StreamIt: A Language and Compiler for the Streaming Domain

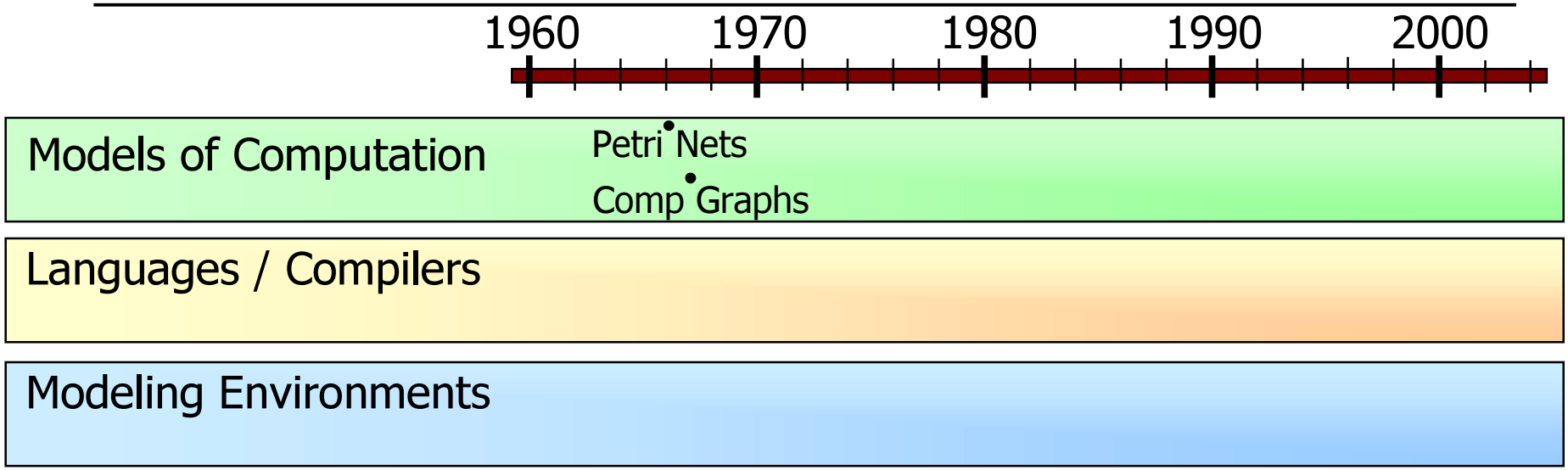
Saman Amarasinghe

Computer Science and Artificial Intelligence Laboratory
Massachusetts Institute of Technology

Outline

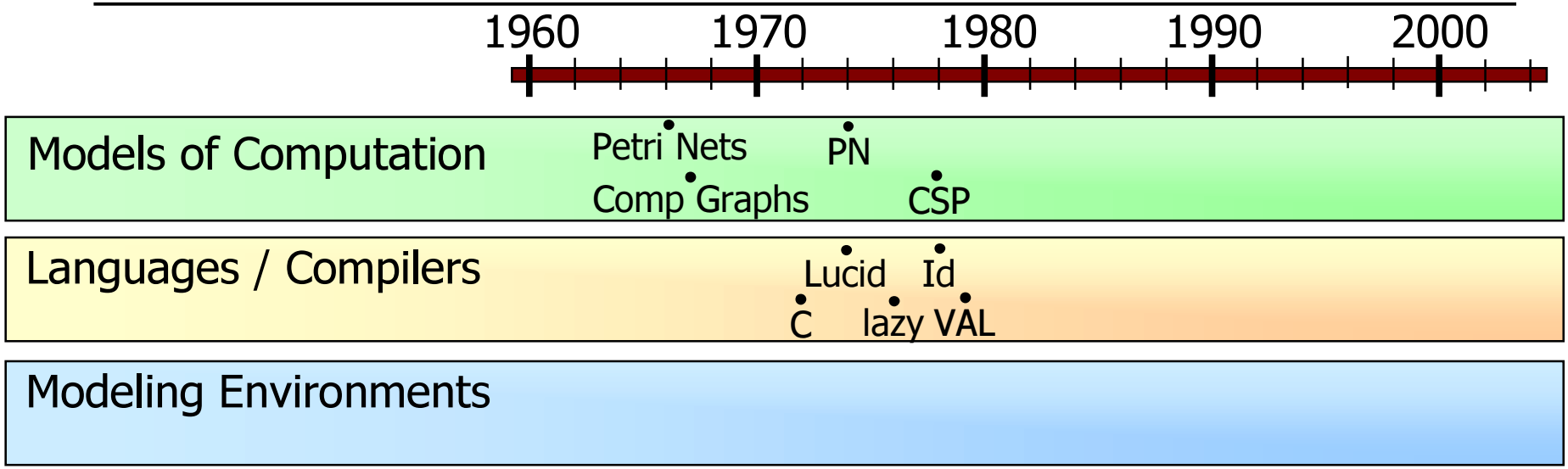
- Historical timeline of Stream Programming
- The StreamIt Language
- DSP Domain Specific Optimizations
- Architecture Specific Optimizations

Timeline: 1960's



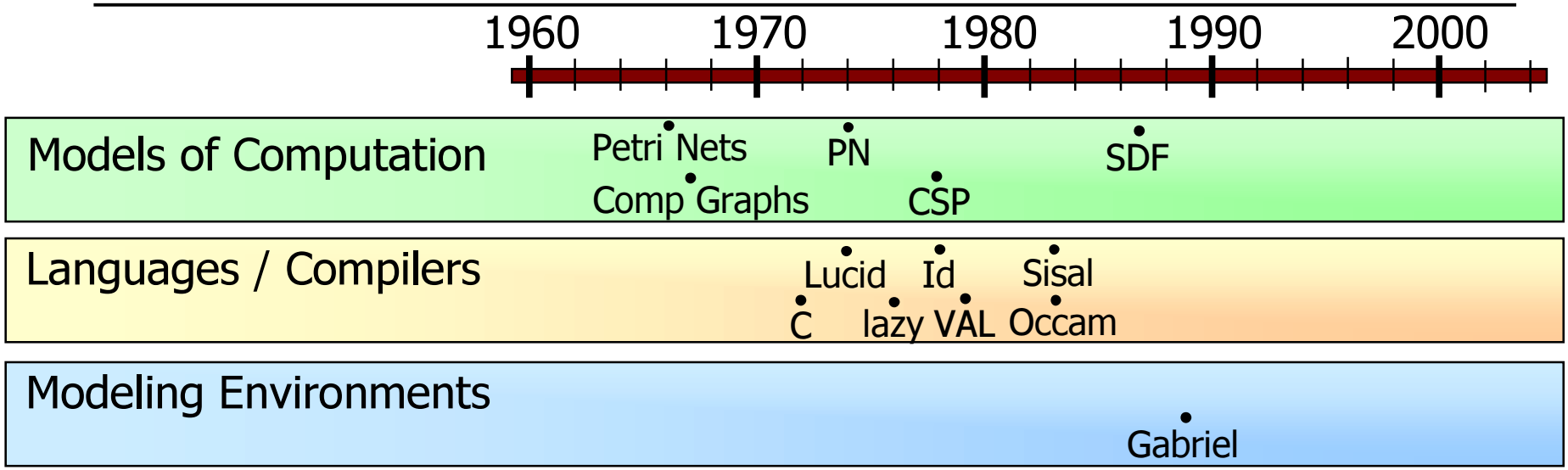
- "Stream" (P.J. Landin) – 1960
  - Linking Algol 60 and lambda calculus, used for loop histories
- Petri Nets (C.A. Petri) – 1966
  - Places, transitions, tokens
- Computation Graphs (Karp, Miller) – 1967
  - Graph with firing actors, minimal firing requirements
  - Formulate determinancy, termination, queuing properties

Timeline: 1970's



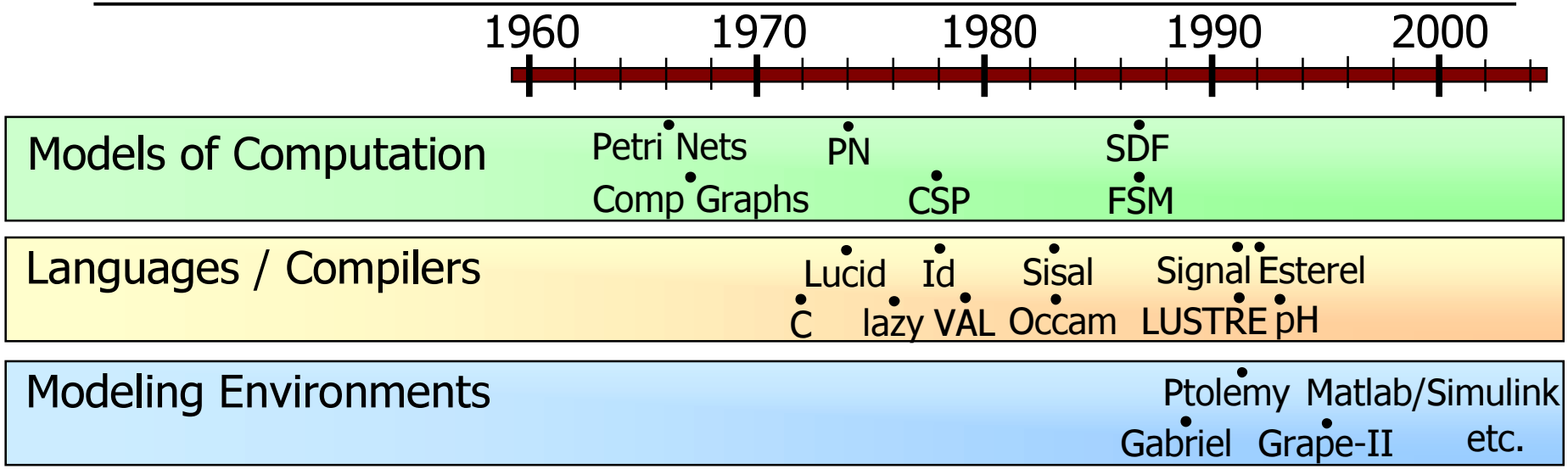
- Process Networks (Kahn) – 1974
  - Sequential threads communicate with unbounded FIFO's
  - Deterministic
- CSP: Communicating Sequential Processes (Hoare) – 1978
  - Sequential threads communicate with rendezvous message-passing
  - Non-deterministic due to guards
- Dataflow languages
  - First version dataflow procedure language (Dennis)
  - Lucid (Ashcroft, Wadge), Id (Arvind, Gostelow), VAL (Dennis)
- Functional languages with lazy evaluation for streams
  - lazy evaluator (Henderson, Morris); Sieve of Eratosthenes (Friedman, Wise)

Timeline: 1980's



- SDF: Synchronous Dataflow (Lee, Messerschmitt) – 1987
  - Actors have static, non-uniform rates; firing is atomic and data-driven
  - Allows static scheduling
- Sisal: Streams and Iteration in a Single Assignment Language – 1983
  - Adds recursion, finite streams to VAL
  - Implementations on many parallel machines
  - IF1 intermediate format
- Occam – 1983
  - Strongly typed procedural language
  - Practical implementation of CSP
- More work on dataflow and functional languages (e.g., M. Broy)

Timeline: 1990's



- Synchronous Languages: Signal, LUSTRE, etc.
  - Designed for expressiveness, verification more so than high performance
- Esterel
  - For reactive programming; event-driven and control-oriented
  - Often implemented in either hardware or software
- pH: Parallel Haskell (Nikhil, Arvind, et al.)
  - Combines lazy functional and dataflow philosophies for high performance
- Ptolemy: Heterogeneous Modeling Environment (Lee et al.)
  - Many contributions to formalisms, scheduling, graph-level optimization
- Commercial Environments (Matlab, SPW, COSSAP, ADS, etc.)
  - Becoming increasingly prevalent

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Von Neumann Languages

- Why C (FORTRAN, C++ etc.) became very successful?
  - Abstracted out the differences of von Neumann machines
    - Register set structure
    - Functional units and capabilities
    - Pipeline depth/width
    - Memory/cache organization
  - Directly expose the common properties
    - Single memory image
    - Single control-flow
    - A clear notion of time
  - Can have a very efficient mapping to a von Neumann machine
  - "C is the portable machine language for von Numann machines"
- Today von Neumann languages are a curse
  - We have squeezed out all the performance out of C
  - We can build more powerful machines
  - But, cannot map C into next generation machines
  - Switching to a data-flow programming paradigm will help

The StreamIt Project

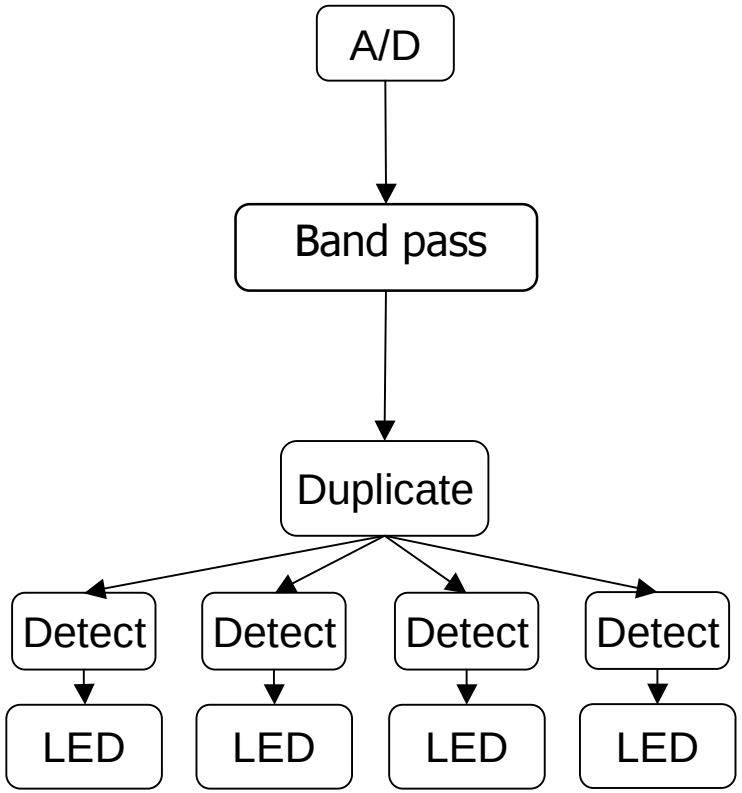
- Goals:
  - Breaks the Von Neumann language barrier
  - Provide a High-Level Programming Paradigm
  - Improve Programmer Productivity
  - Be Compiler Friendly
- What's new?
  - Practical language features for large application development
  - Stream-specific compiler technology

Language Features

- Circular Buffer Management
  - Reuse the data on the tapes using ‘peek’
- Structured Streams
  - Hierarchical
  - Parameterized
- Precise Event Handling
  - A formal notion of time

Example: Freq band detection

- Used in…
  - metal detector
  - garage door opener
  - spectrum analyzer



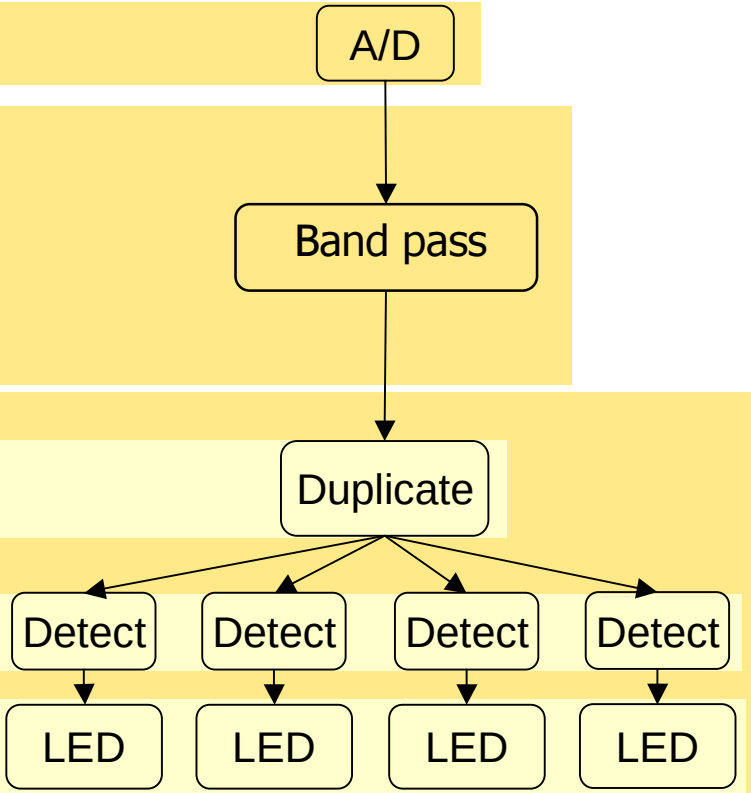
Source:

Application Report SPRA414

Texas Instruments, 1999

Freq band detection 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(1, cFreq-wFreq,
                        cFreq+wFreq, 100);
  add splitjoin {
    split duplicate;
    for (int i=0; i<4; i++) {
      add Detector(i/4);
      add LEDOutput(i);
    }
    join roundrobin(0);
  }
}
```



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  add D2ASource(sFreq);
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                                       float wp, int num) {
      add LowPassFilter(1, wp, num);
      add HighPassFilter(gain, ws, num);
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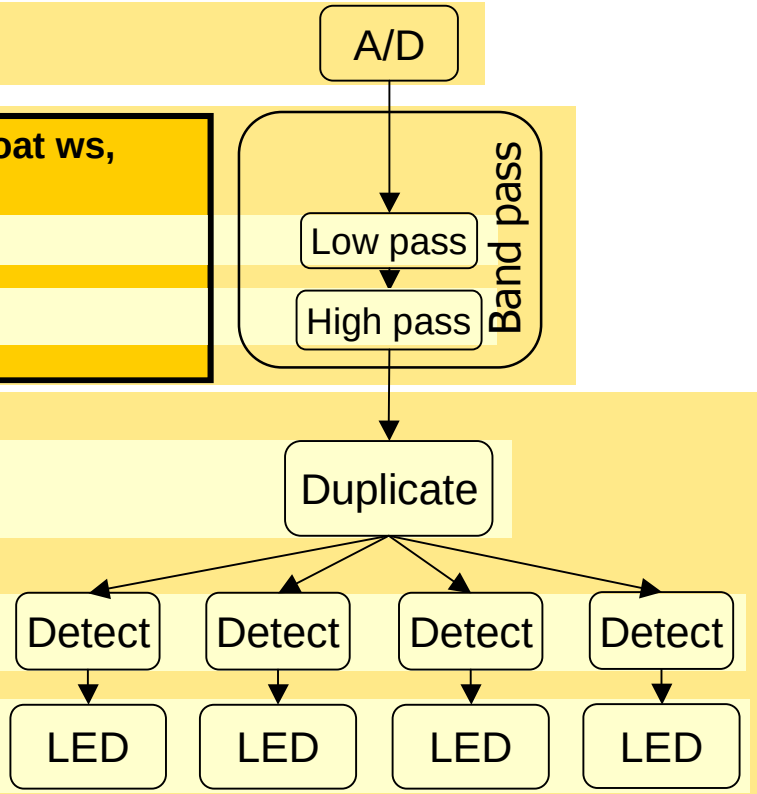

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  }
}
```

```
float->float filter LowPassFilter(float g,
                                  float cFreq, int N)
{

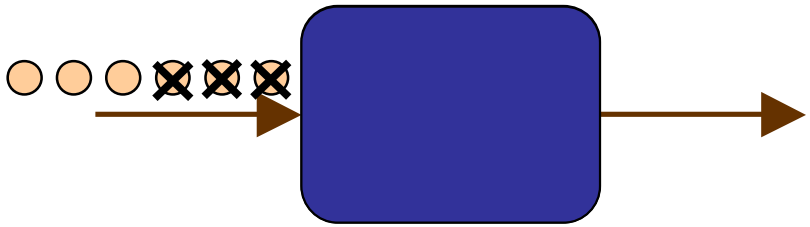
 float[N] h;

 init {
  int OFF = N/2;
  for (int i=0; i<N; i++) {
     h[i] = g*sin(...);
  }
 }

 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();
 }
```

