Cache Aware Optimization of Stream Programs

Janis Sermulins, William Thies, Rodric Rabbah and Saman Amarasinghe

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Streaming Computing Is Everywhere!

- Prevalent computing domain with applications in embedded systems
  - As well as desktops and high-end servers



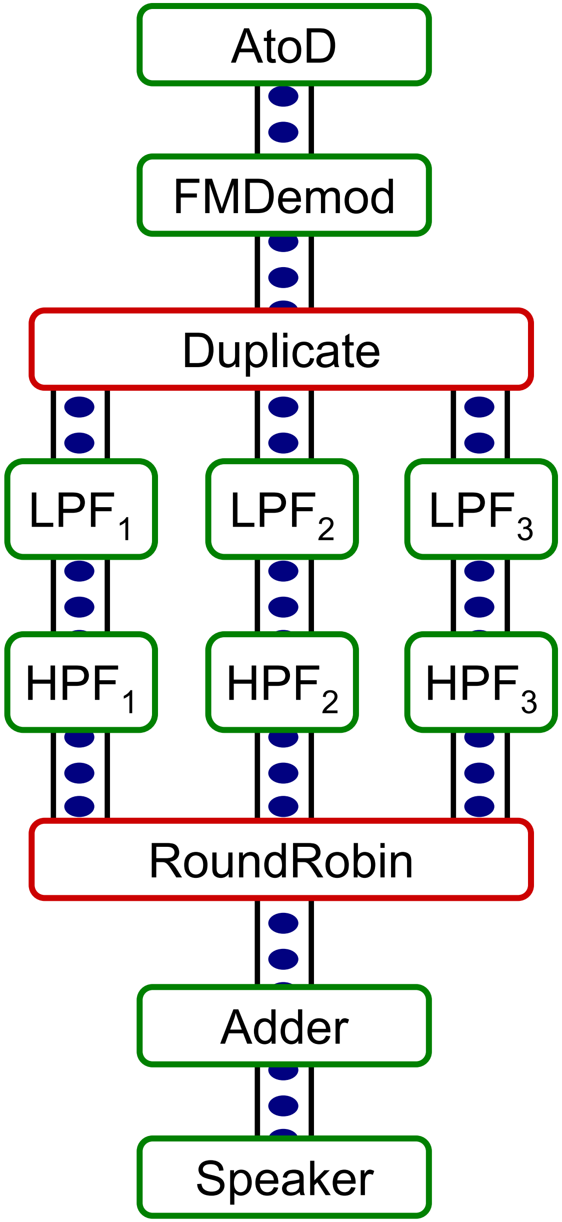







Properties of Stream Programs

- Regular and repeating computation
- Independent actors with explicit communication
- Data items have short lifetimes



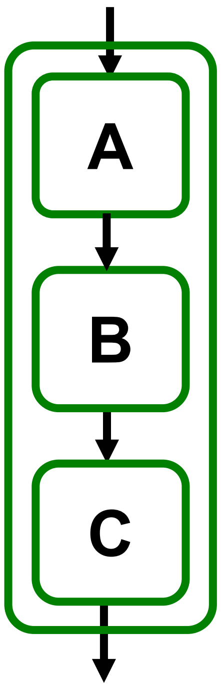
Application Characteristics: Implications on Caching

	Scientific	**Streaming**
Control	Inner loops	Single outer loop
Data	Persistent array processing	Limited lifetime producer-consumer
Working set	Small	Whole-program
Implications	Natural fit for cache hierarchy	Demands novel mapping

Application Characteristics: Implications on Compiler

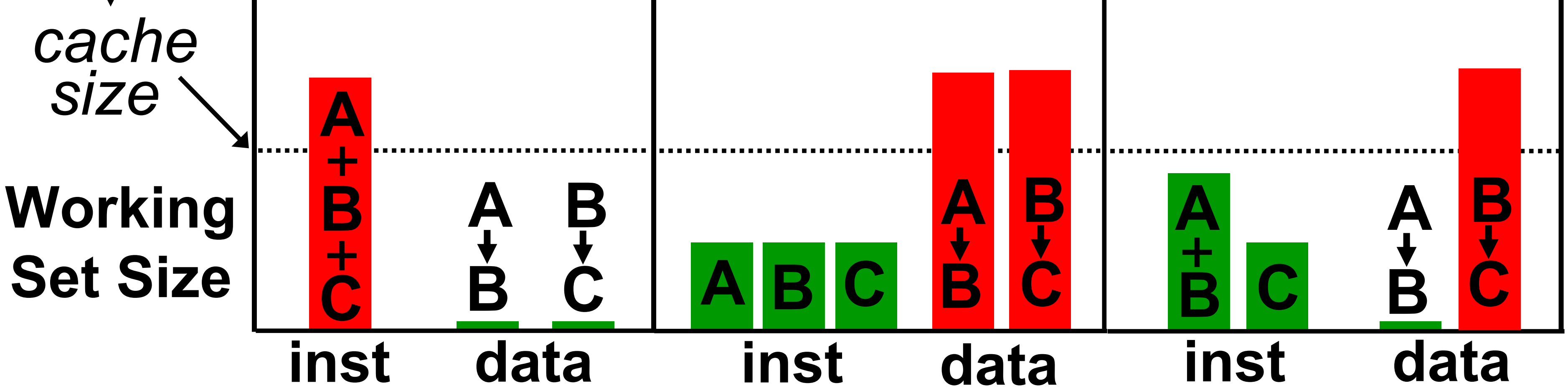
	Scientific	**Streaming**
Parallelism	Fine-grained	Coarse-grained
Data access	Global	Local
Communication	Implicit random access	Explicit producer-consumer
Implications	Limited program transformations	Potential for global reordering

Motivating Example



Baseline	Full Scaling	

for i = 1 to N
  A();
  B();
  C();
end
	for i = 1 to N
	  A();
	for i = 1 to N
	  B();
	for i = 1 to N
	  C();
		for i = 1 to N
		  A();
		  B();
		end
		for i = 1 to N
		  C();



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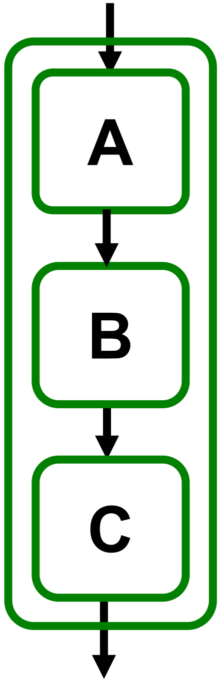
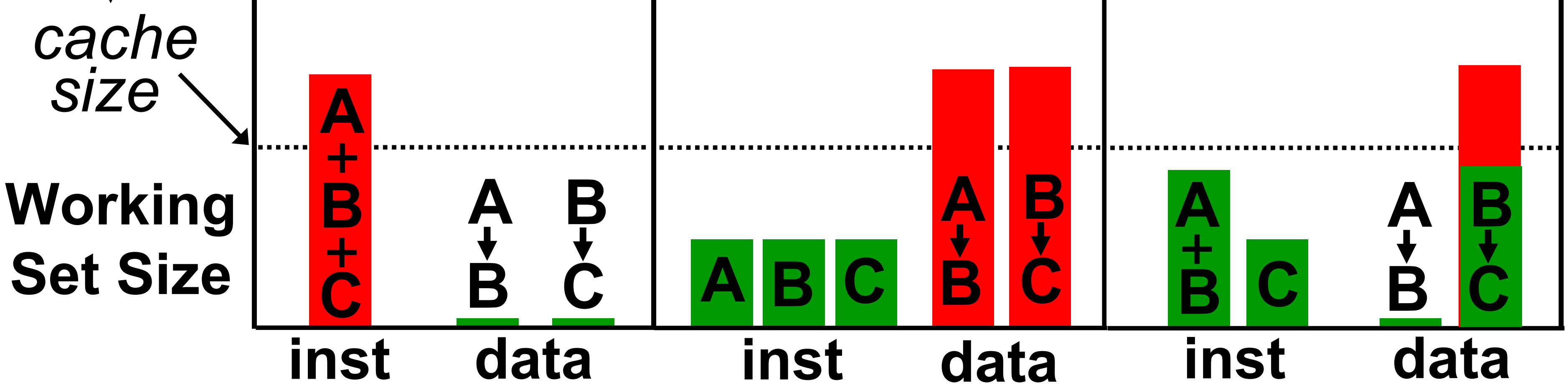


Baseline	Full Scaling	

for i = 1 to N
    A();
    B();
    C();
end
	for i = 1 to N
	    A();
	for i = 1 to N
	    B();
	for i = 1 to N
	    C();
		for i = 1 to 64
		    A();
		    B();
		end
		for i = 1 to 64
		    C();



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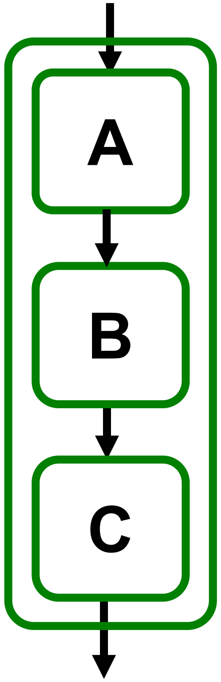

Baseline	Full Scaling	Cache Opt

for i = 1 to N
  A();
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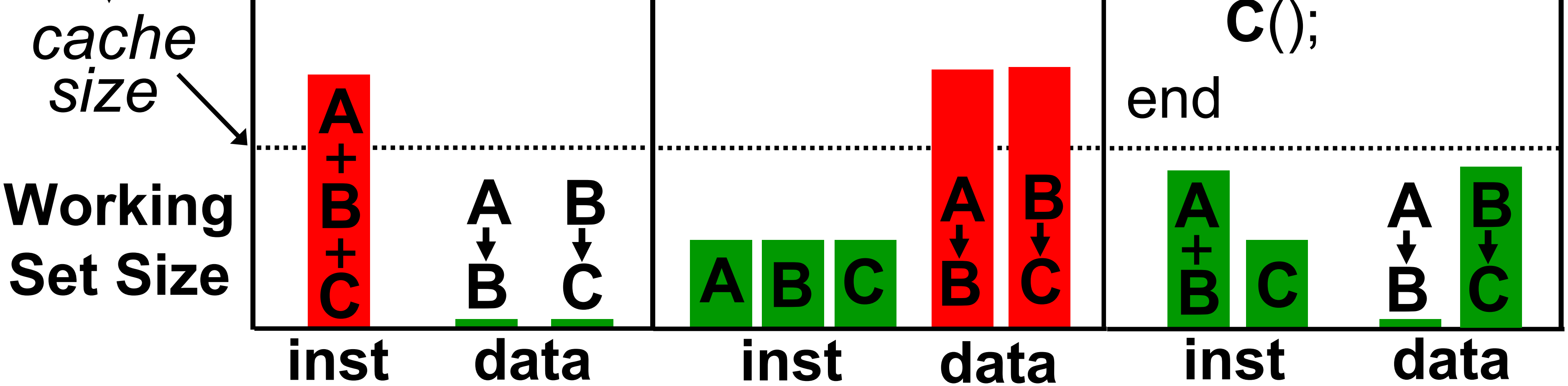
  C();
end
	for i = 1 to N
	  A();
	for i = 1 to N
	  B();
	for i = 1 to N
	  C();
		for i = 1 to N/64
		  for i = 1 to 64
		    A();
		    B();
		  end
		  for i = 1 to 64
		    C();
		end

