A Stream Compiler for Communication-Exposed Architectures

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The Streaming Domain

- Widely applicable and increasingly prevalent
  - Embedded systems
    - Cell phones, handheld computers, DSP's
  - Desktop applications
    - Streaming media
    - Software radio
    - Real-time encryption
    - Graphics packages
  - High-performance servers
    - Software routers (Example: Click)
    - Cell phone base stations
    - HDTV editing consoles
- Based on audio, video, or data stream
  - Predominant data types in the current data explosion

Properties of Stream Programs

- A large (possibly infinite) amount of data
  - Limited lifetime of each data item
  - Little processing of each data item
- Computation: apply multiple filters to data
  - Each filter takes an input stream, does some processing, and produces an output stream
  - Filters are independent and self-contained
- A regular, static computation pattern
  - Filter graph is relatively constant
  - A lot of opportunities for compiler optimizations

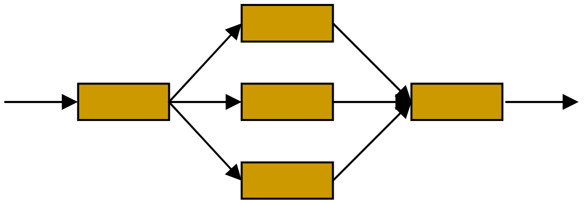
StreamIt: A spatially-aware Language & Compiler

- A language for streaming applications
  - Provides high-level stream abstraction
- Breaks the Von Neumann language barrier
  - Each filter has its own control-flow
  - Each filter has its own address space
  - No global time
  - Explicit data movement between filters
  - Compiler is free to reorganize the computation
- Spatially-aware Compiler
  - Intermediate representation with stream constructs
  - Provides a host of stream analyses and optimizations

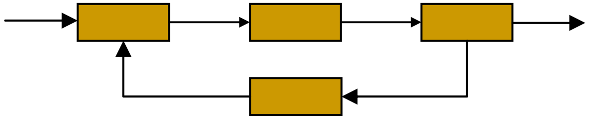
Structured Streams

- Hierarchical structures:
  - Pipeline

  - SplitJoin



  - Feedback Loop



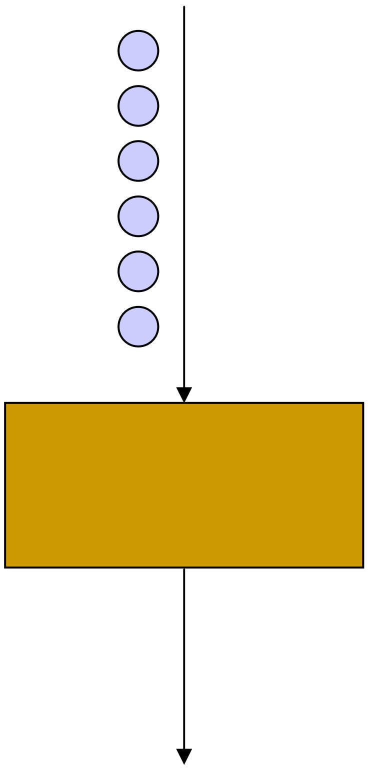
- Basic programmable unit: Filter

Filter Example: LowPassFilter

```
float->float filter LowPassFilter(int N) {
    float[N] weights;

    init {
        for (int i=0; i<N; i++)
            weights[i] = calcWeights(i);
    }

    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();
    }
}
```



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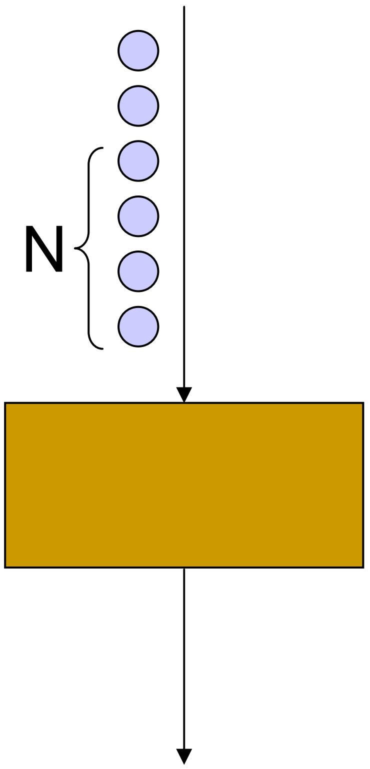

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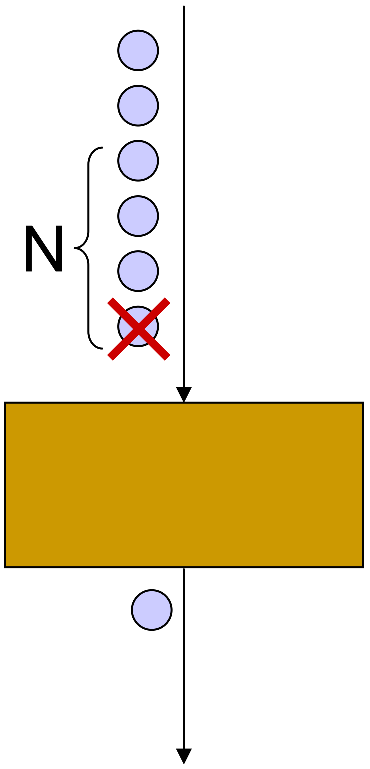

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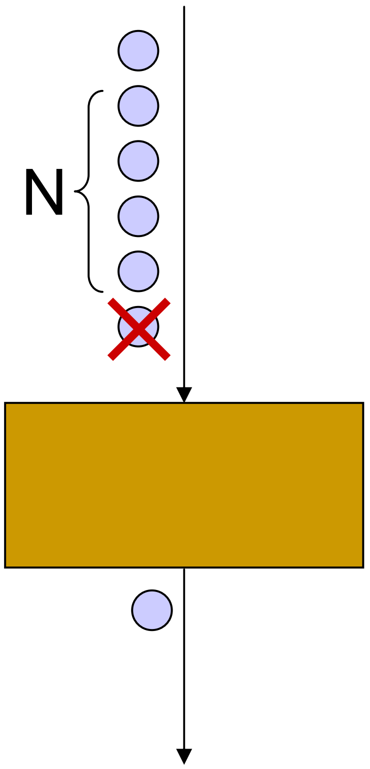

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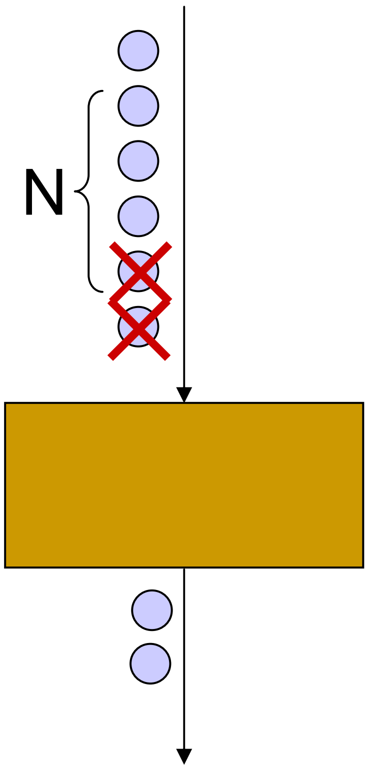
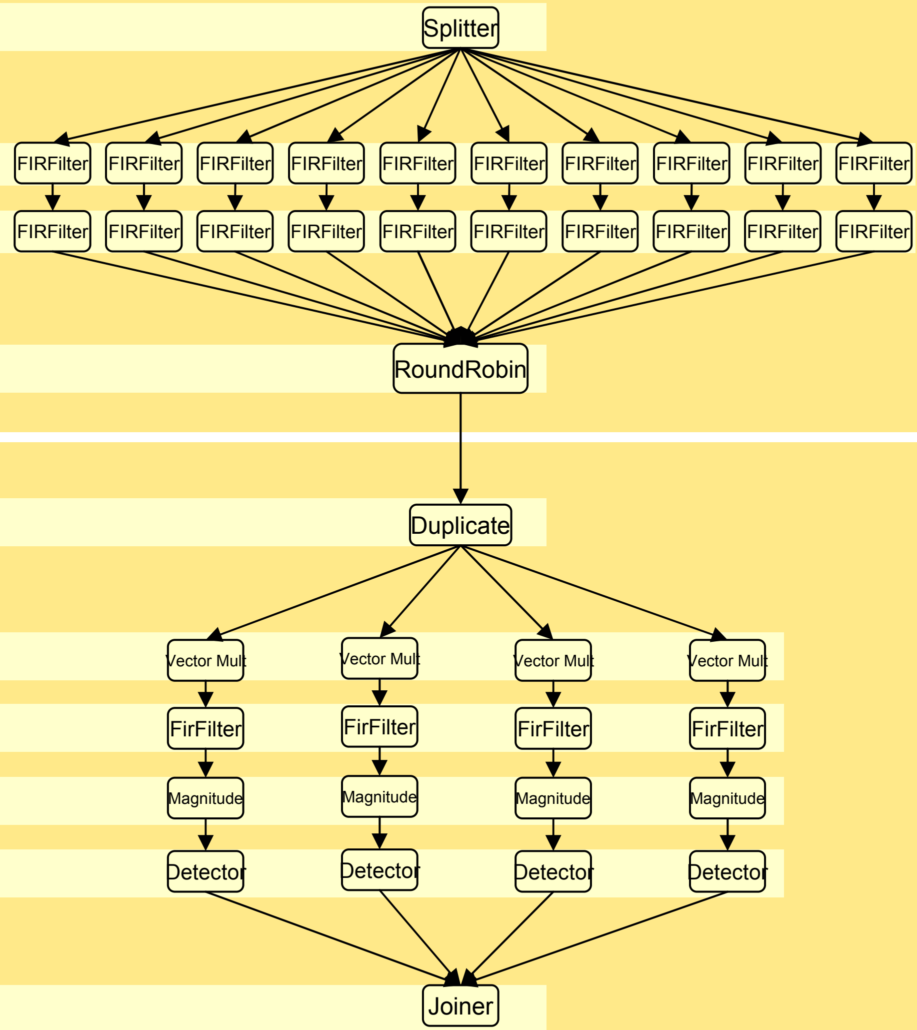


Example: Radar Array Front End

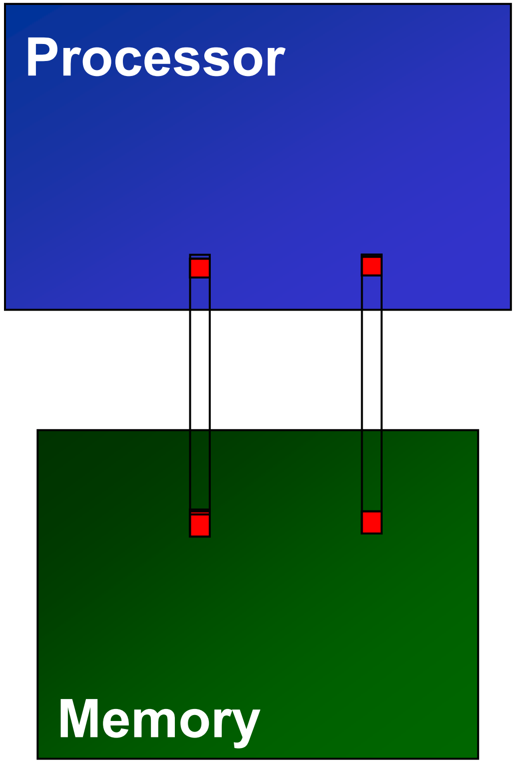
```
complex->void pipeline BeamFormer(int numChannels, int numBeams)
    {
        add splitjoin {
            split duplicate;
            for (int i=0; i<numChannels; i++) {
                add pipeline {
                    add FIR1(N1);
                    add FIR2(N2);
                };
            };
            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);
        };
}
```



How to execute a Stream Graph?
Method 1: Time Multiplexing

- Run one filter at a time

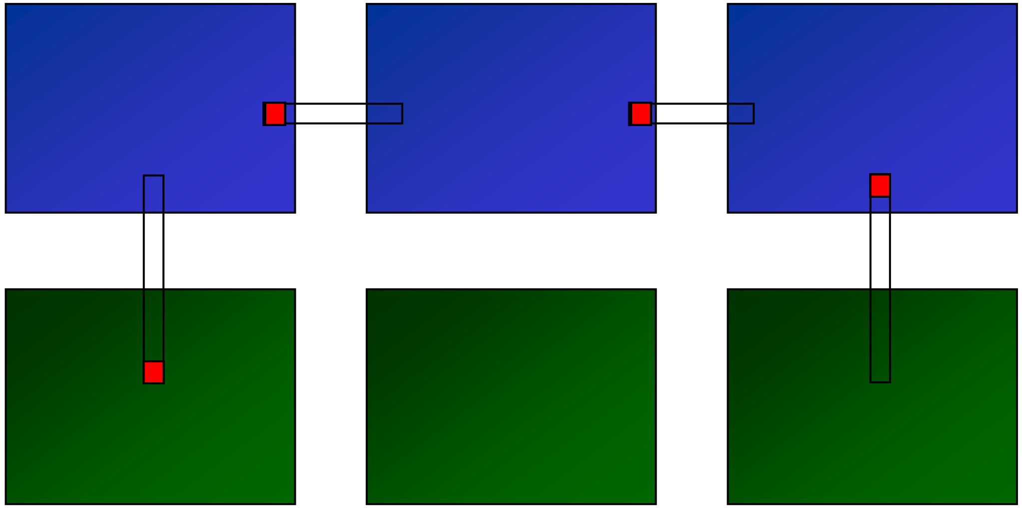
- Pros:
  - Scheduling is easy
  - Synchronization from Memory
- Cons:
  - If a filter run is too short
    - Filter load overhead is high
  - If a filter run is too long
    - Data spills down the cache hierarchy
    - Long latency
  - Lots of memory traffic
    - Bad cache effects
  - Does not scale with spatially-aware architectures



How to execute a Stream Graph? Method 2: Space Multiplexing

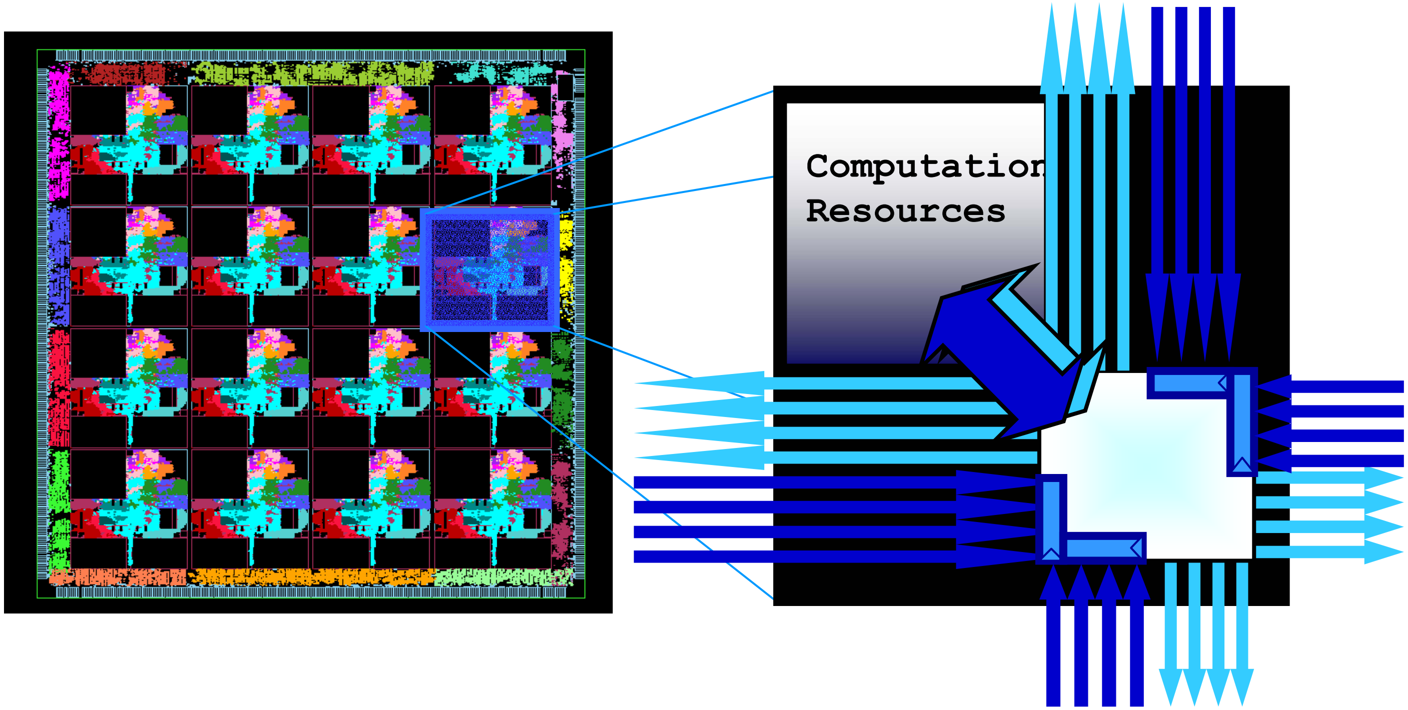
- Map filter per tile and run forever

- Pros:
  - No filter swapping overhead
  - Exploits spatially-aware architectures
    - Scales well
  - Reduced memory traffic
  - Localized communication
  - Tighter latencies
  - Smaller live data set