Freq band detection in StreamIt

```
add LowPassFilter(1, wp, num);
```



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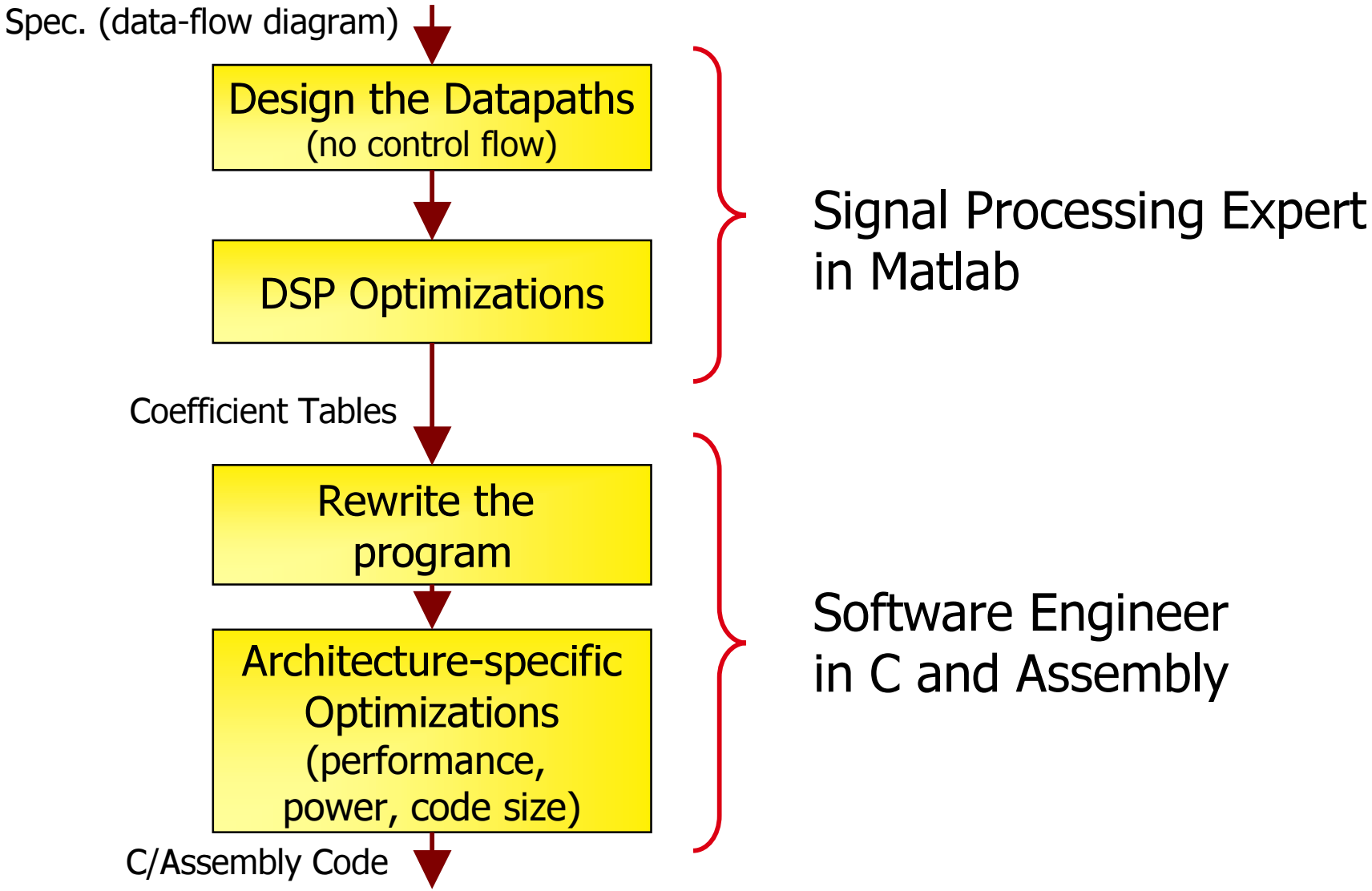
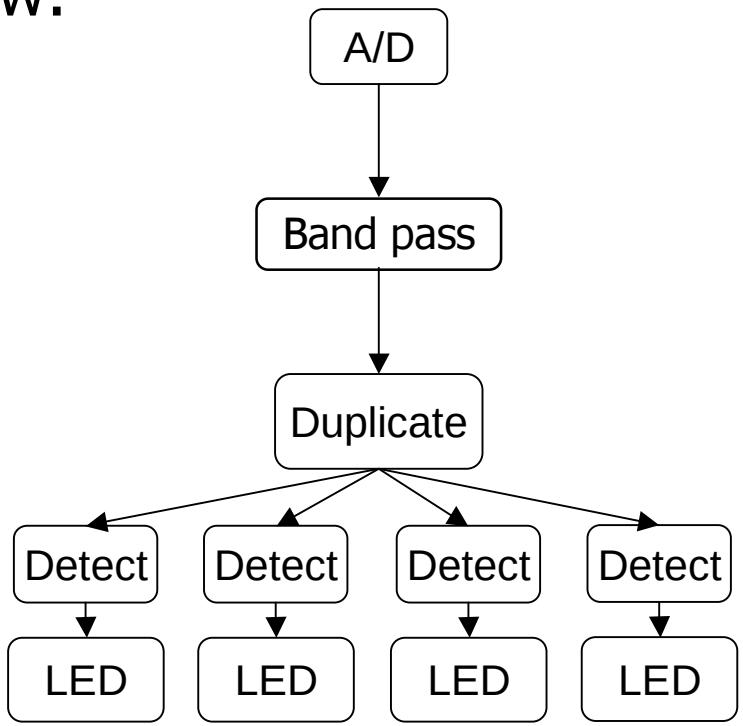
Conventional DSP Design Flow

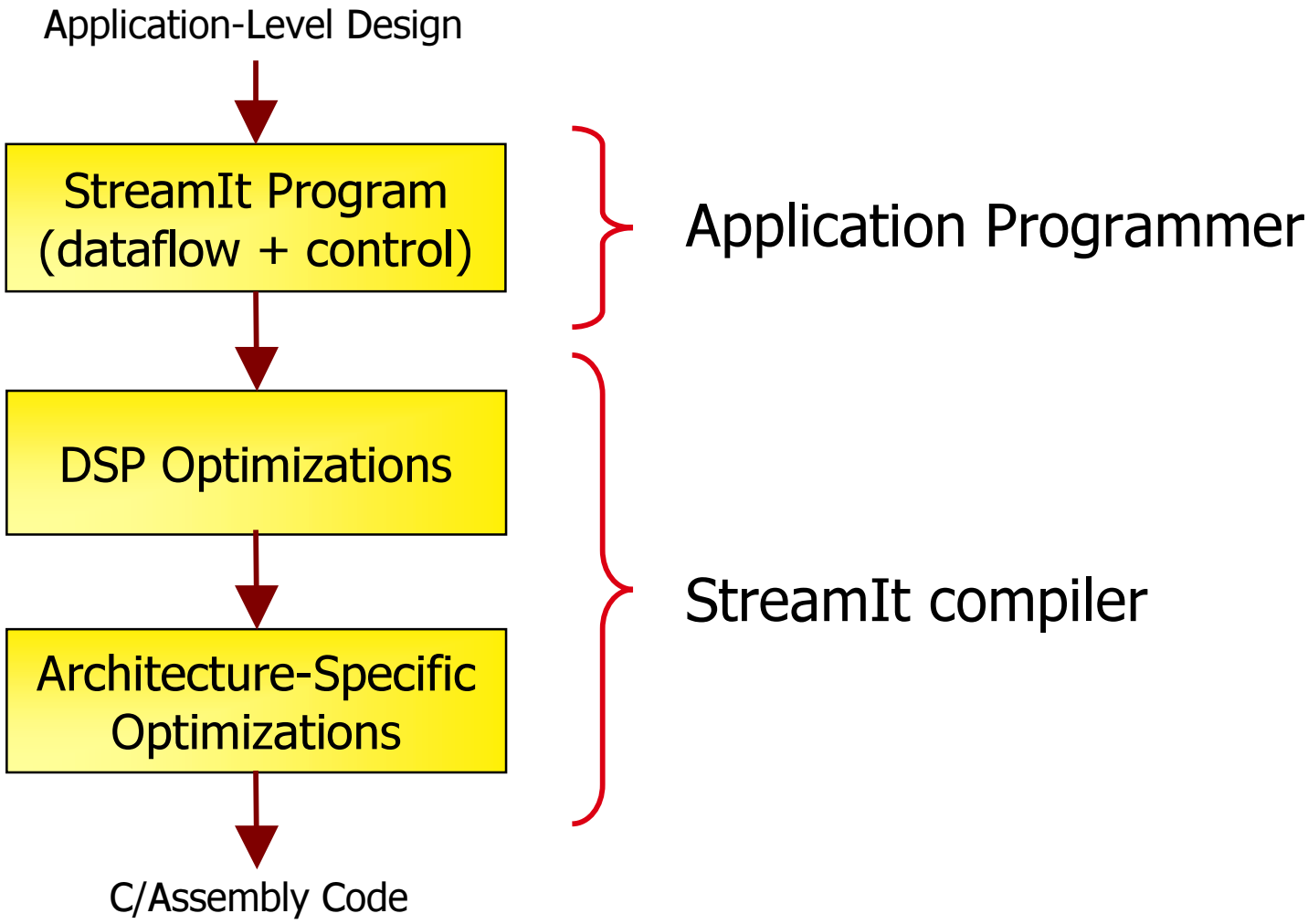


Any Design Modifications?

- Center frequency from 500 Hz to 1200 Hz?
  - According to TI,
    in the conventional design-flow:
    - Redesign filter in MATLAB
    - Cut-and-paste values to EXCEL
    - Recalculate the coefficients
    - Update assembly
  - If using StreamIt
    - Change one constant
    - Recompile



Design Flow with StreamIt



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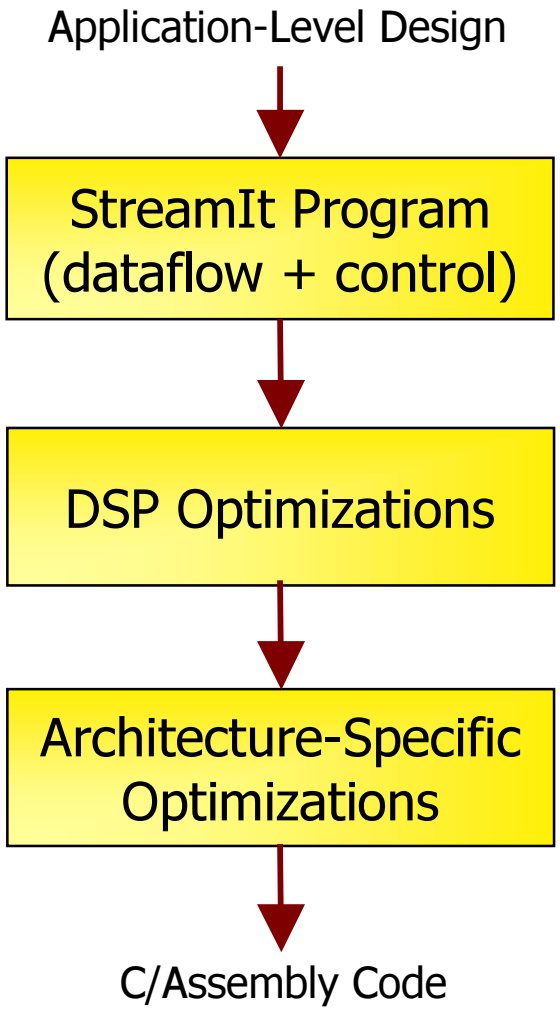


- Benefits of programming in a single, high-level abstraction
  - Modular
  - Composable
  - Portable
  - Malleable
- The Challenge: Maintaining Performance

Our Focus: Linear Filters

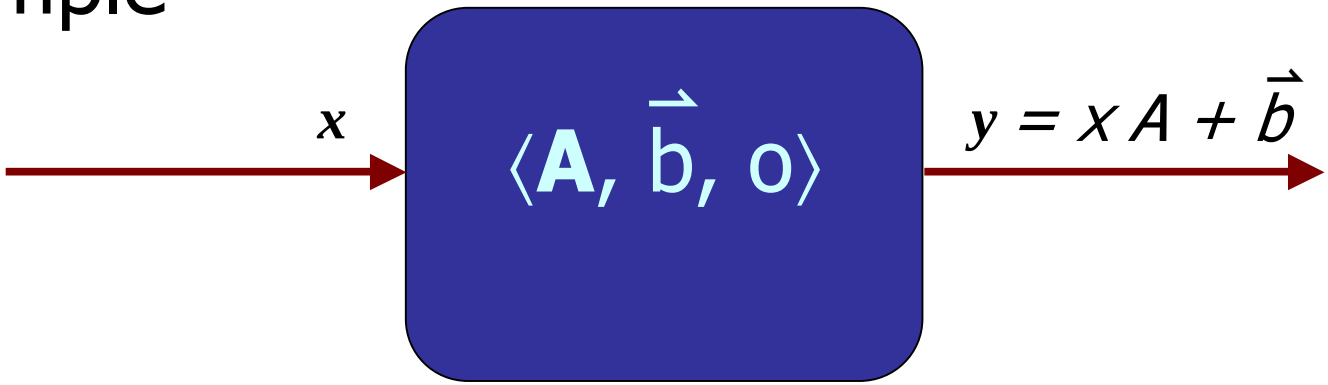
- Most common target of DSP optimizations
  - FIR filters
  - Compressors
  - Expanders
  - DFT/DCT

  } 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



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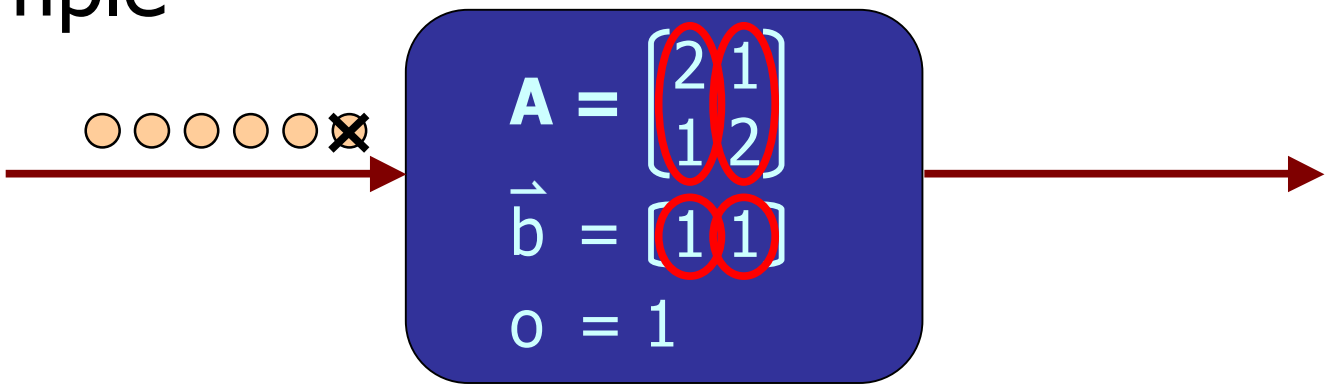
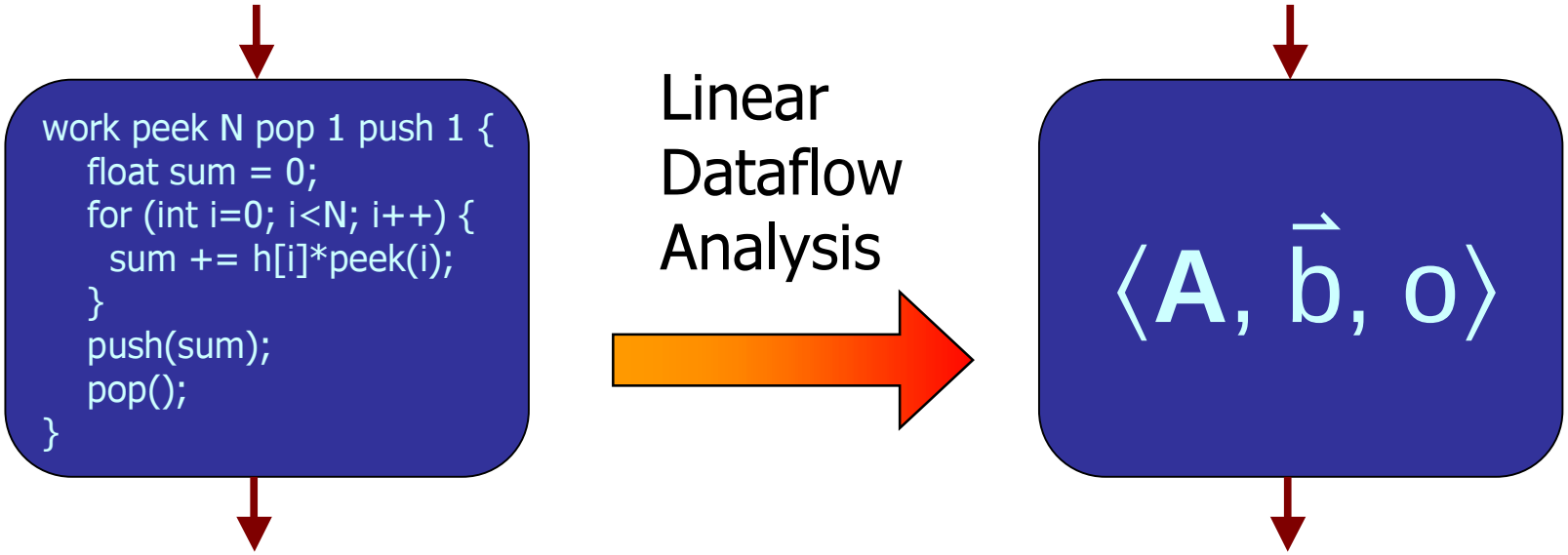


