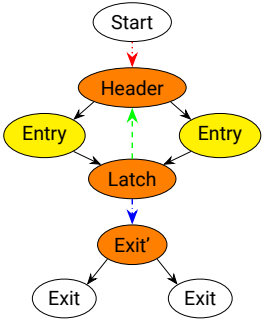
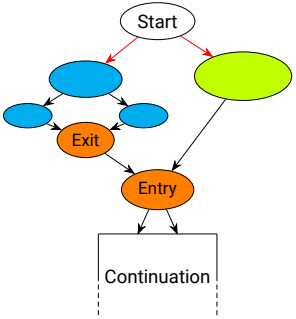
Lifting CFGs to Structured Control Flow in MLIR

Markus Böck
University of Cambridge





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- Does not canonicalize loops
- Transformation APIs inconvenient

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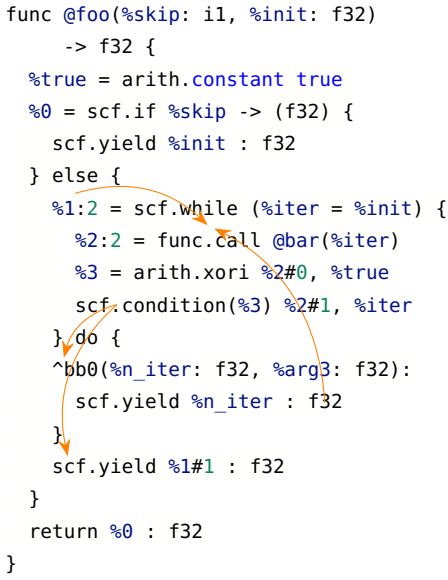

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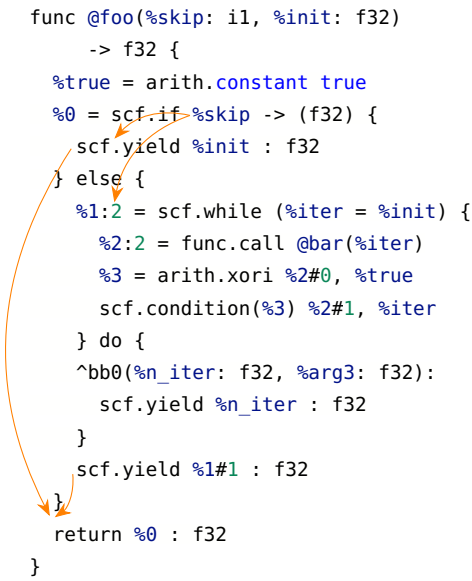

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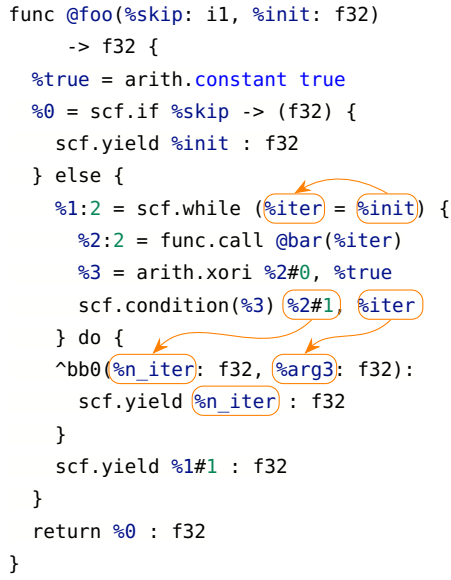

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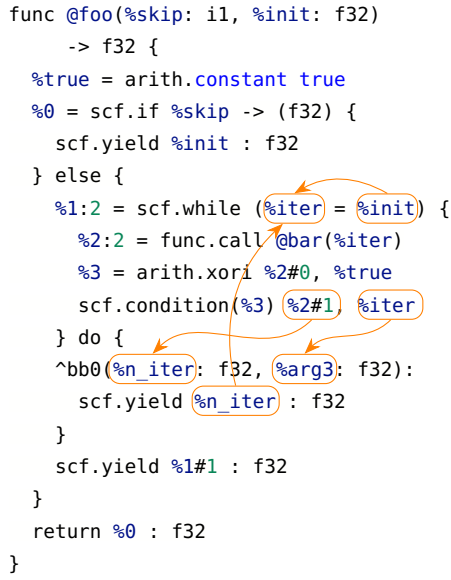