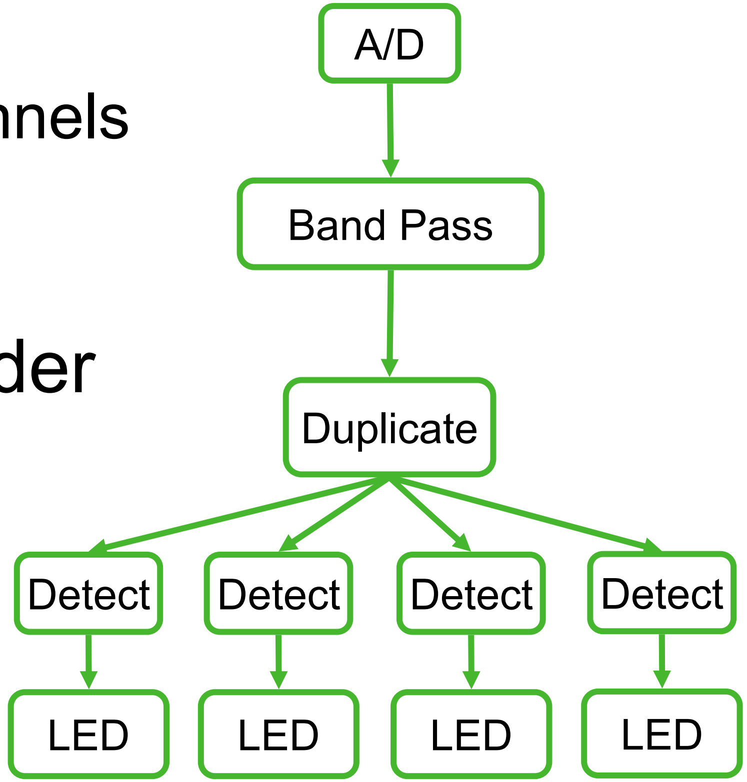


Outline

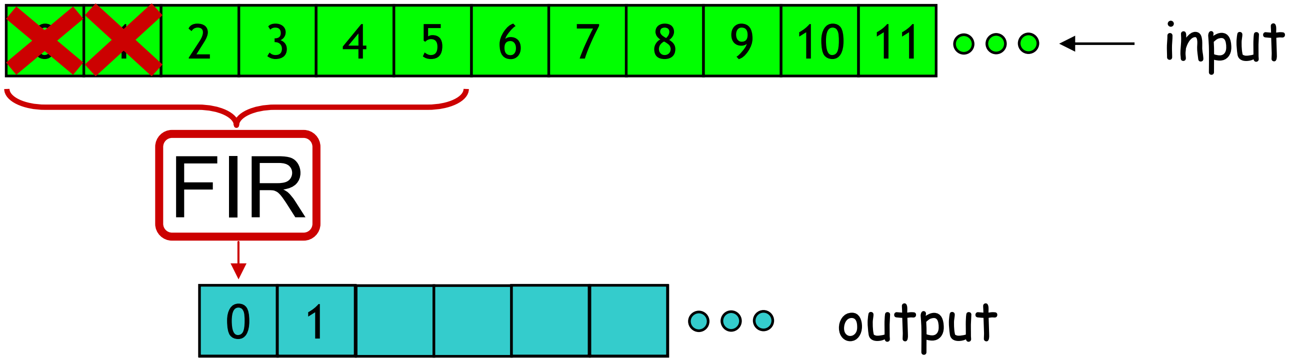
- StreamIt
- Cache Aware Fusion
- Cache Aware Scaling
- Buffer Management
- Related Work and Conclusion

Model of Computation

- Synchronous Dataflow [Lee 92]
  - Graph of autonomous filters
  - Communicate via FIFO channels
  - Static I/O rates
- Compiler decides on an order of execution (schedule)
  - Many legal schedules
  - Schedule affects locality
  - Lots of previous work on minimizing buffer requirements between filters



Example StreamIt Filter

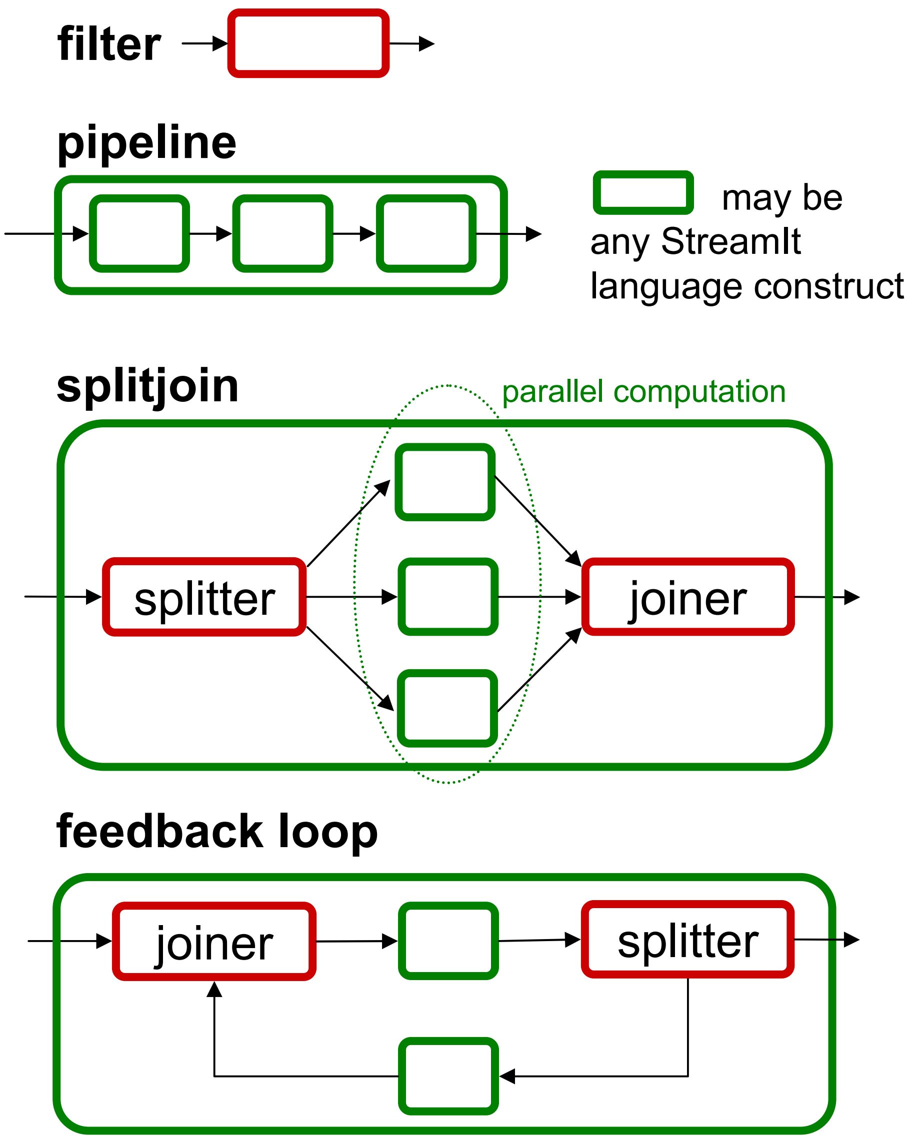



```
float→float filter FIR (int N) {

    work push 1 pop 1 peek N {
        float result = 0;
        for (int i = 0; i < N; i++) {
            result += weights[i] ∗ peek(i);
        }
        push(result);
        pop();
    }
}
```

StreamIt Language Overview

- StreamIt is a novel language for streaming
  - Exposes parallelism and communication
  - Architecture independent
  - Modular and composable
    - Simple structures composed to creates complex graphs
  - Malleable
    - Change program behavior with small modifications

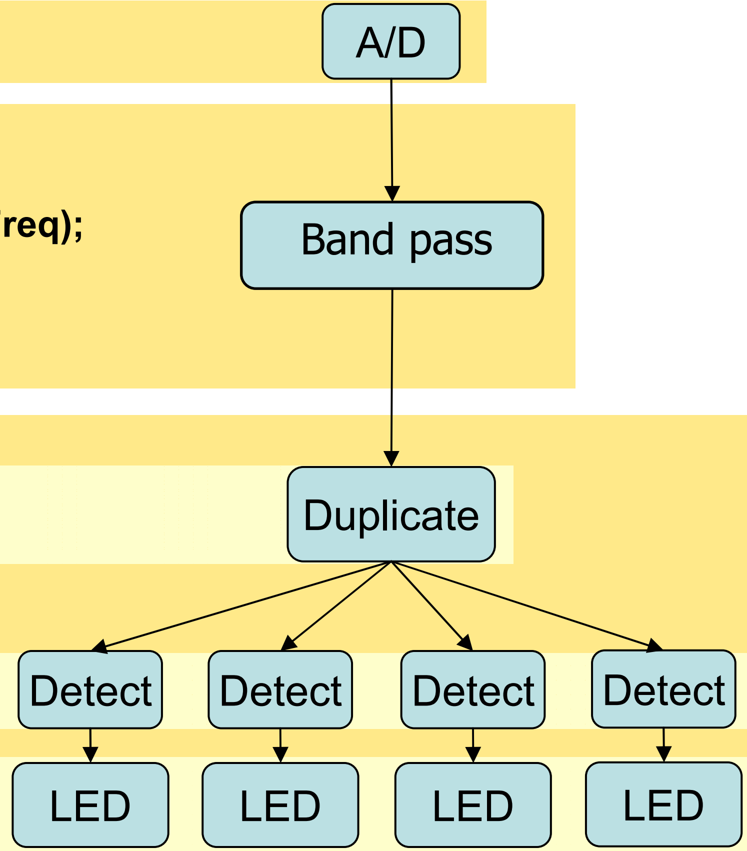


Freq Band Detector in StreamIt

```
void->void pipeline FrequencyBand {
   float sFreq = 4000;
   float cFreq = 500/(sFreq*2*pi);
   float  wFreq = 100/(sFreq*2*pi);
   add D2ASource(sFreq);

   add BandPassFilter(100, cFreq-wFreq, cFreq+wFreq);

   add splitjoin {
      split duplicate;
      for (int i=0; i<4; i++) {
         add pipeline {
            add Detect (i/4);
            add LED (i);
         }
      }
      join roundrobin(0);
   }
}
```



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Fusion

- Fusion combines adjacent filters into a single filter

```
work pop 1 push 2 {
   int a = pop();
   push( a );
   push( a );
}
```

× 1

```
work pop 1 push 1 {
   int b = pop();
   push(b * 2);
}
```

× 2

⇒

```
work pop 1 push 2 {
   int t1, t2;

   int a = pop();
   t1 = a;
   t2 = a;

   int b = t1;
   push(b * 2);

   int c = t2;
   push(c * 2);
}
```

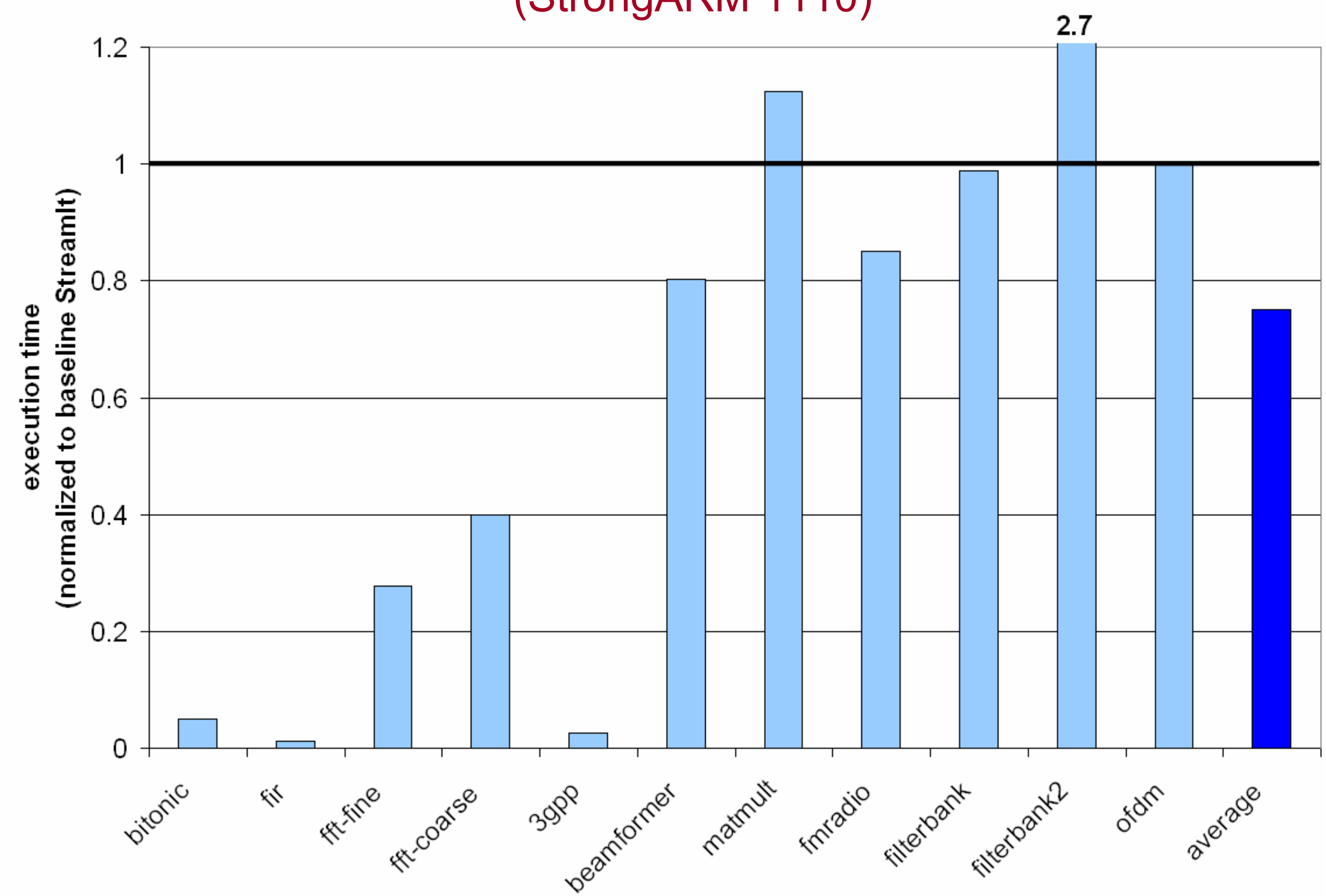
- Reduces method call overhead
- Improves producer-consumer locality
- Allows optimizations across filter boundaries
  - Register allocation of intermediate values
  - More flexible instruction scheduling

