Transform Array Operations to Optimize Memory Access for GPGPU

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SJT402

Overview

1. Motivation
2. Access Patterns
3. Reduction
4. Benchmarks
5. Future Work
6. Conclusion

1. Motivation

107

Bh

Bohrium

[270]

Motivation

- Bohrium
  - Novice
  - Experts
- Performance Gap
  - Reductions
  - Memory Throughput

107

Bh

Bohrium

[270]

Motivation

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NumPy Stencil

```
center = grid[1:-1, 1:-1]
north = grid[0:-2, 1:-1]
east = grid[1:-1, 2:]
west = grid[1:-1, 0:-2]
south = grid[2:, 1:-1]
work = 0.2 * (center + north +
    east + west + south)
delta = np.sum(np.abs(work-center))
center[:] = work
```

Motivation

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OpenCL Kernel Stencil

```
uint gid = get_global_id(0);
if (gid >= width)
   return;
uint w = width + 2;
uint h = height + 2;
DTYPE d = 0.0;
for (uint i = 0; i < height; ++i)
{
    uint offset = i*w;
    DTYPE up     = in[gid+1+offset];
    DTYPE left   = in[gid+w+offset];
    DTYPE right  = in[gid+w+2+offset];
    DTYPE down   = in[gid+1+w*2+offset];
    DTYPE center = in[gid+w+1+offset];
    DTYPE out_center =
(center + up + left + right + down) * 0.2;
    out[gid+w+1+offset] = out_center;
    d += fabs(out_center - center);
}
delta[gid] = d;
```

Motivation

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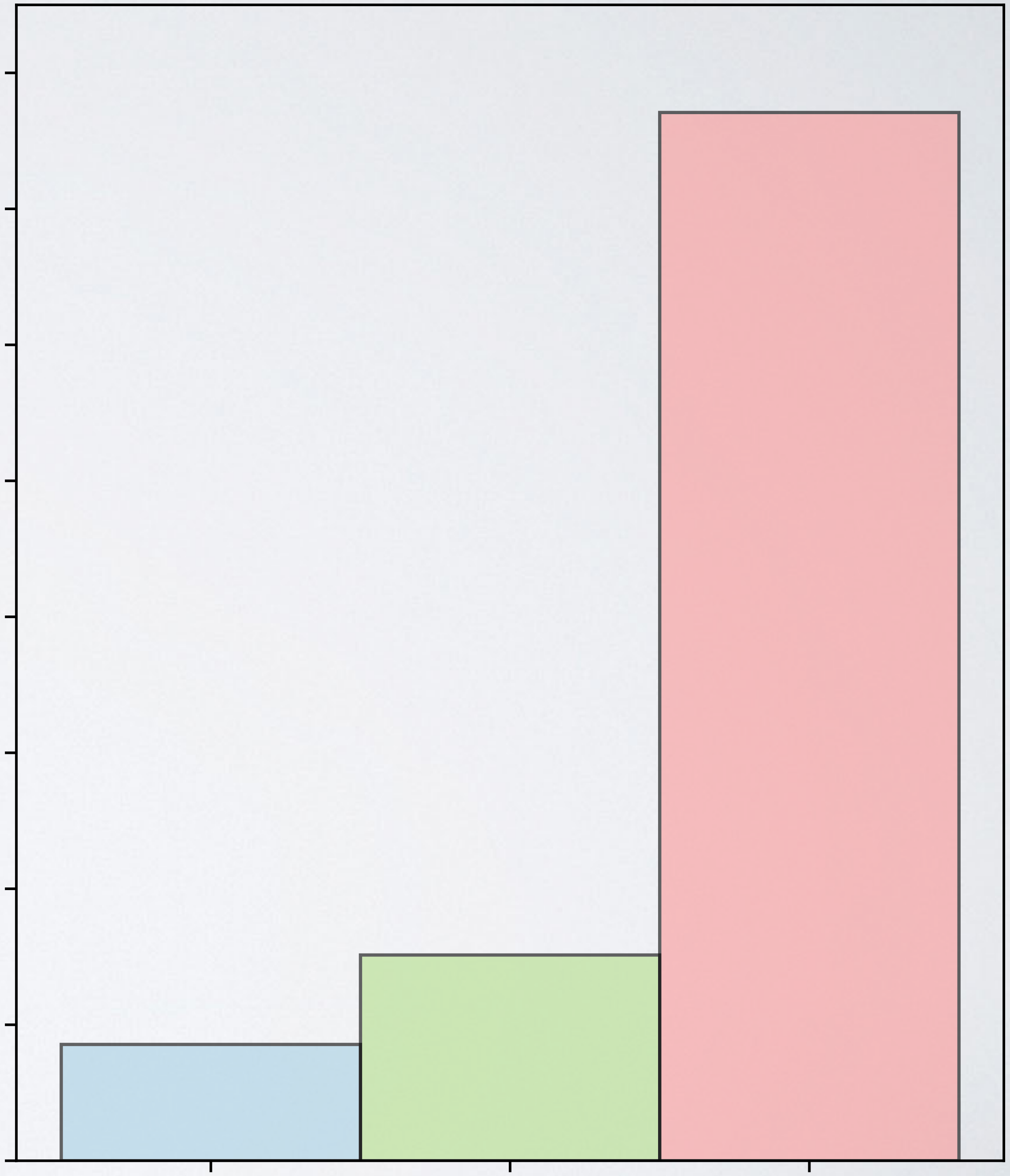

Motivation

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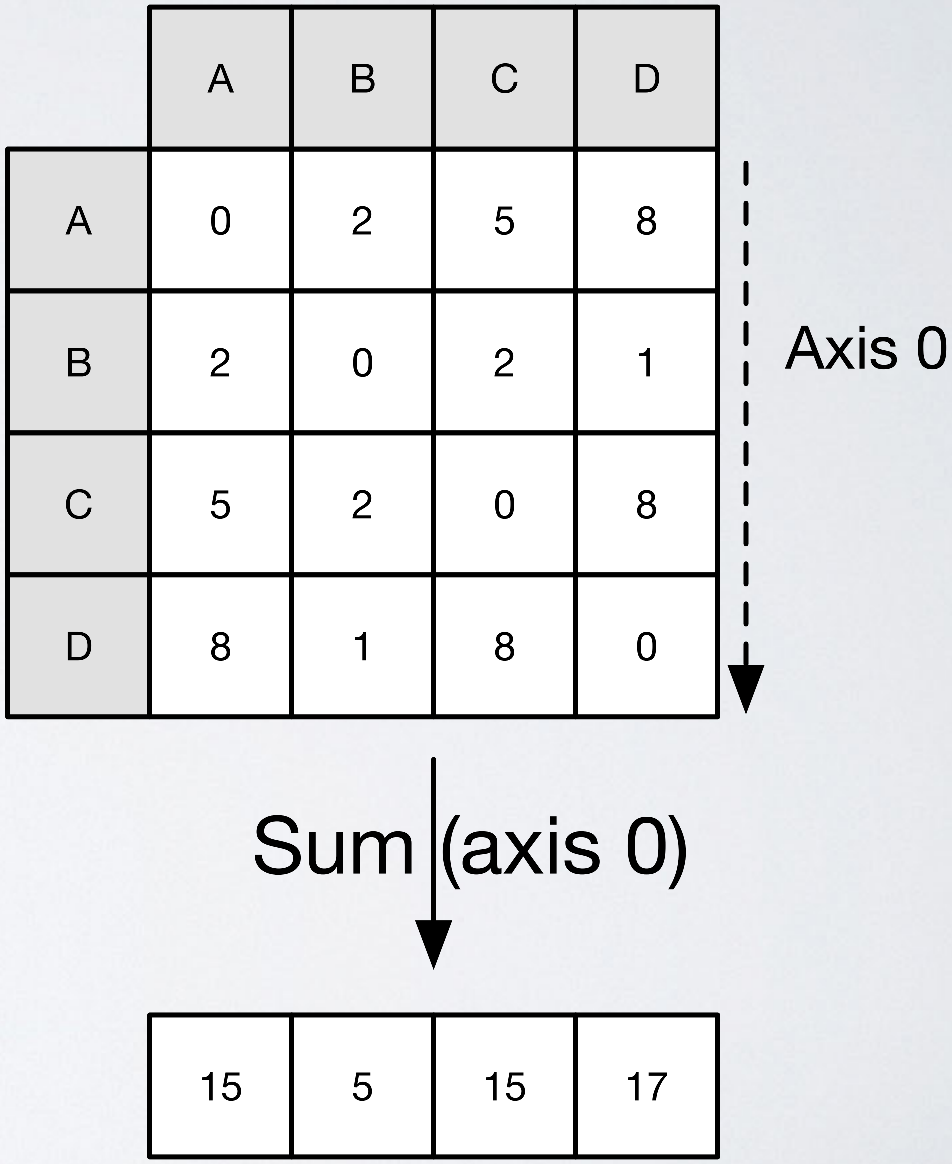

	A	B	C	D
A	0	2	5	8
B	2	0	2	1
C	5	2	0	8
D	8	1	8	0

Axis 0

Sum (axis 0)

15	5	15	17

Motivation

- Bohrium
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- Performance Gap
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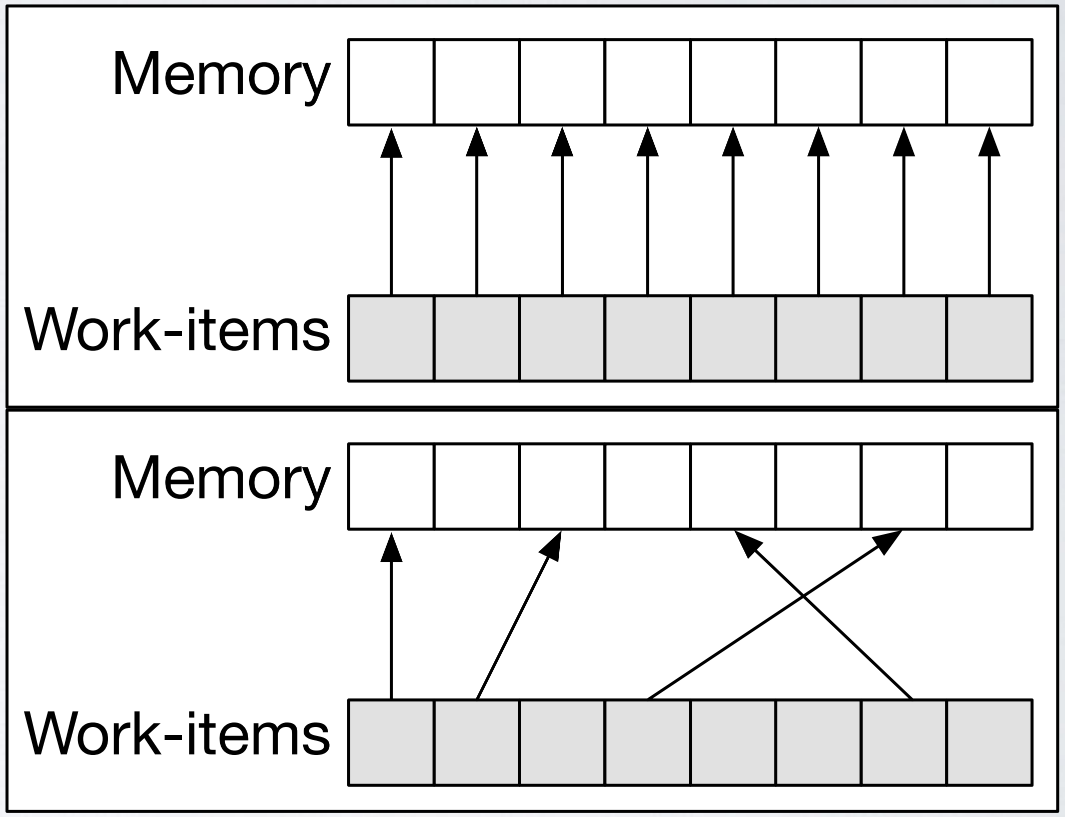
  - Memory Throughput

Nvidia Guidelines

> “Bandwidth is one of the most important gating factors for performance. Almost all changes to code should be made in the context of how they affect bandwidth”

