Input Space Splitting for OpenCL

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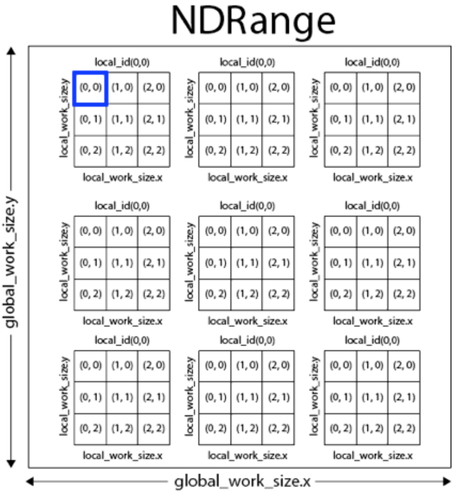
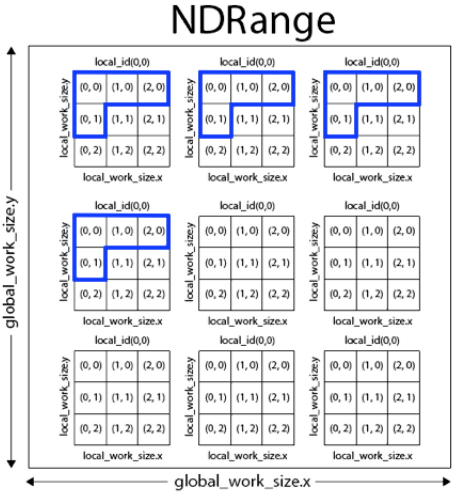
OpenCL: Execution Model



OpenCL: Parallelized & Vectorized



Vectorization (SIMD)

Perform the same operation for multiple vector lanes simultaneously.

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Perform the same operation for multiple vector lanes simultaneously.

Vector Patterns

Consecutive: contiguous entries $\underline{< \mathtt{i}, \mathtt{i}+1, \mathtt{i}+2, \mathtt{i}+3 >}$

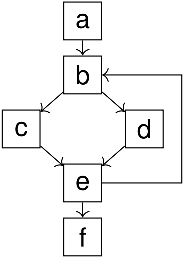
Uniform: single entry $\mathtt{<i,i,i,i>} \rightarrow \mathtt{i}$

Divergent: unrelated entries $\overline{< \mathtt{i}, \mathtt{j}, 7, - >}$

```
for (i = 0; i < 16; i++)
  O[i] = I[i] + 2;
```

```
for (i = 0; i < 16; i += 2)
  O[i] = I[i] + 1;
```

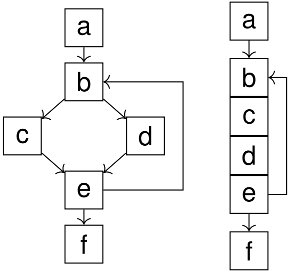
Diverging Control Flow



Thread	Trace
1	a b c e f
2	a b d e f
3	a b c e b c e f
4	a b c e b d e f

- Different threads execute different code paths

Diverging Control Flow

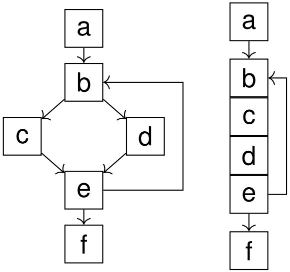


Thread	Trace
1	a b c d e b c d e f
2	a b c d e b c d e f
3	a b c d e b c d e f
4	a b c d e b c d e f

- Different threads execute different code paths
- Execute everything, mask out results of inactive threads (using predication, blending)
- Control flow to data flow conversion on ASTs [Allen & Kennedy '83]
- Whole-Function Vectorization on SSA CFGs [K & H '11]

Non-Divergent Control Flow

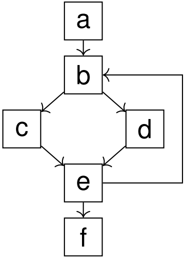
- Idea: optimize cases where threads do not diverge