- Cons:
  - Load balancing is critical
  - Not good for dynamic behavior
  - Requires # filters ≤ # processing elements

The MIT RAW Machine



- A scalable computation fabric
  - 4 x 4 mesh of tiles, each tile is a simple microprocessor
- Ultra fast interconnect network
  - Exposes the wires to the compiler
  - Compiler orchestrate the communication

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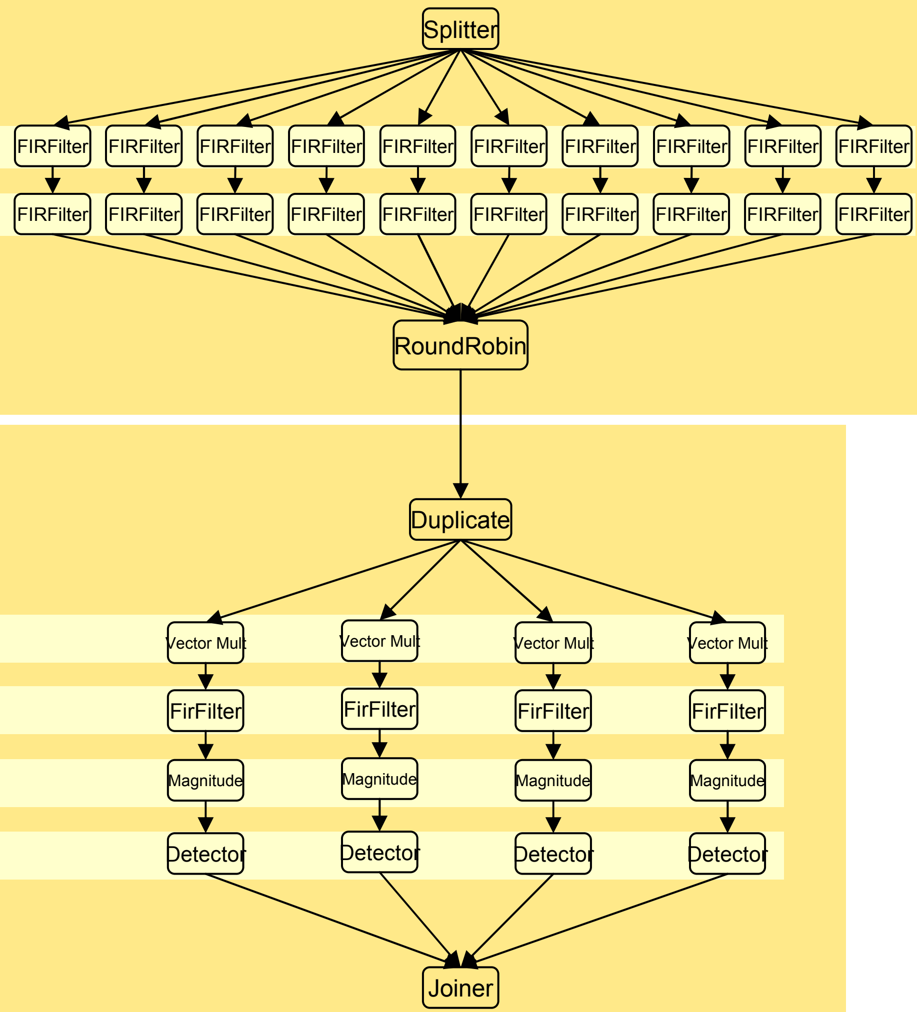
            split duplicate;
            for (int i=0; i<numChannels; i++) {
                add pipeline {
                    add FIR1(N1);

                    add FIR2(N2);
                };
            };
            join roundrobin;
      };
      add splitjoin {
            split duplicate;
            for (int i=0; i<numBeams; i++) {
                add pipeline {
                    add VectorMult();

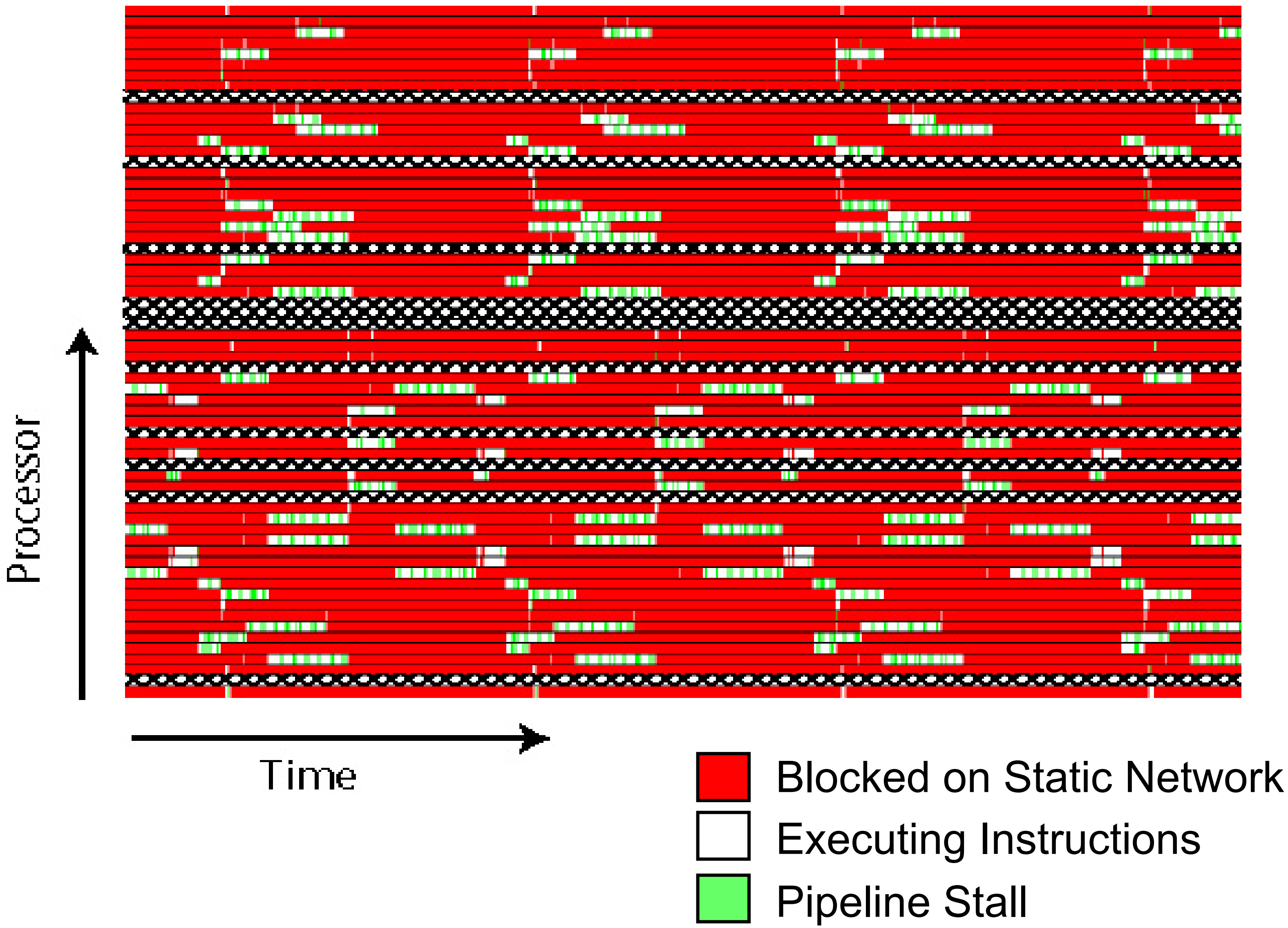
                    add FIR3(N3);

                    add Magnitude();

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



Radar Array Front End on Raw



Bridging the Abstraction layers

- StreamIt language exposes the data movement
  - Graph structure is architecture independent
- Each architecture is different in granularity and topology
  - Communication is exposed to the compiler
- The compiler needs to efficiently bridge the abstraction
  - Map the computation and communication pattern of the program to the PE’s, memory and the communication substrate

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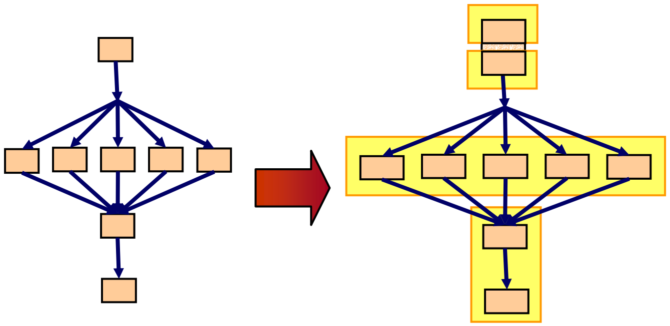
- The compiler needs to efficiently bridge the abstraction
  - Map the computation and communication pattern of the program to the PE's, memory and the communication substrate
- The StreamIt Compiler
  - Partitioning
  - Placement
  - Scheduling
  - Code generation

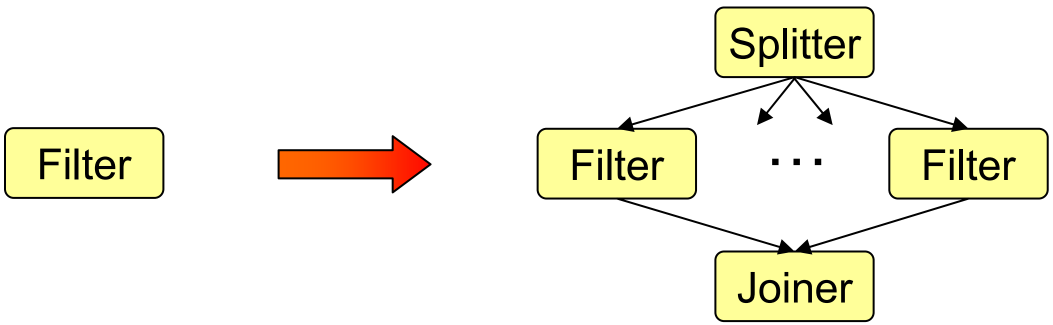
Partitioning: Choosing the Granularity



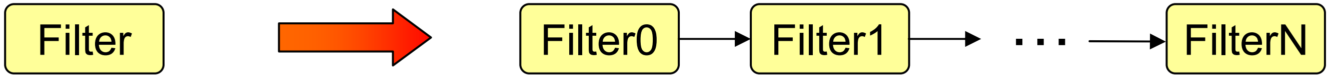
- Mapping filters to tiles
  - – # filters should equal (or a few less than) # of tiles
  - – Each filter should have similar amount of work
    - Throughput determined by the filter with most work
- Compiler Algorithm
  - – Two primary transformations
    - Filter fission
    - Filter fusion
  - – Uses a greedy heuristic

Partitioning - Fission

- Fission - splitting streams
  - Duplicate a filter, placing the duplicates in a SplitJoin to expose parallelism.

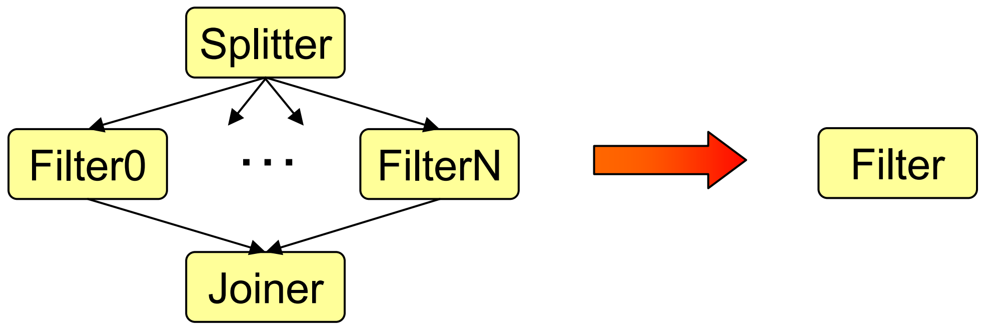


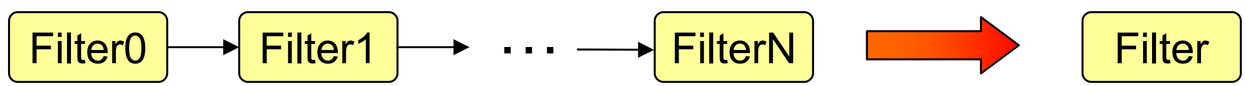
–Split a filter into a pipeline for load balancing



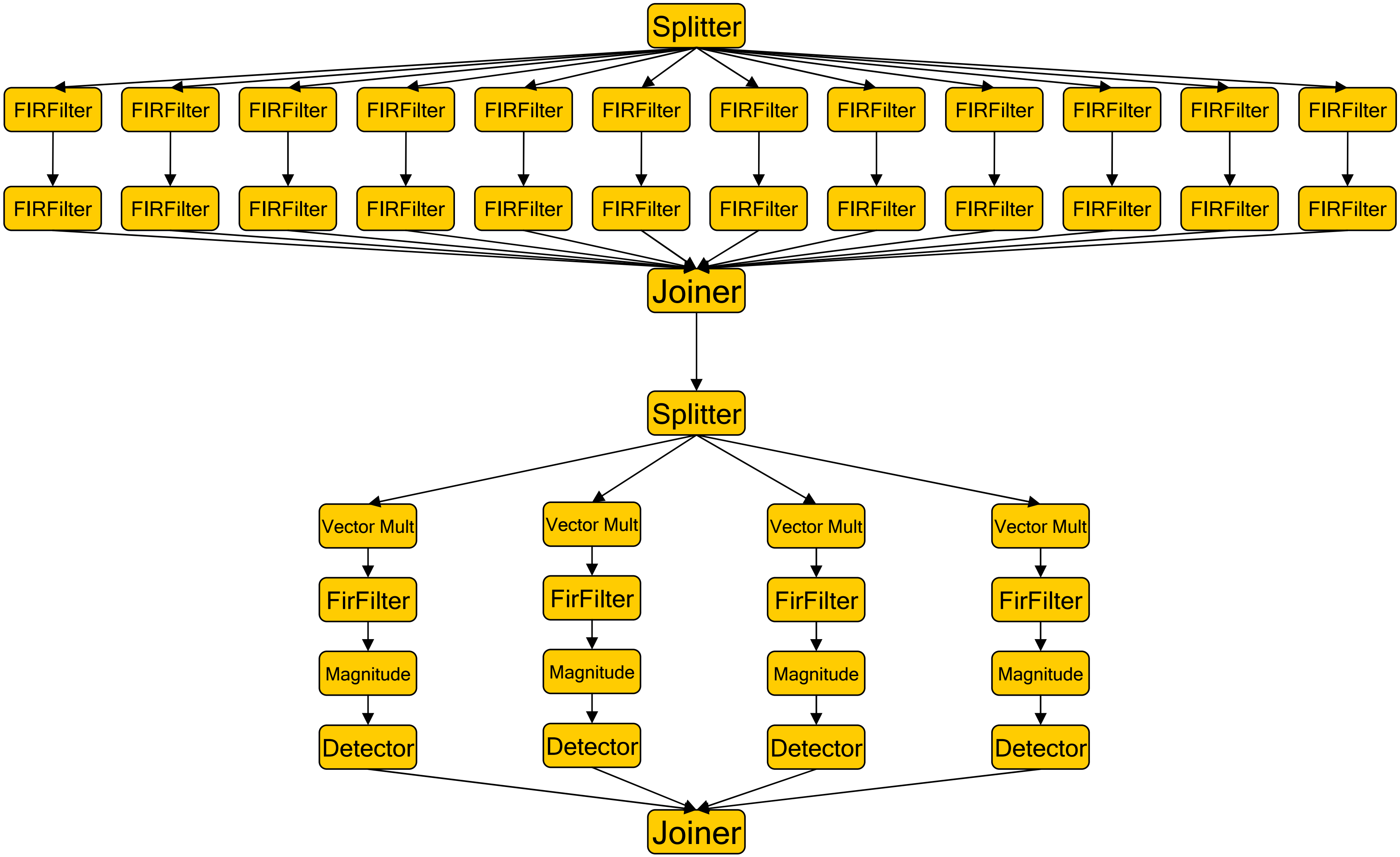
Partitioning - Fusion

- Fusion - merging streams
  - Merge filters into one filter for load balancing and synchronization removal