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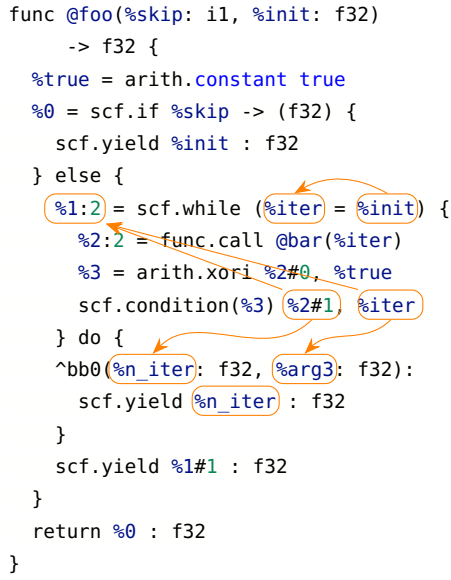

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class WhileOp : public Op<WhileOp, ...> {
public:
  …
  Operation::operand_range getInits();
  MutableOperandRange getInitsMutable();
  Operation::result_range getResults();

  ConditionOp getConditionOp();
  YieldOp getYieldOp();

 Block::BlockArgListType getBeforeArguments();
 Block::BlockArgListType getAfterArguments();
};
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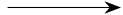

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- Upstream as driver and `--lift-cf-to-scf`
- Paper extended to handle:
  - Block arguments
  - Multiple Return-like operations

Top-level loop

```
def cfg_to_scf(region):
  consolidate_return_likes(region)
  worklist: list[BasicBlock] = [region.entry]
  while len(worklist) != 0:
    start_block = worklist.pop_back()
    assert dominates_all_successors(start_block)

    # Step 1: Cycles → do-while ops.
    worklist += transform_cycles_to_do_while(start_block)
    assert is_dag(start_block)
    # Step 2: Handling branches.
    worklist += transform_branches(start_block)
```

Return-likes

```
func.func @multi_return() -> i32 {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb3
^bb1:
  %0 = "test.test2"() : () -> i32
  return %0 : i32
^bb3:
  %1 = "test.test4"() : () -> i32
  return %1 : i32
}
```

Return-likes

```
func.func @multi_return() -> i32 {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb3
^bb1:
  %0 = "test.test2"() : () -> i32
  return %0 : i32
^bb3:
  %1 = "test.test4"() : () -> i32
  return %1 : i32
}
```

```
func.func @multi_return() -> i32 {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb3
^bb1:
  %0 = "test.test2"() : () -> i32
  cf.br ^bb4(%0 : i32)
^bb3:
  %1 = "test.test4"() : () -> i32
  cf.br ^bb4(%1 : i32)
^bb4(%arg0 : i32):
  return %arg0 : i32
}
```

Return-likes

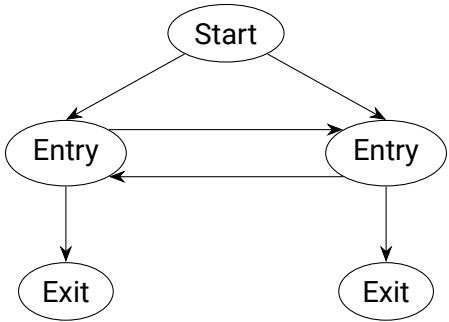
```
func.func @multi_return_likes() -> i32 {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb3
^bb1:
  %0 = "test.test2"() : () -> i32
  exc.raise
^bb3:
  %1 = "test.test4"() : () -> i32
  return %1 : i32
}
```

