VECTORIZING LOOPS WITH VPLAN – CURRENT STATE AND NEXT STEPS

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Key Takeaways

A. Current State: 1st step introducing VPlan to Loop Vectorizer – committed
   1. Records vectorization decisions in VPlan
   2. Drives vector code generation by executing a VPlan

B. Going Forward: shift vectorization process to be VPlan-based
   1. Refine the model, include masking and break Recipes into VPInstructions
   2. Carry out decisions based on VPlan, in addition to recording them
   3. Make decisions based on VPlan, including legal and cost-based analyses

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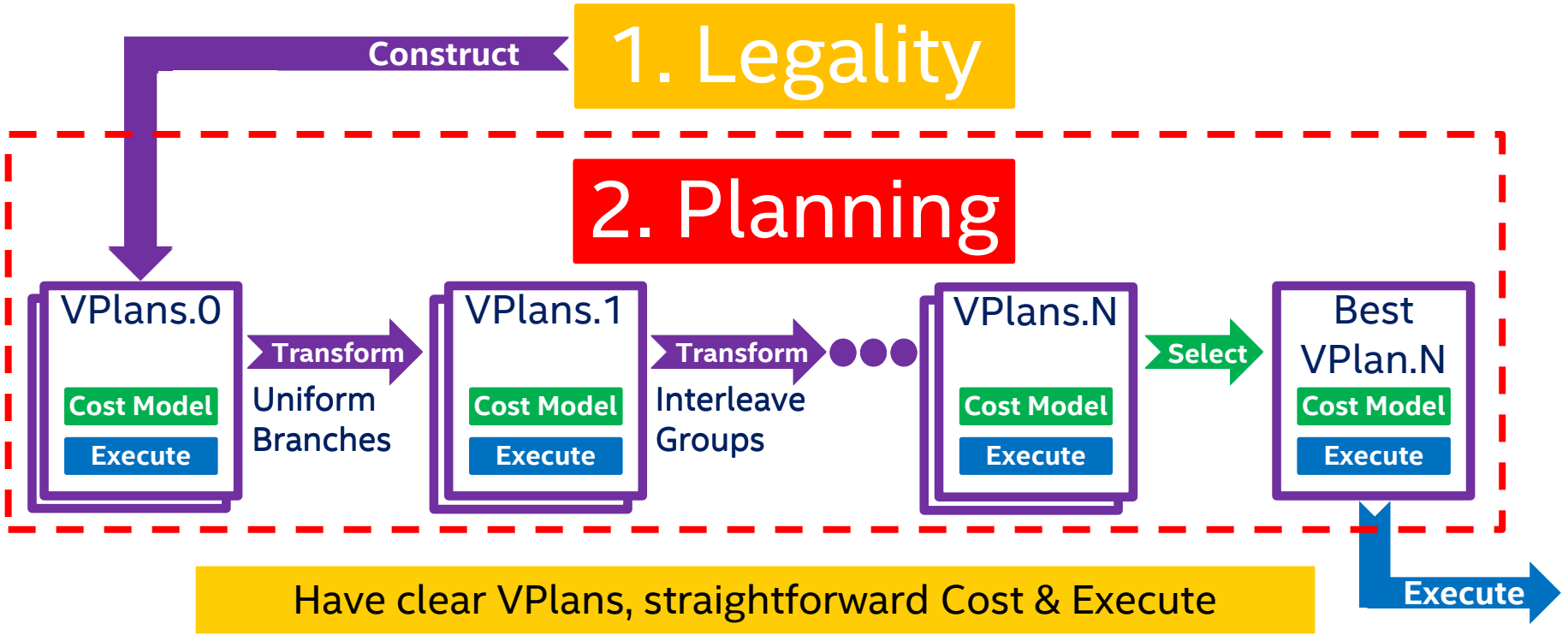
Recap: Loop Vectorization Plan



