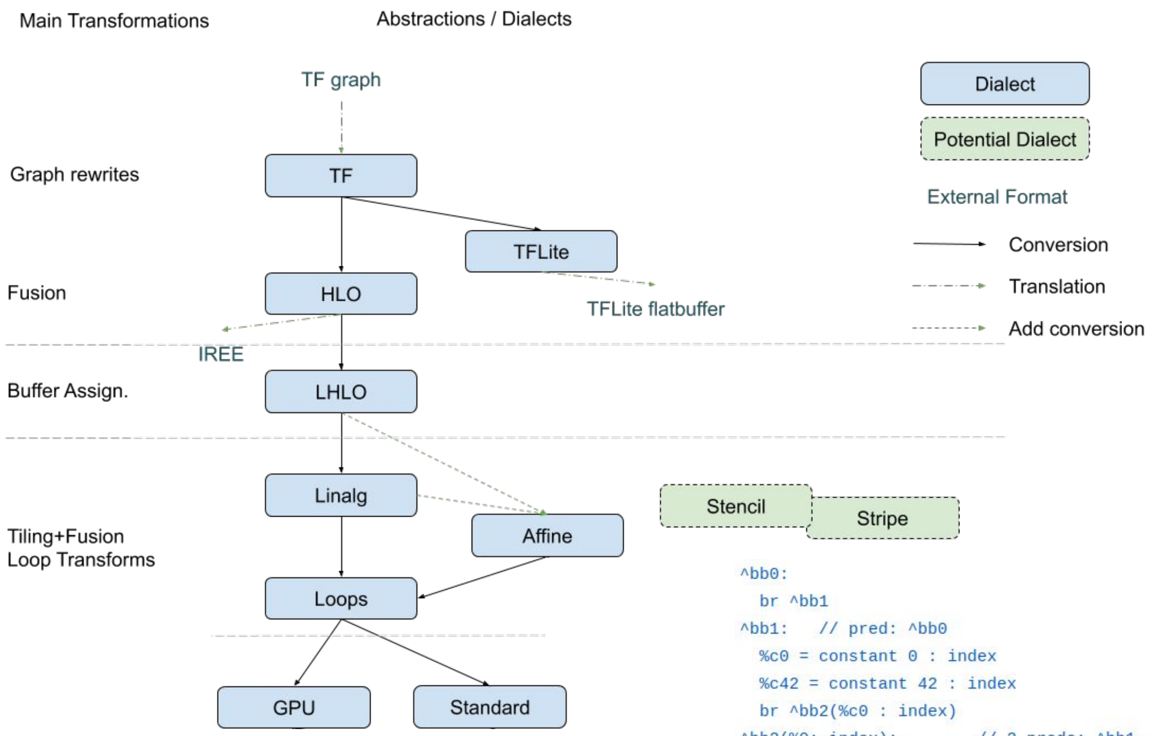
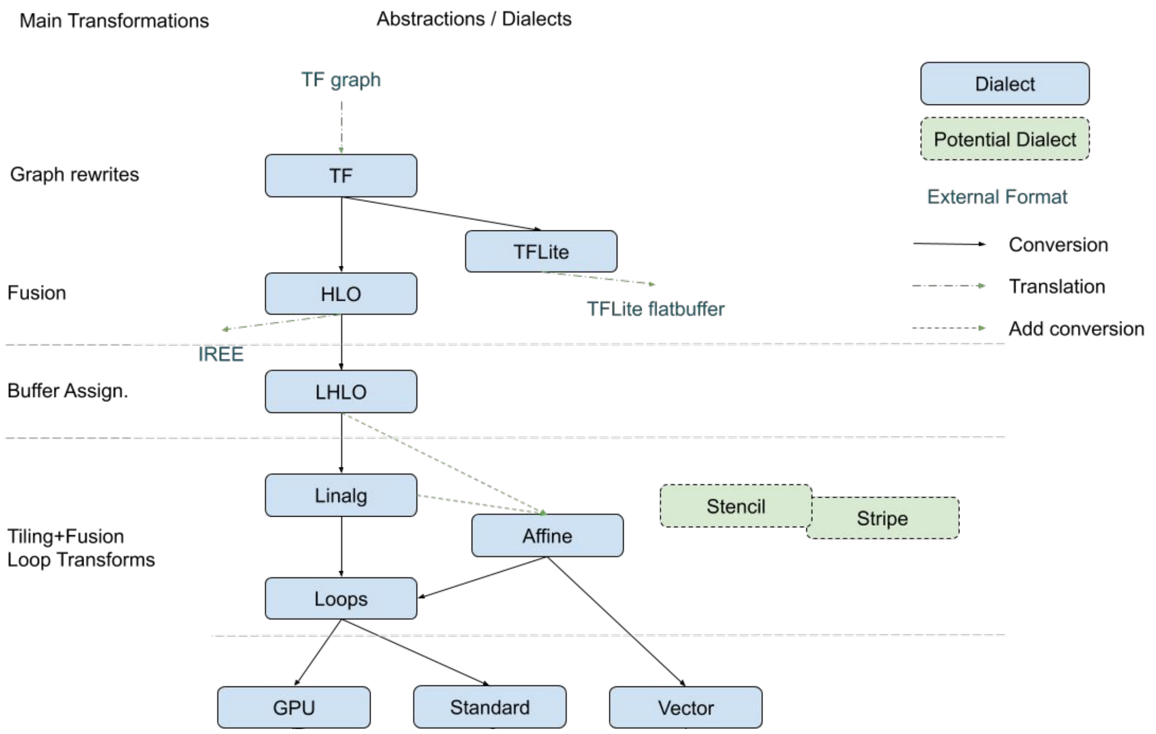



```
^bb0:
  br ^bb1
^bb1:   // pred: ^bb0
  %c0 = constant 0 : index
  %c42 = constant 42 : index
  br ^bb2(%c0 : index)
^bb2(%0: index):        // 2 preds: ^bb1, ^bb11
  %1 = cmpi "slt", %0, %c42 : index
  cond_br %1, ^bb3, ^bb12
^bb3:   // pred: ^bb2
  call @pre(%0) : (index) -> ()
  br ^bb4
^bb4:   // pred: ^bb3
  %c7 = constant 7 : index
  %c56 = constant 56 : index
