MLIR Fundamentals: Understanding Interfaces

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MLIR Summer School – September 9, 2025

Outline

1. What are interfaces and how are they implemented in MLIR?
2. Operation interfaces that abstract over operands / attributes / …
3. Operation interfaces that model control flow
4. Operation interfaces that model operation semantics
5. Operation interfaces that drive analyses
6. Operation interfaces that drive transformations
7. Type interfaces
8. Attribute interfaces
9. Dialect interfaces

Interfaces

- Abstract over common functionality of a operation / type / attribute / dialect.
- Build generic analyses / transformations.
- Can be implemented when defining the operation or at a later point of time (even in a different compilation unit).

Defining an Interface

name of generated C++ class

documentation for the website

```
def OpAsmOpInterface : OpInterface<"OpAsmOpInterface"> {
  let description = [{ ... }];

  let methods = [
    InterfaceMethod<[{
        Get a special name to use when printing the results of this operation.
      }], "void", "getAsmResultNames", (ins "OpAsmSetValueNameFn":$fn), "", "return;">


    InterfaceMethod<...>
  ];
}
```

```
// Conceptually:
virtual void getAsmResultNames(OpAsmSetValueNameFn fn) {
    return;
}
```

Implementing an Interface during Op Definition

```
//===----------------------------------------------------------------------===//
// ExtractOp
//===----------------------------------------------------------------------===//

def Tensor_ExtractOp : Tensor_Op<"extract", [
    DeclareOpInterfaceMethods<OpAsmOpInterface, ["getAsmResultNames"]>,
    Pure,
    TypesMatchWith<"result type matches element type of tensor",
                   "tensor", "result",
                   "::llvm::cast<TensorType>($_self).getElementType()">]> {
  let summary = "element extraction operation";
  let description = [{
    The `tensor.extract` op reads a ranked tensor and returns one element as
    specified by the given indices. The result of the op is a value with the
    same type as the elements of the tensor. The arity of indices must match
    the rank of the accessed value. All indices should all be of `index` type.

    Example:

    ```mlir
    %4 = tensor.extract %t[%1, %2] : tensor<4x4xi32>
    %5 = tensor.extract %rt[%1, %2] : tensor<?x?xi32>
    ```
  }];

  let arguments = (ins AnyRankedTensor:$tensor, Variadic<Index>:$indices);
  let results = (outs AnyType:$result);
  let assemblyFormat = "$tensor `[` $indices `]` attr-dict `:` type($tensor)";

  let hasCanonicalizer = 1;
  let hasFolder = 1;
  let hasVerifier = 1;
}
```

Implements `OpAsmOpInterface` and pre-declares `getAsmResultNames`.

```
// Conceptually:
void getAsmResultNames(OpAsmSetValueNameFn fn) override;
```

```
%extracted0 = tensor.extract %t [%c1] : tensor<9xf32>
```

Implementing an Interface during Op Definition

```
//===----------------------------------------------------------------------===//
// ExtractOp
//===----------------------------------------------------------------------===//

def Tensor_ExtractOp : Tensor_Op<"extract", [
    DeclareOpInterfaceMethods<OpAsmOpInterface, ["getAsmResultNames"]>,
    Pure,
    TypesMatchWith<"result type matches element type of tensor",
                   "tensor", "result",
                   "::llvm::cast<TensorType>($_self).getElementType()">]> {
  let summary = "element extraction operation";
  let description = [{
    The `tensor.extract` op reads a ranked tensor and returns one element as
    specified by the given indices. The result of the op is a value with the
    same type as the elements of the tensor. The arity of indices must match
    the rank of the accessed value. All indices should all be of `index` type.

    Example:

    ```mlir
    %4 = tensor.extract %t[%1, %2] : tensor<4x4xi32>
    %5 = tensor.extract %rt[%1, %2] : tensor<?x?xi32>
    ```
  }];

  let arguments = (ins AnyRankedTensor:$tensor, Variadic<Index>:$indices);
  let results = (outs AnyType:$result);
  let assemblyFormat = "$tensor `[` $indices `]` attr-dict `:` type($tensor)";

  let hasCanonicalizer = 1;
  let hasFolder = 1;
  let hasVerifier = 1;
}
```

Implements `OpAsmOpInterface` and pre-declares `getAsmResultNames`.

```
// Conceptually:
void getAsmResultNames(OpAsmSetValueNameFn fn) override;
```

```
void TensorOp::getAsmResultNames(OpASmSetValueNameFn fn) {
  fn(getResult(), “extracted”);
}
```

```
%extracted0 = tensor.extract %t [%c1] : tensor<9xf32>
```

Implementing an Interface during Op Definition

```
//===----------------------------------------------------------------------===//
// ExtractOp
//===----------------------------------------------------------------------===//

def Tensor_ExtractOp : Tensor_Op<"extract", [
    DeclareOpInterfaceMethods<OpAsmOpInterface, ["getAsmResultNames"]>,
    Pure,
    TypesMatchWith<"result type matches element type of tensor",
                   "tensor", "result",
                   "::llvm::cast<TensorType>($_self).getElementType()">]> {
  let summary = "element extraction operation";
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    The `tensor.extract` op reads a ranked tensor and returns one element as
    specified by the given indices. The result of the op is a value with the
    same type as the elements of the tensor. The arity of indices must match
    the rank of the accessed value. All indices should all be of `index` type.

    Example:

    ```mlir
    %4 = tensor.extract %t[%1, %2] : tensor<4x4xi32>
    %5 = tensor.extract %rt[%1, %2] : tensor<?x?xi32>
    ```
  }];

  let arguments = (ins AnyRankedTensor:$tensor, Variadic<Index>:$indices);
  let results = (outs AnyType:$result);
  let assemblyFormat = "$tensor `[` $indices `]` attr-dict `:` type($tensor)";

  let hasCanonicalizer = 1;
  let hasFolder = 1;
  let hasVerifier = 1;
}
```

Expands to `AlwaysSpeculatable` and `NoMemoryEffects`.

Expands to `MemoryEffectOpInterface` with empty `getEffects` implementation.

```
// Conceptually:
void getEffects(SmallVectorImpl<...> &) override { }
```

```
%extracted0 = tensor.extract %t [%c1] : tensor<9xf32>
```

Implementing an Interface via External Model

```
struct ExtractOpInterface
    : public BufferizableOpInterface::ExternalModel<ExtractOpInterface,
                                                    tensor::ExtractOp> {
  LogicalResult bufferize(Operation *op, RewriterBase &rewriter,
                          const BufferizationOptions &options,
                          BufferizationState &state) const { /* … */ }
};

void mlir::tensor::registerBufferizableOpInterfaceExternalModels(
    DialectRegistry &registry) {
  registry.addExtension(+[](MLIRContext *ctx, tensor::TensorDialect *dialect) {
    ExtractOp::attachInterface<ExtractOpInterface>(*ctx);
  });
}
```

MLIRTensorTransforms

```
void TensorDialect::initialize() {
  addOperations<
#define GET_OP_LIST
#include "mlir/Dialect/Tensor/IR/TensorOps.cpp.inc"
      >();
  declarePromisedInterface<bufferization::BufferizableOpInterface, ExtractOp>();
}
```

MLIRTensorDialect

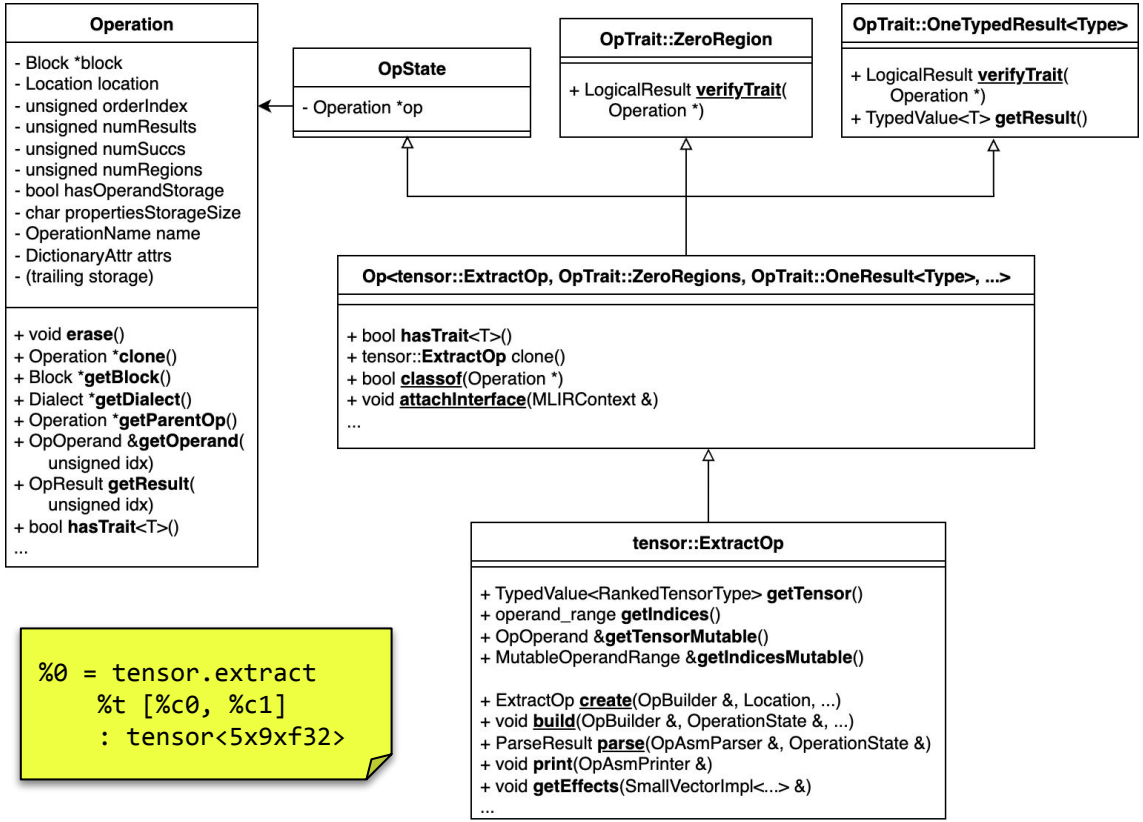
Using an Interface

```
Operation *op = ...;

// Asserts if the interface was promised but not registered.
auto bufferizableOp = cast<BufferizableOpInterface>(op);
bufferizableOp.bufferize(...);

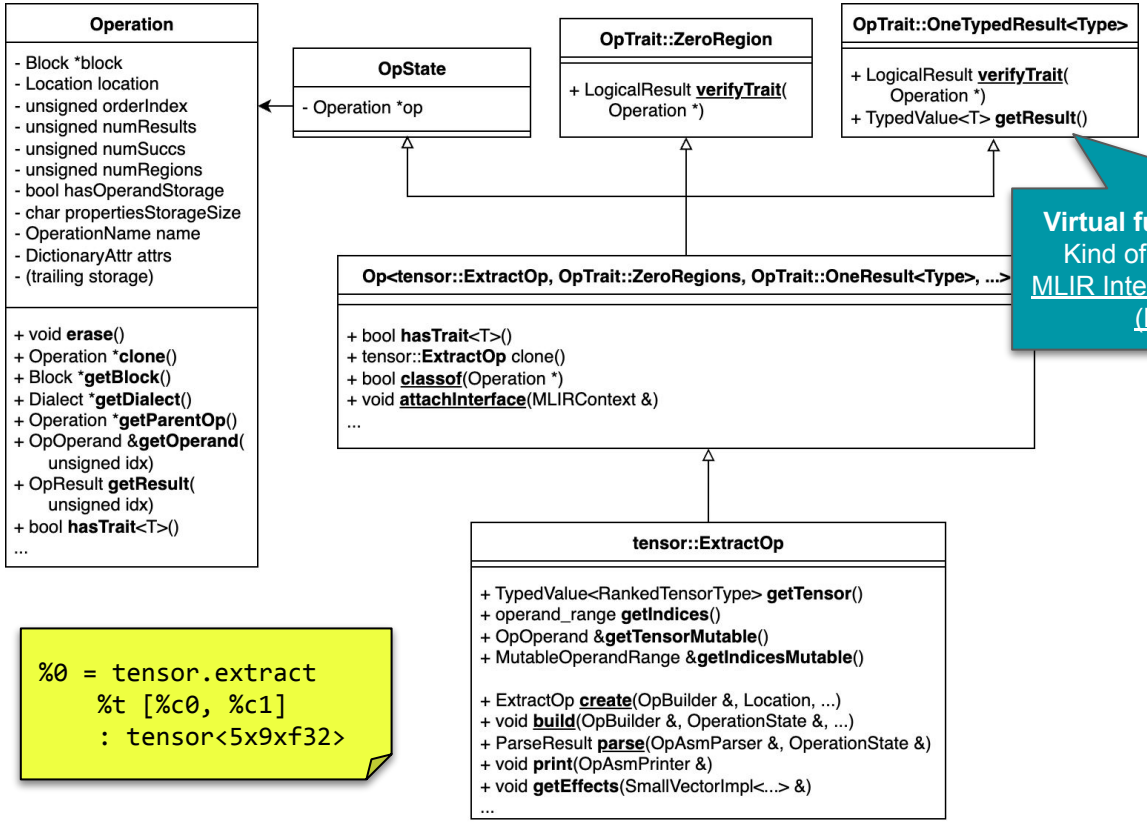
// This won't work if the interface was attached via external model.
tensor::ExtractOp extractOp = builder.create<tensor::ExtractOp>(...);
extractOp.bufferize(...);
```

