Linear Analysis and Optimization of Stream Programs

Masterworks Presentation

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Motivation

- Digital devices, massive computation pervade modern life (cell phones, MP3, HDTV, etc.)
- Devices complex, software more complicated
  - Performance constraints (real time, power consumption) dictate high level of optimization
  - Best performance → assembly (50% cell phone code is written in assembly)
  - Assembly is (very) hard to reuse
- Automatic optimization is critical

Outline

- Motivation
- StreamIt
- Linear Dataflow Analysis
- Performance Optimizations
- Results

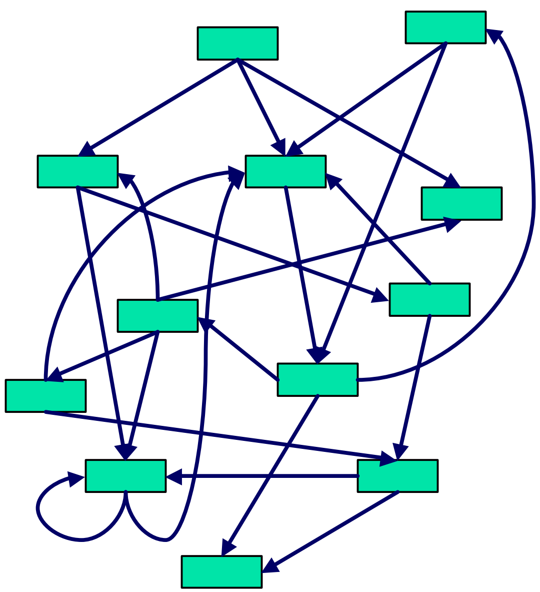
The StreamIt Language

- Goals:
  - High performance
  - Improved programmer productivity (modularity)

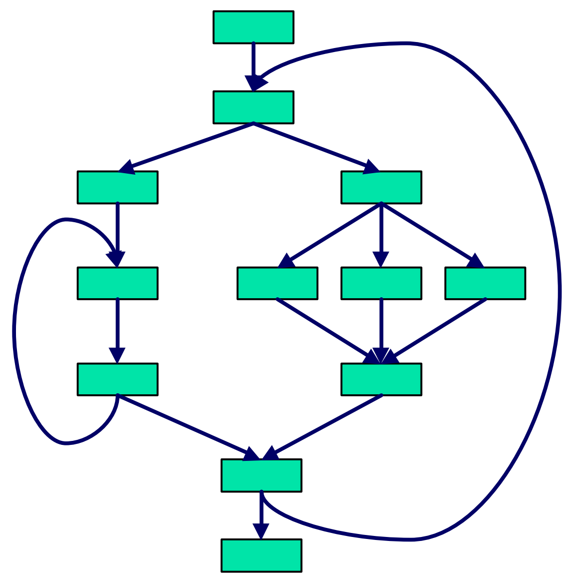
- Contributions:
  - Structured model of streams
  - Compiler buffer management
  - Automated scheduling (Michal Karczmarek)
  - Target complex architecture (Mike Gordon)
  - *Domain specific optimizations (Andrew Lamb)*

Programs in StreamIt

- Traditional: stream programs are graphs
  - No simple textual representation
  - Difficult to analyze and optimize
- Insight: stream programs have structure