Evaluation Methodology

- StreamIt compiler generates C code
  - Baseline StreamIt optimizations
    - Unrolling, constant propagation
  - Compile C code with gcc-v3.4 with -O3 optimizations
- StrongARM 1110 (XScale) embedded processor
  - 370MHz, 16Kb I-Cache, 8Kb D-Cache
  - No L2 Cache (memory 100× slower than cache)
  - Median user time
- Suite of 11 StreamIt Benchmarks
- Evaluate two fusion strategies:
  - Full Fusion
  - Cache Aware Fusion

Results for Full Fusion

(StrongARM 1110)

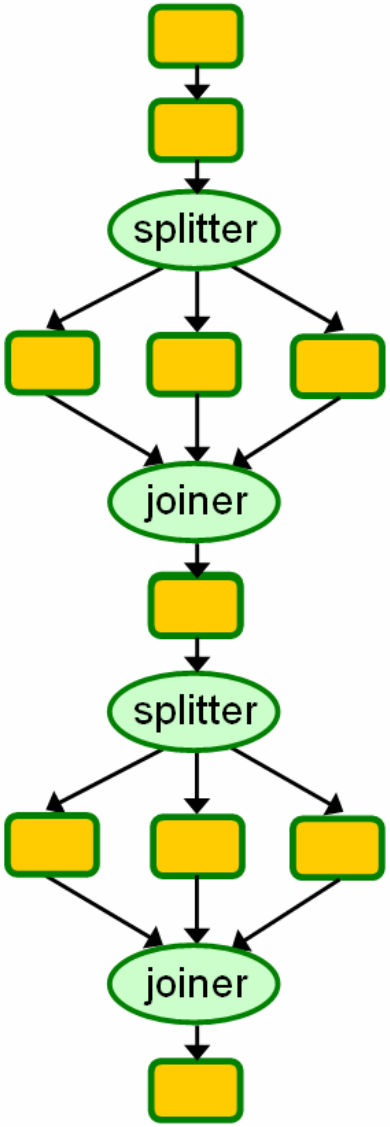


Hazard: The instruction or data working set of the fused program may exceed cache size!

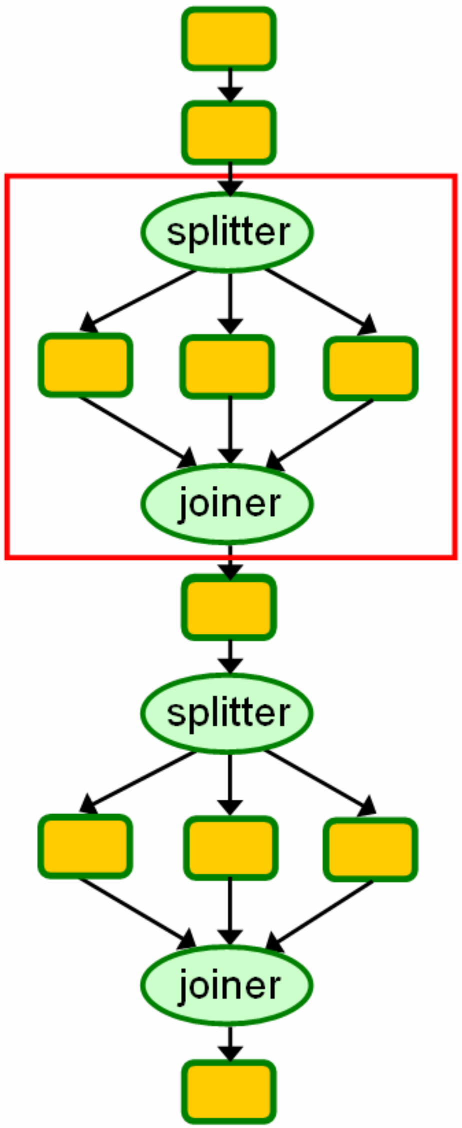
Cache Aware Fusion (CAF)

- Fuse filters so long as:
  - Fused instruction working set fits the I-cache
  - Fused data working set fits the D-cache
- Leave a fraction of D-cache for input and output to facilitate cache aware scaling
- Use a hierarchical fusion heuristic

Hierarchical Fusion Heuristic

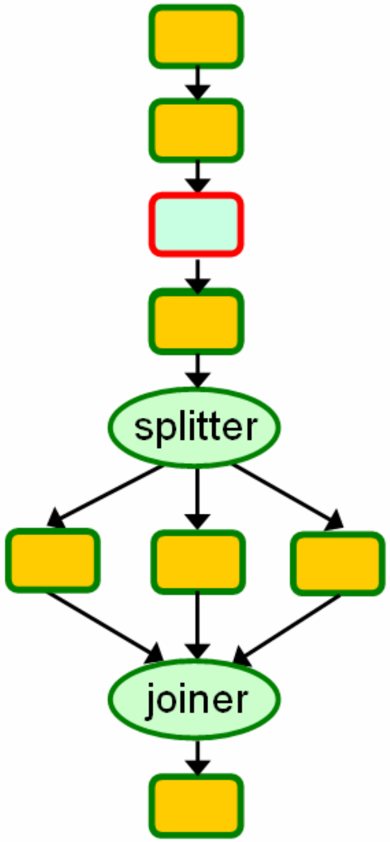


Hierarchical Fusion Heuristic



Does splitjoin fit in cache? Yes!

Hierarchical Fusion Heuristic



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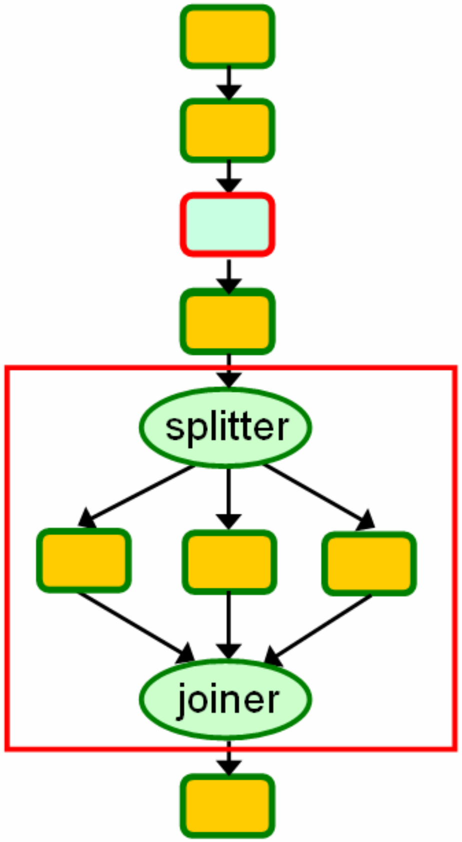

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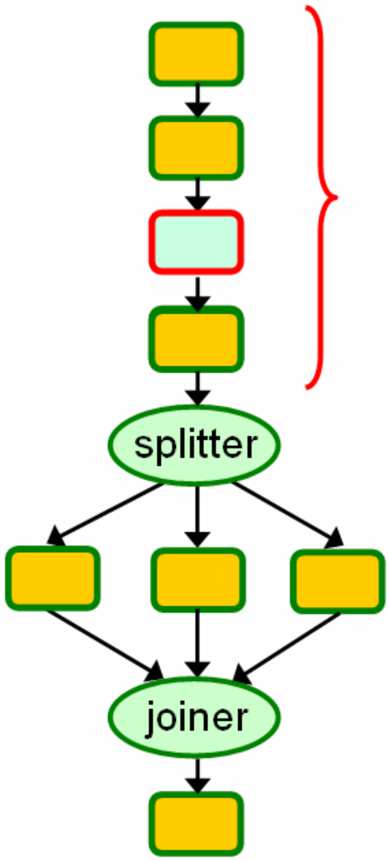
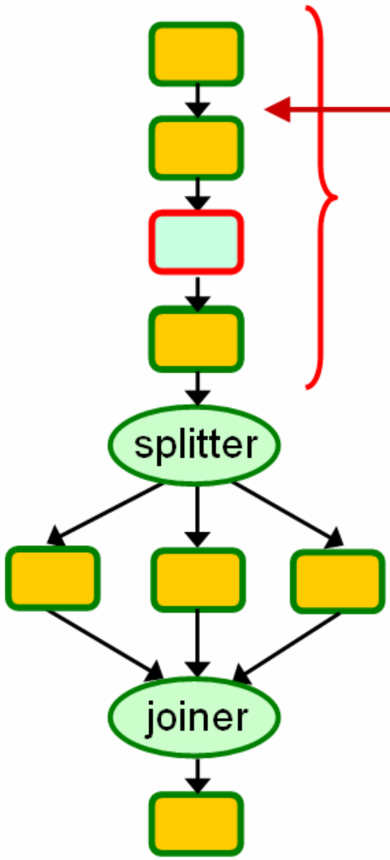


Does pipeline segment fit in cache? No!

Hierarchical Fusion Heuristic

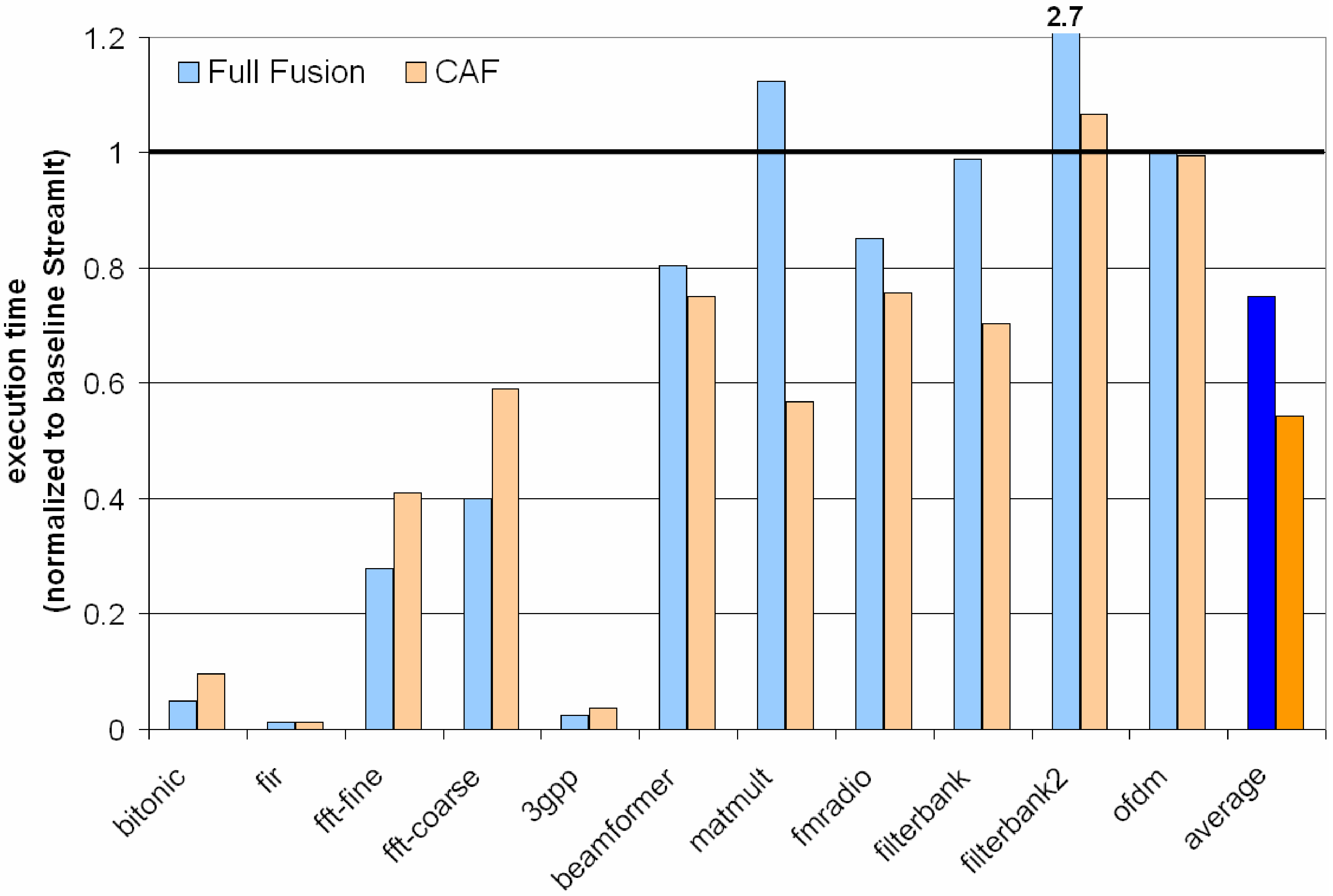


Identify highest bandwidth connection, fuse greedily

Does pipeline segment fit in cache? No!