Return-likes

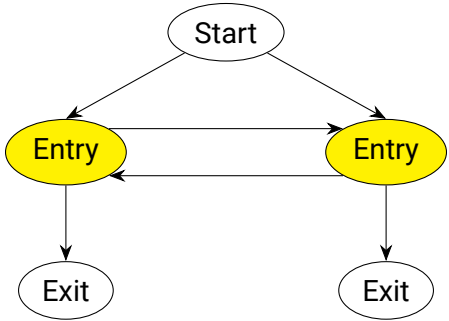
```
func.func @multi_return_likes() -> i32 {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb3
^bb1:
  %0 = "test.test2"() : () -> i32
  exc.raise
^bb3:
  %1 = "test.test4"() : () -> i32
  return %1 : i32
}
```

- Single control flow op remains
- Always top-level
- Only such case

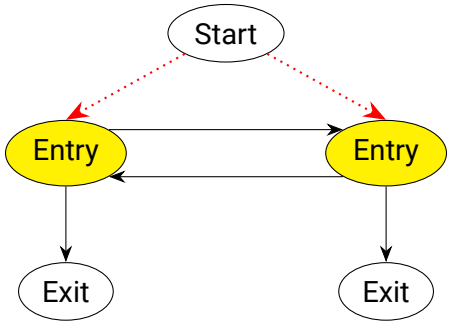
Handling Cycles



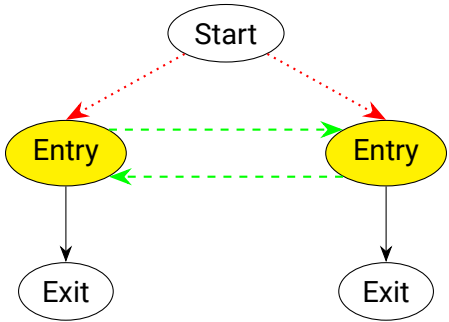