  br ^bb5(%c7 : index)
```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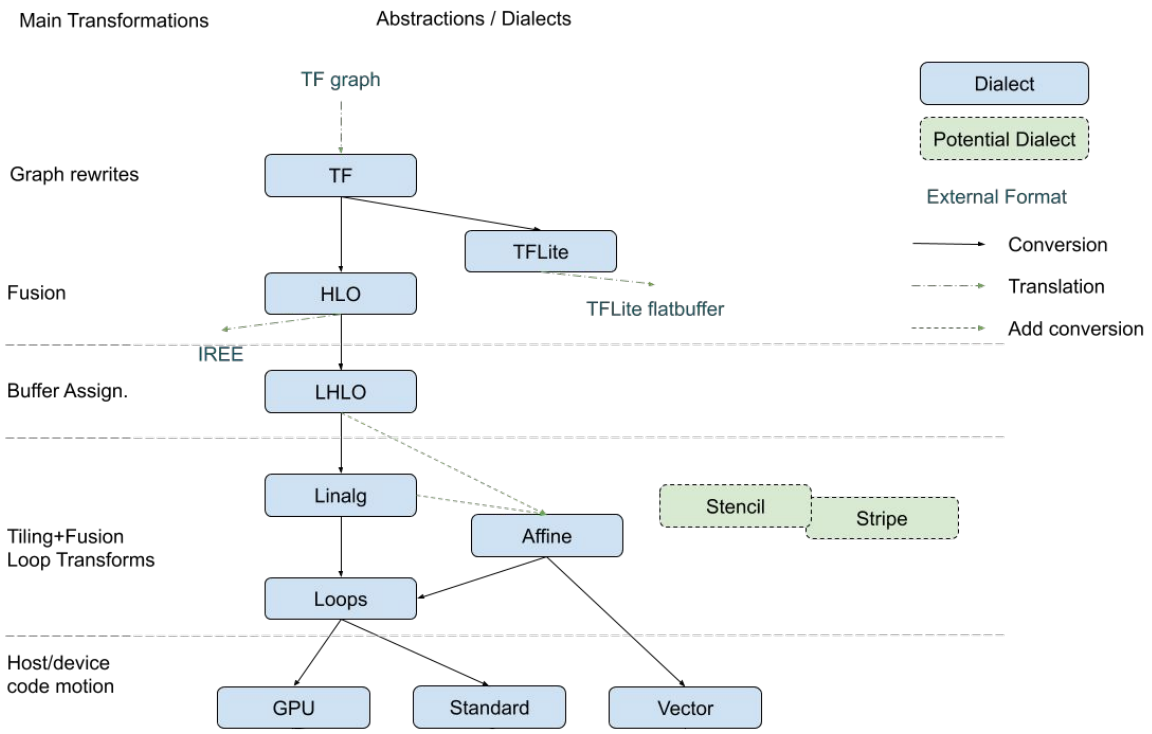
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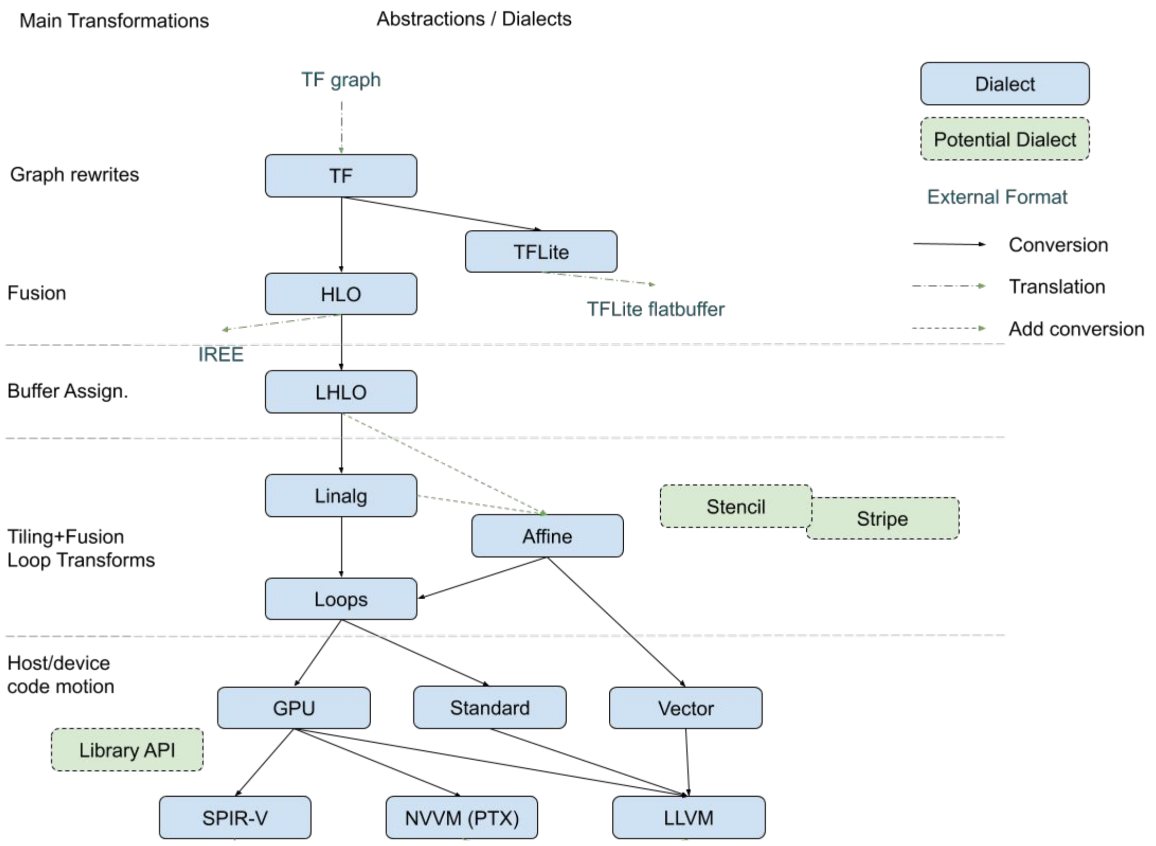
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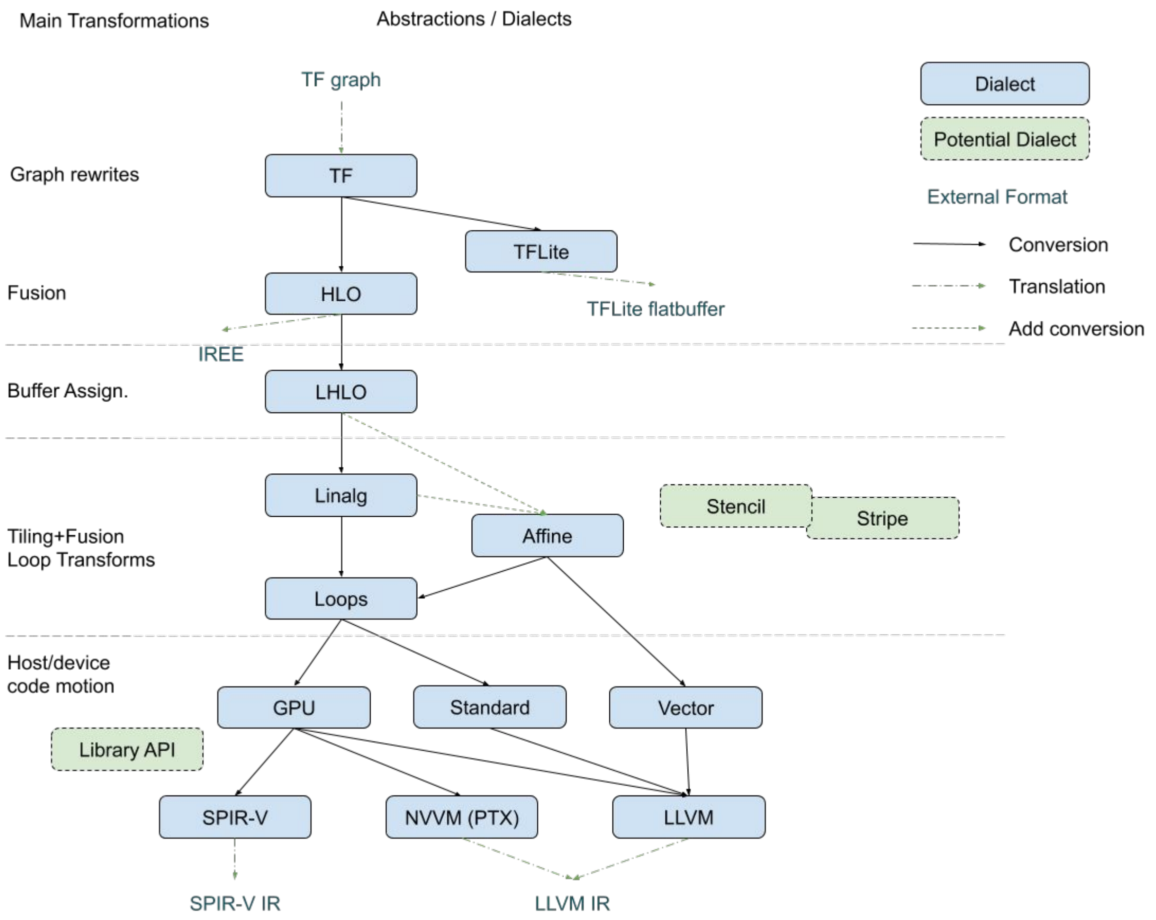
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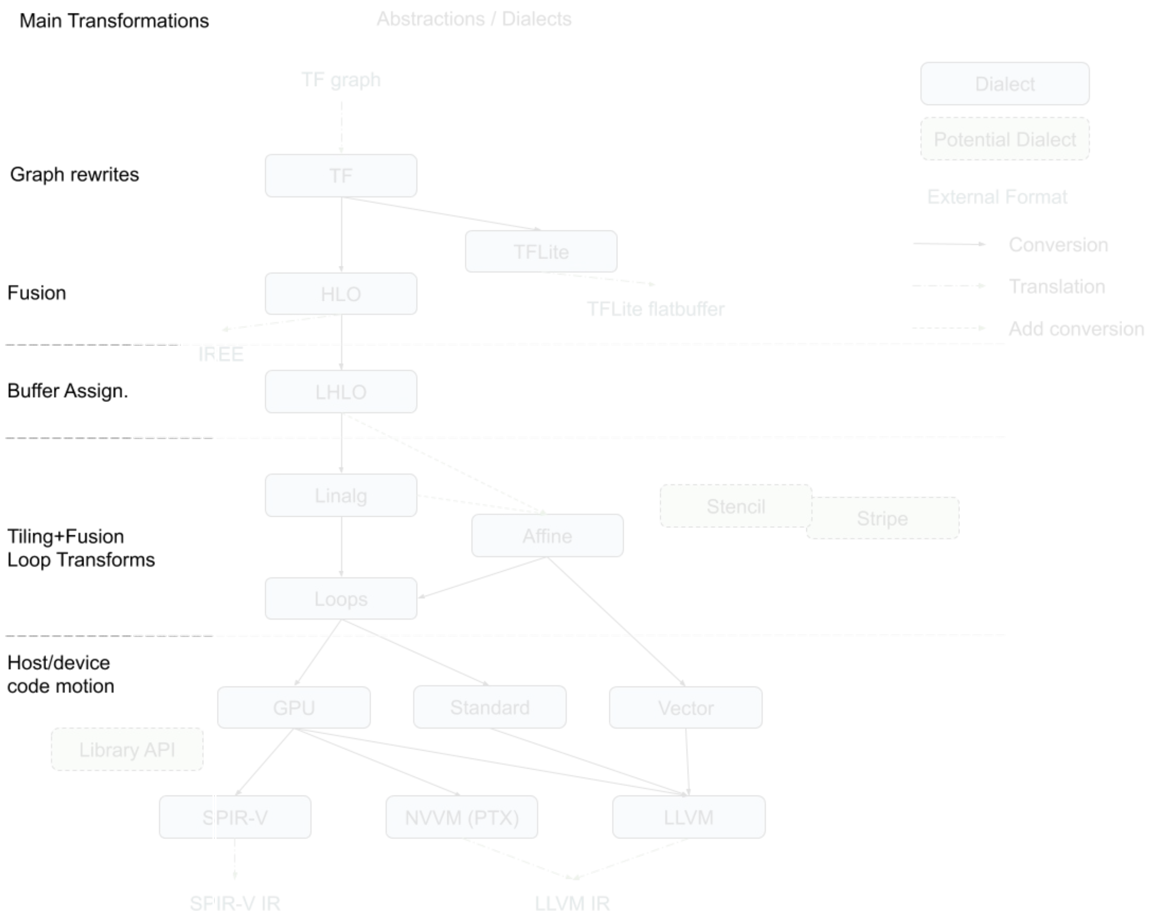
The lowering is not so much about transformations as it is about structure.