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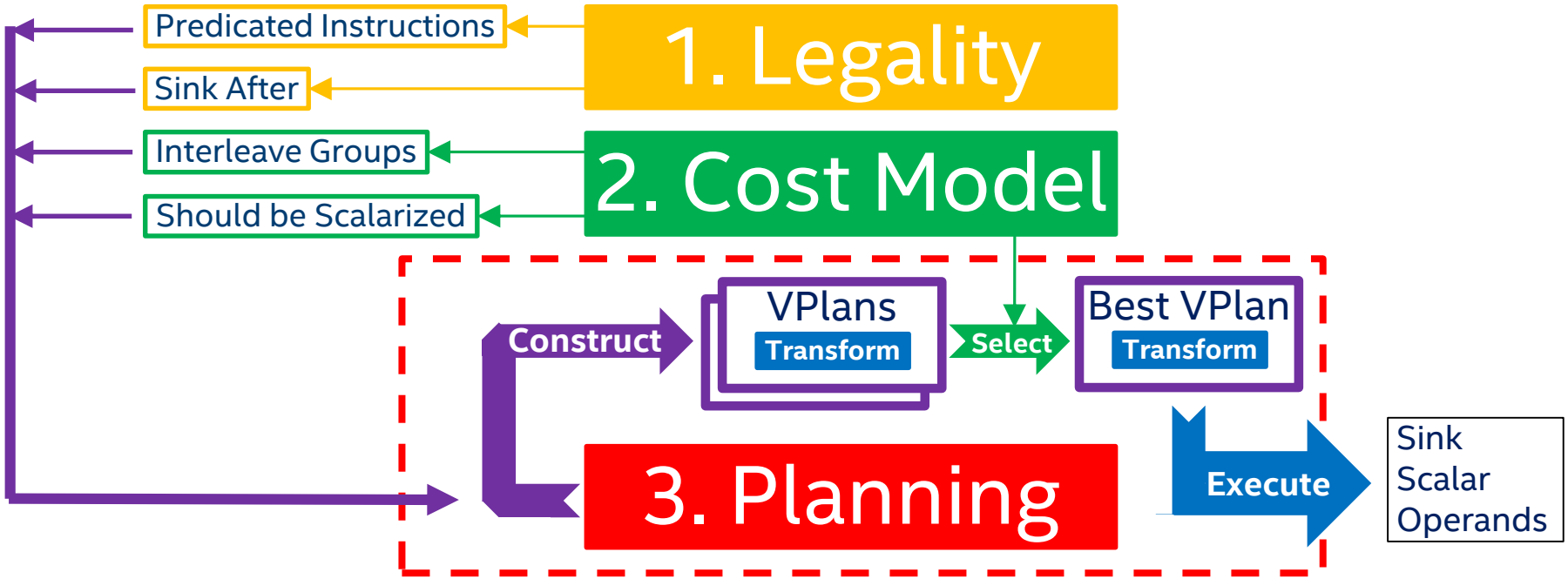
A. CURRENT STATE OF VPLAN

1st Step Committed: VPlan Refactors Transform



Decisions taken up-front, during execute, or as post-pass

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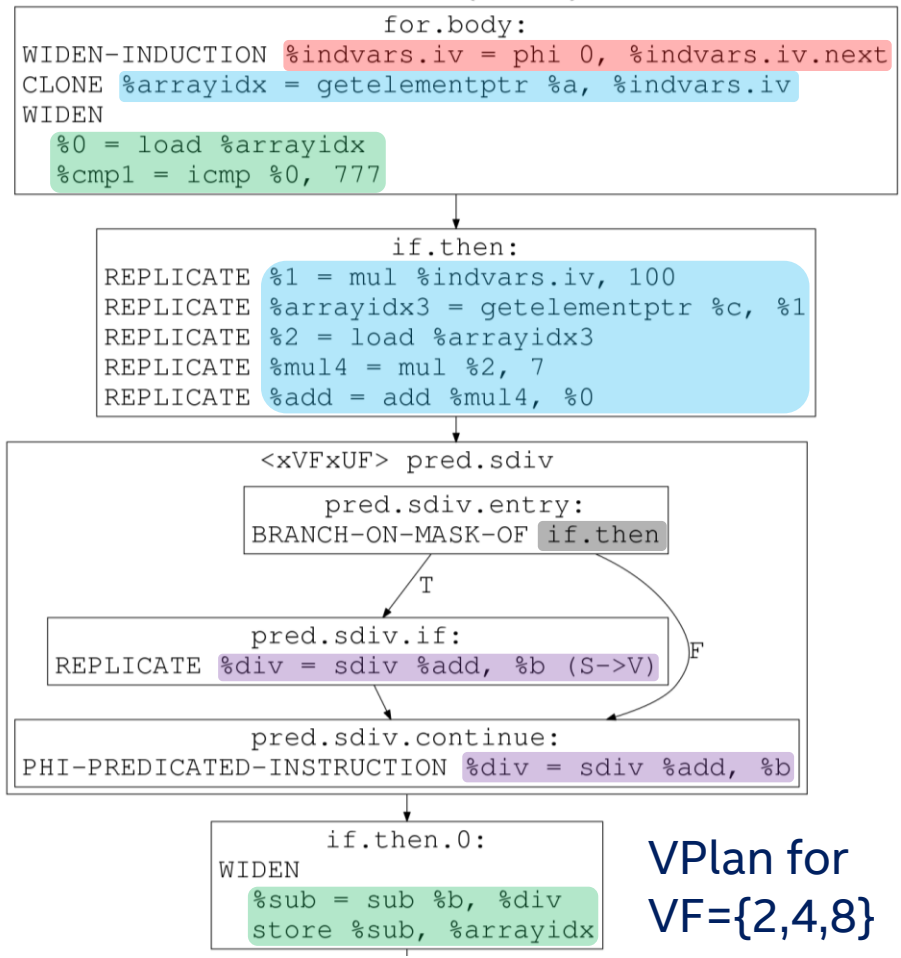
VPlan Model: Current State

```
void foo(int *a, int b, int *c) {
  for (int i = 0; i < 10000; ++i)
    if (a[i] > 777)
      a[i] = b - (c[100*i] * 7 + a[i]) / b;
}
```

