Language, Compiler and Development Support for Stream Computing

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http://cag.csail.mit.edu/streamit

HPL Workshop
May 2004

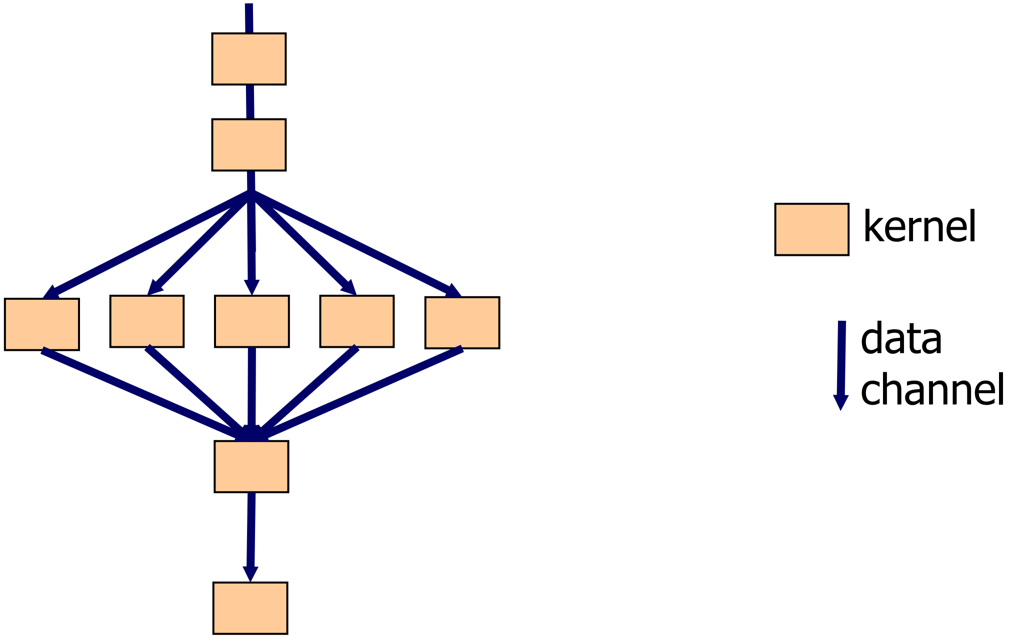
Domain of Streaming Computing

- Increasingly prevalent computing domain with applications in
  - Embedded systems
    - Cell phones, handheld computers, DSPs
  - Desktop workstations
    - Streaming media, real-time encryption, software radio, graphics
  - High-performance servers
    - Software routers, cell phone base stations, radar tracking, HDTV editing consoles, databases

- Predominant data streams include audio, video, and data

What is Stream Computing?

- "A model that uses sequences of data and computation kernels to expose and exploit concurrency and locality for efficiency."
  - Workshop on Streaming Systems, Summer 2003
    http://cag.csail.mit.edu/wss03



Properties of Streaming Programs

- Process large (possibly infinite) amounts of data
  - Data have limited lifetime and undergoes little processing
- Processing consists of a series of data transformations
  - Filter is the basic unit for data transformation
    - Input data  Output data
    - Filters are independent and self-contained
- "Regular" computation patterns
  - Flow of data between filters is mostly constant
  - Many opportunities for compiler optimizations
- Occasional changes in program control (messaging)

HPCS Goals in the Streaming Context

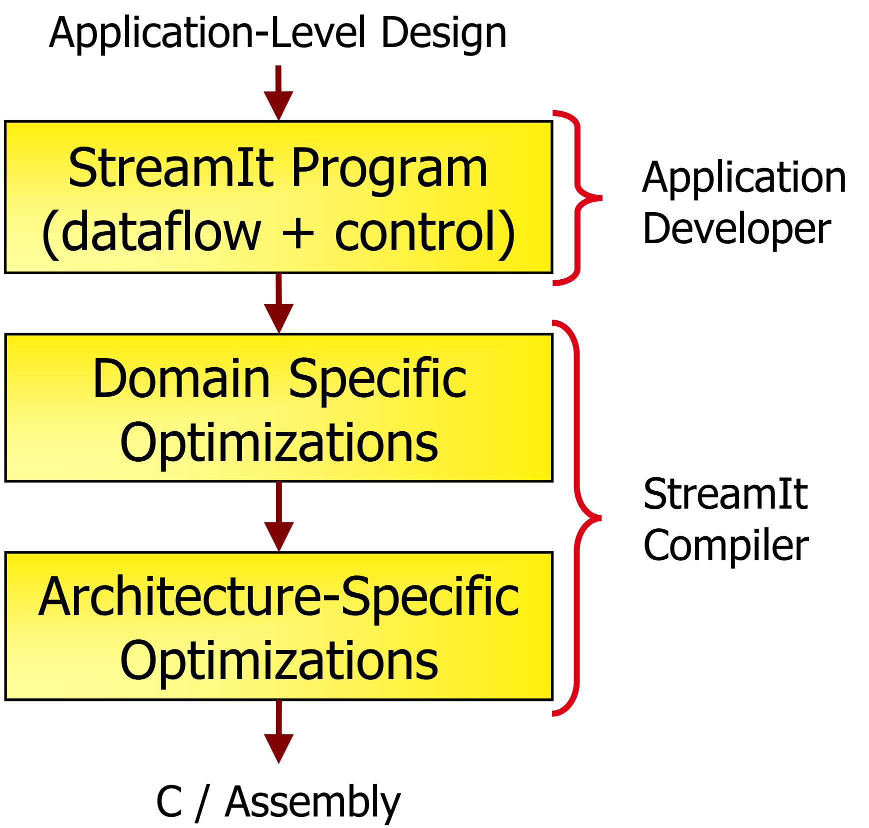
- Stream programming often requires special expertise
  - Conventional programming languages used in large applications make it difficult to extract parallelism
  - Low performance is not acceptable
  - System experts on the critical path