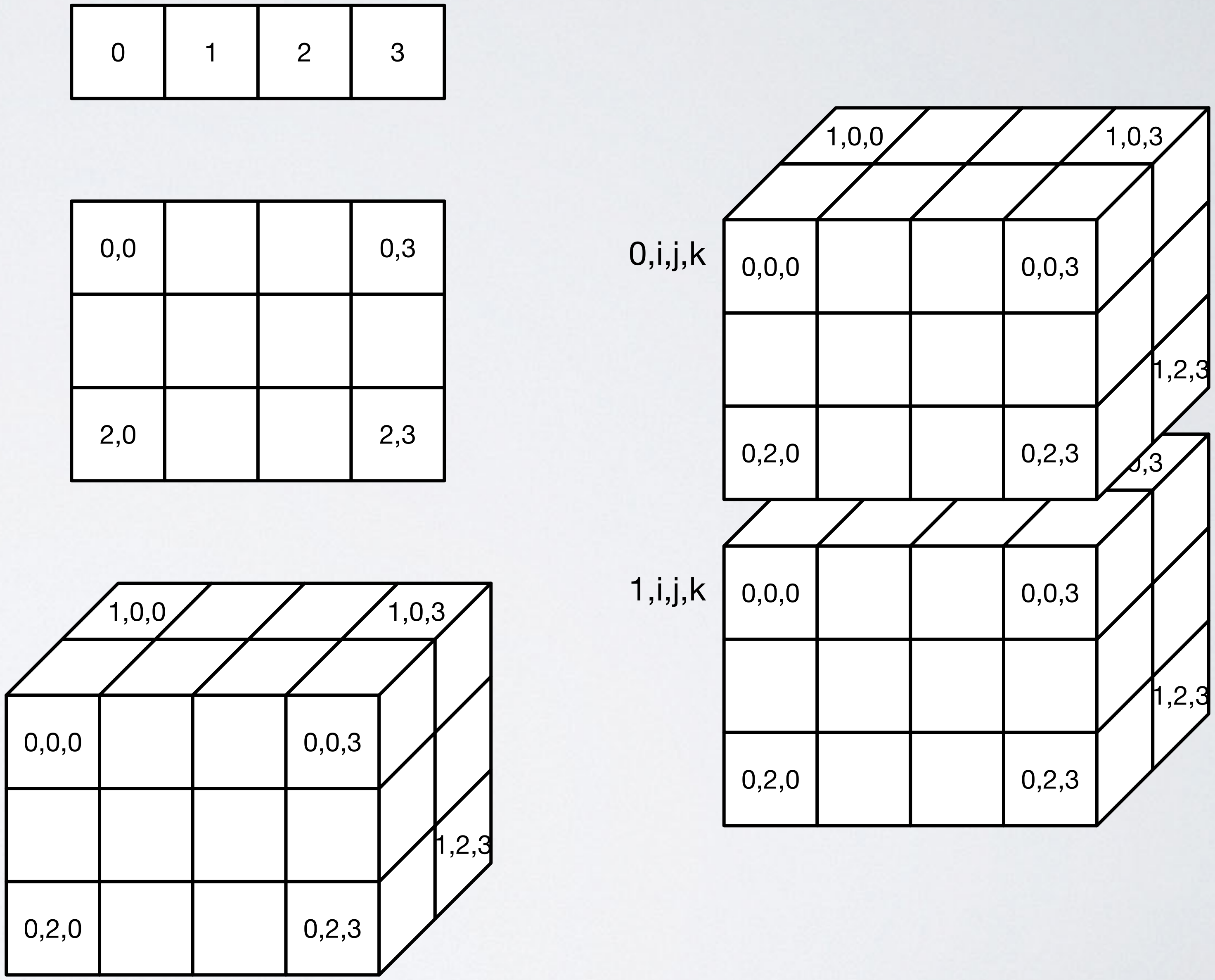
2. Access Patterns

- Tensors
- Inspection
- Changing Access Pattern



Tensors

- Rank
- Strides
- Operations



Tensors

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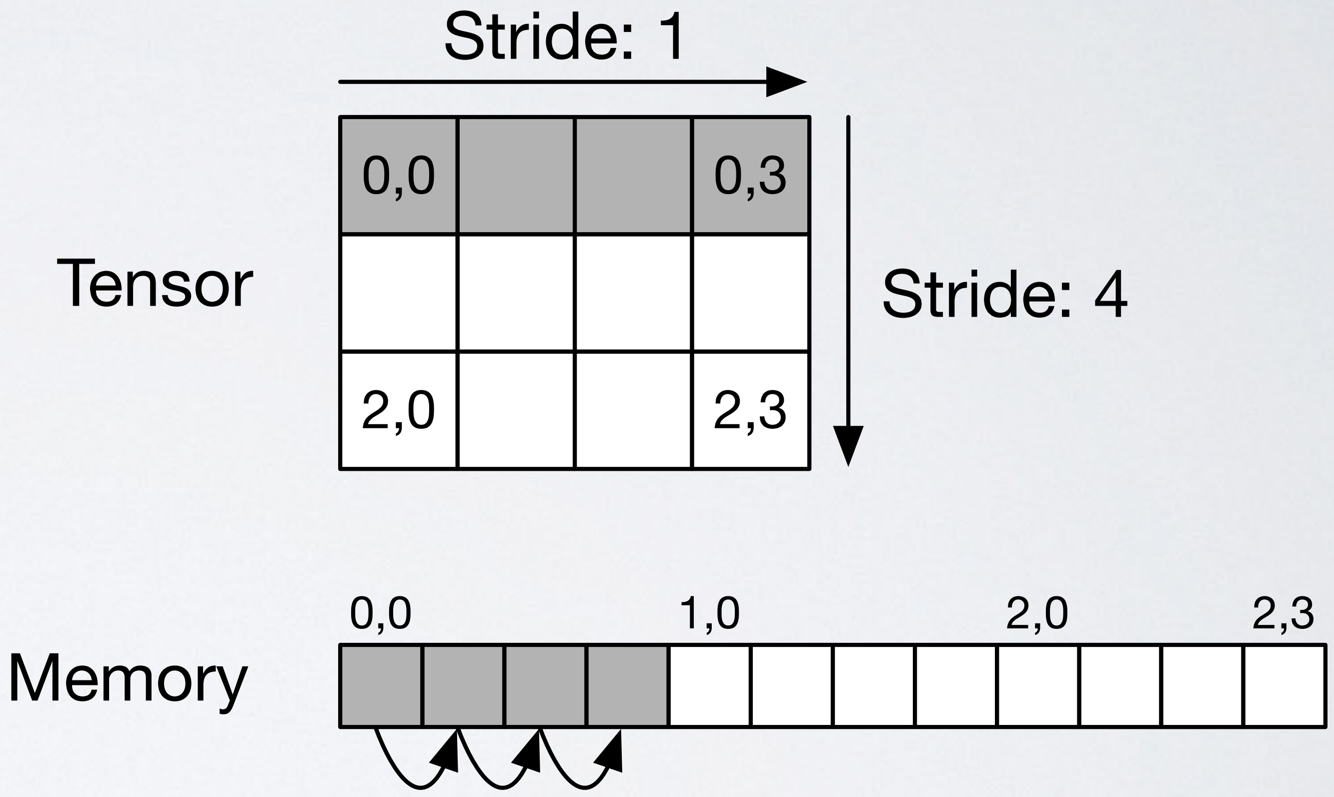
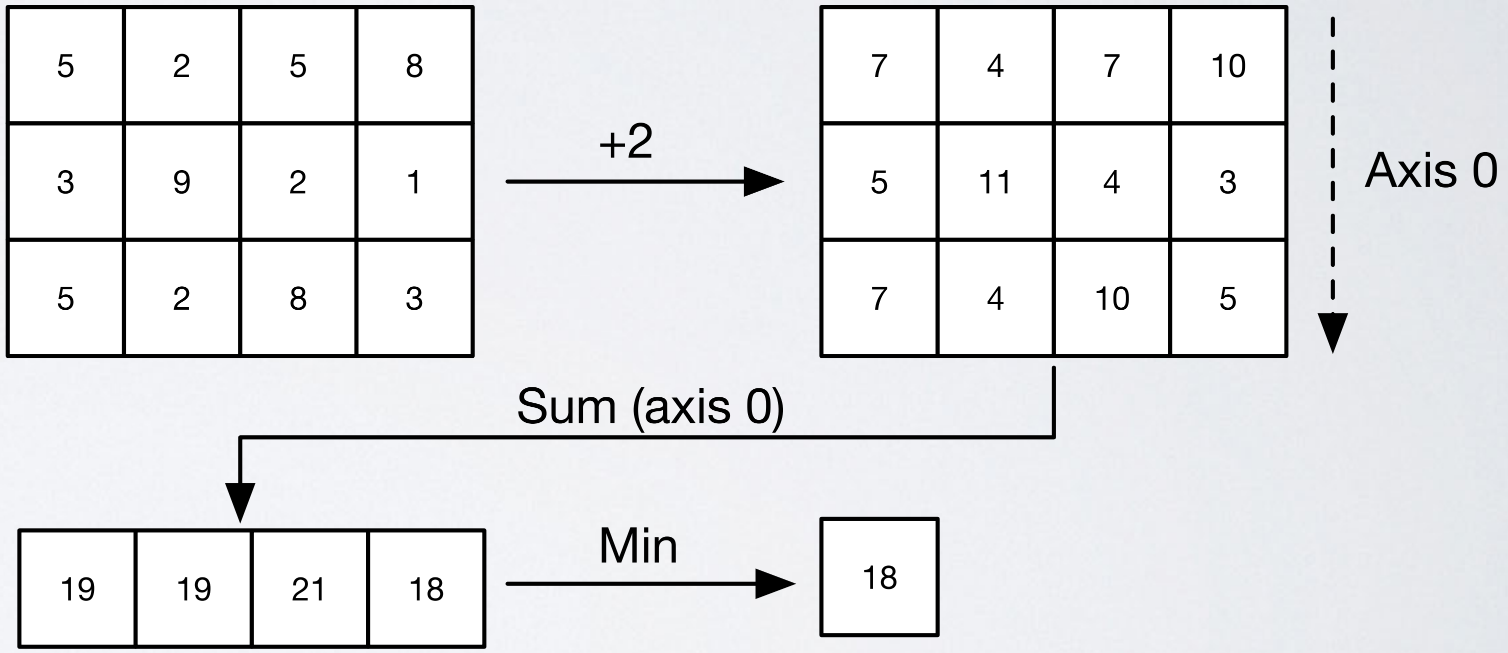


Tensors

- Rank
- Strides
- Operations



5	2	5	8
3	9	2	1
5	2	8	3

7	4	7	10
5	11	4	3
7	4	10	5

19	19	21	18

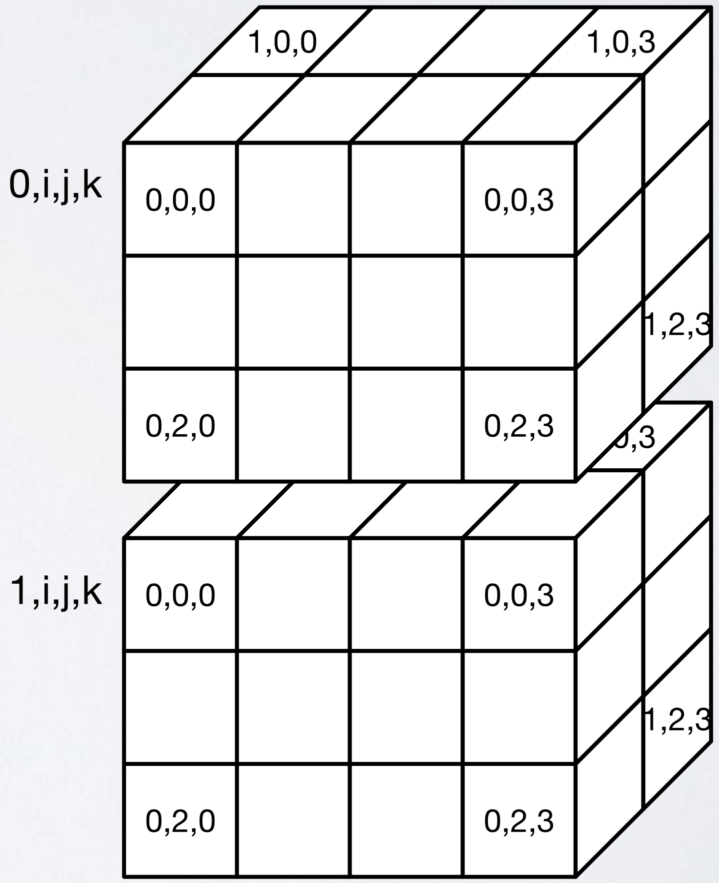
18

Inspection

- Tensor Example
- Generated Code
- Current Pattern
- Coalesced Pattern

Rank-4 tensor with dimensions:

$$50 \times 50 \times 50 \times 50$$



Inspection

Rank-4 tensor with dimensions:

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- Tensor Example
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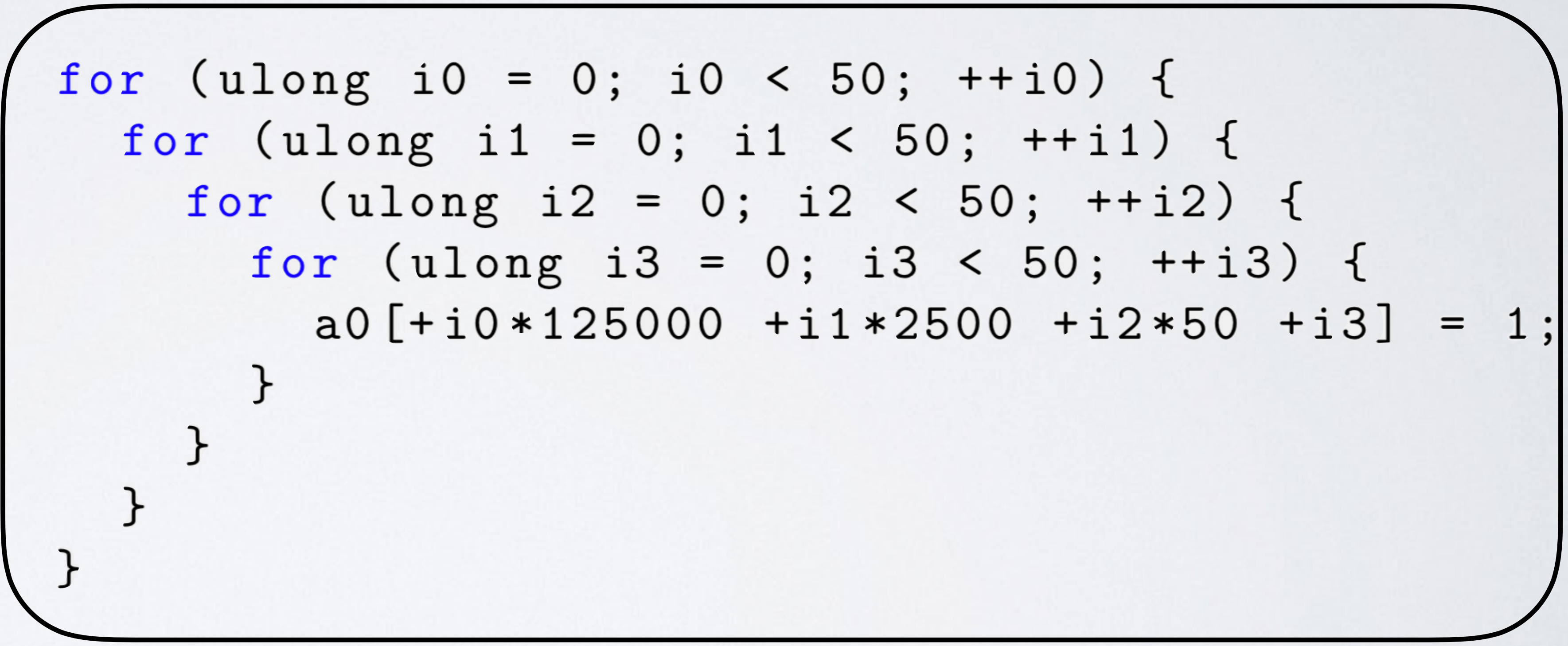


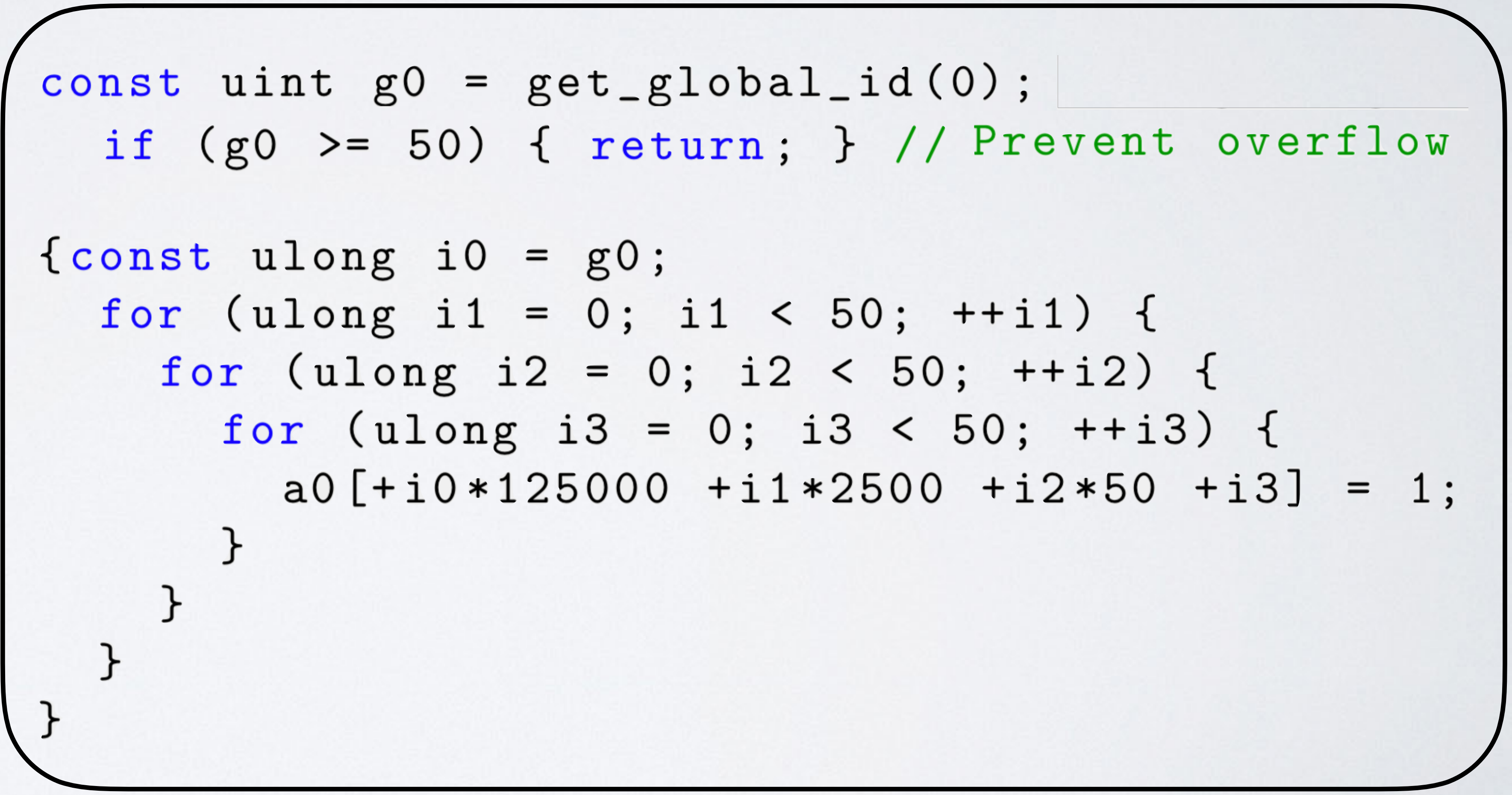
```
for (ulong i0 = 0; i0 < 50; ++i0) {
  for (ulong i1 = 0; i1 < 50; ++i1) {
    for (ulong i2 = 0; i2 < 50; ++i2) {
      for (ulong i3 = 0; i3 < 50; ++i3) {
        a0[+i0*125000 +i1*2500 +i2*50 +i3] = 1;
      }
    }
  }
}
```