LLVM-IR Before Vectorizer

```
for.body:
 %indvars.iv = phi i64 [ 0, %entry ], [ %indvars.iv.next, %for.i
 %arrayidx = getelementptr inbounds i32, i32* %a, i64 %indvars.i
 %0 = load i32, i32* %arrayidx, align 4
 %cmp1 = icmp sgt i32 %0, 777
 br i1 %cmp1, label %if.then, label %for.inc
if.then:
 %1 = mul nuw nsw i64 %indvars.iv, 100
 %arrayidx3 = getelementptr inbounds i32, i32* %c, i64 %1
 %2 = load i32, i32* %arrayidx3, align 4
 %mul4 = mul nsw i32 %2, 7
 %add = add nsw i32 %mul4, %0
 %div = sdiv i32 %add, %b
 %sub = sub nsw i32 %b, %div
 store i32 %sub, i32* %arrayidx, align 4
 br label %for.inc
```



VPlan for VF={2,4,8}

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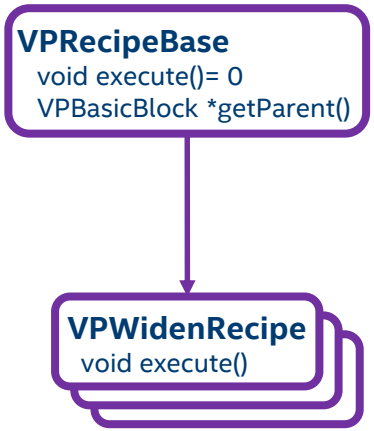
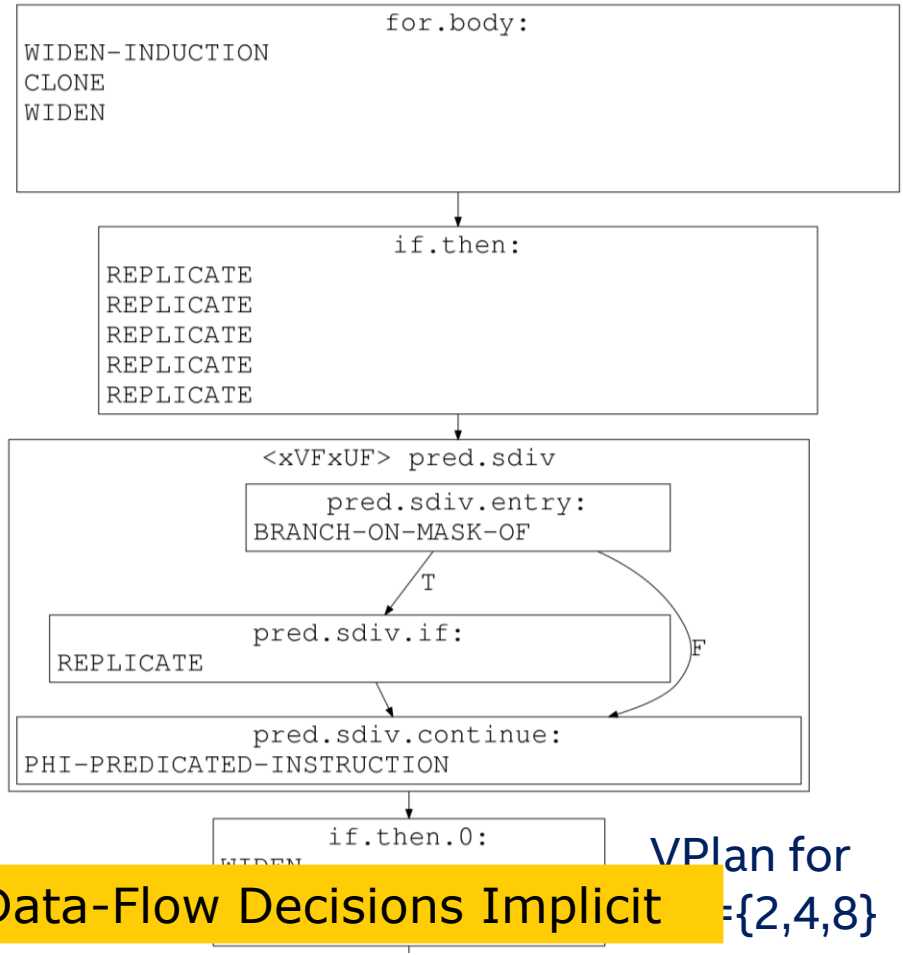
VPlan Model: Current State

Recipe: models a sequence of instructions to appear in the vectorized code. May refer to Ingredients.