Extracting Linear Representation



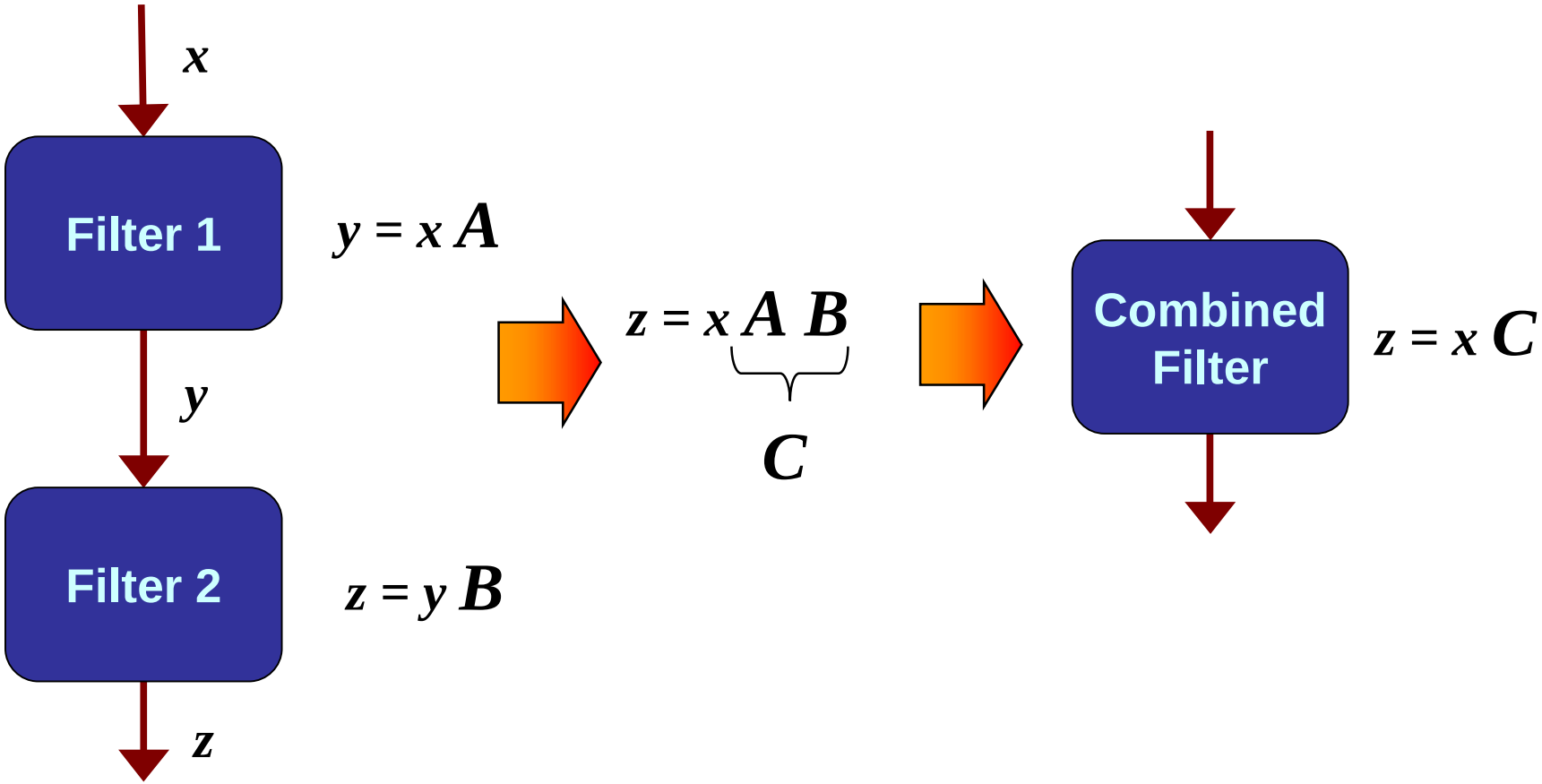
- Resembles constant propagation
- Maintains linear form $\langle \vec{v}, \vec{b} \rangle$ for each variable
  - Peek expression: generate fresh $\vec{v}$
  - Push expression: copy $\vec{v}$ into **A**
  - Pop expression: increment o

Optimizations using Linear Analysis

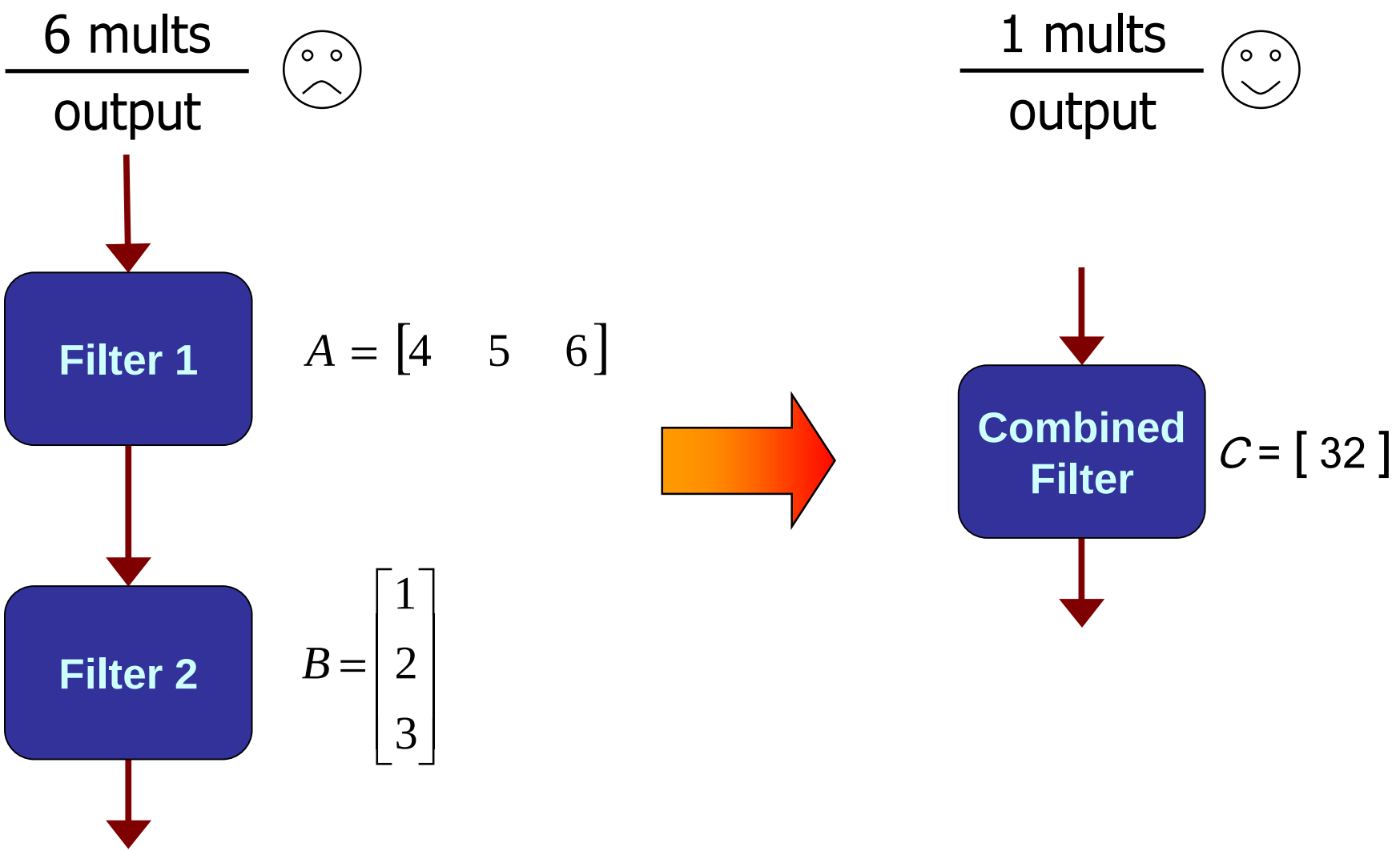
- Combining adjacent linear structures
- Shifting from time to the frequency domain
- Selection of ‘optimal’ set of transformations

1) Combining Linear Filters

- Pipelines and splitjoins can be collapsed
- Example: pipeline

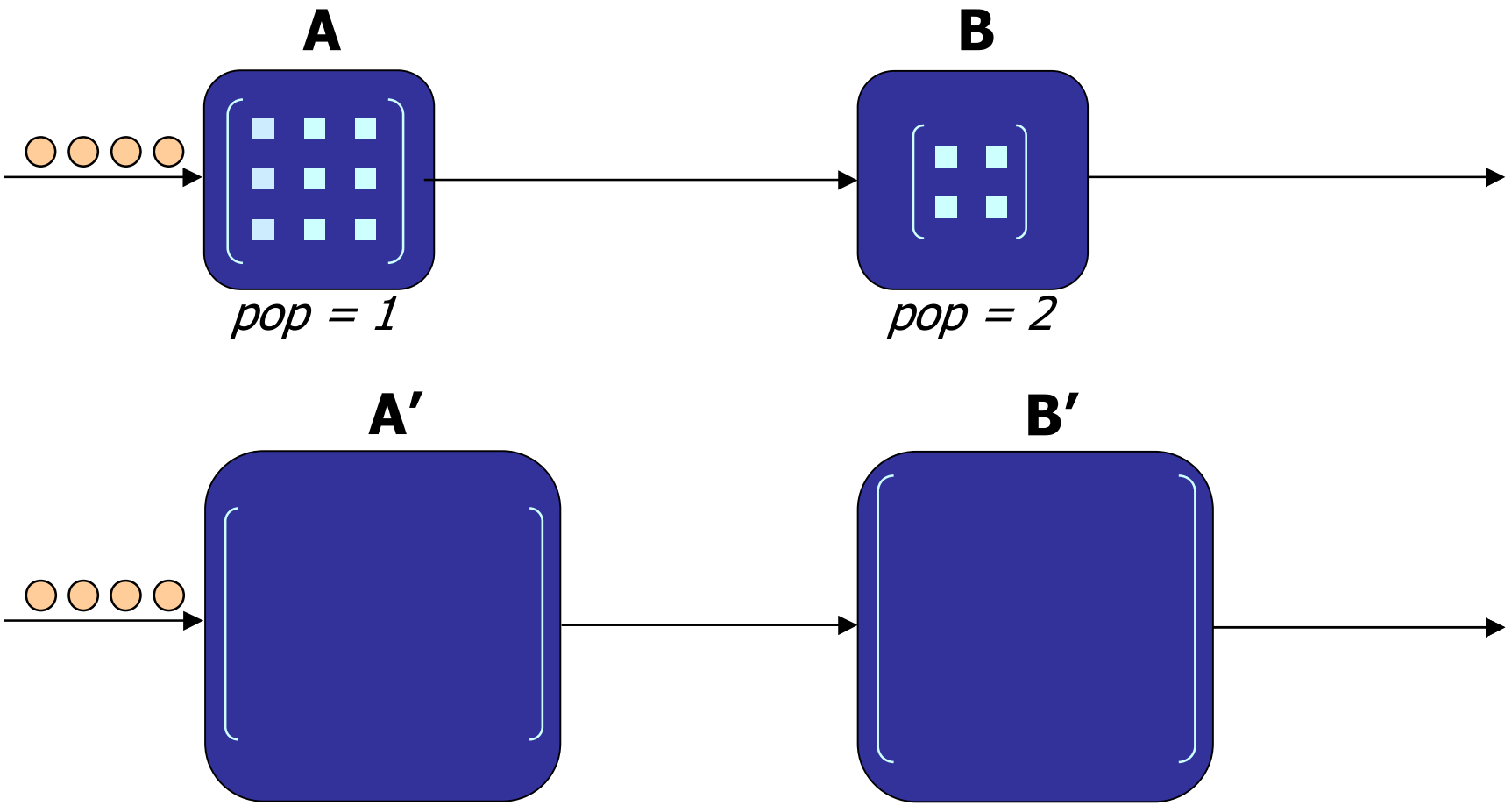


Combination Example



AB for any A and B??

Need to "expand" matrices to a steady-state cycle:



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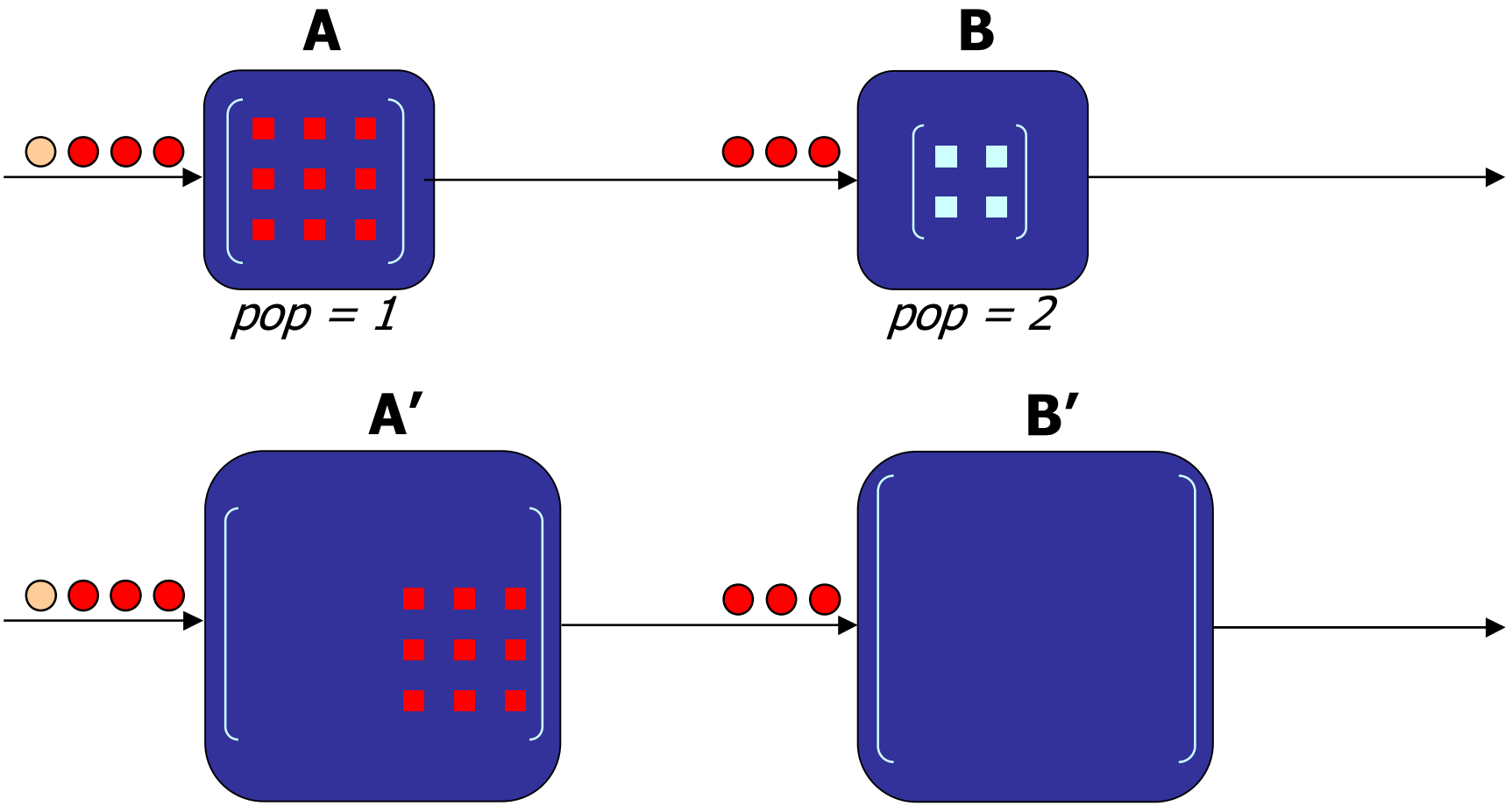

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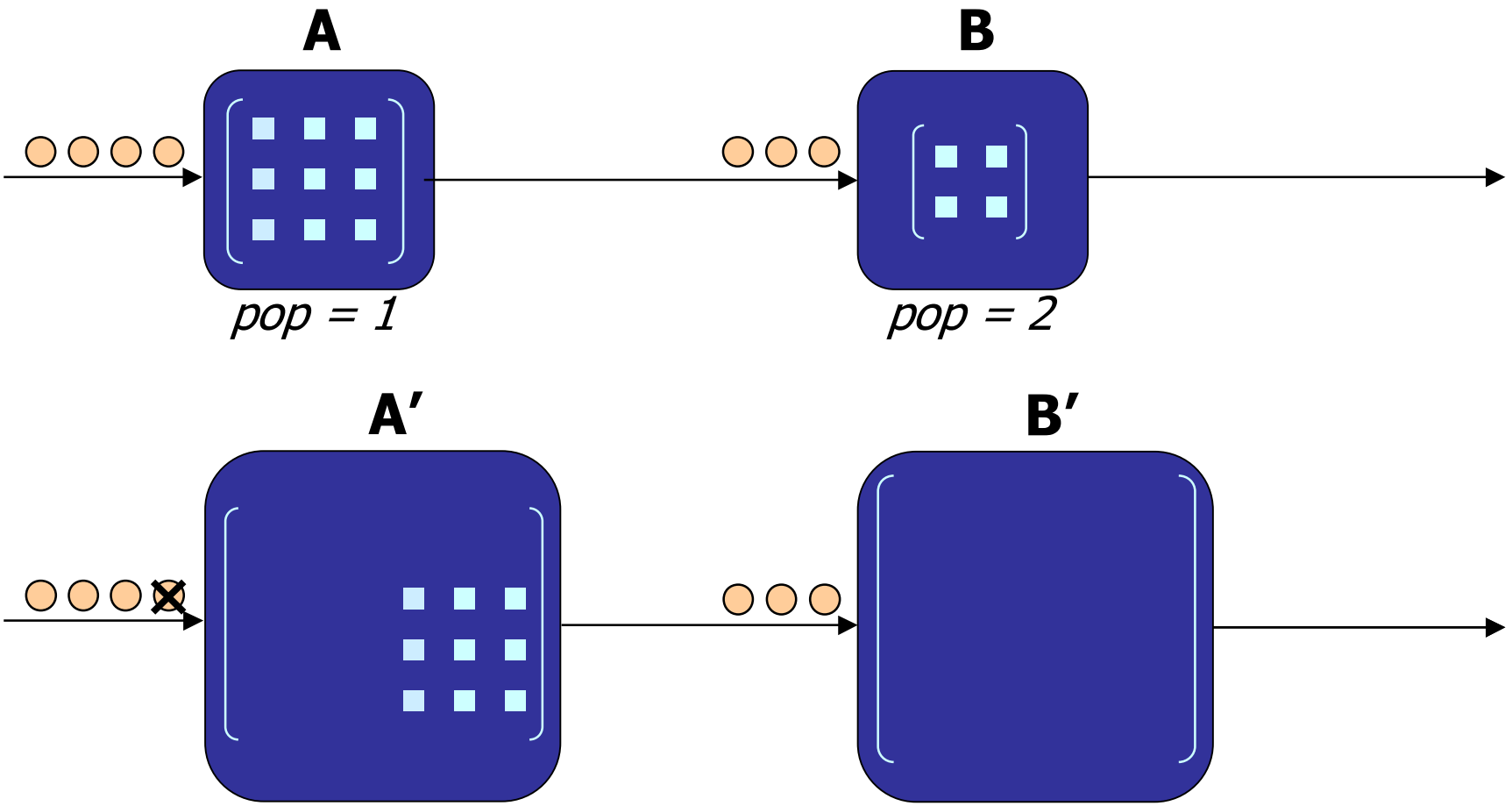

