Visualization of Data Movements and Accesses

Til Mohr

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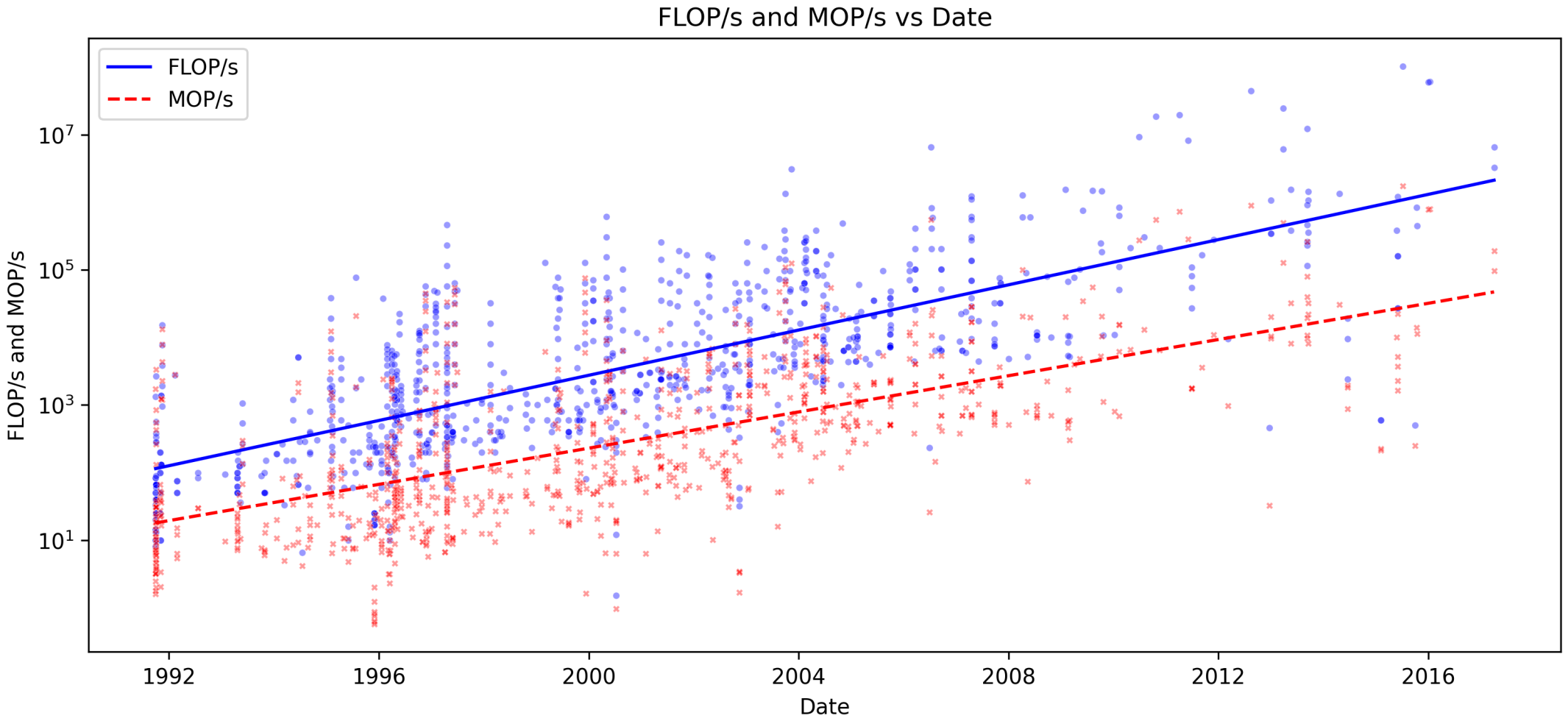
Memory-Related Performance Problems I Processor-Memory Performance Gap



Data: *https://www.cs.virginia.edu/stream/*

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Memory-Related Performance Problems I Data Locality

$$t_{avg} = p \cdot t_c + (1 - p) \cdot t_m \tag{1}$$

t_{avg} : average access time
p : cache hit percentage
t_c : cache access time
t_m : memory access time

$$t_c \ll t_m \tag{2}$$

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
2 let mut sum = 0;
3 for column in 0..2 {
4   for row in 0..2 {
5     sum += matrix.get(row, column);
6   }
7 }
8 sum
```

Matrix:

	0	1
0	1	2
1	3	4

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Memory-Related Performance Problems I Data Locality

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```
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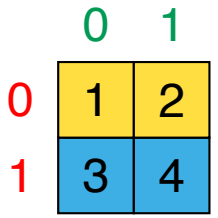
Matrix:



Matrix in Memory:

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

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1 let matrix = Matrix::random(2, 2);
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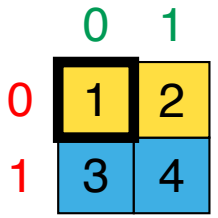
Matrix:



Matrix in Memory:

Current Item:

Cache:

Number of cache misses: **0**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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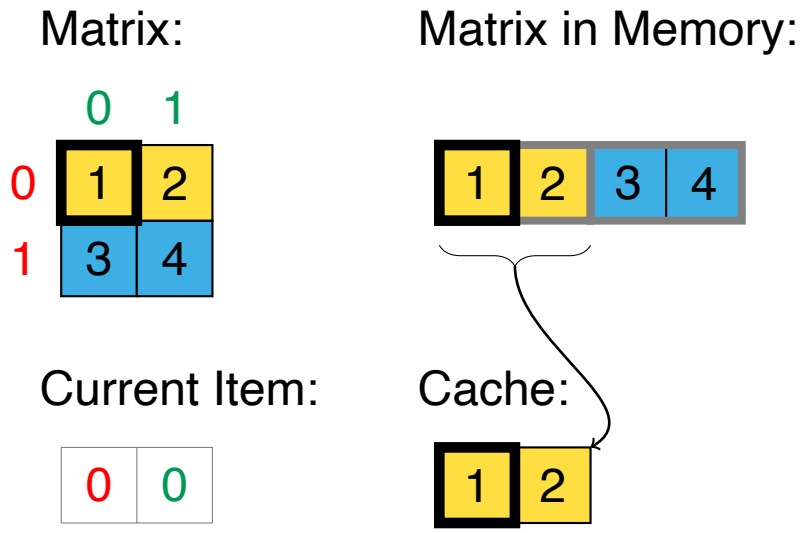

Number of cache misses: **1**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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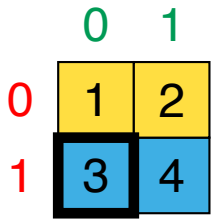
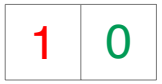
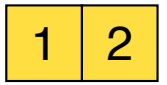


Matrix in Memory:

Current Item:



Cache:



Number of cache misses: **1**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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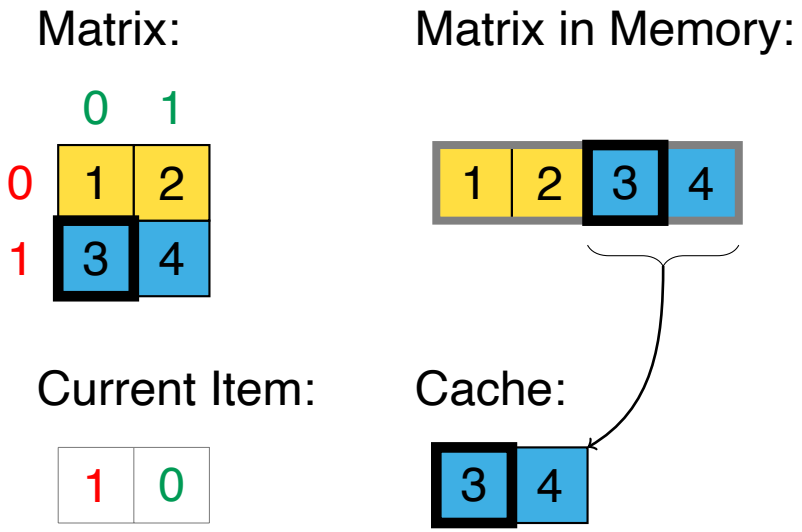

Number of cache misses: **2**

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Memory-Related Performance Problems I Data Locality

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```
1 let matrix = Matrix::random(2, 2);
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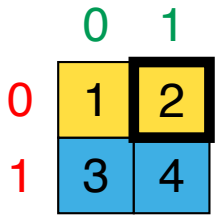
```