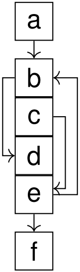


Thread	Trace
1	a b c e b d e f
2	a b c e b d e f
3	a b c e b d e f
4	a b c e b d e f

Non-Divergent Control Flow

- Idea: optimize cases where threads do not diverge



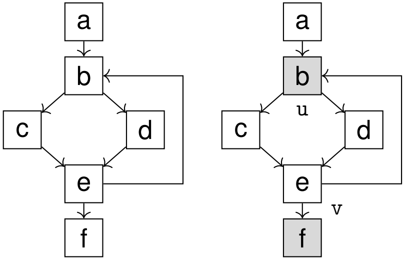


Thread	Trace
1	a b c e b d e f
2	a b c e b d e f
3	a b c e b d e f
4	a b c e b d e f

- Option 1: Insert dynamic predicate-tests & branches to skip paths
  - “Branch on superword condition code” (BOSCC) [Shin et al. PACT’07]
  - Additional overhead for dynamic test
  - Does not help against increased register pressure

Non-Divergent Control Flow

- Idea: optimize cases where threads do not diverge



Thread	Trace
1	a b c e b d e f
2	a b c e b d e f
3	a b c e b d e f
4	a b c e b d e f

- Option 2: Statically prove non-divergence of certain blocks
  - Non-divergent blocks can be excluded from linearization
  - Less executed code, less register pressure
  - More conservative than dynamic test

Non-Divergent Control Flow

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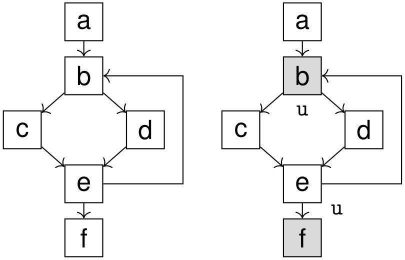
- Idea: optimize cases where threads do not diverge



Thread	Trace
1	a b c e f
2	a b c e f
3	a b c e b d e f
4	a b c e b d e f
5	a b c e b d e f
6	a b c e b d e f

- Option 3: Statically split non-divergence inputs
  - Code versions with improved divergence properties
  - Orthogonal to both other options $\Longrightarrow$ combination possible

2D Convolution

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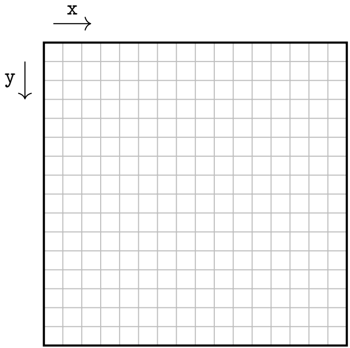
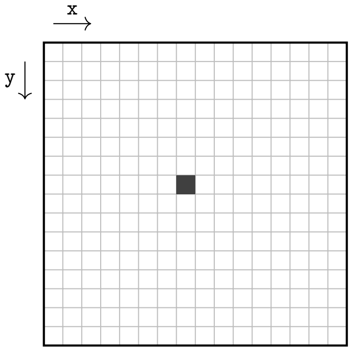
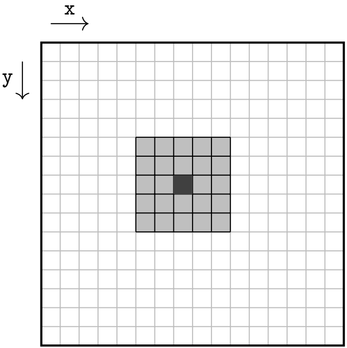


2D Convolution



2D Convolution



2D Convolution

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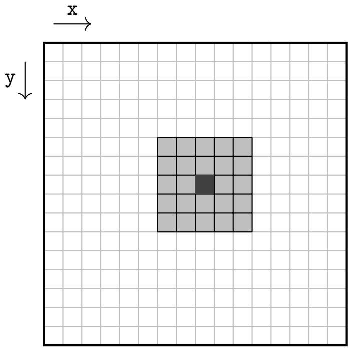