Example: Radar Array Front End (Original)



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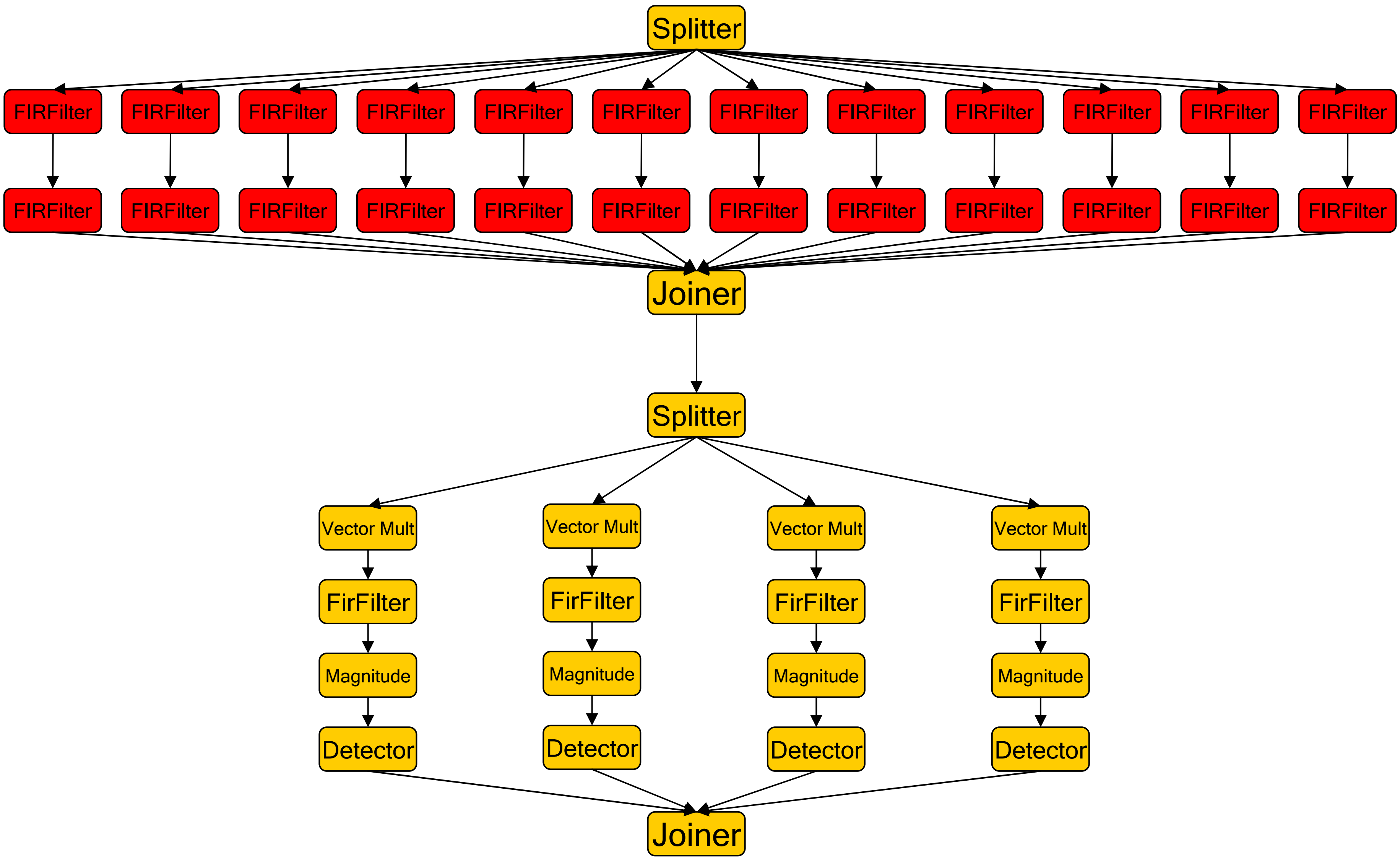

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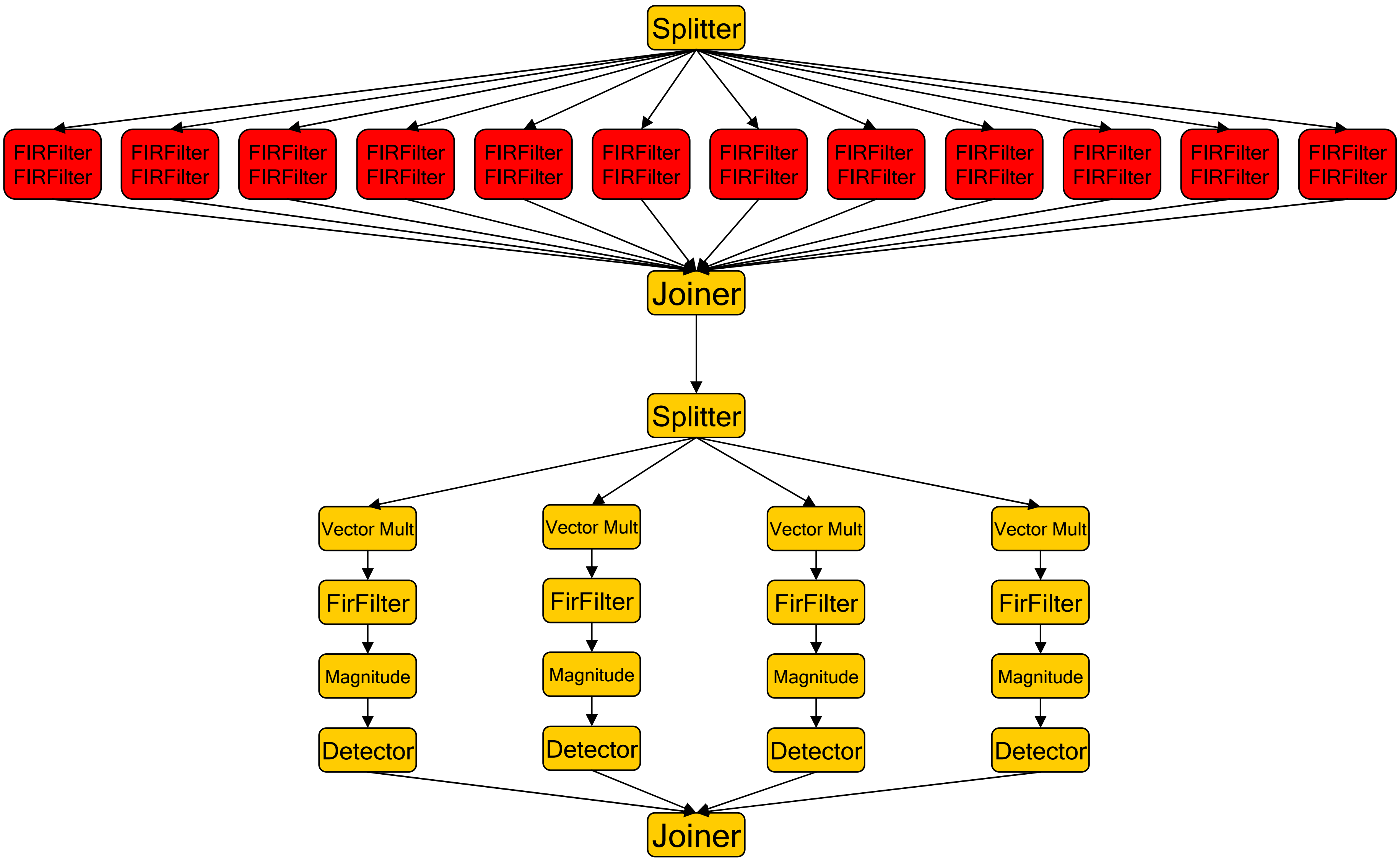

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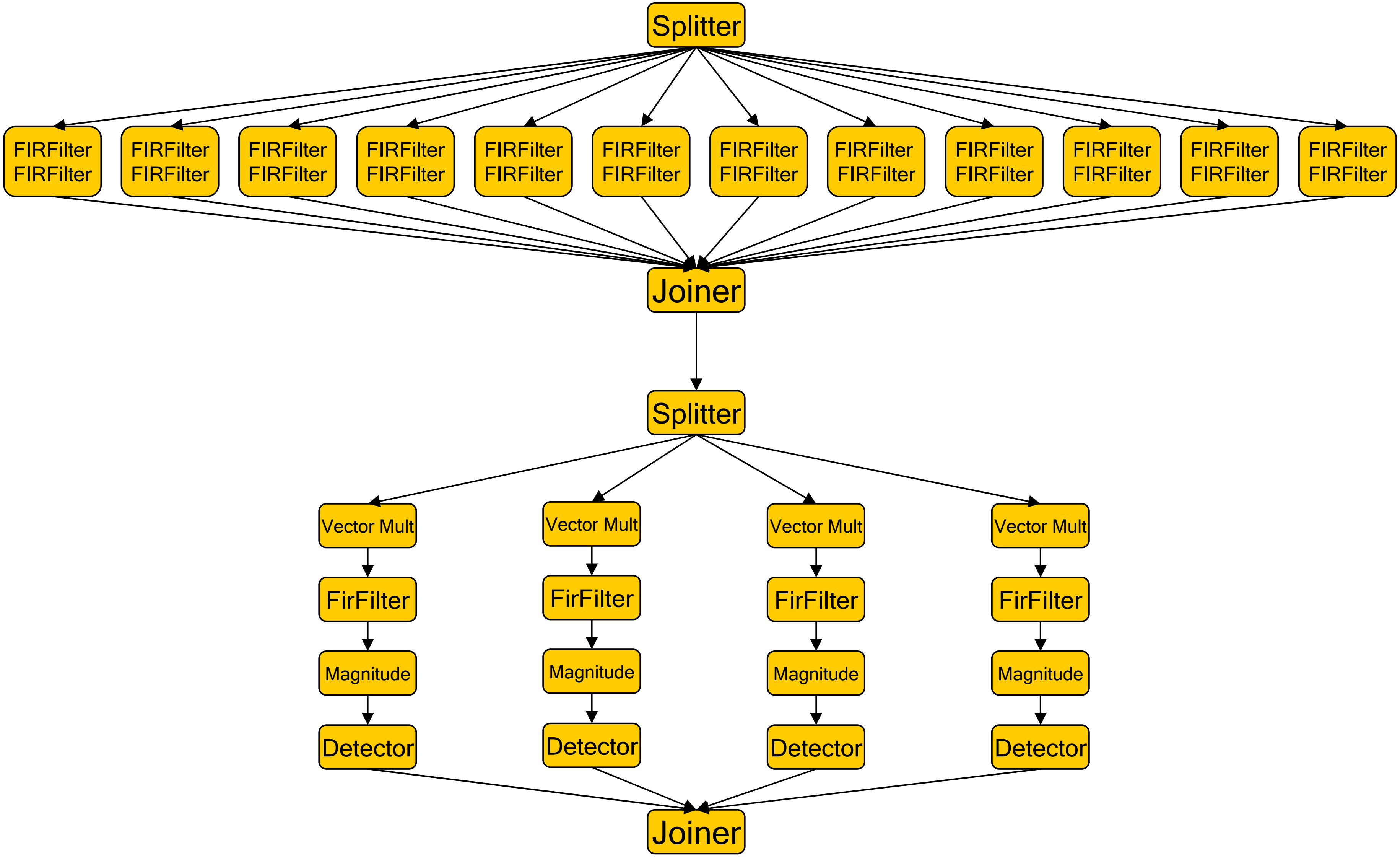

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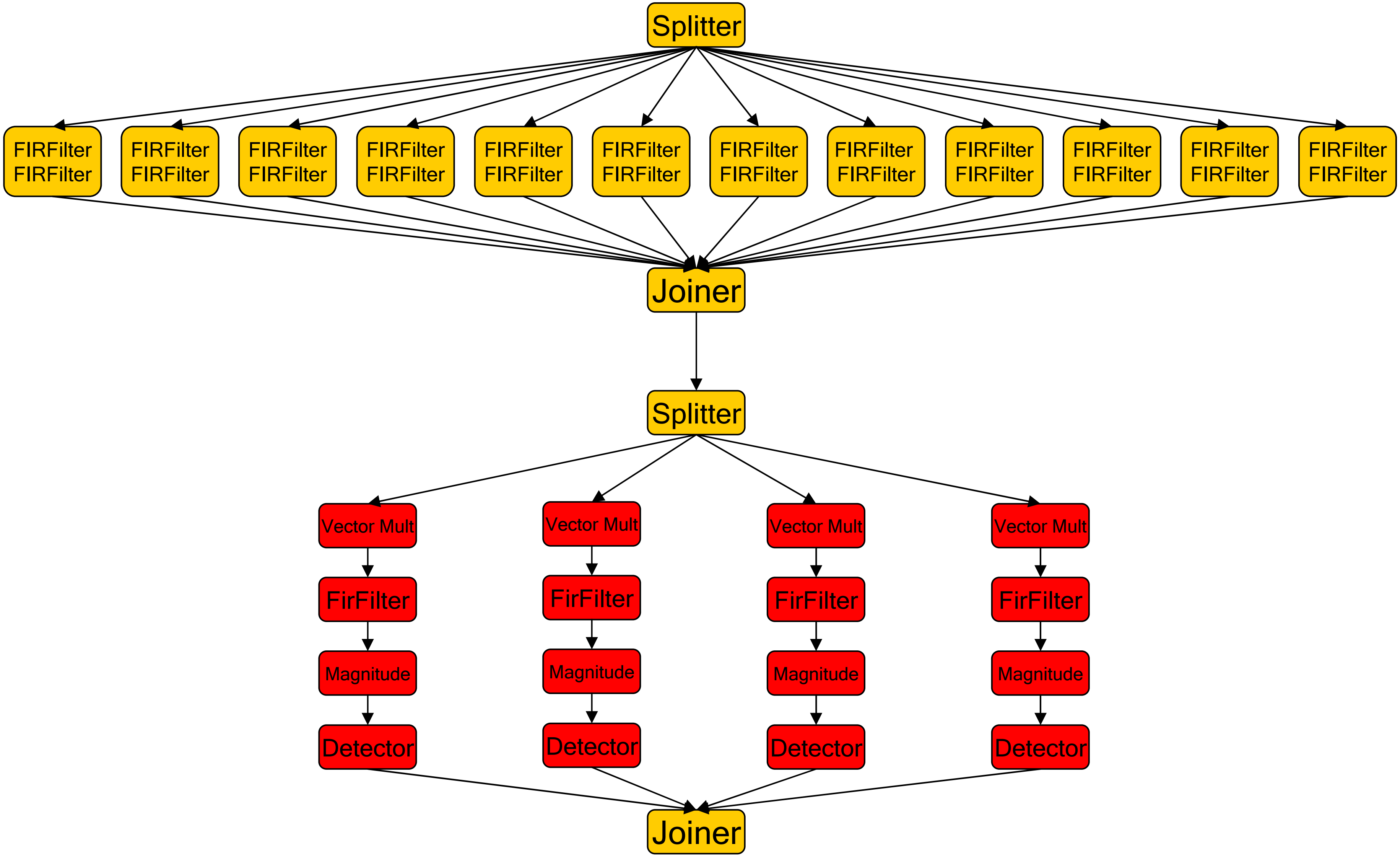