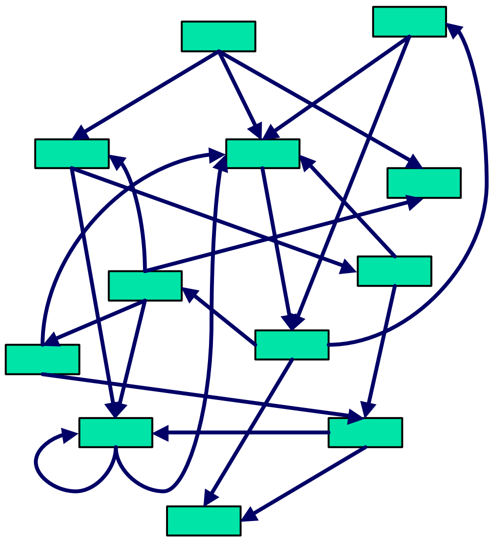
unstructured

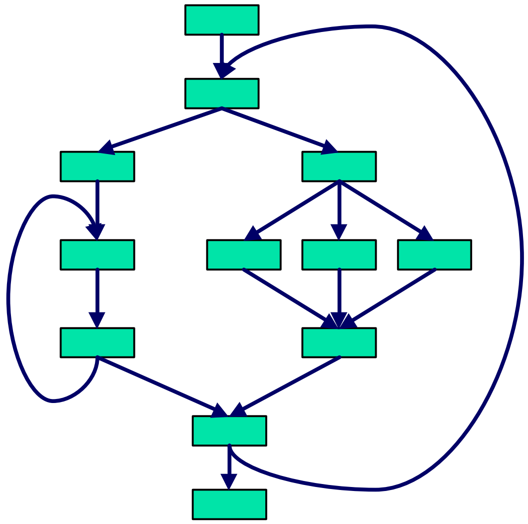


structured

Why Structured Streams?

- Compared to structured control flow





GOTO statements — *if / else / for* statements

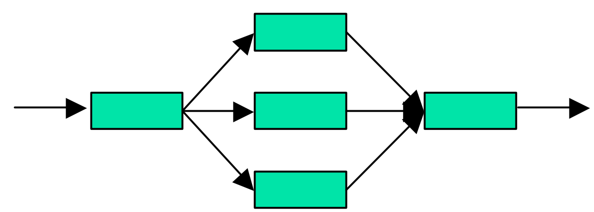
  - PRO: more robust, more analyzable
  - CON: “restricted” style of programming

Structured Streams

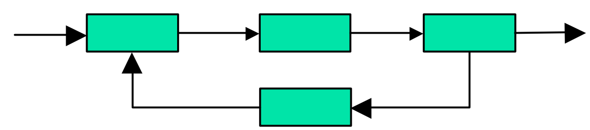
- Basic programmable unit:
  - Filter

- Hierarchical structures:
  - Pipeline

  - SplitJoin



  - Feedback Loop



Representing Filters

- Autonomous unit of computation

  - No access to global resources
  - One input, one output
  - Communicates through FIFO channels
    - **`pop(), peek(index)`**
    - **`push(value)`**
  - “Firing” is the atomic execution step
  - A firing’s peek, pop, push rates must be constant
  - Code within filter is general purpose – like C

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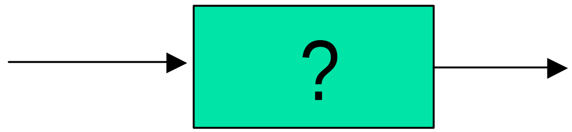
What is a *Linear* Filter?

- Generic filters generate outputs (possibly) based on their inputs



- Linear filters: standard sense of linearity
  - outputs (y_j) are weighted sums of the inputs (x_i) (possibly plus a constant)

$$\vec{y} = \sum_{i=0}^{e-1} a_i x_i + b$$

b constant
a_i constant for all i
e is the number of inputs

Linearity and Matricies

- Represent multiple inputs, multiple outputs with matrix multiply
- We treat inputs (x_i) and outputs (y_j) as vectors of values (**x**, and **y** respectively)
- Filter representation:
  - Matrix of weights **A**
  - Vector of constants **b**
  - peek, pop, push rates
- A filter firing computes:

$$\mathbf{y} = \mathbf{x}\mathbf{A} + \mathbf{b}$$

Extracting Linear Filters

- Goal: convert the filter's imperative code into an equivalent linear node

$$\mathbf{y} = \mathbf{x}\mathbf{A} + \mathbf{b}$$

- Technique: "Linear Dataflow Analysis"
  - Resembles standard constant propagation
  - "Linear form" is a vector and a constant
  - Keep mapping from each expr. to linear form

$$expr \longrightarrow \begin{bmatrix} a_0 \\ \vdots \\ a_{e-1} \end{bmatrix} + b$$