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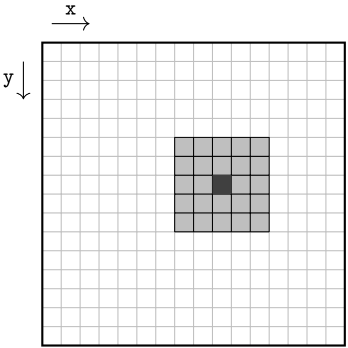

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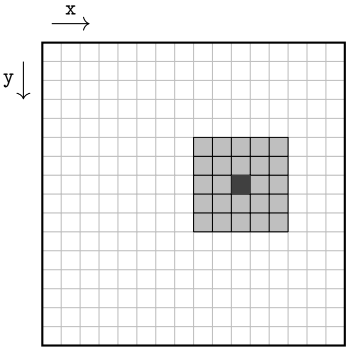
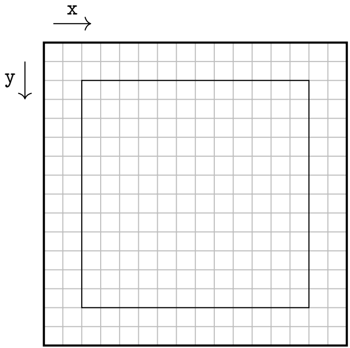


2D Convolution



2D Convolution

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```
int left   = x - 2;
int right  = x + 2;
int top    = y - 2;
int bottom = y + 2;

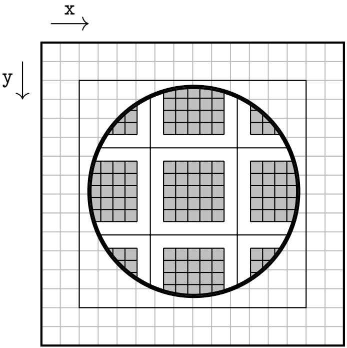
int sum = 0;
for (int i = left; i <= right; ++i)
  for (int j = top; j <= bottom; ++j)
    sum += input[j][i] * mask[j - top][i - left];
output[y][x] = sum;
```

2D Convolution


```
auto left   = x - 2;
auto right  = x + 2;
int top     = y - 2;
int bottom  = y + 2;

int sum = 0;
for (auto i = left; i <= right; ++i)
  for (int j = top; j <= bottom; ++j)
    sum += input[j][i] * mask[j - top][i - left];
output[y][x] = sum;
```

2D Convolution



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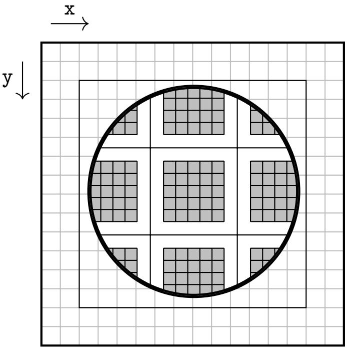

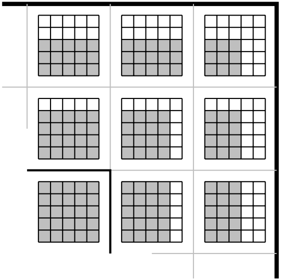

2D Convolution


```
int left   = MAX(0, x - 2);
int right  = MIN(width - 1, x + 2);
int top    = MAX(0, y - 2);
int bottom = MIN(height - 1, y + 2);

int sum = 0;
for (int i = left; i <= right; ++i)
  for (int j = top; j <= bottom; ++j)
    sum += input[j][i] * mask[j - (y - 2)][i - (x - 2)];
output[y][x] = sum;
```

2D Convolution