Matrix:



Matrix in Memory:

Current Item:

Cache:

Number of cache misses: **2**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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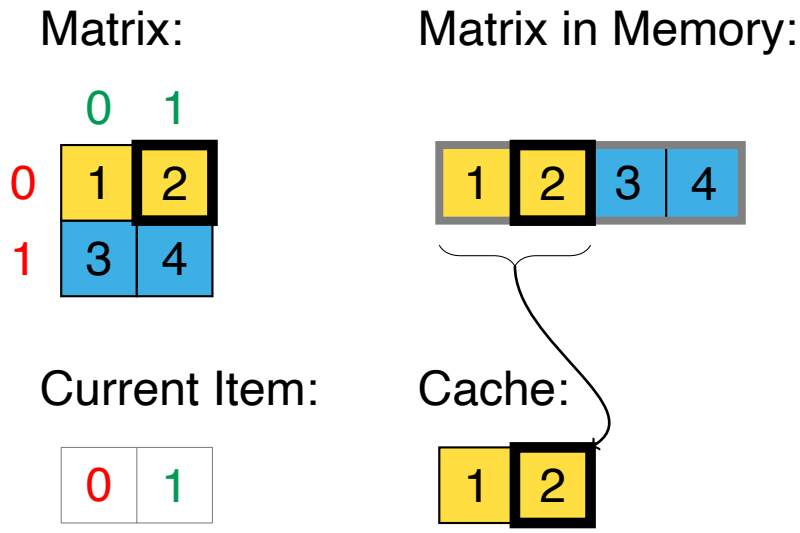

Number of cache misses: **3**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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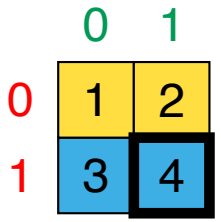
```

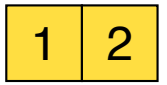
Matrix:



Matrix in Memory:

Current Item:

Cache:



Number of cache misses: **3**

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Memory-Related Performance Problems I Data Locality

Listing 1: Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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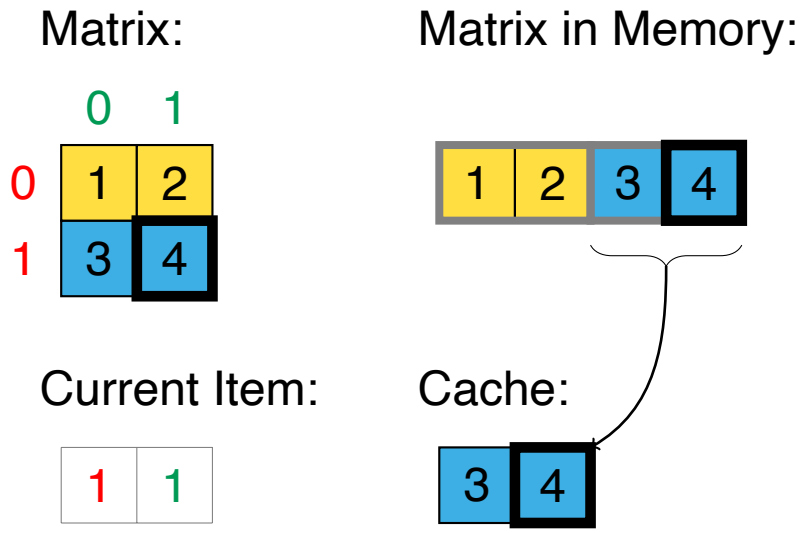

Number of cache misses: **4**

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Memory-Related Performance Problems I Data Locality

Listing 2: Reordered Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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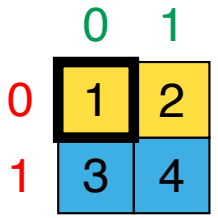
3 for row in 0..2 {
4   for column in 0..2 {
5     sum += matrix.get(row, column);
6   }
7 }
8 sum
```

Matrix:



Matrix in Memory:

Current Item:

Cache:

Number of cache misses: **0**

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Memory-Related Performance Problems I Data Locality