Ingredient: element of the original scalar loop, such as an existing instruction.





VPlan for ={2,4,8}

Control-Flow Decisions Explicit, Data-Flow Decisions Implicit

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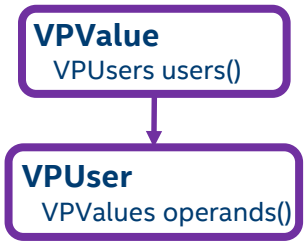
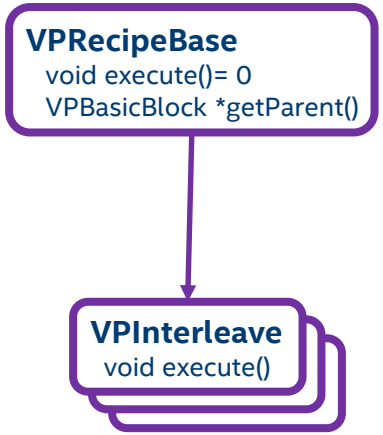
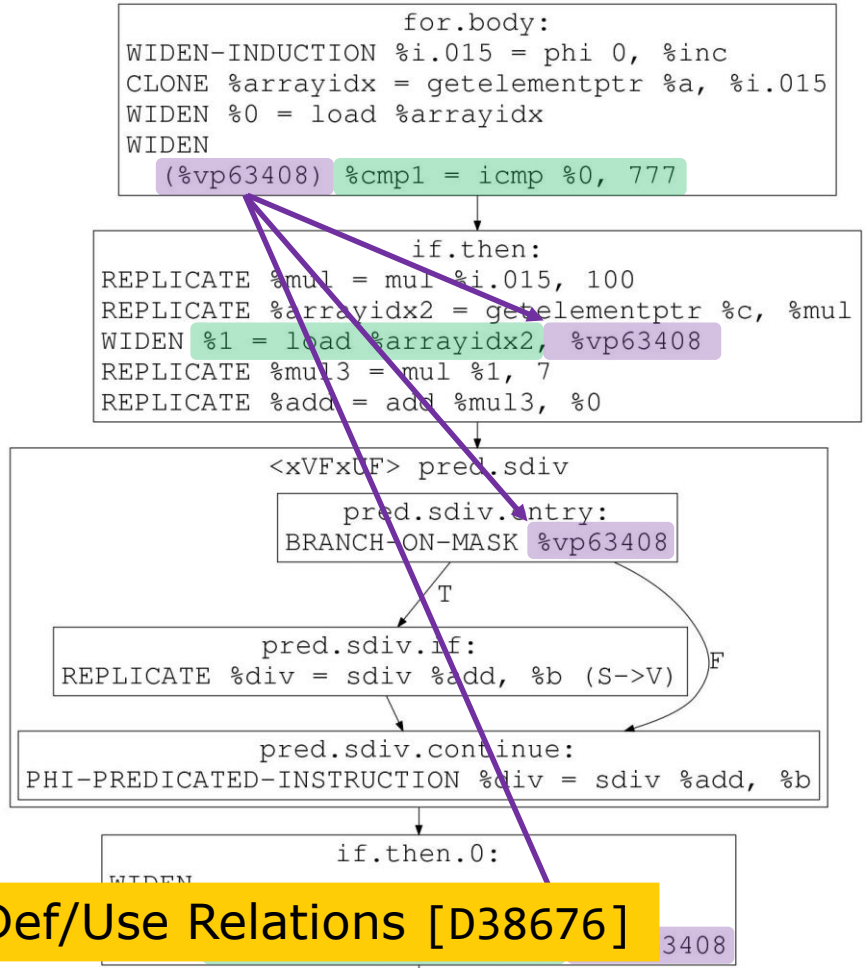
B.1. MODEL MASKING AND INSTRUCTIONS

VPlan Model: Next Step

```
void foo(int *a, int b, int *c) {
  for (int i = 0; i < 10000; ++i)
    if (a[i] > 777)
      a[i] = b - (c[100*i] * 7 + a[i]) / b;
}
```







Model Masking in VPlan using Def/Use Relations [D38676]