Inspection

Rank-4 tensor with dimensions:

$$50 \times 50 \times 50 \times 50$$

- Tensor Example
- Generated Code
- Current Pattern
- Coalesced Pattern



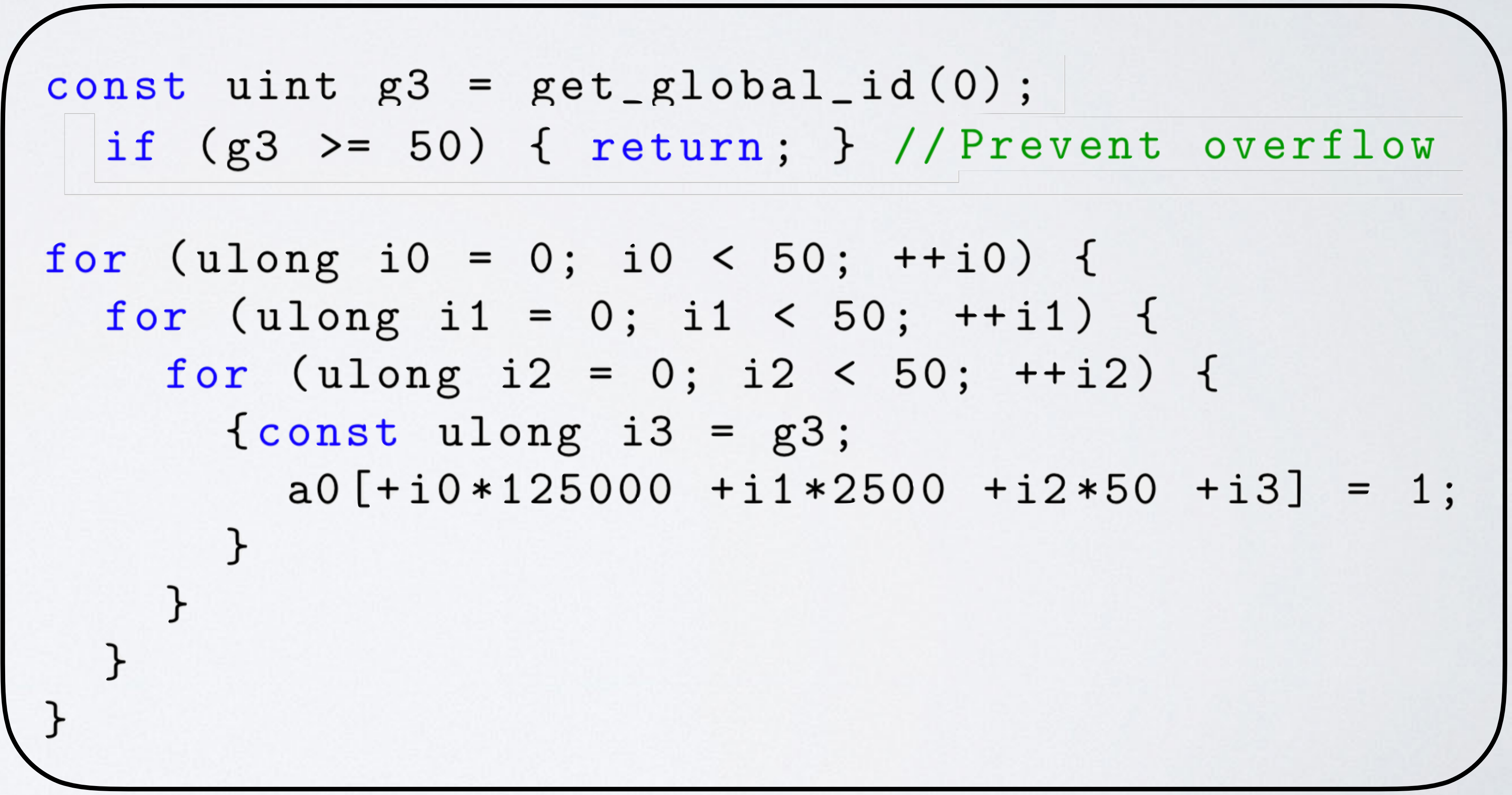
```
const uint g0 = get_global_id(0);
  if (g0 >= 50) { return; } // Prevent overflow

{const ulong i0 = g0;
  for (ulong i1 = 0; i1 < 50; ++i1) {
    for (ulong i2 = 0; i2 < 50; ++i2) {
      for (ulong i3 = 0; i3 < 50; ++i3) {
        a0[+i0*125000 +i1*2500 +i2*50 +i3] = 1;
      }
    }
  }
}
```

Inspection

Rank-4 tensor with dimensions:

$$50 \times 50 \times 50 \times 50$$

- Tensor Example
- Generated Code
- Current Pattern
- **Coalesced Pattern**



```
const uint g3 = get_global_id(0);
  if (g3 >= 50) { return; } //Prevent overflow

for (ulong i0 = 0; i0 < 50; ++i0) {
  for (ulong i1 = 0; i1 < 50; ++i1) {
    for (ulong i2 = 0; i2 < 50; ++i2) {
      {const ulong i3 = g3;
        a0[+i0*125000 +i1*2500 +i2*50 +i3] = 1;
      }
    }
  }
}
```

Changing Access Pattern

- Decide on Parallel Axis
- Implementation
- Results

Truncated Block Structure of Kernel

```
rank: 0, size: 75, sweeps: {}
  rank: 1, size: 75, sweeps: {}
    rank: 2, size: 75, sweeps: {
       BH_ADD_REDUCE a0 a1 3}
      rank: 3, size: 75, sweeps: {
         BH_ADD_REDUCE a2 a3 4}
```

Changing Access Pattern

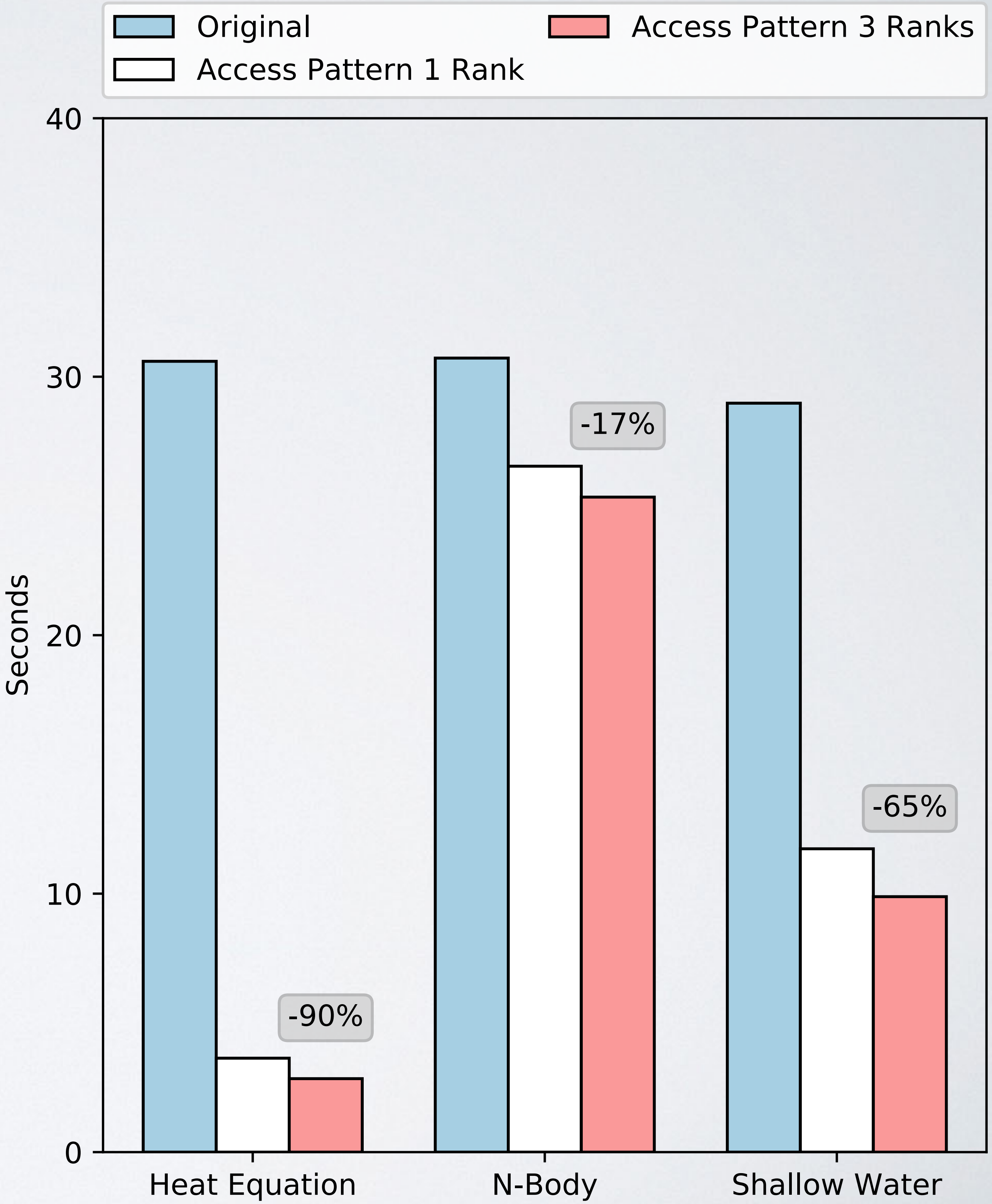
- Decide on Parallel Axis
- Implementation
- Results

Remapped Iterators

```
uint g2 = get_global_id(0);
uint g1 = get_global_id(1);
uint g0 = get_global_id(2);
// ...
i0 = g0
i1 = g1
i2 = g2
```