- Programming high-end machines should not be the "exclusive domain of experts"
  - Use high-level abstractions to naturally describe streaming computation
  - Make the language compiler-friendly
    - Expose parallelism and communication
    - Empower the compiler to perform novel optimization
    - Facilitate an efficient mapping of programs to (future) architectures

StreamIt Overview

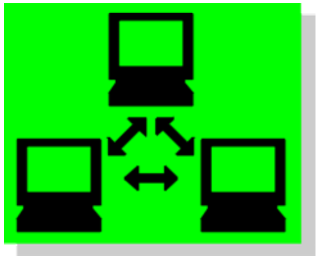
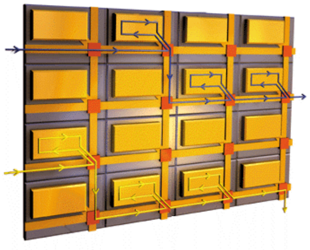
- StreamIt is a high-level, architecture-independent language for stream computing
  - Facilitate the rapid implementation of complex applications
  - Expert-programmer no longer on critical path to achieving high performance
  - StreamIt compiler applies novel domain specific optimizations

design flow with StreamIt



StreamIt in the Big Picture

- Unified programming model with single machine abstraction
  - Expose parallelism and communication
    - Uniprocessor, cluster of workstations, or tiled architecture

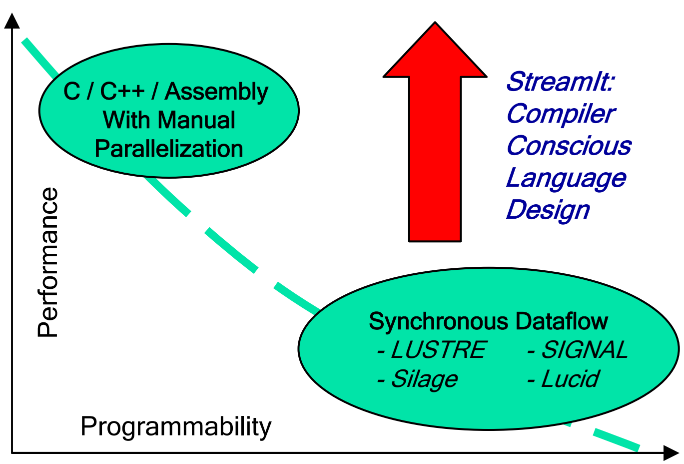
  - Hide granularity of execution, architecture details
  - Natural textual representation
  - Innovative compiler technology focuses on the core set of challenges
    - Versatility, load balancing, fault tolerance, …

provide “performance transparency”, portability, and support for “programming in the large”

Related Work

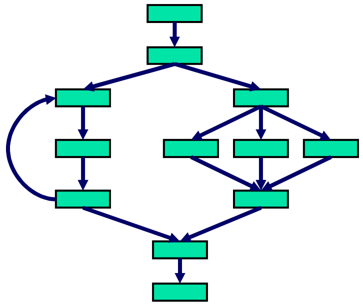
- "Stream languages"
  - KernelC/StreamC, Brook: augment C with data-parallel kernels
  - Cg: allow low-level programming of graphics processors
- Prototyping environments
  - Ptolemy, Simulink, etc.: provide graphical abstractions, but do not focus on compiling for performance or reliability
- Control languages for embedded systems
  - LUSTRE, Esterel, etc.: can verify safety properties, but do not expose high-bandwidth data flow for optimization

- In general, little features for scalable program development, or too abstract and unstructured
  - Compiler cannot perform enough analysis and optimizations
  - StreamIt exposes more task parallelism, and uses constructs that are easier to analyze



StreamIt Language Overview

- A StreamIt program is a structured graph of nodes
  - Nodes are autonomous units of computation
  - Edges are communication channels (FIFOs)

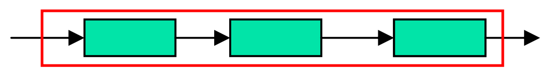


- Hierarchical structure
  - Single-Input to Single-Output language constructs
- Graph components are parameterizable
  - Short and natural recursive stream graph definitions

StreamIt Language Constructs

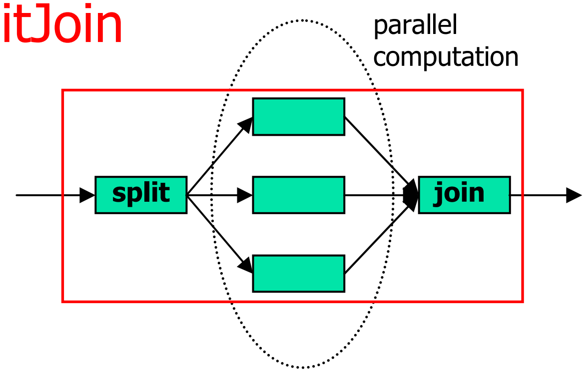
- Language constructs
  - Filter

  - Pipeline

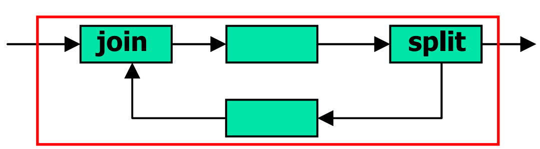


 may be any of the StreamIt language constructs

  - SplitJoin



  - FeedBack Loop

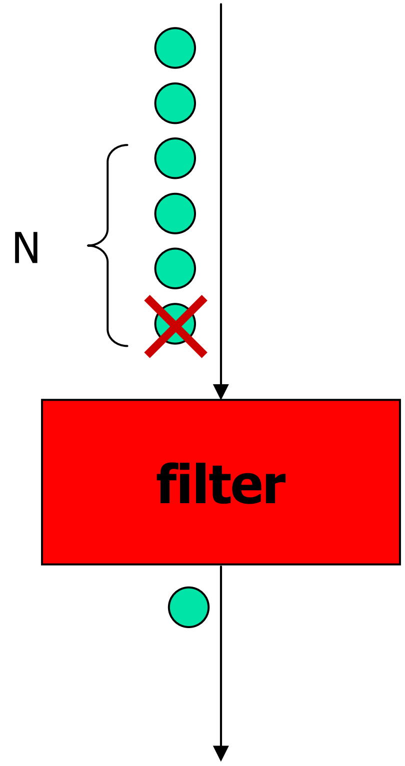


- Programming paradigm is
  - Modular
    - Important for large scale development
  - Malleable
    - Parameterized templates allow program to change behavior with small source code modifications
  - Composable
    - Composition of simple structures creates large and complex graphs
    - Enables inductive reasoning about correctness
  - Portable
    - Application is architecture independent