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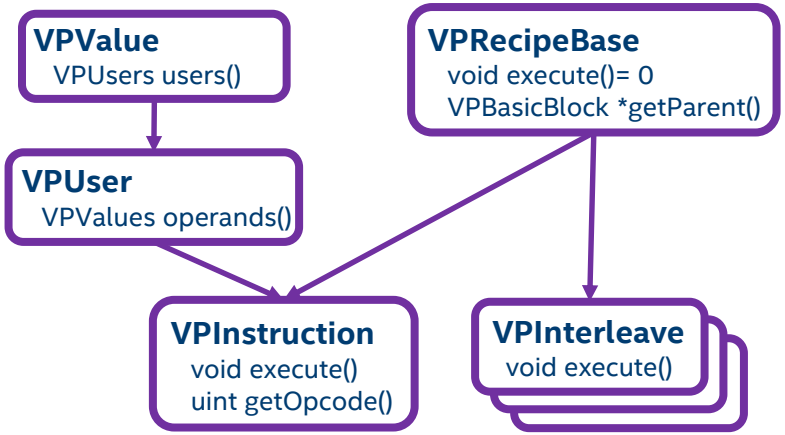
VPlan Model: Next Step (cont'd)

```
void foo(int* a, int b, int* c) {
  for (int i = 0; i < 10000; ++i)
    if (a[i] > 777) {
      c[i] = b;
      if (a[i] > 888)
        a[i] = b;
    }
}
```



VPlan for VF={2,4,8,16}

```
                    for.body:
WIDEN-INDUCTION %i.017 = phi 0, %inc
CLONE %arrayidx = getelementptr %a, %i.017
WIDEN %0 = load %arrayidx
WIDEN
  (%vp27696) %cmp1 = icmp %0, 777
```

```
                    if.then:
CLONE %arrayidx2 = getelementptr %c, %i.017
WIDEN store %b, %arrayidx2, %vp27696
WIDEN %1 = load %arrayidx
WIDEN
  (%vp30784) %cmp4 = icmp %1, 888
```

```
                    if.then5:
EMIT %vp58664 = and %vp30784 %vp27696
WIDEN store %b, %arrayidx, %vp58664
```

VPInstruction: Instruction-level Modeling in VPlan [D38676]

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B.2. FROM RECORDING DECISIONS TO CARRYING THEM OUT

Taking Decision (1/4): Interleave Groups

```
void foo(int *a, int n, int *c) {
  for (int i = 0; i < n; ++i)
    a[i] = 3*c[2*i+1] + c[2*i];
}
```

IR Before Vectorizer

```
foo.body:
  …
  %0 = load i32, %arrayidx
  %mul1 = mul %0, 3
  %1 = load i32, %arrayidx3
  %add4 = add %mul1, %1
  store %add4, %arrayidx5
  …
```

VPlan for VF=4

```
VPInterleaveRecipe:
  %1 = load %arrayidx3
  %0 = load %arrayidx1

VPWidenRecipe:
  %mul1 = mul %0, 3
  %add4 = add %mul1, %1
  store %add4, %arrayidx5
```

Ingredients

VPlan Execution

IR After Vectorizing for VF=4

```
vector.body:
  …
  %all = load <8 x i32>, %5
  %even = shufflevector %all, <0,2,4,6>
  %odd = shufflevector %all, <1,3,5,7>
  %6 = mul %odd, <3,3,3,3>
  %9 = add %6, %even
  store %9, %12
  …
```

Effectively hoists `load %1` to join `load %0`

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Taking Decision (2/4): Unravel 1st Order Recurrence

```
void sink_after(short *a, int *b, int n) {
  for (int i = 0; i < n; ++i)
    b[i] = (a[i] * a[i+1]);
}
```

IR Before Vectorizer

```
foo.body:
  %iv = phi i64 [ 0, %entry ], [ %iv.next, %for.body ]
  %0 = phi i16 [ %.pre, %entry ], [ %1, %for.body ]
  %conv = sext i16 %0 to i32
  %iv.next = add nuw nsw i64 %iv, 1
  %arrayidx2 = getelementptr i16, i16* %a, i64 %iv.next
  %1 = load i16, i16* %arrayidx2
  %conv3 = sext i16 %1 to i32
  %mul = mul nsw i32 %conv3, %conv
  %arrayidx5 = getelementptr i32, i32* %b, i64 %iv
  store i32 %mul, i32* %arrayidx5
  %exitcond = icmp eq i64 %indvars.iv.next, %n
  br i1 %exitcond, label %for.end, label %for.body
```

IR After Vectorizer

```
vector.body
  %iv = phi i64 [ 0, %vec.ph ], [ %iv.next, %vec.body ]
  %recur = phi <4 x i16> [ %recur.init, %vec.ph ],
                         [ %wide.load, %vec.body ]
  …
  %3 = getelementptr inbounds i16, i16* %a, i64 %2
  %wide.load = load <4 x i16>, <4 x i16>* %5, align 2
  %6 = shufflevector <4 x i16> %recur,
                     <4 x i16> %wide.load,
                     <4 x i32> <3, 4, 5, 6>
  %7 = sext <4 x i16> %6 to <4 x i32>
  %8 = sext <4 x i16> %wide.load to <4 x i32>
  %9 = mul nsw <4 x i32> %8, %7
```

Phase-ordering: first sink cast after load, then hoist interleave load [PR34743]