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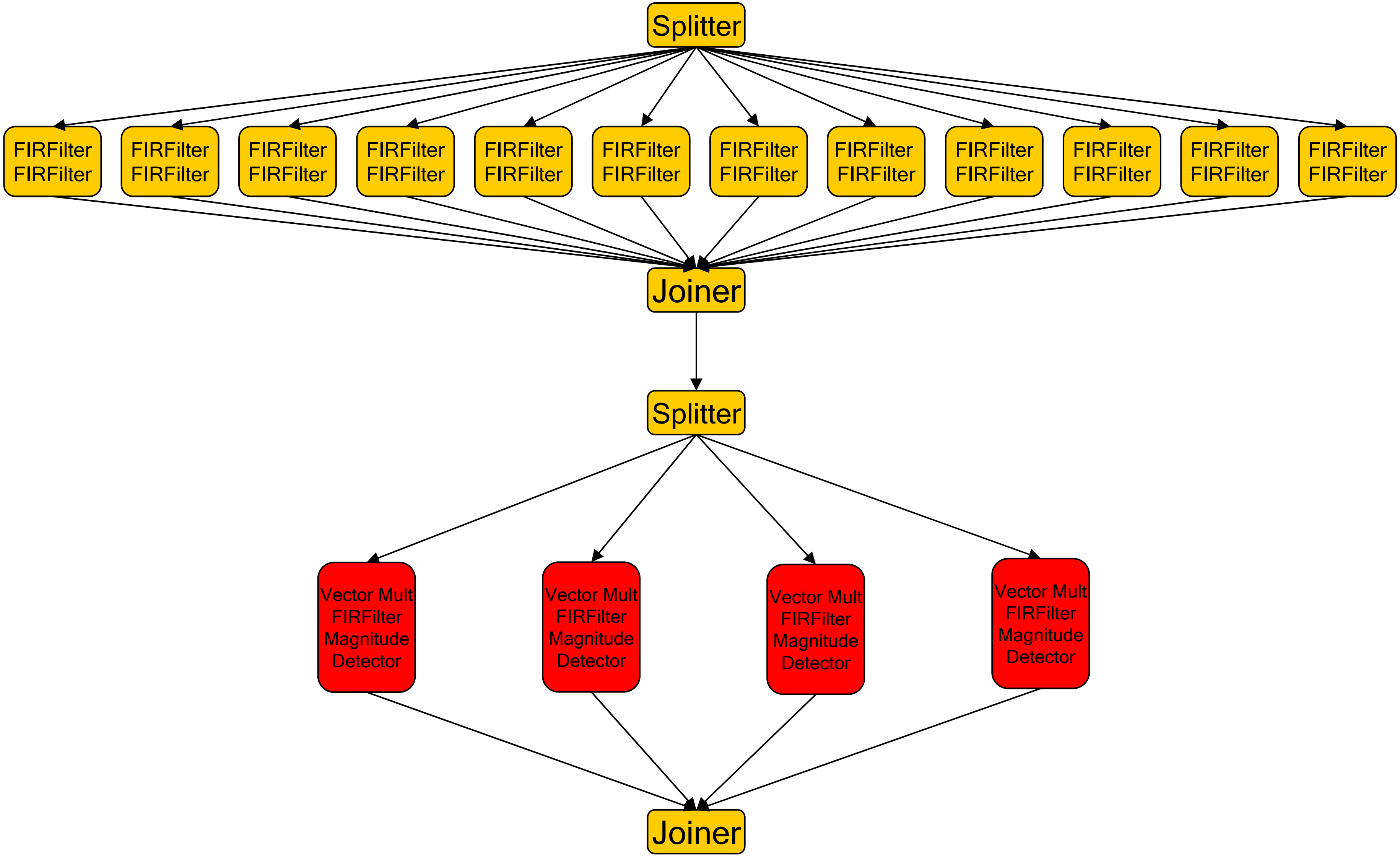

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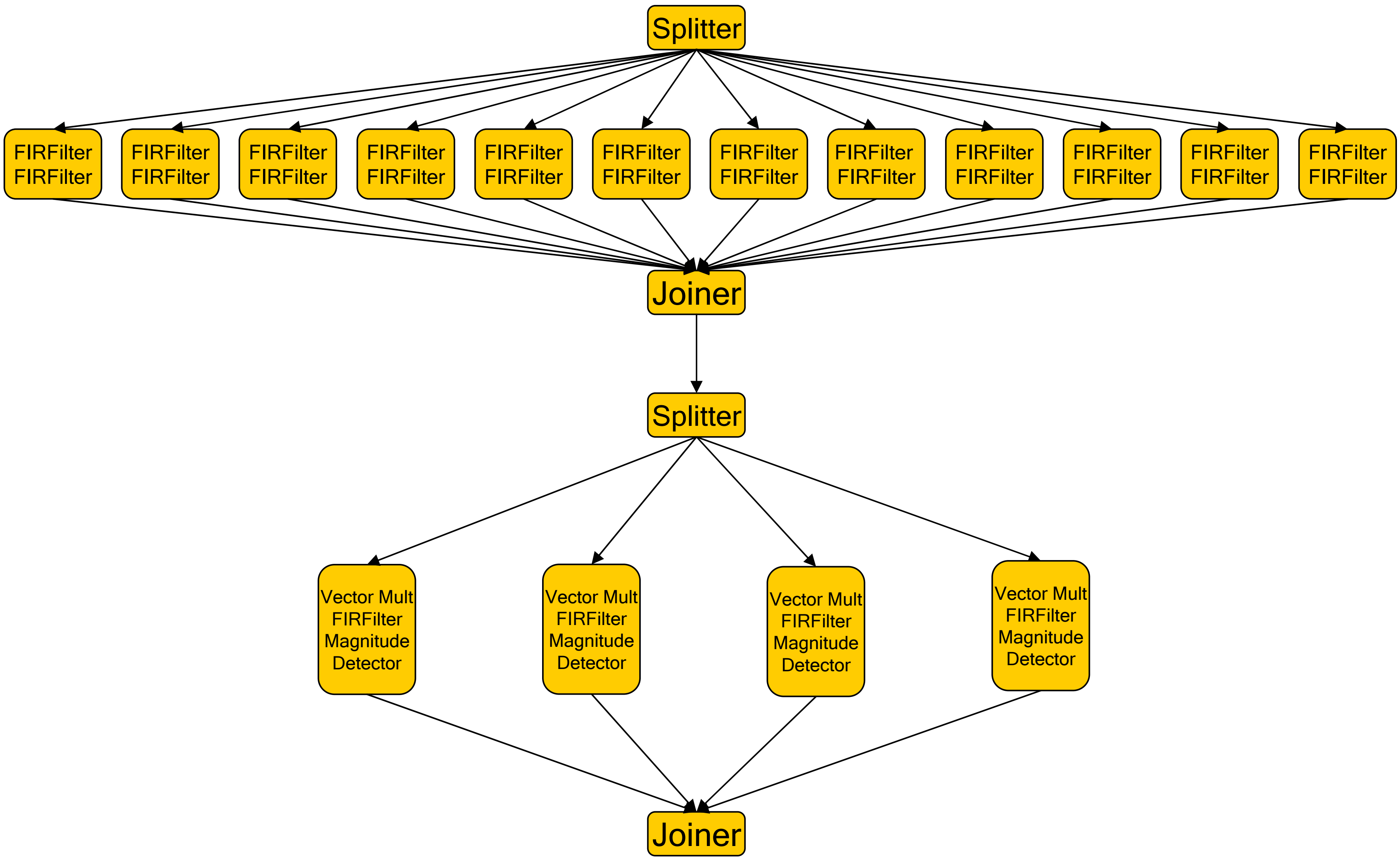

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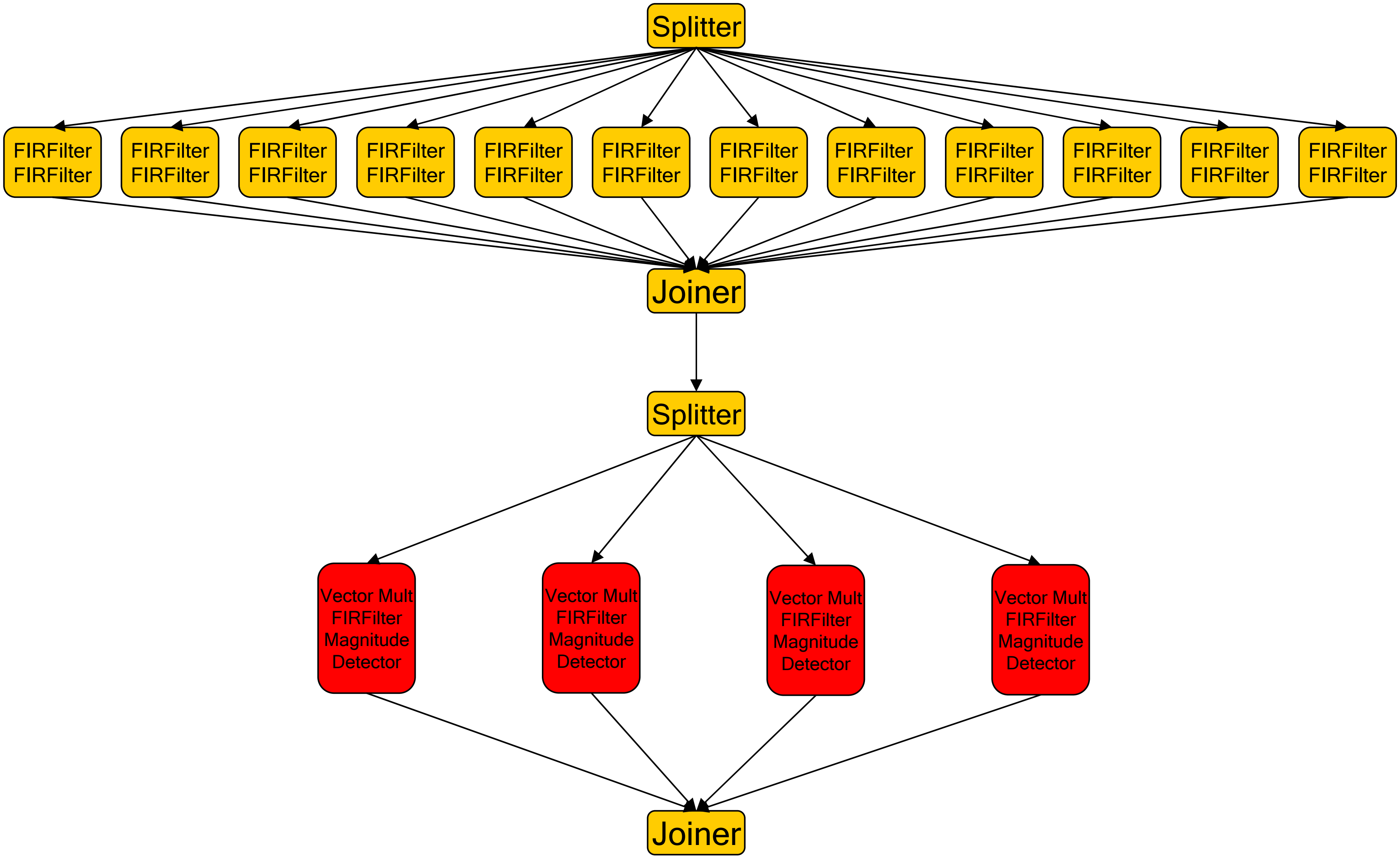