Listing 2: Reordered Matrix Summation

```
1 let matrix = Matrix::random(2, 2);
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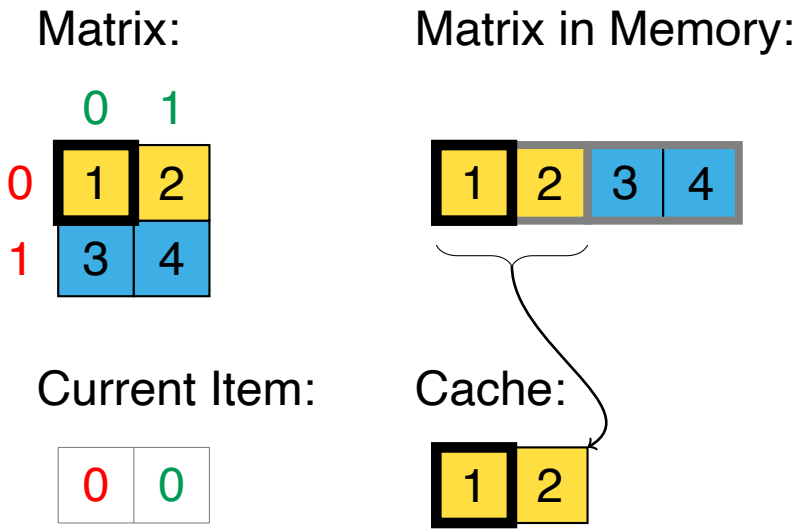

Number of cache misses: **1**

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Memory-Related Performance Problems I Data Locality

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```
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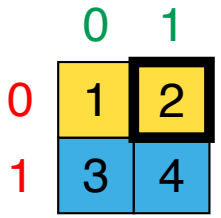
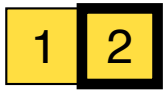


Matrix in Memory:

Current Item:

Cache:



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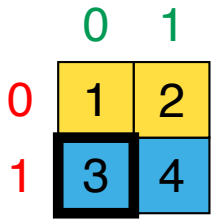

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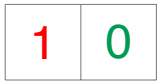
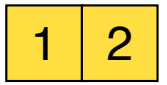


Cache:



Number of cache misses: **1**

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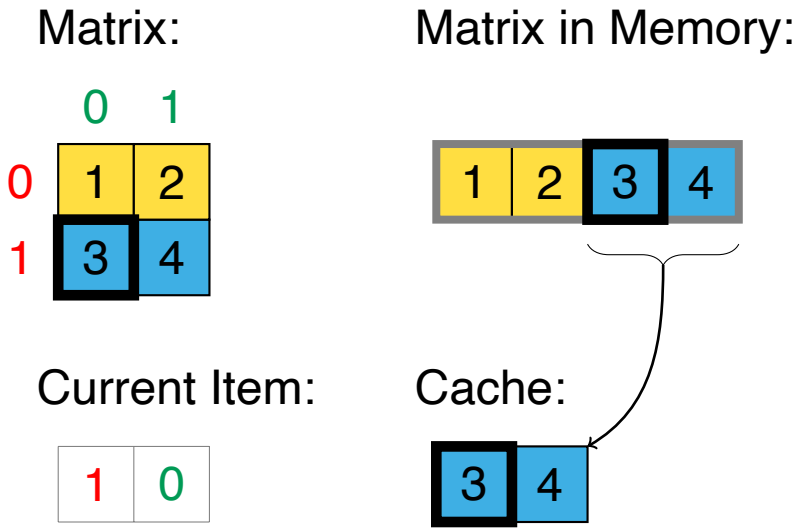

Number of cache misses: **2**

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Memory-Related Performance Problems I Data Locality

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```
1 let matrix = Matrix::random(2, 2);
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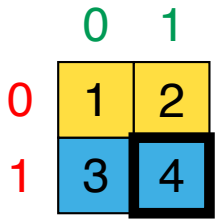
Matrix:



Matrix in Memory:

Current Item:

Cache:

Number of cache misses: **2**

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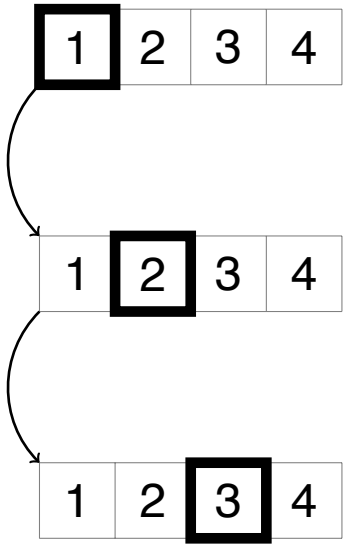
Memory-Related Performance Problems I Data Locality

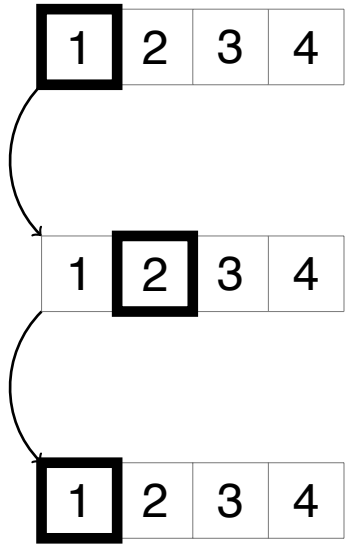
Spacial Locality

- Data that is referenced spatially close together is likely to be accessed in the near future



Temporal Locality

- Data that is referenced in the near past is likely to be accessed in the near future



How to optimize a program for data locality?

How to optimize a program for data locality?