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Taking Decision (3/4): Predication

- Must convert divergent branches using masking
- Much more challenging for outer-loop vectorization
  - Earlier today: *VPlan + RV: A Proposal* by Simon Moll and Sebastian Hack
  - Last year's *Extending LoopVectorizer:* by Hideki Saito:

```
// vectorize here
for (i = ilb; i < iub; ++i) {
  …
  for (j = jlb(i); j < jub(i); ++j) {
    while (cond(i, j)) { … }
```

```
julb = hmin(jlb(i));
juub = hmax(jub(i));
cont1 = T;
for (j = julb; j < juub; ++j) {
  if (jlb(i) <= j && j < jub(i) && cont1) {
    cont2 = cond(i, j);
    while (hor(cont2)) {
      if (cont2) {
        …
        cont2 = cond(i, j);
      }
    }
    if (…) cont1 = F;
    if (!hor(cont1)) break;
```

Take Predication Decisions by Transforming One VPlan to Another

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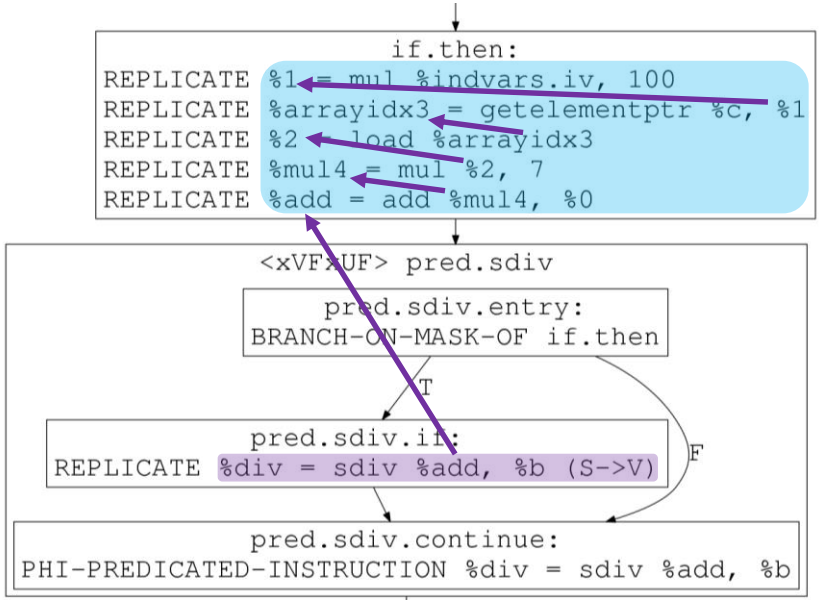
Taking Decision (4/4): SinkScalarOperands



Requires Fine-grain Modeling of Def/Use at instruction-level

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B.3. FROM CARRYING OUT DECISIONS TO MAKING THEM

Use VPlan to also Make Vectorization Decisions

- Instead of first making the decisions, and then using VPlan to carry them out
- Run cost-based analyses on VPlan
  - Based on cost estimates computed by VPlan
  - Based on VPInstruction model
- Apply desired decisions by transforming VPlan, potentially versioning it
  - Based on “what-if” versioning support