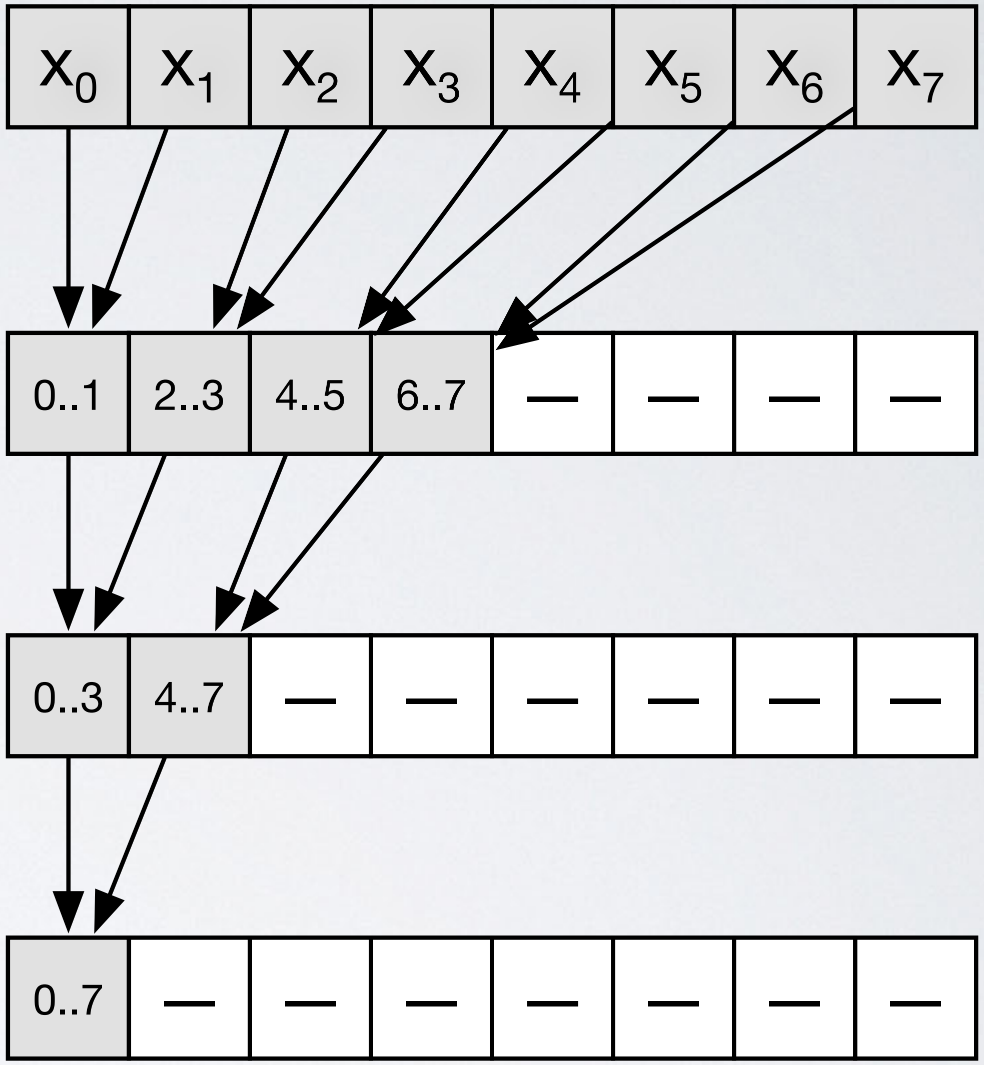
Changing Access Pattern

- Decide on Parallel Axis
- Implementation
- Results



3. Reduction

- Hardware Constraints
- Access Pattern in Reductions



x_0 x_1 x_2 x_3 x_4 x_5 x_6 x_7

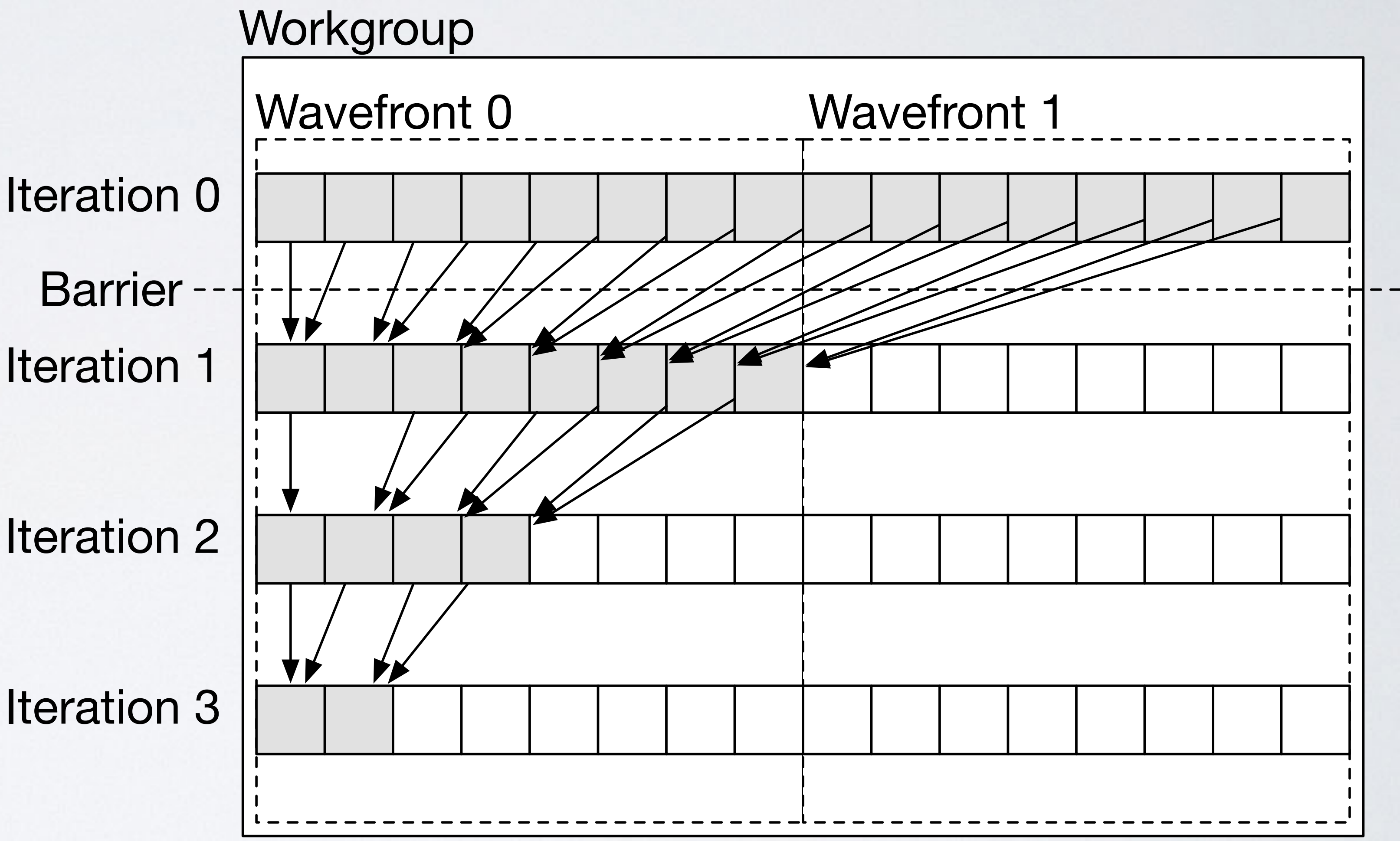
0..1 2..3 4..5 6..7 — — — —

0..3 4..7 — — — — — —

0..7 — — — — — — —

Hardware Constraints

- Wavefronts
- Work-groups
- Bohrium



Hardware Constraints

- Wavefronts
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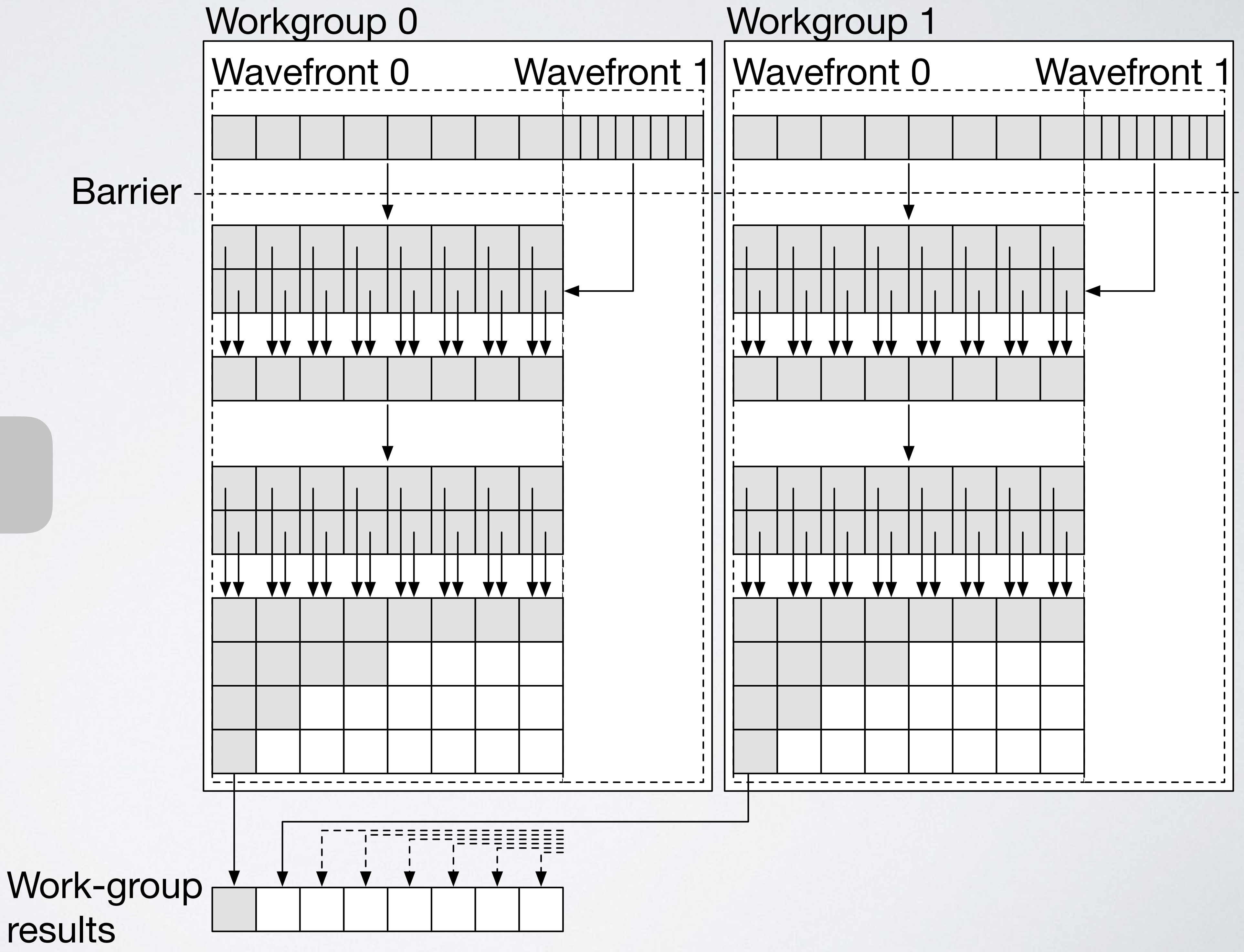

Hardware Constraints

- Wavefronts
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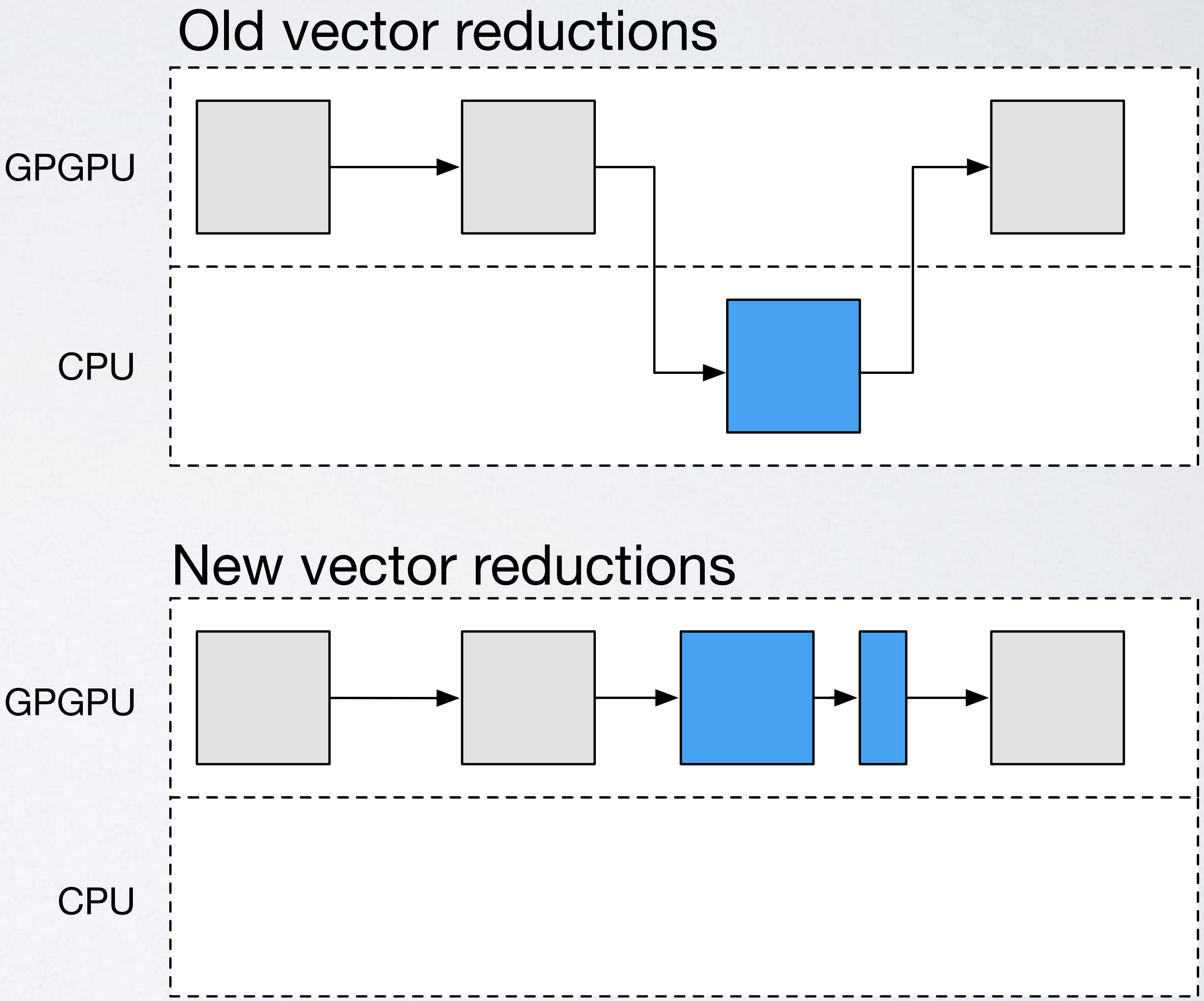
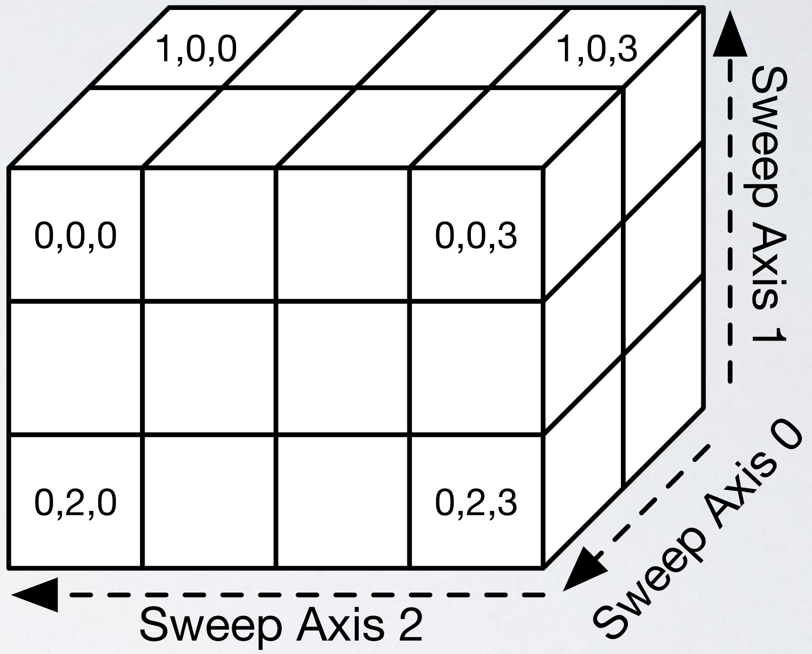
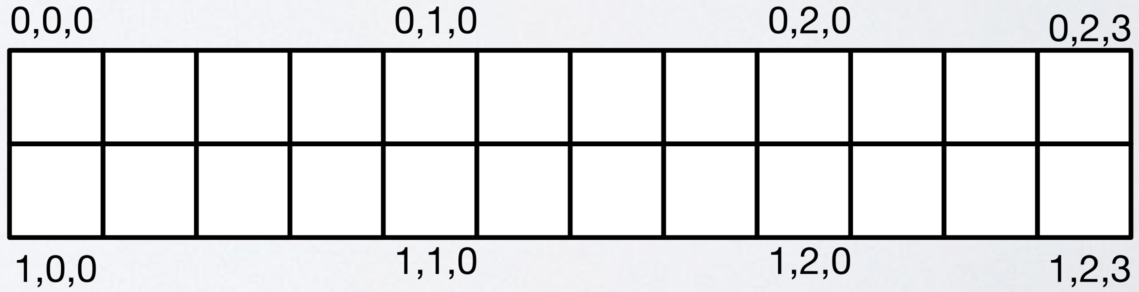