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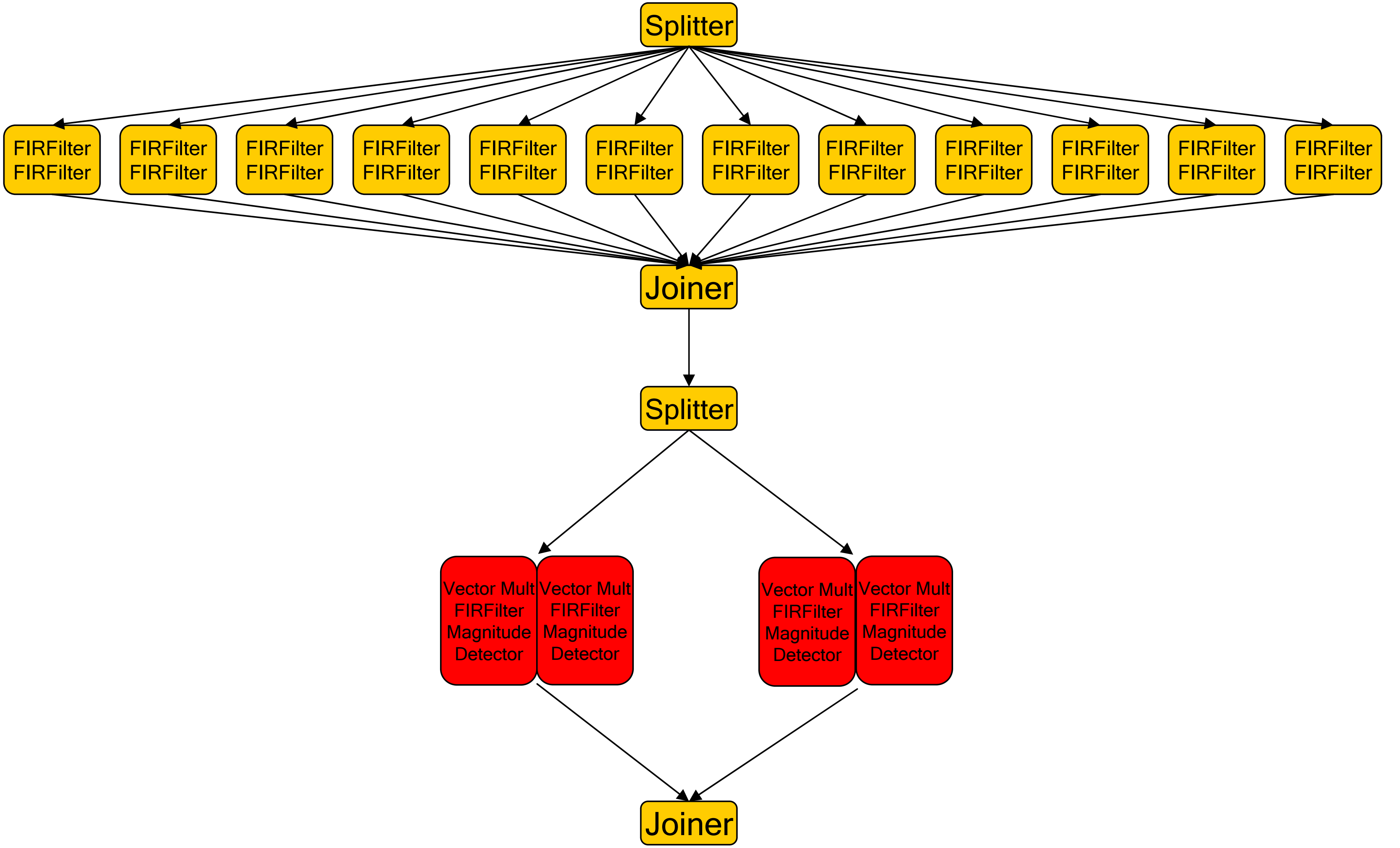
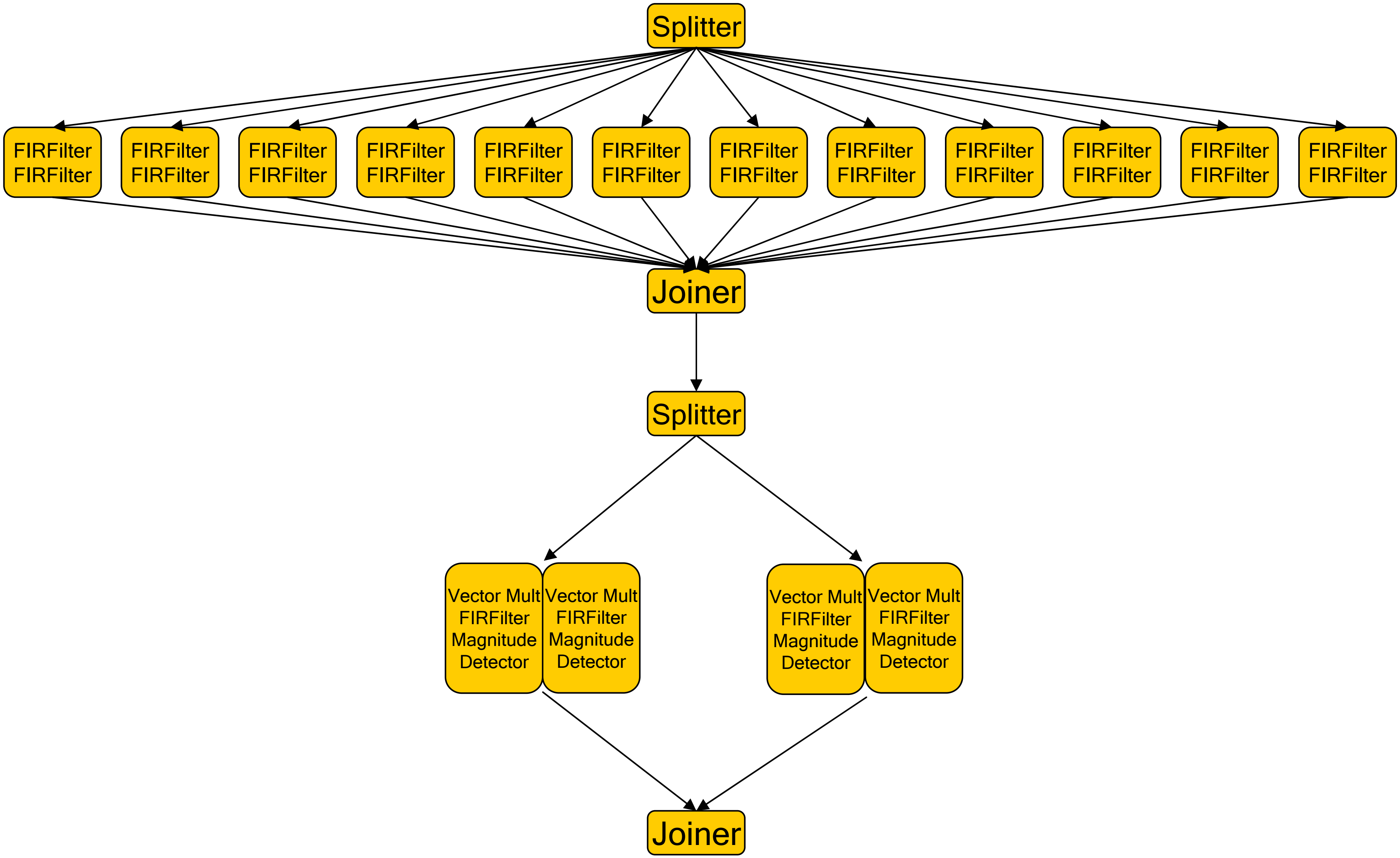
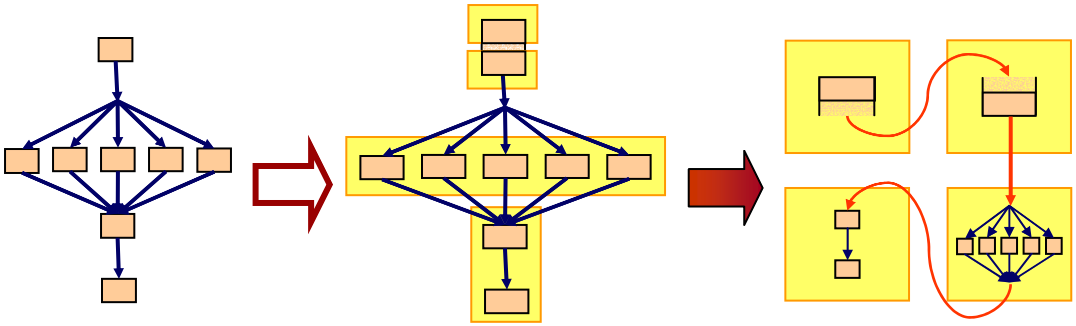


Example: Radar Array Front End (Balanced)

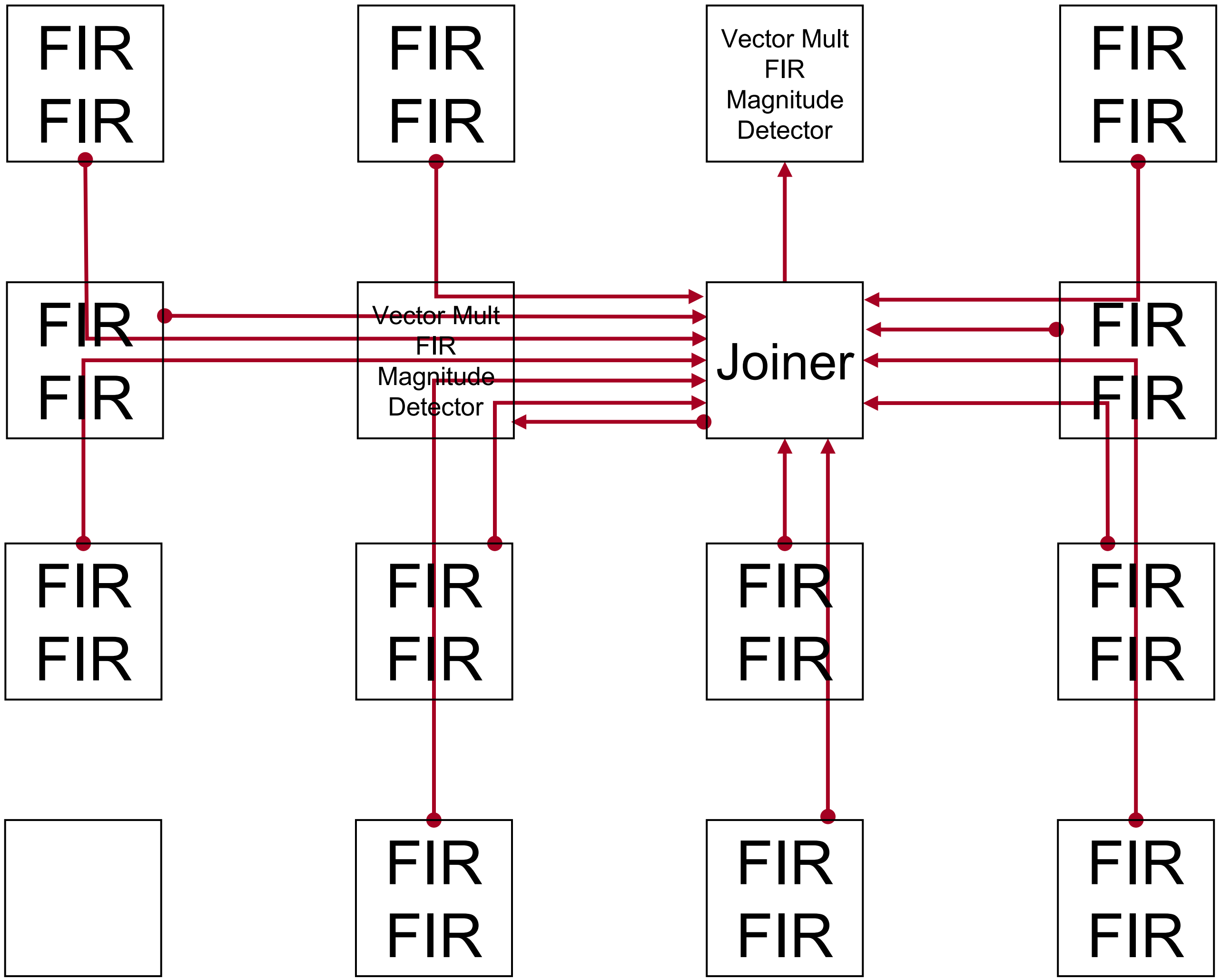


Placement: Minimizing Communication

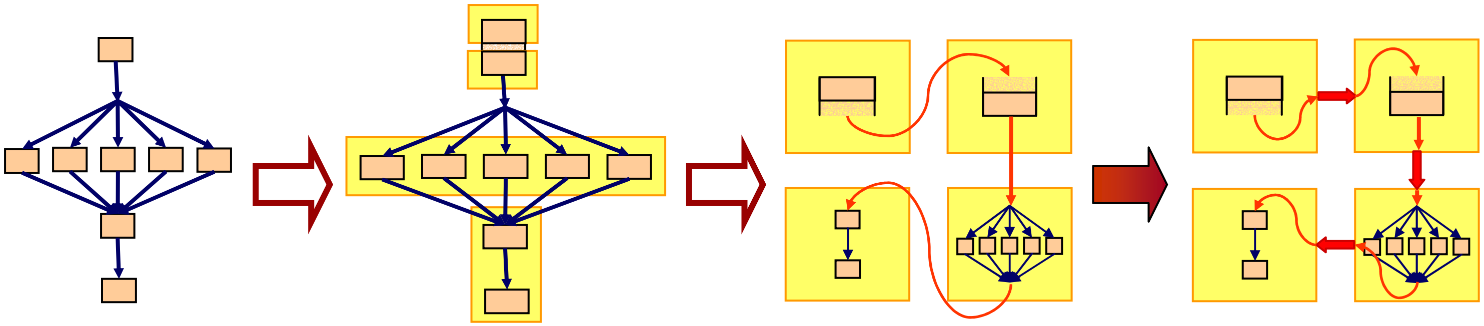


- Assign filters to tiles
  - Communicating filters → try to make them adjacent
  - Reduce overlapping communication paths
  - Reduce/eliminate cyclic communication if possible
- Compiler algorithm
  - Uses Simulated Annealing

Placement for Partitioned Radar Array Front End



Scheduling: Communication Orchestration

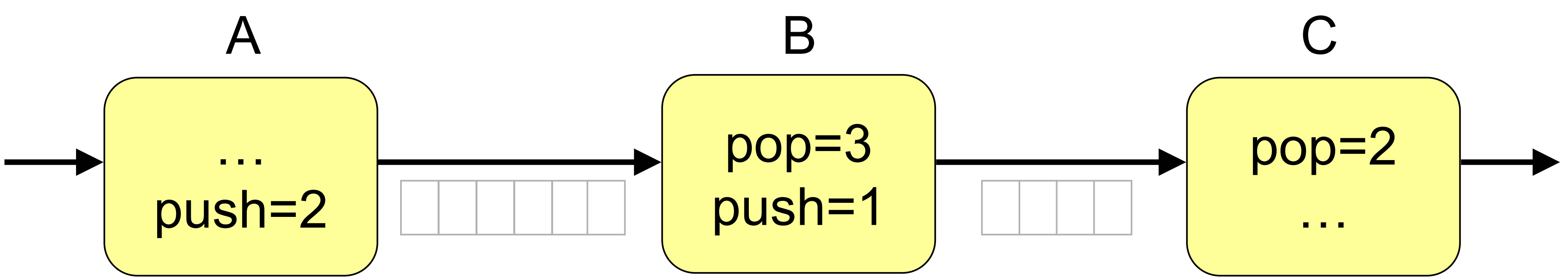


- Create a communication schedule
- Compiler Algorithm
  - Calculate an initialization and steady-state schedule
  - Simulate the execution of an entire cyclic schedule
  - Place static route instructions at the appropriate time

Steady-State Schedule

- All data pop/push rates are constant
- Can find a Steady-State Schedule
  - # of items in the buffers are the same before and the after executing the schedule
  - There exist a unique minimum steady state schedule

- Schedule = { }



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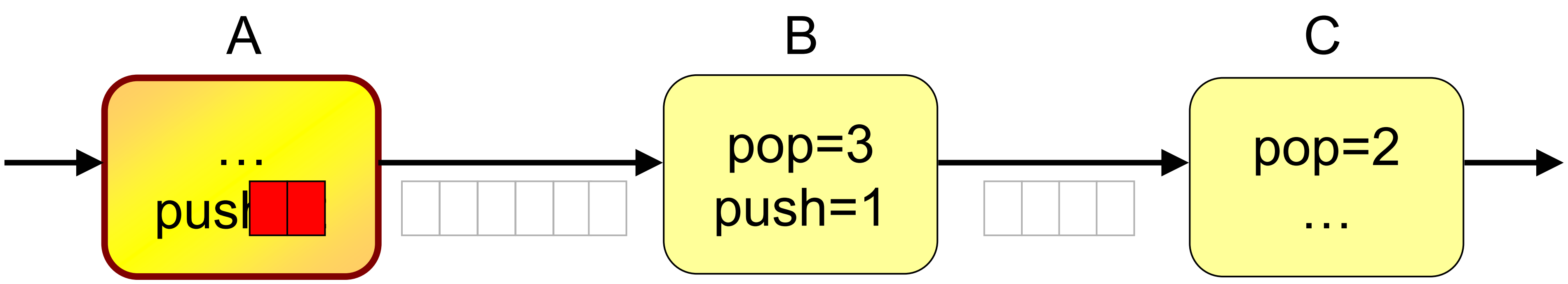

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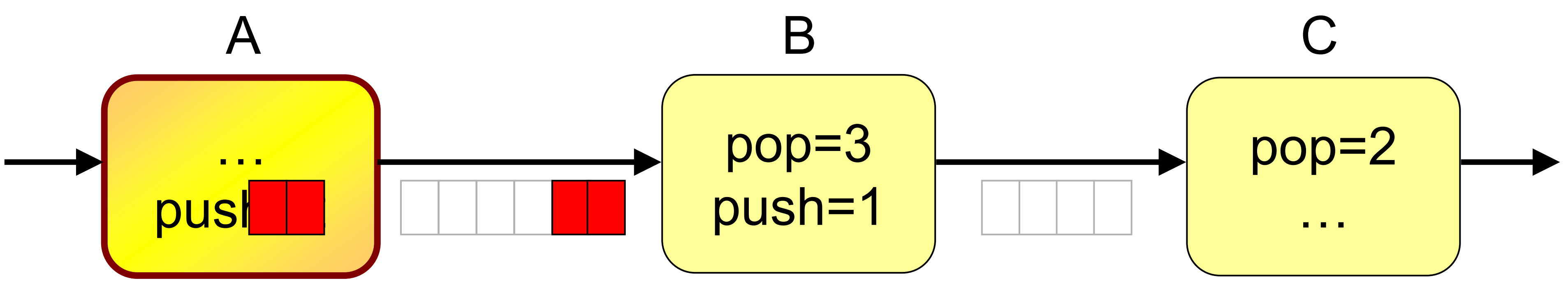

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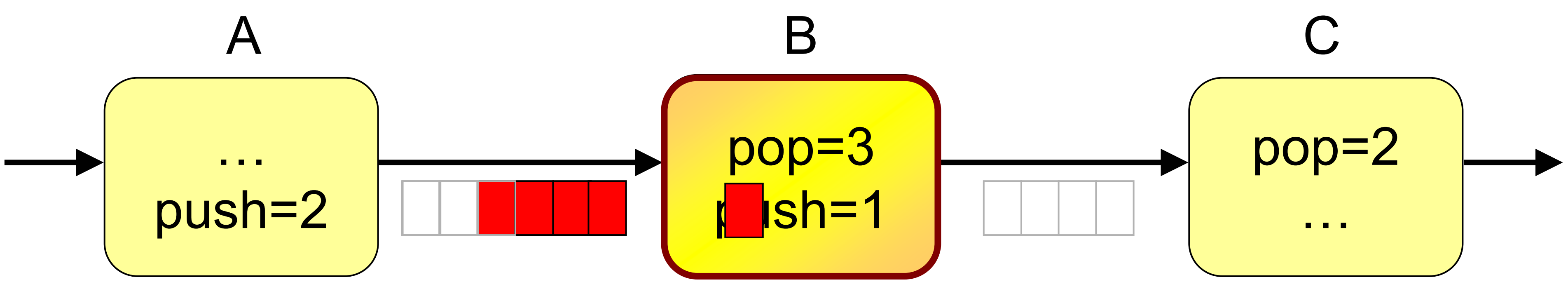
- Schedule = { A, A, B }