```
auto left   = MAX(0, x - 2);
auto right  = MIN(width - 1, x + 2);
int top     = MAX(0, y - 2);
int bottom  = MIN(height - 1, y + 2);

int sum = 0;
for (auto i = left; i <= right; ++i)
  for (int j = top; j <= bottom; ++j)
    sum += input[j][i] * mask[j - (y - 2)][i - (x - 2)];
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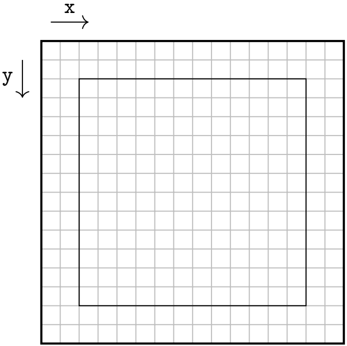
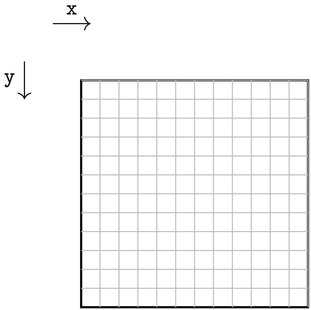
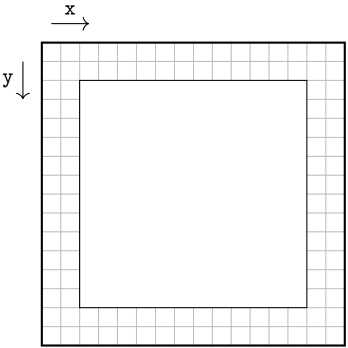
Input Space Splitting



Input Space Splitting





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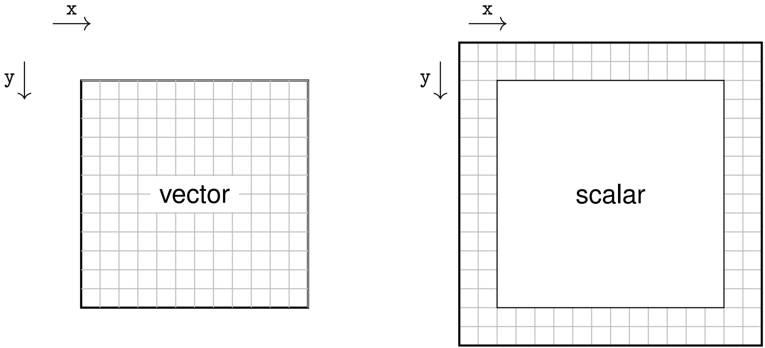

The Polyhedral Model

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```
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
```

The Polyhedral Model


```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j++) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
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```

The Polyhedral Model


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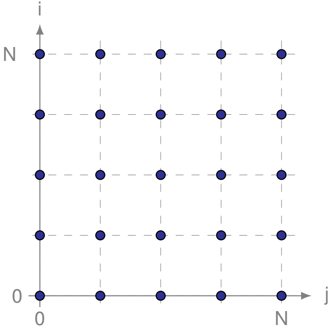

$$\mathcal{I}_S = \{(S, (i, j)) \mid 0 \leq i \leq N \wedge 0 \leq j \leq N\}$$

The Polyhedral Model

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j++) {
S:  A[i][j] = /* ... */;
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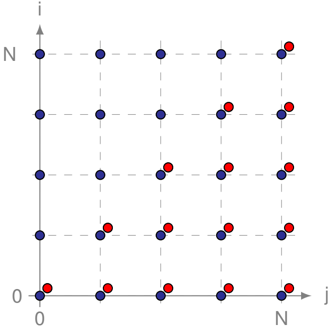
```

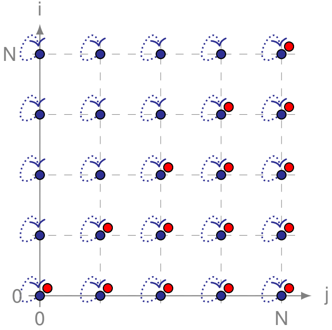


$$\mathcal{I}_S = \{(S, (i, j)) \mid 0 \leq i \leq N \wedge 0 \leq j \leq N\}$$

$$\mathcal{I}_P = \{(P, (i, j)) \mid 0 \leq i \leq N \wedge 0 \leq j \leq i\}$$

The Polyhedral Model

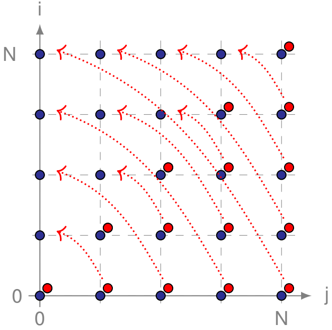

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j++) {
S:   A[i][j] = /* ... */;
     if (j <= i)
P:     A[i][j]+= A[j][i];
  }
```