Access Pattern in Reductions

- Axis
- Column-wise
- Row-wise
- Transposing





Access Pattern in Reductions

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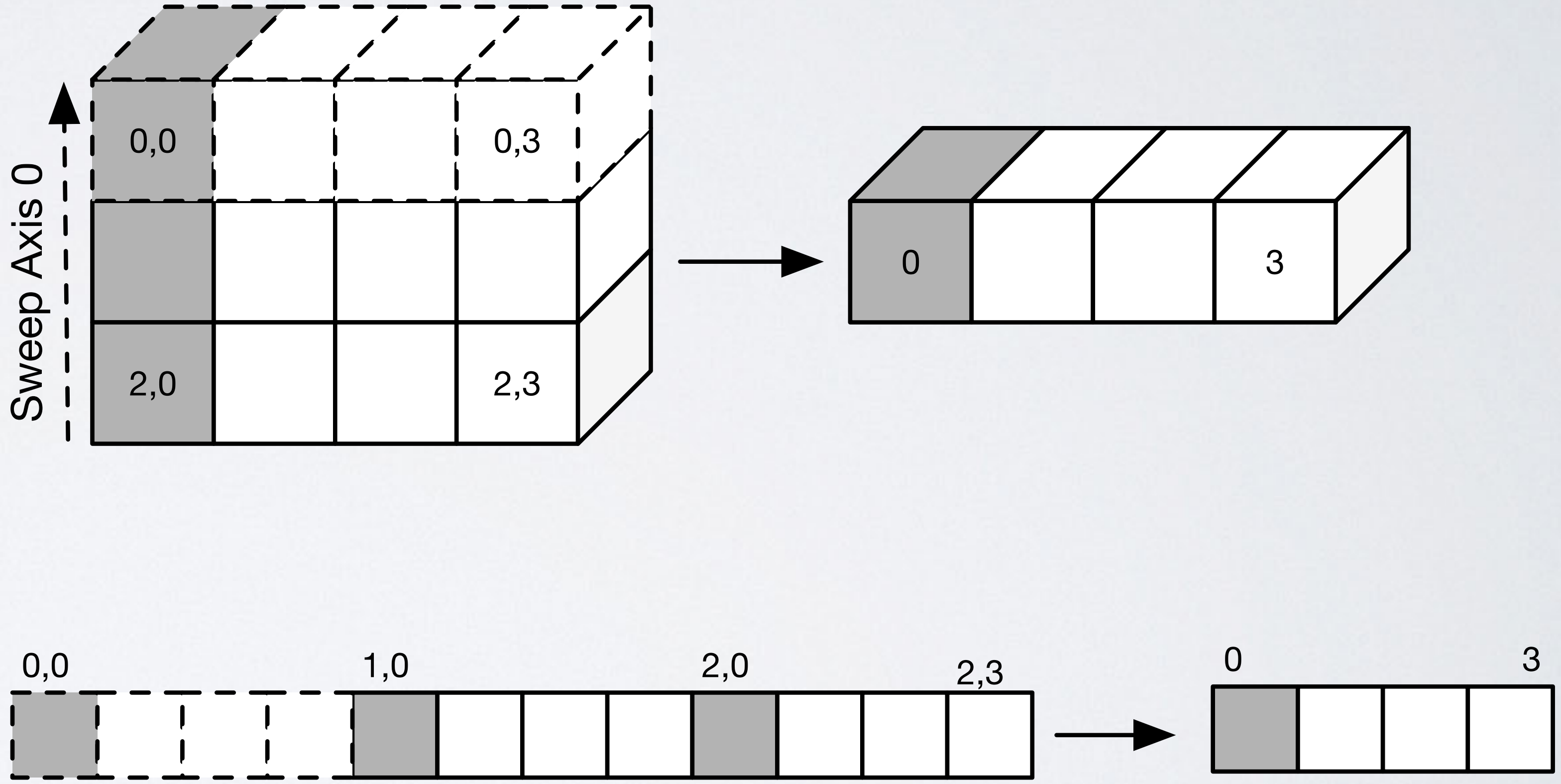
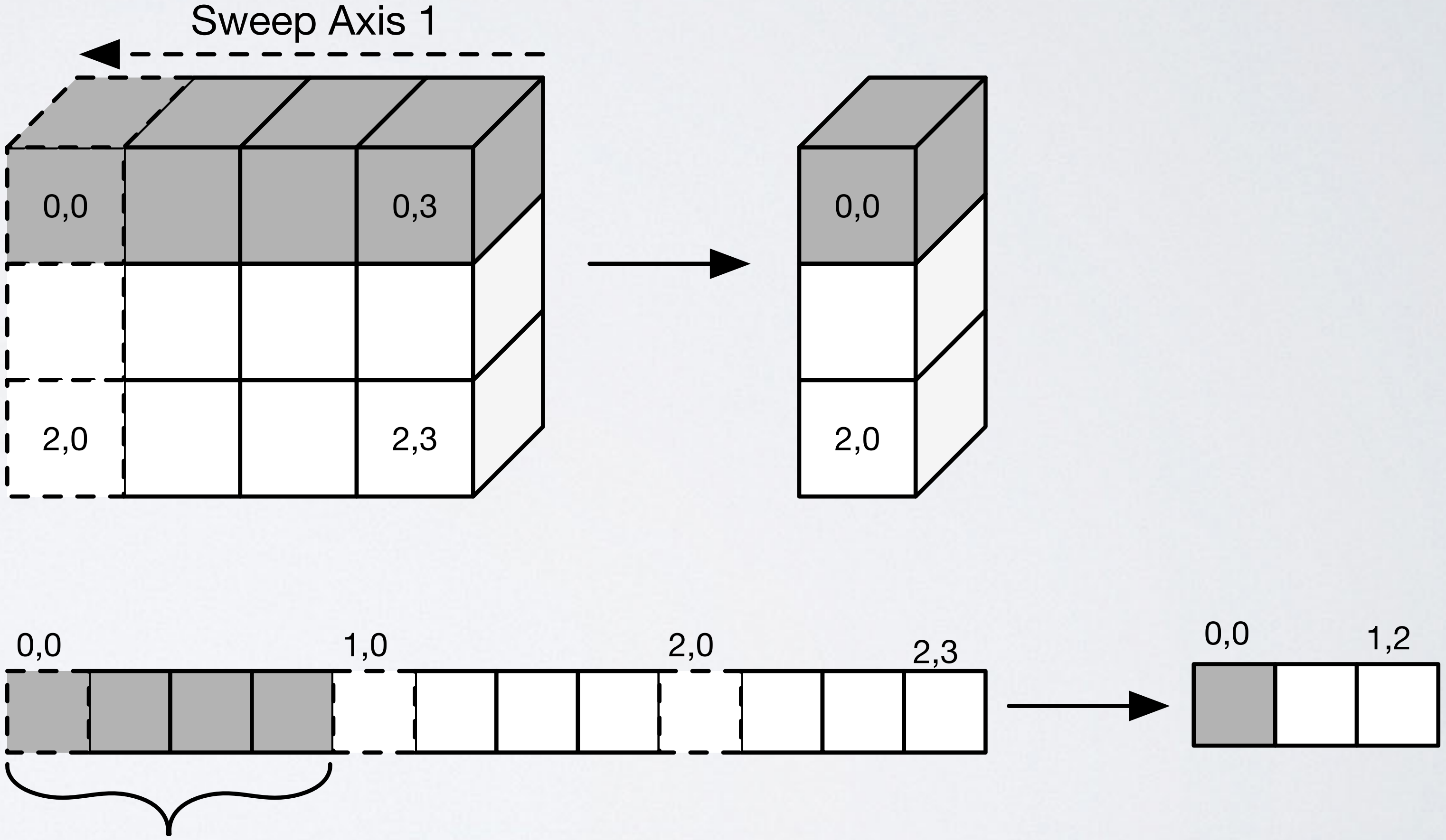


Access Pattern in Reductions

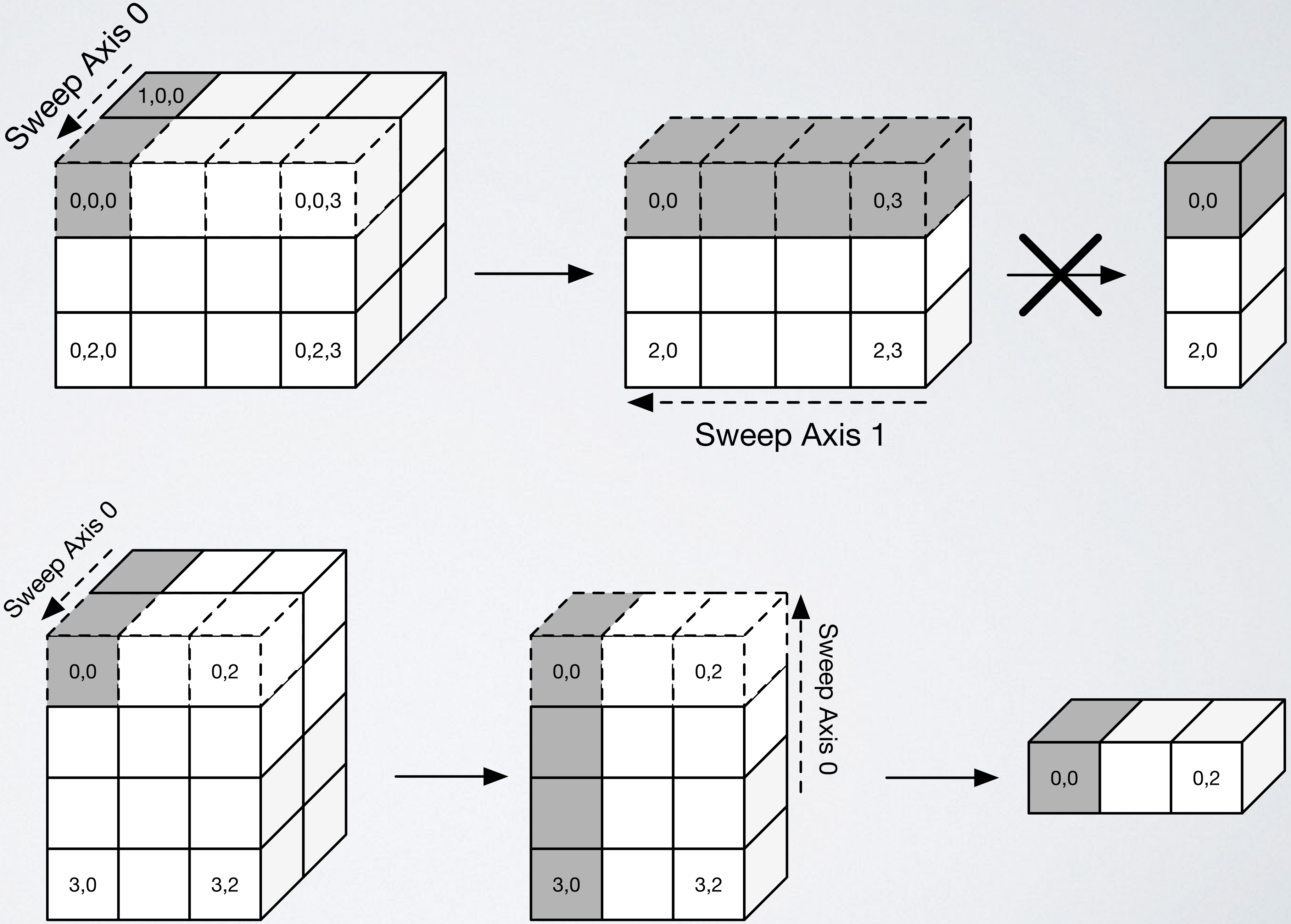
- Axis
- Column-wise
- Row-wise
- Transposing