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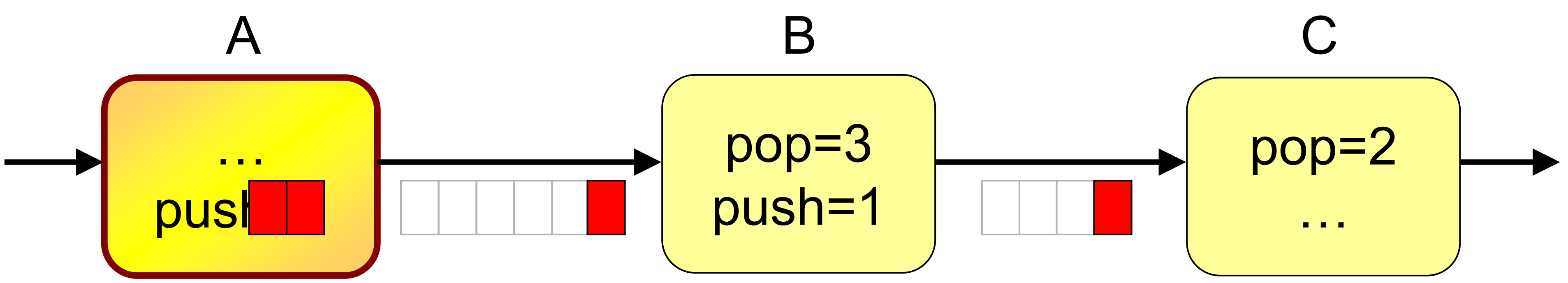

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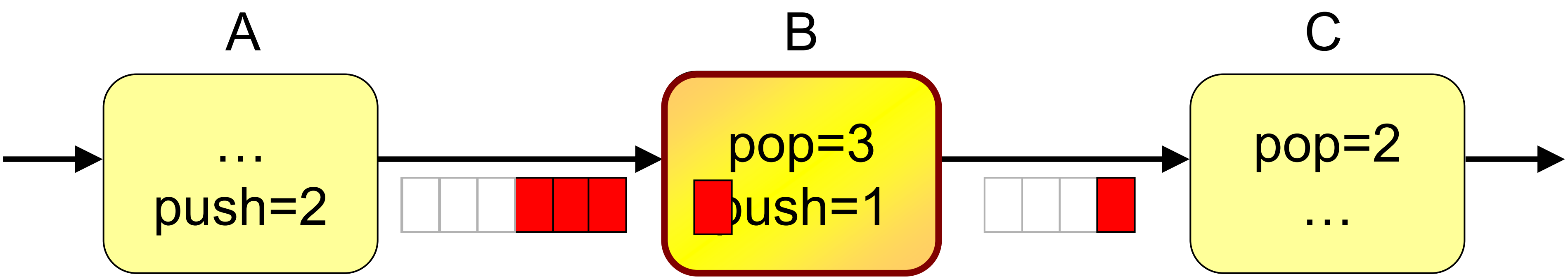

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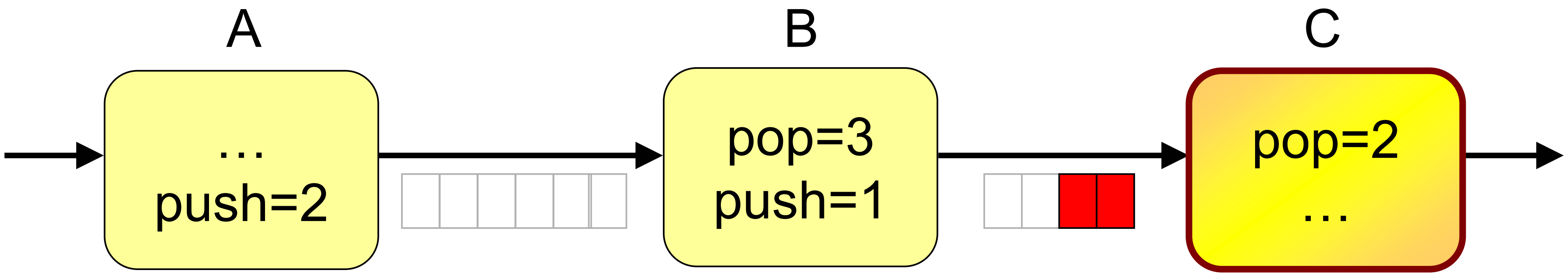
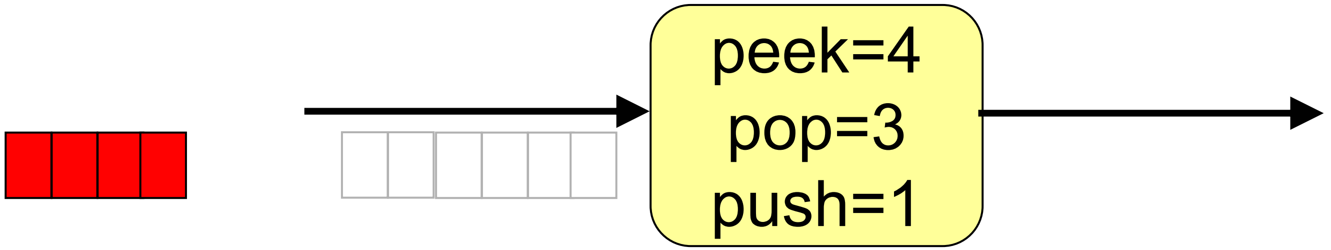
- Schedule = { A, A, B, A, B, C }



Initialization Schedule

- When peek > pop, buffer cannot be empty after firing a filter
- Buffers are not empty at the beginning/end of the steady state schedule
- Need to fill the buffers before starting the steady state execution



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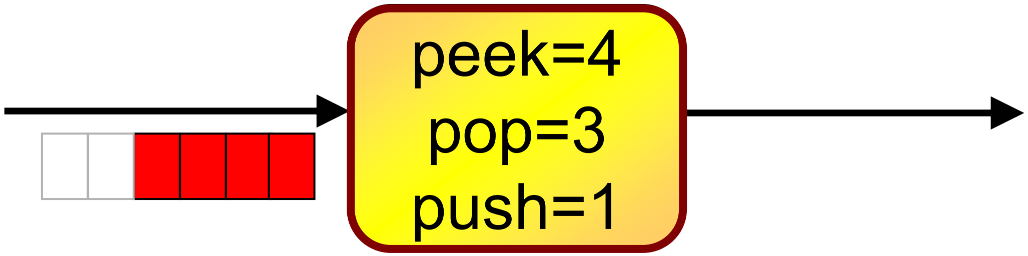
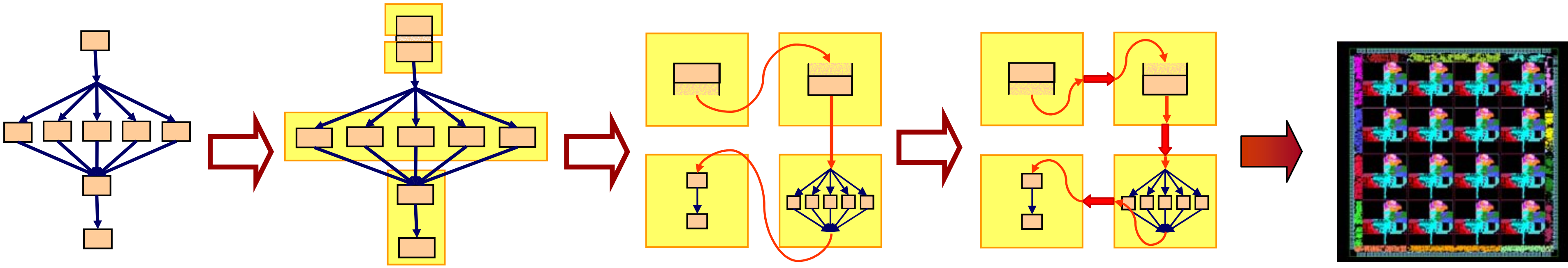
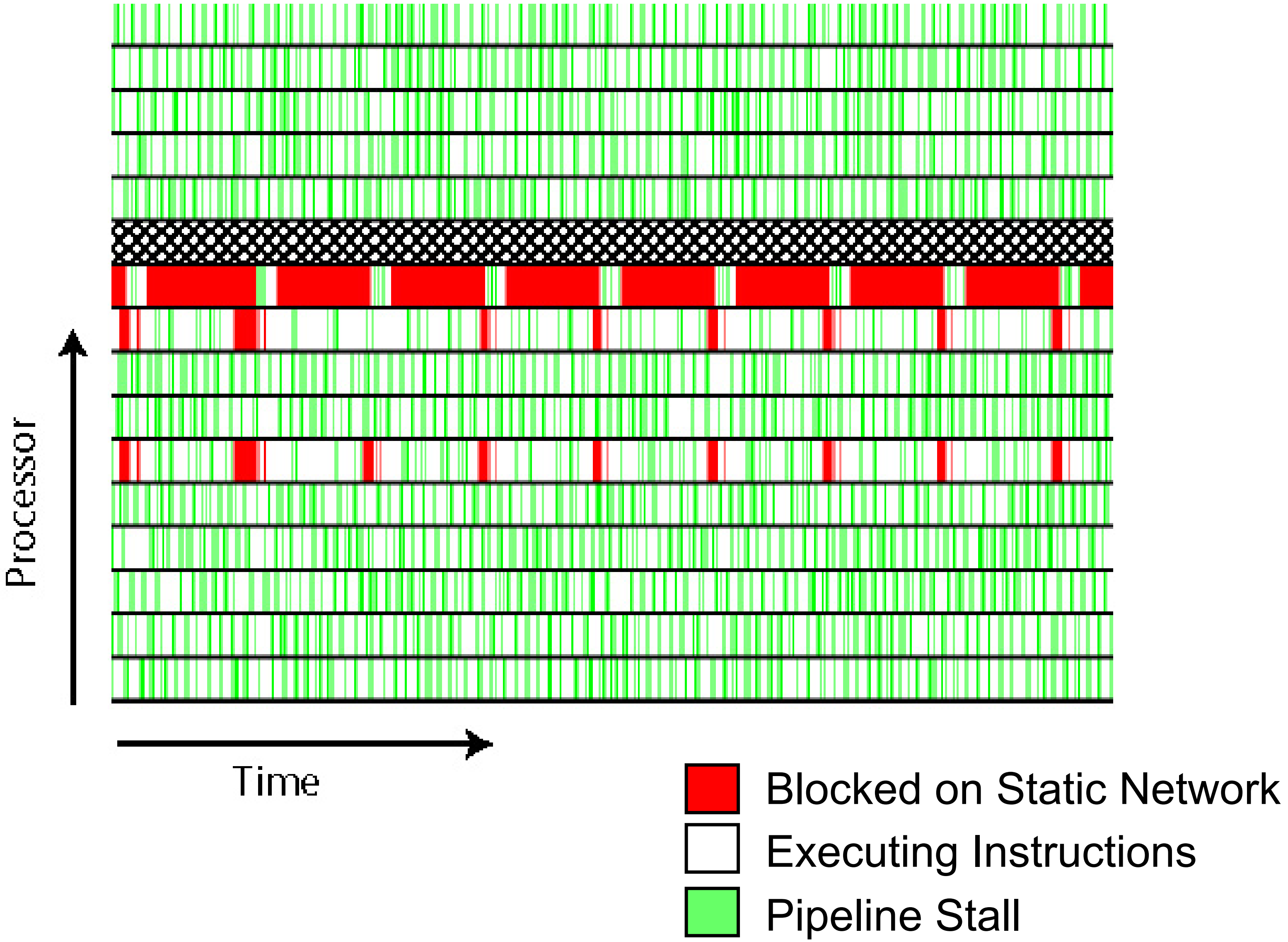


Code Generation: Optimizing tile performance

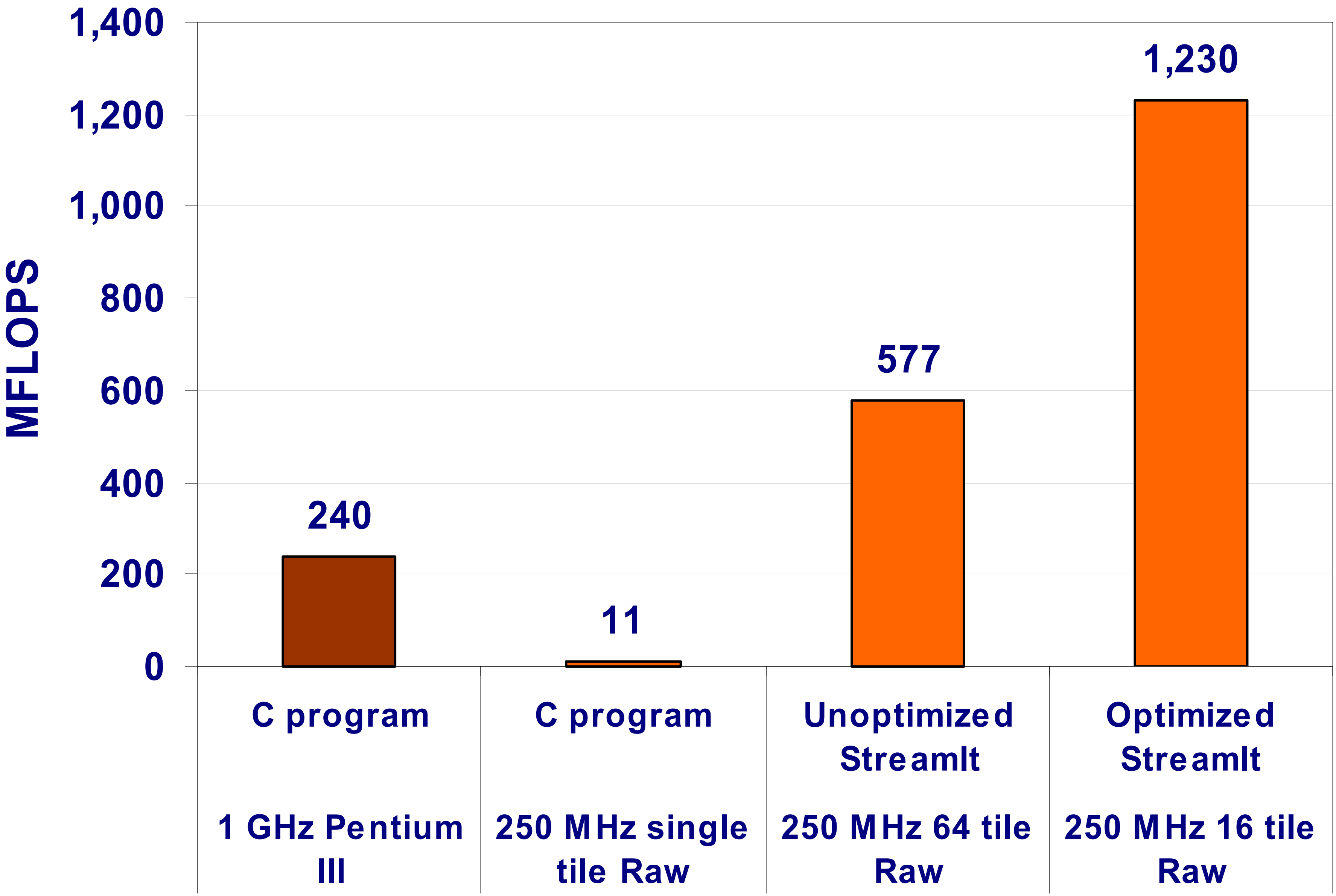


- Creates code to run on each tile
  - Optimized by the existing node compiler
- Generates the switch code for the communication