Hierarchical Fusion Heuristic

Full Fusion vs. CAF



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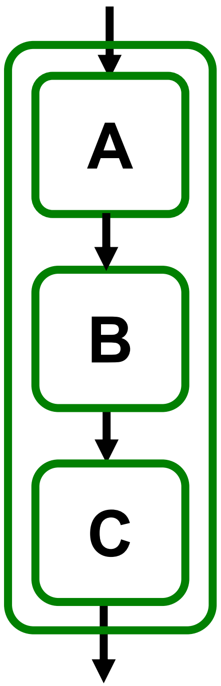
Improving Instruction Locality

✗ cache miss ✓ cache hit



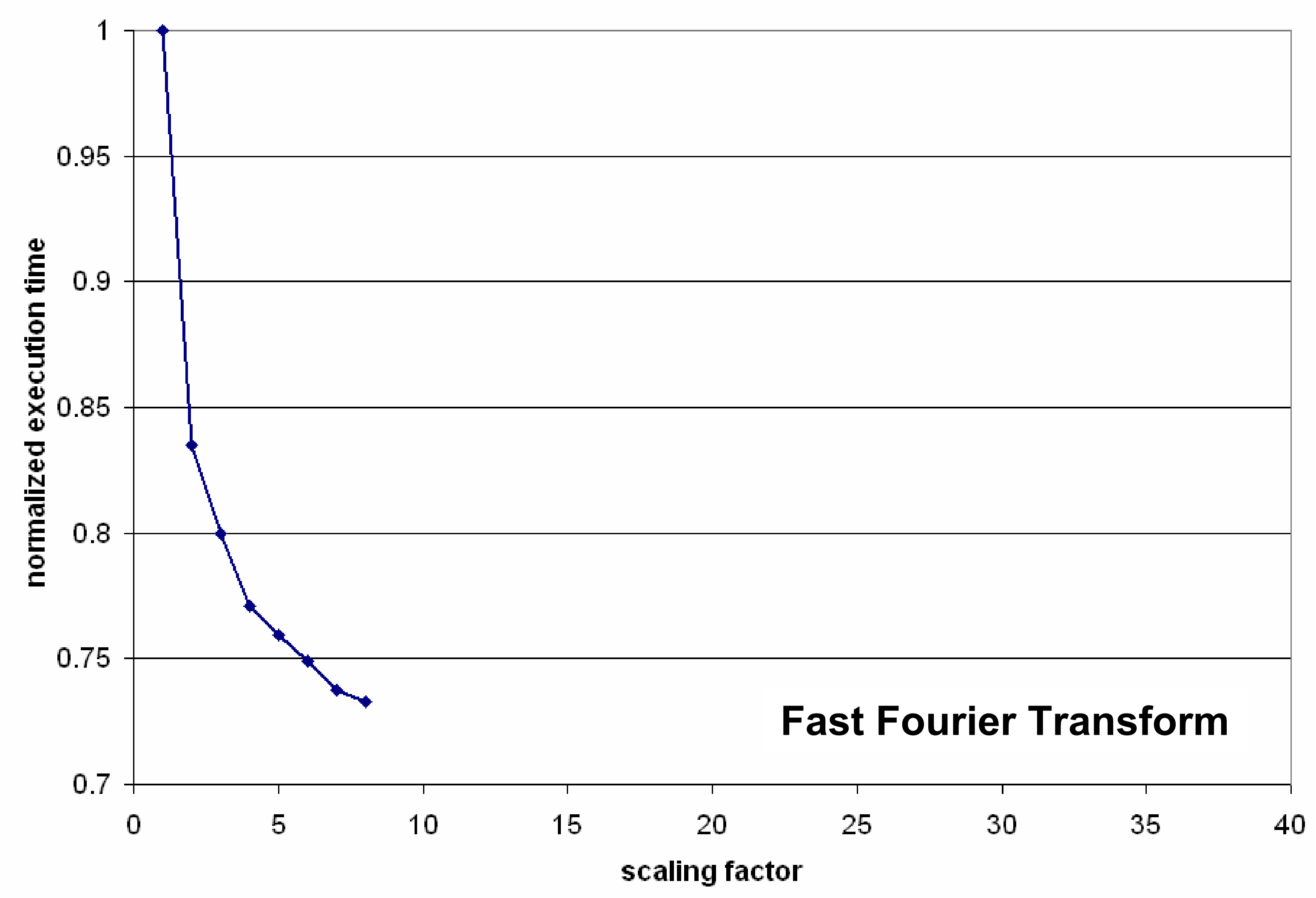
Baseline	Full Scaling
for i = 1 to N	for i = 1 to N
A(); ✗ ✗ ✗ ...	**A**(); ✗ ✓ ✓ ✓ ...
B(); ✗ ✗ ✗ ...	for i = 1 to N
C(); ✗ ✗ ✗ ...	**B**(); ✗ ✓ ✓ ✓ ...
end	for i = 1 to N
	C(); ✗ ✓ ✓ ✓ ...
miss rate = 1	**miss rate = 1 / N**

cache size

Working Set Size

Baseline	Full Scaling
A+B+C	**A** **B** **C**
inst	**inst**

Impact of Scaling



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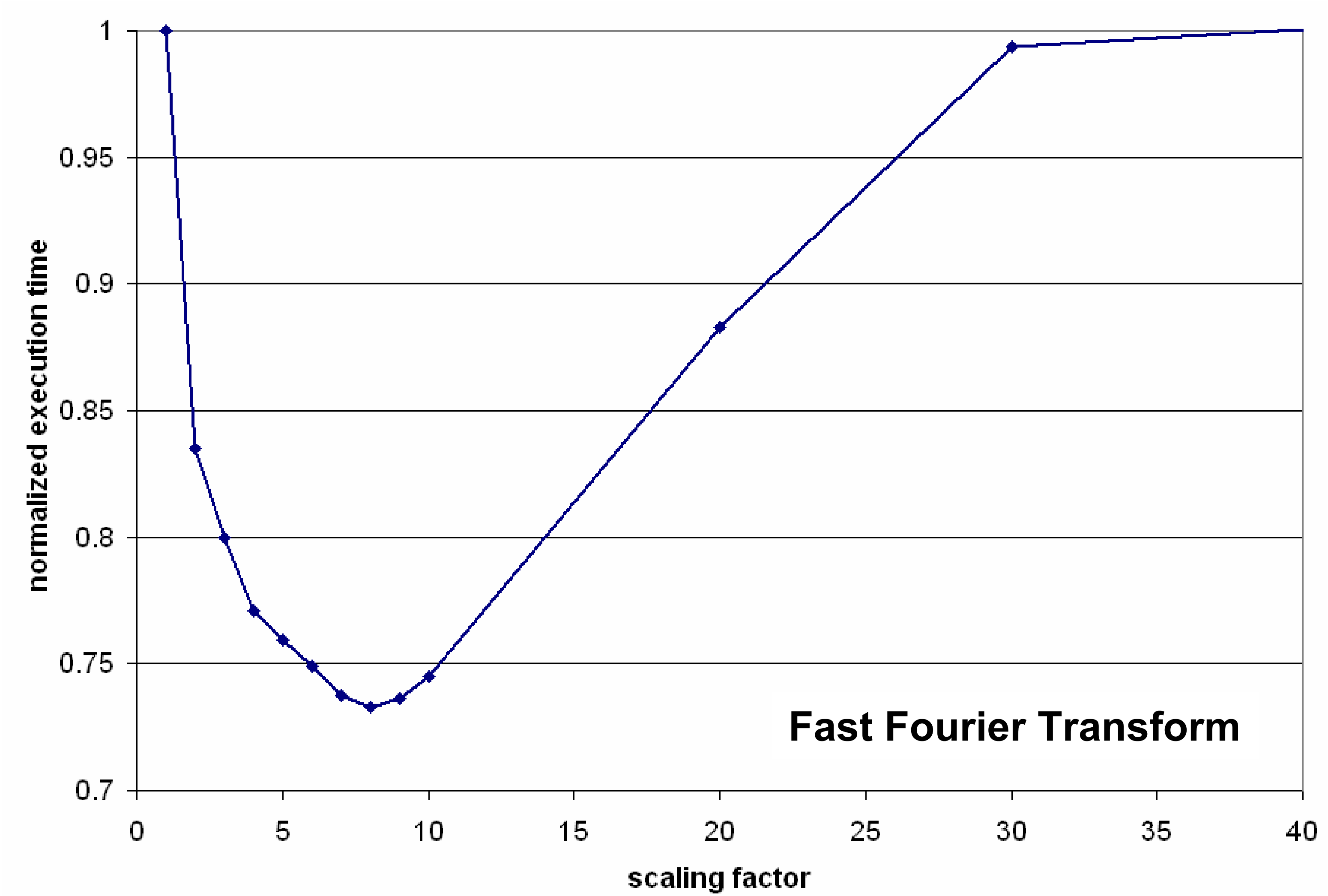
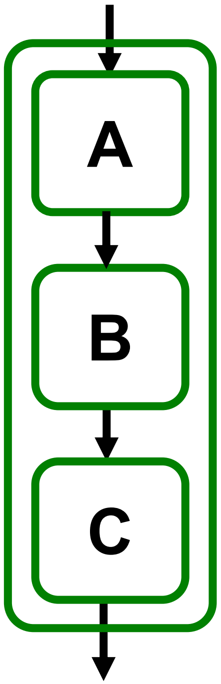
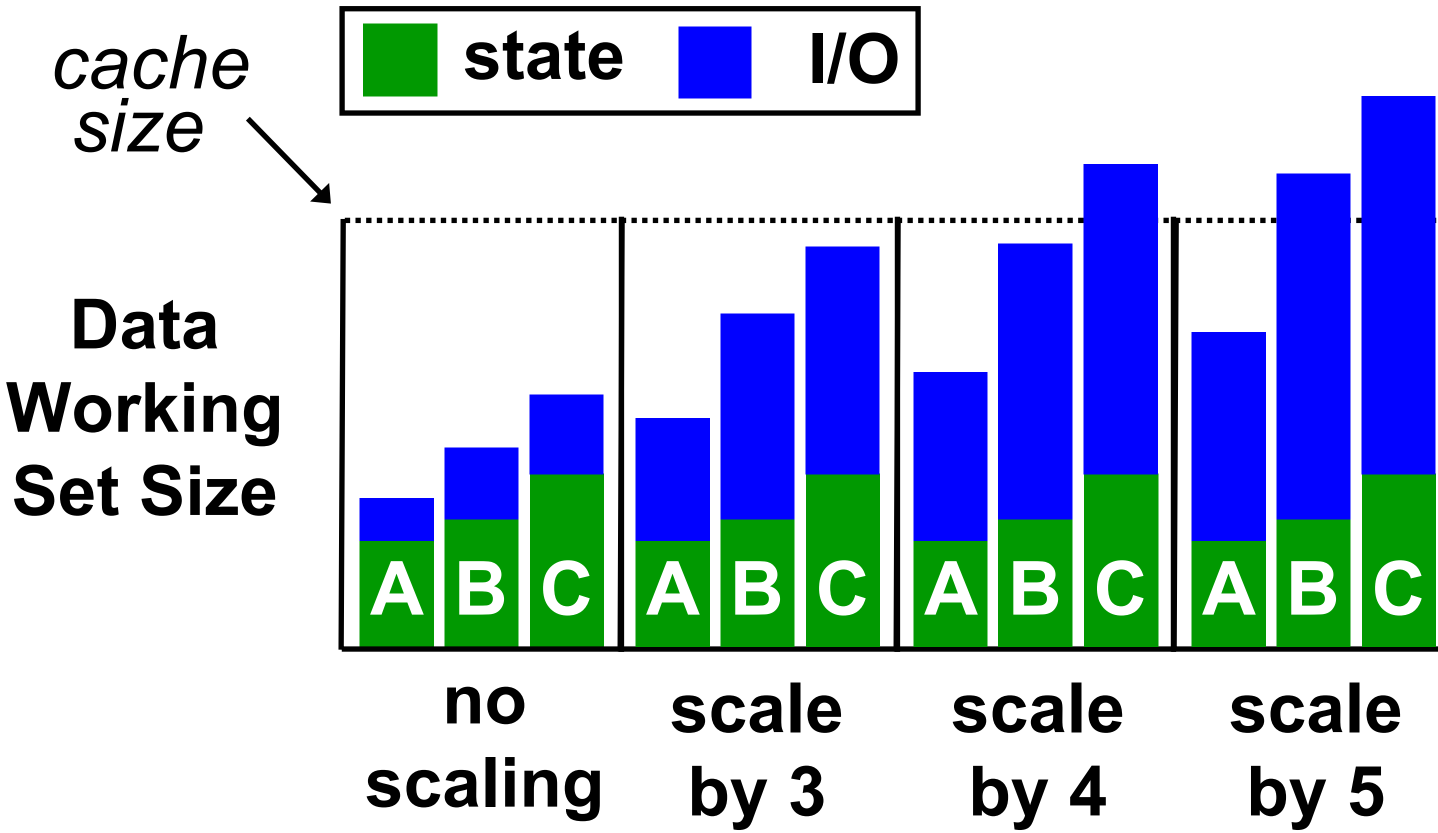