$$\mathcal{F}_{S} = \{(S, (i, j)) \to (i, j)\}$$

The Polyhedral Model

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j++) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```



$$\mathcal{F}_{\mathtt{S}} = \{(\mathtt{S}, (\mathtt{i}, \mathtt{j})) \rightarrow (\mathtt{i}, \mathtt{j})\}$$

$$\mathcal{F}_{\mathtt{P}_1} = \{(\mathtt{P}, (\mathtt{i}, \mathtt{j})) \rightarrow (\mathtt{i}, \mathtt{j})\} \quad \mathcal{F}_{\mathtt{P}_2} = \{(\mathtt{P}, (\mathtt{i}, \mathtt{j})) \rightarrow (\mathtt{j}, \mathtt{i})\}$$

Splitting Predicates

Full Tile Predicate

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

Splitting Predicates

Full Tile Predicate

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\text{Full}_{\text{S}} = \{(\text{S}, (i, j)) \mid (j - (j \bmod 8)) + 7 \leq N\}$$

Splitting Predicates

Full Tile Predicate


```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\text{Full}_{\texttt{S}} = \{(\texttt{S}, (i, j)) \mid (j - (j \bmod 8)) + 7 \leq N\}$$

$$\text{Full}_{\texttt{P}} = \{(\texttt{P}, (i, j)) \mid (j - (j \bmod 8)) + 7 \leq \texttt{min}(i, N)\}$$

Splitting Predicates

Uniform Access Predicate

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\mathrm{Uni}_{\mathcal{F}_S} = \{(S,(i,j)) \mid \mathcal{F}_S\,(i,j+1) = \mathcal{F}_S\,(i,j)\}$$

Splitting Predicates

Uniform Access Predicate


```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\mathrm{Uni}_{\mathcal{F}_S} = \{(S,(i,j)) \mid \mathcal{F}_S\,(i,j+1) = \mathcal{F}_S\,(i,j)\}$$

$$\mathrm{Uni}_{\mathcal{F}_{P_1}} = \{(P,(i,j)) \mid \mathcal{F}_{P_1}(i,j+1) = \mathcal{F}_{P_1}(i,j)\}$$

$$\mathrm{Uni}_{\mathcal{F}_{P_2}} = \{(P,(i,j)) \mid \mathcal{F}_{P_2}(i,j+1) = \mathcal{F}_{P_2}(i,j)\}$$

Splitting Predicates

Uniform Access Predicate


```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\text{Uni}_{\mathcal{F}_S} = \{(S,(i,j)) \mid \mathcal{F}_S\,(i,j+1) = \mathcal{F}_S\,(i,j)\} = \{\}$$

$$\text{Uni}_{\mathcal{F}_{P_1}} = \{(P,(i,j)) \mid \mathcal{F}_{P_1}(i,j+1) = \mathcal{F}_{P_1}(i,j)\} = \{\}$$

$$\text{Uni}_{\mathcal{F}_{P_2}} = \{(P,(i,j)) \mid \mathcal{F}_{P_2}(i,j+1) = \mathcal{F}_{P_2}(i,j)\} = \{\}$$

Splitting Predicates

Consecutive Access Predicate


```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\text{Cons}_{\mathcal{F}_S} = \{(S,(i,j)) \mid \mathcal{F}_S(i,j+1) = \mathcal{F}_S(i,j)+1\}$$

$$\text{Cons}_{\mathcal{F}_{P_1}} = \{(P,(i,j)) \mid \mathcal{F}_{P_1}(i,j+1) = \mathcal{F}_{P_1}(i,j)+1\}$$

$$\text{Cons}_{\mathcal{F}_{P_2}} = \{(P,(i,j)) \mid \mathcal{F}_{P_2}(i,j+1) = \mathcal{F}_{P_2}(i,j)+1\}$$