Filters as Computational Elements

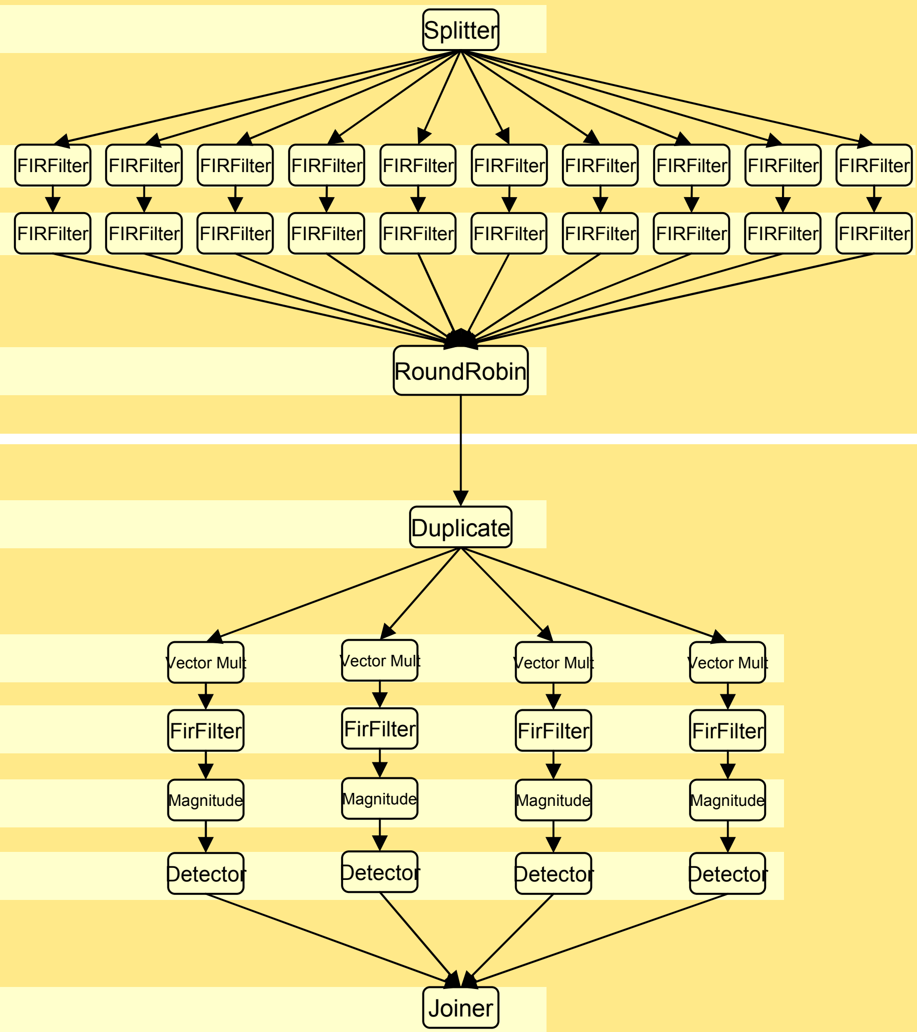
- Filters are the basic programmable units
  - An initialization function and a steady-state work function
  - Communicate via FIFOs: pop(), peek(index), push(value)

```
float→float filter FIR (int N) {
    float[N] weights;
    init {
        weights = calculate_weights(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();
    }
}
```



Example Application–Radar Front-End

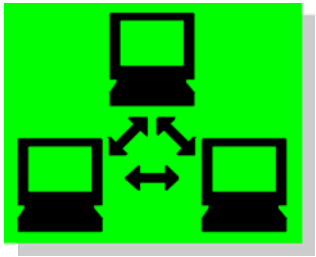
```
complex→ void pipeline BeamFormer(int numChannels, int numBeams) {
    add splitjoin {
        split duplicate;
        for (int i=0; i<numChannels; i++) {
            add pipeline {
                add FIR1(N1);

                add FIR2(N2);
            };
        };
        join roundrobin;
    };

    add splitjoin {
        split duplicate;
        for (int i=0; i<numBeams; i++) {
            add pipeline {
                add VectorMult();

                add FIR3(N3);

                add Magnitude();

                add Detect();
            };
        };
        join roundrobin(0);
    };
}
```



StreamIt Compiler

StreamIt Compiler Overview

- The StreamIt language hides granularity of execution and architecture details
  - Compiler backend supports
    Uniprocessor, cluster of workstations, and MIT Raw


- Innovative compiler technology focuses on the core set of challenges to deliver high performance in future architectures
  - Automating domain specific optimizations
    - Optimization of linear streams
    - Translation to the frequency domain
  - Partitioning, layout, routing, …