Handling Cycles



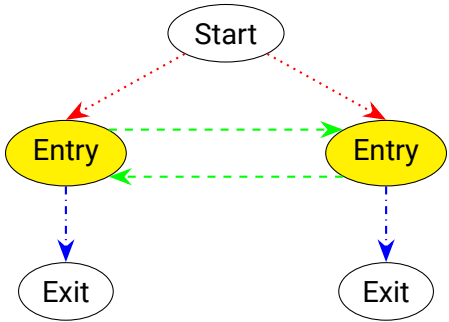
Handling Cycles



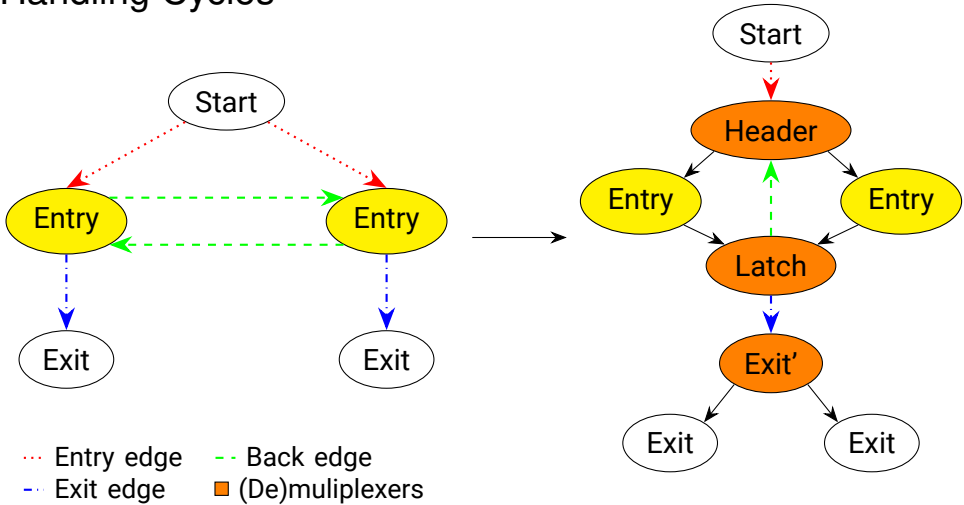
Handling Cycles



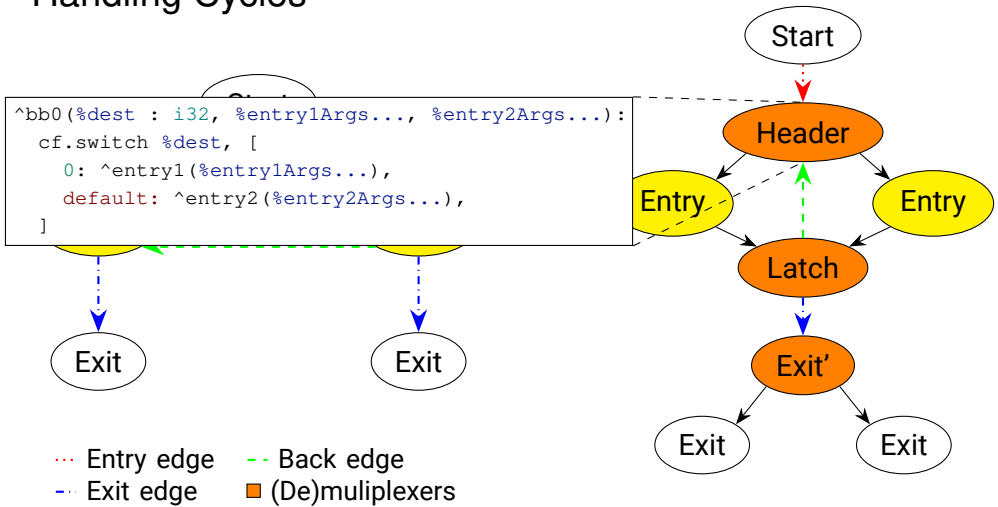
Handling Cycles



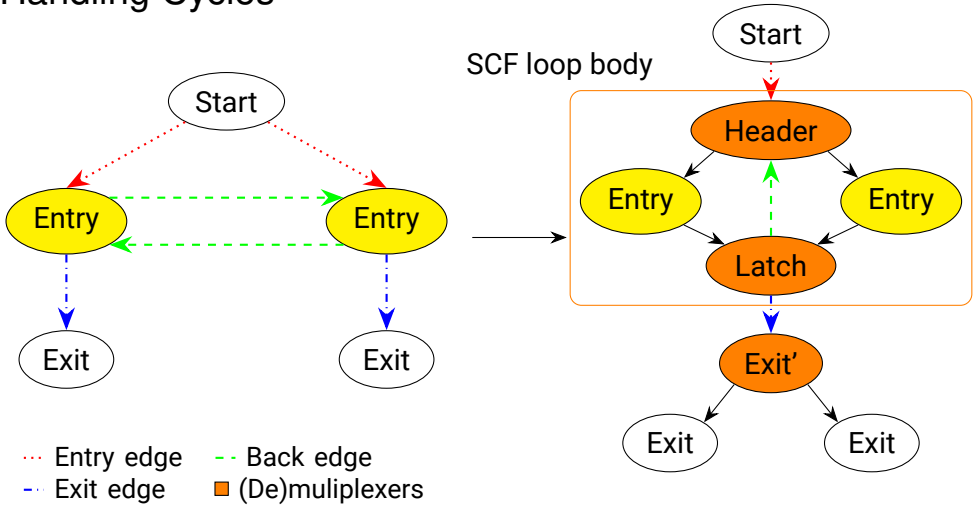
Handling Cycles



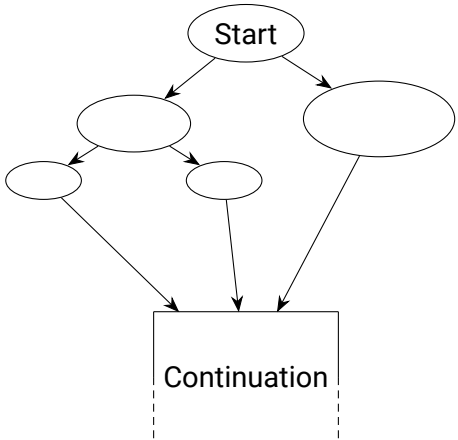
Handling Cycles



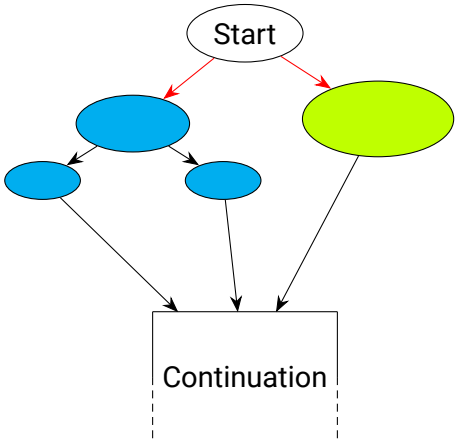
Handling Cycles



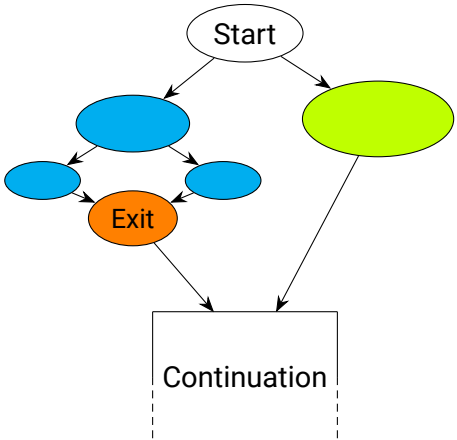