Operations and Traits (simplified)

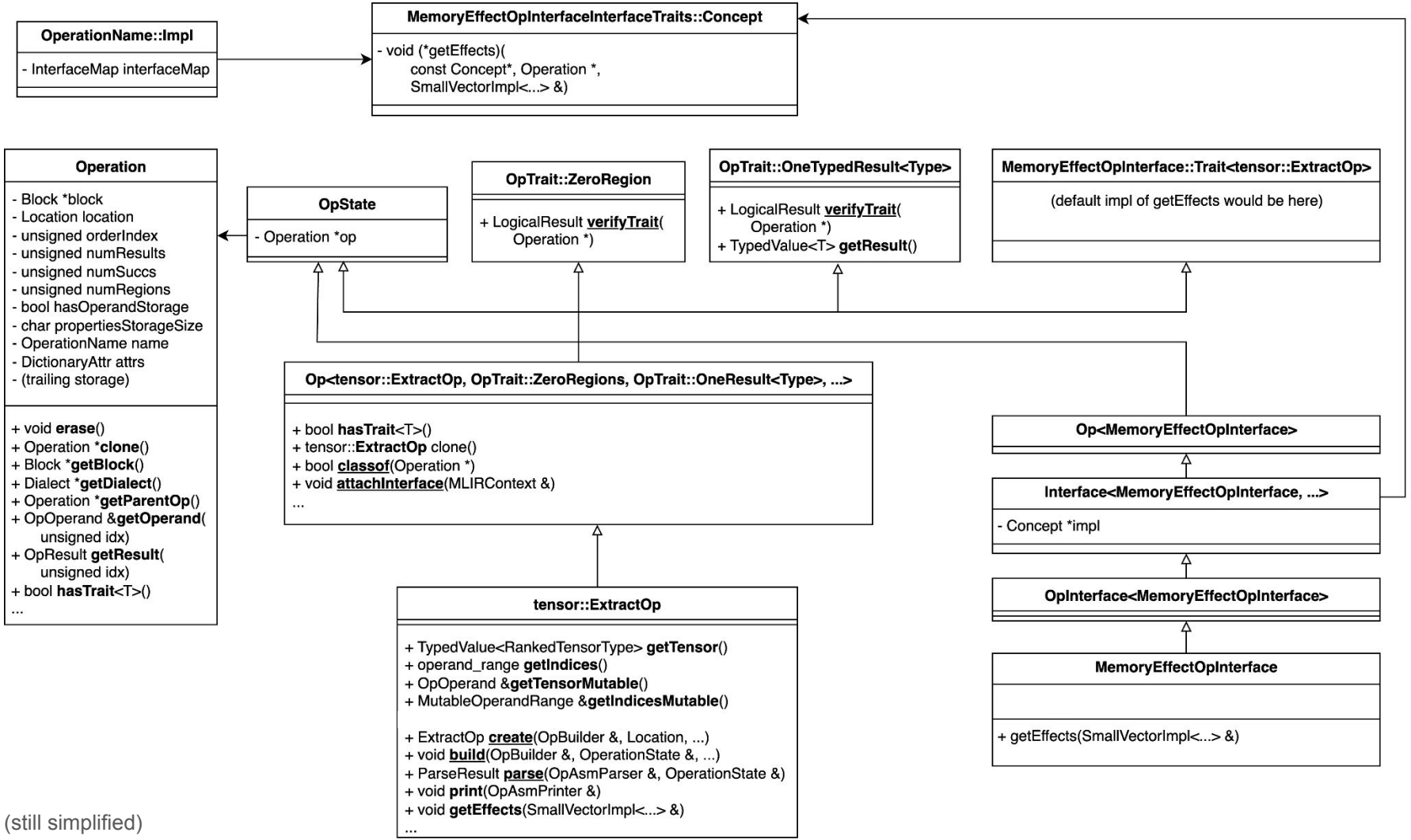


- All state is stored in `Operation`.
- `tensor::ExtractOp` is auto-generated and contains convenience functions with richer types, operand names, etc.
- `Op<...>` provides common convenience functions.
- Traits can provide common convenience function on a per-op basis.

Operations and Traits (simplified)



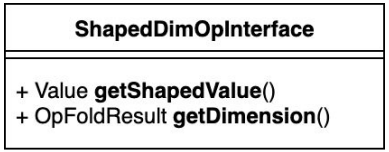
- All state is stored in `Operation`.
- `tensor::ExtractOp` is
- `Op<...>` provides common convenience functions.
- Traits can provide common convenience function on a per-op basis.



(still simplified)

Interfaces that Abstract over Operands / Attributes / …

ShapedDimOpInterface



- Provides access to shaped value and dimension.
- Used in the Affine dialect to prevent a dependency on `TensorDialect`.
- Can the dependency on `MemRefDialect` be removed?

```
%0 = memref.dim %m, %c0 : memref<?xf32>

%1 = tensor.dim %t, %c0 : tensor<?xf32>
```

OffsetSizeAndStrideOpInterface

OffsetSizeAndStrideOpInterface

+ unsigned **getOffsetSizeAndStrideStartOperandIndex**()
+ std::array<unsigned, 3> **getArrayAttrMaxRanks**()
+ OperandRange **getOffsets**()
+ OperandRange **getSizes**()
+ OperandRange **getStrides**()
+ ArrayRef<int64_t> **getStaticOffsets**()
+ ArrayRef<int64_t> **getStaticSizes**()
+ ArrayRef<int64_t> **getStaticStrides**()
+ SmallVector<OpFoldResult> **getMixedOffsets**()
+ SmallVector<OpFoldResult> **getMixedSizes**()
+ SmallVector<OpFoldResult> **getMixedStrides**()
+ bool **isDynamicOffset**(unsigned idx)
+ bool **isDynamicSize**(unsigned idx)
+ bool **isDynamicStride**(unsigned idx)
+ Value **getDynamicOffset**(unsigned idx)
+ Value **getDynamicSize**(unsigned idx)
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+ int64_t **getStaticOffset**(unsigned idx)
+ int64_t **getStaticSize**(unsigned idx)
+ int64_t **getStaticStride**(unsigned idx)
+ unsigned **getIndexOfDynamicOffset**(unsigned idx)
+ unsigned **getIndexOfDynamicSize**(unsigned idx)
+ unsigned **getIndexOfDynamicStride**(unsigned idx)
+ bool **isSameAs**(
  OffsetSizeAndStrideOpInterface other,
  function<bool(OpFoldResult, OpFoldResult)> cmp)
+ bool **hasUnitStride**()
+ bool **hasZeroOffset**()

- Provides uniform access to offsets, sizes, strides.
- Supports mixed static/dynamic values.
- Provides uniform op verification:
  - Matching number of offsets, sizes, strides.
  - Correct number of dynamic operands.

```
%0 = tensor.extract_slice %src [0, %o][15, %sz][1, 1]
    : tensor<?x?xf32> to tensor<15x?xf32>

%1 = tensor.insert_slice %src into %dest [0, %o][15, %sz][1, 1]
    : tensor<15x?xf32> into tensor<?x1024xf32>

%2 = memref.subview %buffer [0][15][2]
    : memref<15xf32> to memref<5xf32, strided<[2]>>
```

OffsetSizeAndStrideOpInterface

OffsetSizeAndStrideOpInterface

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```
static_offsets = [0, -9223372036854775807]
offsets = [%o]
```

```
%0 = tensor.extract_slice %src [0, %o][15, %sz][1, 1]
    : tensor<?x?xf32> to tensor<15x?xf32>

%1 = tensor.insert_slice %src into %dest [0, %o][15, %sz][1, 1]
    : tensor<15x?xf32> into tensor<?x1024xf32>

%2 = memref.subview %buffer [0][15][2]
    : memref<15xf32> to memref<5xf32, strided<[2]>>
```

OffsetSizeAndStrideOpInterface

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- Supports mixed static/dynamic values.
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  - Matching number of offsets, sizes, strides.
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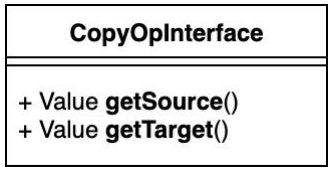
TODO: These should not be interface methods.

```
%0 = tensor.extract_slice %src [0, %o][15, %sz][1, 1]
    : tensor<?x?xf32> to tensor<15x?xf32>

%1 = tensor.insert_slice %src into %dest [0, %o][15, %sz][1, 1]
    : tensor<15x?xf32> into tensor<?x1024xf32>

%2 = memref.subview %buffer [0][15][2]
    : memref<15xf32> to memref<5xf32, strided<[2]>>
```

CopyOpInterface



- Provides uniform access to source / destination.
- No uses in MLIR. Was added together with the `CopyRemovalPass`, which no longer exists.
- Delete this interface? Adding code to LLVM / MLIR is “easy”, what’s our process for deprecating / deleting code? Should we encourage it more?

```
memref.copy %src, %dst : memref<?xf32> to memref<?xf32>

%0 = bufferization.clone %src : memref<?xf32> to memref<?xf32>
```

missing: `linalg.copy` (used to implement it)

ViewLikeOpInterface

- Provides uniform access to the view source / destination.
- Implies some sort of aliasing. The interface description is vague.
- Used by patterns (`memref.extract_aligned_pointer_as_index`) and bufferization-related passes to understand data flow.

```
%0 = memref.assume_alignment %buffer, 128 : memref<?xf32>
%1 = memref.cast %buffer : memref<?xf32> to memref<64xf32>
%2 = memref.subview %buffer[0][15][2] : memref<15xf32> to memref<5xf32, strided<[2]>>
%3 = llvm.getelementptr %ptr[%offset] : (!llvm.ptr, i64) -> !llvm.ptr, i32
%4 = ptr.ptr_add %x, %off : !ptr.ptr<#ptr.generic_space>, i32
%5 = amdgpu.fat_raw_buffer_cast %m : memref<...> to memref<...>
%6 = xegpu.create_tdesc %src, %cst : ui64, vector<4xindex> -> !xegpu.tensor_desc<...>
```

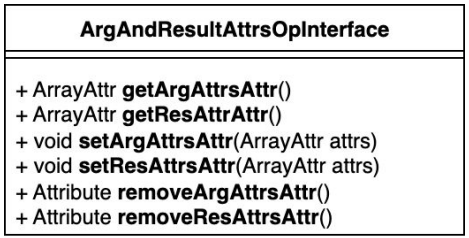
ViewLikeOpInterface

- Provides uniform access to the view source / destination.
- Implies some sort of aliasing. The interface description is vague.
- Used by patterns (`memref.extract_ali` bufferization-related pa

A view-like operation "views" a buffer in a potentially different way. It takes in a (view of) buffer (and potentially some other operands) and returns another view of buffer.