Linear Filter Optimizations

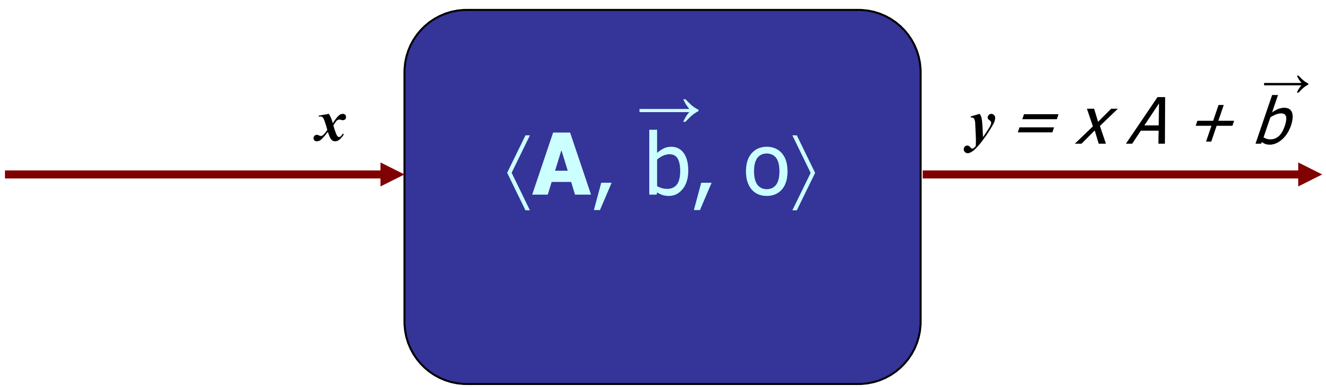
- Most common target of DSP optimizations
  - FIR filters
  - Compressors
  - Expanders
  - DFT/DCT

  Output is weighted sum of inputs

- Example optimizations:
  - Combining Adjacent Nodes
  - Translating to Frequency Domain

Representing Linear Filters

- A linear filter is a tuple $\langle \mathbf{A}, \vec{b}, o \rangle$
  - **A**: matrix of coefficients
  - $\vec{b}$: vector of constants
  - o: number of items popped
- Example



Extracting Linear Representation

```
work peek N pop 1 push 1 {
    float sum = 0;
    for (int i=0; i<N; i++) {
      sum += h[i]*peek(i);
    }
    push(sum);
    pop();
}
```