  - Extract linear form for each value pushed

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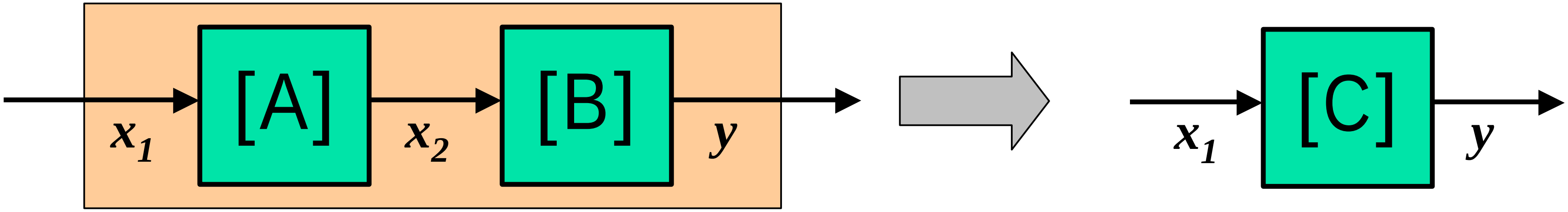
1. Combining Linear Filters

- Pipelines and splitjoins containing only linear filters can be collapsed into a single node
- Example: pipeline with peek(B)=pop(B)



$$\left.\begin{array}{l} x_2 = x_1 A \\ y = x_2 B \end{array}\right\} \; y = x_1 A' B' = x_1 C$$

$$C = A' B'$$

where A' and B' have been scaled and duplicated so that the dimensions match.

2. Frequency Replacement

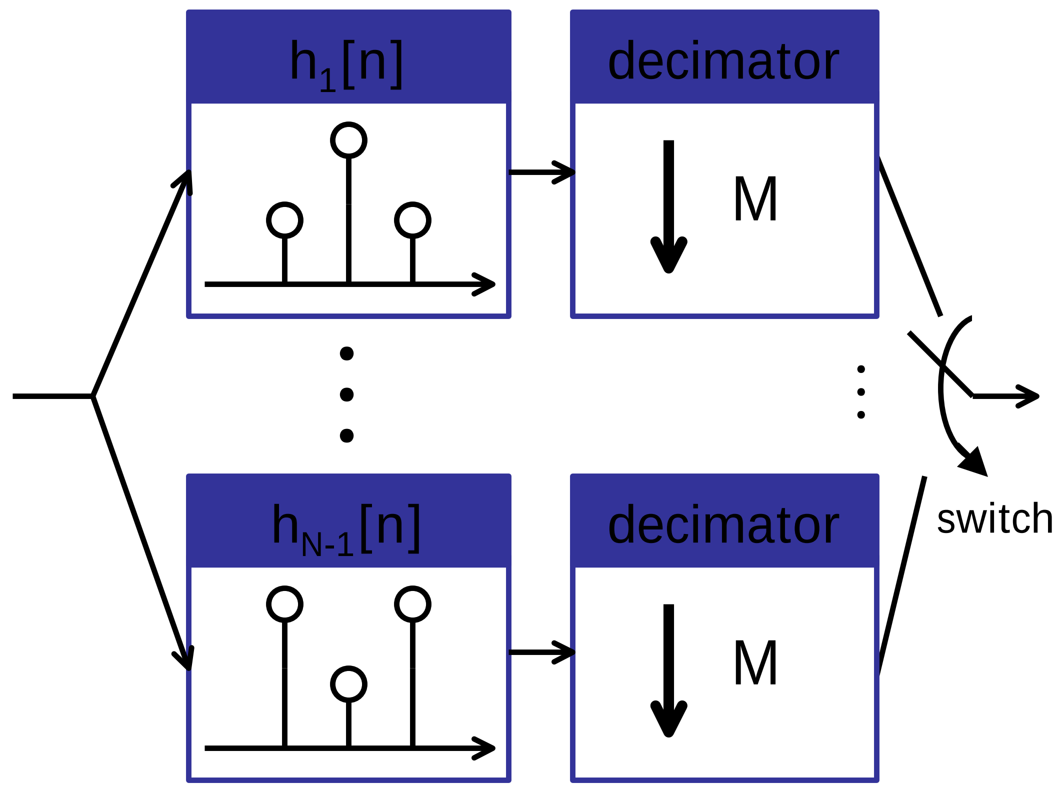
- First, identify linear nodes with FIR filters from discrete time linear systems