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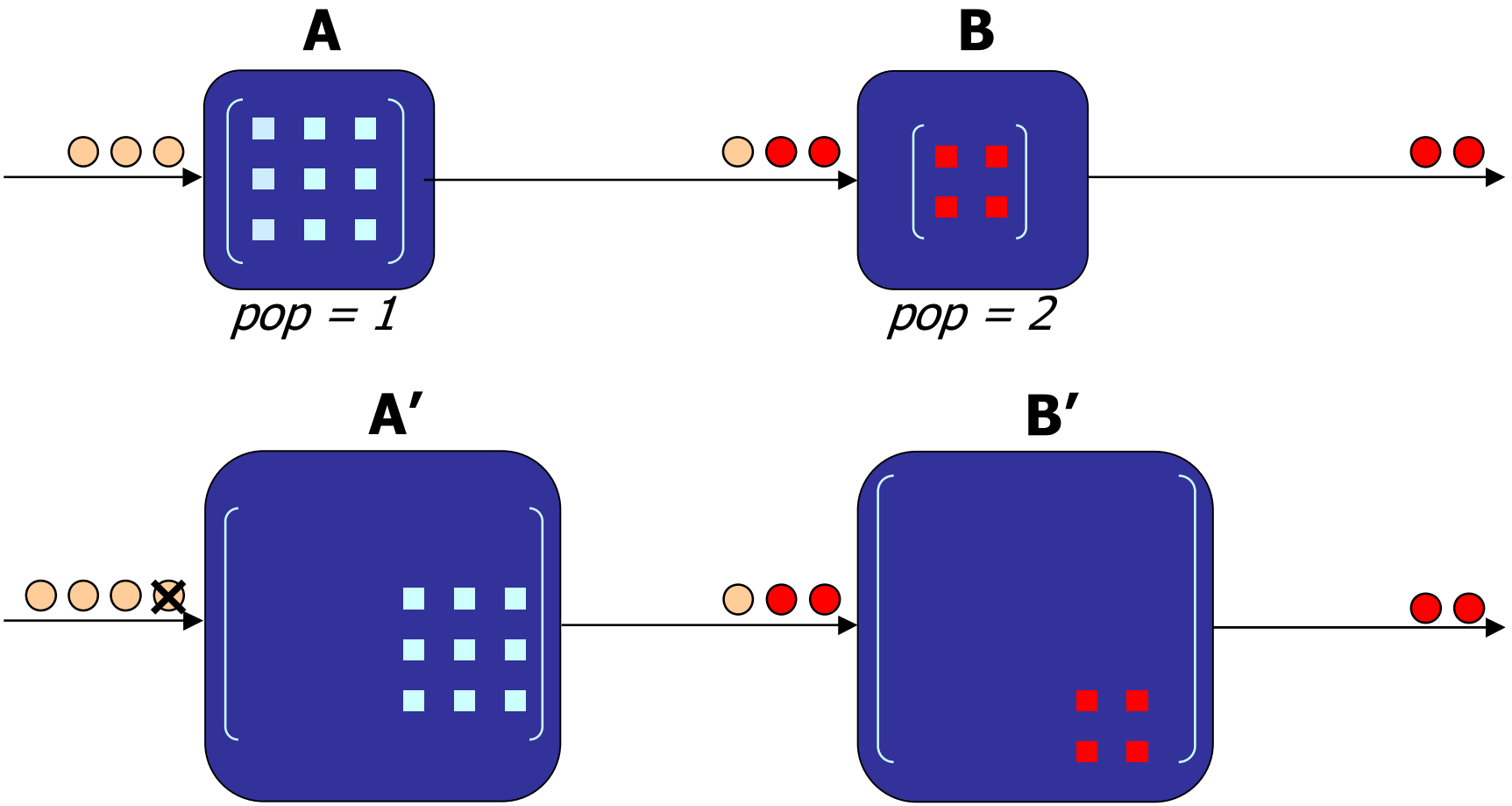

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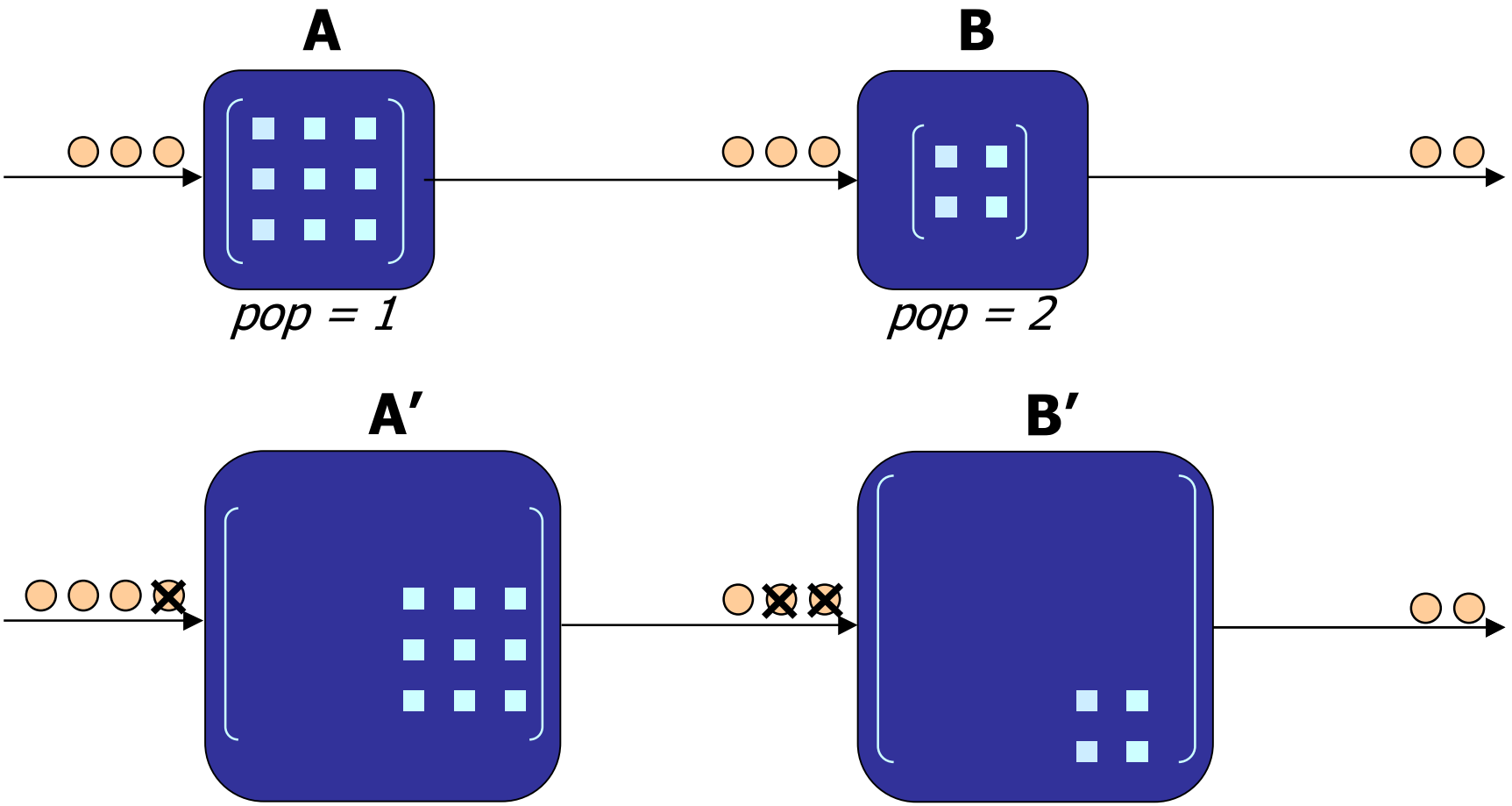

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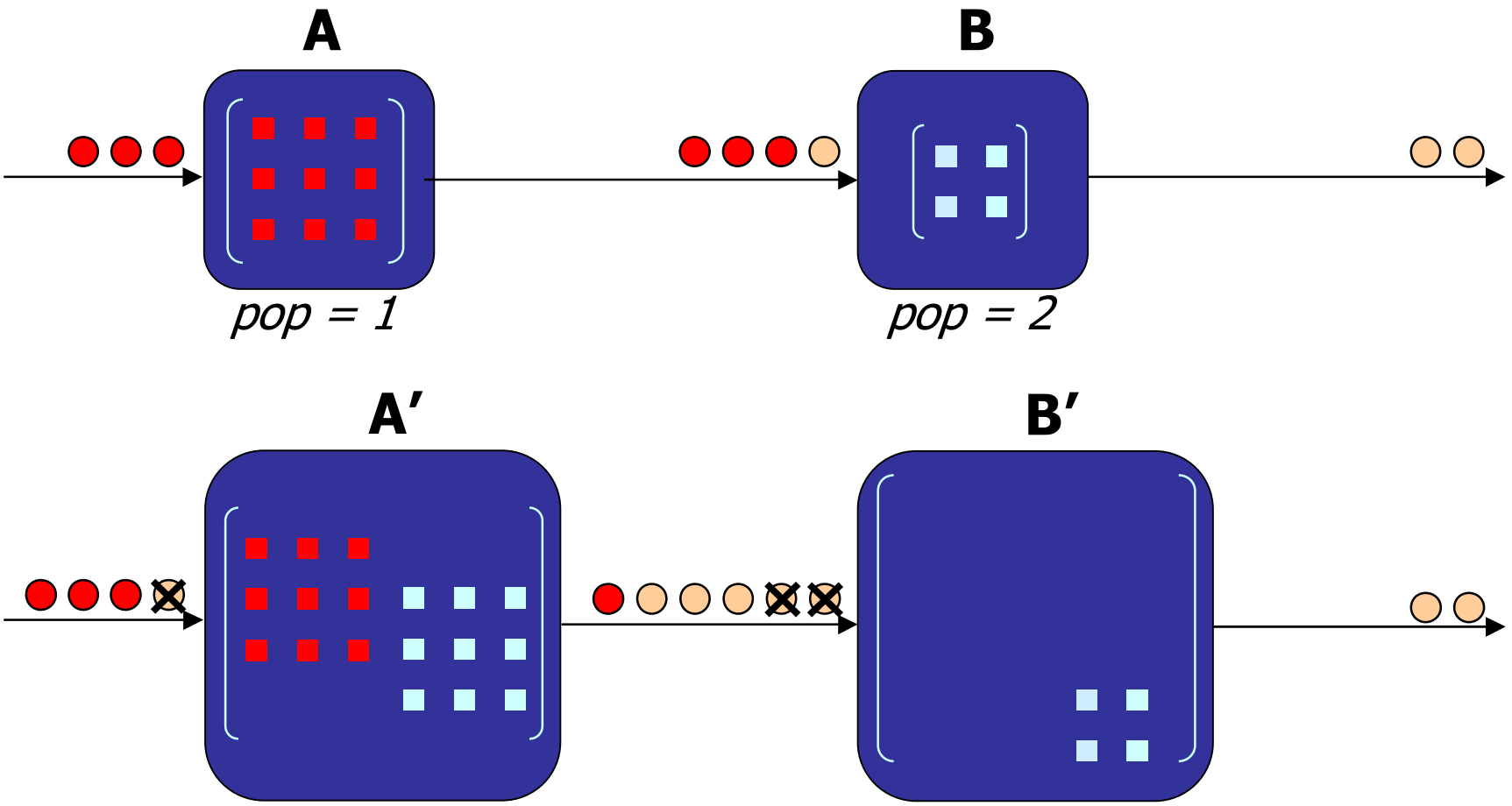

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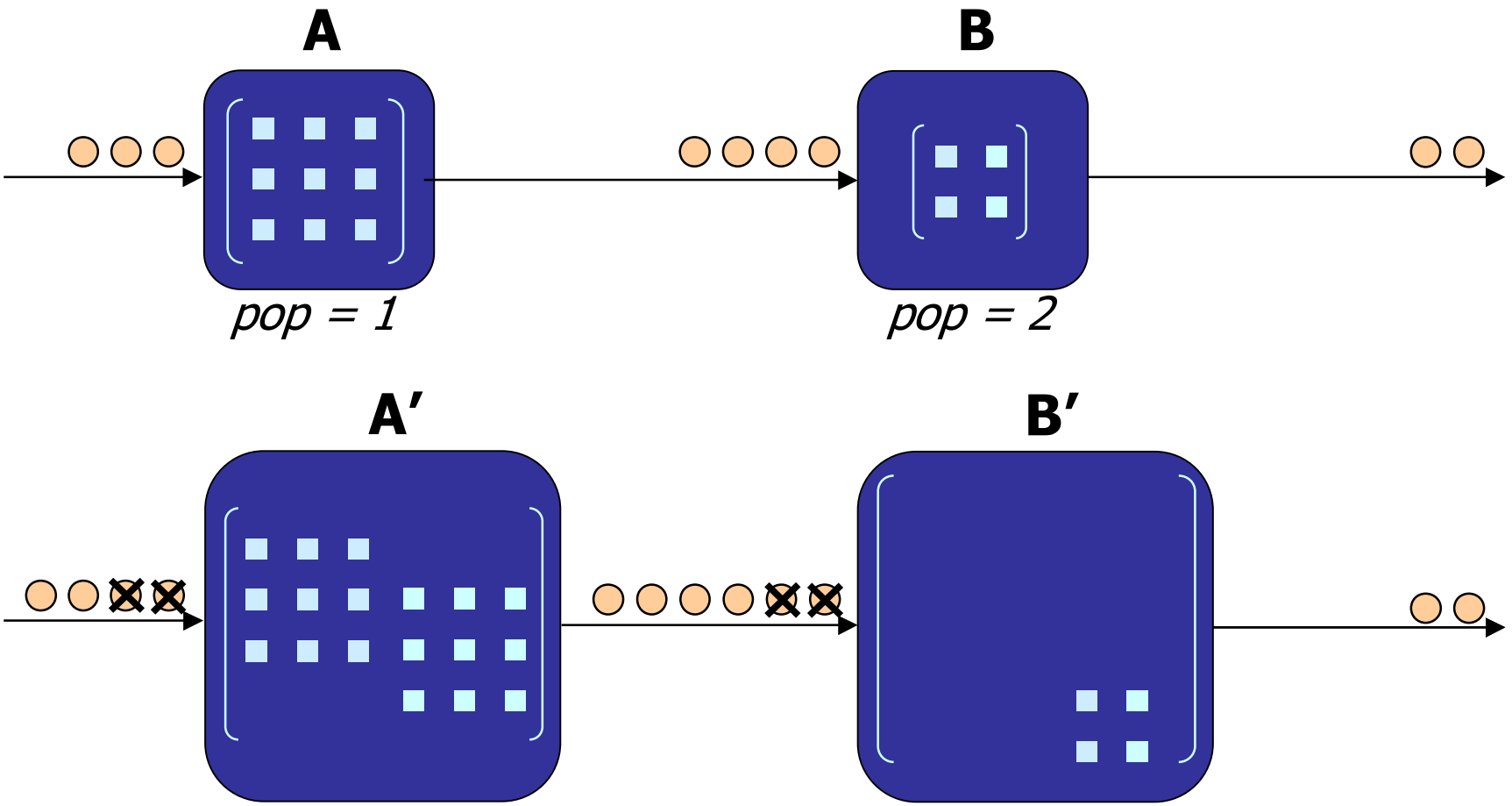