Splitting Predicates

Consecutive Access Predicate

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8) {
S:  A[i][j] = /* ... */;
    if (j <= i)
P:    A[i][j]+= A[j][i];
  }
```

$$\mathrm{Cons}_{\mathcal{F}_S} = \{(S, (i,j)) \mid \mathcal{F}_S\,(i, j+1) = \mathcal{F}_S\,(i,j) + 1\} = \mathcal{I}_S$$

$$\mathrm{Cons}_{\mathcal{F}_{P_1}} = \{(P, (i,j)) \mid \mathcal{F}_{P_1}(i, j+1) = \mathcal{F}_{P_1}(i,j) + 1\} = \mathcal{I}_P$$

$$\mathrm{Cons}_{\mathcal{F}_{P_2}} = \{(P, (i,j)) \mid \mathcal{F}_{P_2}(i, j+1) = \mathcal{F}_{P_2}(i,j) + 1\} = \{\}$$

CFG simplification

Hoisting conditionals

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8)
    if (i <= NumParticles) {
S:      ...
    }
```

CFG simplification

Hoisting conditionals

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8)
    if (i <= NumParticles) {
S:      ...
    }
```

```
for (int i = 0; i <= NumParticles; i++)
  for (int j = 0; j <= i; j += 8)
S:  ...
```

CFG simplification

Hoisting conditionals

```
for (int i = 0; i <= N; i++)
  for (int j = 0; j <= N; j += 8)
    if (reverse) {
S:      ...
    } else {
P:      ...
    }
```

CFG simplification

Hoisting conditionals

```
 for (int i = 0; i <= N; i++)
   for (int j = 0; j <= N; j += 8)
     if (reverse) {
 S:    ...
     } else {
 P:    ...
     }