Handling branches



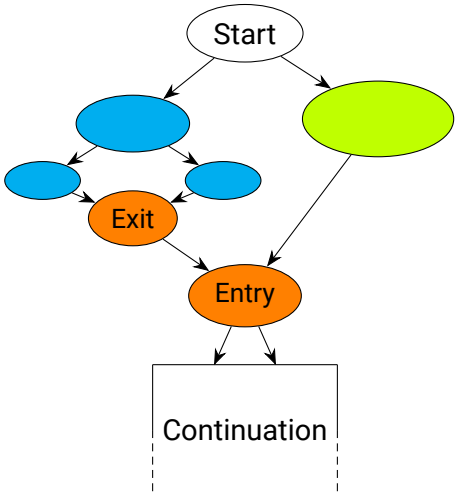
Handling branches



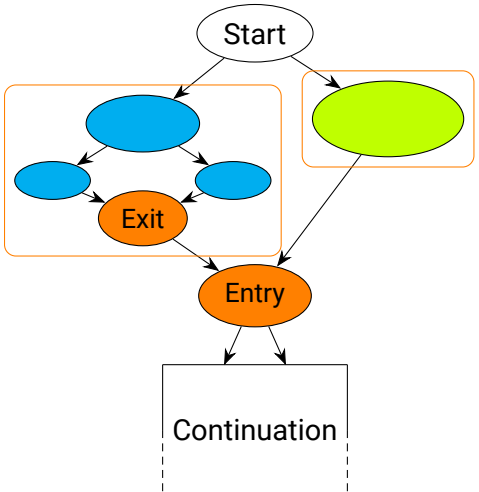
Handling branches



Handling branches



Handling branches



Results

```
func.func @simple_if() {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb2
^bb1:
  "test.test2"() : () -> ()
  cf.br ^bb3
^bb2:
  "test.test3"() : () -> ()
  cf.br ^bb3
^bb3:
  "test.test4"() : () -> ()
  return
}
```