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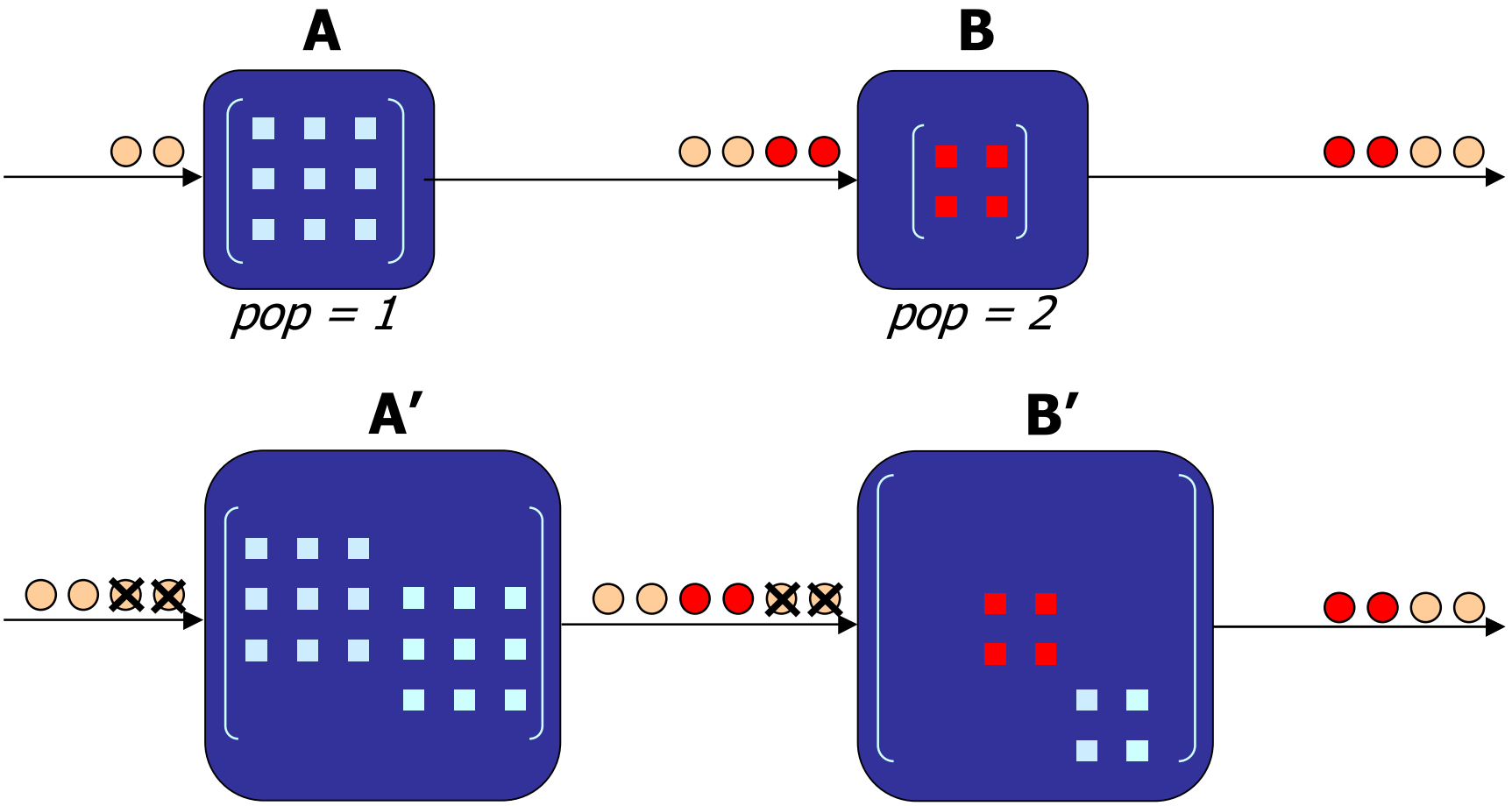

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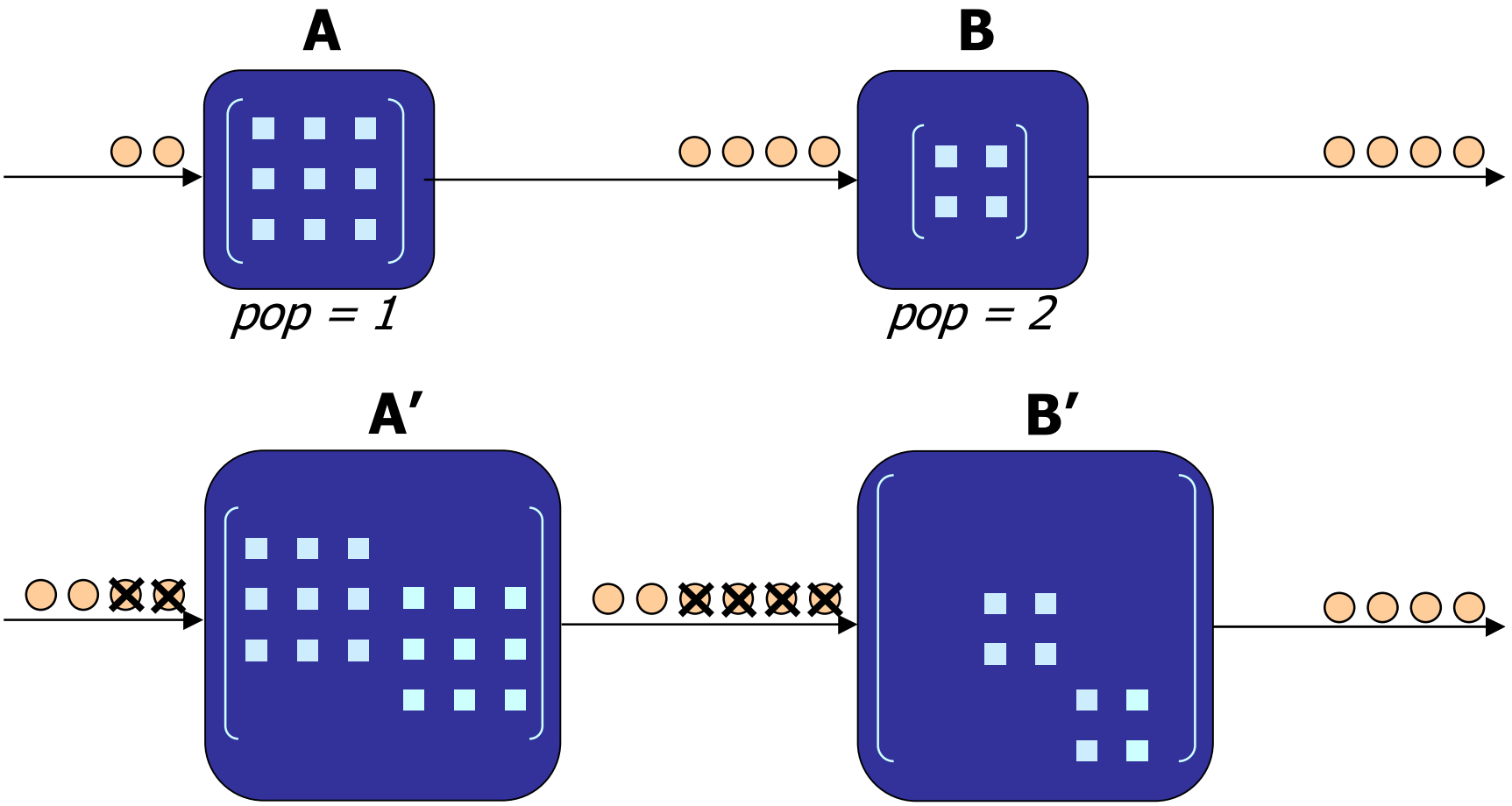

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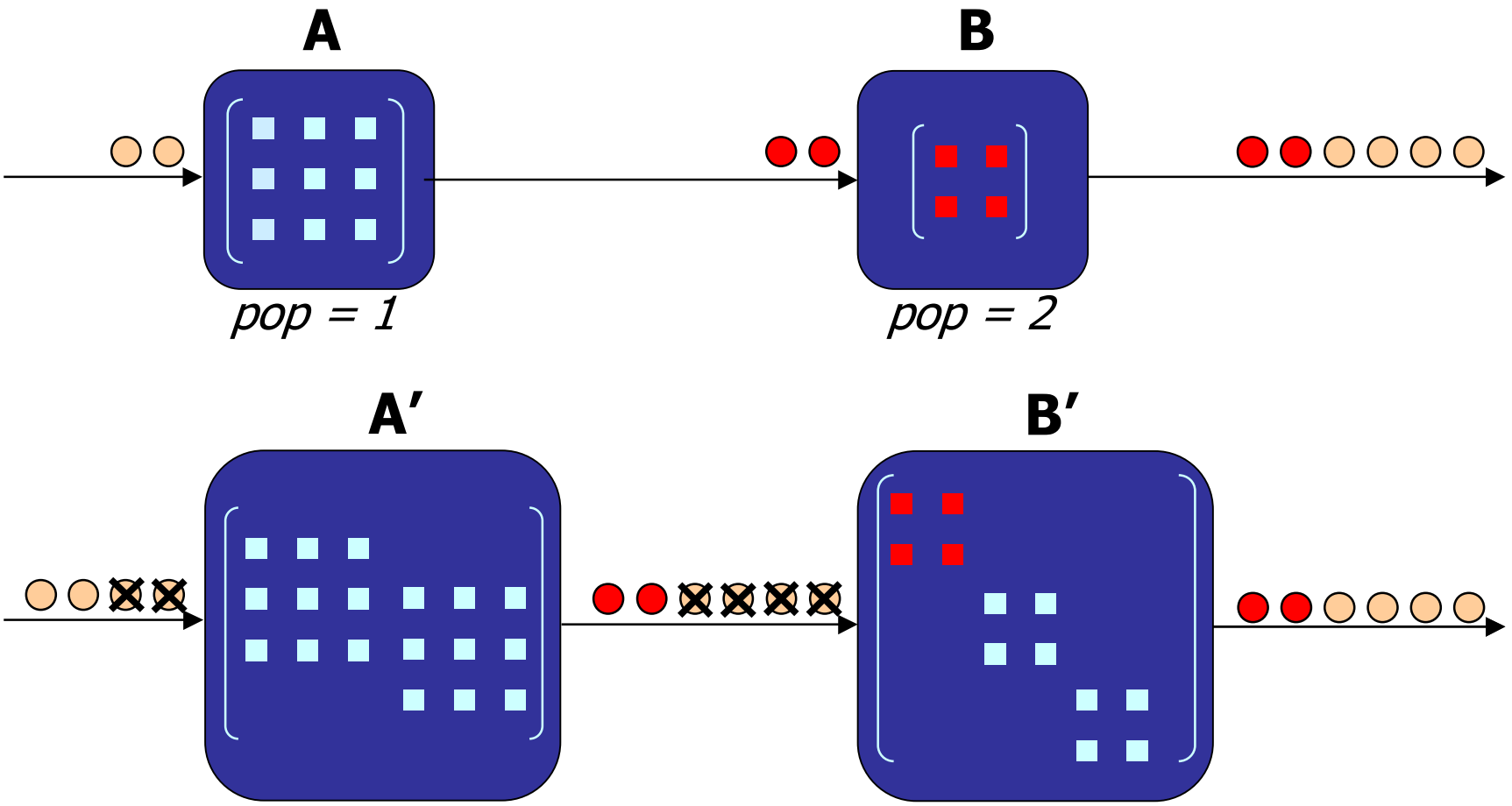

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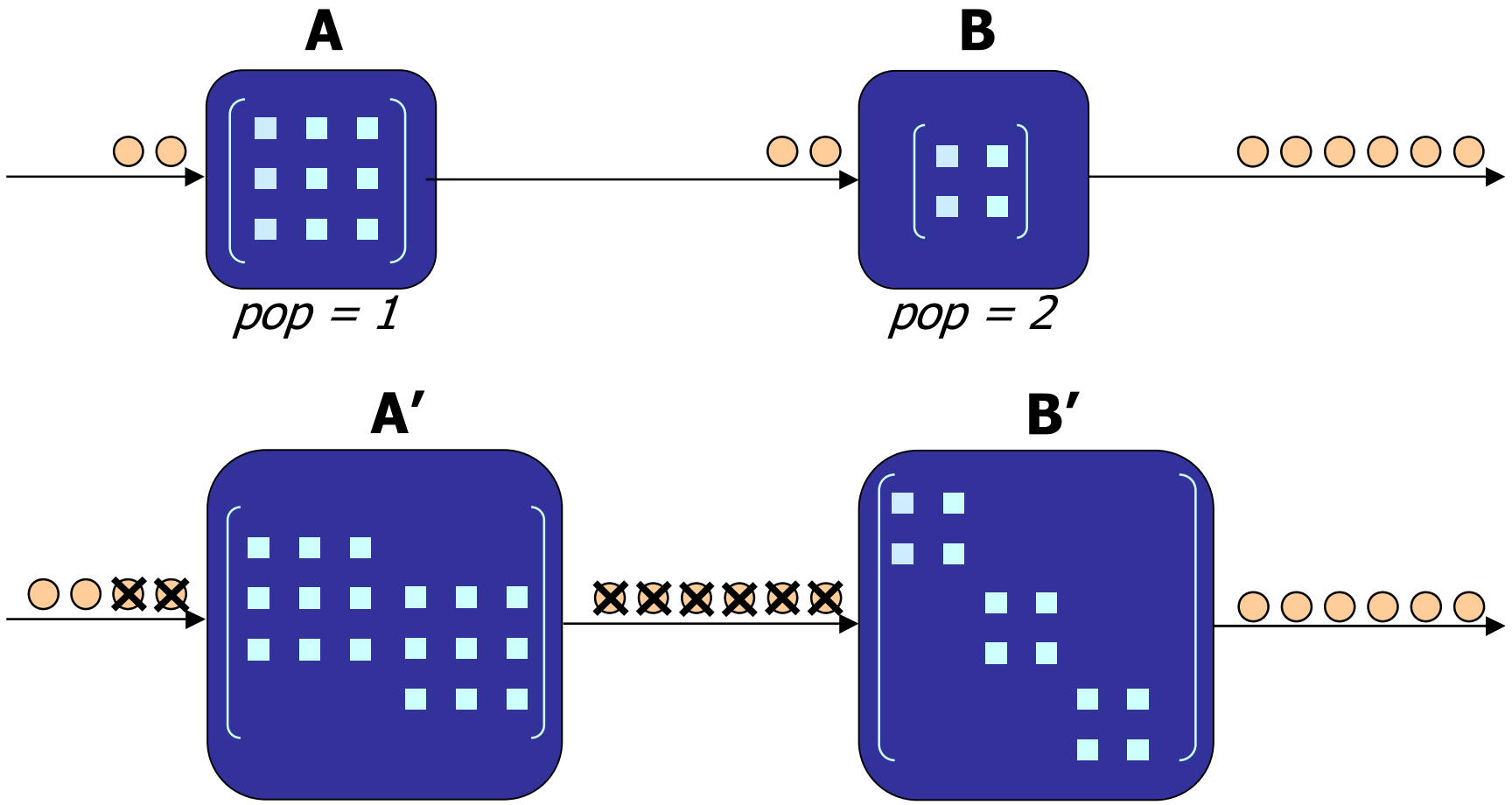

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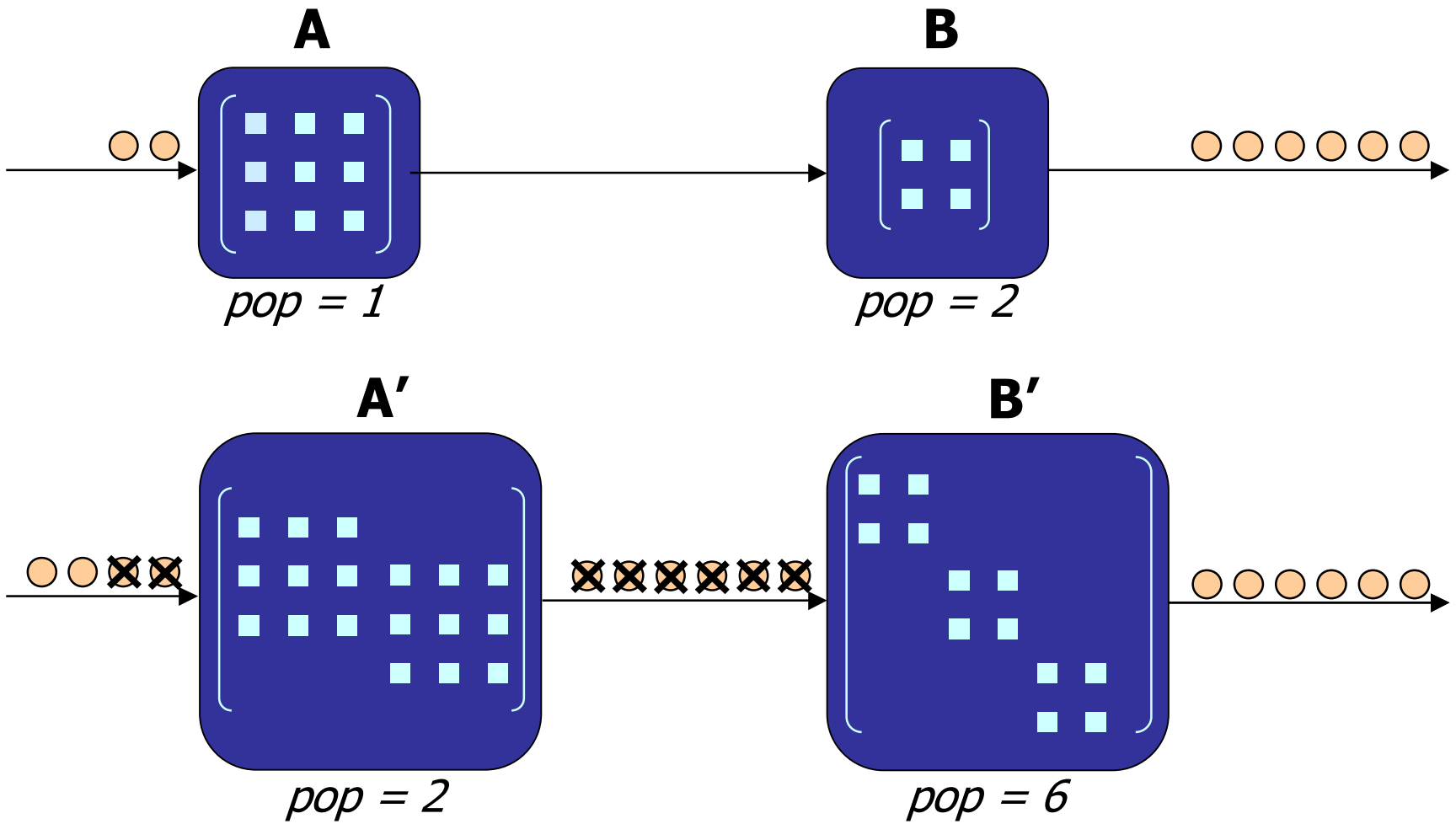