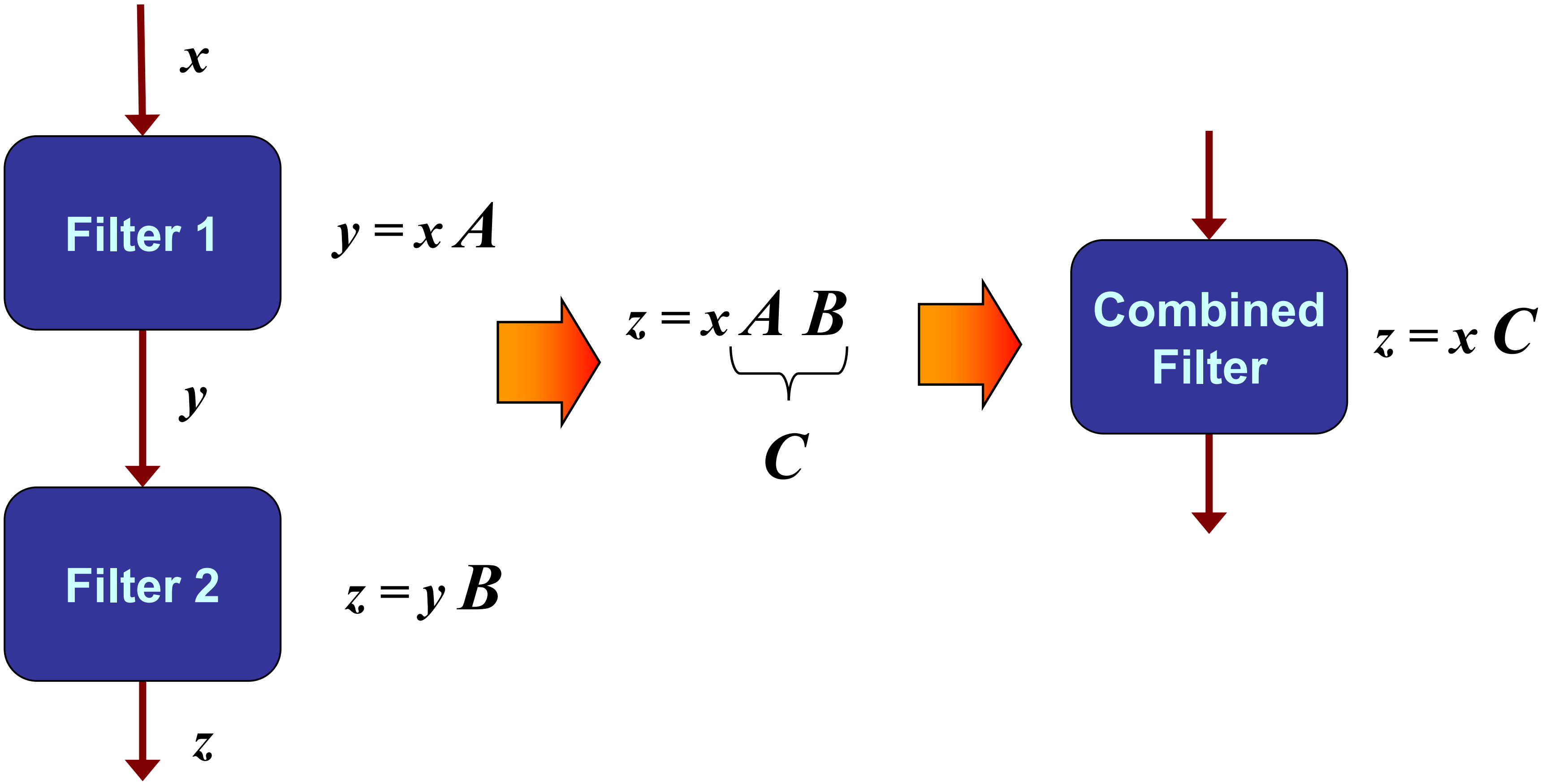
Linear
Dataflow
Analysis

$$\langle \mathbf{A}, \vec{b}, o \rangle$$

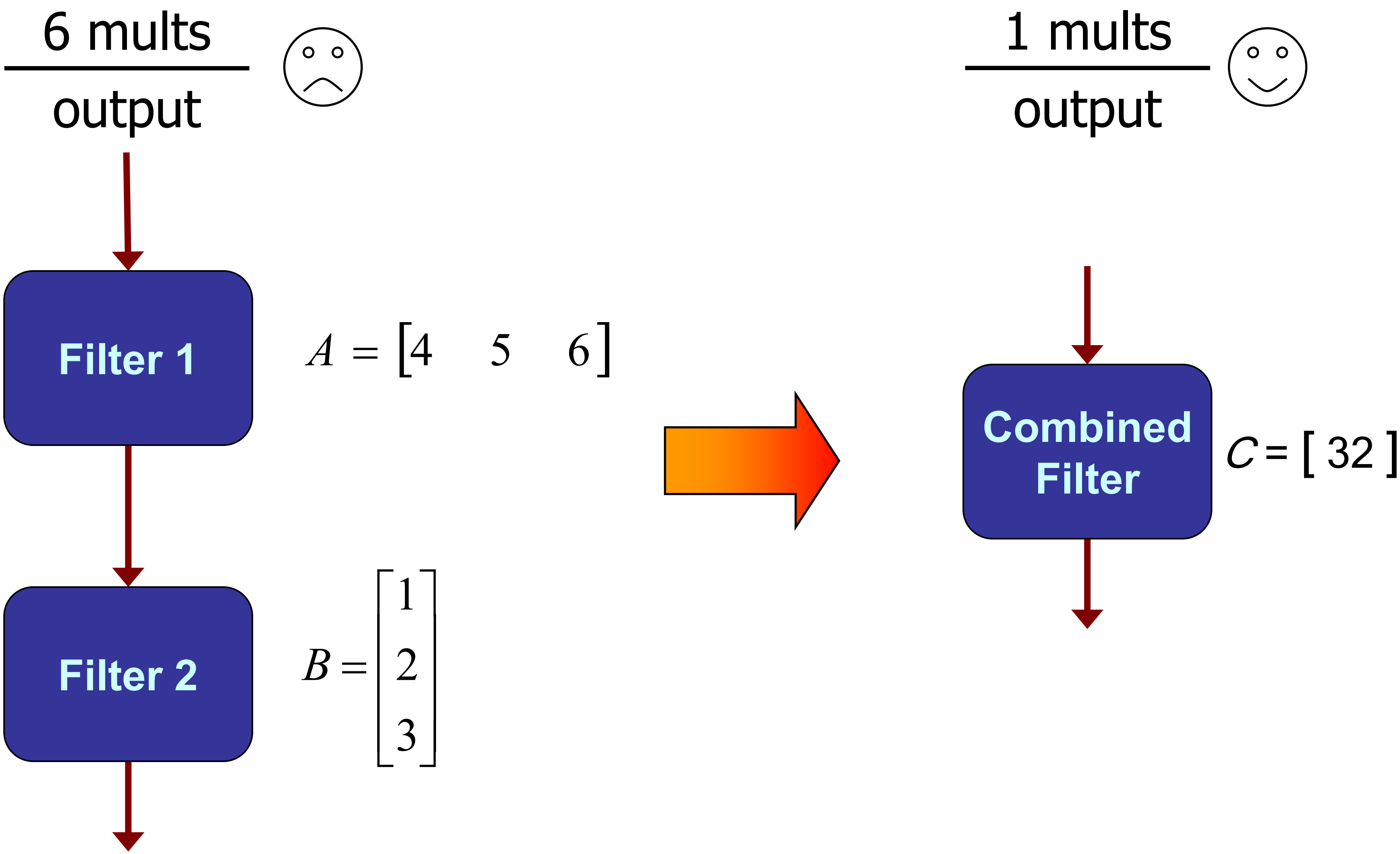
- Resembles constant propagation
- Maintains linear form $\langle \vec{v}, \vec{b} \rangle$ for each variable
  - Peek expression: generate fresh $\vec{v}$
  - Push expression: copy $\vec{v}$ into **A**
  - Pop expression: increment o