Results

```
func.func @simple_if() {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb2
^bb1:
  "test.test2"() : () -> ()
  cf.br ^bb3
^bb2:
  "test.test3"() : () -> ()
  cf.br ^bb3
^bb3:
  "test.test4"() : () -> ()
  return
}
```

```
func.func @simple_if() {
  %0 = "test.test1"() : () -> i1
  scf.if %0 {
    "test.test2"() : () -> ()
  } else {
    "test.test3"() : () -> ()
  }
  "test.test4"() : () -> ()
  return
}
```

Results

```
func.func @if_with_block_args() -> index {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb2
^bb1:
  %1 = "test.test2"() : () -> (index)
  cf.br ^bb3(%1: index)
^bb2:
  %2 = "test.test3"() : () -> (index)
  cf.br ^bb3(%2: index)
^bb3(%3: index):
  "test.test4"() : () -> ()
  return %3 : index
}
```

Results

```
func.func @if_with_block_args() -> index {
  %cond = "test.test1"() : () -> i1
  cf.cond_br %cond, ^bb1, ^bb2
^bb1:
  %1 = "test.test2"() : () -> (index)
  cf.br ^bb3(%1: index)
^bb2:
  %2 = "test.test3"() : () -> (index)
  cf.br ^bb3(%2: index)
^bb3(%3: index):
  "test.test4"() : () -> ()
  return %3 : index
}
```

```
func.func @if_with_block_args() -> index {
  %0 = "test.test1"() : () -> i1
  %1 = scf.if %0 -> (index) {
    %2 = "test.test2"() : () -> index
    scf.yield %2 : index
  } else {
    %2 = "test.test3"() : () -> index
    scf.yield %2 : index
  }
  "test.test4"() : () -> ()
  return %1 : index
}
```

Results

```
func.func @while_loop() {
  "test.test1"() : () -> ()
  cf.br ^bb1
^bb1:
  %cond = "test.test2"() : () -> i1
  cf.cond_br %cond, ^bb2, ^bb3
^bb2:
  "test.test3"() : () -> ()
  cf.br ^bb1
^bb3:
  "test.test4"() : () -> ()
  return
}
```

Results

```
func.func @while_loop() {
  "test.test1"() : () -> ()
  cf.br ^bb1
^bb1:
  %cond = "test.test2"() : () -> i1
  cf.cond_br %cond, ^bb2, ^bb3
^bb2:
  "test.test3"() : () -> ()
  cf.br ^bb1
^bb3:
  "test.test4"() : () -> ()
  return
}
```

```
func.func @while_loop() {
  %c1_i32 = arith.constant 1 : i32
  %c0_i32 = arith.constant 0 : i32
  "test.test1"() : () -> ()
  scf.while : () -> () {
    %0 = "test.test2"() : () -> i1
    %1:2 = scf.if %0 -> (i32, i32) {
      "test.test3"() : () -> ()
      scf.yield %c0_i32, %c1_i32 : i32, i32
    } else {
      scf.yield %c1_i32, %c0_i32 : i32, i32
    }
    %2 = arith.trunci %1#1 : i32 to i1
    scf.condition(%2)
  } do {
    scf.yield
  }
  "test.test4"() : () -> ()
  return
}
```

Results

```
func.func @while_loop_with_block_args() {
  %1 = "test.test1"() : () -> index
  cf.br ^bb1(%1: index)
^bb1(%2: index):
  %cond:2 = "test.test2"()
  cf.cond_br %cond#0, ^bb2(%cond#1: i64),
                      ^bb3(%2: index)
^bb2(%3: i64):
  %4 = "test.test3"(%3) : (i64) -> index
  cf.br ^bb1(%4: index)
^bb3(%5: index):
  "test.test4"() : () -> ()
  return %5 : index
}
```