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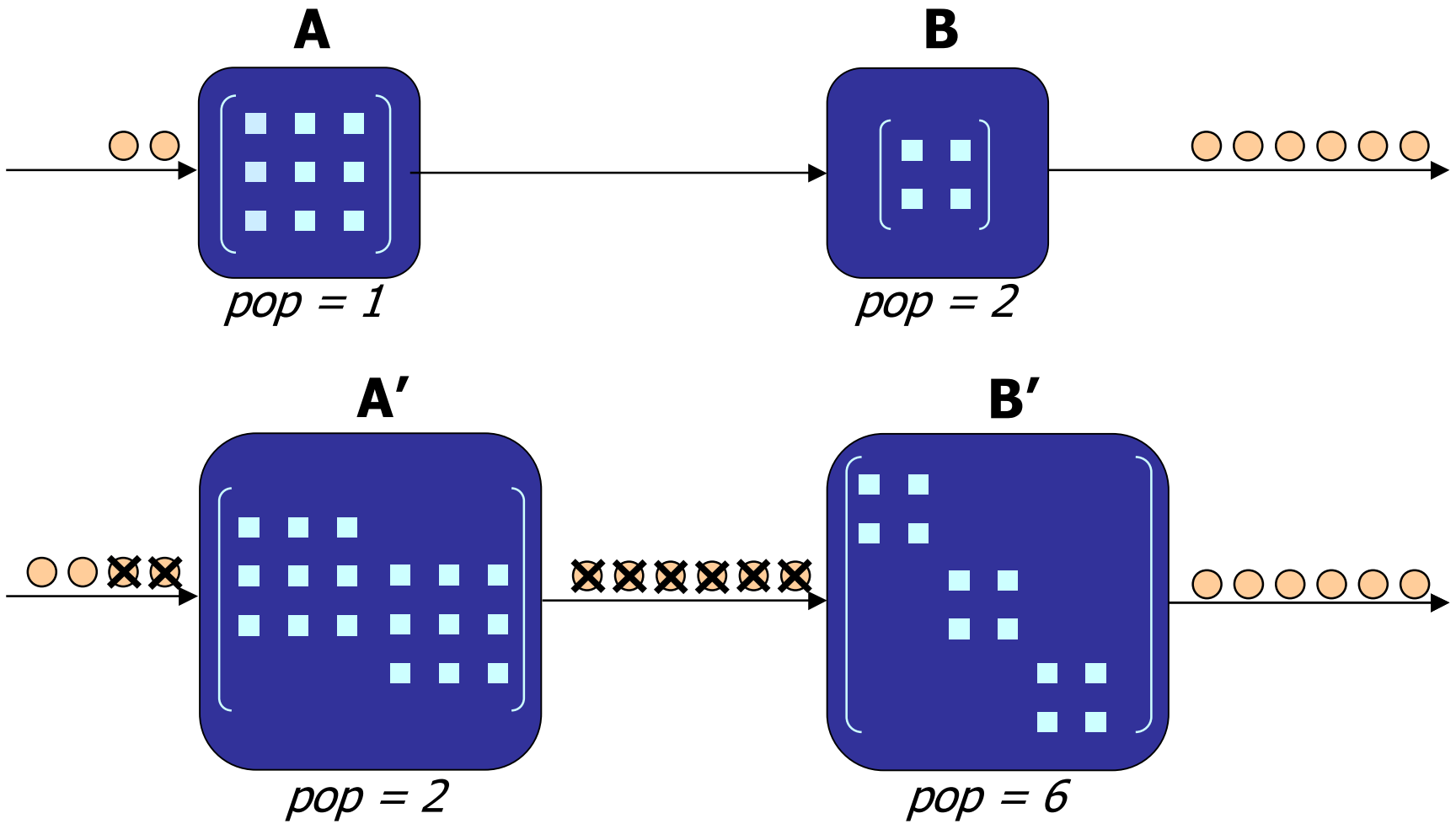
Expanded dimensions match a steady-state cycle:



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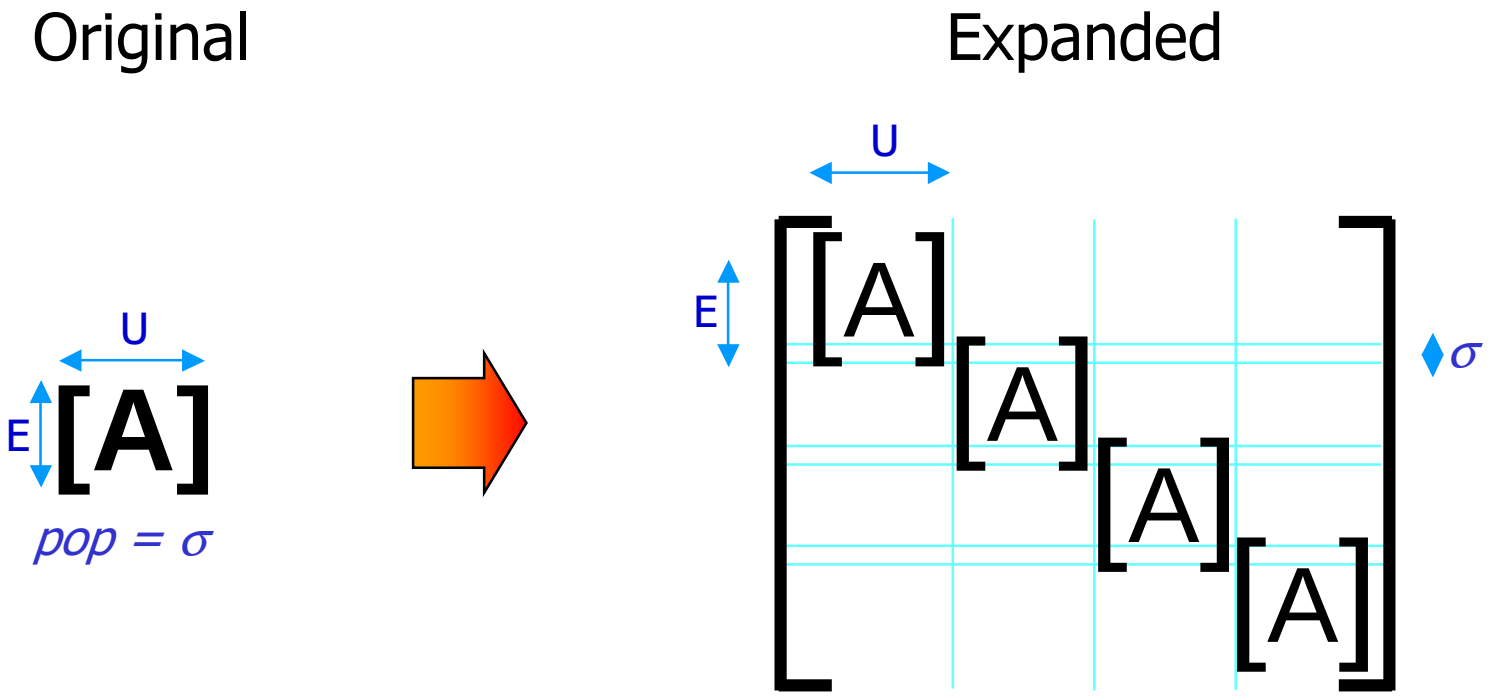
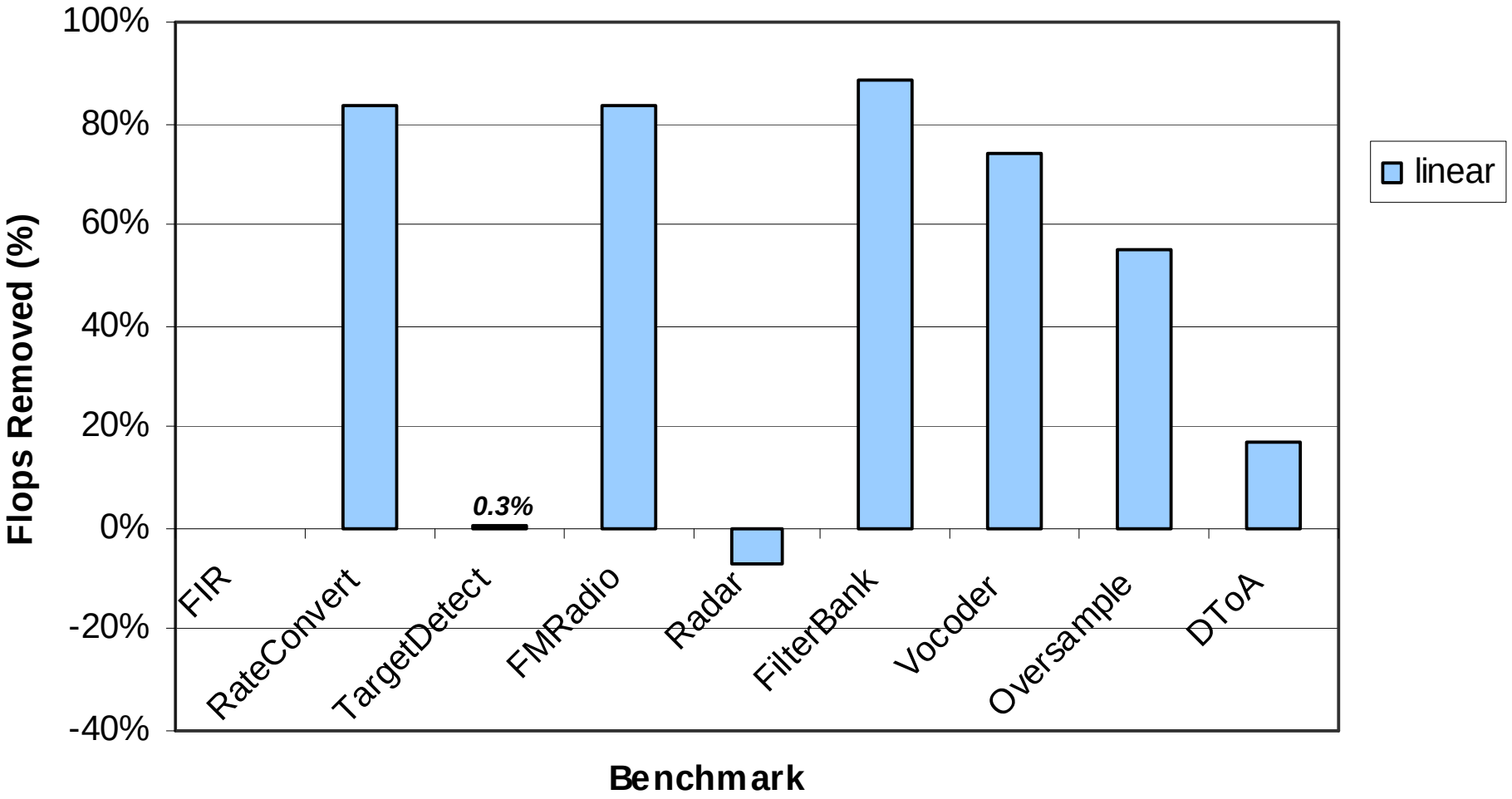
- Linear Expansion

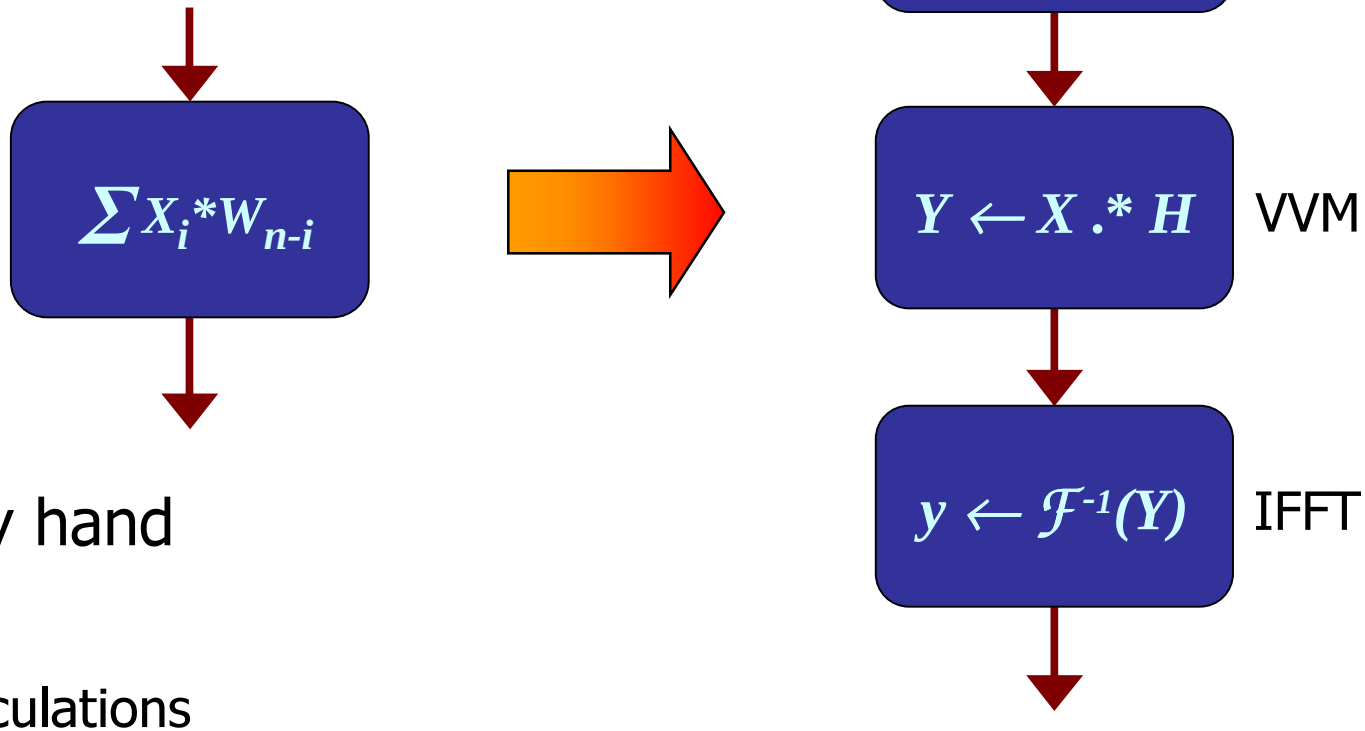


Floating-Point Operations Reduction



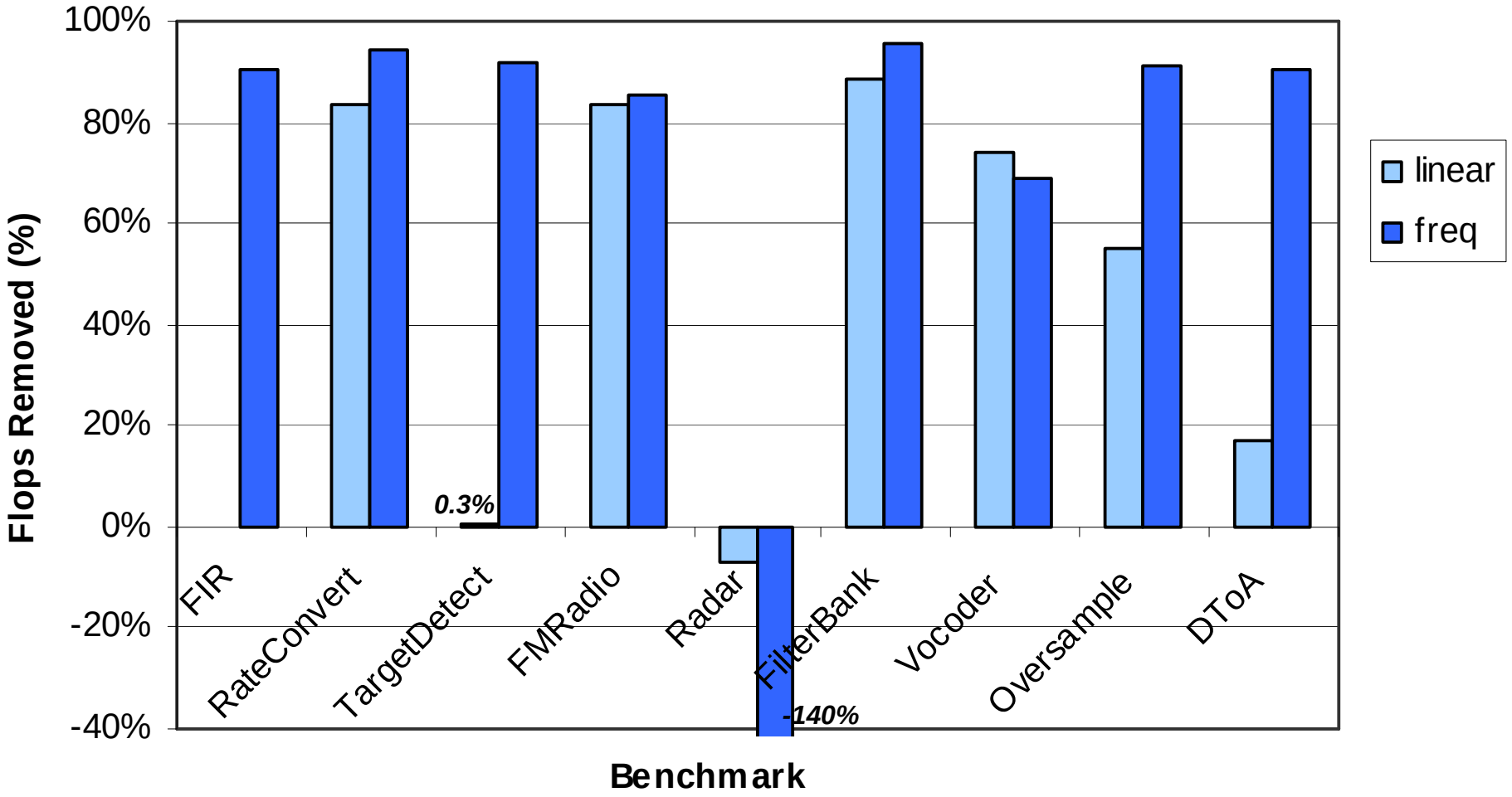
2) From Time to Frequency Domain

- Convolutions can be done cheaply in the Frequency Domain



- Painful to do by hand
  - Blocking
  - Coefficient calculations
  - Startup etc.