Or rather having the right structure at the right time.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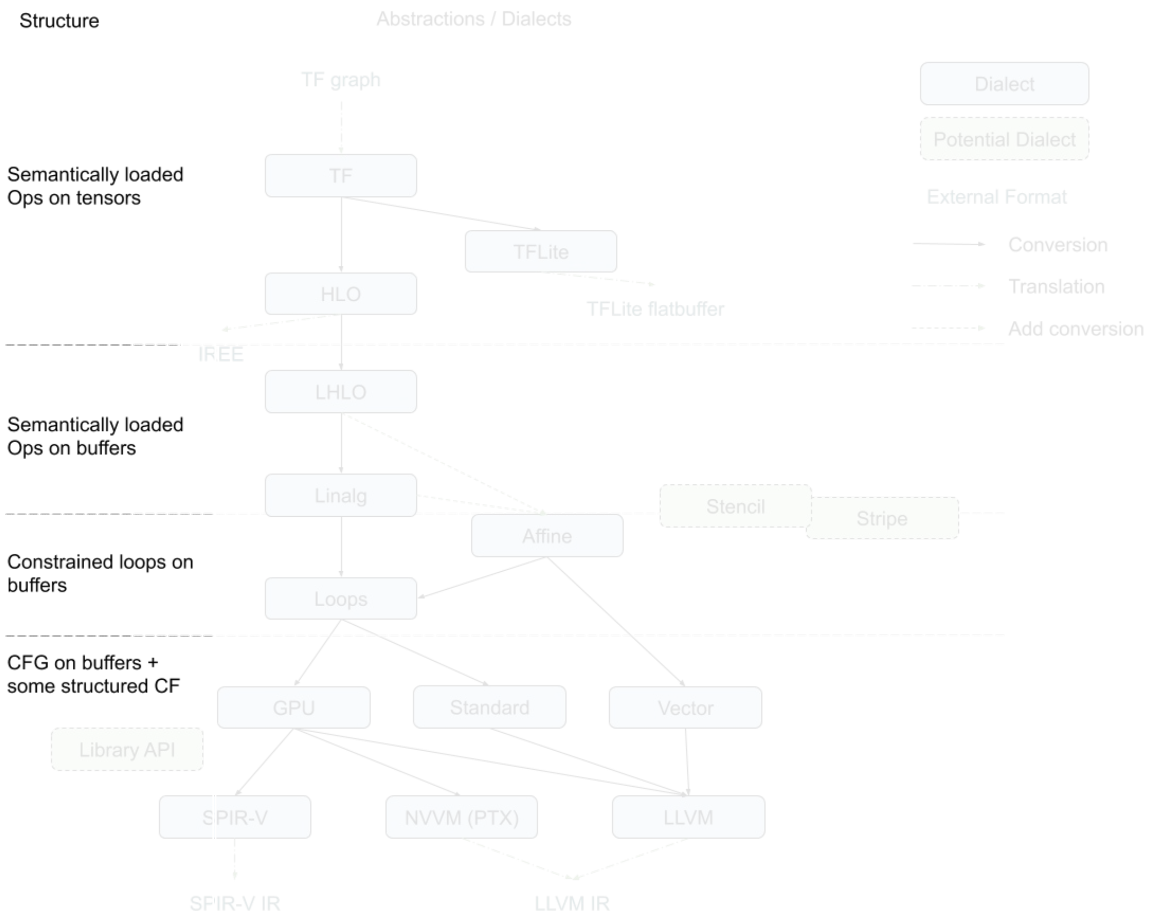
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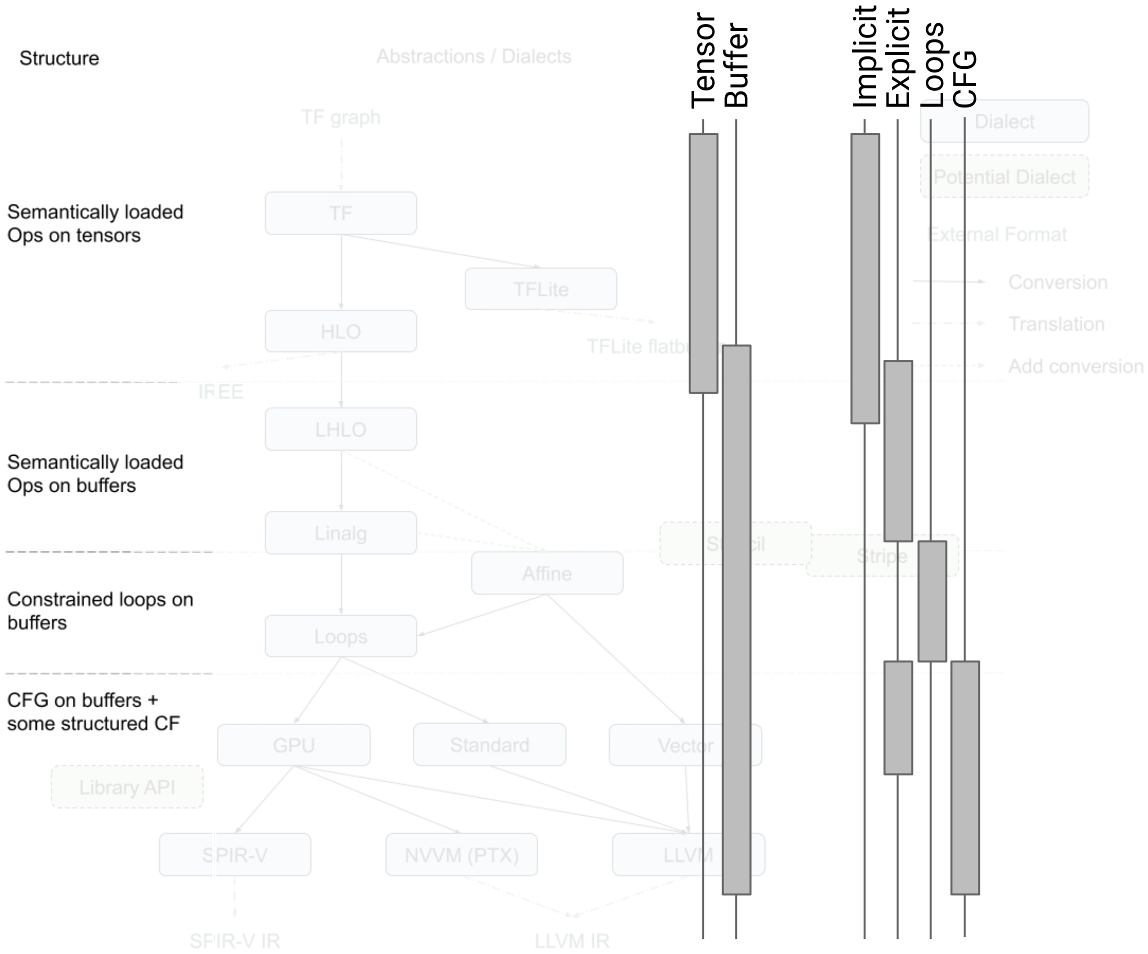
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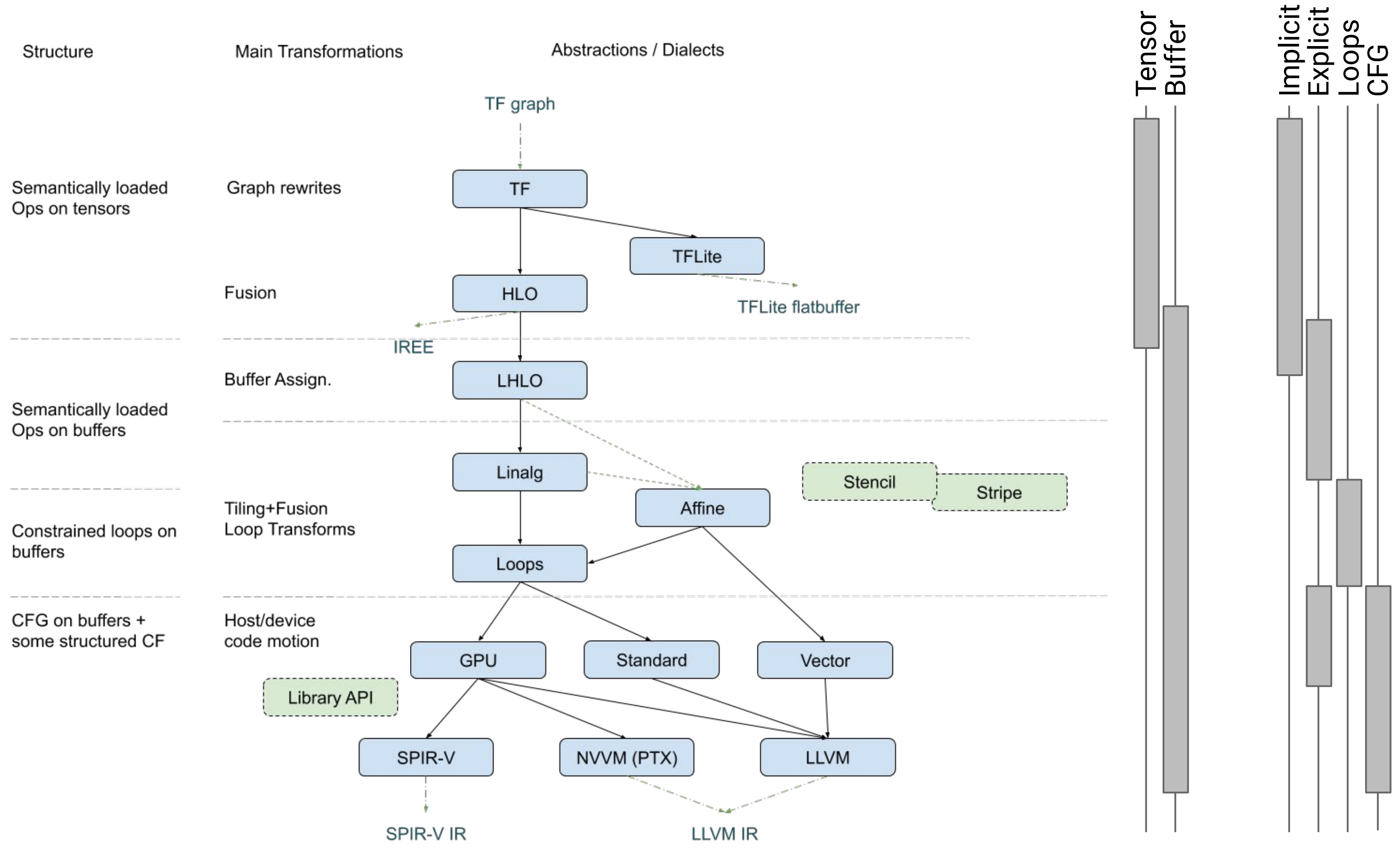
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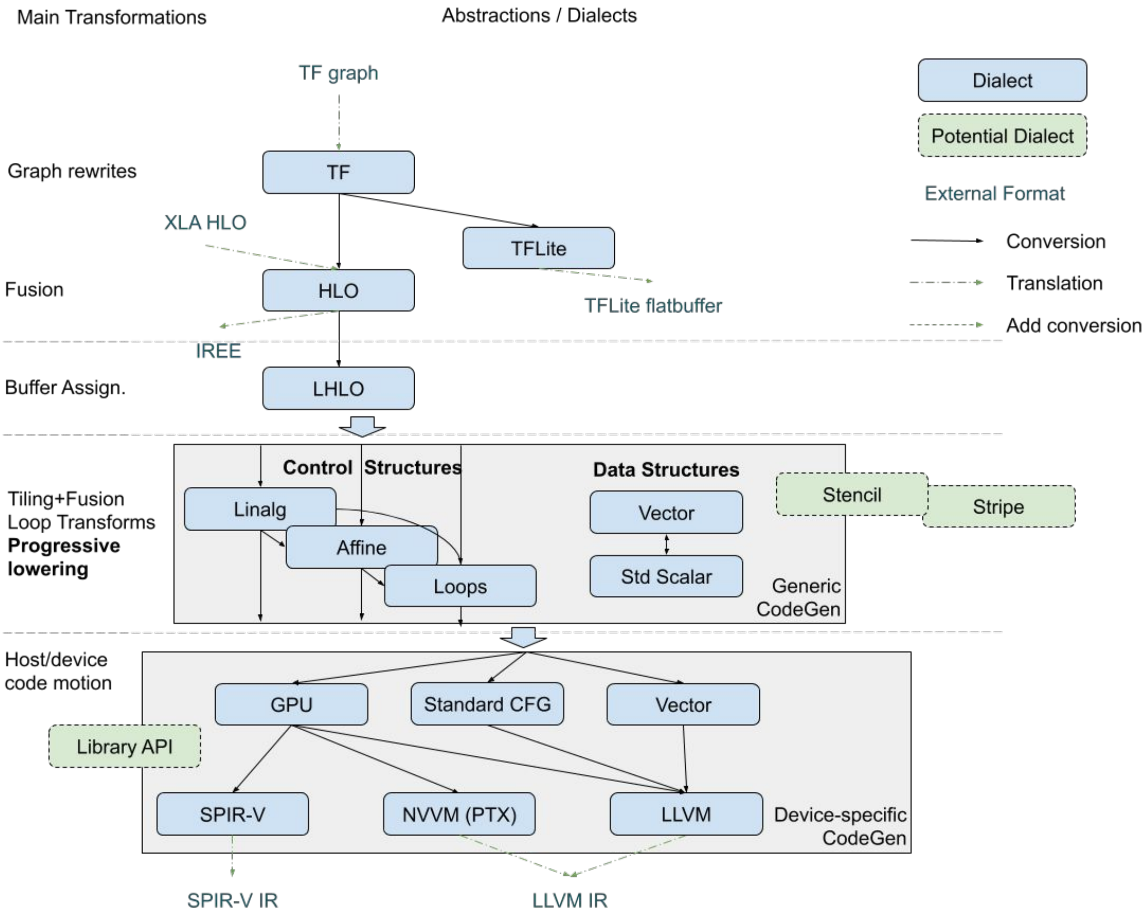

