INTRODUCING VPLAN TO THE LOOP VECTORIZER

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March 27-28, 2017 European LLVM Developers Meeting

Saarland Informatics Campus, Saarbrücken, Germany
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Notice revision #20110804
Key Takeaways

1. VPlan is an ongoing incremental effort to upgrade Loop Vectorizer's infrastructure and extend its capabilities.

2. This effort is underway: first step introduces VPlan, reroutes vectorization decisions through it; early patches committed.

3. VPlan’s coverage to be extended in multiple directions going forward.
The Need for VPlan

- LLVM’s Loop Vectorizer (LV) is used extensively to optimize a large class of innermost loops
- But adding advanced vectorization techniques to LV is hard
  - Recent improvements already struggle
    - *Keep predicated instructions in the same block* [D26555]
  - Upcoming improvements magnify the difficulty
    - RFC: Extending LV to vectorize outerloops [llvm-dev]
    - *Extending LoopVectorizer towards supporting OpenMP4.5 SIMD and outer loop auto-vectorization* [LLVM US'16]
    - RV: A Unified Region Vectorizer for LLVM - now on github [llvm-dev]
- LV could vectorize loops better, and vectorize more loops

Need to upgrade LV’s infrastructure to extend its capabilities
LV's Current Design and Major Limitations

1. Legality
   - RT aliasing checks
   - Must be scalarized
   - Uniform values
   - Requires predication
   - Interleave groups

2. Cost Model
   - Interleave groups
   - Should be scalarized
   - Sink to predicated BB

3. Transform
   - + post-step: predicate

L1. Output assumed to be a single basic block
L2. Hard to keep Cost aligned with Transform manually
L3. Decisions recorded independently

// Notice: any optimization or new instruction that go into the code below should be also be implemented in the cost-model.
Predication as a Post-Vectorization Step

Transform:

- \( %a = ... \)
- \( %x = \text{sdiv} \%a, \%b \)
- \( \text{br} \ %\text{cmp} \)

Cost Model simulates Transform to calculate cost and optimize

Transformed:

- \( %a = ... \)
- \( %a1 = ... \)
- \( %p0 = \text{extractelement} \%\text{cmp}, 0 \)
- \( %p1 = \text{extractelement} \%\text{cmp}, 1 \)
- \( %x0 = \text{sdiv} \%a0, \%b \)
- \( %x1 = \text{sdiv} \%a1, \%b \)
- \( \text{br} \ %p0 \)
- \( \text{br} \ %p1 \)

+ post-step: predicate

+ post-step opt: sink scalar operands
VPlan Definitions

**VPlan**: a vectorized code candidate. Uses a Hierarchical CFG (HCFG)

**Block**: an element of HCFG representing the control-flow of the vectorized code.

**Basic Block**: a leaf Block, contains a sequence of **Recipes**.

**Region**: an SESE subgraph of the HCFG. Models vectorization semantics such as predication and replication.

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

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

VPlans calculate their cost and execute into IR
Recipe Example 1: Widening One-by-One

Source Code

```c
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

IR After Vectorizing for VF=4

VPlan for VF=4

VPlan strives to be lightweight by leveraging source IR
Recipe Example 2: Interleave Group

Source Code

```
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

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

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
    ...
```

Recipes capture simple and complex patterns as units of Cost
Modeling Decisions by Planning VPlans

1. Legality

2. Planning

VPlans designed with tentative optimization in mind
How VPlan Addresses the Identified Limitations

LV’s current limitation (recap)

1. Output assumed to be a single basic block
2. Hard to keep Cost aligned with Transform manually
3. Decisions recorded independently

LV with VPlan

1. Full control-flow is modelled explicitly
2. Single model of vectorized code simplifies and aligns both Cost and Transform
3. Single model represents a vectorized code candidate to manifest vectorization decisions explicitly
INTRODUCING VPLAN - CURRENT STATUS
Introducing VPlan by Refactoring Transform

LV's current design (recap)

1. Legality
2. Cost Model
3. Transform
   + post-step: predicate

LV with VPlan firstly introduced

1. Legality
2. Cost Model
3. Planning

Best VPlan.1
Transform
Execute

Optimize
Sink
Scalar
Operands

VPlans.0
Transform
Construct
Interleave
groups
Should be
scalarized

VPlans.1
Transform
Select

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Introducing VPlan by Refactoring Transform, Cont’d

1st major step being committed gradually
A Concrete VPlan Example

Source Code