Combining Linear Filters

- Pipelines and splitjoins can be collapsed
- Example: pipeline

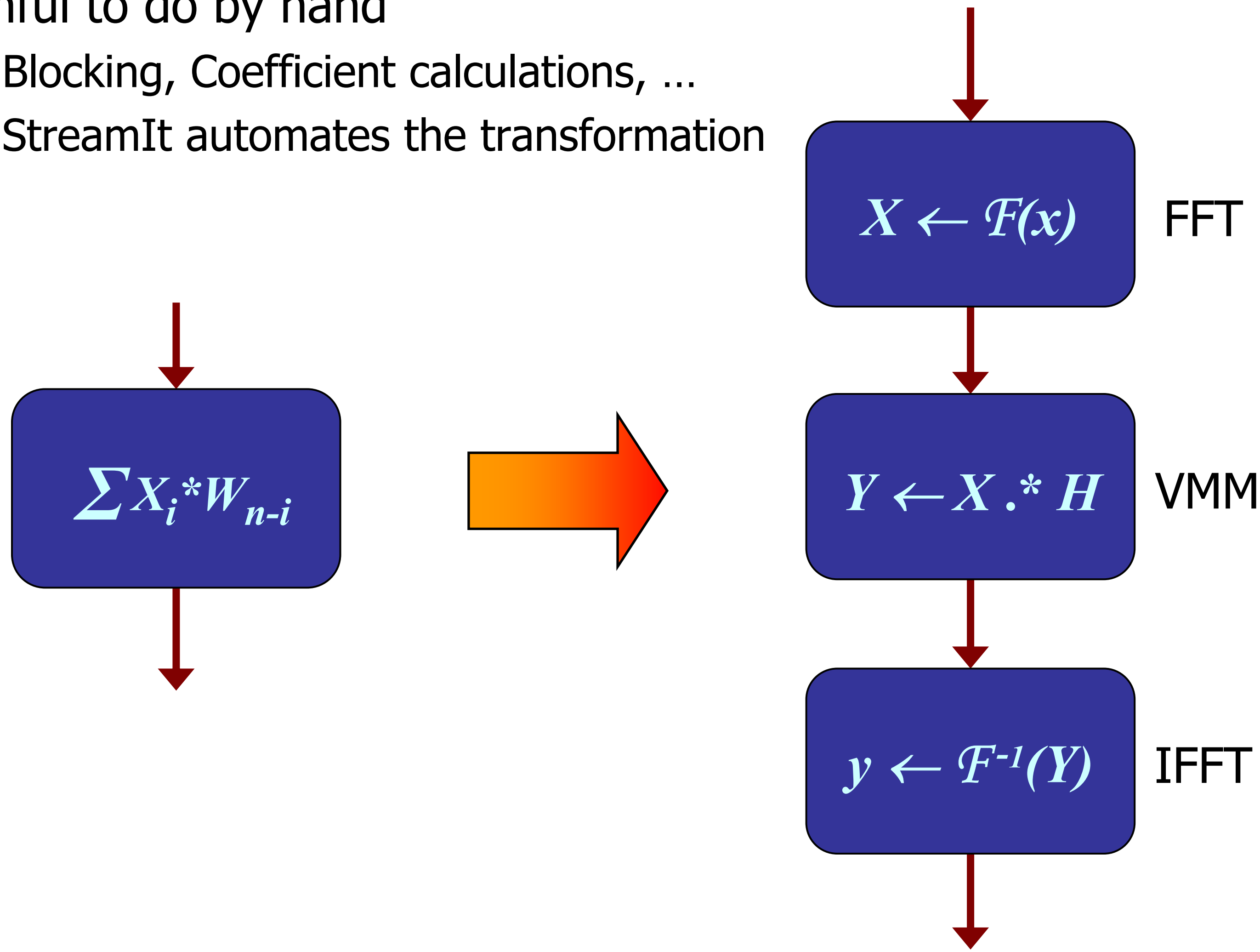


Combination Example

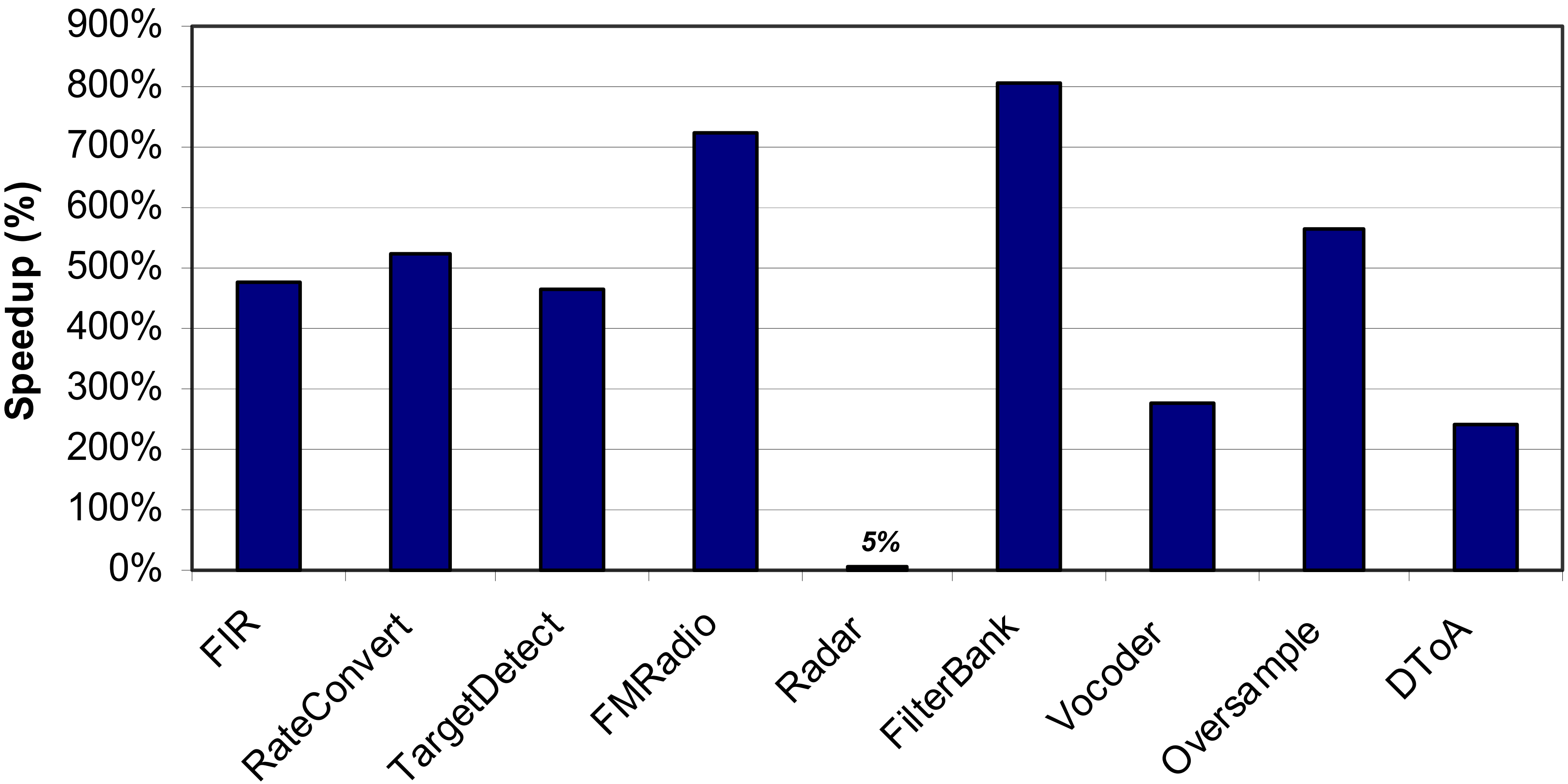


From Time to Frequency Domain

- Convolutions are cheap in the Frequency Domain
  - Painful to do by hand
    - Blocking, Coefficient calculations, …
    - StreamIt automates the transformation