```
%0 = memref.assume_alignment %buf
%1 = memref.cast %buffer : memref<?xf32> to memref<64xf32>
%2 = memref.subview %buffer[0][15][2] : memref<15xf32> to memref<5xf32, strided<[2]>>
%3 = llvm.getelementptr %ptr[%offset] : (!llvm.ptr, i64) -> !llvm.ptr, i32
%4 = ptr.ptr_add %x, %off : !ptr.ptr<#ptr.generic_space>, i32
%5 = amdgpu.fat_raw_buffer_cast %m : memref<...> to memref<...>
%6 = xegpu.create_tdesc %src, %cst : ui64, vector<4xindex> -> !xegpu.tensor_desc<...>
```

ArgAndResultAttrsOpInterface

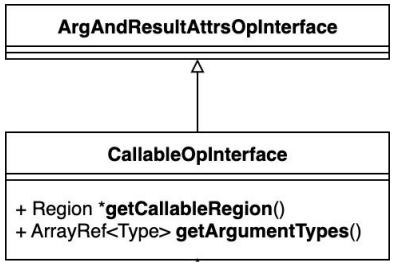


- Provides uniform access to argument and result attributes.
- Applicable to calling ops and callable ops.
- One array attribute per argument / result.

```
func.func @main(%arg0 : tensor<?xf32> {bufferization.writable = true}) …

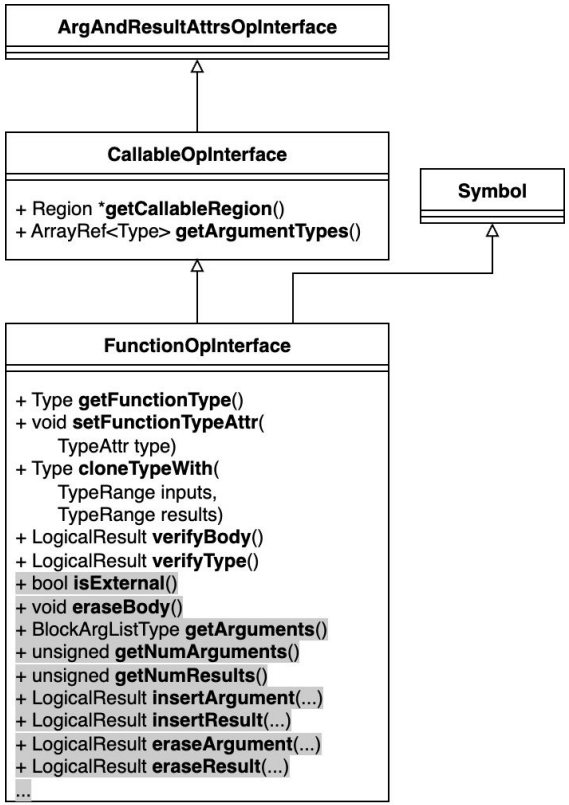
gpu.func @kernel(%arg0 : tensor<?xf32> {bufferization.writable = true}) …
```

CallableOpInterface



- Something that can be called.
- Typically a function.
- Interfaces can inherit from other interfaces.

FunctionOpInterface



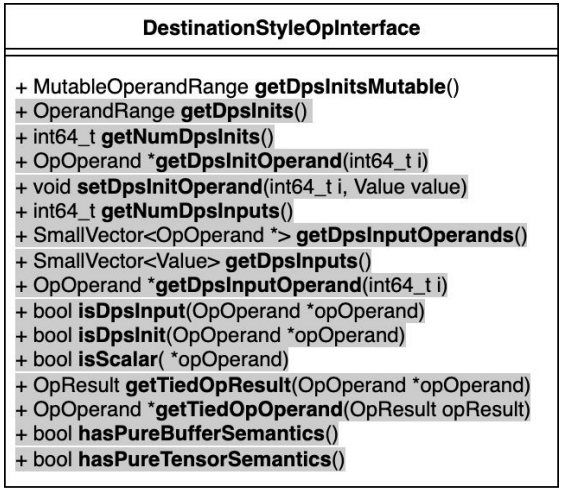
- Ops with a symbol and a callable region.
- Leading arguments of the entry block are function arguments.
- Has a function type.

```
func.func @main(%arg0 : tensor<?xf32>) -> tensor<?xf32> {
    return %arg0 : tensor<?xf32>
}

func.func private @foo() -> i32

llvm.func @malloc(i64) -> !llvm.ptr
```

DestinationStyleOpInterface



- Destination-style ops have two kind of operands: **inputs** and **inits**.
- Each init has a “tied” op result. They must have the same type. (Dynamic dimension sizes must match.)
- Used as a “hint” by the other transformations (tiling, bufferization). Semantics are loosely defined.

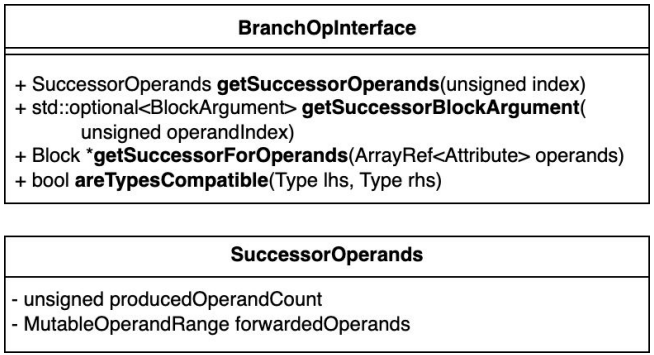
```
%0 = tensor.insert_slice %src into %dest [0][5][1]
    : tensor<5xf32> into tensor<?xf32>

%1 = linalg.matmul ins(%A, %B: tensor<4x8xf32>, tensor<8x12xf32>)
                   outs(%C: tensor<4x12xf32>) -> tensor<4x12xf32>

%2 = linalg.generic ...
```

Interfaces that Model Control Flow

BranchOpInterface



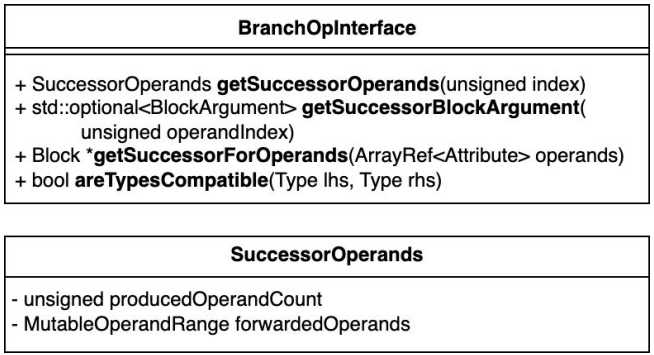

```
getSuccessorOperands(0) = ???
getSuccessorOperands(1) = ???
```

- Models control flow between basic blocks within a region.
- Verifies that operand types and block argument types match.
- Queried by dataflow analysis, live analysis, bufferization, …

```
func.func @foo(%a: i32, %b: i16, %c: i1) {
  cf.cond_br %c, ^bb1(%b : i16), ^bb2(%a : i32, %a : i32)
^bb1(%arg0: i16):
  // …
^bb2(%arg1: i32, %arg2: i32):
  // …
}
```

successors

BranchOpInterface



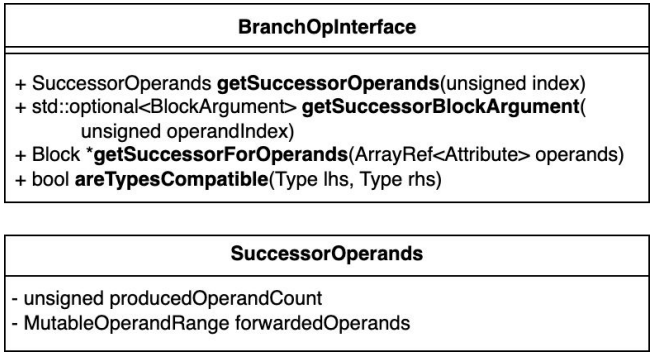

```
getSuccessorOperands(0) = [%b]
getSuccessorOperands(1) = [%a, %a]
```

- Models control flow between basic blocks within a region.
- Verifies that operand types and block argument types match.
- Queried by dataflow analysis, live analysis, bufferization, …

```
func.func @foo(%a: i32, %b: i16, %c: i1) {
  cf.cond_br %c, ^bb1(%b : i16), ^bb2(%a : i32, %a : i32)
^bb1(%arg0: i16):
  // …
^bb2(%arg1: i32, %arg2: i32):
  // …
}
```

successors

BranchOpInterface



- Models control flow between basic blocks within a region.
- Verifies that operand types and block argument types match.
- Queried by dataflow analysis, live analysis, bufferization, …

```
getSuccessorOperands(0) = [%b]
getSuccessorOperands(1) = [%a, %a]
getSuccessorBlockArgument(0) = %arg0
getSuccessorBlockArgument(1) = %arg1
getSuccessorBlockArgument(2) = %arg2
```

```
func.func @foo(%a: i32, %b: i16, %c: i1) {
  cf.cond_br %c, ^bb1(%b : i16), ^bb2(%a : i32, %a : i32)
^bb1(%arg0: i16):
  // …
^bb2(%arg1: i32, %arg2: i32):
  // …
}
```

successors

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getSuccessorRegions**(
  RegionBranchPoint,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getRegionInvocationBounds**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<InvocationBounds> &)
+ bool **areTypesCompatible**(Type, Type)

RegionBranchTerminatorOpInterface

+ MutableOperandRange **getMutableSuccessorOperands**(
  RegionBranchPoint)
+ void **getSuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)

RegionBranchPoint

+ bool isParent()
+ Region *getRegionOrNull()

RegionSuccessor

+ bool isParent()
+ Region *getSuccessor()
+ ValueRange getSuccessorInputs()

- Models control flow between regions.
- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

```
%0 = scf.for %iv = %lb to %ub step %step
             iter_args(%arg0 = %init) -> f32 {
  %1 = arith.addf %arg0, %arg0 : f32
  scf.yield %1 : f32
}
```

```
getSuccessorRegions(BODY) = ???
getSuccessorRegions(PARENT) = ???
```

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getSuccessorRegions**(
  RegionBranchPoint,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getRegionInvocationBounds**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<InvocationBounds> &)
+ bool **areTypesCompatible**(Type, Type)

RegionBranchTerminatorOpInterface

+ MutableOperandRange **getMutableSuccessorOperands**(
  RegionBranchPoint)
+ void **getSuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)

RegionBranchPoint

+ bool isParent()
+ Region *getRegionOrNull()

RegionSuccessor

+ bool isParent()
+ Region *getSuccessor()
+ ValueRange getSuccessorInputs()

- Models control flow between regions.
- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

```
%0 = scf.for %iv = %lb to %ub step %step
             iter_args(%arg0 = %init) -> f32 {
  %1 = arith.addf %arg0, %arg0 : f32
  scf.yield %1 : f32
}
```

```
getSuccessorRegions(BODY) = [(BODY, [%arg0]), (PARENT, [%0])]
getSuccessorRegions(PARENT) = [(BODY, [%arg0]), (PARENT, [%0])]
```

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
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  ArrayRef<Attribute> operands,
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  RegionBranchPoint)
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  ArrayRef<Attribute> operands,
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- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