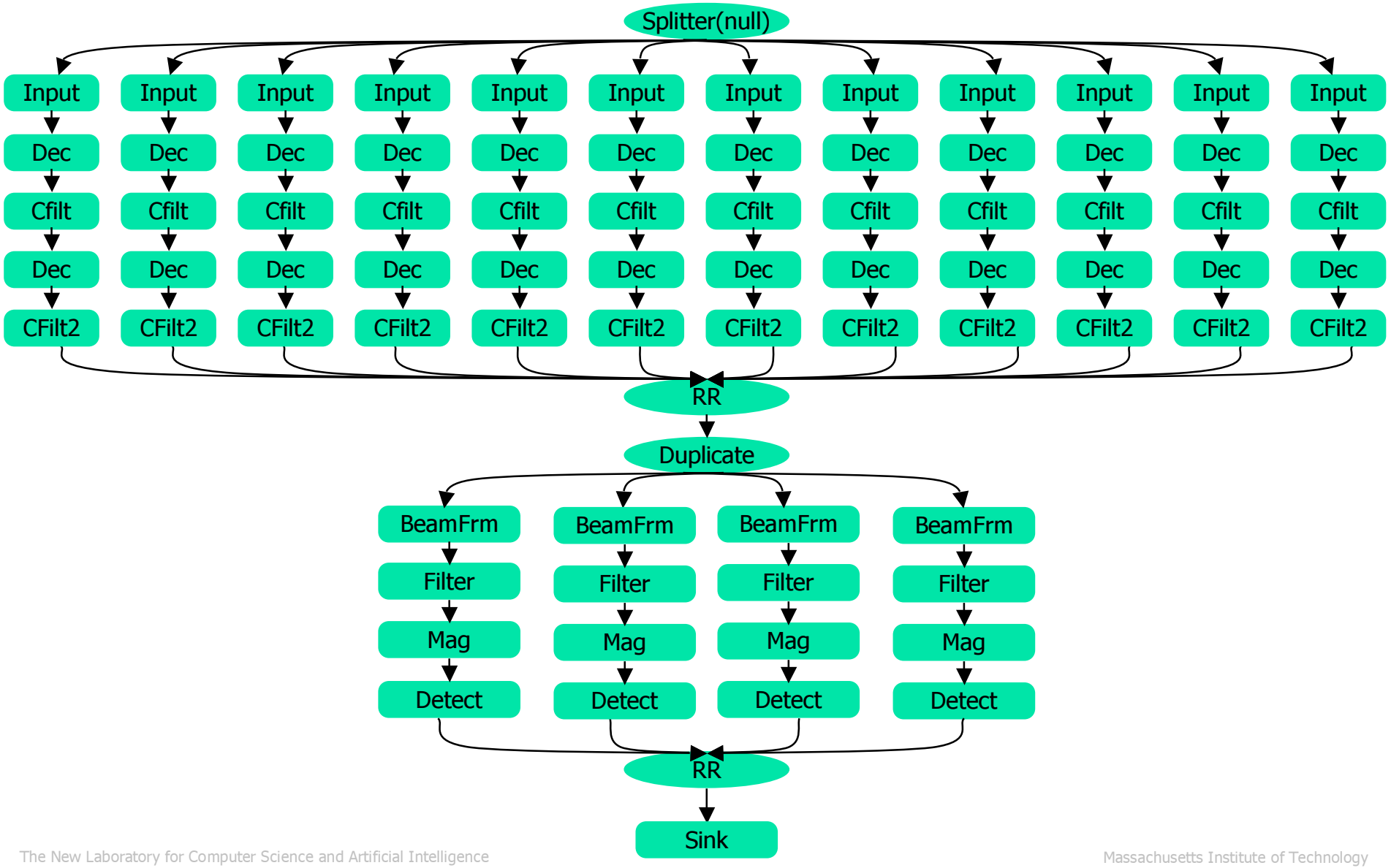
Floating-Point Operations Reduction



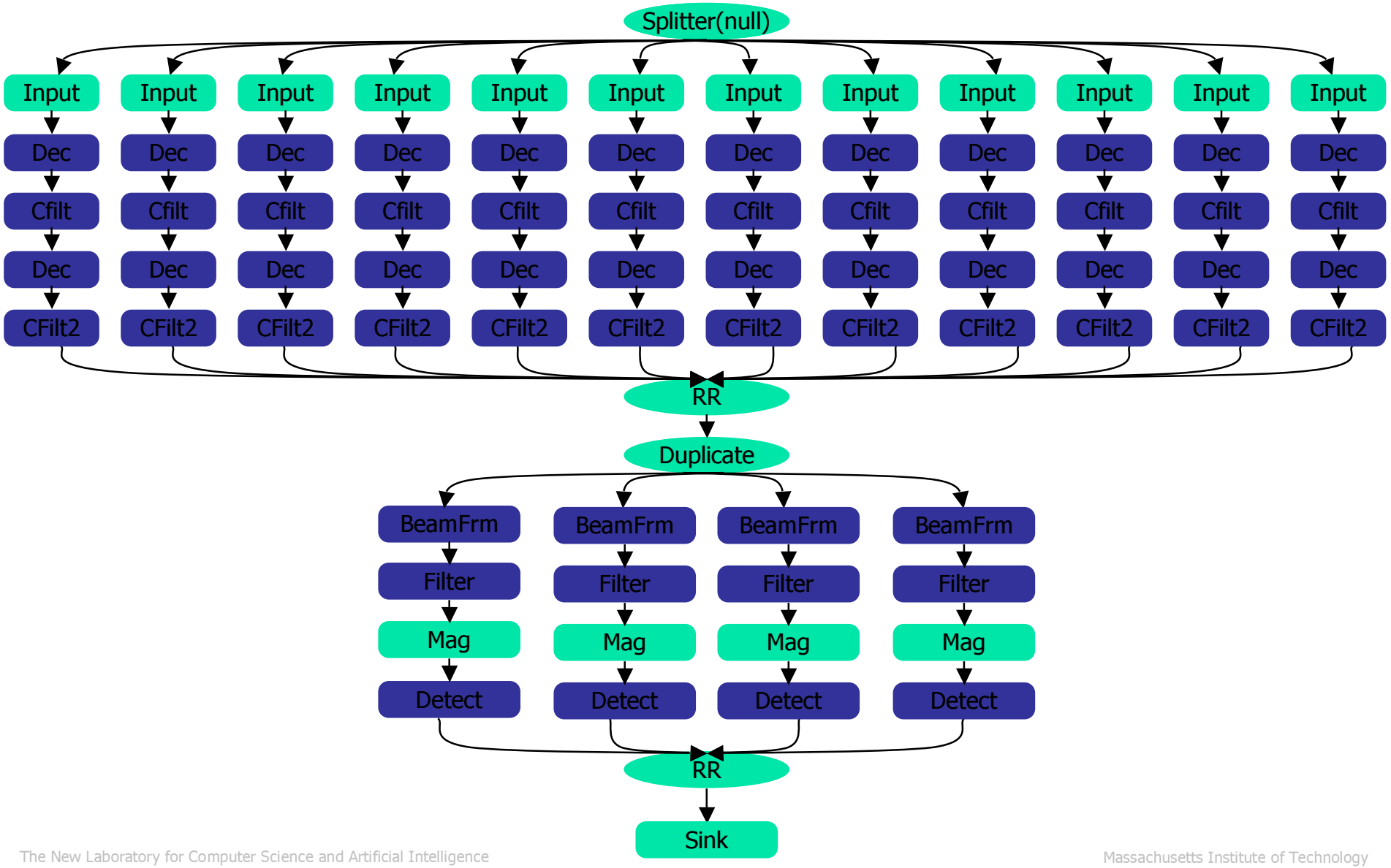
3) Transformation Selection

- When to apply what transformations?
  - Linear filter combination can increase the computation cost
  - Shifting to the Frequency domain is expensive for filters with pop > 1
    - Compute all outputs, then decimate by pop rate
  - Some expensive transformations may later enable other transformations, reducing the overall cost

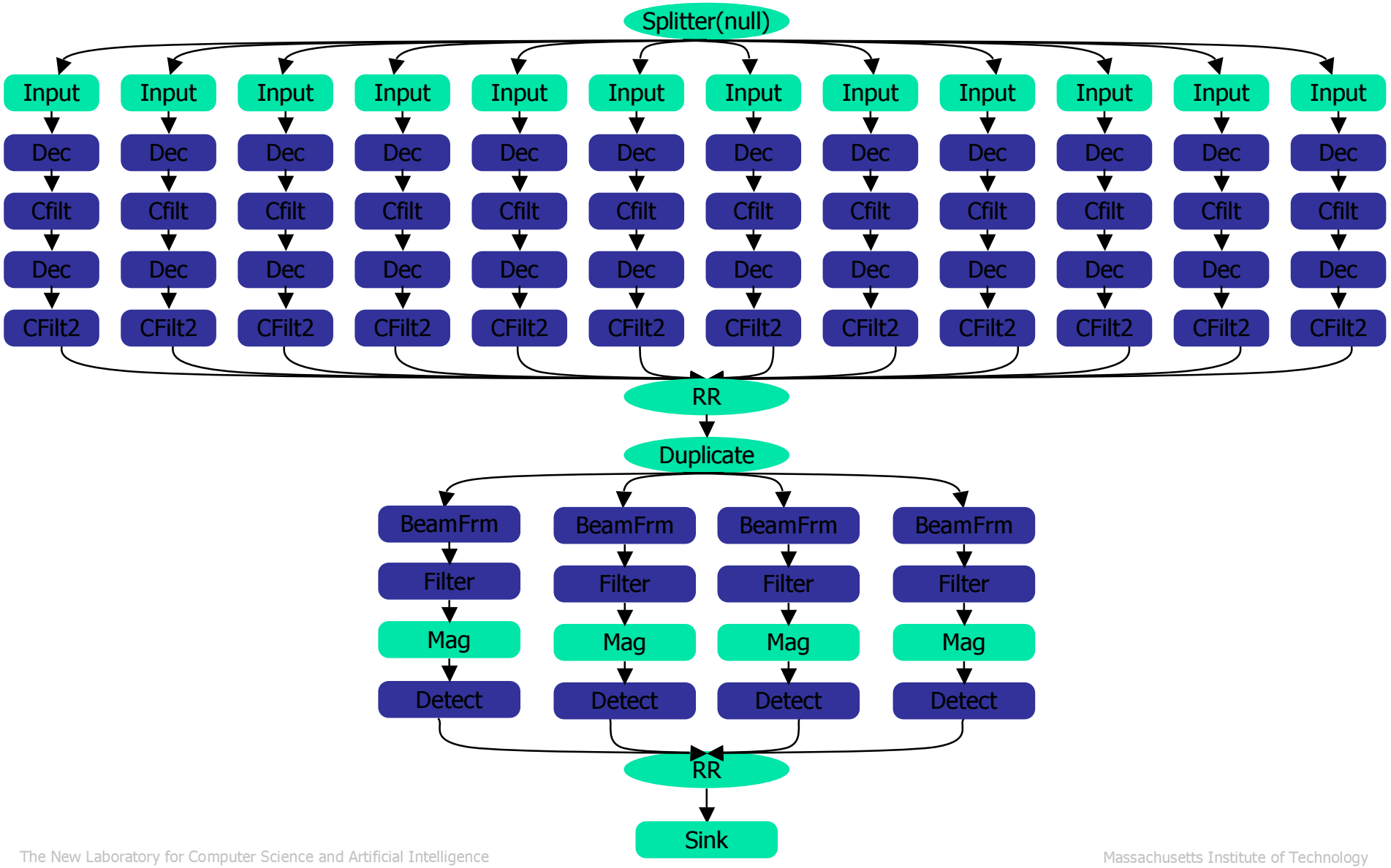
Radar


Splitter(null)
Input
Dec
Cfilt
Dec
CFilt2
RR
Duplicate
BeamFrm
Filter
Mag
Detect
RR
Sink

Radar (Linear Analysis)



Radar (Maximal Linear Combination)



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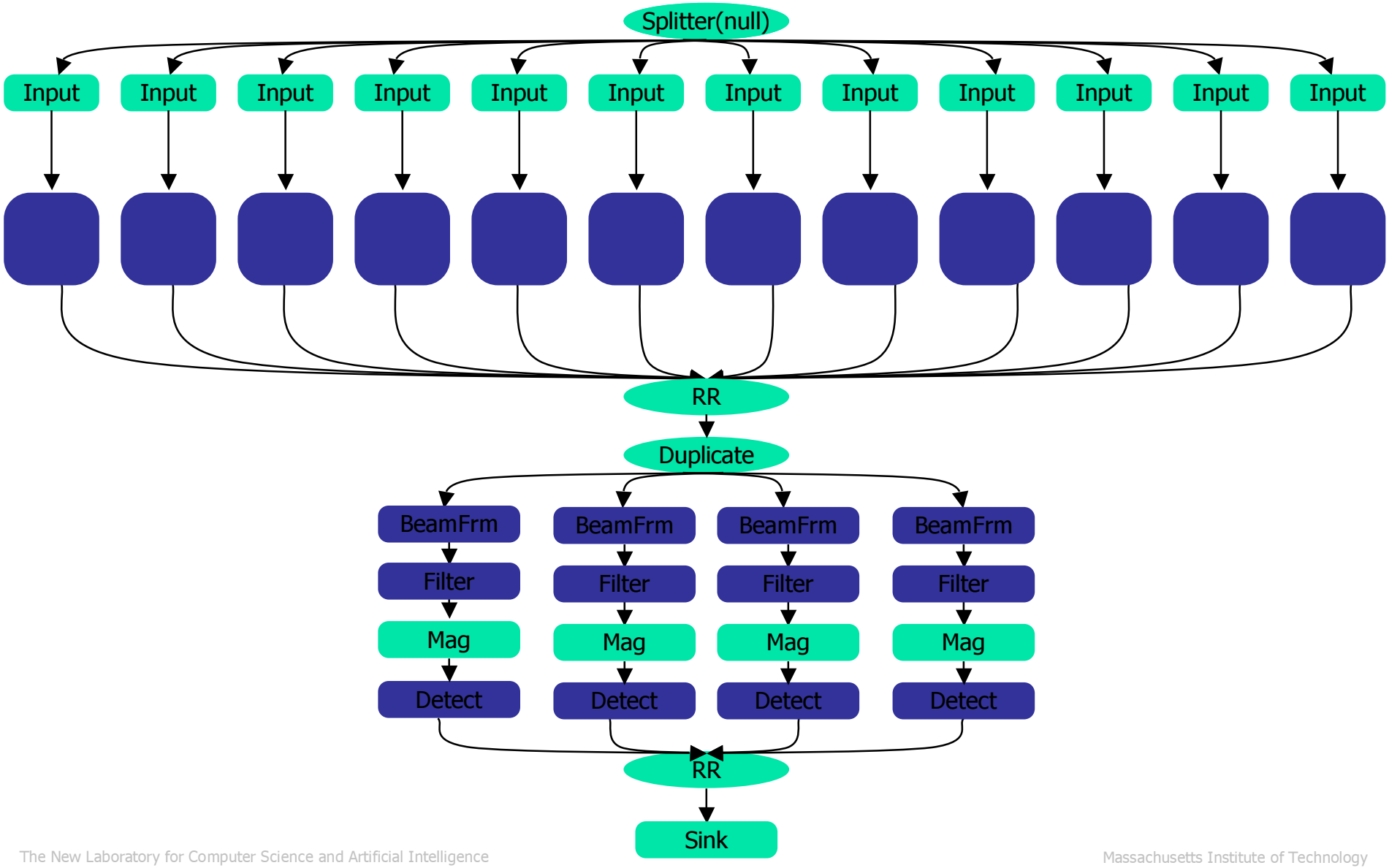
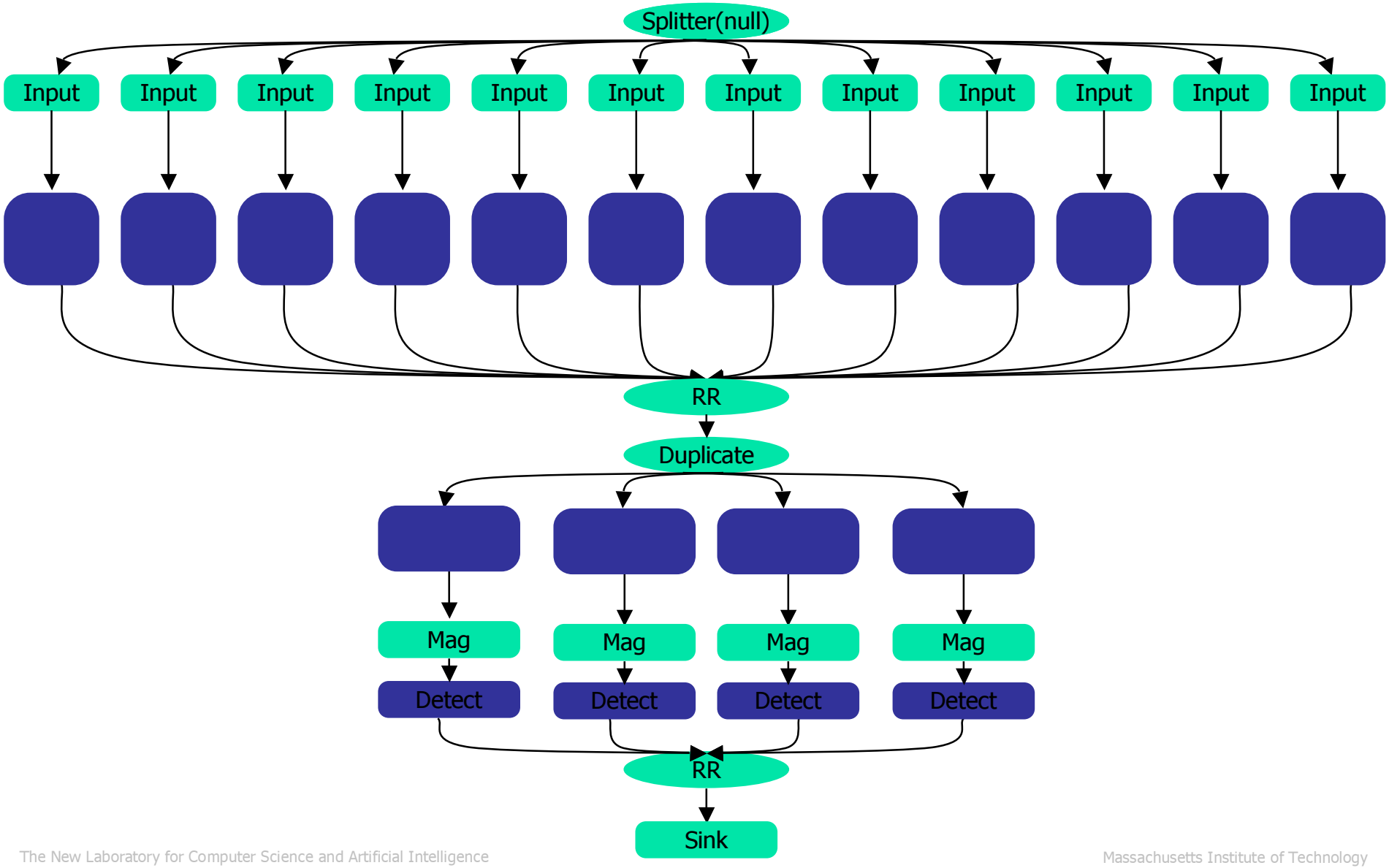
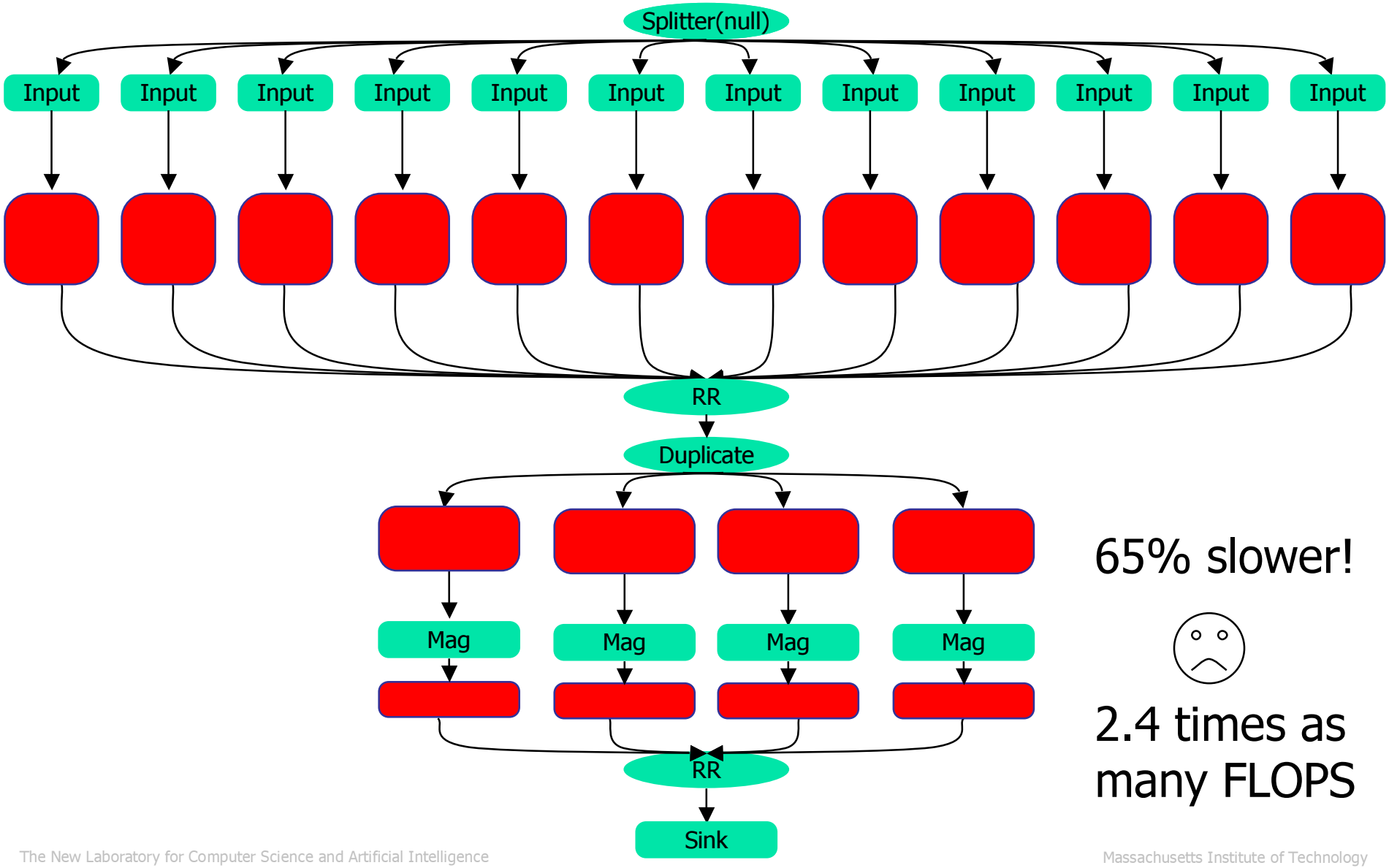