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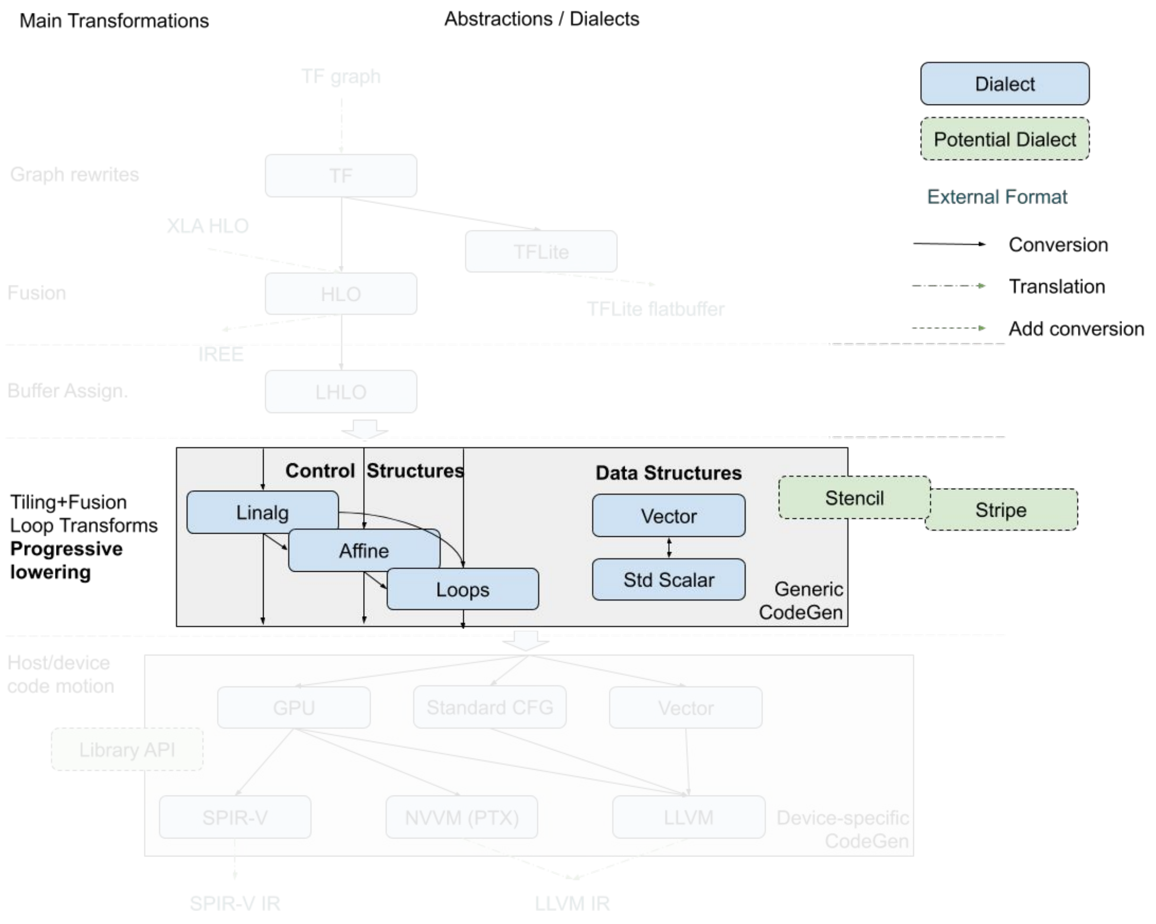