```
%0 = scf.for %iv = %lb to %ub step %step
             iter_args(%arg0 = %init) -> f32 {
  %1 = arith.addf %arg0, %arg0 : f32
  scf.yield %1 : f32
}
```

```
getSuccessorRegions(BODY) = [(BODY, [%arg0]), (PARENT, [%0])]
getSuccessorRegions(PARENT) = [(BODY, [%arg0]), (PARENT, [%0])]
getEntrySuccessorOperands(BODY) = [%init]
getEntrySuccessorOperands(PARENT) = [%init]
getMutableSuccessorOperands(scf.yield) = [%1]
```

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)
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  RegionBranchPoint,
  SmallVectorImpl<RegionSuccessor> &)
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  ArrayRef<Attribute> operands,
  SmallVectorImpl<InvocationBounds> &)
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+ Region *getSuccessor()
+ ValueRange getSuccessorInputs()

- Models control flow between regions.
- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

before region

after region

```
%0, %1 = scf.while (%arg0 = %init) : (f32) -> (f32, f32) {
  scf.condition(%c) %arg0, %arg0 : f32, f32
} do {
^bb0(%arg1: f32, %arg2: f32):
  scf.yield %arg1 : f32
}
```

```
getSuccessorRegions(PARENT) = ???
getSuccessorRegions(BEFORE) = ???
getSuccessorRegions(AFTER) = ???
```

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getSuccessorRegions**(
  RegionBranchPoint,
  SmallVectorImpl<RegionSuccessor> &)
+ void **getRegionInvocationBounds**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<InvocationBounds> &)
+ bool **areTypesCompatible**(Type, Type)

RegionBranchTerminatorOpInterface

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  RegionBranchPoint)
+ void **getSuccessorRegions**(
  ArrayRef<Attribute> operands,
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- Models control flow between regions.
- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

before region

after region

```
%0, %1 = scf.while (%arg0 = %init) : (f32) -> (f32, f32) {
  scf.condition(%c) %arg0, %arg0 : f32, f32
} do {
^bb0(%arg1: f32, %arg2: f32):
  scf.yield %arg1 : f32
}
```

```
getSuccessorRegions(PARENT) = [(BEFORE, [%arg0])]
getSuccessorRegions(BEFORE) = [(AFTER, [%arg1, %arg2], (PARENT, [%0, %1])]
getSuccessorRegions(AFTER) = [(BEFORE, [%arg0])]
```

RegionBranchOpInterface

RegionBranchOpInterface

+ OperandRange **getEntrySuccessorOperands**(
  RegionBranchPoint)
+ void **getEntrySuccessorRegions**(
  ArrayRef<Attribute> operands,
  SmallVectorImpl<RegionSuccessor> &)
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  SmallVectorImpl<RegionSuccessor> &)
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+ Region *getSuccessor()
+ ValueRange getSuccessorInputs()

- Models control flow between regions.
- Verifies that types matches along control flow edges.
- Queried by dataflow analysis, live analysis, bufferization, …

before region

after region

```
%0, %1 = scf.while (%arg0 = %init) : (f32) -> (f32, f32) {
  scf.condition(%c) %arg0, %arg0 : f32, f32
} do {
^bb0(%arg1: f32, %arg2: f32):
  scf.yield %arg1 : f32
}
```

```
getSuccessorRegions(PARENT) = [(BEFORE, [%arg0])]
getSuccessorRegions(BEFORE) = [(AFTER, [%arg1, %arg2], (PARENT, [%0, %1])]
getSuccessorRegions(AFTER) = [(BEFORE, [%arg0])]
getEntrySuccessorOperands(BEFORE) = [%init]
getMutableSuccessorOperands(scf.condition) = [%arg0, %arg0]
getMutableSuccessorOperands(scf.yield) = [%arg1]
```

LoopLikeOpInterface

LoopLikeOpInterface

+ bool **isDefinedOutsideOfLoop**(Value)
+ SmallVector<Region *> **getLoopRegions**()
+ LogicalResult **promoteIfSingleIteration**(
  RewriterBase &)
+ std::optional<SmallVector<Value>>
  getLoopInductionVars()
+ std::optional<SmallVector<OpFoldResult>>
  getLoopLowerBounds()
+ std::optional<SmallVector<OpFoldResult>>
  getLoopUpperBounds()
+ std::optional<SmallVector<OpFoldResult>>
  getLoopSteps()
+ MutableArrayRef<OpOperand> **getInitsMutable**()
+ BlockArgListType **getRegionIterArgs**()
+ std::optional<MutableArrayRef<OpOperand>>
  getYieldedValuesMutable()
+ std::optional<ResultRange> **getLoopResults**()
+ FailureOr<LoopLikeOpInterface>
  replaceWithAdditionalYields(
  RewriterBase &, ValueRange, ...)
+ BlockArgument **getTiedLoopRegionIterArg**(
  OpOperand *)
+ BlockArgument **getTiedLoopRegionIterArg**(
  OpResult)
+ OpOperand ***getTiedLoopInit**(BlockArgument)
+ OpOperand ***getTiedLoopInit**(OpResult)
+ OpOperand ***getTiedLoopYieldedValue**(
  BlockArgument)
+ OpOperand ***getTiedLoopYieldedValue**(OpResult)

- Provides uniform access to LB, UB, step, loop-carried variables and repetitive regions.
- Verifies that number and types of init values, region iter arguments, op results match. (Same as `RegionBranchOpInterface`, but better error messages.)
- Queried by LICM and Linalg hoisting (`replaceWith...`).

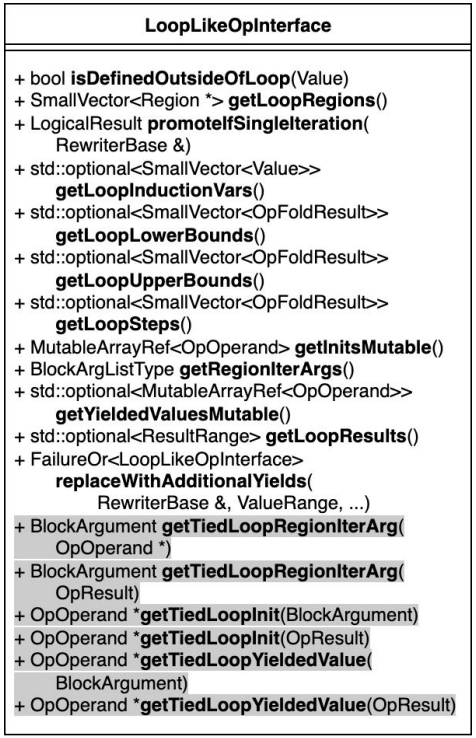
region iter arg

init operand

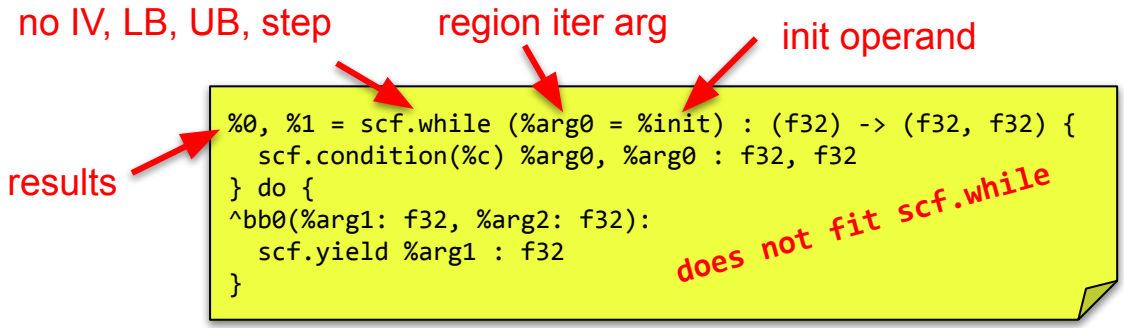
results

```
%0 = scf.for %iv = %lb to %ub step %step
              iter_args(%arg0 = %init) -> f32 {
  %1 = arith.addf %arg0, %arg0 : f32
  scf.yield %1 : f32
}
```

LoopLikeOpInterface

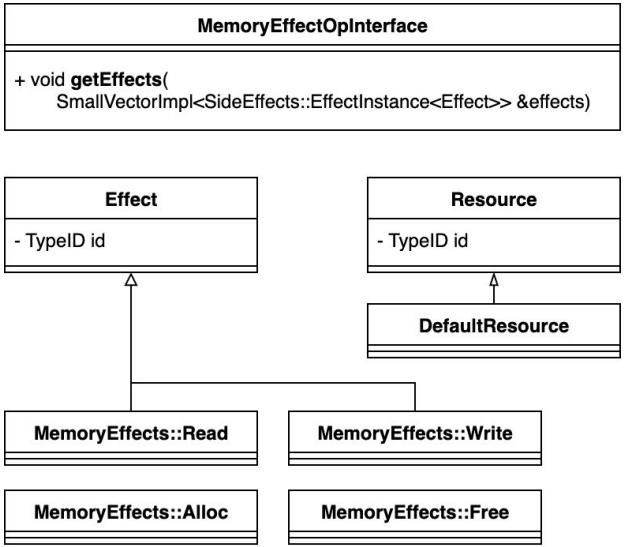


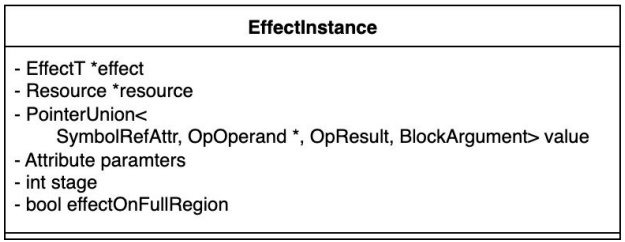
- Provides uniform access to LB, UB, step, loop-carried variables and repetitive regions.
- Verifies that number and types of init values, region iter arguments, op results match. (Same as `RegionBranchOpInterface`, but better error messages.)
- Queried by LICM and Linalg hoisting (`replaceWith...`).



Interfaces that Model Operation Semantics

MemoryEffectsOpInterface






```
+ hasUnknownEffects(Operation *op)
+ hasSingleEffect<EffectTy>(Operation *op)
+ hasEffect<EffectTy>(Operation *op)
+ hasSingleEffect<...>(Operation *op, ValueTy val)
+ hasEffect<...>(Operation *op, ValueTy val)
+ mightHaveEffect<EffectTy>(Operation *op)
+ mightHaveEffect<...>(Operation *op, ValueTy val)
+ bool isTriviallyDead(Operation *op)
+ isMemoryEffectFree(Operation *op)
```

- Models **potential** side effects of an operation on a per-operand/result basis.
- Queried by various analyses and transformations such as CSE, hoisting, DCE (greedy rewriter).

```
%0 = memref.load %buffer[%c0, %c0] : memref<?x?xf32>
memref.store %val, %buffer[%c0, %c0] : memref<?x?xf32>
memref.alloc() : memref<128xf32>
vector.print %val : f32
transform.loop.promote_if_one_iteration %loop : !transform.op<"scf.for">
```

MemoryEffectsOpInterface

In C++:

```
void LoadOp::getEffects(SmallVectorImpl<SideEffects::EffectInstance<MemoryEffects::Effect>> &effects) {
  effects.emplace_back(MemoryEffects::Read::get(),
                       getMemref(),
                       SideEffects::DefaultResource::get());
}
```

effect kind

operand/result

In TableGen:

```
def LoadOp : MemRef_Op<"load", ...> {
  let arguments = (ins Arg<AnyMemRef, "the reference to load from", [MemRead]>:$memref,
                       Variadic<Index>:$indices);
}
```

`MemoryEffectsOpInterface`

- Side effect modelling in MLIR is on an opt-in basis.
- If op does not implement the `MemoryEffectsOpInterface`, but the `RecursiveMemoryEffects` trait: side effects are **derived from the ops in the regions** of the operation.
- If op implements neither the `MemoryEffectsOpInterface` nor the `RecursiveMemoryEffects` trait: **side effects are unknown**. Analyses / transformations must treat it conservatively.
- `NoMemoryEffects` TableGen helper.

`AlwaysSpeculatable` (trait)

- Speculation means executing the operation at an earlier point of time. E.g., hoisting or moving to an earlier place in the IR.
- Typically not implemented by itself. Often implemented together with `NoMemoryEffects`. **`Pure = NoMemoryEffects + AlwaysSpeculatable.`**
- Most tensor / vector ops are pure.