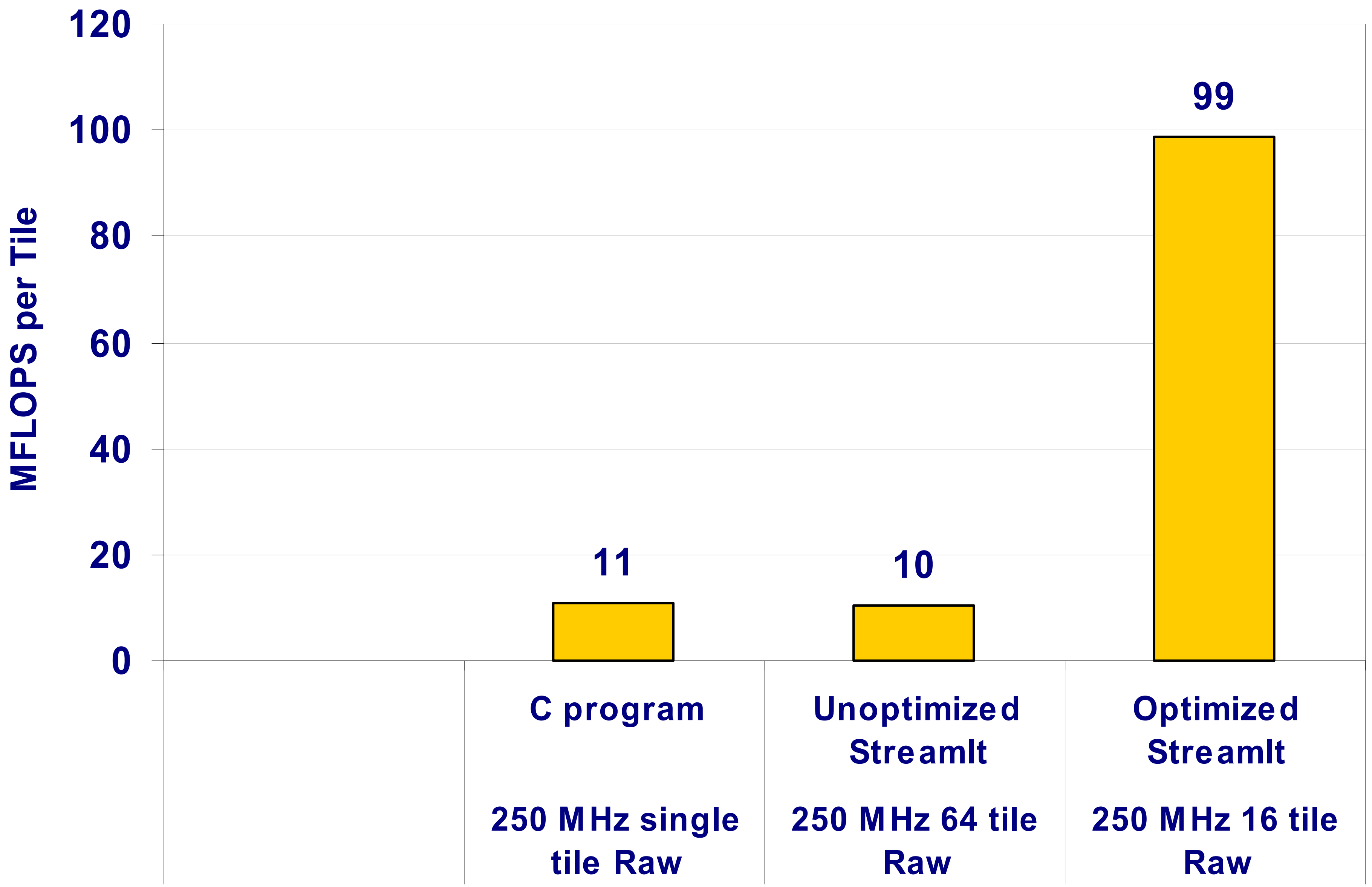
Performance Results for Radar Array Front End



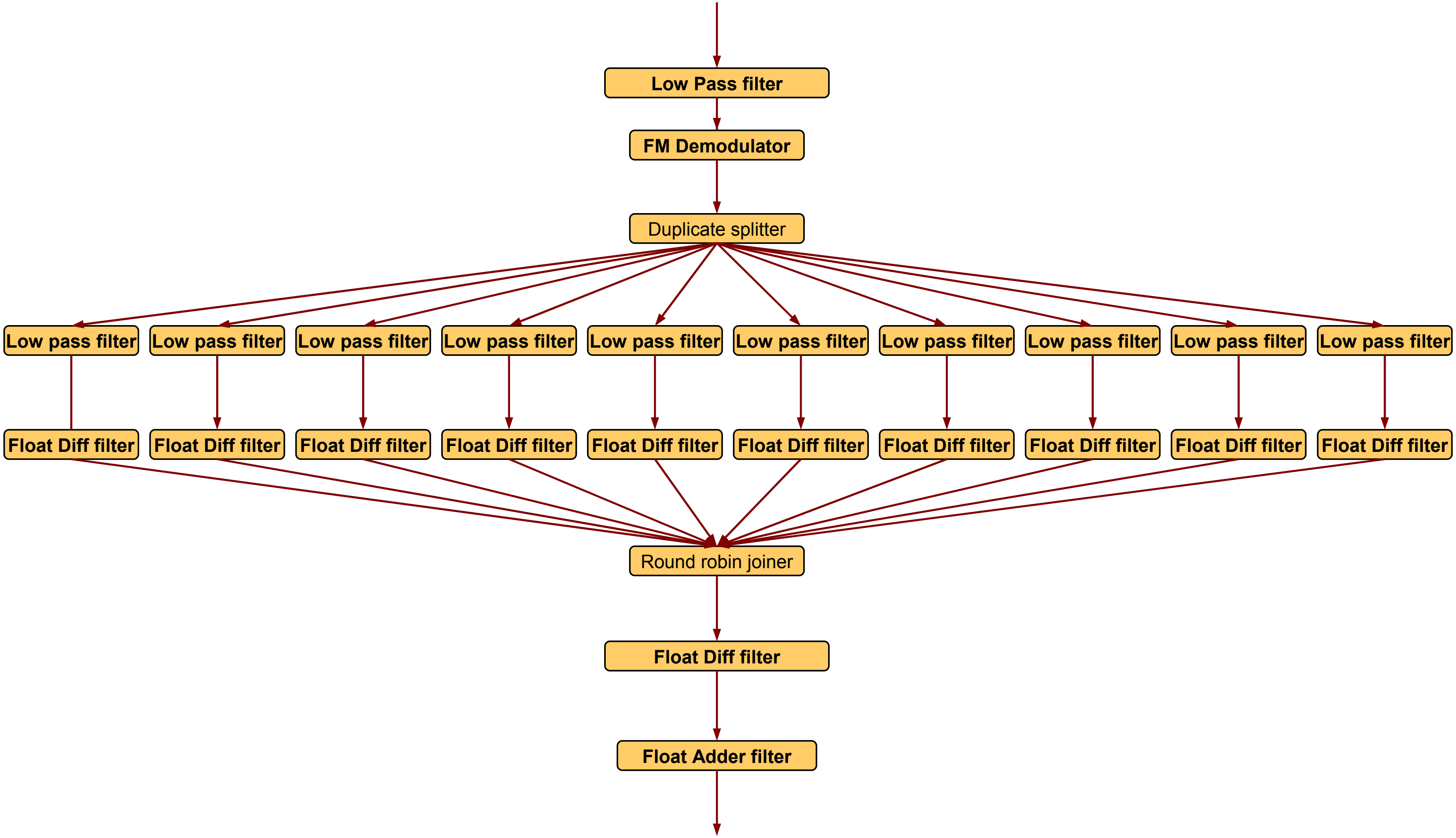
Performance of Radar Array Front End



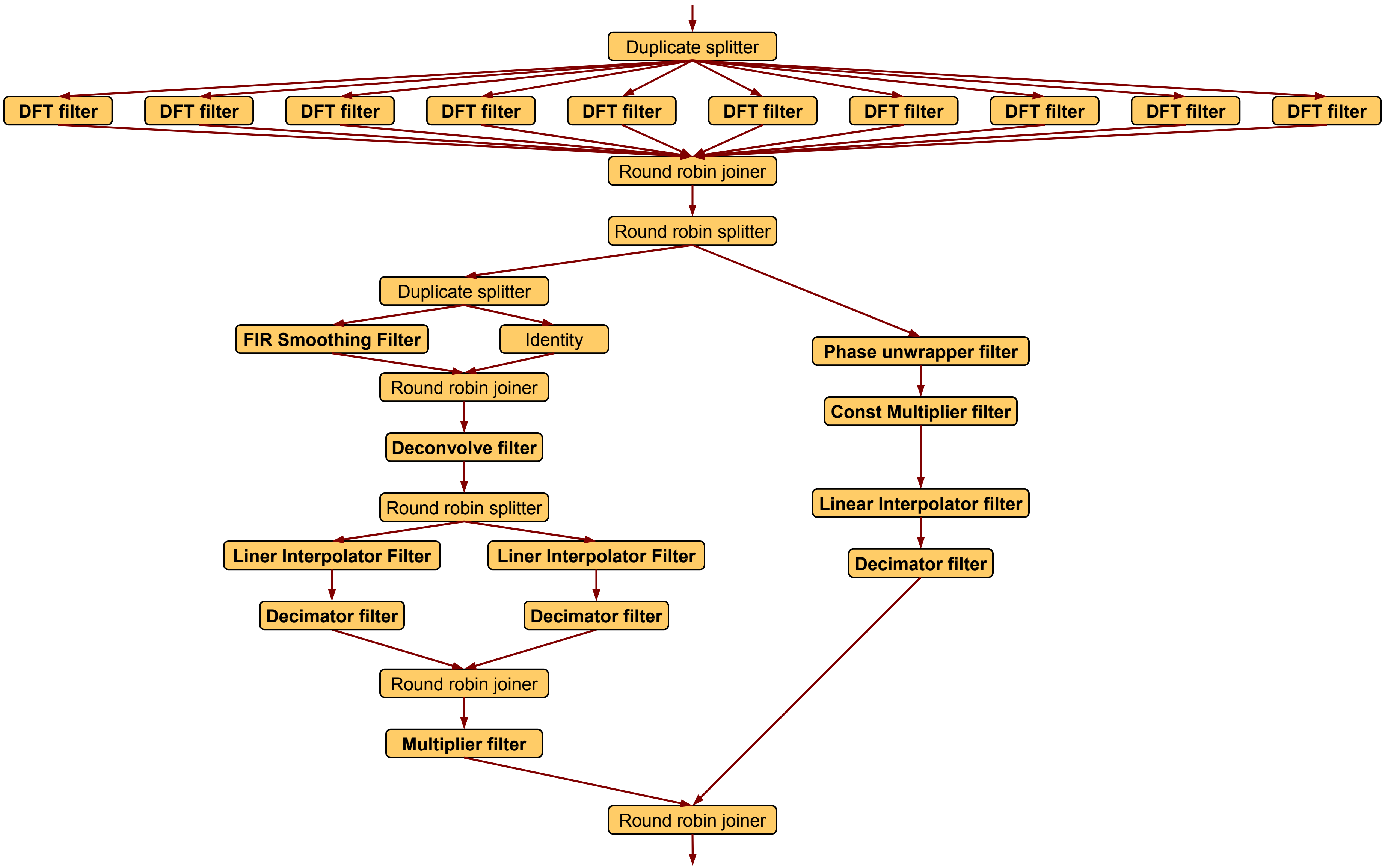
Utilization of Radar Array Front End



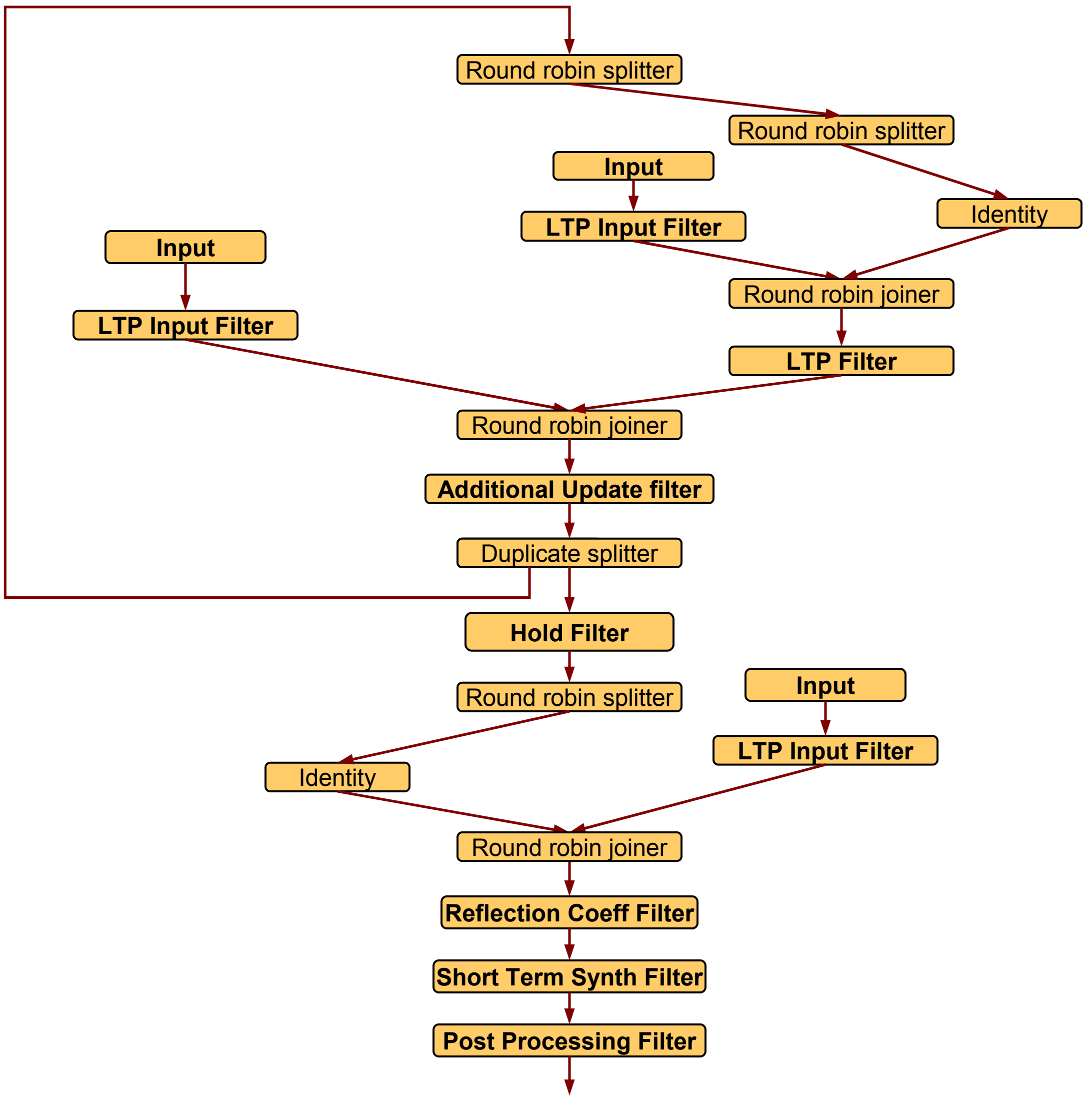
StreamIt Applications: FM Radio with an Equalizer