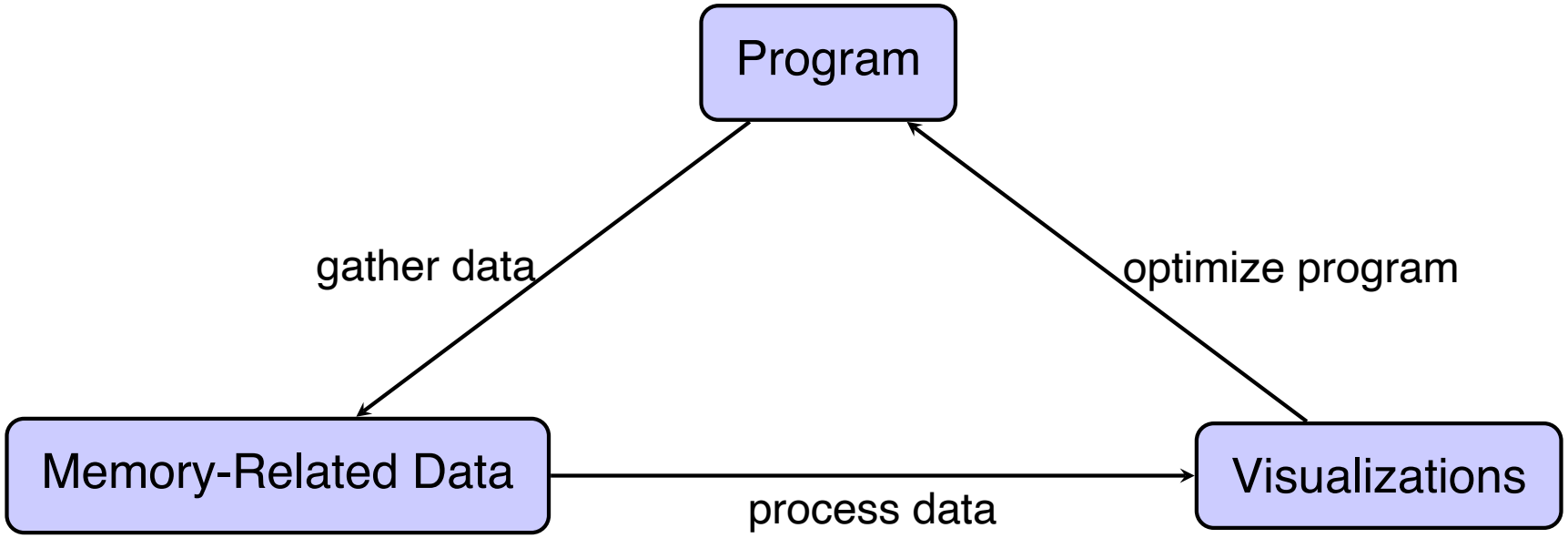
$\rightarrow$ **Visualization-guided optimization**

Outline

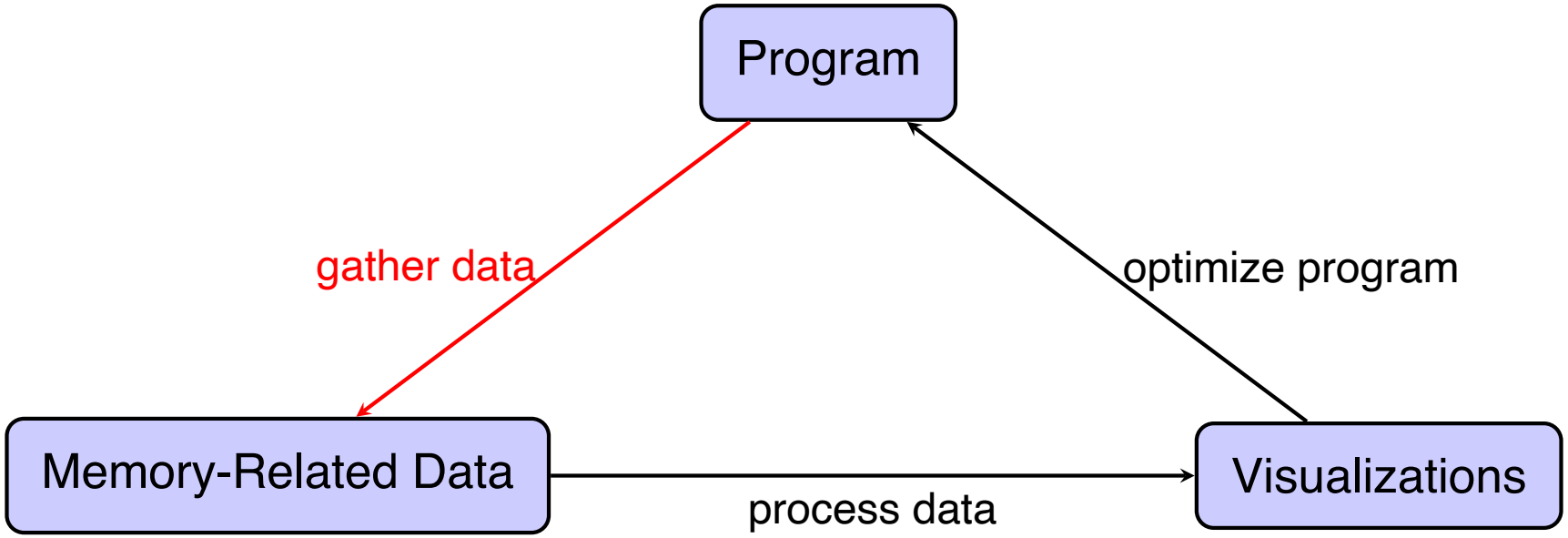
- Overview of the Optimization Workflow
- Data Gathering Approaches
- Visualization Techniques
- Specific Optimization Tool
- Conclusion

Overview of the Optimization Workflow

Visualization-Guided Optimization



Visualization-Guided Optimization



Data Gathering Approaches

Goal: Acquire Memory-Related Data for Visualization

- Data Accesses
  - Memory locations / variables
  - Frequencies
- Data access patterns
  - Nested loops
- Cache performance
  - Hit/miss rates
  - Utilization
  - Amount of data transfer in between different cache levels and main memory

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Run Program and Capture Memory-Related Information

- Hardware counters
  - Counts cache hits/misses
- Tracing / profiling
- Store source code references alongside memory-related information

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Run Program and Capture Memory-Related Information

- Hardware counters
  - Counts cache hits/misses
- Tracing / profiling
- Store source code references alongside memory-related information

☺ Very accurate
  - Real program data
  - Actual physical hardware

☹ Can be very slow

☹ Possible large overhead for very granular data

☹ Cannot easily analyze just parts of the program

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[1] (Alexandru Calotoiu et al.)

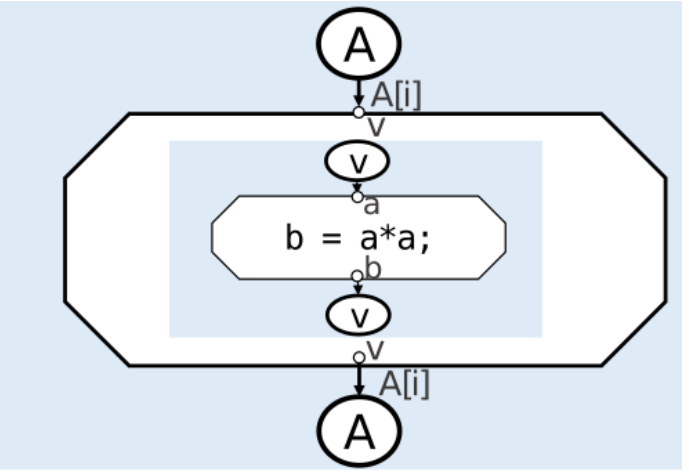
Analyze the Programs Source Code for Data Accesses

- Extract any data access information purely from the source code
- Compile the program into a Data-Flow Oriented IR
- Statistics gathered by analyzing the IR
  - Algorithmic intensity
  - Volume of data circulating in the program