```
%0 = tensor.empty() : tensor<5xf32>

%1 = tensor.extract %t [%pos] : f32 from tensor<128xf32>
```

AlwaysSpeculatable

```
%0 = ... : tensor<*xf32>
%false = arith.constant false
%c5 = arith.constant 5 : index

scf.if %c {
  %sz = tensor.dim %0, %c5 : tensor<*xf32>
  vector.print %sz : index
}
```

AlwaysSpeculatable

```
%0 = ... : tensor<*xf32>
%false = arith.constant false
%c5 = arith.constant 5 : index

scf.if %c {
  %sz = tensor.dim %0, %c5 : tensor<*xf32>
  vector.print %sz : index
}
```

Can you hoist the op?

AlwaysSpeculatable: Counter Example

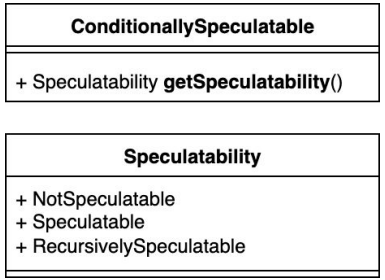
```
%0 = ... : tensor<*xf32>
%false = arith.constant false
%c5 = arith.constant 5 : index

scf.if %c {
  %sz = tensor.dim %0, %c5 : tensor<*xf32>
  vector.print %sz : index
}
```

Can you hoist the op? No, because the op has UB.

The `tensor.dim` operation takes a tensor and a dimension operand of type `index`. It returns the size of the requested dimension of the given tensor. **If the dimension index is out of bounds, the behavior is undefined.**

`ConditionallySpeculatable` (interface)




```
Speculation::Speculatability DimOp::getSpeculatability() {
  auto constantIndex = getConstantIndex();
  if (!constantIndex)
    return Speculation::NotSpeculatable;

  auto rankedSourceType = dyn_cast<RankedTensorType>(getSource().getType());
  if (!rankedSourceType)
    return Speculation::NotSpeculatable;

  if (rankedSourceType.getRank() <= constantIndex)
    return Speculation::NotSpeculatable;

  return Speculation::Speculatable;
}
```

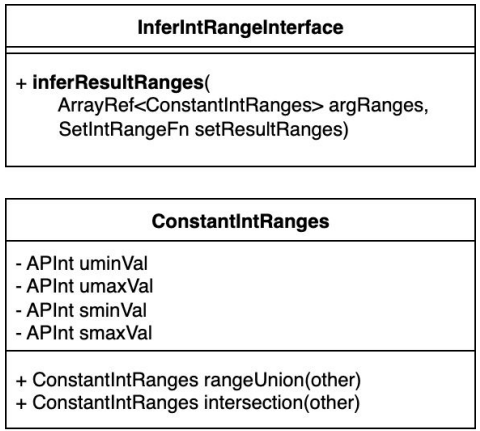
speculatable if index is guaranteed to be in-bounds

`AlwaysSpeculatable` / `ConditionallySpeculatable`

- `AlwaysSpeculatable` (and `Pure`) is a nice property. It enables many transformations and makes some analyses simpler.
- Undefined Behavior (UB) is a big hammer: it prevents any speculation. (And the program can no longer continue executing in a meaningful way.)
- Best practice (?): Give your operations poison semantics instead of UB.
  - Poison = Deferred undefined behavior. Propagated by most ops (poison in ⇒ poison out), but some ops turn it into immediate undefined behavior (e.g., `cf.cond_br`, memory access ptr).
  - Should `tensor.dim` be pure and have poison semantics?
  - Many ops (`tensor.extract`, `tensor.insert`, `tensor.extract_slice`, …) are underspecified. They are pure, but their out-of-bounds semantics are not specified.

Interfaces that Drive Analyses

InferIntRangeInterface



- Given the integer range of the operands, infer the range of the results.
- Models both signed and unsigned integer semantics.
- Queried by `IntegerRangeAnalysis` (data flow analysis).
- `arith-int-range-narrowing`: Pass that reduces the bitwidth of integer SSA values (to make the computation faster, use less memory).

```
func.func @test(%arg0: i8) {                        // range(%arg0) = [-128, 127]
  %0 = arith.constant 5 : i8                        // range(%0)    = [5, 5]
  %1 = arith.addi %arg0, %0 overflow<nsw> : i8      // range(%1)    = [-123, 127]
  …
}
```

ValueBoundsOpInterface

```
+ void populateBoundsForIndexValue(
      Value value,
      ValueBoundsConstraintSet &cstr)
+ void populateBoundsForShapedValueDim(
      Value value, int64_t dim,
      ValueBoundsConstraintSet &cstr)
```

ValueBoundsConstraintSet::Variable

```
- AffineMap map
- ValueDimList mapOperand
```

ValueBoundsConstraintSet

```
- FlatLinearConstraint cstr
- StopConditionFn stopCondition

+ LogicalResult computeBound(
      AffineMap &resultMap,
      ValueDimList &resultOperands,
      BoundType type,
      const Variable &var,
      StopConditionFn stopCondition)
+ LogicalResult computeDependentBound(
      ..., ValueRange dependencies)
+ LogicalResult computeIndependentBound(
      ...., ValueRange independencies)
+ FailureOr<int64_t> computeConstantBound(...)
+ bool compare(Variable lhs,
      ComparisonOperator cmp, Variable rhs)
+ FailureOr<bool> areOverlappingSlices(
      HyperrectangularSlice slice1,
      HyperrectangularSlice slice2)
+ FailureOr<bool> areEquivalentSlices(...)
```

ValueBoundsOpInterface

- Populates a constraint set with lower/upper/equality bounds of integer-typed SSA values and/or dimension sizes of shaped values.
- Ops that implement `DestinationStyleOpInterface` are supported out of the box.
- Bounds can be expressed in terms of other SSA values.

```
%c1 = arith.constant 1 : i8           // %c1 = 1
%0 = arith.addi %a, %c1 : i8          // %a = %c1 + 1
%2 = arith.select %c, %0, %1 : i8     // %a <= %0 <= %a + 1
```

Ex.: Matmul Tiling [4, 9, 4] – Rediscover Static Information

```
func.func @tile_linalg_matmul(%arg0: tensor<128x128xf32>, %arg1: tensor<128x128xf32>, %arg2: tensor<128x128xf32>) -> tensor<128x128xf32> {
 %0 = scf.for %arg3 = %c0 to %c128 step %c4 iter_args(%arg4 = %arg2) -> (tensor<128x128xf32>) {
   %1 = scf.for %arg5 = %c0 to %c128 step %c9 iter_args(%arg6 = %arg4) -> (tensor<128x128xf32>) {
     %2 = scf.for %arg7 = %c0 to %c128 step %c4 iter_args(%arg8 = %arg6) -> (tensor<128x128xf32>) {
       %3 = affine.min affine_map<(d0) -> (-d0 + 128, 9)>(%arg5)
       %extracted_slice = tensor.extract_slice %arg0[%arg3, %arg7] [4, 4] [1, 1] : tensor<128x128xf32> to tensor<4x4xf32>
       %extracted_slice_0 = tensor.extract_slice %arg1[%arg7, %arg5] [4, %3] [1, 1] : tensor<128x128xf32> to tensor<4x?xf32>
       %extracted_slice_1 = tensor.extract_slice %arg8[%arg3, %arg5] [4, %3] [1, 1] : tensor<128x128xf32> to tensor<4x?xf32>
       %4 = linalg.matmul ins(%extracted_slice, %extracted_slice_0 : tensor<4x4xf32>, tensor<4x?xf32>)
                          outs(%extracted_slice_1 : tensor<4x?xf32>) -> tensor<4x?xf32>
       %inserted_slice = tensor.insert_slice %4 into %arg8[%arg3, %arg5] [4, %3] [1, 1] : tensor<4x?xf32> into tensor<128x128xf32>
       scf.yield %inserted_slice : tensor<128x128xf32>
     }
     scf.yield %2 : tensor<128x128xf32>
   }
   scf.yield %1 : tensor<128x128xf32>
 }
 return %0 : tensor<128x128xf32>
}
```

compute constant UB for dim(%4, 1) → 10 (open bound)

Ex.: Matmul Tiling [4, 9, 4] – Rediscover Static Information

```
func.func @tile_linalg_matmul(%arg0: tensor<128x128xf32>, %arg1: tensor<128x128xf32>, %arg2: tensor<128x128xf32>) -> tensor<128x128xf32> {
 %0 = scf.for %arg3 = %c0 to %c128 step %c4 iter_args(%arg4 = %arg2) -> (tensor<128x128xf32>) {
   %1 = scf.for %arg5 = %c0 to %c128 step %c9 iter_args(%arg6 = %arg4) -> (tensor<128x128xf32>) {
     %2 = scf.for %arg7 = %c0 to %c128 step %c4 iter_args(%arg8 = %arg6) -> (tensor<128x128xf32>) {
       %3 = affine.min affine_map<(d0) -> (-d0 + 128, 9)>(%arg5)
       %extracted_slice = tensor.extract_slice %arg0[%arg3, %arg7] [4, 4] [1, 1] : tensor<128x128xf32> to tensor<4x4xf32>
       %extracted_slice_0 = tensor.extract_slice %arg1[%arg7, %arg5] [4, %3] [1, 1] : tensor<128x128xf32> to tensor<4x?xf32>
       %extracted_slice_1 = tensor.extract_slice %arg8[%arg3, %arg5] [4, %3] [1, 1] : tensor<128x128xf32> to tensor<4x?xf32>
       %4 = linalg.matmul ins(%extracted_slice, %extracted_slice_0 : tensor<4x4xf32>, tensor<4x?xf32>)
                          outs(%extracted_slice_1 : tensor<
       %inserted_slice = tensor.insert_slice %4 into %arg8[
       scf.yield %inserted_slice : tensor<128x128xf32>
     }
     scf.yield %2 : tensor<128x128xf32>
   }
   scf.yield %1 : tensor<128x128xf32>
 }
 return %0 : tensor<128x128xf32>
}
```

```
Constraint set: 4 variables
(%4  %extracted_slice_1  %3   %arg7     const)
 1   -1                  0    0         0        = 0
 0   1                   -1   0         0        = 0
 0   0                   -1   -1        128      >= 0
 0   0                   -1   0         9        >= 0
```

compute constant UB for dim(%4, 1) → 10 (open bound)

`FlatLinearConstraints` (MLIR Presburger library)

$$Ax + b = 0$$

$$Ax + b \geq 0$$

one variable per SSA value

coefficients stored as a matrix

- Linear combination of variables
- Multiplication/division of variables is not supported
- Corresponds to the “flattened form” of `AffineExprs`
- Relevant API:
  - project out a variable (Fourier-Motzkin elimination)
  - compute LB/UB of a variable
  - check if constraint set is “empty”

ValueBoundsOpInterface