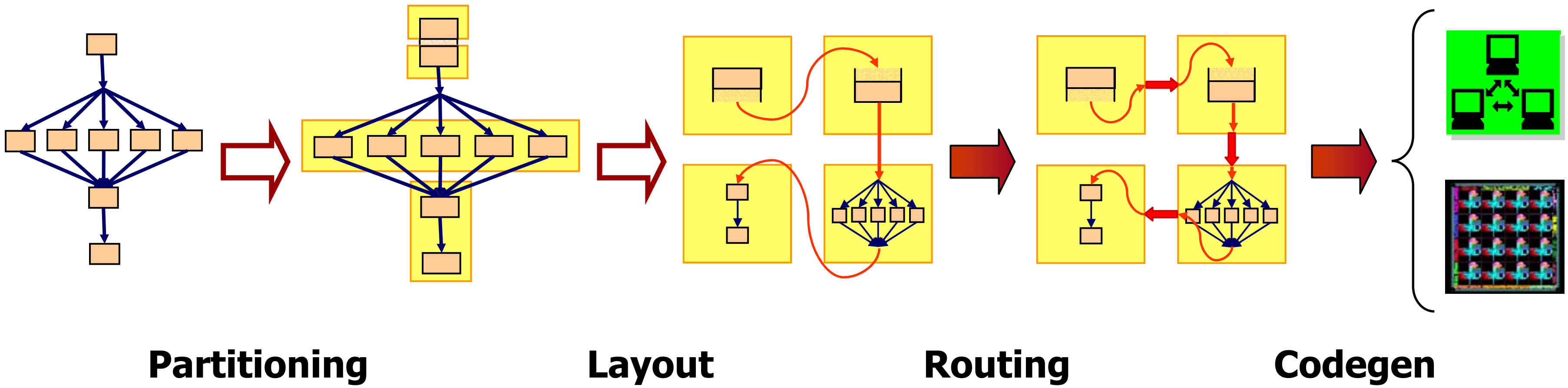


Linear Optimization of Stream Graph



On a Pentium IV

Backend for Parallel Platforms



- StreamIt exposes communication patterns
  - Automatic generation and optimization of routing code
  - Otherwise, may require extensive (assembly) programming

    FIR – Raw backend

    - 15 statements of StreamIt code achieve the same performance as 352 statements of manually-tuned C

    Frequency Hopping Radio – cluster backend

    - 50% higher throughput and 35% less communication, when using StreamIt's messaging construct

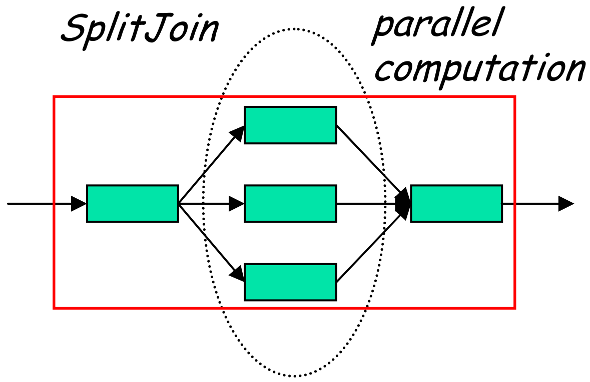
Development Support

StreamIt Development Tool (SDT)

- Graphical development environment
- Text editor
  - Key-word highlighting and indentation schemes
- Graphical editor for the rapid prototyping of stream applications
  - Fast composition of stream graphs
- Graphical debugger
  - Step by step execution
  - Inspection and modification of program variables
- Online help manuals
- Integrated with the IBM Eclipse Tool Platform
  - Available at http://cag.csail.mit.edu/streamit/html/eclipse-plugin.html

Debugging Parallel StreamIt Programs

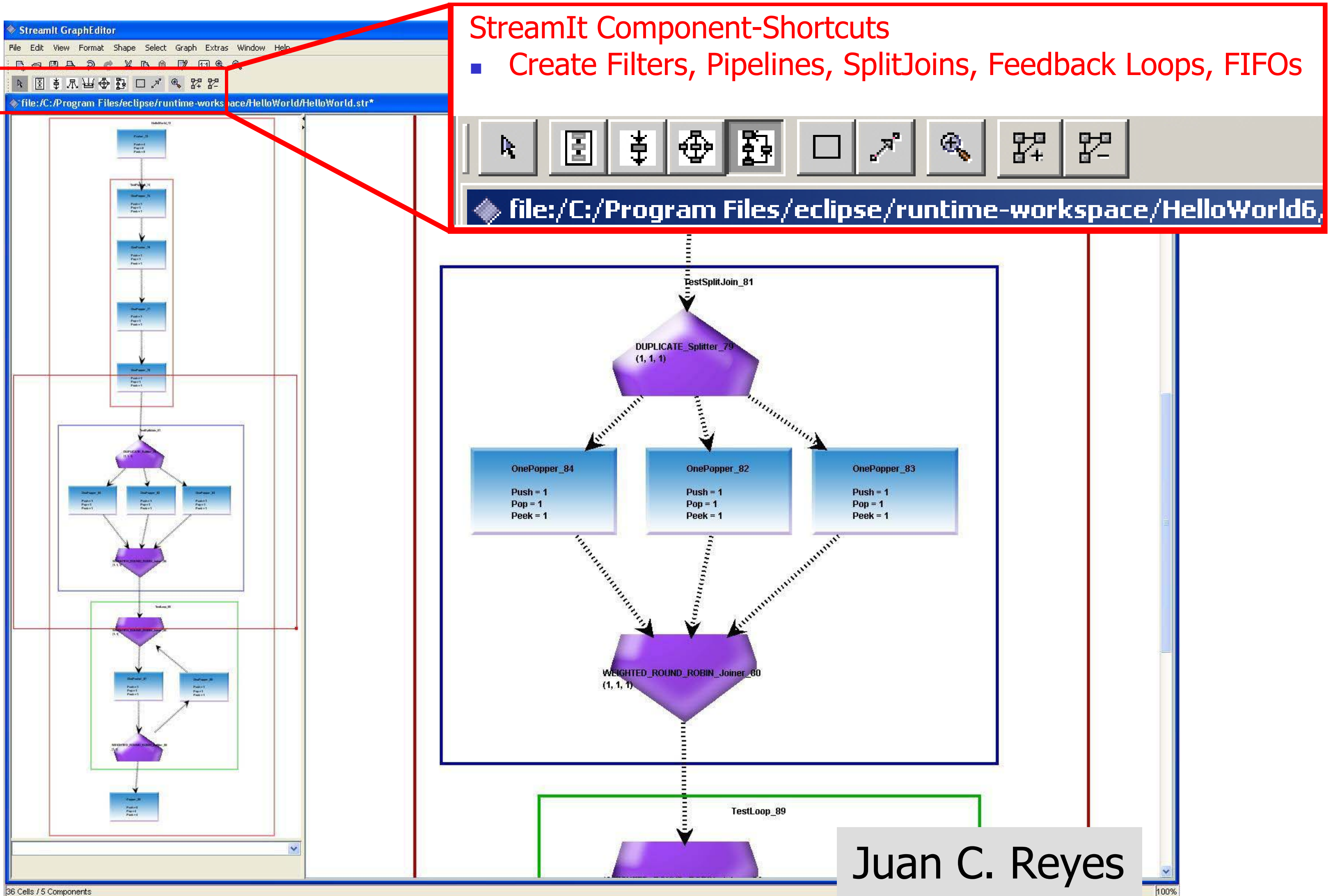
- Parallelism and communication are exposed
  - Tracking the flow of data in a stream graph affords a frame of reference for reasoning about "time"
  - Powerful advantage when debugging parallel programs