```
void square(double &v) {
      v = v * v;
}

// ...

square(A[i]);
```



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Data Gathering Approaches I Static Analyis

Analyze the Programs Source Code for Data Accesses

- Extract any data access information purely from the source code
- Compile the program into a Data-Flow Oriented IR
- Statistics gathered by analyzing the IR
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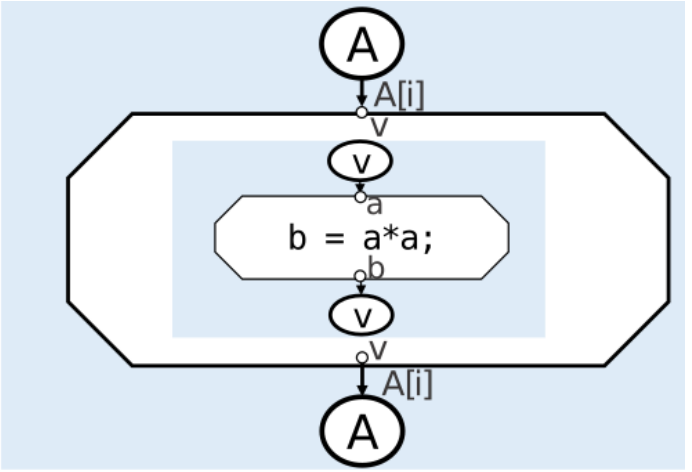

☺ Very fast

☺ Provides holistic view of the program and its performance

☹ Very abstract analysis
  - Memory layout of data is not considered
  - Hardware architecture unknown
  - No information about real-world cache performance

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Imitate the Programs Memory Accesses on a Simulated Cache Hierarchy

- Replicate actual hardware through software
  - Cache hierarchy (size, associativity, etc.)
  - Cache replacement policies
  - Cache coherence protocols
- Simulate the programs memory-wise on the simulated hardware
  - Memory (de-)allocations