```
struct AddIOpInterface
   : public ValueBoundsOpInterface::ExternalModel<AddIOpInterface, AddIOp> {
 void populateBoundsForIndexValue(Operation *op, Value value,
                                  ValueBoundsConstraintSet &cstr) const {
   auto addIOp = cast<AddIOp>(op);
   assert(value == addIOp.getResult() && "invalid value");

   cstr.bound(value) == cstr.getExpr(addIOp.getLhs()) + cstr.getExpr(addIOp.getRhs());
 }
};
```

op result or block argument

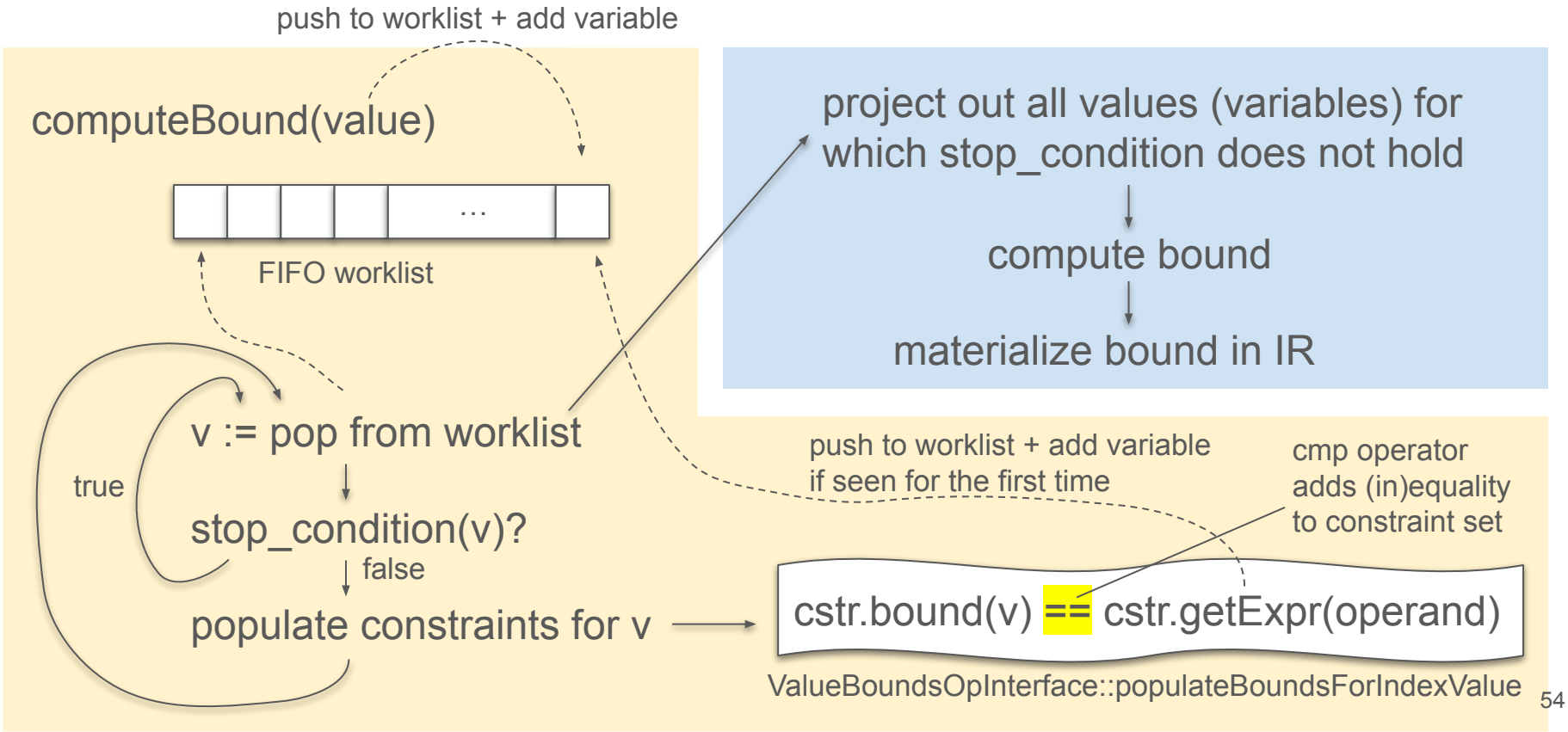
get affine expr for SSA value

affine expression, constant or SSA value

comparison operators(==, <, <=, >=, >) are overloaded

not a (dataflow) analysis!

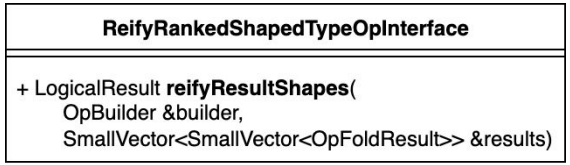
Computing Bounds: Worklist-Driven IR Analysis



`ValueBoundsOpInterface` Limitations

- Cannot model overflows: integers have infinite precision (`DynamicAPInt`).
- Non-linear constraints (e.g., multiplying two SSA values) cannot be modelled.
- Cannot distinguish between signed/unsigned integer semantics.
- Performance issues: A brand new constraint set is built for each query.
  (Entire IR is traversed for each query, until the stop condition is reached.)

ReifyRankedShapedTypeOpInterface



- Materialize (dynamic) dimension sizes as SSA values.
- Simplifies `memref/tensor.dim` ops: `-resolve-ranked-shaped-type-result-dims`

```
%0 = tensor.pad %arg0 low[2, %arg1, 3, %arg1] high[3, 3, %arg1, 2] {
^bb0(%arg2: index, %arg3: index, %arg4: index, %arg5: index):
  tensor.yield %pad_value : f32
} : tensor<1x2x2x?xf32> to tensor<6x?x?x?xf32>
```

```
%c6 = arith.constant 6 : index
%c2 = arith.constant 2 : index
%c3 = arith.constant 3 : index
%0 = arith.addi %c2, %arg1 : index
%1 = arith.addi %0, %c3 : index
%dim = tensor.dim %arg0, %c3 : tensor<1x2x2x?xf32>
%2 = arith.addi %dim, %0 : index

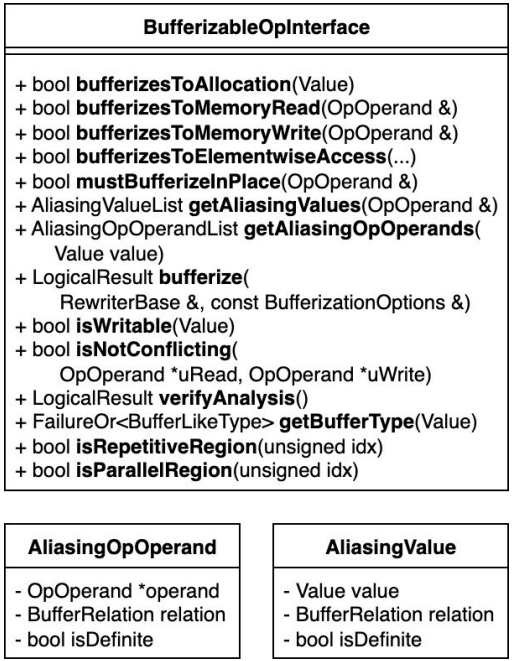
⇒ [ %c6, %1, %1, %2 ]
```

`ReifyRankedShapedTypeOpInterface`

- Can this interface be replaced by `ValueBoundsOpInterface`?
- `ValueBoundsConstraintSet` can be queried to compute an equality bound for an op result `%0` in terms of other SSA values.
- Certain arithmetic operations cannot be represented in the constraint set:
  `%0 = arith.muli %a, %b : i32`
- Current `ValueBoundsConstraintSet` may be too inefficient.

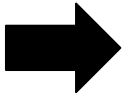
Interfaces that Drive Transformations

BufferizableOpInterface



- `-one-shot-bufferize` converts tensor IR to memref IR.
- Tensors are “abstract” values that do not have memory locations. Memrefs are pointers + metadata (shape, etc.).
- Bufferization typically happens towards the end of a compilation pipeline.

```
func.func @test(%a: tensor<5xf32>)
    -> tensor<5xf32> {
  %cst = arith.constant 0.0 : f32
  %0 = linalg.fill ins(%cst) outs(%a)
      -> tensor<5xf32>
  %r = tensor.extract %a[0] : tensor<5xf32>
  vector.print %r : f32
  return %0 : tensor<5xf32>
}
```



```
func.func @test(%a: memref<5xf32>)
    -> memref<5xf32> {
  %cst = arith.constant 0.0 : f32
  %copy = memref.alloc() : memref<5xf32>
  memref.copy %a, %copy
  linalg.fill ins(%cst) outs(%copy)
  %r = memref.load %a[0] : memref<5xf32>
  vector.print %r : f32
  return %copy : memref<5xf32>
}
```

History of One-Shot Bufferize

- One-Shot Bufferize used to be a monolithic component, with a hard-coded list of supported operations. (Living in `Linalg/Transforms`.)
- Today, One-Shot Bufferize is interface-based, extensible and interface implementations live in their respective dialects.

```
LogicalResult mlir::linalg::bufferizeOp(
    Operation *op, BlockAndValueMapping &bvm, BufferizationAliasInfo &aliasInfo,
    AllocationCallbacks allocationFns,
    DenseMap<FuncOp, FunctionType> *bufferizedFunctionTypes) {
  OpBuilder b(op->getContext());
  return TypeSwitch<Operation *, LogicalResult>(op)
      // Skip BufferCast and TensorLoad ops.
      .Case<memref::BufferCastOp, memref::TensorLoadOp>(
          [&](auto) { return success(); })
      .Case<ExtractSliceOp, InitTensorOp, InsertSliceOp, LinalgOp, scf::ForOp,
            scf::IfOp, tensor::CastOp, TiledLoopOp, VectorTransferOpInterface>(
          [&](auto op) {
            LDBG("Begin bufferize:\n" << op << '\n');
            return bufferize(b, op, bvm, aliasInfo, allocationFns);
          })
      .Case<tensor::DimOp, tensor::ExtractOp, ReturnOp, linalg::YieldOp,
            scf::YieldOp>([&](auto op) {
        LDBG("Begin bufferize:\n" << op << '\n');
        return bufferize(b, op, bvm, aliasInfo);
      })
      .Case([&](CallOpInterface op) {
        LDBG("Begin bufferize:\n" << op << '\n');
        if (!bufferizedFunctionTypes)
```

BufferizableOpInterface

- Models future memory read/write side effects:
  - `bufferizesToMemoryRead`: does the bufferized op have a “read” side effect?
  - `bufferizesToMemoryWrite`: does the bufferized op have a “write” side effect?
  - Cannot reason about tensor subsets yet.
- Models future alias sets:
  - `getAliasingOpOperand`: can a given op result share the same buffer with an operand?
  - `getAliasingOpResult`: can a given operand share the same buffer with an op result?
  - `%0 = tensor.insert %f into %t[0] : tensor<5xf32>`
    - %t and %0 can share the same buffer. (In the absence of a RaW conflict.)
    - Can bufferize to: `memref.store %f, buffer(%t) : memref<5xf32>`
- Interface function that actually bufferizes the IR.

default implementation for `DestinationStyleOpInterface`

Read-after-Write (RAW) Conflict

```
// Definition
%1 = linalg.fill ins(%cst1) outs(...) -> tensor<5xf32>

// Conflicting Write → Cannot reuse buffer(%1) because we still need the value of %1.
%2 = linalg.fill ins(%cst2) outs(%1) -> tensor<5xf32>
```

aliasingOpOperand(%2) = %1
⇒ Try to reuse *buffer*(%2) = *buffer*(%1)

bufferizes to mem write

```
// Read
%3 = tensor.extract %1[%c0] : tensor<5xf32>
```

bufferizes to mem read

Bufferization of `tensor.extract_slice` / `insert_slice`

alias set: {%t, %0, %1, %2}

```
%t = ...  // definition
%0 = tensor.extract_slice %t [0][5][1] : tensor<10xf32> to tensor<5xf32>

%1 = linalg.fill ins(%cst) outs(%0) -> tensor<5xf32>

%2 = tensor.insert_slice %1 into %t [0][5][1] : tensor<5xf32> into tensor<10xf32>
```

bufferizes to mem write

bufferizes to mem read

CONFLICT?

Bufferization of `tensor.extract_slice` / `insert_slice`

alias set: {%t, %0, %1, %2}

```
%t = ...  // definition
%0 = tensor.extract_slice %t [0][5][1] : tensor<10xf32> to tensor<5xf32>

%1 = linalg.fill ins(%cst) outs(%0) -> tensor<5xf32>

%2 = tensor.insert_slice %1 into %t [0][5][1] : tensor<5xf32> into tensor<10xf32>
```

bufferizes to mem write

bufferizes to mem read

No, because `tensor.insert_slice` reads only the part of %t that is not written by `linalg.fill`. (Tensor subsets are *non-overlapping*.)

Bufferization of `tensor.gather` / `scatter` (not implemented)

alias set: {%t, %0, %1, %2}

```
%t = ...  // definition
%0 = tensor.gather %t ...