Segmented Reduction Preferred

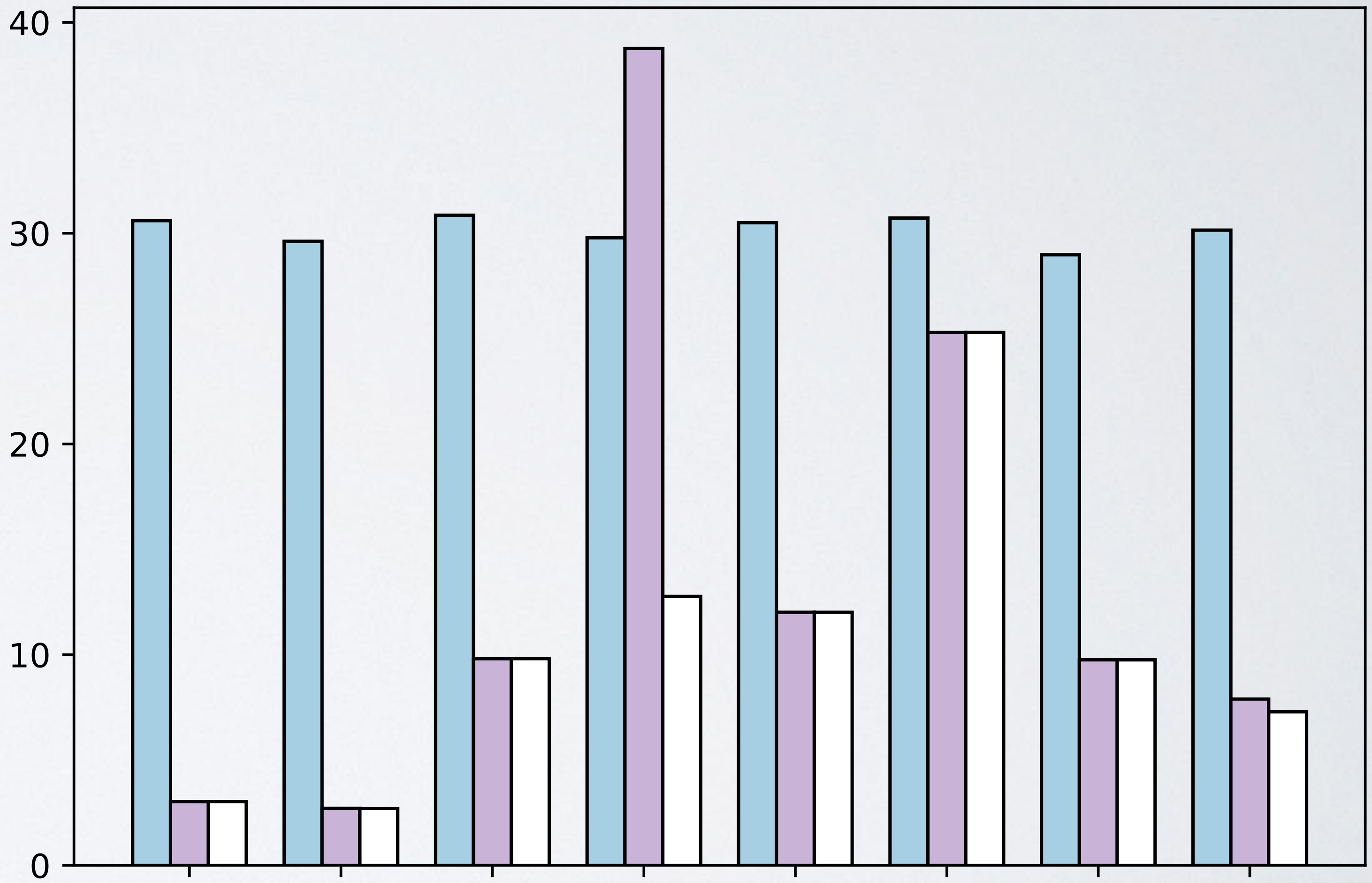
Access Pattern in Reductions

- Axis
- Column-wise
- Row-wise
- Transposing



4. Benchmarks

- Benchmark Suite
- Handwritten vs. Bohrium

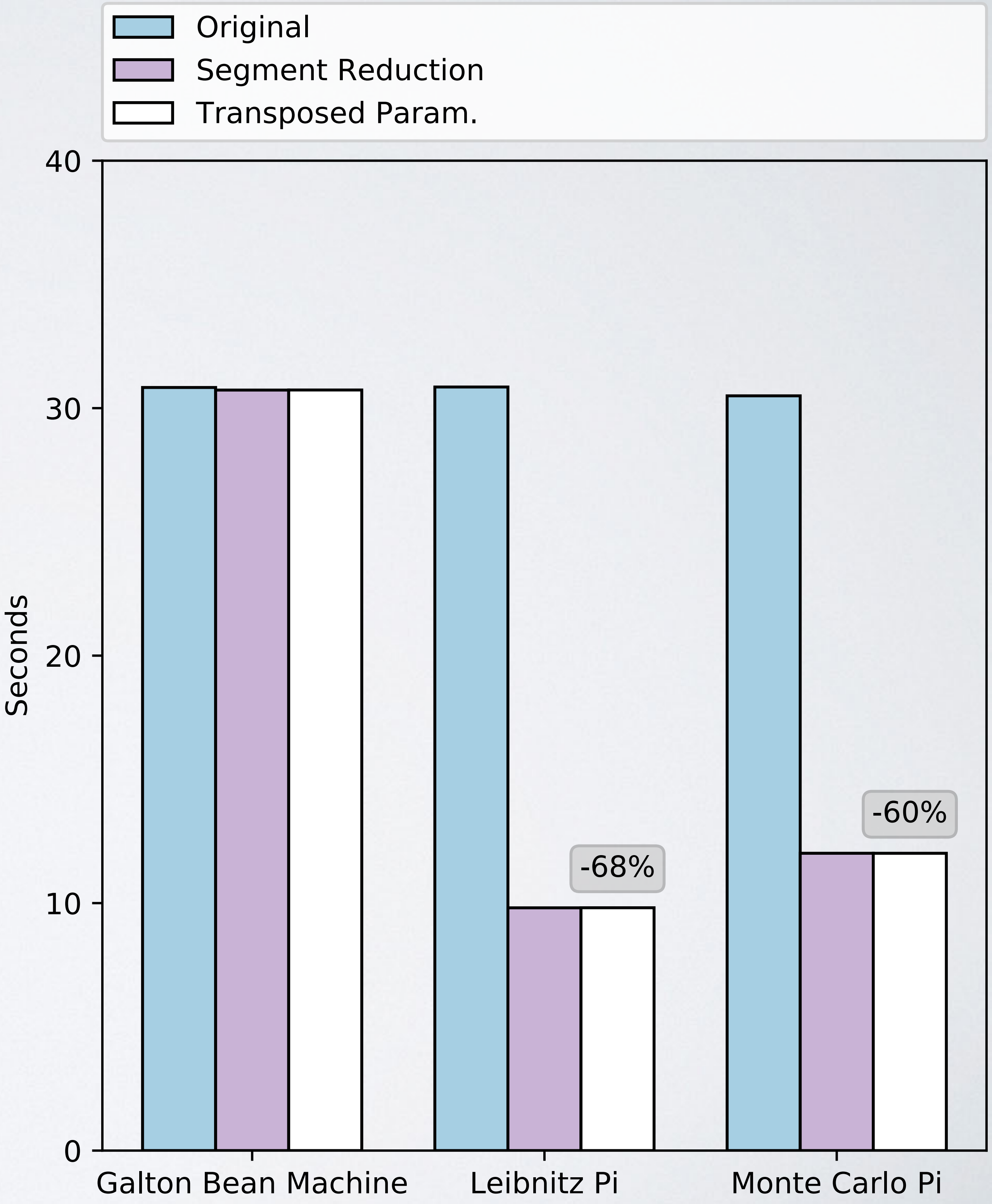


Benchmark Suite

- Embarrassingly Parallel
- Finite Difference
- Streaming/Reduction

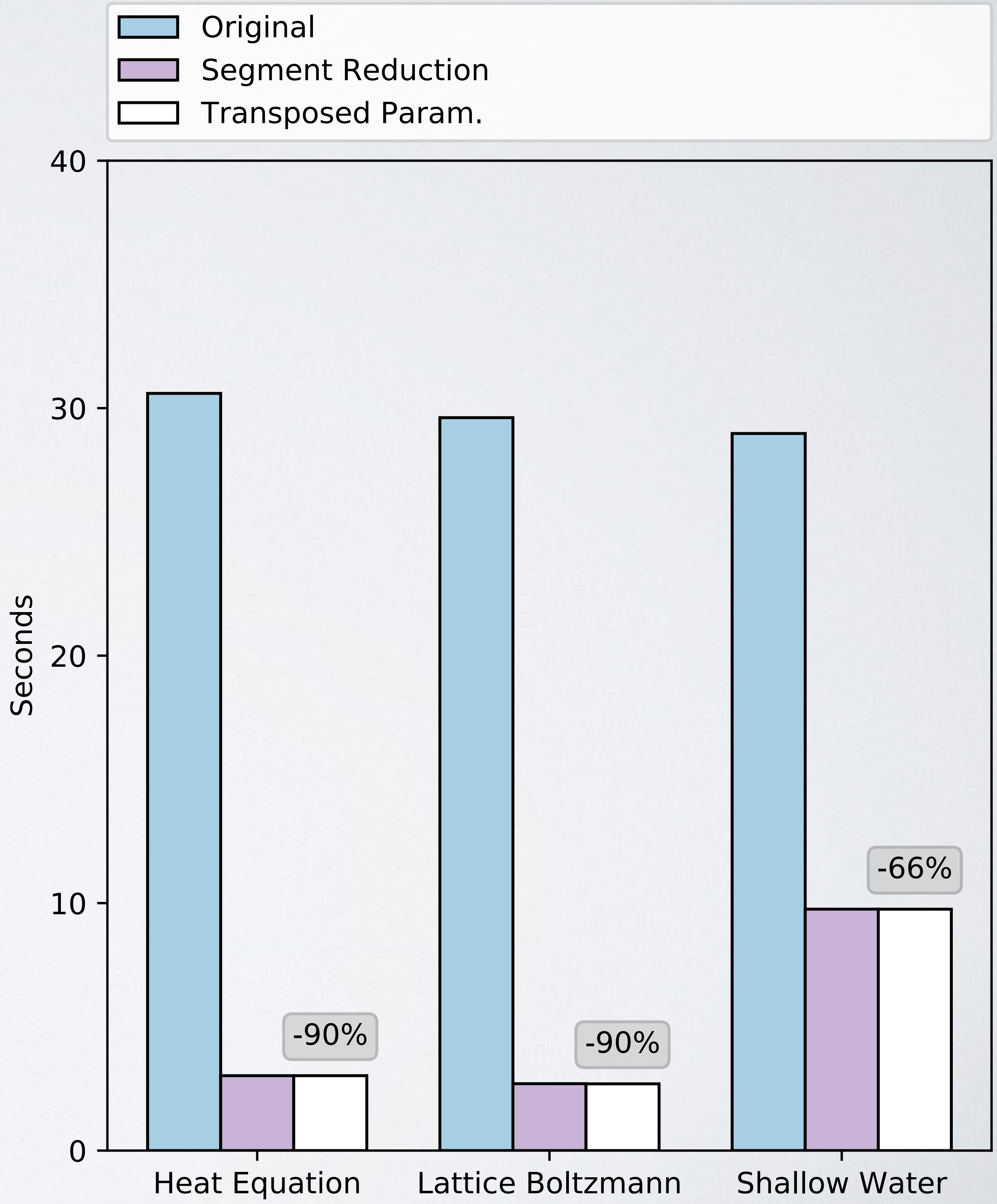
Benchmark Suite

- Embarrassingly Parallel
  I. Galton Bean Machine
  II. Leibnitz Pi
  III. Monte Carlo Pi
- Finite Difference
- Streaming/Reduction



Benchmark Suite

- Embarrassingly Parallel
- Finite Difference
    I. Heat Equation
    II. Lattice Boltzmann
    III. Shallow Water
- Streaming/Reduction



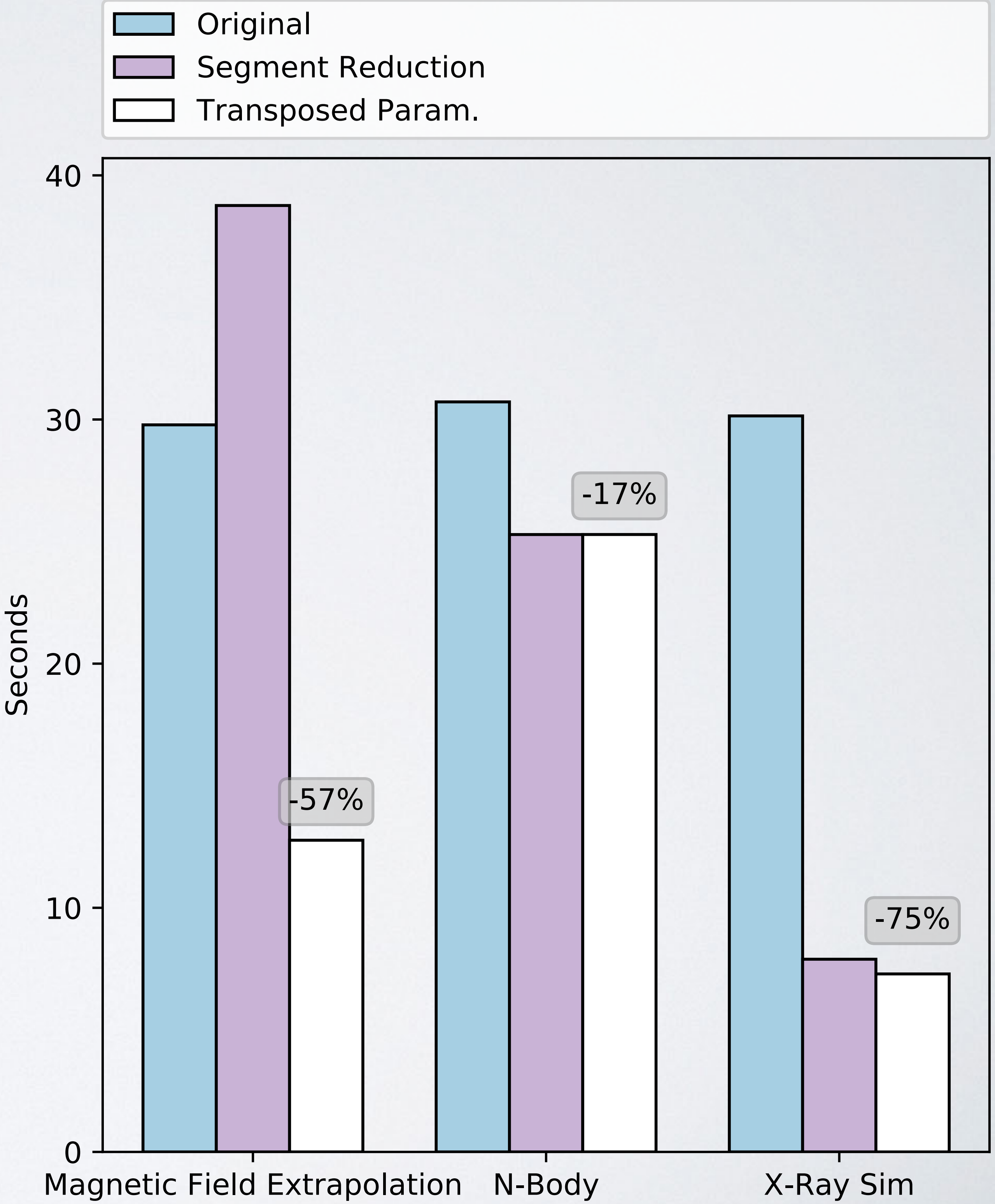
Benchmark Suite

- Embarrassingly Parallel
- Finite Difference
- Streaming/Reduction

I. Magnetic Field Extrapolation

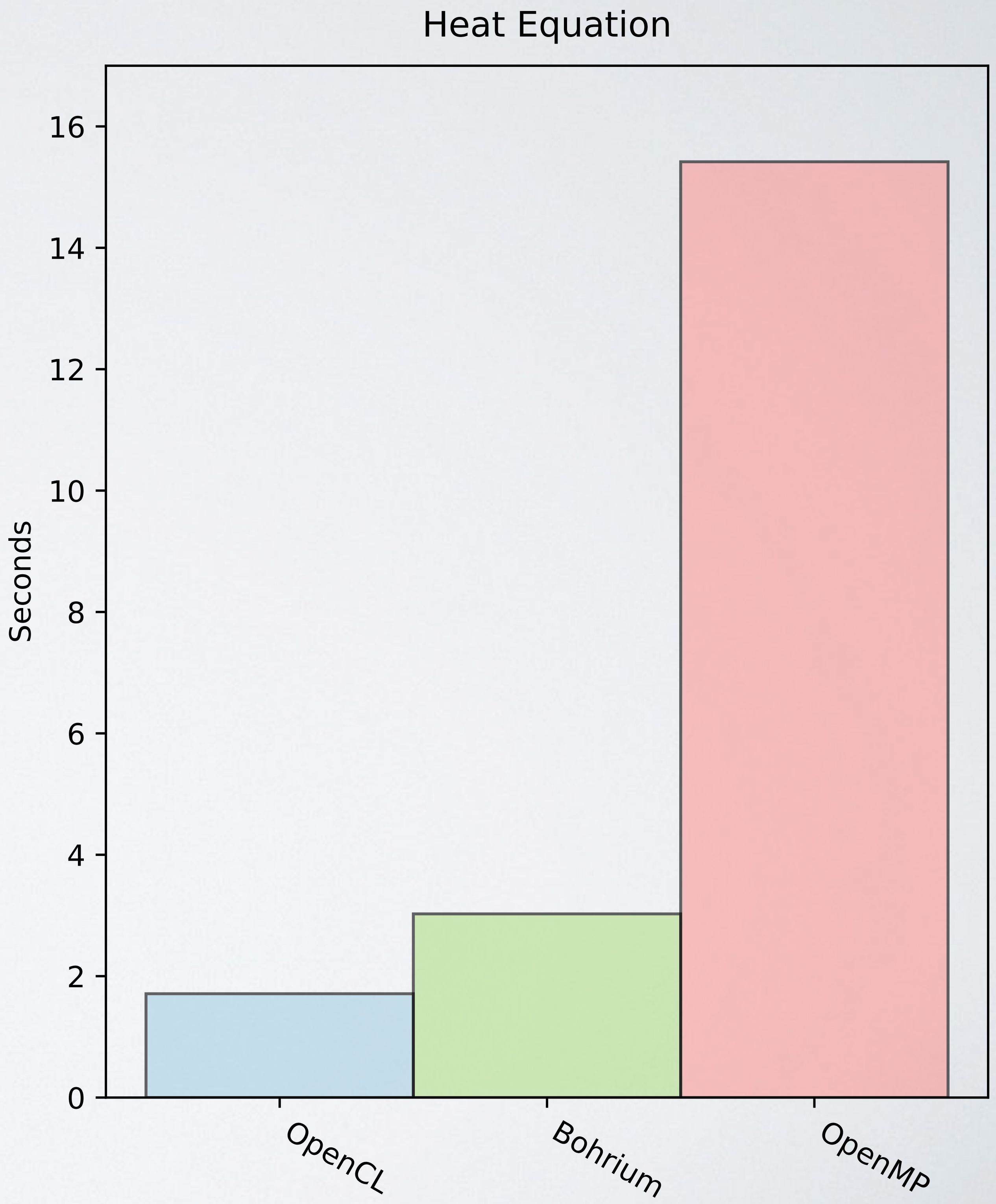
II. N-body

III. X-ray Sim



Handwritten vs. Bohrium

- Handwritten version
- NumPy version
- Complexity of simulations



5. Future Work

v2.0

- Problem with MFE
- Throughput
- Next Focus Points

Problem with MFE

- Access Pattern
- Handling the Access Pattern

MFE Kernel Stripped of Constant Strides
Param. 128 × 1 × 1

```
s8_8 = a8[ +i3*75 +i4];
t6 = a7[ +i2*5625 +i3*75 +i4]
     * s8_8;
```