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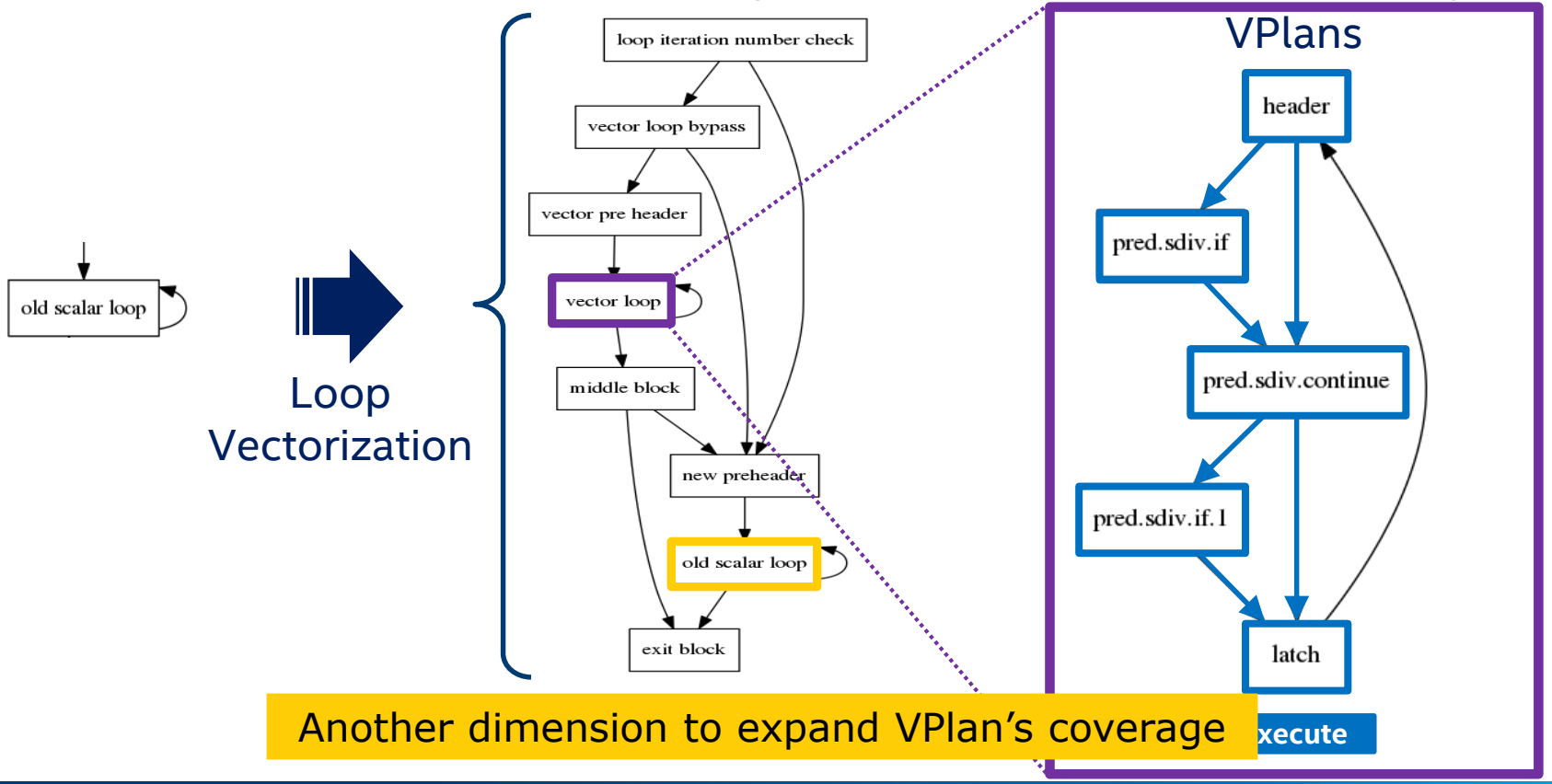
Expand VPlan's Scope Beyond Vector Loop Body



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Taking Decision (1/4): Interleave Groups – revisit

```
void foo(int *a, int n, int *c) {
  for (int i = 0; i < n; ++i)
    a[i] = 3*c[2*i+1] + c[2*i];
}
```

IR Before Vectorizer

```
foo.body:
  …
  %0 = load i32, %arrayidx
  %mul1 = mul %0, 3
  %1 = load i32, %arrayidx3
  %add4 = add %mul1, %1
  store %add4, %arrayidx5
  …
```

VPlan for VF=4

```
VPInterleaveRecipe:
  %1 = load %arrayidx3
  %0 = load %arrayidx1

VPWidenRecipe:
  %mul1 = mul %0, 3
  %add4 = add %mul1, %1
  store %add4, %arrayidx5
```

Ingredients

VPlan Execution

IR After Vectorizing for VF=4

```
vector.body:
  …
  %all = load <8 x i32>, %5
  %even = shufflevector %all, <0,2,4,6>
  %odd = shufflevector %all, <1,3,5,7>
  %6 = mul %odd, <3,3,3,3>
  %9 = add %6, %even
  store %9, %12
  …
```

Combining two `load %0, %1` into one `load %all` – looks familiar?

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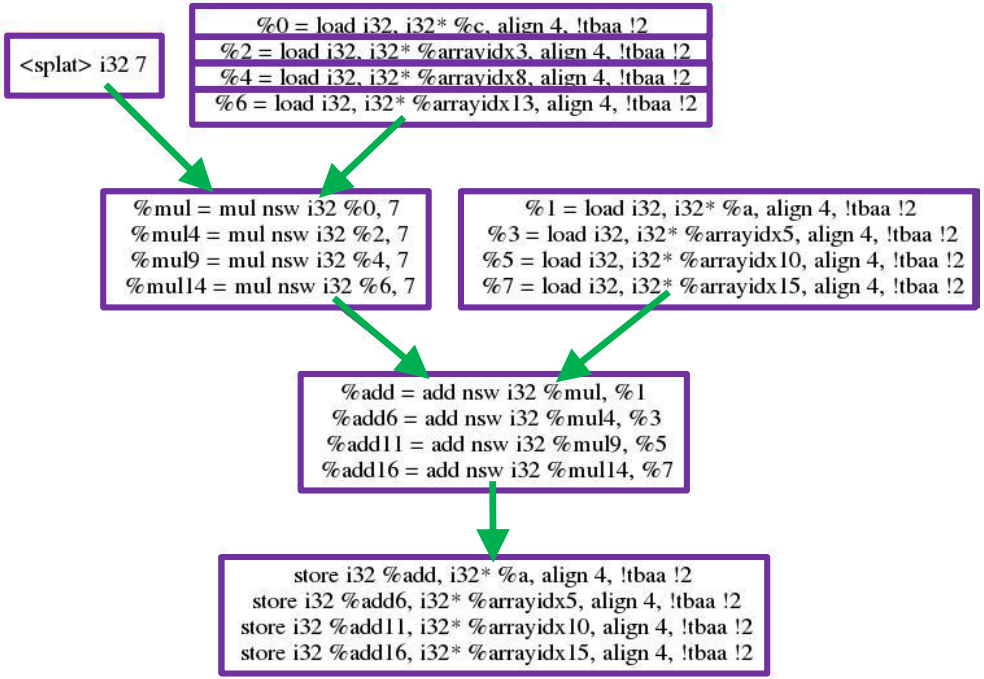
A Model for Vectorized Instructions?

```
void foo(int * restrict a, int b, int *c) {
  a[0] = c[0] * 7 + a[0];
  a[1] = c[2] * 7 + a[1];
  a[2] = c[1] * 7 + a[2];
  a[3] = c[3] * 7 + a[3];
}
```