How Much To Scale?





Our Scaling Heuristic:

- Scale as much as possible
- Ensure at least 90% of filters have data working sets that fit into cache

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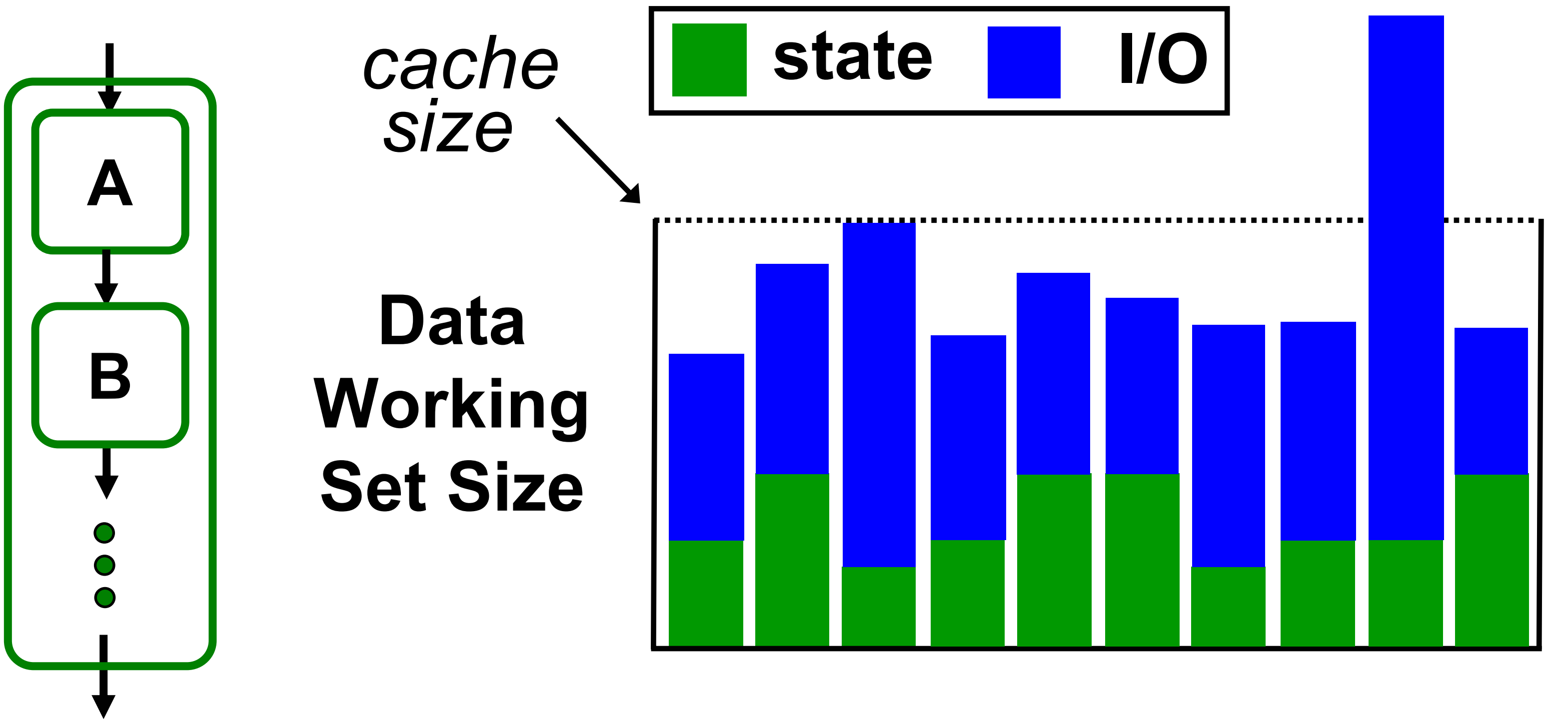

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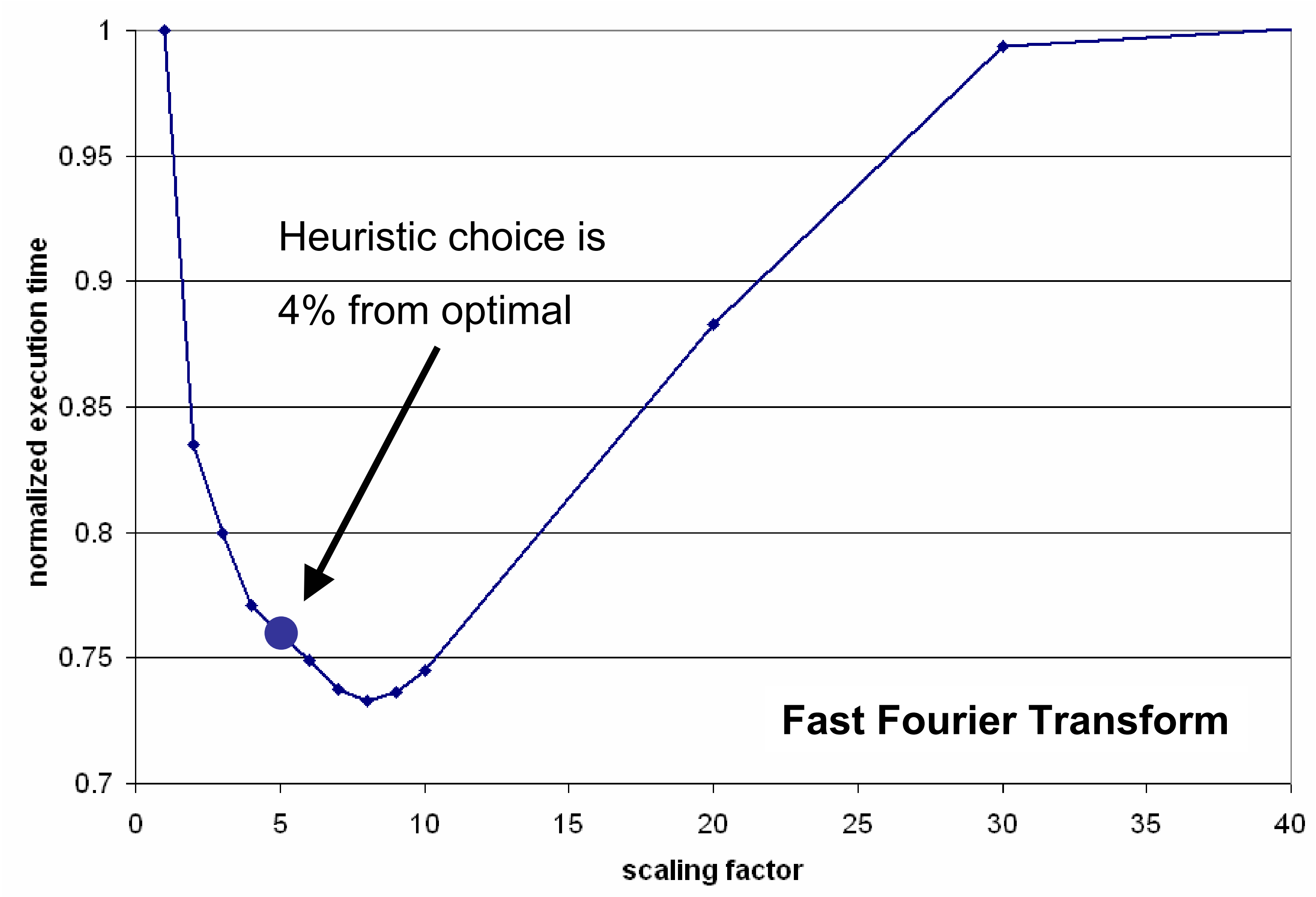
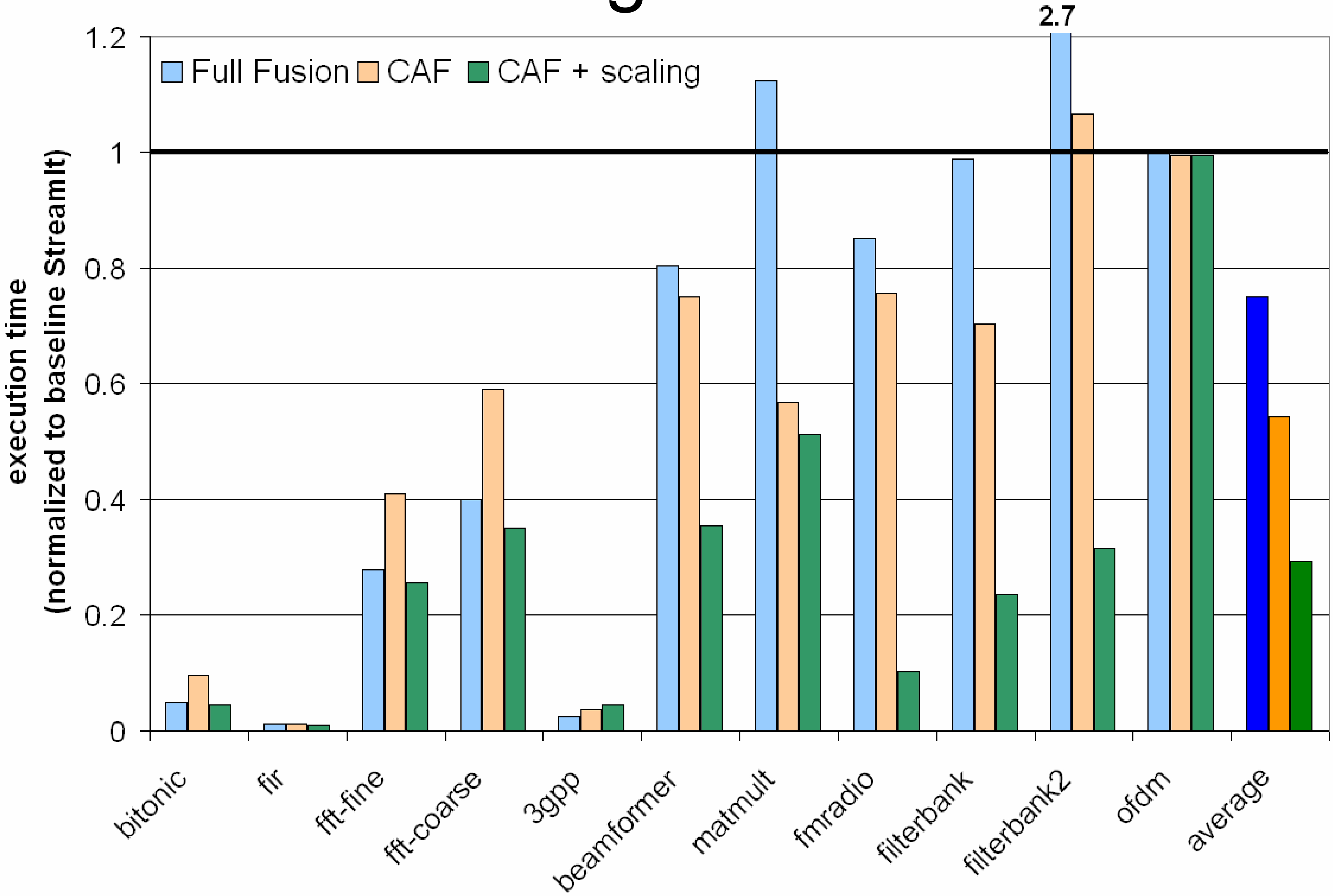