MFE Kernel Stripped of Constant Strides
Param. 1 × 2 × 64

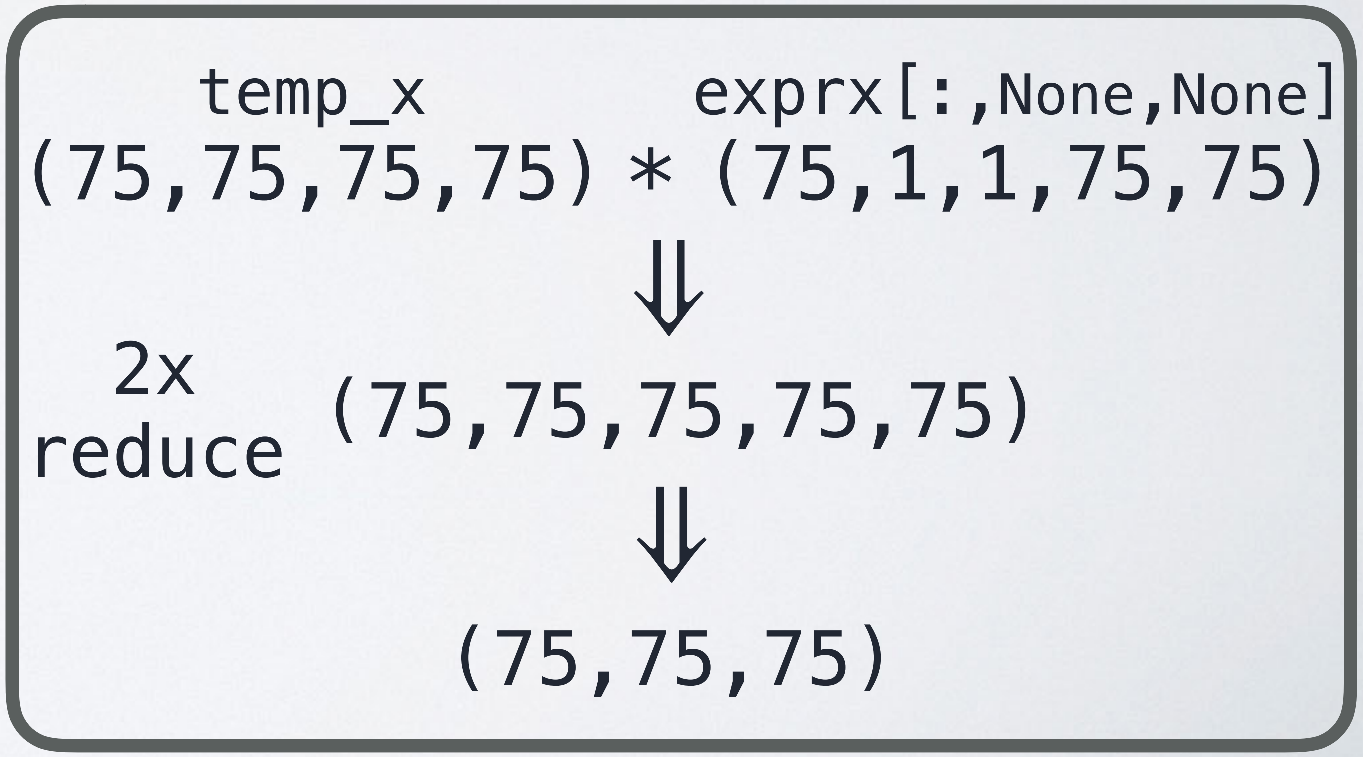
```
s8_8 = a8[ +i0*5625 +i3*75 +i4];
t6 = a7[ +i3*75 +i4] * s8_8;
```

Problem with MFE

- Access Pattern
- Handling the Access Pattern

MFE NumPy Code

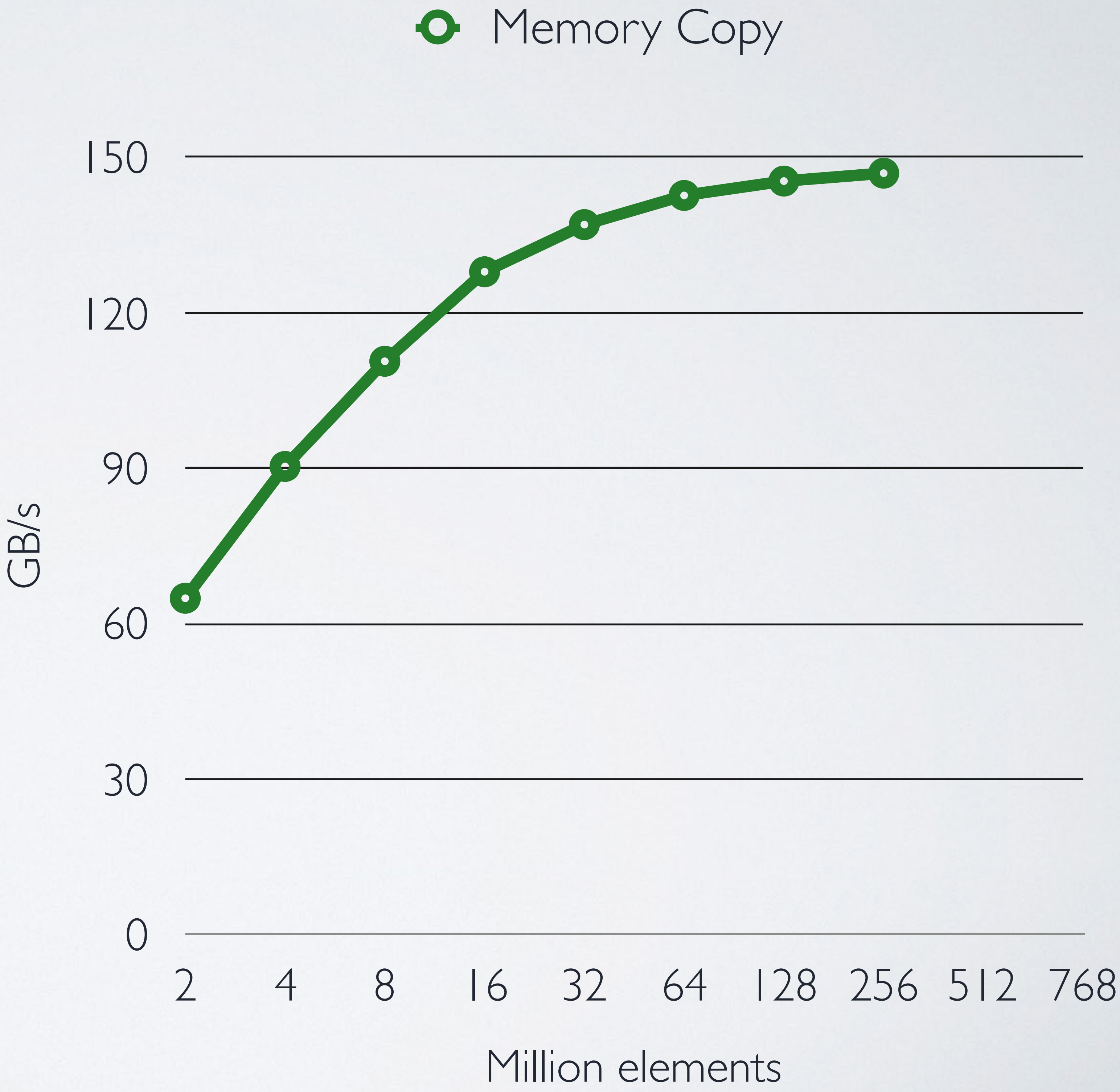
```
np.sum(
 np.sum(
  temp_x * exprx[:, None, None],
  -1),
 -1)
```



```
    temp_x        exprx[:,None,None]
(75,75,75,75) * (75,1,1,75,75)
                  ⇓
  2x
reduce (75,75,75,75,75)
                  ⇓
           (75,75,75)
```

Throughput

- Memory Copy
- Vector Reduction
- Segmented Reduction



Throughput

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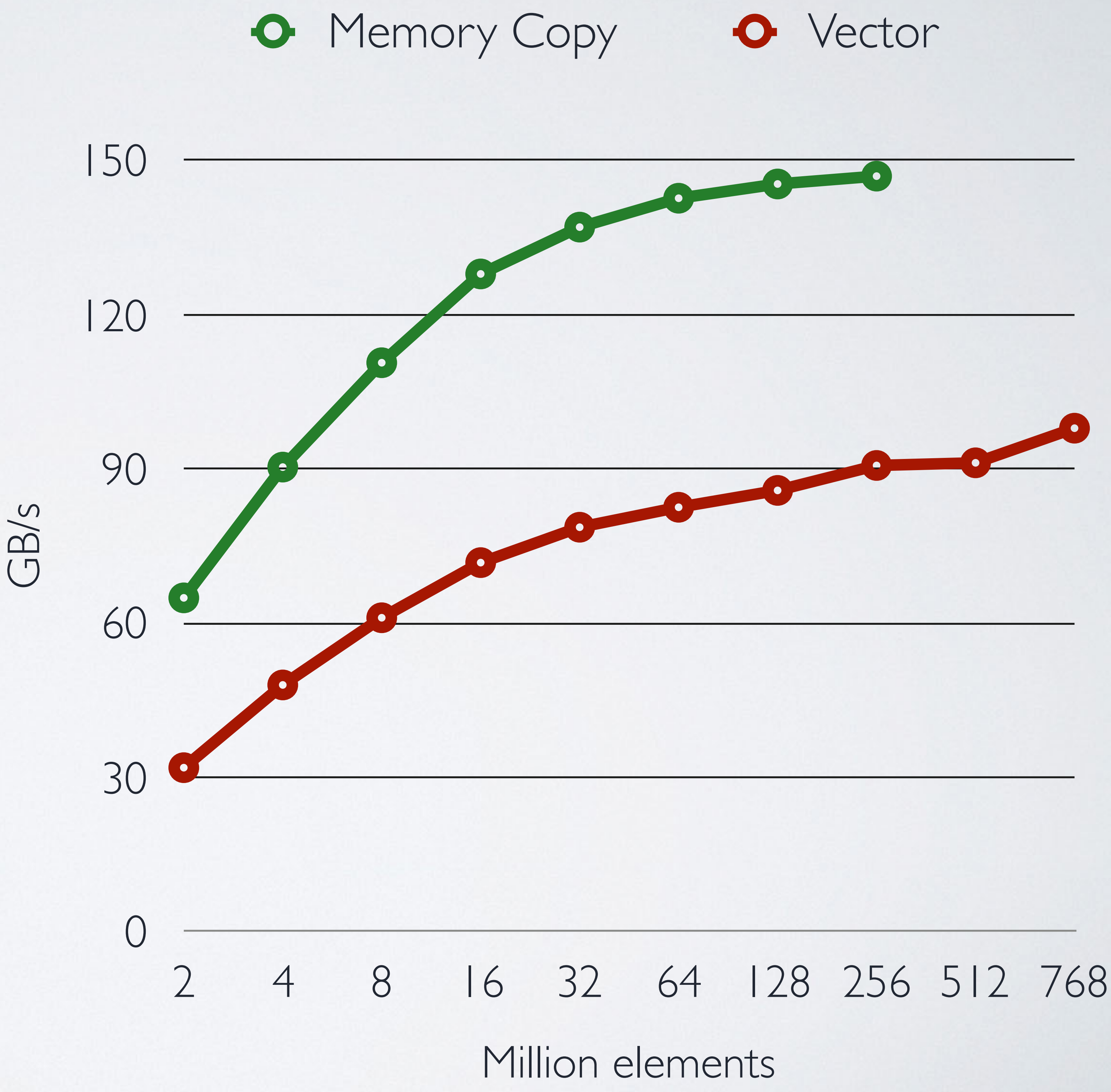

Throughput

- Memory Copy
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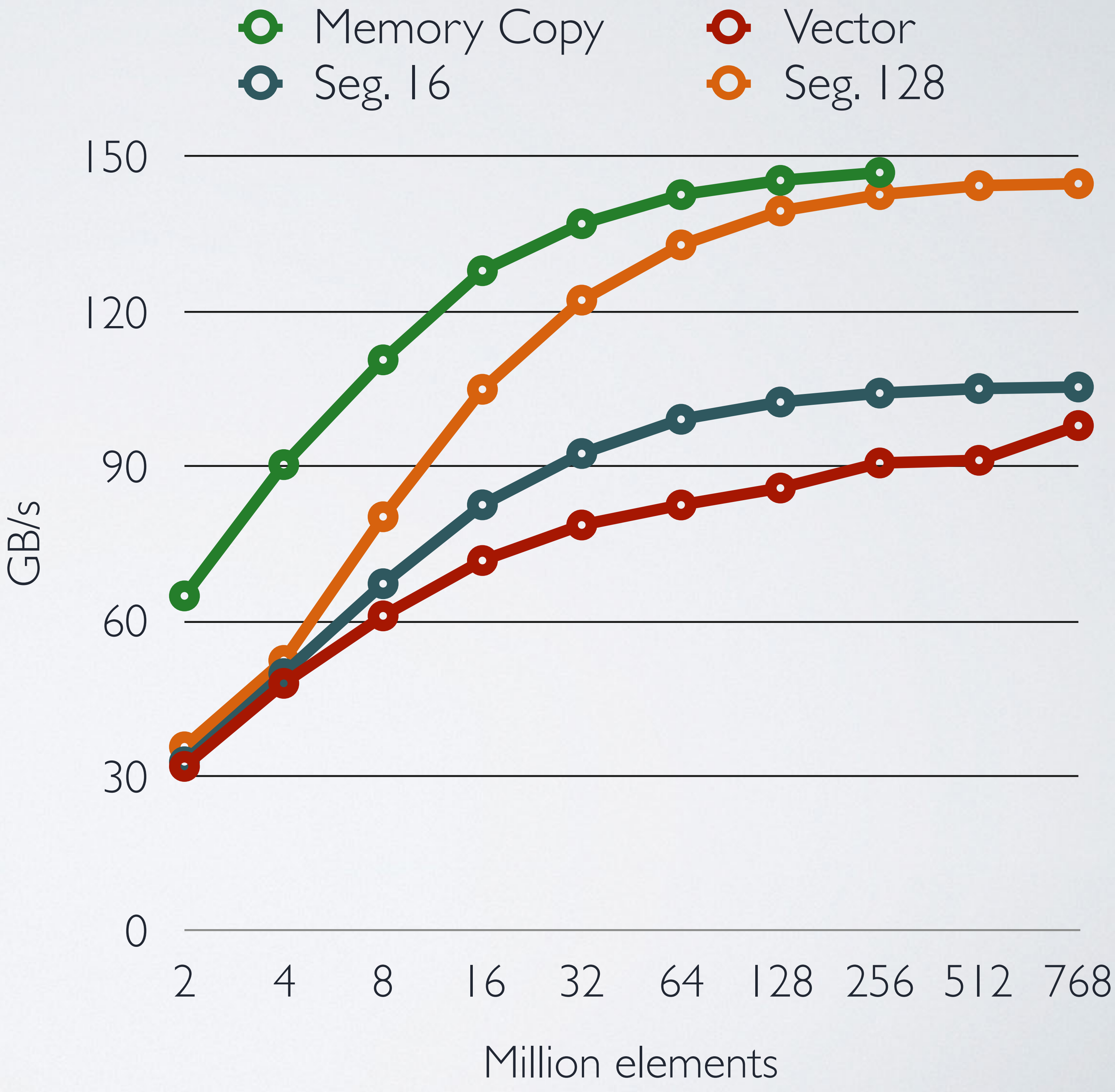