versus

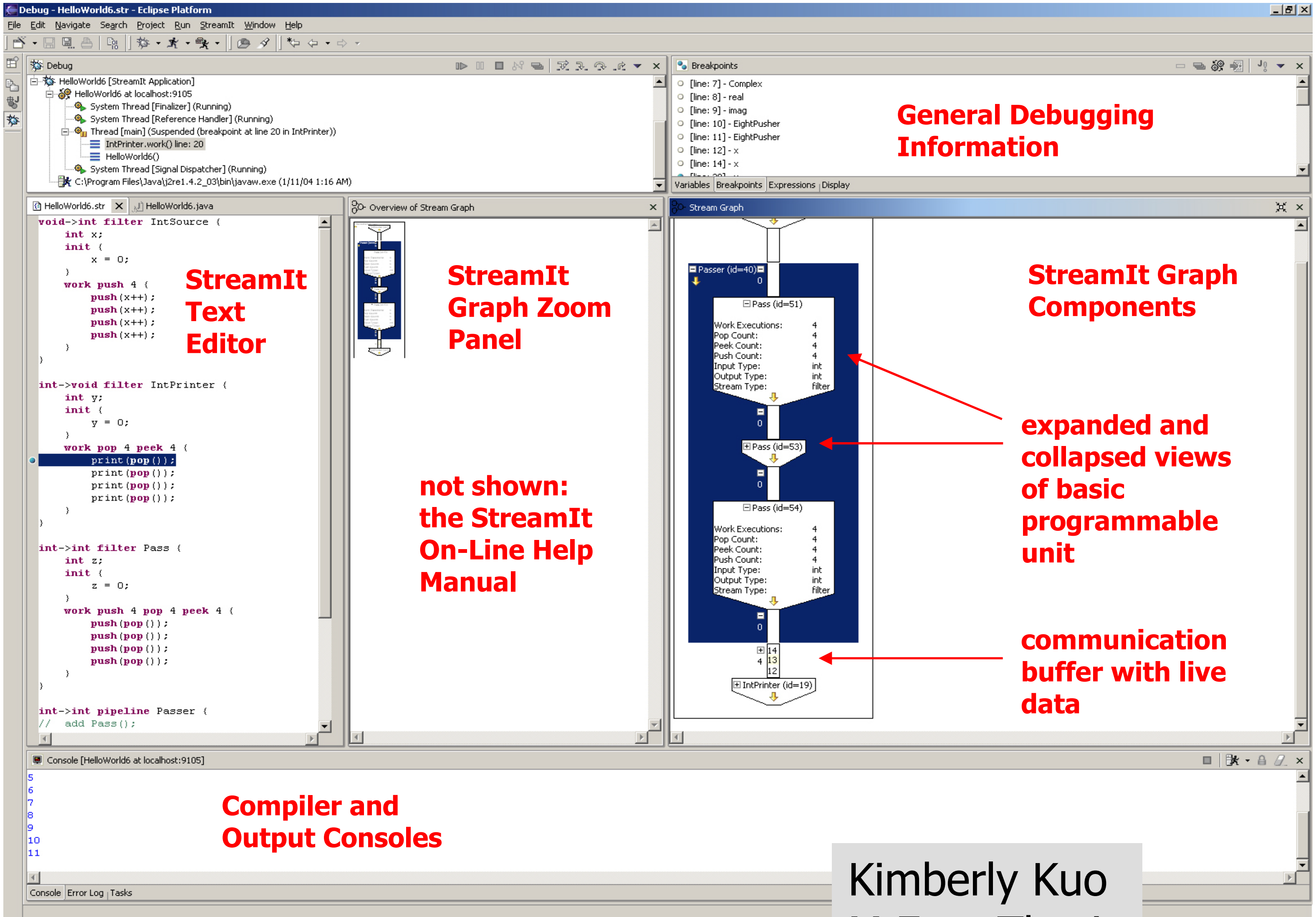
- Multiple threads with independent program counters
- Non-deterministic execution

StreamIt Graphical Editor



Juan C. Reyes
M.Eng. Thesis

StreamIt Debugging Environment



Kimberly Kuo
M.Eng. Thesis

Programmer Evaluation of the SDT

- A detailed study was held in April to evaluate the SDT from a user’s perspective
  - Monitored environment to track user progress on a core set of problems
    - Language and SDT tutorial
    - Pre-study and post-study questionnaires
    - Post-study interview
- Visualization capabilities in the SDT considered "invaluable" to some users
  - Especially when stream graphs were large (and generated recursively)
- The ability to track the flow of data was also considered extremely helpful
- Many lessons learned!

For More Information

StreamIt Homepage

http://cag.csail.mit.edu/streamit

download papers, benchmarks, compiler, SDT, ...