  - Data accesses

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Imitate the Programs Memory Accesses on a Simulated Cache Hierarchy

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  - Cache coherence protocols
- Simulate the programs memory-wise on the simulated hardware
  - Memory (de-)allocations
  - Data accesses

☺ Very detailed
  - Insights about the memory-layout of data
  - Enables step-by-step analysis of the caches

☺ Allows to analyze only parts of the program

☹ Requires precise parameterization

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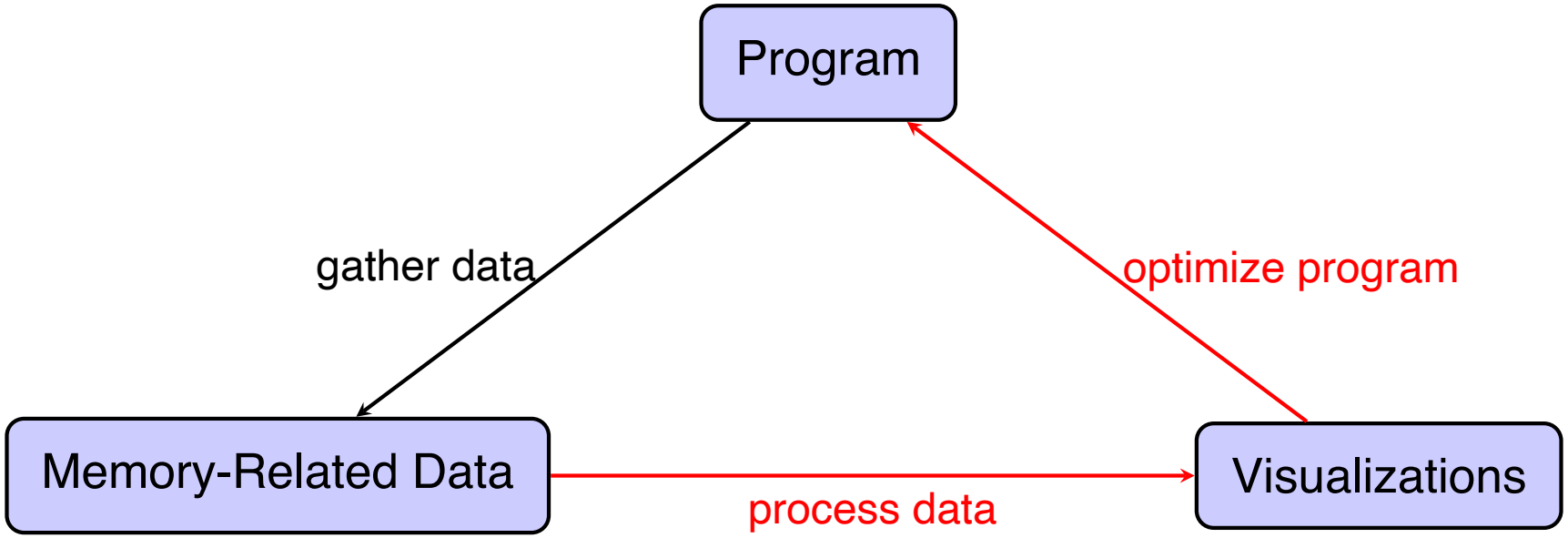
Visualization-Guided Optimization

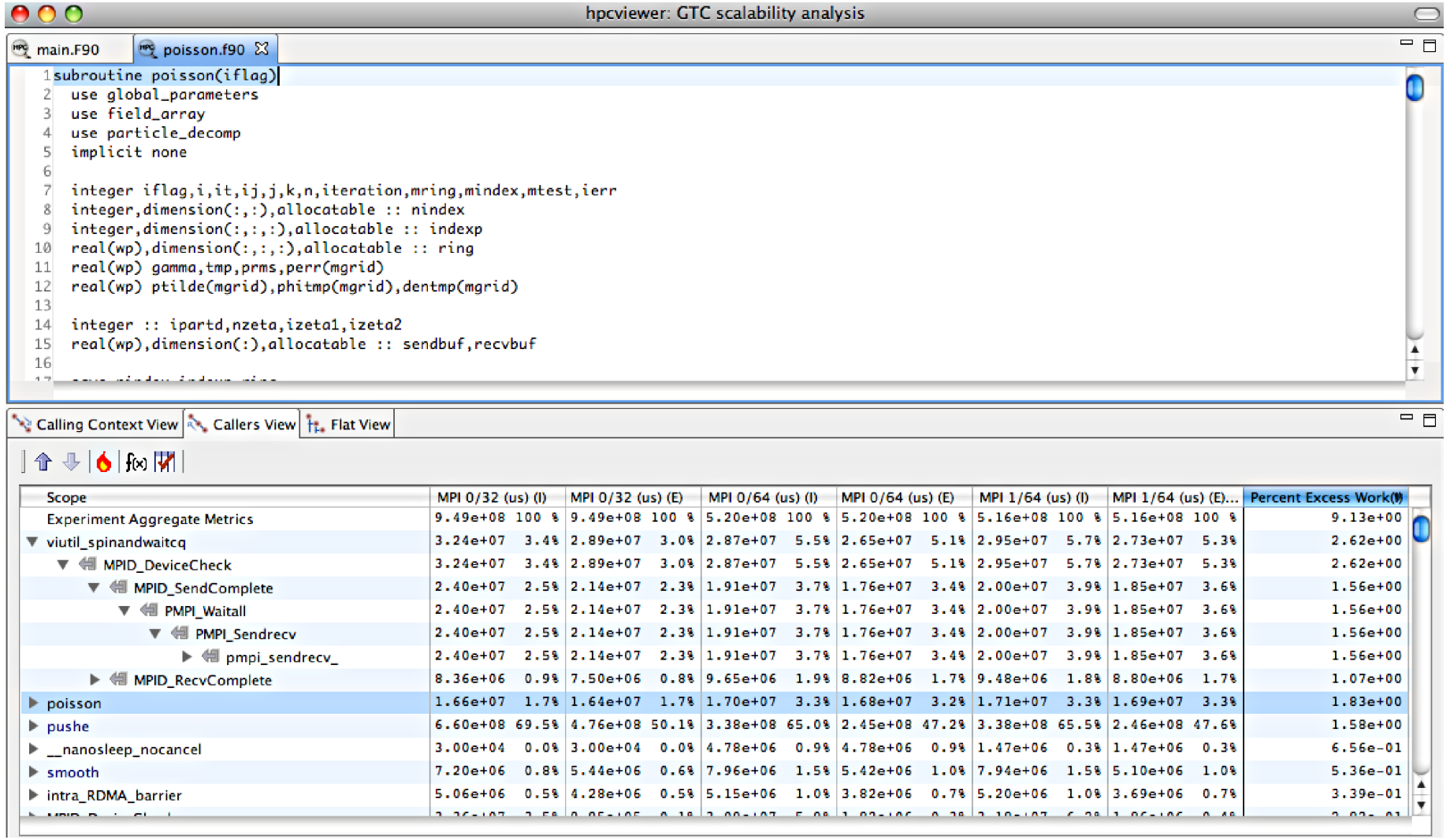


Goal: Display & Explain Bottlenecks

- Balance between intuitiveness and informational value
- Three broad categories:
  - High-level visualizations
  - Intermediate-level visualizations
  - Low-level visualizations

[2] (Laksono Adhianto et al.)

Visualization Techniques I High-Level



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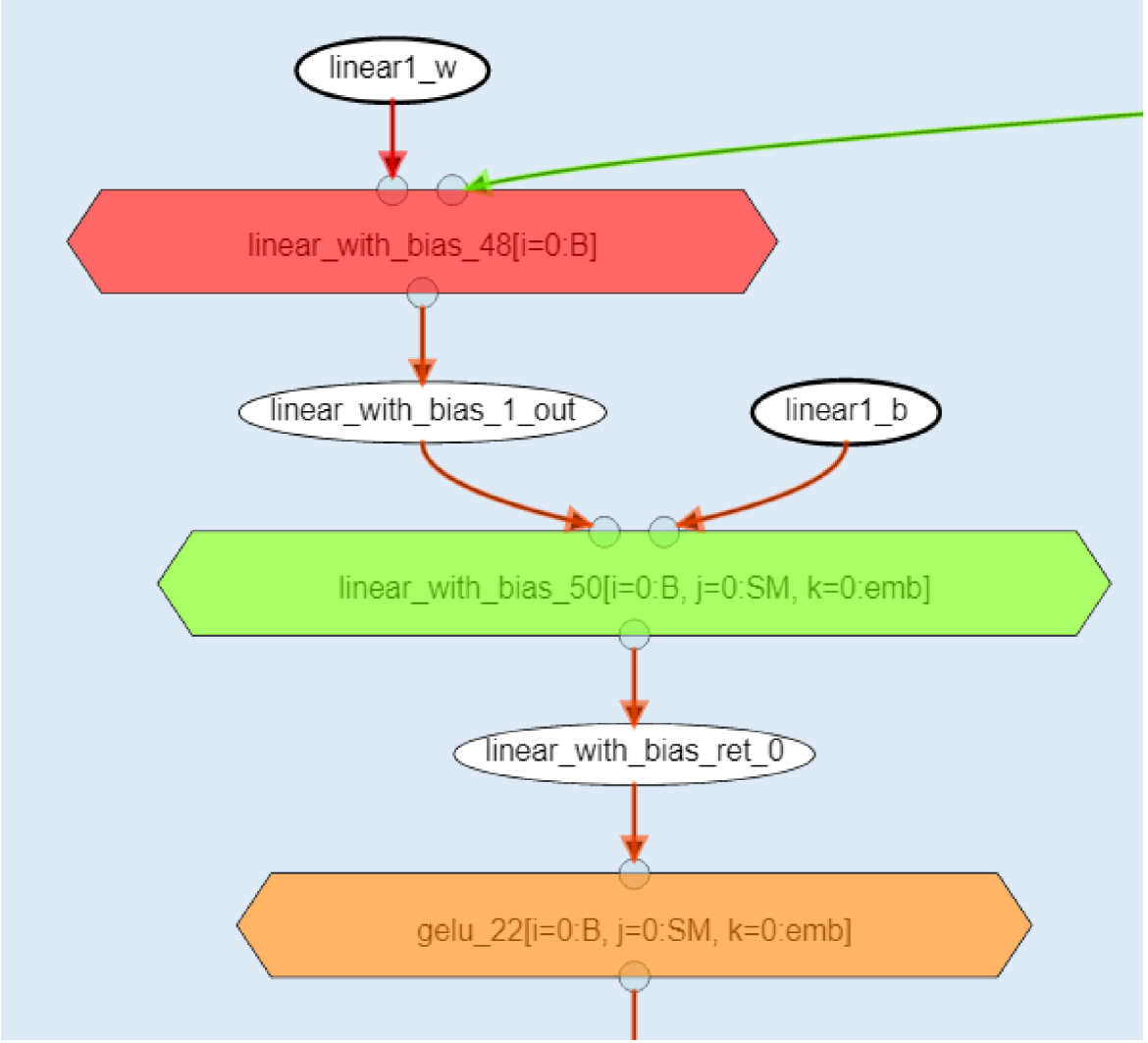