λ=(A,b,3,M,N)

$$A=\begin{bmatrix} 2 & \dots & 1 \\ 1 & \dots & 2 \\ 2 & \dots & 1 \end{bmatrix} b=\begin{bmatrix} 0 & \cdots & 0 \end{bmatrix}$$

Linear Node

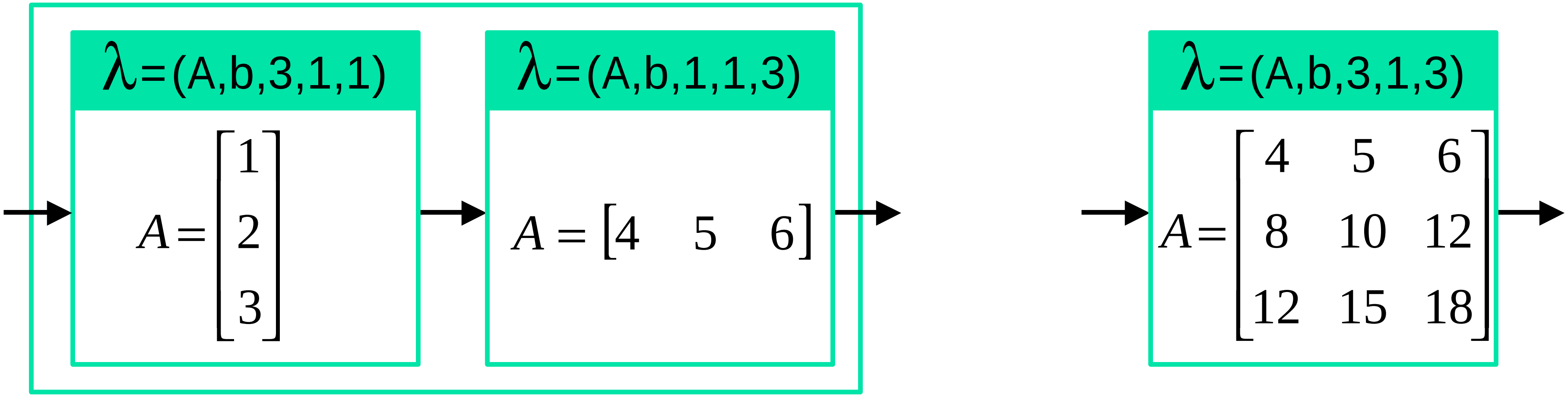
λ=(A,b,peek,pop,push)



DT System

3. Automatic Selection

- Applying optimizations blindly is not good
- Combination example:



$\frac{\text{2 mults}}{\text{output}}$

originally

$\frac{\text{3 mults}}{\text{output}}$

after "optimization"