Throughput

- Memory Copy
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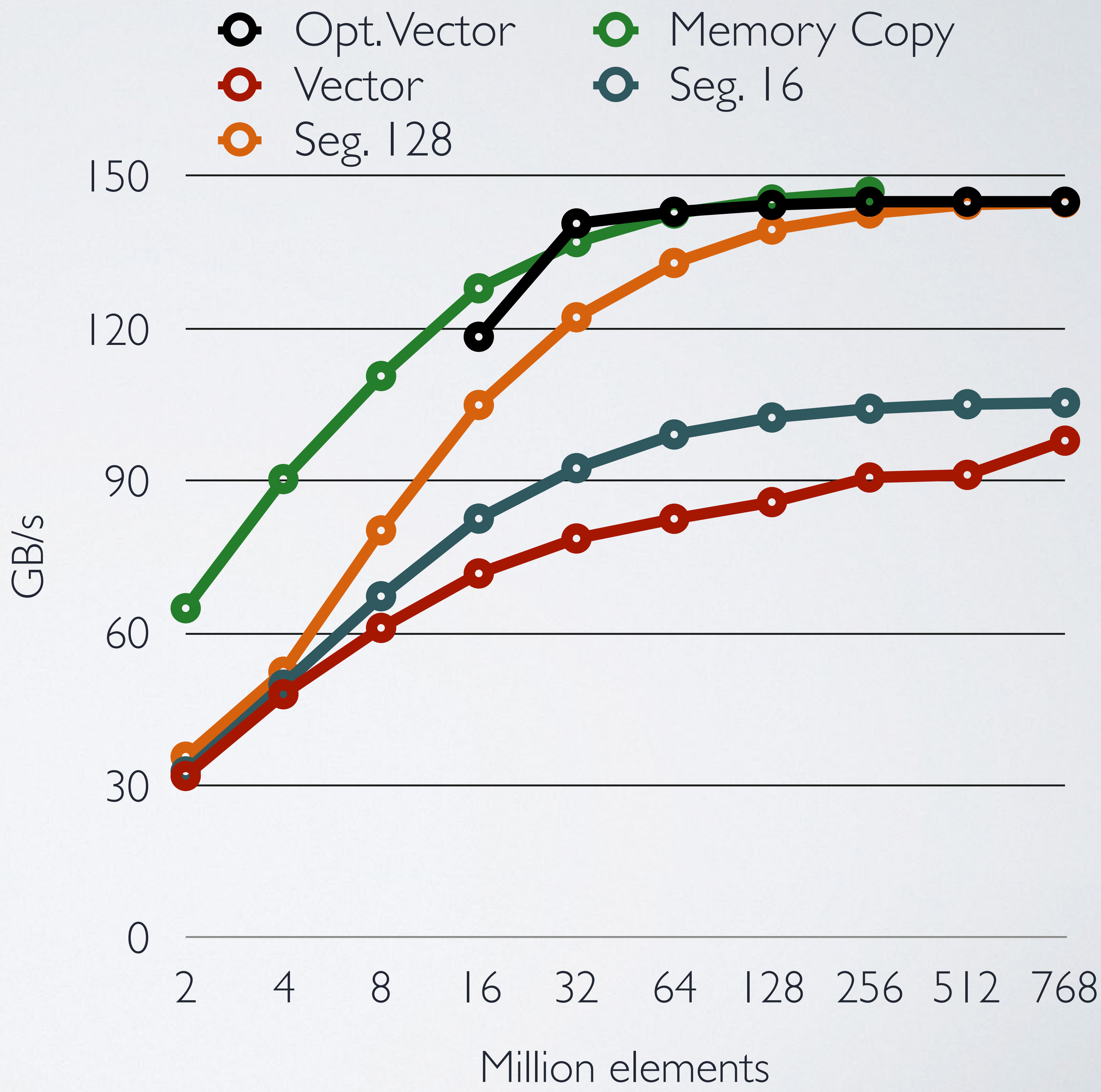
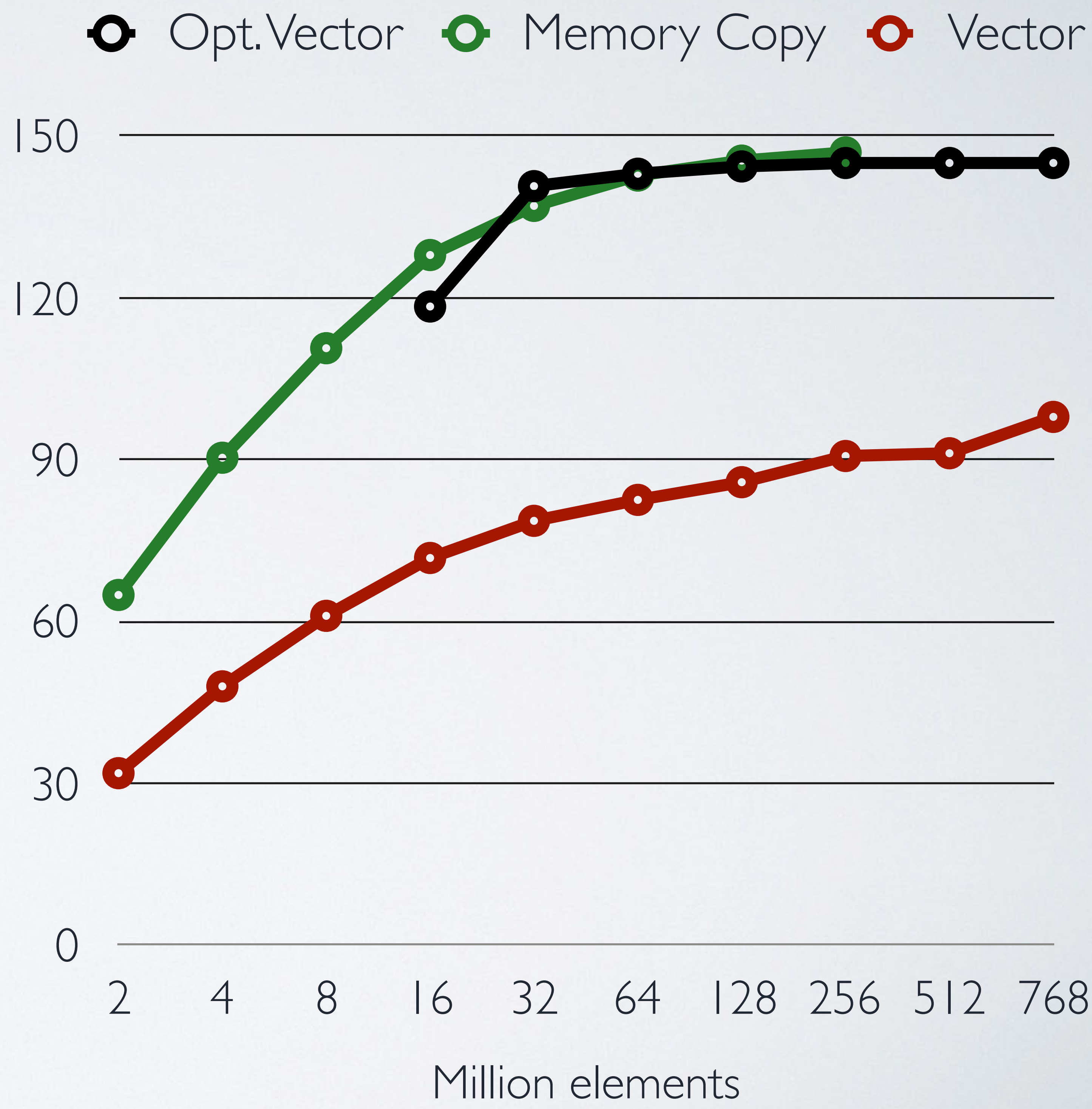
- Segmented Reduction



Next Focus Points

- Memory Throughput
- "Chicken or the egg" Issues
- Kernel-based Parameters
- Reshape and Transform



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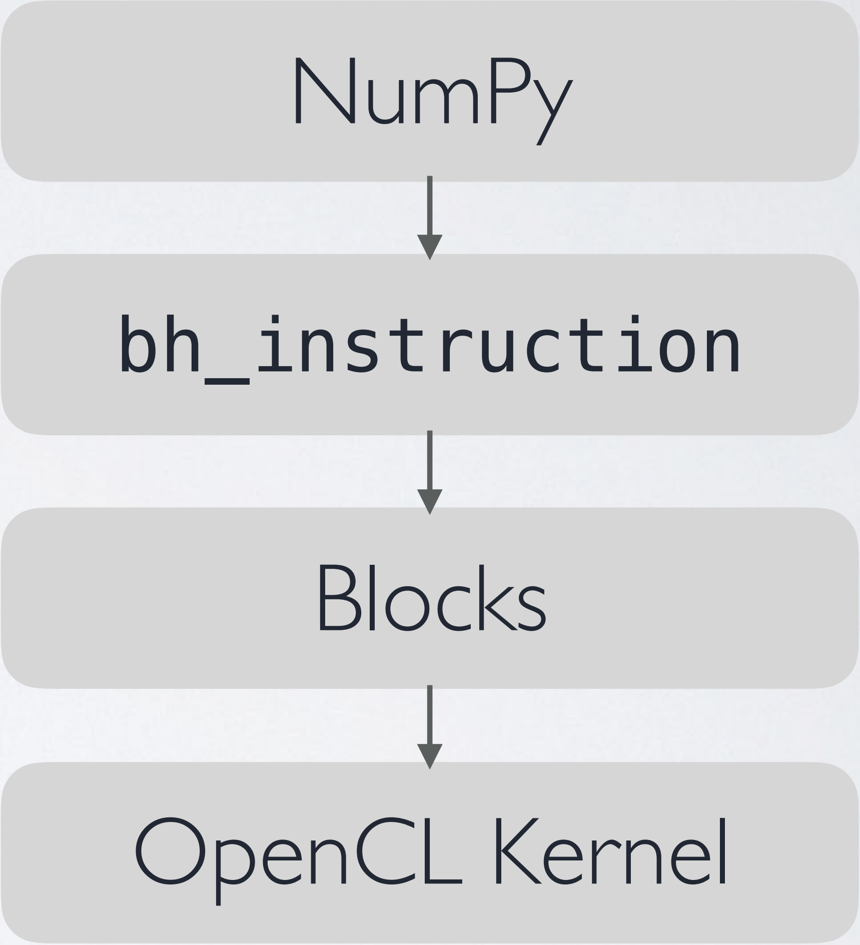

NumPy

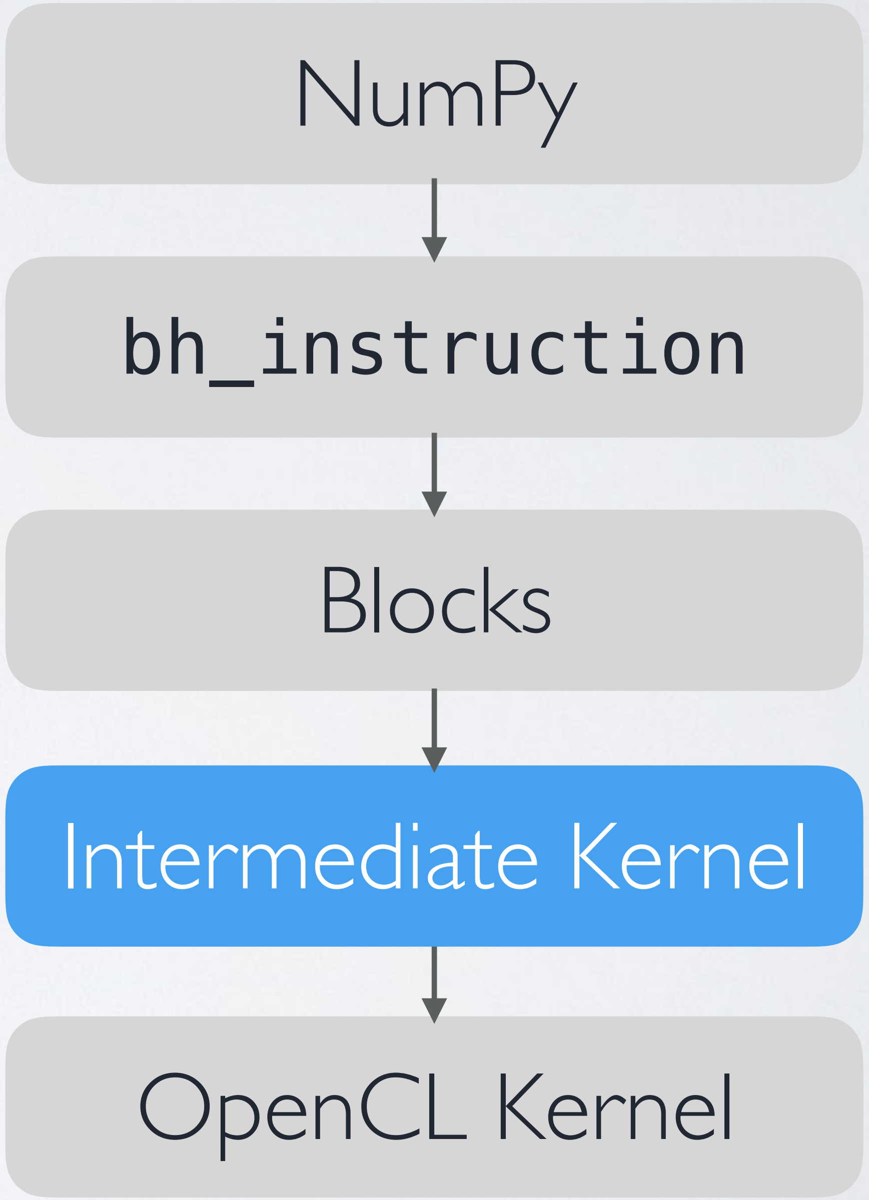
`bh_instruction`

Blocks

OpenCL Kernel

Next Focus Points

- Memory Throughput
- “Chicken or the egg” Issues
- Kernel-based Parameters
- Reshape and Transform



NumPy

`bh_instruction`

Blocks

Intermediate Kernel

OpenCL Kernel

Next Focus Points

- Memory Throughput
- “Chicken or the egg” Issues
- Kernel-based Parameters
- Reshape and Transform

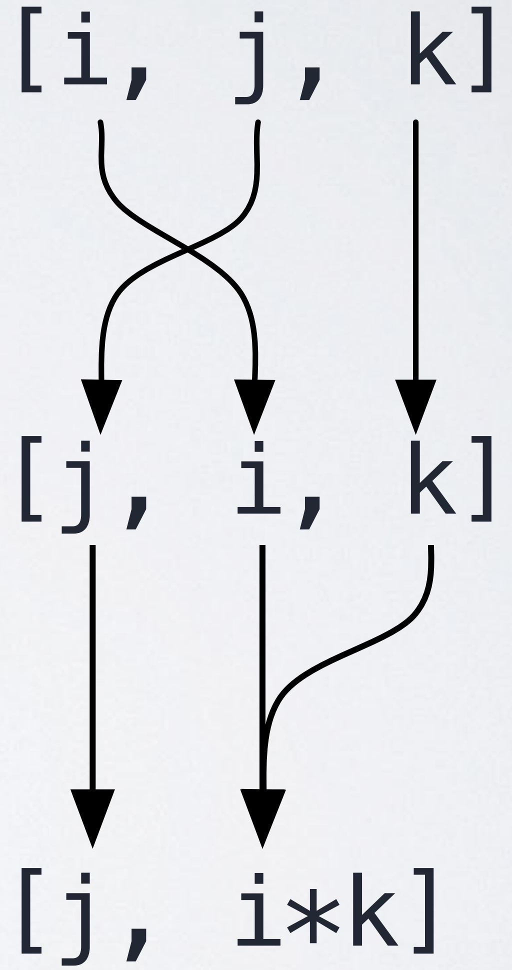
```
exprx[:,None,None]
(75,1,1,75,75)
```

⇓

```
uint g2 = get_global_id(0);
uint g1 = get_global_id(1);
uint g0 = get_global_id(2);
```

Next Focus Points

- Memory Throughput
- “Chicken or the egg” Issues
- Kernel-based Parameters
- Reshape and Transform



6. Conclusion

- Vector Reduction
- Access Pattern
- Performance Gap
- Reflection

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