Results

```
func.func @while_loop_with_block_args() {
  %1 = "test.test1"() : () -> index
  cf.br ^bb1(%1: index)
^bb1(%2: index):
  %cond:2 = "test.test2"()
  cf.cond_br %cond#0, ^bb2(%cond#1: i64),
                      ^bb3(%2: index)
^bb2(%3: i64):
  %4 = "test.test3"(%3) : (i64) -> index
  cf.br ^bb1(%4: index)
^bb3(%5: index):
  "test.test4"() : () -> ()
  return %5 : index
}
```

```
func.func @while_loop_with_block_args() -> index {
  %0 = ub.poison : index
  %1 = "test.test1"() : () -> index
  %2:2 = scf.while (%arg0 = %1) {
    %3:2 = "test.test2"() : () -> (i1, i64)
    %4 = scf.if %3#0 -> (index) {
      %5 = "test.test3"(%3#1) : (i64) -> index
      scf.yield %5 : index
    } else {
      scf.yield %0 : index
    }
    scf.condition(%3#0) %4, %arg0 : index, index
  } do {
  ^bb0(%arg0: index, %arg1: index):
    scf.yield %arg0 : index
  }
  "test.test4"() : () -> ()
  return %2#1 : index
}
```

Results

```
func.func @switch_with_fallthrough(
    %flag: i32, %arg1 : f32, %arg2 : f32) {
  cf.switch %flag : i32, [
    default: ^bb1(%arg1 : f32),
    0: ^bb2(%arg2 : f32),
    1: ^bb3
  ]

^bb1(%arg3 : f32):
  %0 = call @foo(%arg3) : (f32) -> f32
  cf.br ^bb2(%0 : f32)

^bb2(%arg4 : f32):
  call @bar(%arg4) : (f32) -> ()
  cf.br ^bb3

^bb3:
  return
}
```

Results

```
func.func @switch_with_fallthrough(
    %flag: i32, %arg1 : f32, %arg2 : f32) {
  cf.switch %flag : i32, [
    default: ^bb1(%arg1 : f32),
    0: ^bb2(%arg2 : f32),
    1: ^bb3
  ]

^bb1(%arg3 : f32):
  %0 = call @foo(%arg3) : (f32) -> f32
  cf.br ^bb2(%0 : f32)

^bb2(%arg4 : f32):
  call @bar(%arg4) : (f32) -> ()
  cf.br ^bb3

^bb3:
  return
}
```

```
func.func @switch_with_fallthrough(
    %arg0: i32, %arg1: f32, %arg2: f32) {
  %c1_i32 = arith.constant 1 : i32
  %0 = ub.poison : f32
  %c0_i32 = arith.constant 0 : i32
  %1 = arith.index_castui %arg0 : i32 to index
  %2:2 = scf.index_switch %1 -> f32, i32
  case 0 {
    scf.yield %arg2, %c0_i32 : f32, i32
  }
  case 1 {
    scf.yield %0, %c1_i32 : f32, i32
  }
  default {
    %4 = func.call @foo(%arg1) : (f32) -> f32
    scf.yield %4, %c0_i32 : f32, i32
  }
  %3 = arith.index_castui %2#1 : i32 to index
  scf.index_switch %3
  case 0 {
    func.call @bar(%2#0) : (f32) -> ()
    scf.yield
  }
  default {
  }
  return
}
```

Results

```
func.func @multi_entry_loop(%cond: i1) {
  %0 = arith.constant 6 : i32
  %1 = arith.constant 5 : i32
  cf.cond_br %cond, ^bb0, ^bb1

^bb0:
  %exit = call @comp1(%0) : (i32) -> i1
  cf.cond_br %exit, ^bb2(%0 : i32), ^bb1

^bb1:
  %exit2 = call @comp2(%1) : (i32) -> i1
  cf.cond_br %exit2, ^bb2(%1 : i32), ^bb0

^bb2(%arg3 : i32):
  call @foo(%arg3) : (i32) -> ()
  return
}
```