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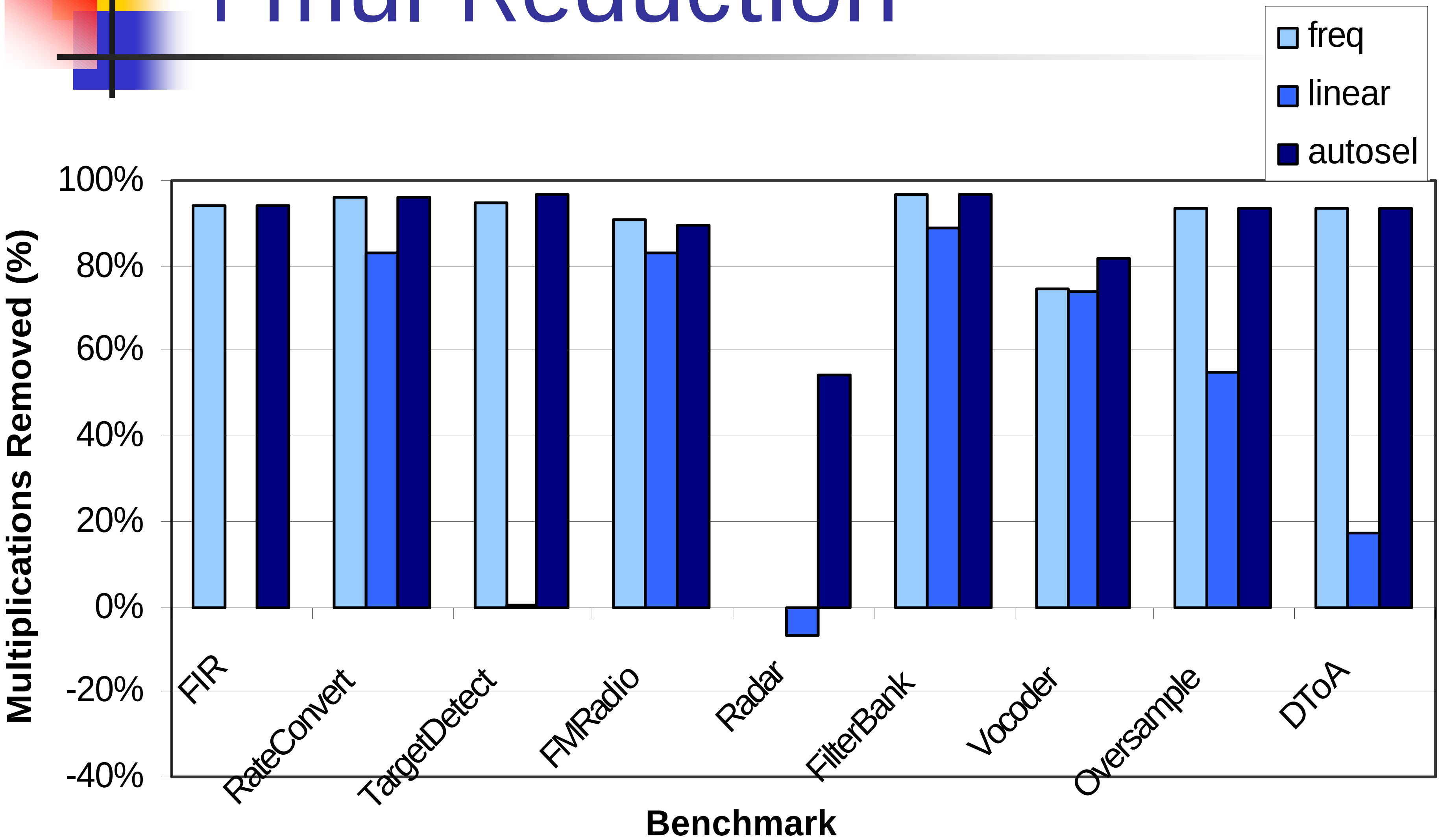
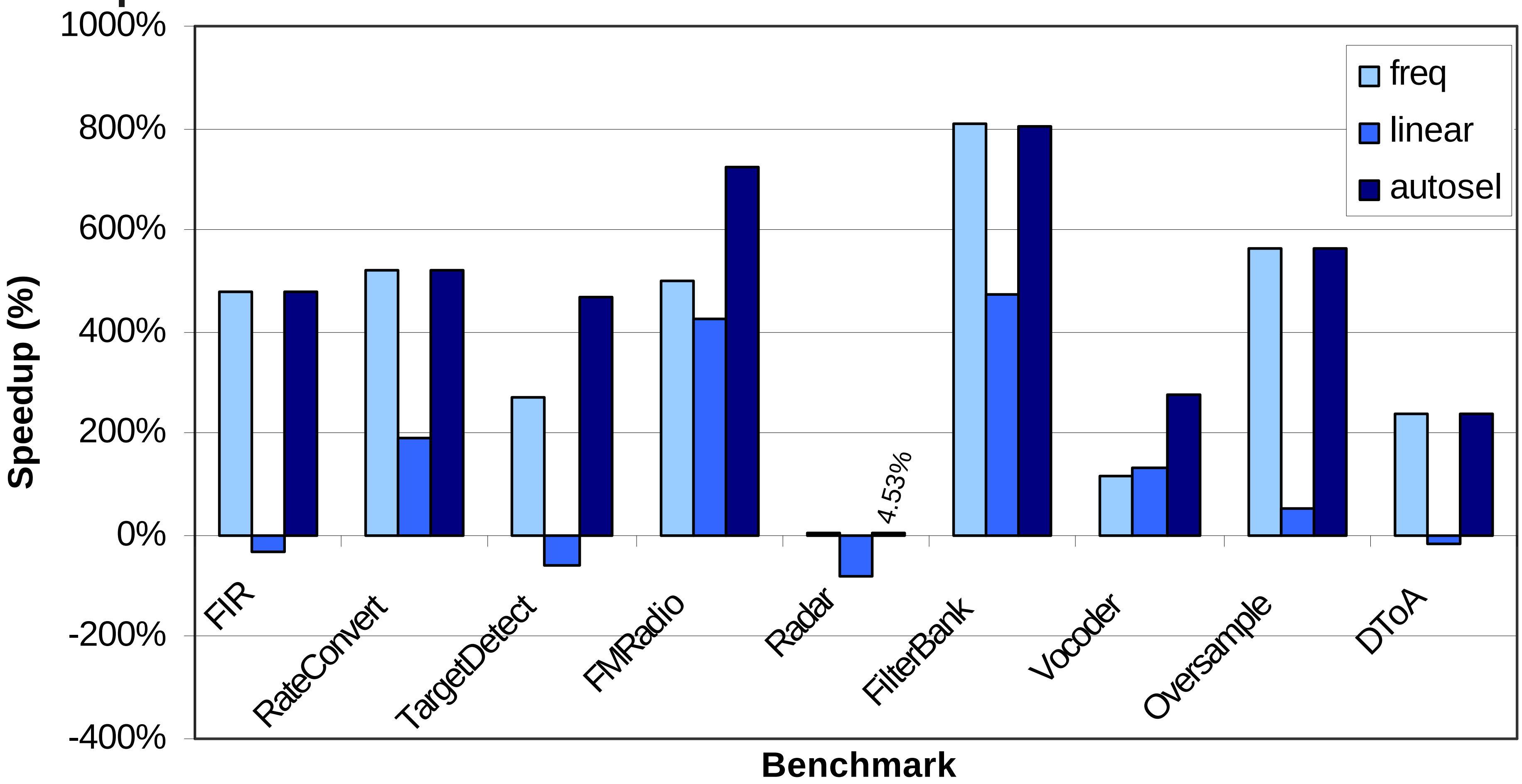
Fmul Reduction



Execution Speedup



Conclusion

- StreamIt is a new language for high performance DSP applications
- Personal research contributions:
  - Dataflow analysis determines a linear node that represents input/output relationship
  - Combination and optimization using linear nodes
  - Average performance speedup of 450%

Using StreamIt and domain specific optimizations, modularity does not sacrifice performance.