Scaling Results



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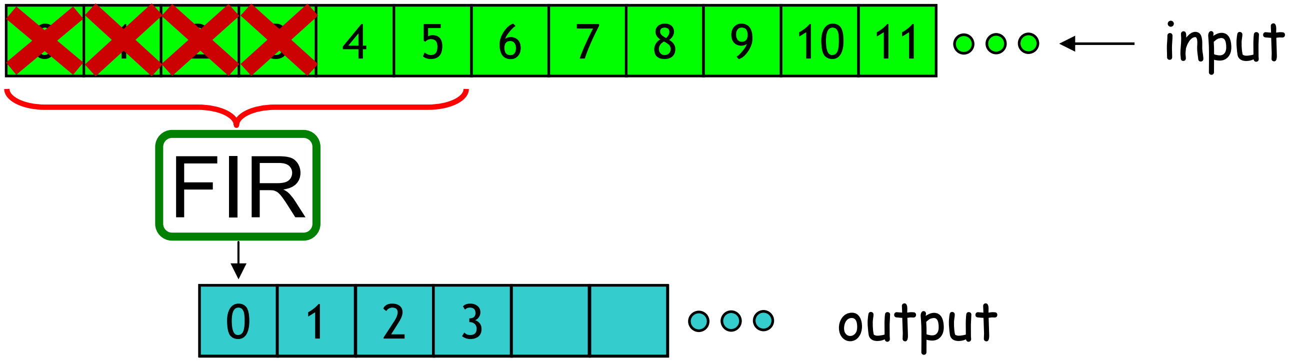
Sliding Window Computation