if (reverse) {
  for (int i = 0; i <= N; i++)
    for (int j = 0; j <= i; j += 8)
  S:  ...
} else {
  for (int i = 0; i <= N; i++)
    for (int j = 0; j <= i; j += 8)
  P:  ...
}
```

Predicate Based Domain Splitting

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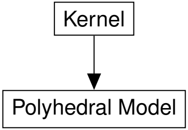
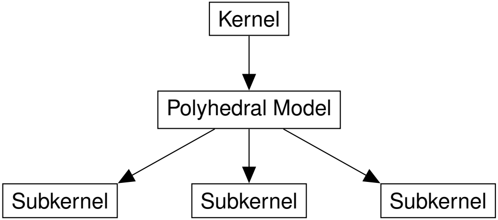
Kernel

Predicate Based Domain Splitting



Predicate Based Domain Splitting



Predicate Based Domain Splitting

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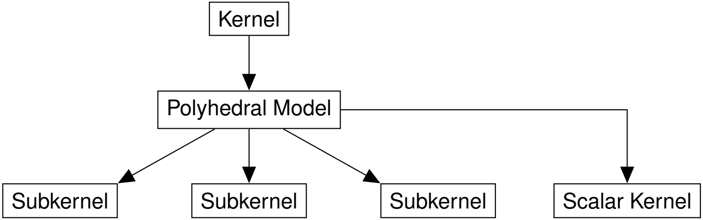

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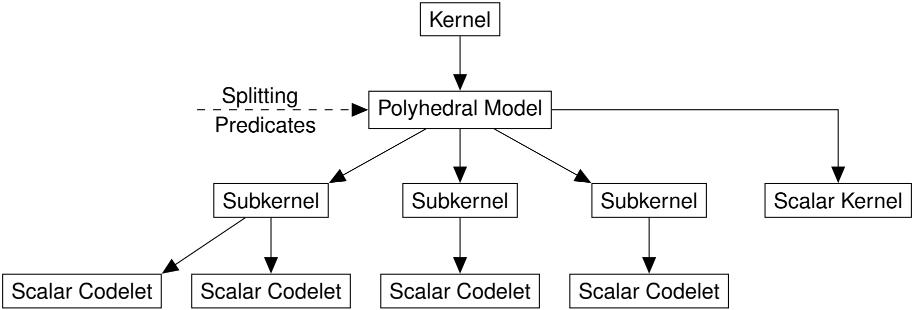
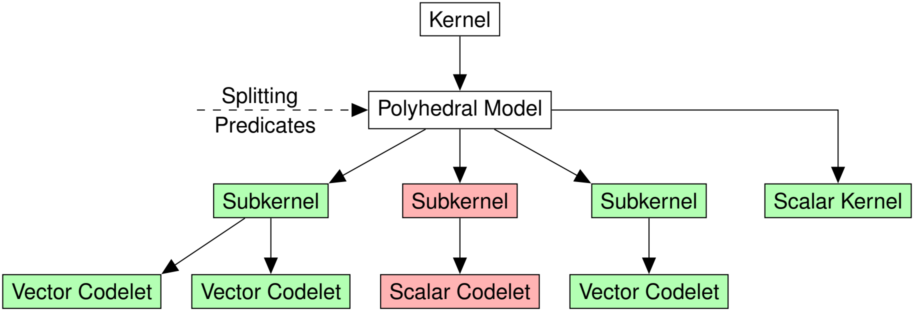
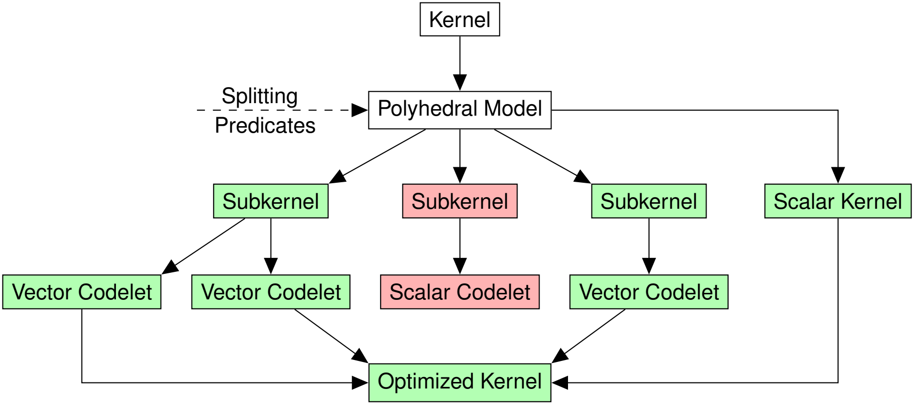


Predicate Based Domain Splitting

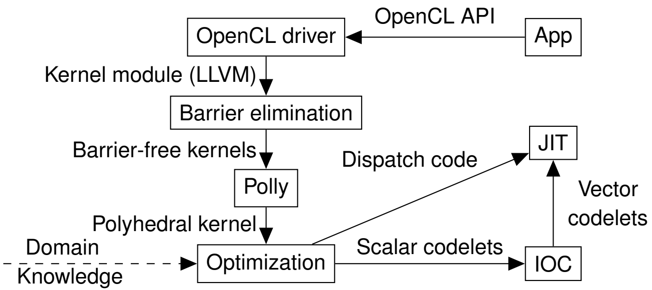


Predicate Based Domain Splitting



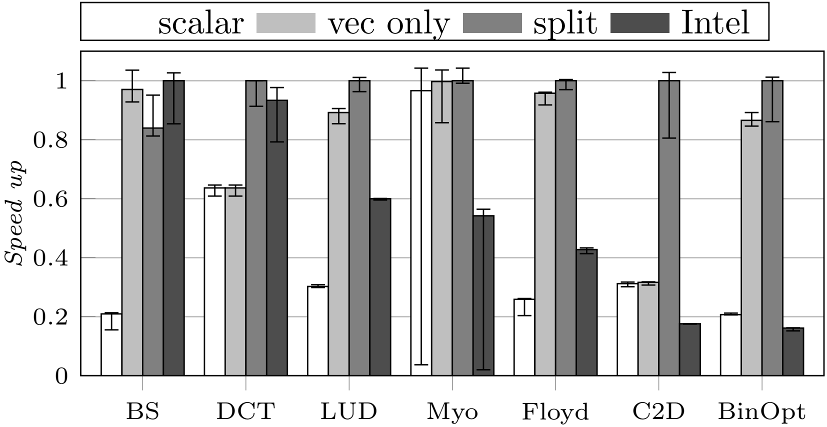
Evaluation

Pipeline



Evaluation

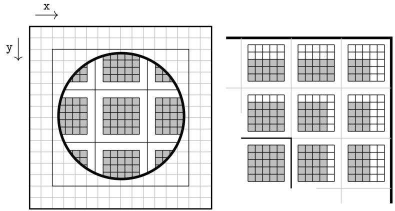
Performance

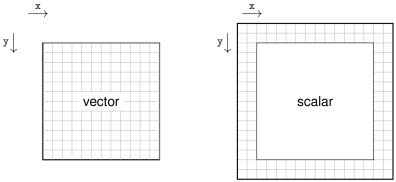


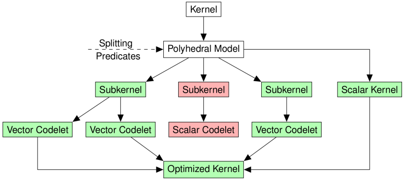
Ongoing Work

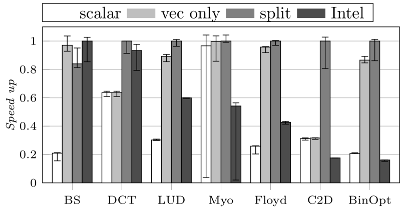