[3] (Philipp Schaad)

Visualization Techniques I High-Level



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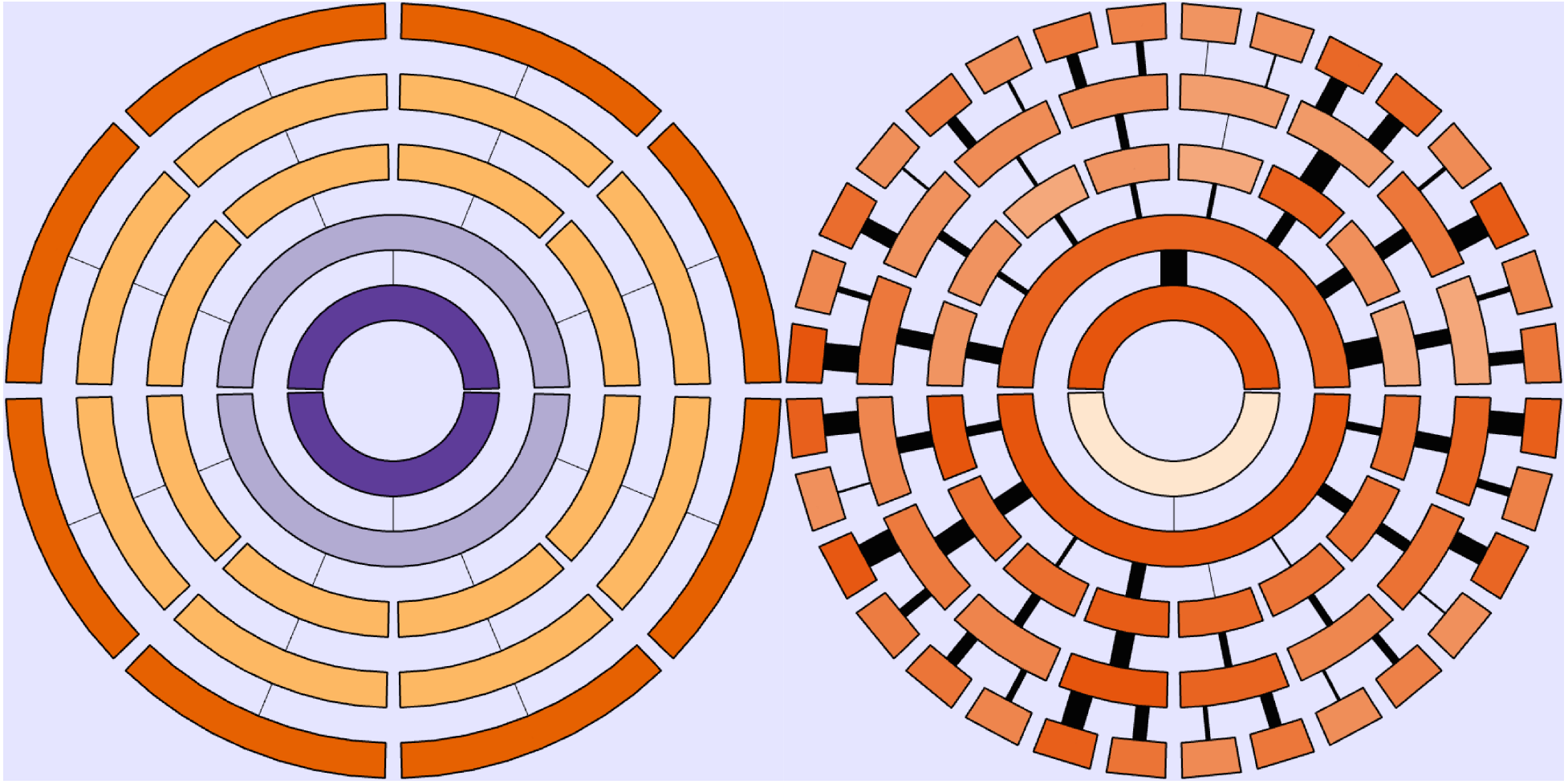
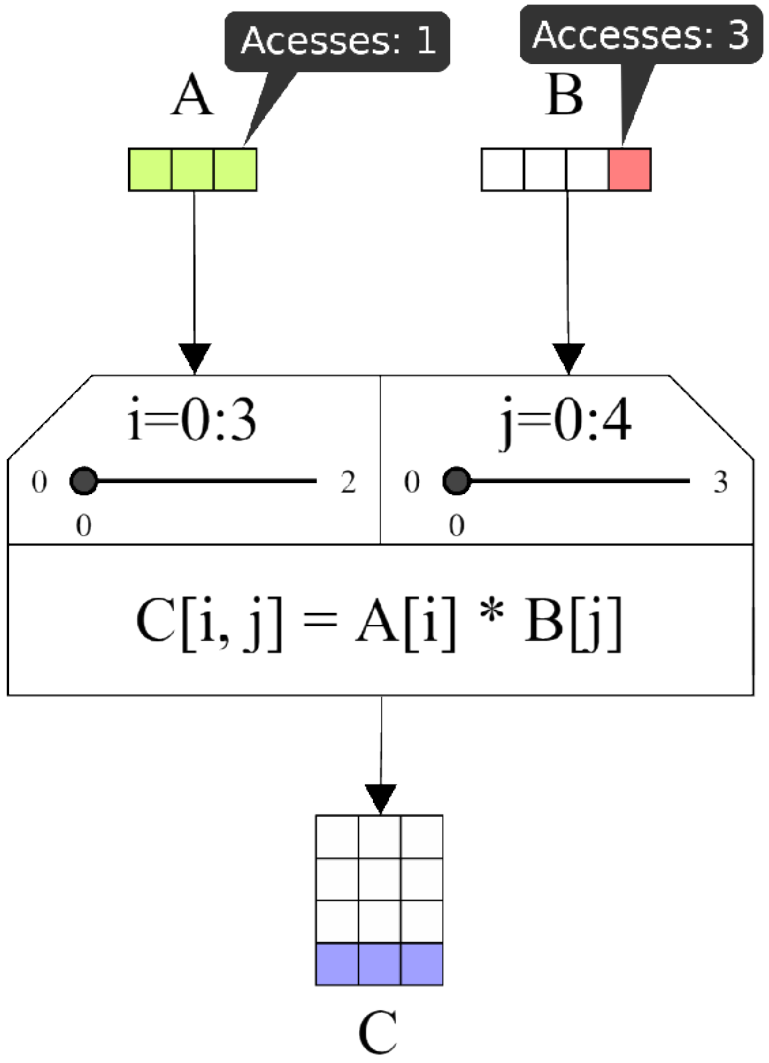
[4] (Alfredo Giménez et al.)

Visualization Techniques I Intermediate-Level



[3] (Philipp Schaad et al.)

Visualization Techniques I Low-Level



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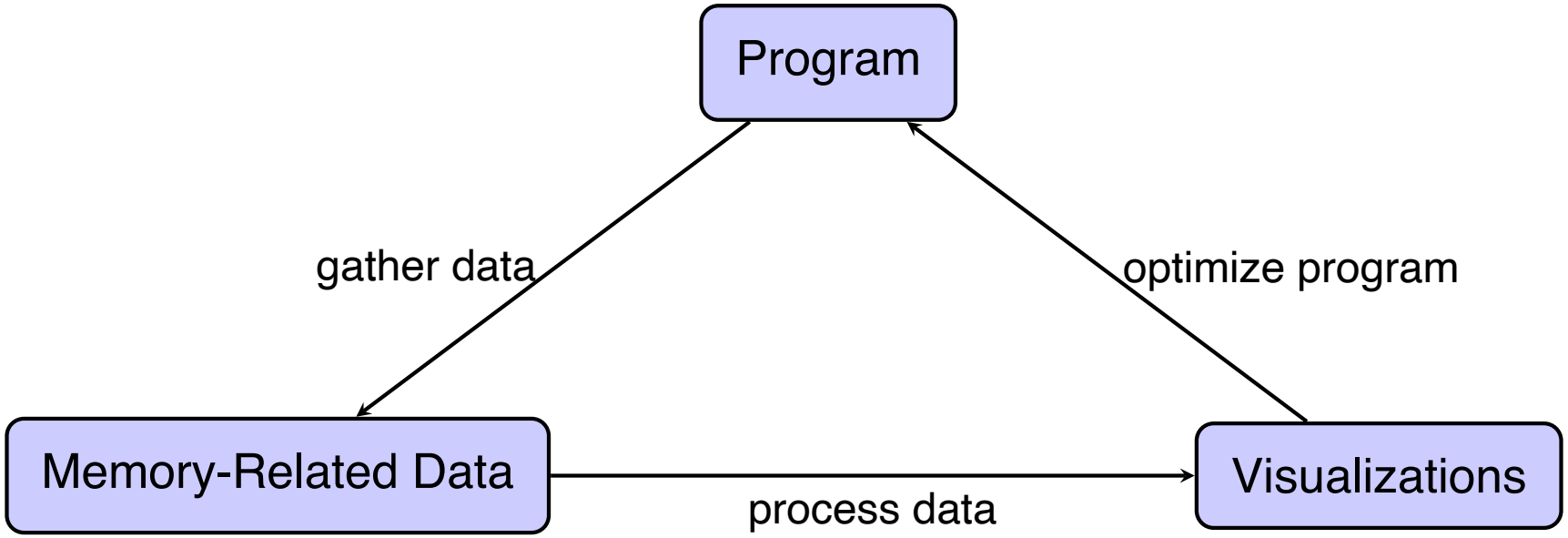
Overview of the Optimization Workflow

Visualization-Guided Optimization



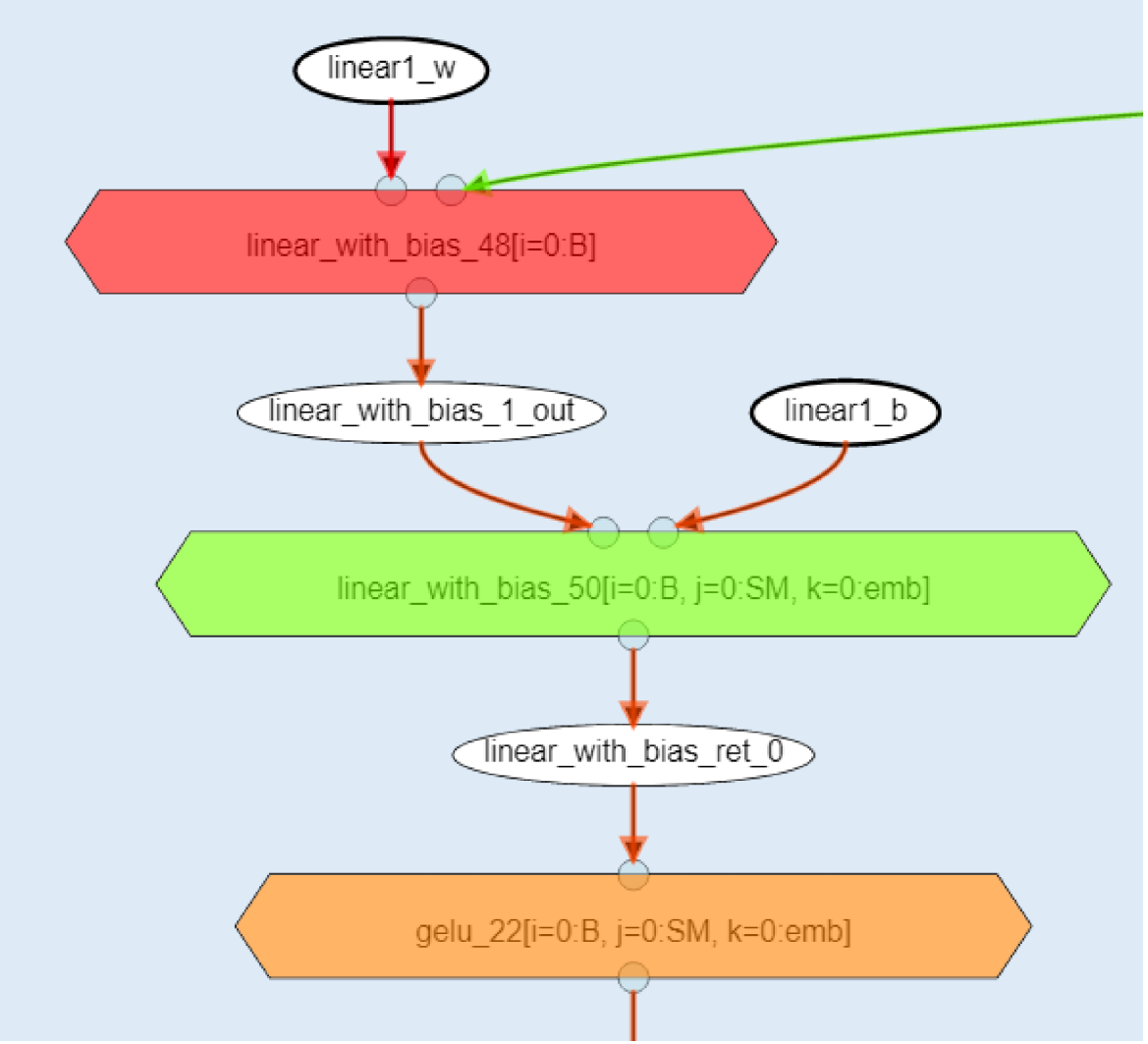
Boosting Performance Optimization with Interactive Data Movement Visualization

Two-Tier Program Analysis

Global Level

- Static analysis of the program
- High-level visualizations

→ Identify regions of interest



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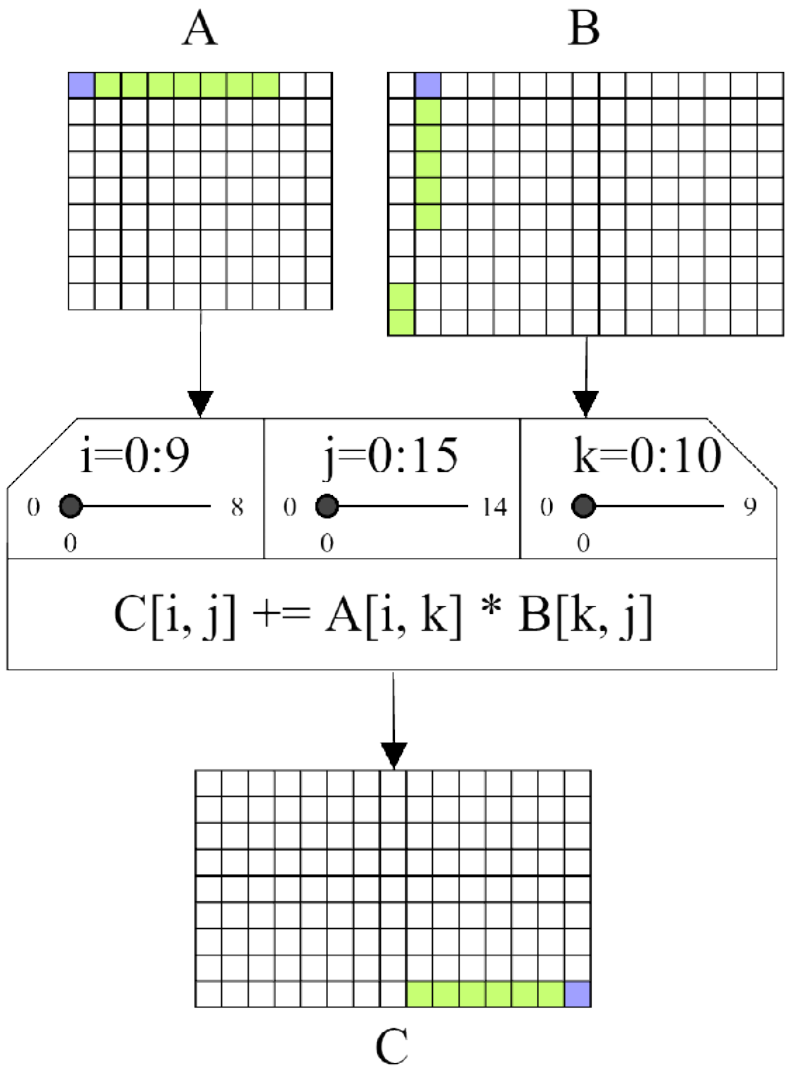
Boosting Performance Optimization with Interactive Data Movement Visualization

Two-Tier Program Analysis

Local Level

- Cache simulation
- Low-level visualizations

→ Understand the data movements and access patterns