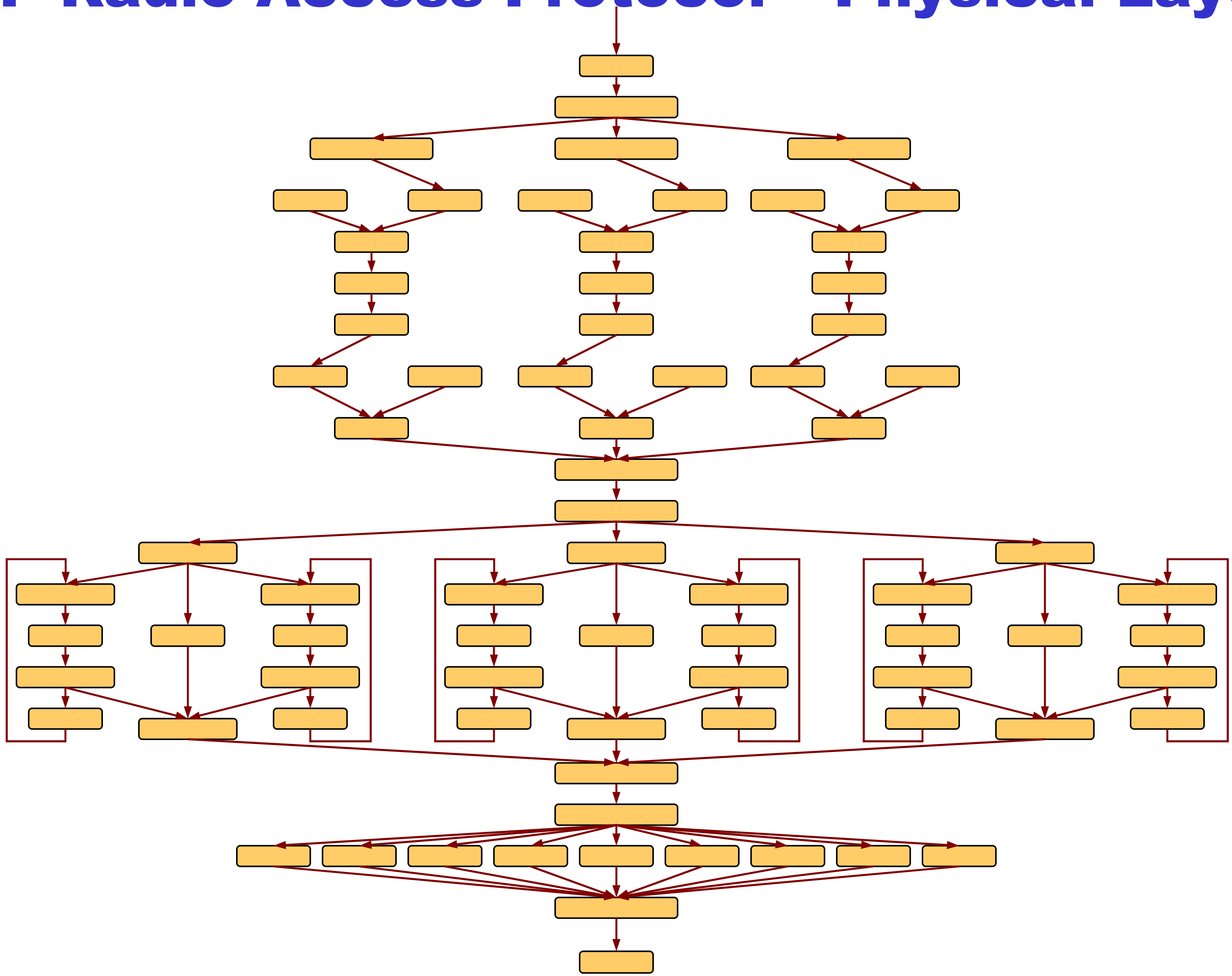
StreamIt Applications: Vocoder



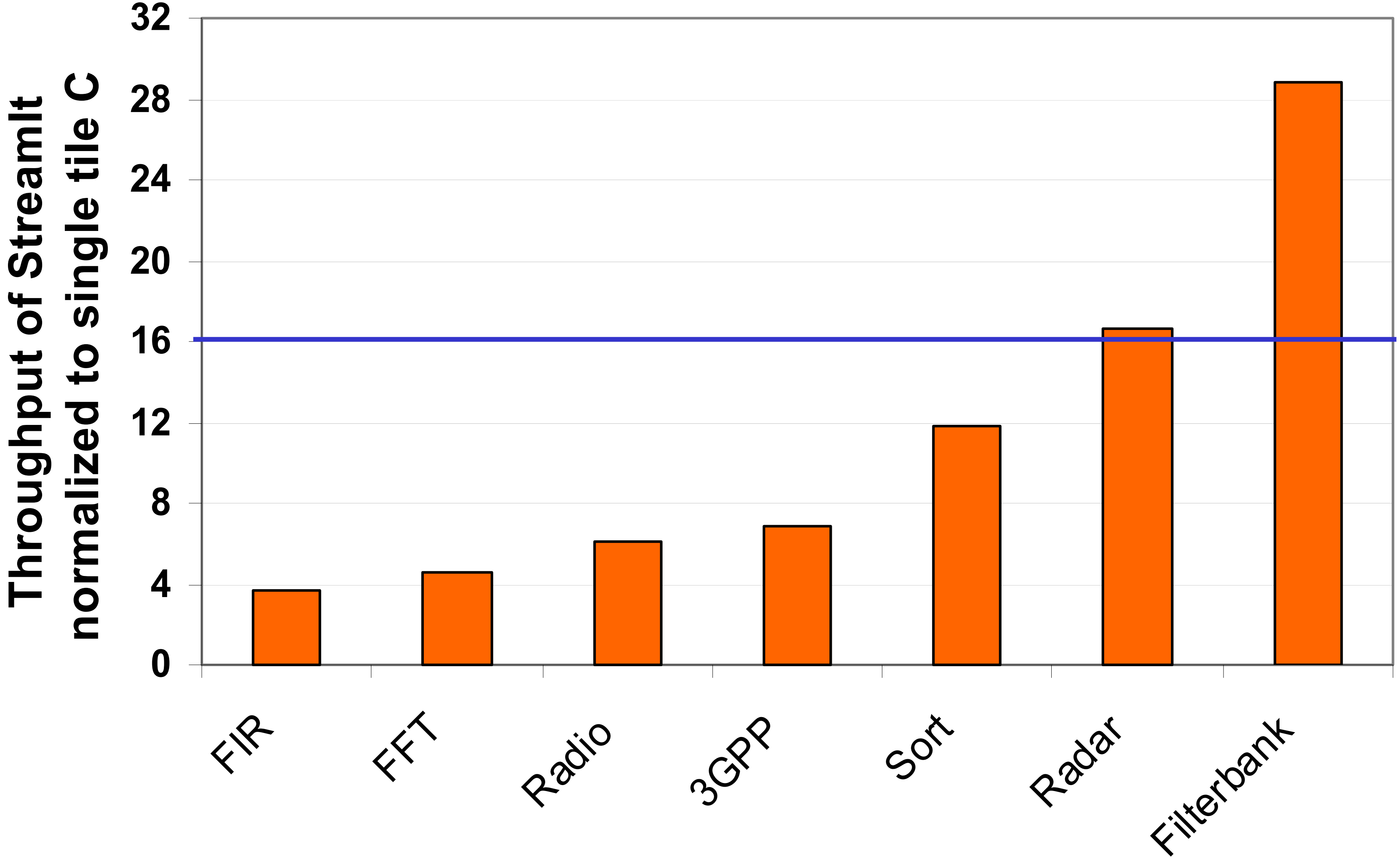
StreamIt Applications: GSM decoder



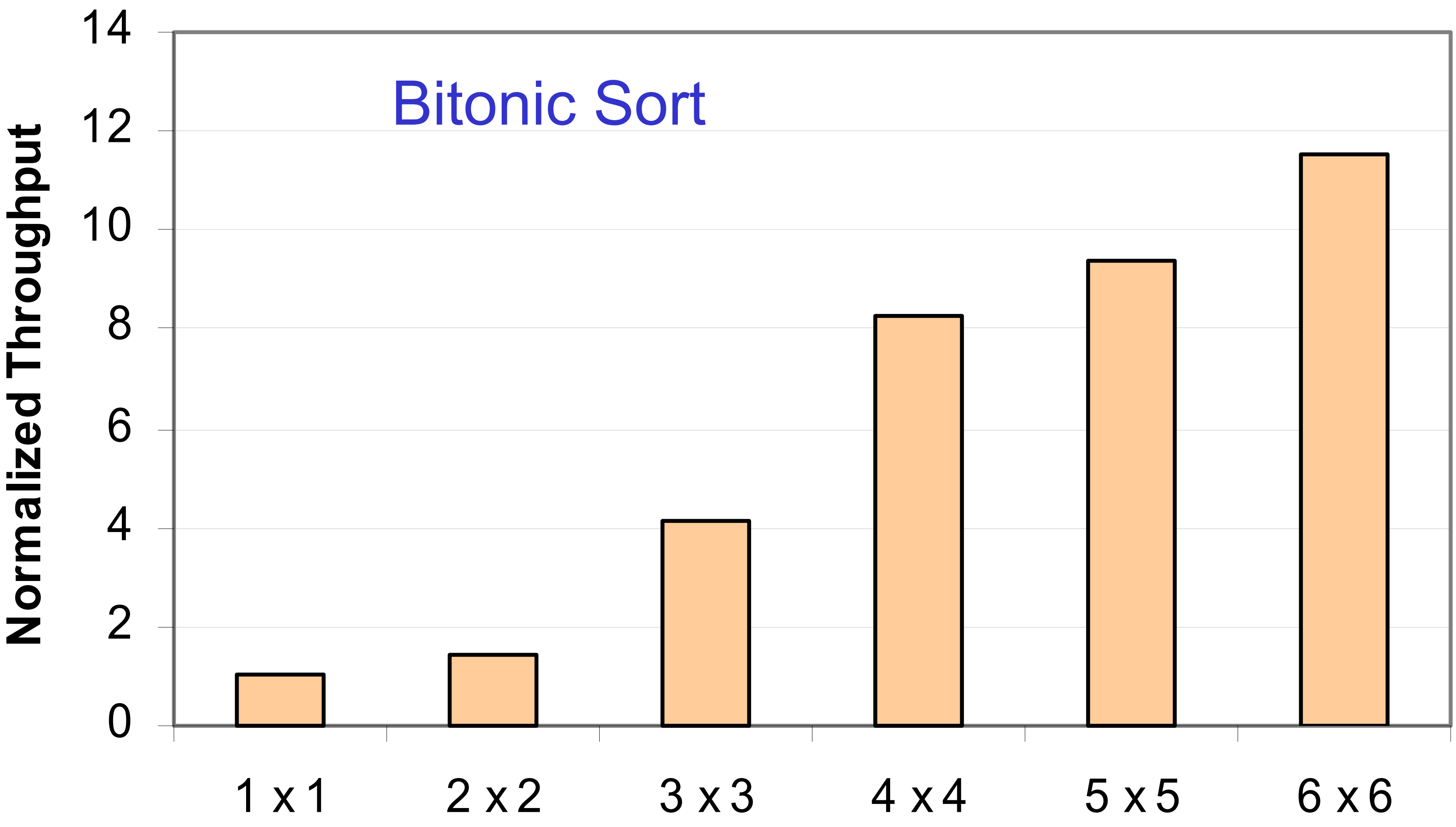
StreamIt Applications: 3GPP Radio Access Protocol – Physical Layer



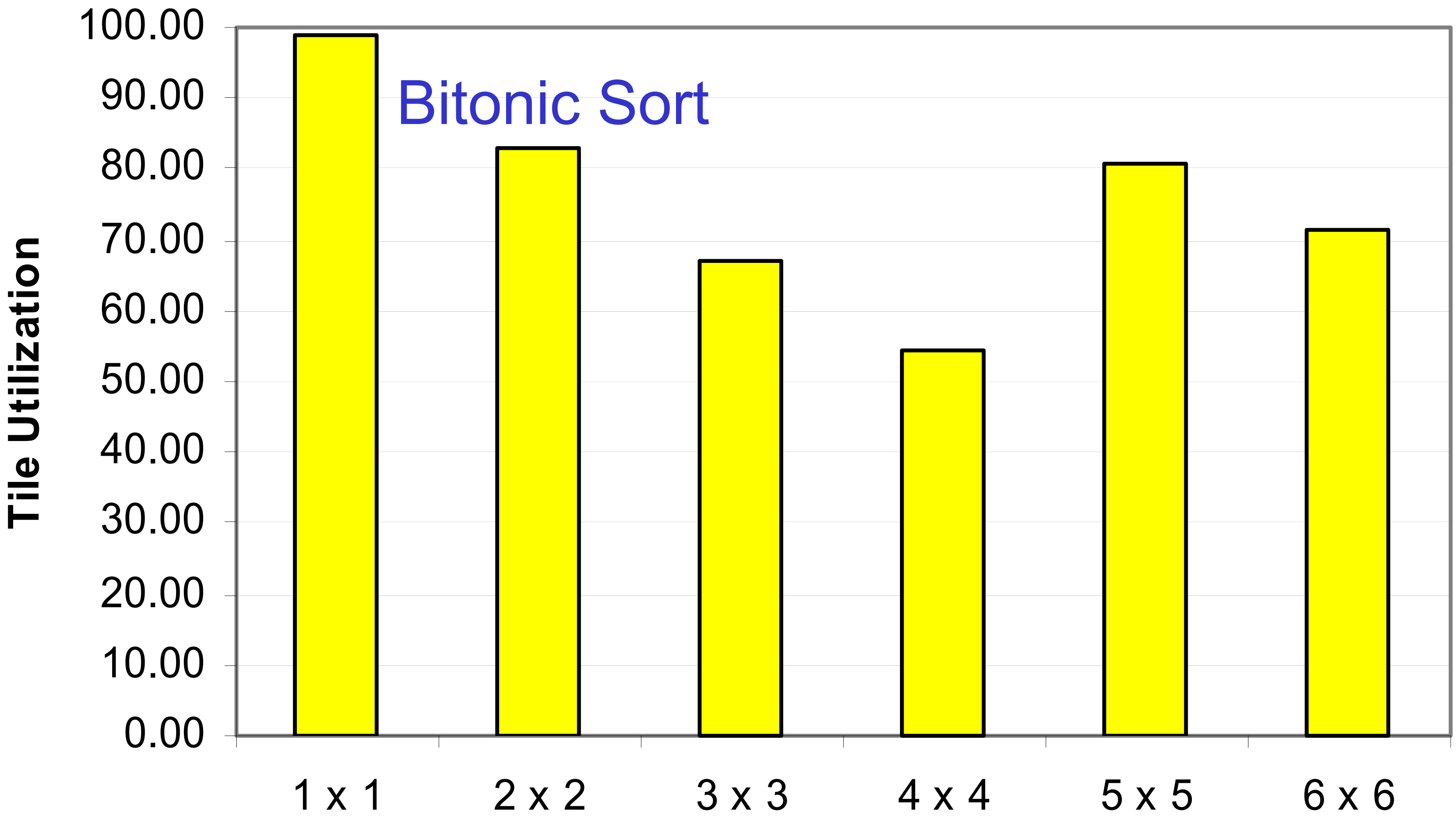
Application Performance



Scalability of StreamIt



Scalability of StreamIt



Related Work

- Stream-C / Kernel-C (Dally et. al)
  - Compiled to Imagine with time multiplexing
  - Extensions to C to deal with finite streams
  - Programmer explicitly calls stream “kernels”
  - Need program analysis to overlap streams / vary target granularity
- Brook (Buck et. al)
  - Architecture-independent counterpart of Stream-C / Kernel-C
  - Designed to be more parallelizable
- Ptolemy (Lee et. al)
  - Heterogeneous modeling environment for DSP
  - Many scheduling results shared with StreamIt
  - Don’t focus on language development / optimized code generation
- Other languages
  - Occam, SISAL – not statically schedulable
  - LUSTRE, Lucid, Signal, Esterel – don’t focus on parallel performance

Conclusion

- Streaming Programming Model
  - An important class of applications
  - Can break the von Neumann bottleneck
  - A natural fit for a large class of applications
  - Straightforward mapping to the architectural model
- StreamIt: A Machine Language for Communication Exposed Architectures
  - Expose the common properties
    - Multiple instruction streams
    - Software exposed communication
    - Fast local memory co-located with execution units
  - Hide the differences
    - Granularity of execution units
    - Type and topology of the communication network
    - Memory hierarchy
- A good compiler can eliminate the overhead of abstraction