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Structured Ops Rationale

Philosophy: Transformations First

Transformations are the difference between

- a compiler (-O0)
- an optimizing compiler (-Ox)

Transformations are applied statically, they need some static information

Observation: Useful IR Entities That Bring Structure

Structured Types

- N-D vectors, memref, strided memref, memref with layout
- Dynamic evolution (ragged and sparse memref)
- Less regular but structured types: trees, concurrent hash maps, ...

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Structured Iterators

- Defined by data, not just a bag of control-flow
- Properties that enable transformations (parallel, reduction, tilable etc)

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Structured Iterators

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Structured Ops **combine** 3 “things”

- Tie structured types and structured iterators in a coherent unit
- Properties to simplify analyses and transformations
- High-level correspondence with library calls

Structured Ops Abstraction - Buffers

Structured Ops At The Buffer Level

Encode key properties in the **type system**, consistent with DSL philosophy

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, reduction],
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

Structured Ops At The Buffer Level

Key property: Input and Output Buffer Operands + Types

```
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    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
for … {
  …
  for … {
    %a = "load" %A[..., ...]: memref<?x?xf32>
    %b = "load" %B[..., ...]: memref<?x?xf32>
    %c = "load" %C[..., ...]: memref<?x?xf32>
    %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element types
    "store" %cc, %C[..., ...]: memref<?x?xf32>
} … }
```

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```

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  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
for … {
  …
    for … {
      %a = "load" %A[..., ...]: memref<?x?xf32>
      %b = "load" %B[..., ...]: memref<?x?xf32>
      %c = "load" %C[..., ...]: memref<?x?xf32>
      %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element types
      "store" %cc, %C[..., ...]: memref<?x?xf32>
} … }
```

Google

Structured Ops At The Buffer Level

Key property: Input and Output Buffer Operands + Types

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
for … {
  …
  for … {
    %a = "load" %A[..., ...]: memref<?x?xf32>
    %b = "load" %B[..., ...]: memref<?x?xf32>
    %c = "load" %C[..., ...]: memref<?x?xf32>
    %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element types
    "store" %cc, %C[..., ...]: memref<?x?xf32>
} … }
```

Google

Structured Ops At The Buffer Level

Key property: Domain traversal (Reversible mappings from iterations to data type)

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
%M = "dim" %A, 0: index
%K = "dim" %A, q: index
%KK = "dim" %B, 0: index
%N = "dim" %B, 1: index
%MM = "dim" %C, 0: index
%NN = "dim" %C, 1: index
%eq = "eq" %M, %MM: i1   // inferred iteration space is consistent with data
"assert" %eq: (i1) -> ()
            ...
for %m = 0 to %M {
  for %n = 0 to %N {
    for %k = 0 to %K {
      %a = "load" %A[%m, %k]: memref<?x?xf32>
      %b = "load" %B[%k, %n]: memref<?x?xf32>
      %c = "load" %C[%m, %n]: memref<?x?xf32>
      %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element type
      "store" %cc, %C[%m, %n]: memref<?x?xf32>
}}}
```

Google

Structured Ops At The Buffer Level

Key property: Domain traversal (Reversible mappings from iterations to data type)

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
%M = "dim" %A, 0: index
%K = "dim" %A, q: index
%KK = "dim" %B, 0: index
%N = "dim" %B, 1: index
%MM = "dim" %C, 0: index
%NN = "dim" %C, 1: index
%eq = "eq" %M, %MM: i1   // inferred iteration space is consistent with data
"assert" %eq: (i1) -> ()
        ...
for %m = 0 to %M {
  for %n = 0 to %N {
    for %k = 0 to %K {
      %a = "load" %A[%m, %k]: memref<?x?xf32>
      %b = "load" %B[%k, %n]: memref<?x?xf32>
      %c = "load" %C[%m, %n]: memref<?x?xf32>
      %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element type
      "store" %cc, %C[%m, %n]: memref<?x?xf32>
}}}
```

Structured Ops At The Buffer Level

Key property: Domain traversal (Reversible mappings from iterations to data type)

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
%M = "dim" %A, 0: index
%K = "dim" %A, q: index
%KK = "dim" %B, 0: index
%N = "dim" %B, 1: index
%MM = "dim" %C, 0: index
%NN = "dim" %C, 1: index
%eq = "eq" %M, %MM: i1    // inferred iteration space is consistent with data
"assert" %eq: (i1) -> ()
            ...
for %m = 0 to %M {
  for %n = 0 to %N {
    for %k = 0 to %K {
      %a = "load" %A[%m, %k]: memref<?x?xf32>
      %b = "load" %B[%k, %n]: memref<?x?xf32>
      %c = "load" %C[%m, %n]: memref<?x?xf32>
      %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element type
      "store" %cc, %C[%m, %n]: memref<?x?xf32>
}}}
```

Structured Ops At The Buffer Level

Key property: Custom computation with region (or MLIR function)

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
...
for %m = 0 to %M {
  for %n = 0 to %N {
    for %k = 0 to %K {
      %a = "load" %A[%m, %k]: memref<?x?xf32>
      %b = "load" %B[%k, %n]: memref<?x?xf32>
      %c = "load" %C[%m, %n]: memref<?x?xf32>
      %d = mulf %a, %b: f32                          // region body inlined
      %e = addf %d, %c: f32
      "store" %e, %C[%m, %n]: memref<?x?xf32>
}}}
```

Google

Structured Ops At The Buffer Level

Key property: Implicit iterator types (future: explicit mapping to virtual processor id)

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, reduction],
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
// iterator_types used for transformations,
// carry semantic information about dependences
```

Structured Ops At The Buffer Level

Key property: May correspond to an external library call

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, re
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
func @matmul_f32 (memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>) -> ()
call @matmul_f32 (%A, %B, %C): (memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>) -> ()

func @matmul_f32 (!llvm<"{ float*, i64, [2 x i64], [3 x i64] }*">,
                  !llvm<"{ float*, i64, [2 x i64], [3 x i64] }*">,
                  !llvm<"{ float*, i64, [2 x i64], [3 x i64] }*">) -> ()
llvm.call @matmul_f32 (%A, %B, %C): (!llvm<"{ float*, i64, [2 x i64], [3 x i64] }*">...) -> ()
```

Structured Ops At The Buffer Level

For more properties see the backup slides.

```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 1, args_out = 1,
  iterator_types = [parallel, parallel, r
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

```
%M = "dim" %A, 0: index
%K = "dim" %A, q: index
%KK = "dim" %B, 0: index
%N = "dim" %B, 1: index
%MM = "dim" %C, 0: index
%NN = "dim" %C, 1: index
%eq = "eq" %M, %MM: i1   // inferred iteration space is consistent with data
"assert" %eq: (i1) -> ()
            ...
for %m = 0 to %M {
  for %n = 0 to %N {
    for %k = 0 to %K {
      %a = "load" %A[%m, %k]: memref<?x?xf32>
      %b = "load" %B[%k, %n]: memref<?x?xf32>
      %c = "load" %C[%m, %n]: memref<?x?xf32>
      %cc = "compute"(%a, %b, %c): (f32, f32, f32) -> (f32) // compute arg types match element type
      "store" %cc, %C[%m, %n]: memref<?x?xf32>
}}}
```

Recap: Structured Ops At The Buffer Level

Encode key properties in the type system, consistent with DSL philosophy

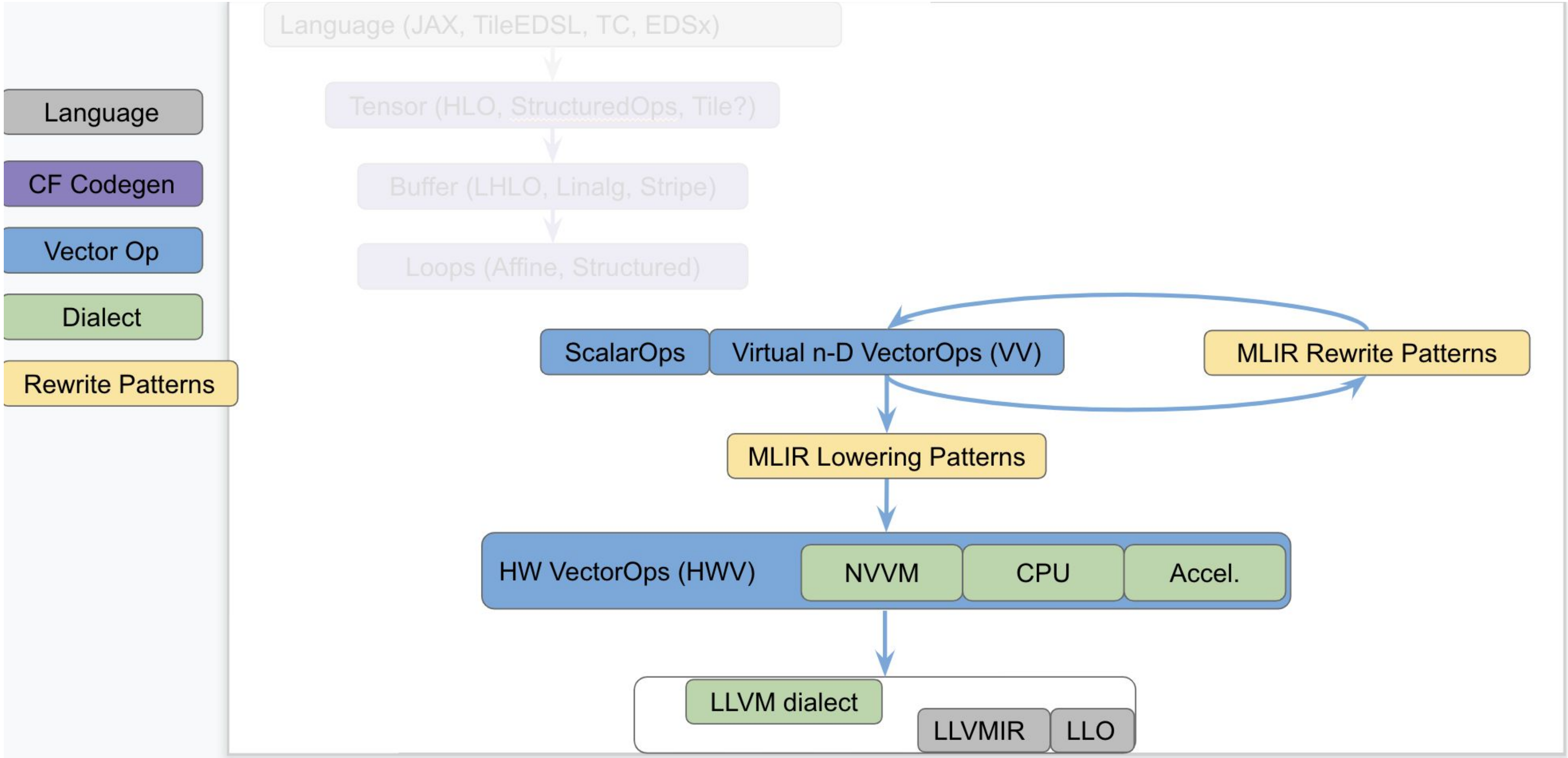
```
#matmul_accesses = [
  (m, n, k) -> (m, k),
  (m, n, k) -> (k, n),
  (m, n, k) -> (m, n)
]
#matmul_trait = {
  args_in = 2, args_out = 1,
  iterator_types = [parallel, parallel, reduction],
  indexing = #matmul_accesses,
  library_call = "matmul_f32"
}
"s.op" #matmul_trait (%A, %B, %C) {
  ^bb0(%a: f32, %b: f32, %c: f32):
    %d = mulf %a, %b: f32
    %e = addf %c, %d: f32
    "s.yield" %e: f32
} : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