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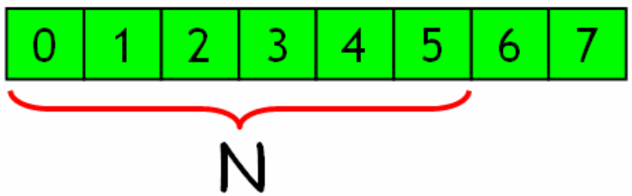
        push(result);
        pop();
    }
}
```

Buffer Management

Circular Buffer:



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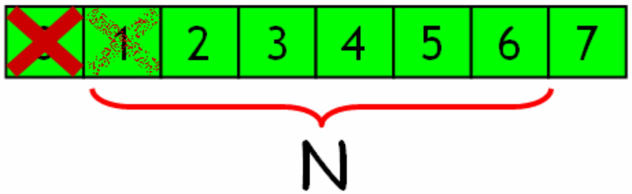

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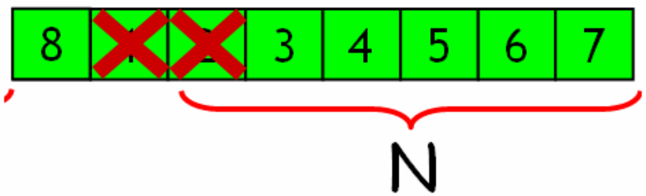

peek(i) → A[(head + i) mod 8]

Buffer Management

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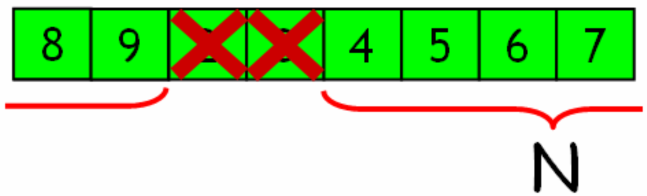

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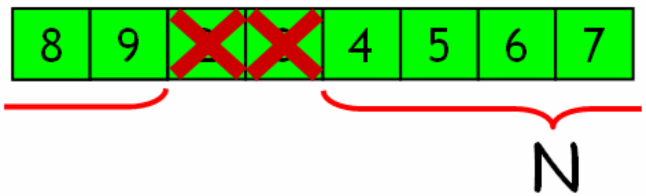

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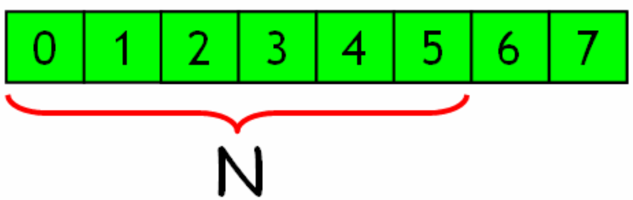

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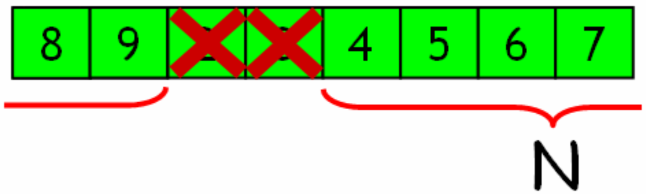

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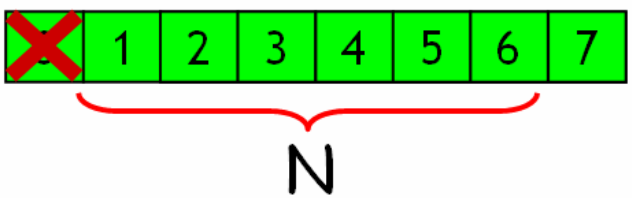

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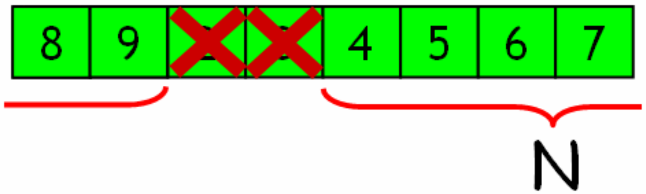

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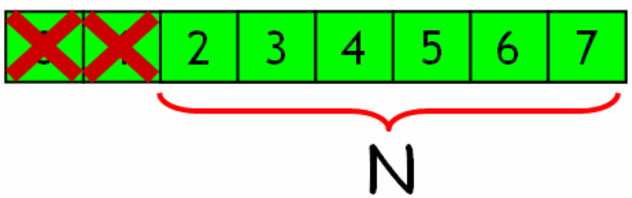

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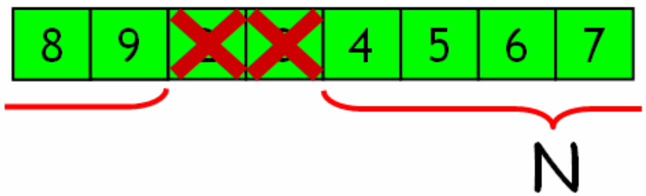

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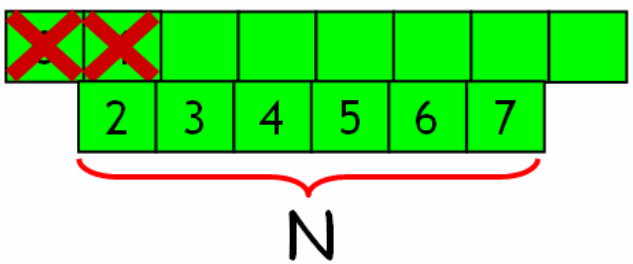

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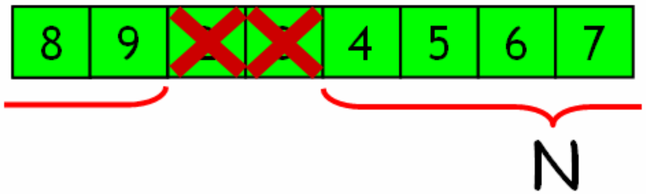

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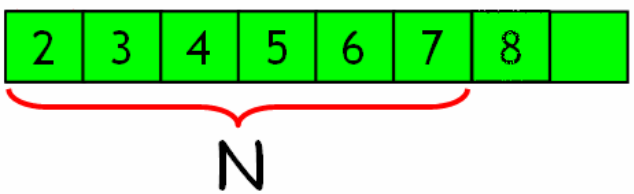

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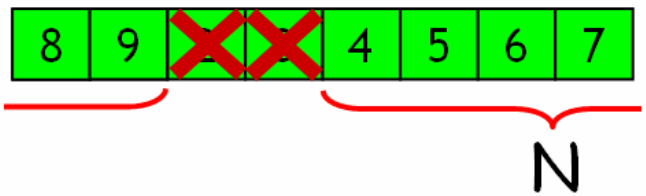

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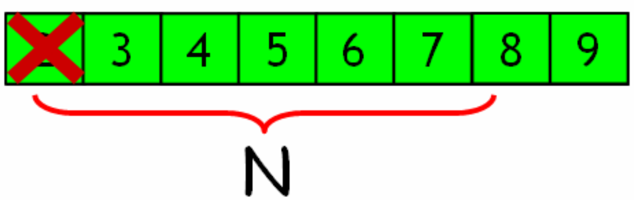

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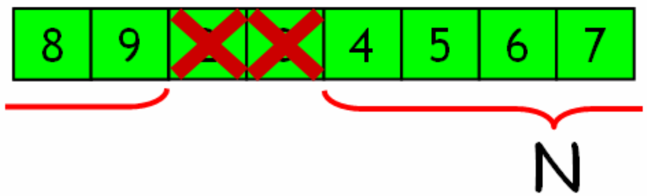

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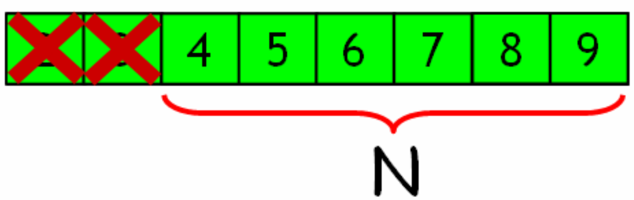

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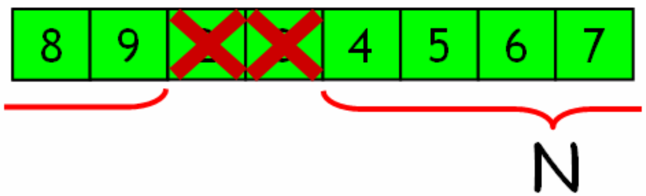

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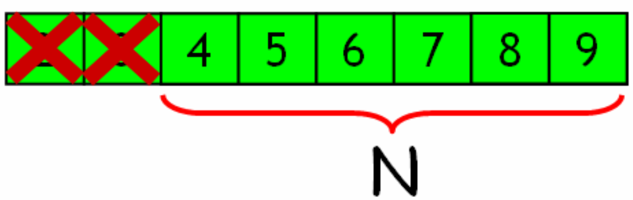
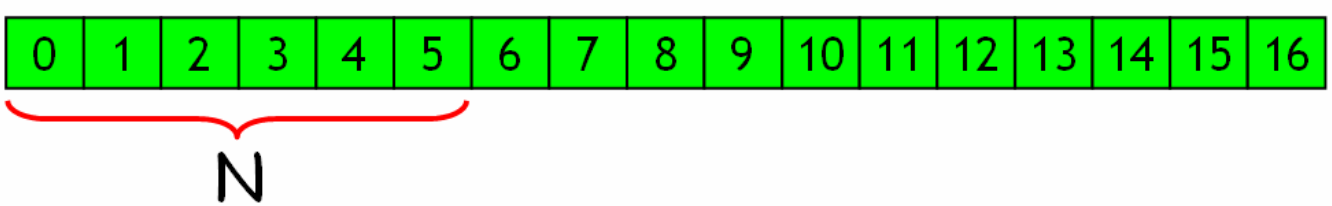


Copy-Shift + Scaling:



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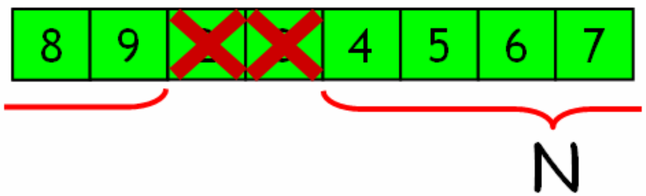

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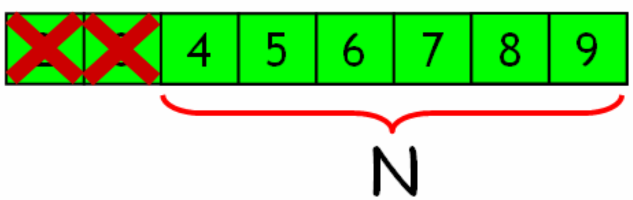

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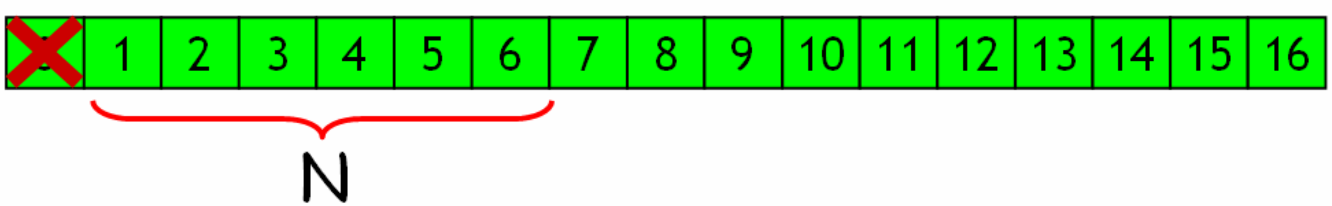

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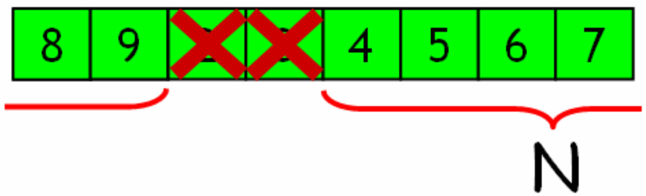

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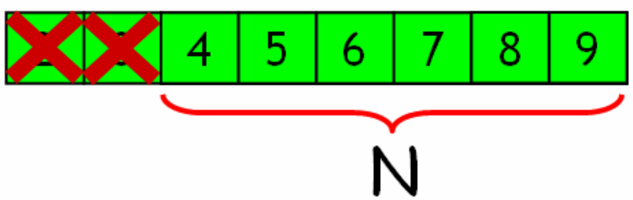
Copy-Shift:



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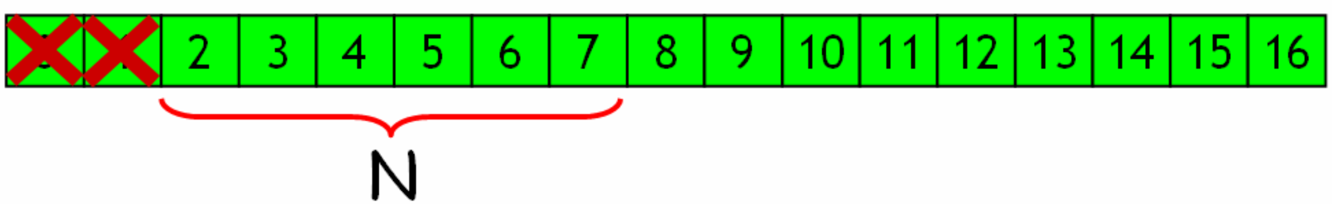
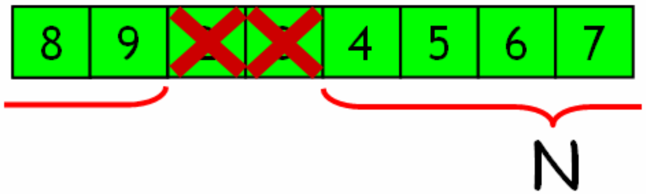


Buffer Management

Circular Buffer:



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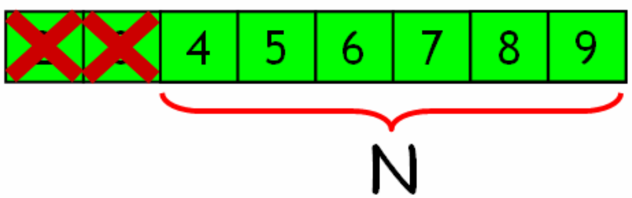

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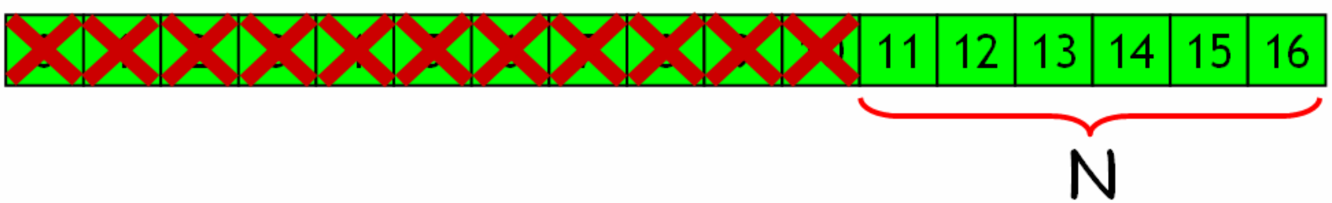

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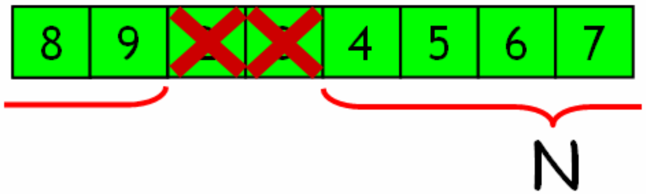

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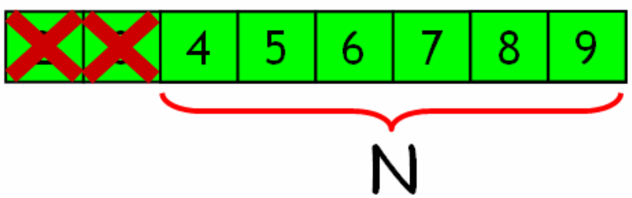

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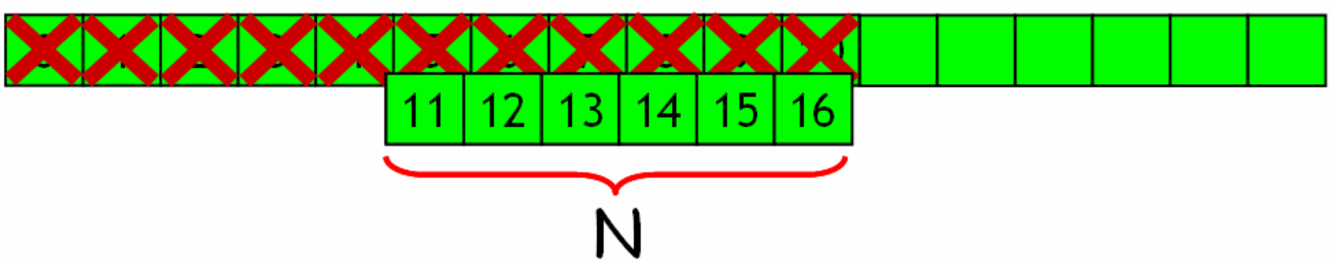

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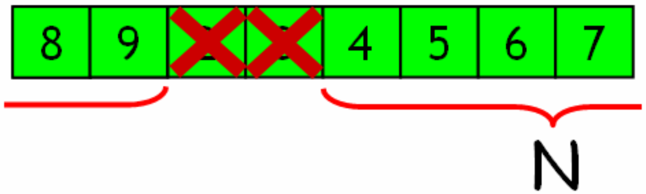

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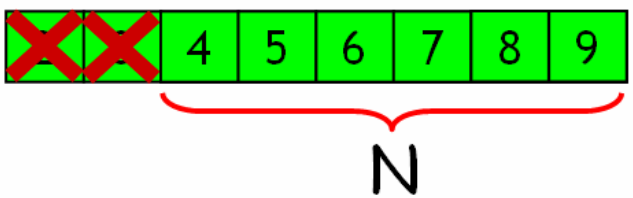

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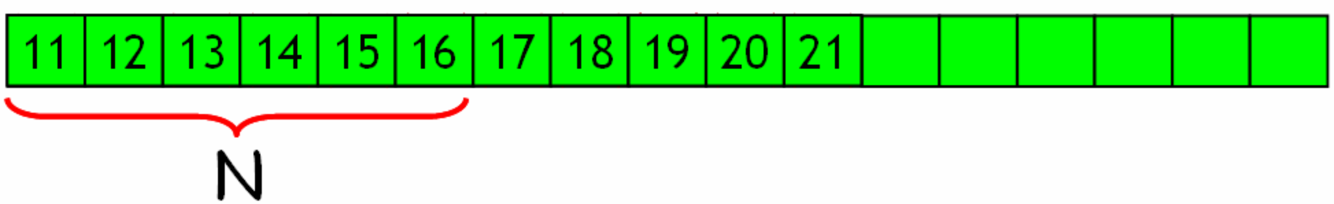

Buffer Management

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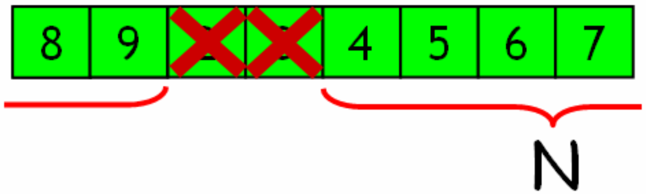

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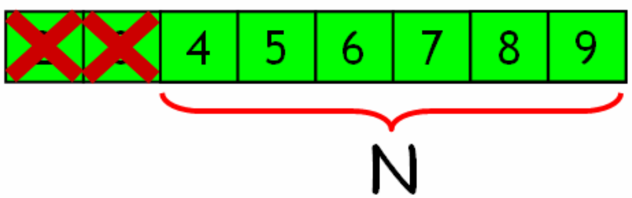

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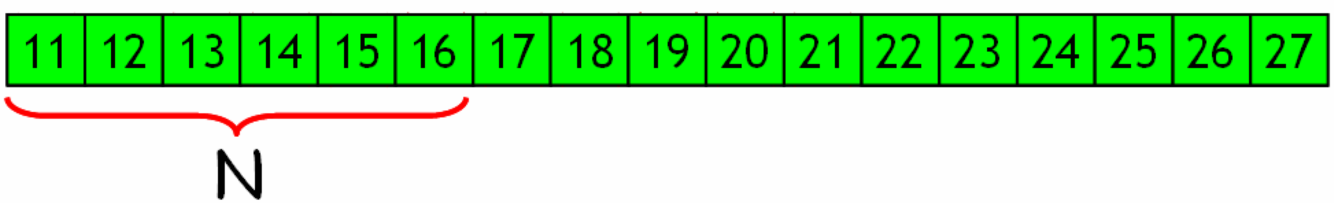
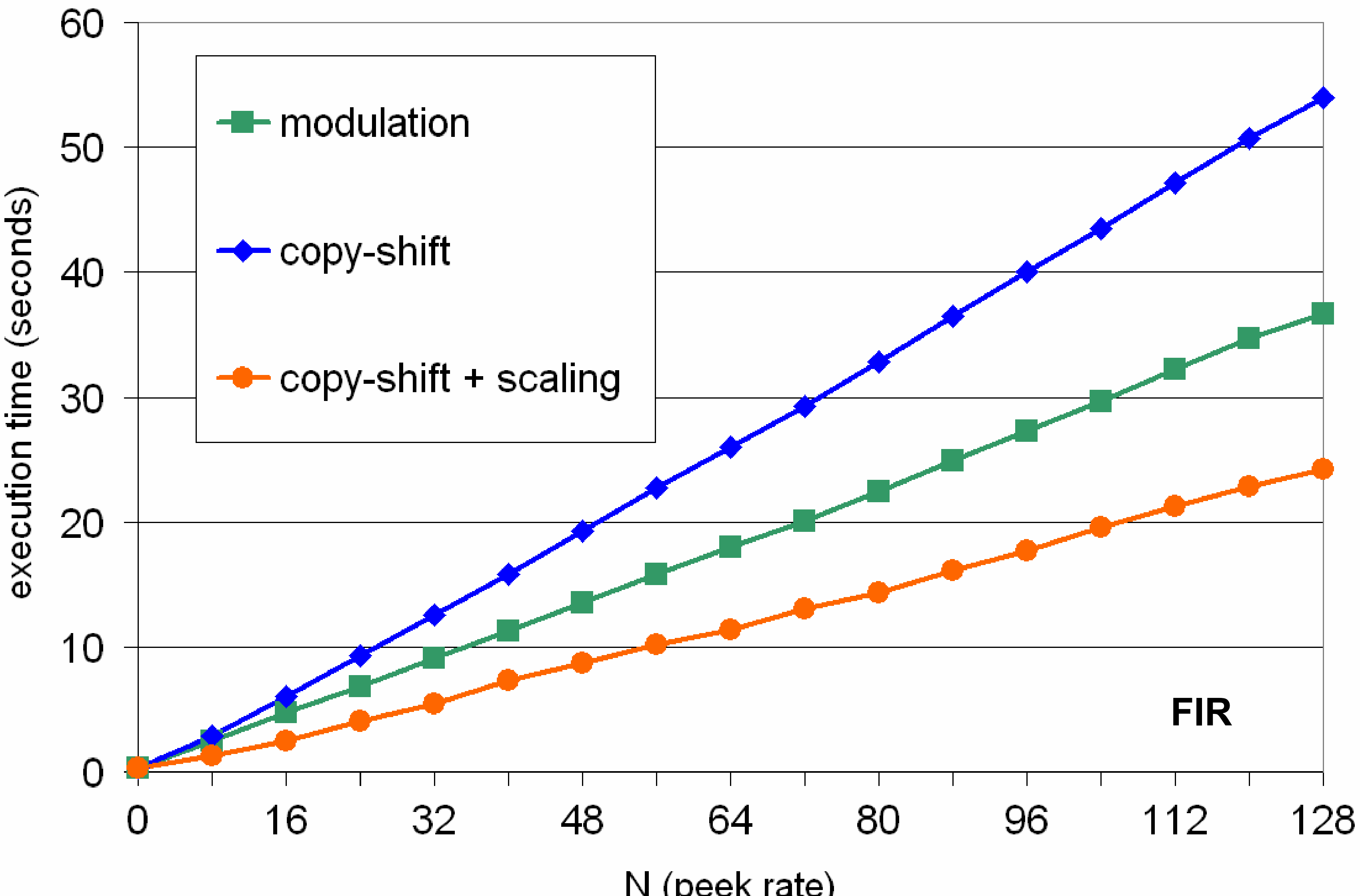


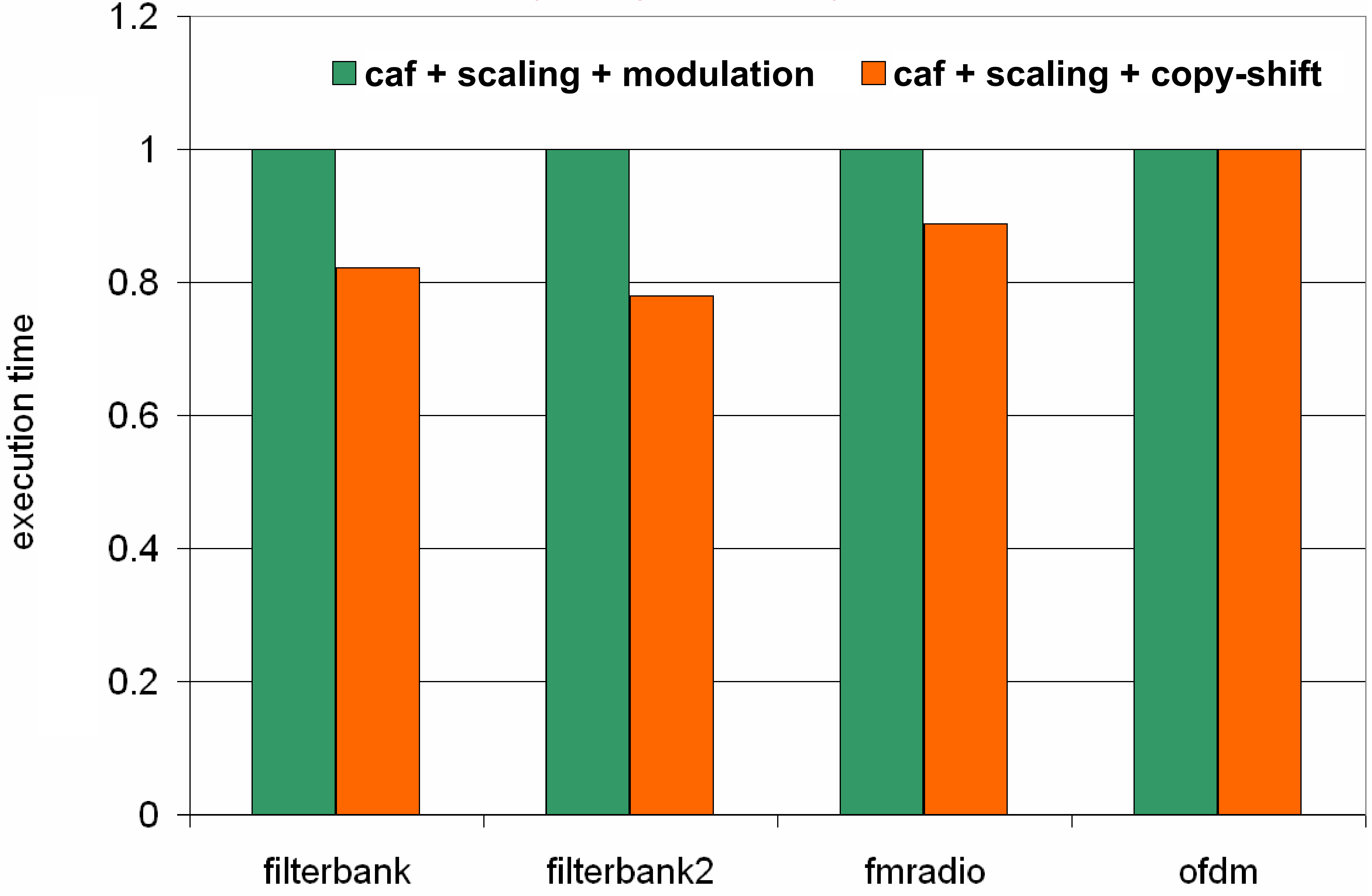
Performance vs. Peek Rate

(StrongARM 1110)

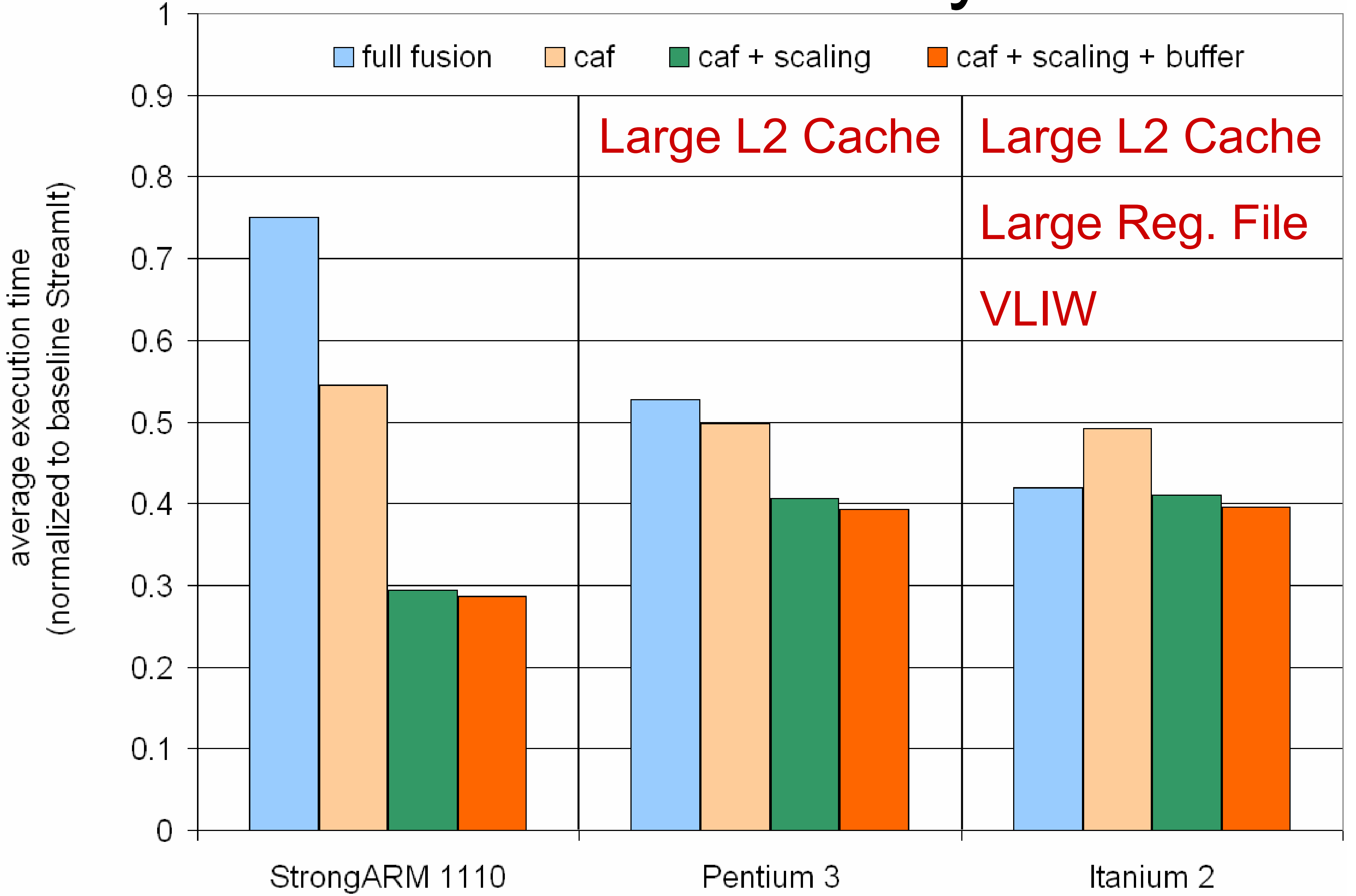


Evaluation for Benchmarks

(StrongARM 1110)



Results Summary



Outline

- StreamIt
- Cache Aware Fusion
- Cache Aware Scaling
- Buffer Management
- Related Work and Conclusion

Related work

- Minimizing buffer requirements
  - S.S. Bhattacharyya, P. Murthy, and E. Lee
    - Software Synthesis from Dataflow Graphs (1996)
    - AGPAN and RPMC: Complimentary Heuristics for Translating DSP Block Diagrams into Efficient Software Implementations (1997)
    - Synthesis of Embedded software from Synchronous Dataflow Specifications (1999)
  - P.K.Murthy, S.S. Bhattacharyya
    - A Buffer Merging Technique for Reducing Memory Requirements of Synchronous Dataflow Specifications (1999)
    - Buffer Merging – A Powerful Technique for Reducing Memory Requirements of Synchronous Dataflow Specifications (2000)
  - R. Govindarajan, G. Gao, and P. Desai
    - Minimizing Memory Requirements in Rate-Optimal Schedules (1994)

- Fusion
  - T. A. Proebsting and S. A. Watterson, Filter Fusion (1996)

- Cache optimizations
  - S. Kohli, Cache Aware Scheduling of Synchronous Dataflow Programs (2004)

Conclusions

- Streaming paradigm exposes parallelism and allows massive reordering to improve locality
- Must consider both data and instruction locality
  - Cache Aware Fusion enables local optimizations by judiciously increasing the instruction working set
  - Cache Aware Scaling improves instruction locality by judiciously increasing the buffer requirements
- **Simple optimizations have high impact**
  - Cache optimizations yield significant speedup over both baseline and full fusion on an embedded platform