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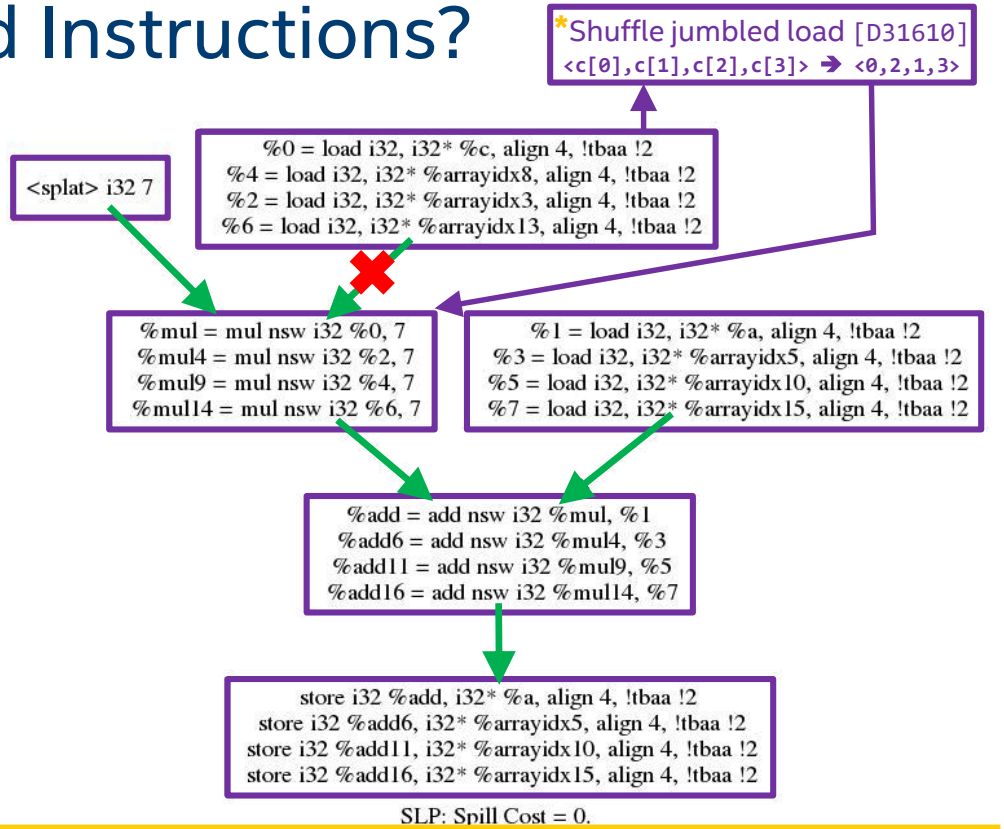
A Model for Vectorized Instructions?

```
void foo(int * restrict a, int b, int *c) {
  a[0] = c[0] * 7 + a[0];
  a[1] = c[2] * 7 + a[1];
  a[2] = c[1] * 7 + a[2];
  a[3] = c[3] * 7 + a[3];
}
```



Def/Use Model for New & Ingredient-based Instructions & Dependences

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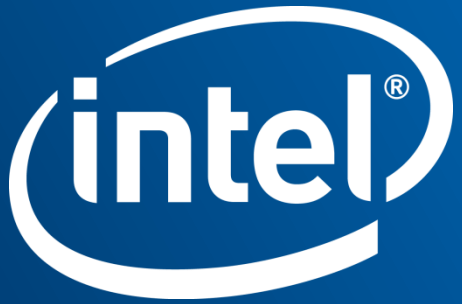
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