```c
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:      ; preds = %for.inc, %entry
    %i.015 = phi i32 [ 0, %entry ], [ %inc, %for.inc ]
    %arrayidx = getelementptr inbounds i32, i32* %a, i32 %i.015
    %0 = load i32, i32* %arrayidx, align 4
    %cmp1 = icmp sgt i32 %0, 777
    br i1 %cmp1, label %if.then, label %for.inc

if.then:       ; preds = %for.body
    %mul = mul nuw nsw i32 %i.015, 100
    %arrayidx2 = getelementptr inbounds i32, i32* %c, i32 %mul
    %1 = load i32, i32* %arrayidx2, align 4
    %mul3 = mul nsw i32 %1, 7
    %add = add nsw i32 %mul3, %0
    %div = sdiv i32 %add, %b
    %sub = sub nsw i32 %b, %div
    store i32 %sub, i32* %arrayidx, align 4
    br label %for.inc

for.inc:       ; preds = %for.body, %if.then
    %inc = add nuw nsw i32 %i.015, 1
    %exitcond = icmp eq i32 %inc, 10000
    br i1 %exitcond, label %for.cond.cleanup, label %for.body
```

VPlan for VF={2,4,8}

```
BB10
WIDEN INT INDUCTION (needs scalars):
%i.015 = phi 0, %inc
BUILD SCALAR STEPS:
%inc = phi 0, %inc
SCALARIZE:
%arrayidx = getelementptr %a, %i.015
VECTORIZE:
%0 = load %arrayidx
%cmp1 = icmp %0, 777

BB11
VECTORIZE:
%mul = mul %i.015, 100
SCALARIZE:
%arrayidx2 = getelementptr %c, %mul
%1 = load %arrayidx2
%mul3 = mul %1, 7
%add = add %mul3, %0

BB14
EXTRACT MASK BIT:
if.then
  if.then
    %div = sdiv %add, %b
    store i32 %sub, %arrayidx
  br label %for.inc
  %exitcond = icmp eq i32 %inc, 10000
  br i1 %exitcond, label %for.cond.cleanup, label %for.body

BB15
MERGE SCALARIZE BRANCH:
%div = sdiv %add, %b
%sub = sub %b, %div
store %sub, %arrayidx
```
VPlan-based sinkScalarOperands optimization (1/3)

**BB11**

**VECTORIZE:**
%mul = mul %i.015, 100

**SCALARIZE:**
%arrayidx2 = getelementptr %c, %mul %1 = load %arrayidx2
%mul3 = mul %1, 7
%add = add %mul3, %0

**<xVFxFUF> region13**

**BB14**

**EXTRACT MASK BIT:**
if.then

**BB12**

**SCALARIZE:**
%div = sdiv %add, %b

**BB15**

**MERGE SCALARIZE BRANCH:**
%div = sdiv %add, %b

**Initial State**

**BB11**

**VECTORIZE:**
%mul = mul %i.015, 100

**SCALARIZE:**
%arrayidx2 = getelementptr %c, %mul %1 = load %arrayidx2
%mul3 = mul %1, 7
%add = add %mul3, %0

**<xVFxFUF> region13**

**BB14**

**EXTRACT MASK BIT:**
if.then

**BB12**

**SCALARIZE:**
%add = add %mul3, %0
%div = sdiv %add, %b

**BB15**

**MERGE SCALARIZE BRANCH:**
%div = sdiv %add, %b

**Sink {add}**
VPlan-based sinkScalarOperands optimization (2/3)

**BB11**

VECTORIZE:
%mul = mul %i.015, 100

SCALARIZE:
%arrayidx2 = getelementptr %c, %mul
%1 = load %arrayidx2

<xVFxF> region13

**BB14**

EXTRACT MASK BIT:
if.then

if.then

if.then

**BB12**

SCALARIZE:
%mul3 = mul %1, 7

SCALARIZE:
%add = add %mul3, %0

SCALARIZE:
%div = sdiv %add, %b

**BB15**

MERGE SCALARIZE BRANCH:
%div = sdiv %add, %b

Sink {add, mul}

**BB11**

VECTORIZE:
%mul = mul %i.015, 100

SCALARIZE:
%arrayidx2 = getelementptr %c, %mul

<xVFxF> region13

**BB14**

EXTRACT MASK BIT:
if.then

if.then

if.then

**BB12**

SCALARIZE:
%1 = load %arrayidx2

SCALARIZE:
%mul3 = mul %1, 7

SCALARIZE:
%add = add %mul3, %0

SCALARIZE:
%div = sdiv %add, %b

**BB15**

MERGE SCALARIZE BRANCH:
%div = sdiv %add, %b

Sink {add, mul, load}
VPlan-based sinkScalarOperands optimization optimization (3/3)

Post-vectorization optimization modelled with VPlan

Sink {add, mul, load, gep}
Key Takeaways

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