Automatically Sugar Into (NYI)

```
s.matmul (%A, %B, %C) : memref<?x?xf32>, memref<?x?xf32>, memref<?x?xf32>
```

Structured Ops Abstraction - Vectors

Positioning of Vector Dialects



Structured Ops At The Vector Level

Encode key properties in the **type system**, consistent with DSL philosophy

```
#contraction_accesses = [
  (b0, f0, f1, c0, c1) -> (c0, b0, c1, f0),
  (b0, f0, f1, c0, c1) -> (b0, c1, c0, f1),
  (b0, f0, f1, c0, c1) -> (b0, f0, f1)
]
#contraction_trait = {
   indexing_maps = #contraction_accesses,
   iterator_types = [parallel, parallel, parallel, reduction, reduction]
}
```

```
%0 = vector.contract #contraction_trait %lhs, %rhs, %acc
      : vector<7x8x16x15xf32>, vector<8x16x7x5xf32> into vector<8x15x5xf32>
```

Structured Ops At The Vector Level

Encode key properties in the **type system**, consistent with DSL philosophy

```
#contraction_accesses = [
 (b0, f0, f1, c0, c1) -> (c0, b0, c1, f0),
 (b0, f0, f1, c0, c1) -> (b0, c1, c0, f1),
 (b0, f0, f1, c0, c1) -> (b0, f0, f1)
]
#contraction_trait = {
  indexing_maps = #contraction_accesses,
  iterator_types = [parallel, parallel, parallel, reduction, reduction]
}

%0 = vector.contract #contraction_trait0 %lhs, %rhs, %acc
      : vector<7x8x16x15xf32>, vector<8x16x7x5xf32> into vector<8x15x5xf32>
```

Structure

- Reduction dimensions known
  - enables selective unrolling
- Reduction dimensions separate (e.g. conv spatial dimensions)
  - avoids reshape

Structured Ops At The Vector Level

Encode key properties in the **type system**, consistent with DSL philosophy

```
#contraction_accesses = [
  (b0, f0, f1, c0, c1) -> (c0, b0, c1, f0),
  (b0, f0, f1, c0, c1) -> (b0, c1, c0, f1),
  (b0, f0, f1, c0, c1) -> (b0, f0, f1)
]
#contraction_trait = {
  indexing_maps = #c
  iterator_types = [parallel, parallel, parallel, reduction, reduction]
}

%0 = vector.contract #contraction_trait0 %lhs, %rhs, %acc
      : vector<7x8x16x15xf32>, vector<8x16x7x5xf32> into vector<8x15x5xf32>
```

Structure

- Reduction dimensions known
  - enables selective unrolling
- Reduction dimensions separate (e.g. conv spatial dimensions)
  - avoids reshape
- Operates on large vector aggregates (e.g. multiples of HW vector size).
- Aggregates multiple reduction dimension iterations
  - enables unroll and jam, unroll and pack

Declarative Transformations with Composable Patterns

Google

Structured Ops Transformations

Structured Ops allow the following composable transformations:

- Parametric Tiling
- Promotion to Temporary Buffer
- Producer-Consumer Fusion
- Mapping to Parallel HW
- Rewrite as Loop around finer-grained structured op
- Rewrite in Vector Form
- Call an HPC library (e.g. cuDNN, cuB, cuTLASS, MKL-DNN, BLIS, swizzle inventor)
- Lower to Affine
- Lower to LLVM
- Unroll to smaller vector form
- Vector rewrite patterns

How Are Structured Ops Transformations Composable?

Structured Ops provide a natural anchor point for pattern matching and rewriting

- Composes with transformations
  - tiling produces loops + structured ops
  - mapping produces loops + structured ops
  - fusion produces imperfectly nested loops + structured ops
- Structure
  - no need for complex matching rules on non-local pieces of IR

Until we **decide** to lower out of structured ops

⟶ Expose composable building blocks to define an optimization strategy: semi-automatic “schedule” like Halide, or fully automatic heuristic

Declarative Transformations (1) Multi-level Tiling

Match `s.matmul` (any type)

Capture op and arguments by name

Filter ops not marked as "L3"

```
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[2000, 3000, 4000], "L3"> $op), [(Constraint<Or<[HasNoMarker, HasMarker<"MEM">]>> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[200, 300, 400], "L2"> $op), [(Constraint<HasMarker<"L3">> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[20, 30, 40], "L1"> $op), [(Constraint<HasMarker<"L2">> $op)]>;
```

Tile by “sizes” and mark as tiled for "L1"

Transformations: Declarative Multi-level Tiling

```
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[2000, 3000, 4000], "L3"> $op), [(Constraint<Or<[HasNoMarker, HasMarker<"MEM">]>> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[200, 300, 400], "L2"> $op), [(Constraint<HasMarker<"L3">> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[20, 30, 40], "L1"> $op), [(Constraint<HasMarker<"L2">> $op)]>;
```

```
s.matmul (%A, %B, %C) : memref<?x?xf32, offset: ?, strides: [?, 1]> ...
```

Apply Tile<[2000, 3000, 4000], "L3">

Transformations (1) Declarative Multi-level Tiling

```
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[2000, 3000, 4000], "L3"> $op), [(Constraint<Or<[HasNoMarker, HasMarker<"MEM">]>> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[200, 300, 400], "L2"> $op), [(Constraint<HasMarker<"L3">> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[20, 30, 40], "L1"> $op), [(Constraint<HasMarker<"L2">> $op)]>;
```

Apply Tile<[2000, 3000, 4000], "L3">

```
...
for %i = %c0 to %6 step %c2000 {
  for %k = %c0_0 to %7 step %c3000 {
    for %k = %c0_1 to %8 step %c4000 {
      %9 = affine.apply (d0) -> (d0 + 2000)(%i)
      ...
      %16 = s.subview %A[%12, %13, %c1, %14, %15, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      %21 = s.subview %B[%17, %18, %c1, %19, %20, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      %26 = s.subview %C[%22, %23, %c1, %24, %25, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      s.matmul (%16, %21, %26) {__internal__ = "L3"} : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>,  ...
```

Apply Tile<[200, 300, 400], "L2">

Transformations (1) Declarative Multi-level Tiling

```
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[2000, 3000, 4000], "L3"> $op), [(Constraint<Or<[HasNoMarker, HasMarker<"MEM">]>> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[200, 300, 400], "L2"> $op), [(Constraint<HasMarker<"L3">> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[20, 30, 40], "L1"> $op), [(Constraint<HasMarker<"L2">> $op)]>;
```

Apply Tile<[200, 300, 400], "L2">

```
...
for %i = %c0 to %0 step %c2000 {
  for %j = %c0 to %2 step %c3000 {
    for %k = %c0 to %1 step %c4000 {
      %3 = affine.apply (d0) -> (d0)(%i)
      ...
      %7 = s.subview %A[%3, %4, %c1, %5, %6, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      %12 = s.subview %B[%8, %9, %c1, %10, %11, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      %17 = s.subview %C[%13, %14, %c1, %15, %16, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      for %ii = %c0_0 to %24 step %c200 {
        for %jj = %c0_1 to %25 step %c300 {
          for %kk = %c0_2 to %26 step %c400 {
            %27 = affine.apply (d0) -> (d0 + 200)(%ii)
            ...
            %34 = s.subview %7[%30, %31, %c1, %32, %33, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
            ...
            %39 = s.subview %12[%35, %36, %c1, %37, %38, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
            ...
            %44 = s.subview %17[%40, %41, %c1, %42, %43, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
            s.matmul (%34, %39, %44) {__internal_linalg_transform__ = "L2"} : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)> ...
```