- Model synchronization the Polyhedral Model.
- Apply polyhedral optimizations (scheduling).
- Improve the representation of non-affine parts.

Conclusion

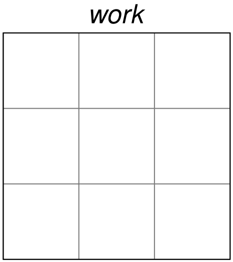

x
y


x
y
vector
x
y
scalar

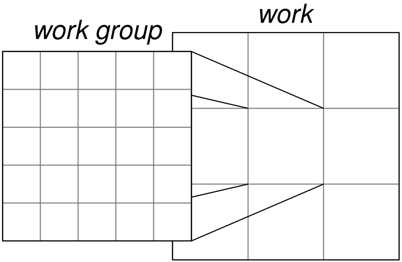

Kernel
Splitting Predicates
Polyhedral Model
Subkernel
Subkernel
Subkernel
Scalar Kernel
Vector Codelet
Vector Codelet
Scalar Codelet
Vector Codelet
Optimized Kernel


scalar
vec only
split
Intel
Speed up
0
0.2
0.4
0.6
0.8
1
BS
DCT
LUD
Myo
Floyd
C2D
BinOpt

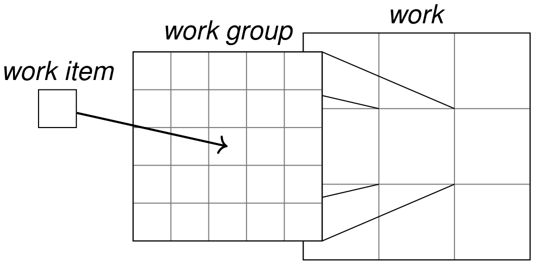
OpenCL Programming Model



OpenCL Programming Model



OpenCL Programming Model



Codelet Score

$$Score_n(k) := \begin{cases} \Sigma_{Q \in k, \mathcal{F} \in \mathbb{F}_Q} & \\ \quad w_{cons} \| Box(Cons_{\mathcal{F}}(d_k)) \| & \text{if } n \geq w \\ \quad + w_{uni} \| Box(Uni_{\mathcal{F}}(d_k)) \| & \\ 0 & otw. \end{cases}$$

Access Splitting Predicate

$$\mathcal{I}_k^C := \bigcap_{Q \in k} \bigcap_{\substack{\mathcal{F} \in \mathbb{F}_Q, st \\ Cons_{\mathcal{F}}(d_k) \neq \varnothing}} Cons_{\mathcal{F}}(d_k) \ .$$

Full Tile Predicate