Results

```
func.func @multi_entry_loop(%cond: i1) {
  %0 = arith.constant 6 : i32
  %1 = arith.constant 5 : i32
  cf.cond_br %cond, ^bb0, ^bb1

^bb0:
  %exit = call @comp1(%0) : (i32) -> i1
  cf.cond_br %exit, ^bb2(%0 : i32), ^bb1

^bb1:
  %exit2 = call @comp2(%1) : (i32) -> i1
  cf.cond_br %exit2, ^bb2(%1 : i32), ^bb0

^bb2(%arg3 : i32):
  call @foo(%arg3) : (i32) -> ()
  return
}
```

```
func.func @multi_entry_loop(%arg0: i1) {
  %true = arith.constant true
  %c1_i32 = arith.constant 1 : i32
  %c0_i32 = arith.constant 0 : i32
  %c6_i32 = arith.constant 6 : i32
  %c5_i32 = arith.constant 5 : i32
  %0 = arith.extui %arg0 : i1 to i32
  %1:2 = scf.while (%arg1 = %0) : (i32) -> (i32, i32) {
    %2 = arith.index_castui %arg1 : i32 to index
    %3:4 = scf.index_switch %2 -> i32, i32, i32, i32
    case 0 {
      %5 = func.call @comp2(%c5_i32) : (i32) -> i1
      %6 = arith.extui %5 : i1 to i32
      %7 = arith.xori %5, %true : i1
      %8 = arith.extui %7 : i1 to i32
      scf.yield %c1_i32, %c5_i32, %6, %8 : i32, i32, i32, i32
    }
    default {
      %5 = func.call @comp1(%c6_i32) : (i32) -> i1
      %6 = arith.extui %5 : i1 to i32
      %7 = arith.xori %5, %true : i1
      %8 = arith.extui %7 : i1 to i32
      scf.yield %c0_i32, %c6_i32, %6, %8 : i32, i32, i32, i32
    }
    %4 = arith.trunci %3#3 : i32 to i1
    scf.condition(%4) %3#0, %3#1 : i32, i32
  } do {
  ^bb0(%arg1: i32, %arg2: i32):
    scf.yield %arg1 : i32
  }
  call @foo(%1#1) : (i32) -> ()
  return
}
```

Custom dialects

```
/// Transformation lifting any dialect implementing control flow graph
/// operations to a dialect implementing structured control flow operations.
/// `region` is the region that should be transformed.
/// The implementation of `interface` is responsible for the conversion of the
/// control flow operations to the structured control flow operations.
FailureOr<bool> transformCFGToSCF(Region &region,
  CFGToSCFInterface &interface, DominanceInfo &dominanceInfo);
```

Custom dialects - Branches

```
class CFGToSCFInterface {
  /// 'controlFlowCondOp' → SCF op.
  virtual FailureOr<Operation *>
  createStructuredBranchRegionOp(
    OpBuilder &builder, Operation *controlFlowCondOp,
    TypeRange resultTypes, MutableArrayRef<Region> regions) = 0;
```

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  virtual FailureOr<Operation *>
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  /// Create 'yield' op.
  virtual LogicalResult createStructuredBranchRegionTerminatorOp(
    Location loc, OpBuilder &builder, Operation *branchRegionOp,
    Operation *replacedControlFlowOp, ValueRange results) = 0;
```

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  /// 'controlFlowCondOp' -> SCF op.
  virtual FailureOr<Operation *>
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    OpBuilder &builder, Operation *controlFlowCondOp,
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  /// Create 'yield' op.
  virtual LogicalResult createStructuredBranchRegionTerminatorOp(
    Location loc, OpBuilder &builder, Operation *branchRegionOp,
    Operation *replacedControlFlowOp, ValueRange results) = 0;
```

Custom dialects - Loops

```
class CFGToSCFInterface {
  …
  virtual FailureOr<Operation *> createStructuredDoWhileLoopOp(
    OpBuilder &builder, Operation *replacedOp, ValueRange loopValuesInit,
    Value condition, ValueRange loopValuesNextIter, Region &&loopBody) = 0;
```

Custom dialects - Loops

```
class CFGToSCFInterface {
  …
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```

Future and enabled work

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- Further lifting
  - Induction variables (`scf.for`)
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- Structured exception handling?
- Improving runtime complexity