Apply Tile<[20, 30, 40], "L1">

Google

Transformations (1) Declarative Multi-level Tiling

```
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[2000, 3000, 4000], "L3"> $op), [(Constraint<Or<[HasNoMarker, HasMarker<"MEM">]>> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[200, 300, 400], "L2"> $op), [(Constraint<HasMarker<"L3">> $op)]>;
def : Pat<(MatmulOp:$op $A, $B, $C), (Tile<[20, 30, 40], "L1"> $op), [(Constraint<HasMarker<"L2">> $op)]>;
```

Apply Tile<[20, 30, 40], "L1">

```
...
for %i = %c0 to %0 step %c2000 {
  for %j = %c0 to %2 step %c3000 {
    for %k = %c0 to %1 step %c4000 {
      %3 = affine.apply (d0) -> (d0 + 2000)(%i)
      ...
      %11 = s.subview %C[%D, %9, %c1, %E, %10, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
      ...
      for %arg6 = %c0 to %12 step %c200 {
        for %arg7 = %c0 to %14 step %c300 {
          for %arg8 = %c0 to %13 step %c400 {
            %15 = affine.apply (d0) -> (d0)(%arg6)
            ...
            %29 = s.subview %11[%25, %26, %c1, %27, %28, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
            ...
            for %arg9 = %c0_0 to %36 step %c20 {
              for %B0 = %c0_1 to %37 step %c30 {
                for %B1 = %c0_2 to %38 step %c40 {
                  %39 = affine.apply (d0) -> (d0 + 20)(%arg9)
                  ...
                  %46 = s.subview %19[%42, %43, %c1, %44, %45, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
                  ...
                  %51 = s.subview %24[%47, %48, %c1, %49, %50, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
                  ...
                  %56 = s.subview %29[%52, %53, %c1, %54, %55, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
                  s.matmul (%46, %51, %56) {__internal__ = "L1"} : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>, ...
```

Transformations (2) Declarative Producer-Consumer Fusion

Match `s.matmul` (any type)

Capture op and arguments by name

```
def : Pat<(MatmulOp:$consumer $A, $B, $C), (TileAndFuse<[100, 150], "L2"> $consumer),
        [ (Constraint<HasNoLinalgTransformMarker> $consumer), (Constraint<IsProducedByOpOfType<"MatmulOp">> $consumer, $A)],
        (addBenefit 1)>;
```

Explicitly give higher priority

Filter ops whose first argument is not produced by a `s.matmul` (any type)

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Transformations (2) Declarative Producer-Consumer Fusion

```
def : Pat<(MatmulOp:$consumer $A, $B, $C), (TileAndFuse<[100, 150], "L2"> $consumer),
      [ (Constraint<HasNoLinalgTransformMarker> $consumer), (Constraint<IsProducedByOpOfType<"MatmulOp">> $consumer, $A)],
      (addBenefit 1)>;
```

```
// This will not be fused as it would violate dependencies. It will just get tiled for all levels of the memory hierarchy.
s.matmul (%A, %A, %C) : memref<?x?xf32, offset: ?, strides: [?, 1]>, ...

// This will be fused into the last op and bypass s.generic.
s.matmul (%A, %B, %C) : memref<?x?xf32, offset: ?, strides: [?, 1]>, ...

// This will not be fused or transformed at all since there are no patterns on it. However it will be reordered because there are no dependencies.
s.generic #some_generic_trait %A, %D {
  ^bb(%a: f32, %b: f32) :
    "s.yield" %a : f32
} : memref<?x?xf32, offset: ?, strides: [?, 1]>, memref<?x?xf32, offset: ?, strides: [?, 1]>

// This will be fused into and then will continue tiling.
s.matmul (%C, %D, %E) : memref<?x?xf32, offset: ?, strides: [?, 1]>, ...
```

Apply TileAndFuse<[100, 150], "L2">

Transformations (2) Declarative Producer-Consumer Fusion

```
def : Pat<(MatmulOp:$consumer $A, $B, $C), (TileAndFuse<[100, 150], "L2"> $consumer),
    [ (Constraint<HasNoLinalgTransformMarker> $consumer), (Constraint<IsProducedByOpOfType<"MatmulOp">> $consumer, $A)],
    (addBenefit 1)>;
```

```
...
s.matmul (%A, %A, %C) : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>, …

s.generic #some_generic_trait %A, %D {
^bb0(%arg5: f32, %arg6: f32): // no predecessors
  "s.yield" %arg5 : f32
}: memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>, memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
…

for %arg5 = %c0_0 to %6 step %c100 {
  for %arg6 = %c0_1 to %7 step %c150 {
    %9 = affine.apply (d0) -> (d0 + 100)(%arg5)
    ...
    %14 = s.subview %C[%11, %12, %c1, %c0_3, %13, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    ...
    %18 = s.subview %D[%c0_5, %15, %c1, %16, %17, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    ...
    %23 = s.subview %E[%19, %20, %c1, %21, %22, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    ...
    %25 = s.subview %A[%11, %12, %c1, %c0_10, %24, %c11] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    %26 = s.subview %B[%c0_10, %24, %c11, %c0_3, %13, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    %27 = s.subview %C[%11, %12, %c1, %c0_3, %13, %c1] : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>
    s.matmul (%25, %26, %27) {__internal__ = "L2"} : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>, ...
    s.matmul (%14, %18, %23) {__internal__ = "L2"} : memref<?x?xf32, (d0, d1)[s0, s1] -> (d0 * s1 + s0 + d1)>, ...
```

Apply whichever of Tile<[2000, 3000, 4000], "L3">, Tile<[200, 300, 400], "L2"> or Tile<[20, 30, 40], "L1"> comes first, iteratively