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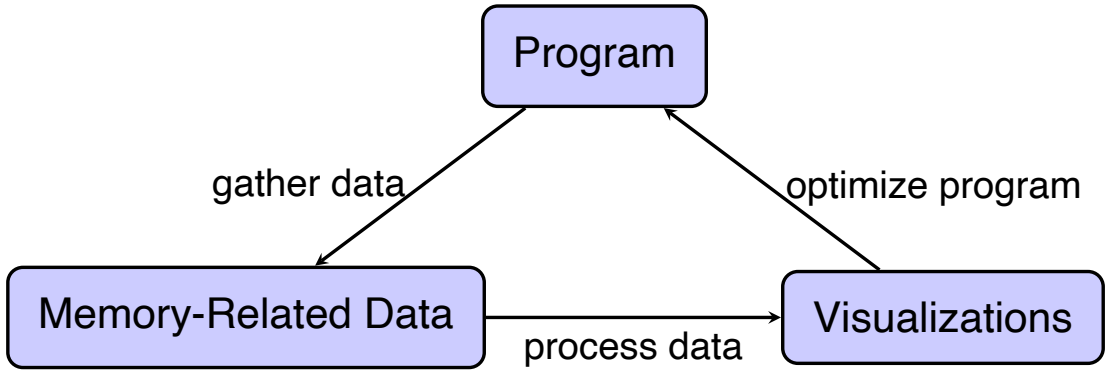
Conclusion

- Importance of data locality due to processor-memory gap
- Data Gathering Methods:
  - Dynamic Analysis
  - Static Analysis
  - Cache Simulation
- Visualization: High-level to fine-grained insights
- Future goals: Automatic optimization in compilers



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[2] Laksono Adhianto et al. “HPCToolkit: Tools for performance analysis of optimized parallel programs”. In: *Concurrency and Computation: Practice and Experience* 22.6 (2010), pp. 685-701.

[3] Philipp Schaad. “Boosting Performance Engi- neering with Visual Interactive Optimization and Analysis”. MA thesis. ETH Zurich, 2021.

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[5] Philipp Schaad, Tal Ben-Nun, and Torsten Hoefler. “Boosting performance optimization with interactive data movement visualization”. In: *SC22: International Conference for High Performance Computing, Networking, Storage and Analysis* (2022), pp. 1-16.