%1 = linalg.fill ins(%cst) outs(%0) -> tensor<5xf32>
```

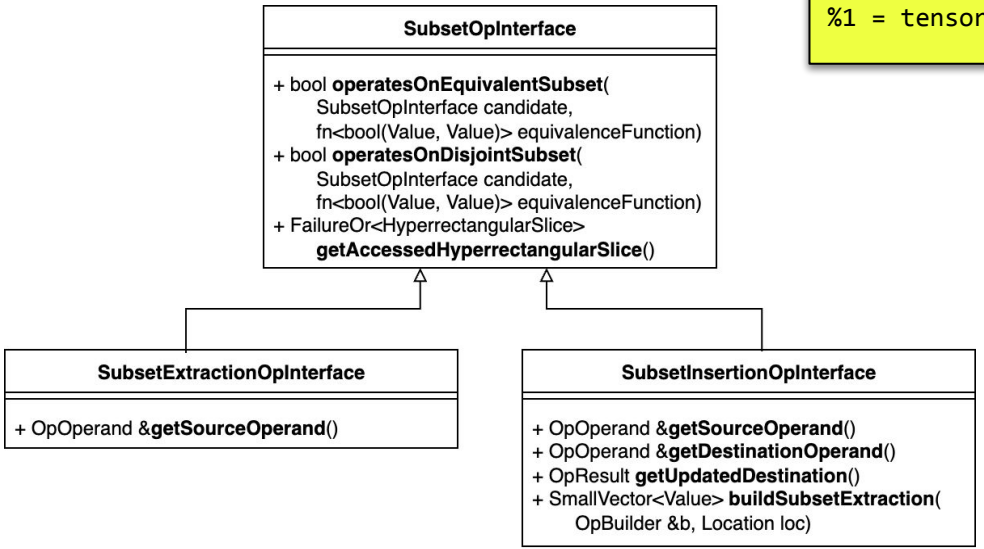
bufferizes to mem write

```
%2 = tensor.scatter %1 into %t ...
```

bufferizes to mem read

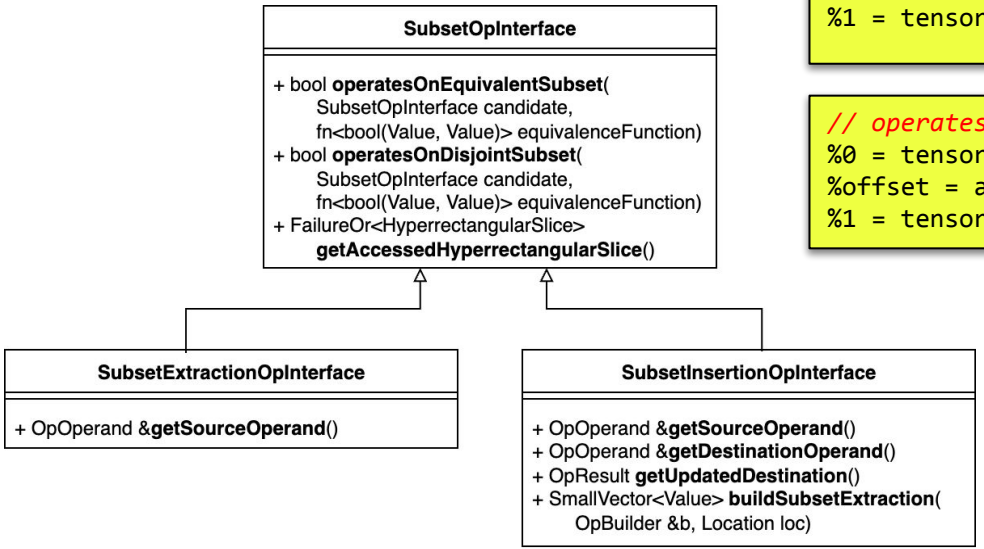
CONFLICT?

SubsetInsertion / ExtractionOpInterface




```
// operatesOnEquivalentSubset ⇒ true
%0 = tensor.extract_slice %t [9][5][1] : …
%1 = tensor.insert_slice … into %t [9][5][1] : …
```

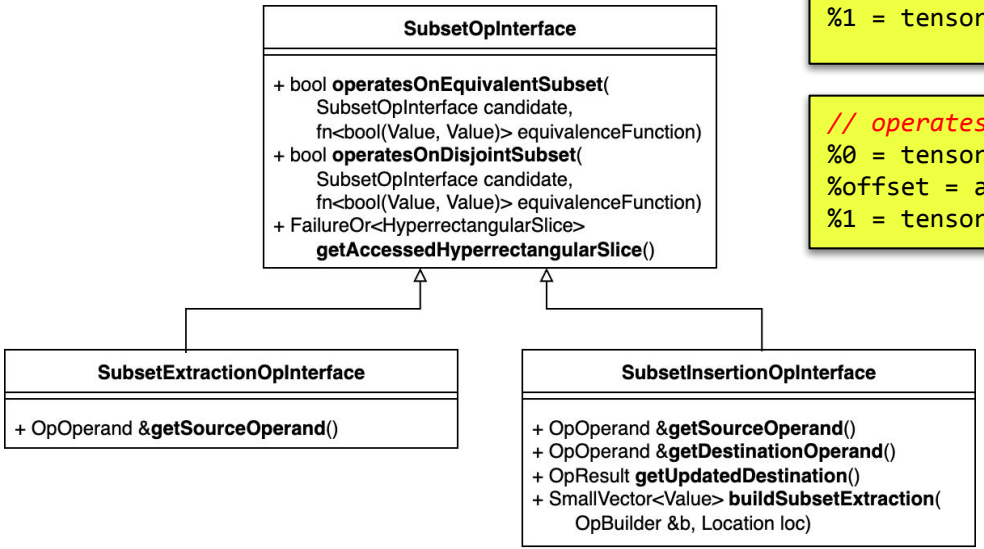
SubsetInsertion / ExtractionOpInterface




```
// operatesOnEquivalentSubset ⇒ true
%0 = tensor.extract_slice %t [9][5][1] : …
%1 = tensor.insert_slice … into %t [9][5][1] : …
```

```
// operatesOnEquivalentSubset ⇒ ???
%0 = tensor.extract_slice %t [9][5][1] : …
%offset = arith.addi %c4, %c5 : index
%1 = tensor.insert_slice … into %t [%offset][5][1] : …
```

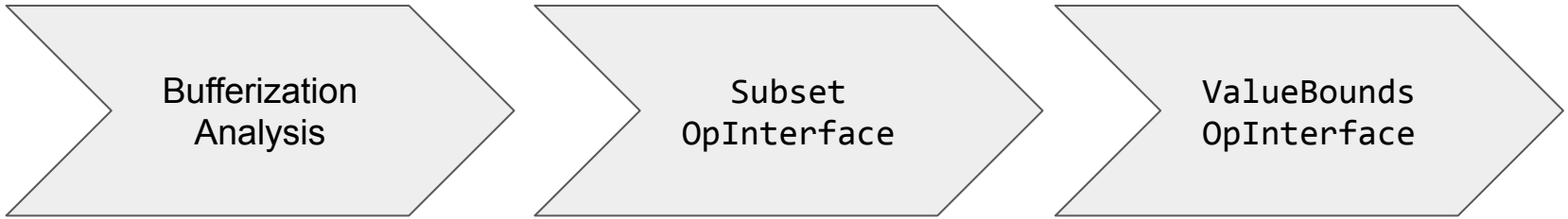
SubsetInsertion / ExtractionOpInterface




```
// operatesOnEquivalentSubset ⇒ true
%0 = tensor.extract_slice %t [9][5][1] : …
%1 = tensor.insert_slice … into %t [9][5][1] : …
```

```
// operatesOnEquivalentSubset ⇒ true
%0 = tensor.extract_slice %t [9][5][1] : …
%offset = arith.addi %c4, %c5 : index
%1 = tensor.insert_slice … into %t [%offset][5][1] : …
```

operatesOnEquivalentSubset queries
ValueBoundsConstraintSet
::areEquivalentSlices(...)



(BufferizableOpInterface)

TilingInterface

TilingInterface

+ SmallVector<IteratorType> **getLoopIteratorTypes**()
+ SmallVector<Range> **getIterationDomain**(OpBuilder &)
+ FailureOr<TilingResult> **getTiledImplementation**(
  OpBuilder &, ArrayRef<OpFoldResult> offsets,
  ArrayRef<OpFoldResult> sizes)
+ LogicalResult **getResultTilePosition**(....)
+ FailureOr<TilingResult> **generateResultTileValue**(...)
+ FailureOr<TilingResult>
  getTiledImplementationFromOperandTiles(...)
+ LogicalResult **getIterationDomainTileFromOperandTiles**(...)
+ LogicalResult **getIterationDomainTileFromResultTile**(...)
+ LogicalResult **generateScalarImplementation**(...)

TilingResult

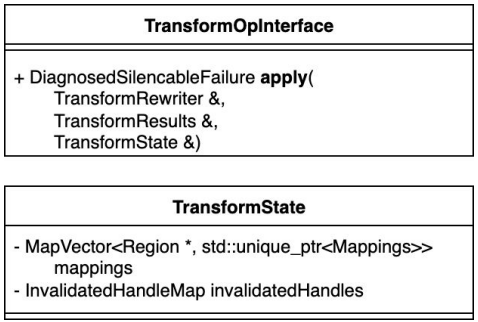
- SmallVector<Operation *> tiledOps
- SmallVector<Value> tiledValues
- SmallVector<Operation *> generatedSlices

+ FailureOr<TiledLinalgOp> **tileLinalgOp**(
  RewriterBase &, LinalgOp, const LinalgTilingOptions &)
+ FailureOr<SCFTilingResult> **tileUsingSCF**(
  RewriterBase &, TilingInterface op, const SCFTilingOptions &)

- Used by the Linalg tiling infrastructure to tile an operation with tensor semantics.
- Best understood by studying MLIR test cases.