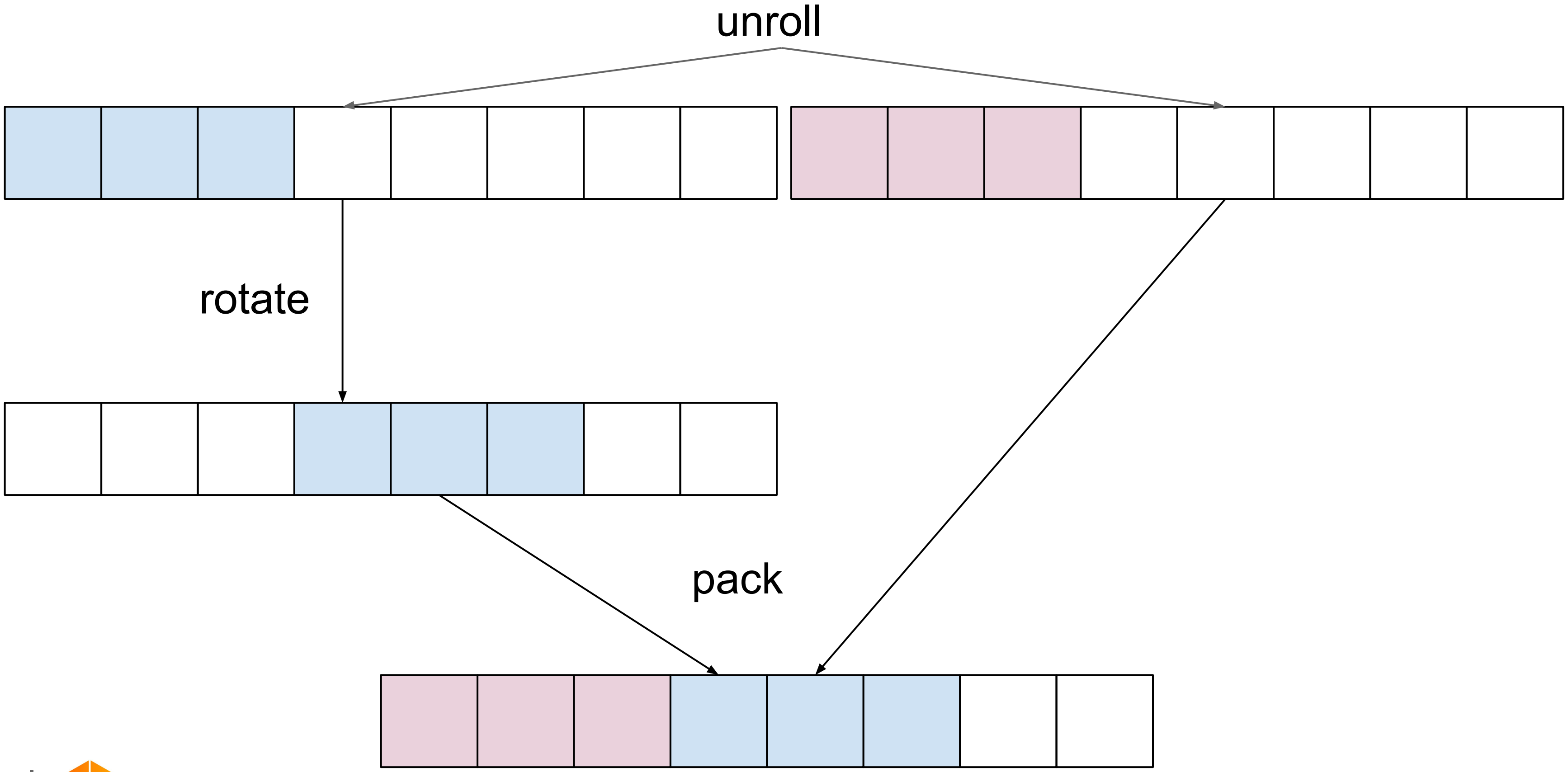
Google

Transformations (2) Declarative Producer-Consumer Fusion

```
def : Pat<(MatmulOp:$consumer $A, $B, $C), (TileAndFuse<[100, 150], "L2"> $consumer),
      [ (Constraint<HasNoLinalgTransformMarker> $consumer), (Constraint<IsProducedByOpOfType<"MatmulOp">> $consumer, $A)],
      (addBenefit 1)>;
```

```
...
for %arg5 = %c0 to %0 step %c2000 {
 for %arg6 = %c0 to %2 step %c3000 {
  for %arg7 = %c0 to %1 step %c4000 {
   ...
   %13 = s.subview %arg2[%arg5, %11, %c1, %arg6, %12, %c1] : memref<?x?xf32, #map3>
   for %arg8 = %c0 to %14 step %c200 {
    for %arg9 = %c0 to %16 step %c300 {
     for %arg10 = %c0 to %15 step %c400 {
      ...
      %25 = s.subview %13[%arg8, %23, %c1, %arg9, %24, %c1] : memref<?x?xf32, #map3>
      for %arg11 = %c0 to %26 step %c20 {
       for %arg12 = %c0 to %28 step %c30 {
        for %arg13 = %c0 to %27 step %c40 {
         %49 = s.subview %37[%arg14, %47, %c1, %arg15, %48, %c1] : memref<?x?xf32, #map3>
         s.matmul (%43, %46, %49) : memref<?x?xf32, #map3>, memref<?x?xf32, #map3>, memref<?x?xf32, #map3>
...
s.generic #some_generic_trait %arg0, %arg3 {
^bb0(%arg5: f32, %arg6: f32):       // no predecessors
 s.yield %arg5 : f32
}: memref<?x?xf32, #map3>, memref<?x?xf32, #map3>
...
for %arg5 = %c0 to %3 step %c100 {
 for %arg6 = %c0 to %4 step %c150 {
  ...
  %17 = s.subview %arg2[%arg5, %5, %c1, %c0, %6, %c1] : memref<?x?xf32, #map3>
  for %arg7 = %c0 to %18 step %c20 {
   for %arg8 = %c0 to %20 step %c30 {
    for %arg9 = %c0 to %19 step %c40 {
     ...
     %32 = s.subview %17[%arg7, %30, %c1, %arg8, %31, %c1] : memref<?x?xf32, #map3>
     s.matmul (%26, %29, %32) : memref<?x?xf32, #map3>, memref<?x?xf32, #map3>, memref<?x?xf32, #map3>
  for %arg7 = %c0 to %21 step %c20 {
   for %arg8 = %c0 to %23 step %c30 {
    for %arg9 = %c0 to %22 step %c40 {
     ...
     %32 = s.subview %13[%arg7, %30, %c1, %arg8, %31, %c1] : memref<?x?xf32, #map3>
     s.matmul (%26, %29, %32) : memref<?x?xf32, #map3>, memref<?x?xf32, #map3>, memref<?x?xf32, #map3>
```

Declarative Transformations (3) Unroll and Pack



Declarative Transformations (3) Unroll and Pack

1. Match: Vector_ContractionOp

1. Match: Shape[6, 4, 5, 3]

2. Unroll: reduction dimension 1 by factor 2

3. Tag: unrolled reduction dimension 1

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

4. Match: “unrolled” marker

5. Pack: pack 2 iterations of reduction dimension 1 into one vector register

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Declarative Transformations (3) Unroll and Pack

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

```
%0 = vector.contract #contraction_trait %lhs, %rhs, %acc
      : vector<6x4x3xf32>, vector<5x4x3xf32> into vector<6x5xf32>
```

Declarative Transformations (3) Unroll and Pack

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

```
// Unroll reduction dimension 1 by a factor of 2
%0 = vector.slice %arg0 {offsets = [0, 0, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%1 = vector.slice %arg1 {offsets = [0, 0, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%2 = vector.contract #contraction_trait %0, %1, %acc : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>

%3 = vector.slice %arg0 {offsets = [0, 2, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%4 = vector.slice %arg1 {offsets = [0, 2, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%5 = vector.contract #contraction_trait %3, %4, %2 : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>
```

Declarative Transformations (3) Unroll and Pack

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

```
// Match and transform first unrolled contraction op
%0 = vector.slice %arg0 {offsets = [0, 0, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%1 = vector.slice %arg1 {offsets = [0, 0, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%2 = vector.contract #contraction_trait %0, %1, %acc : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>

%3 = vector.slice %arg0 {offsets = [0, 2, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%4 = vector.slice %arg1 {offsets = [0, 2, 0], sizes = [5, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%5 = vector.contract #contraction_trait %3, %4, %2 : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>
```

Declarative Transformations (3) Unroll and Pack

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

```
// Slice and pack LHS vectors
%0 = vector.slice %arg0 {offsets = [0, 0, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%1 = vector.slice %arg1 {offsets = [0, 0, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%2 = vector.contract #contraction_trait %0, %1, %acc : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>

%2 = vector.slice %0 {offsets = [0, 0, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%3 = vector.slice %0 {offsets = [0, 1, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%4 = vector.rotate %3 : vector<6x1x3xf32>
%5 = vector.pack %2, %4 : vector<6x1x6xf32>
```

Declarative Transformations (3) Unroll and Pack

```
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;
```

```
// Slice and pack RHS vectors
%0 = vector.slice %arg0 {offsets = [0, 0, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%1 = vector.slice %arg1 {offsets = [0, 0, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%2 = vector.contract #contraction_trait %0, %1, %acc : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>

%2 = vector.slice %0 {offsets = [0, 0, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%3 = vector.slice %0 {offsets = [0, 1, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%4 = vector.rotate %3 : vector<6x1x3xf32>
%5 = vector.pack %2, %4 : vector<6x1x6xf32>

%6 = vector.slice %1 {offsets = [0, 0, 0], sizes = [6, 1, 3]} : vector<5x2x3xf32> to vector<5x1x3xf32>
%7 = vector.slice %1 {offsets = [0, 1, 0], sizes = [6, 1, 3]} : vector<5x2x3xf32> to vector<5x1x3xf32>
%8 = vector.rotate %7 : vector<5x1x3xf32>
%9 = vector.pack %6, %8 : vector<5x1x6xf32>
```

Declarative Transformations (3) Unroll and Pack

def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Unroll<[6, 2, 5, 3], "UnrollReductionDim1"> $op), [(Constraint<HasShape<[6, 4, 5, 3]>> $op)]>;
def : Pat<(Vector_ContractionOp:$op $A, $B, $C), (Pack<[1, 2, 1, 1], "PackDim1"> $op), [(Constraint<HasMarker<"UnrollReductionDim1">> $op)]>;

```
// Create new contraction op operating on packed registers (better vector unit utilization)
%0 = vector.slice %arg0 {offsets = [0, 0, 0], sizes = [6, 2, 3]} : vector<6x4x3xf32> to vector<6x2x3xf32>
%1 = vector.slice %arg1 {offsets = [0, 0, 0], sizes = [5, 2, 3]} : vector<5x4x3xf32> to vector<5x2x3xf32>
%2 = vector.contract #contraction_trait %0, %1, %acc : vector<6x2x3xf32>, vector<5x2x3xf32> into vector<6x5xf32>

%2 = vector.slice %0 {offsets = [0, 0, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%3 = vector.slice %0 {offsets = [0, 1, 0], sizes = [6, 1, 3]} : vector<6x2x3xf32> to vector<6x1x3xf32>
%4 = vector.rotate %3 : vector<6x1x3xf32>
%5 = vector.pack %2, %4 : vector<6x1x6xf32>

%6 = vector.slice %1 {offsets = [0, 0, 0], sizes = [6, 1, 3]} : vector<5x2x3xf32> to vector<5x1x3xf32>
%7 = vector.slice %1 {offsets = [0, 1, 0], sizes = [6, 1, 3]} : vector<5x2x3xf32> to vector<5x1x3xf32>
%8 = vector.rotate %7 : vector<5x1x3xf32>
%9 = vector.pack %6, %8 : vector<5x1x6xf32>

%10 = vector.contract #contraction_trait %5, %9, %acc : vector<6x1x6xf32>, vector<5x1x6xf32> into vector<6x5xf32>
```

Conclusion

MLIR Codegen: Making Good Use of Structure

This is the vision underlying our design and implementation for MLIR codegen
- Harness hardware and (domain-specific) language heterogeneity
- Simplify writing and maintaining retargetable analyses and transformations

Structure is static information that enables the **composition** of the following steps
- Defining standard and custom ops for HPC and ML
  - capturing op, iterator and type-specific properties
- Progressive lowering to loops, hardware/library blocks, hybrid of both
  - enabling key transformations (tile, fuse, transpose, copy to smaller buffer)
  - lower to control flow & side-effects only when and where it makes sense
  - offer declarative patterns leveraging MLIR rewriting and legalization logic
  - expose hardware constraints and cost model = *f*(hardware)

Feedback welcome!

Questions?

Thank you!