```
//      CHECK: %[[TD0:.*]] = scf.for {{.*}} to {{.*}} step {{.*}} iter_args(%[[TC0:.*]] = %[[TC]]) ... {
//      CHECK:   %[[TD1:.*]] = scf.for {{.*}} to {{.*}} step {{.*}} iter_args(%[[TC1:.*]] = %[[TC0]]) ... {
//      CHECK:     %[[TD2:.*]] = scf.for {{.*}} to {{.*}} step {{.*}} iter_args(%[[TC2:.*]] = %[[TC1]]) ... {
//      CHECK:       %[[sTA:.*]] = tensor.extract_slice %[[TA]][{{.*}}]
//      CHECK:       %[[sTB:.*]] = tensor.extract_slice %[[TB]][{{.*}}]
//      CHECK:       %[[sTC:.*]] = tensor.extract_slice %[[TC2]][{{.*}}]
//      CHECK:       %[[sTD:.*]] = linalg.matmul ins(%[[sTA]], %[[sTB]] : tensor<4x4xf32>, tensor<4x4xf32>)
// CHECK-SAME:                                  outs(%[[sTC]] : tensor<4x4xf32>) -> tensor<4x4xf32>
//      CHECK:       %[[TD:.*]] = tensor.insert_slice %[[sTD]] into %[[TC2]][{{.*}}]
//      CHECK:       scf.yield %[[TD]] : tensor<128x128xf32>
//      CHECK:     scf.yield %[[TD2]] : tensor<128x128xf32>
//      CHECK:   scf.yield %[[TD1]] : tensor<128x128xf32>
%0 = linalg.matmul  ins(%arg0, %arg1: tensor<128x128xf32>, tensor<128x128xf32>)
                    outs(%arg2: tensor<128x128xf32>) -> tensor<128x128xf32>
```

TransformOpInterface

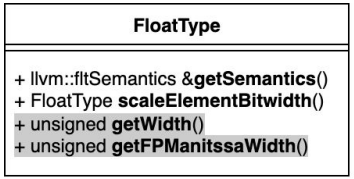


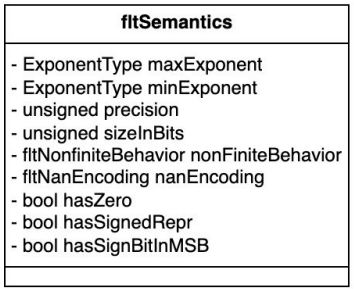
- Implemented by transform dialect ops.
- `apply()` executes the transform dialect op.

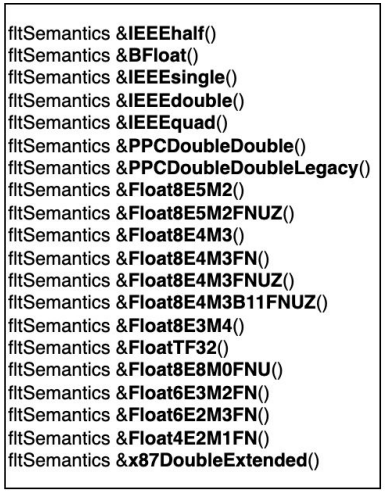
```
module attributes {transform.with_named_sequence} {
  transform.named_sequence @__transform_main(
        %arg1: !transform.any_op {transform.readonly}) {
    %0 = transform.structured.match ops{["linalg.matmul"]} in %arg1
        : (!transform.any_op) -> !transform.any_op
    %1, %loops:3 = transform.structured.tile_using_for %0
        tile_sizes [4, 4, 4]
        : (!transform.any_op)
        -> (!transform.any_op, !transform.any_op,
            !transform.any_op, !transform.any_op)
    transform.yield
  }
}
```

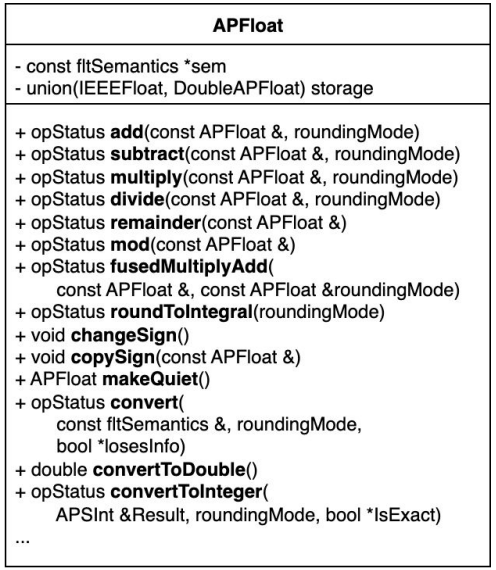
Type Interfaces

FloatType









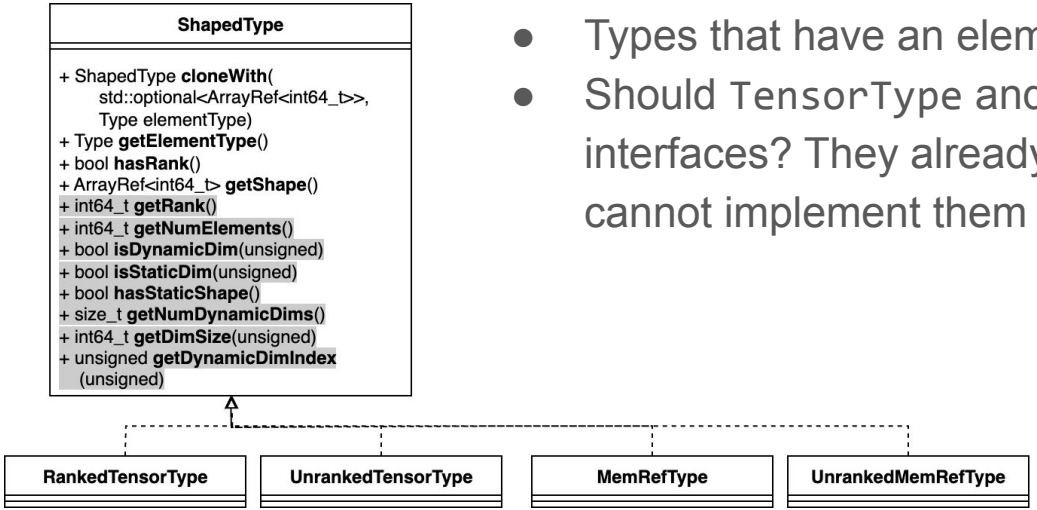

```
f32
f64
f8E4M3FN
```

- FP types are defined in LLVM (`fltSemantics`; code is a mess, needs rewrite…).
- FP values are represented as `APFloat`.
- MLIR types / attributes are just a wrapper around these LLVM objects.

`IntegerType` Interface?

- Does not exist today. Has been requested a few times by OSS folks.
  - Define your own integer type, while being able to reuse `arith` dialect ops.
- Example: Integer type that carries divisibility information. Does not compose well with `arith` operations (`AllTypesMatch`).

ShapedType

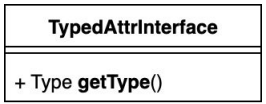


- Types that have an element type and **may have** a shape.
- Should `TensorType` and `BaseMemRefType` be public interfaces? They already behave like interfaces, but you cannot implement them on new types.

```
tensor<10x20xf32>
tensor<*xf32>
memref<10x20xf32>
memref<*xf32>
```

Attribute Interfaces

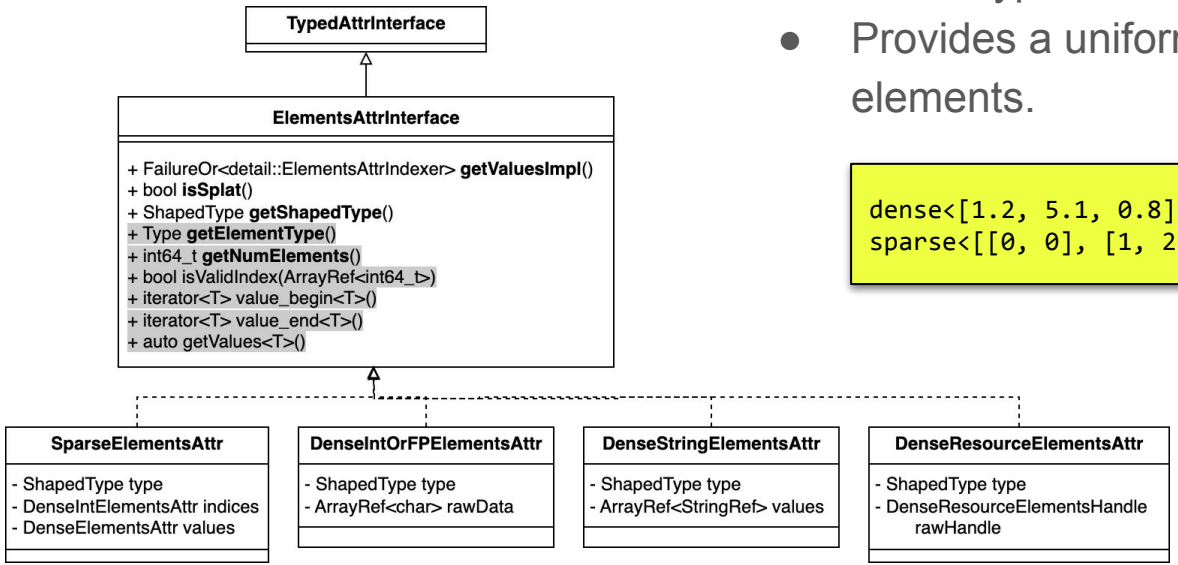
TypedAttrInterface



- Query the type of an attribute in a uniform way.
- Examples: `FloatAttr`, `IntegerAttr`

```
2.1 : f32
127 : i8
dense<[1.2, 5.1, 0.8]> : tensor<3xf16>
```

ElementsAttrInterface

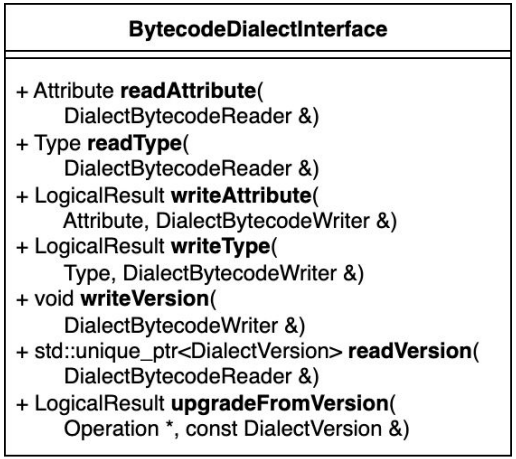


- Abstracts over constant elements with a vector or tensor type.
- Provides a uniform C++ API to iterate / query elements.

```
dense<[1.2, 5.1, 0.8]> : tensor<3xf16>
sparse<[[0, 0], [1, 2]], [1, 5]> : tensor<3x4xi32>
```

Dialect Interfaces

BytecodeDialectInterface



- Bytecode is a more space-efficient storage of IR.
- Every dialect has a version.
- Dialects provide hooks to read/write attributes/types.
- Dialects provide hooks to upgrade bytecode of an older version to a newer version.

Open Questions / Discussion

Interface Promise breaks Modularity

- Dialect compilation unit must depend on all compilation units that contain implemented interfaces. Even those that are implemented via external model.
  - Example: `TensorDialect` must depend on `BufferizationDialect` to promise the interface.
- An interface defined outside of the `MLIRIR` cannot be promised for `builtin` operations / types / attributes / dialect and requires hard-coding the op.
  - Example: `builtin.module` cannot implement `DataLayoutOpInterface`.
  - Example: `builtin` dialect cannot implement Inliner dialect interface.
  - Example: `OpAsmOpInterface`, `SymbolOpInterface` cannot be defined in `MLIRInterfaces`.
- We are giving preferential treatment to upstream interfaces. Downstream interface do not have to be (and cannot be) promised.

Swappable Interface Implementations

- External interface registrations are tracked in the MLIR context (`OperationName::Impl::interfaceMap`).
- OSS folks occasionally ask for customizable op interfaces, i.e.:
  - A hook to unregister an interface: remove the interface from the interface map.
  - Allow registration of another external model.
  - Example: Customizable `BufferizableOpInterface` implementation.

Other Interfaces

```
CastOpInterface
SelectLikeOpInterface
ReturnLike
DataLayoutOpInterface
DialectFoldInterface
InferTypeOpInterface
InferShapedTypeOpInterface
BlobAttrInterface
DestinationStyleOpInterface
HasParallelRegion
ParallelCombiningOpInterface
RuntimeVerifiableOpInterface
VectorUnrollOpInterface
VectorTransferOpInterface
DerivedAttributeOpInterface
```

```
PromotableAllocationOpInterface
PromotableMemOpInterface
PromotableOpInterface
DestructurableAllocationOpInterface
Symbol
SymbolUserOpInterface
BytecodeOpInterface
VectorElementTypeInterface
IndexingMapOpInterface
MemRefElementTypeInterface
PtrLikeTypeInterface
BlobAttrInterface
…
```