Radar (Maximal Linear Combination)



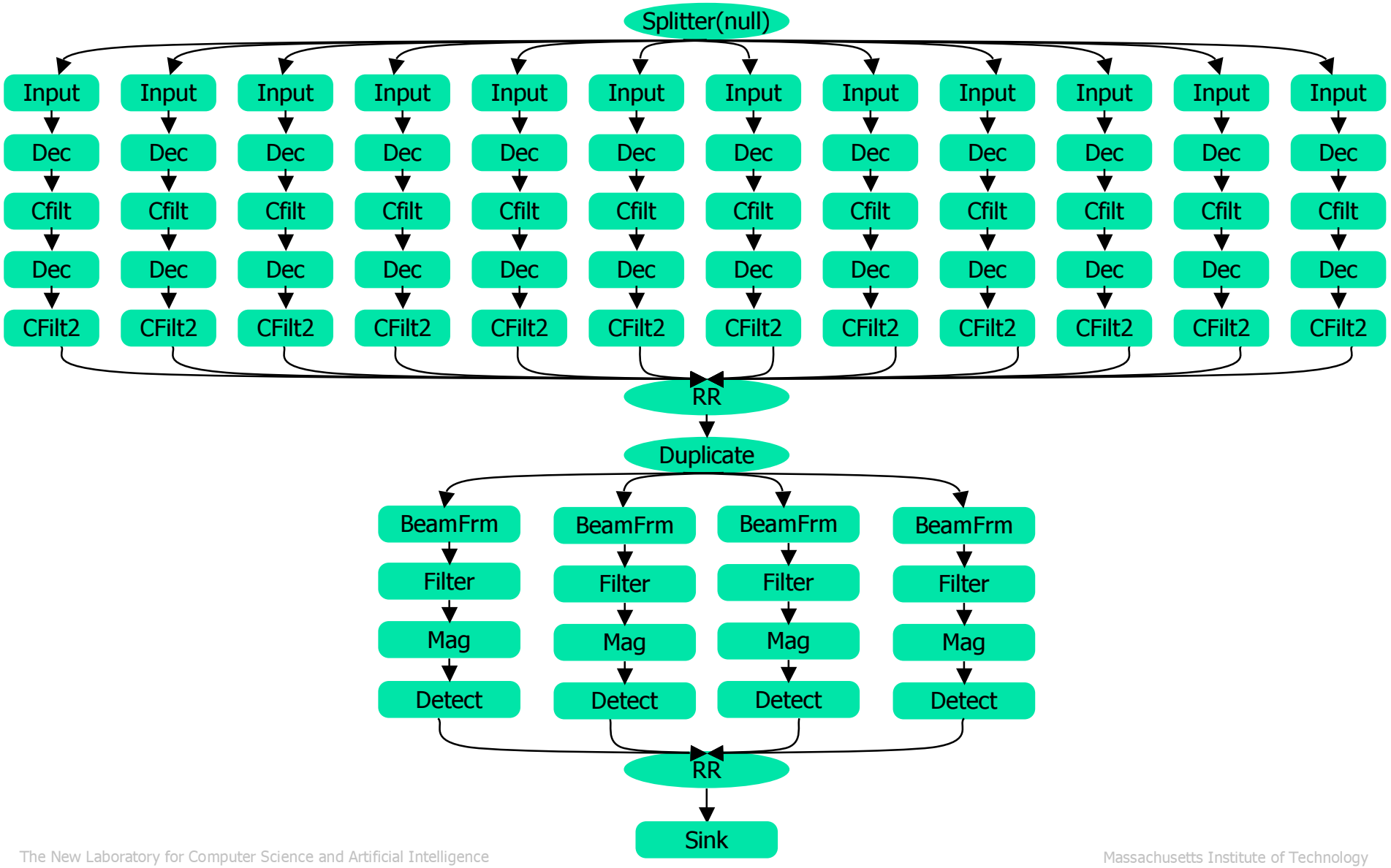
Radar (Maximal Frequency)



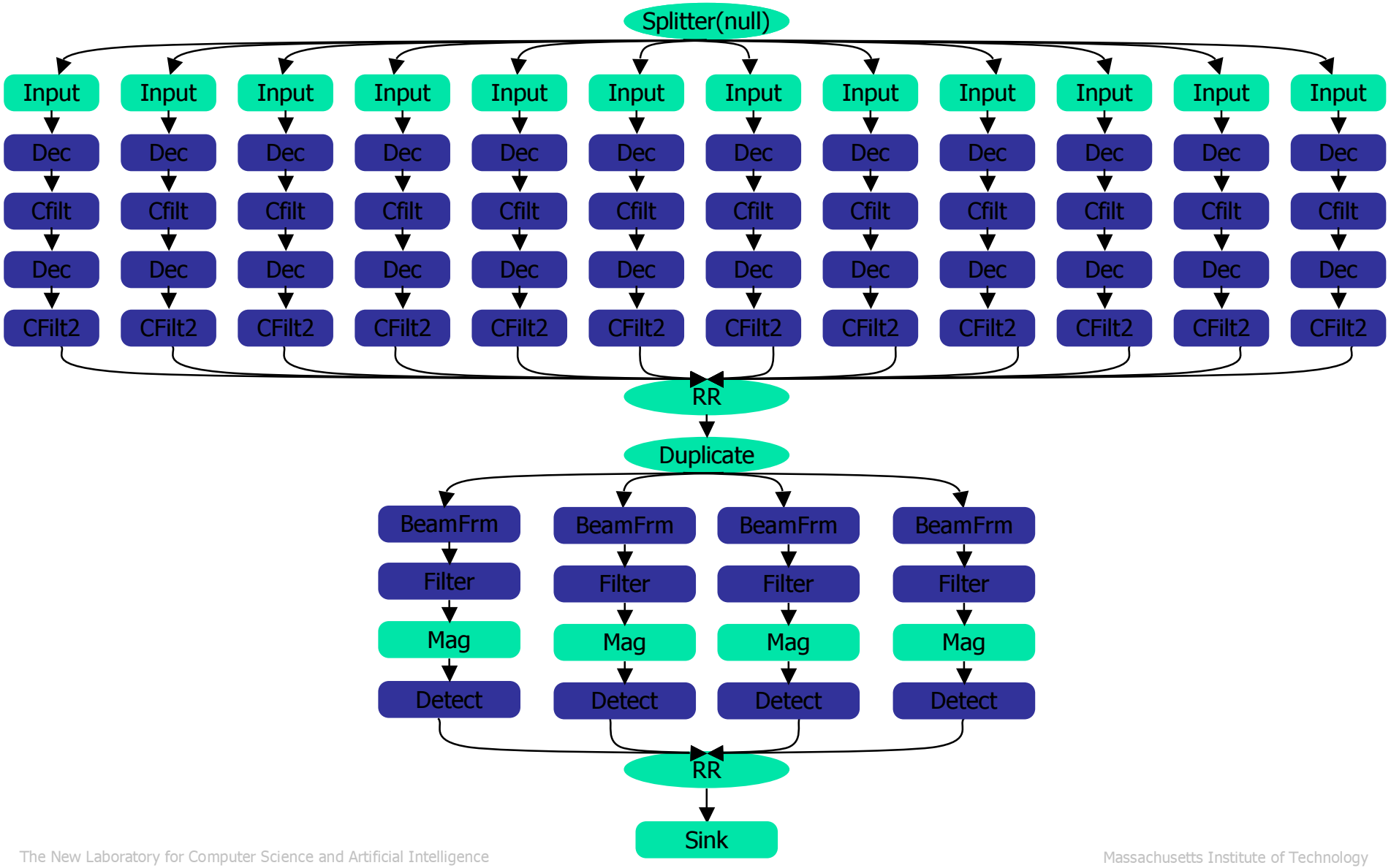
65% slower!

2.4 times as many FLOPS

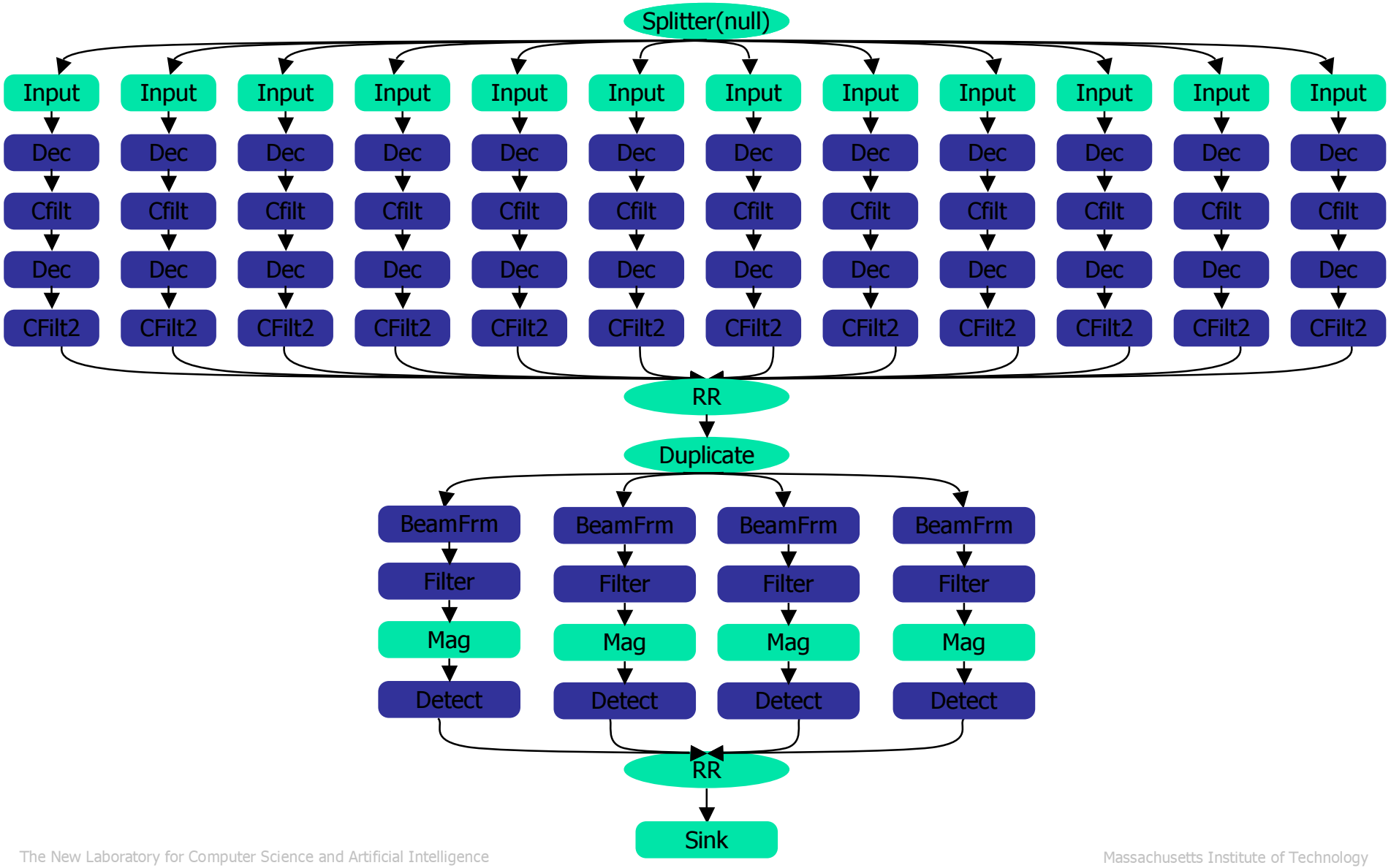
Radar


Splitter(null)
Input
Dec
Cfilt
Dec
CFilt2
RR
Duplicate
BeamFrm
Filter
Mag
Detect
RR
Sink

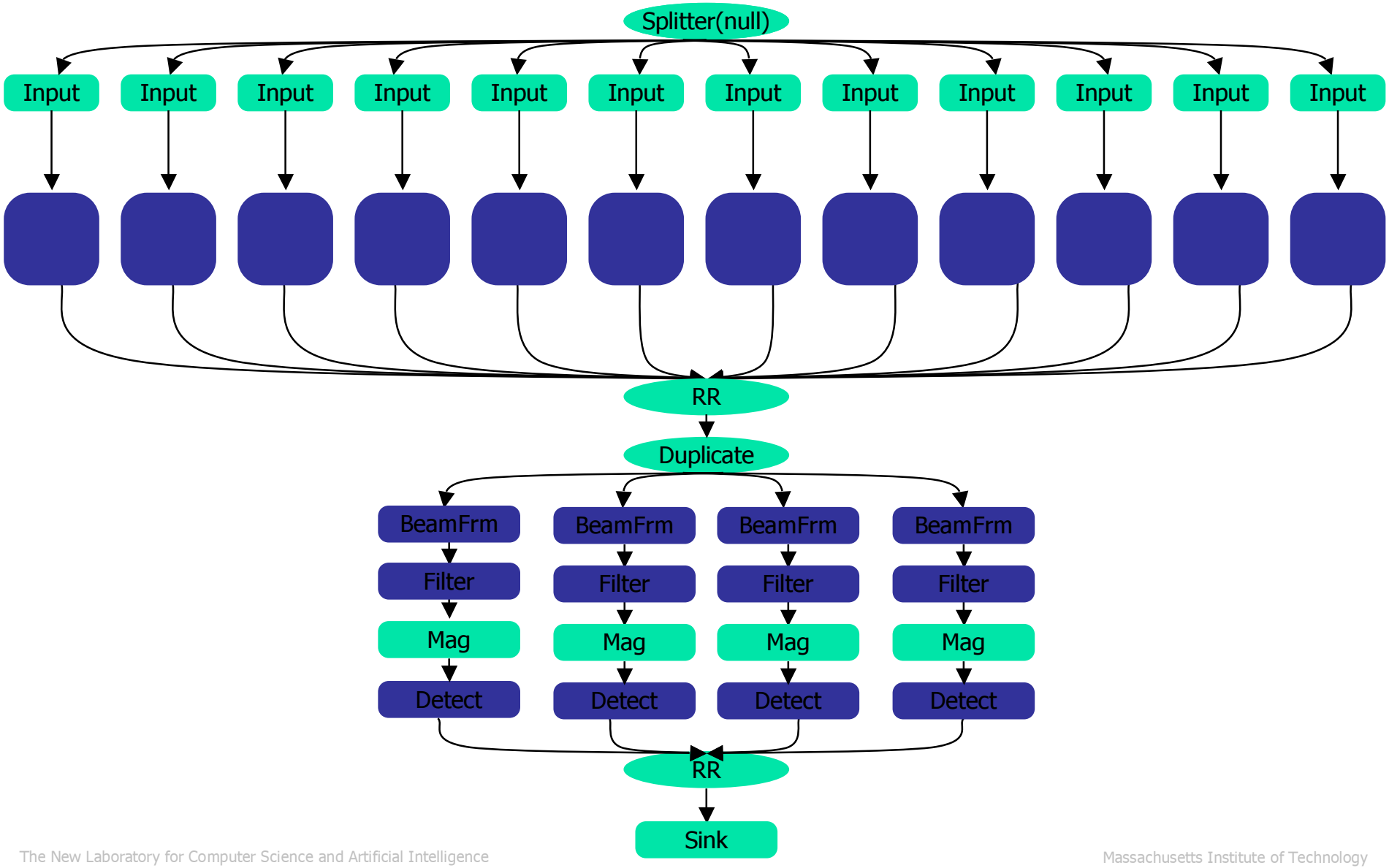
Radar (Linear Analysis)



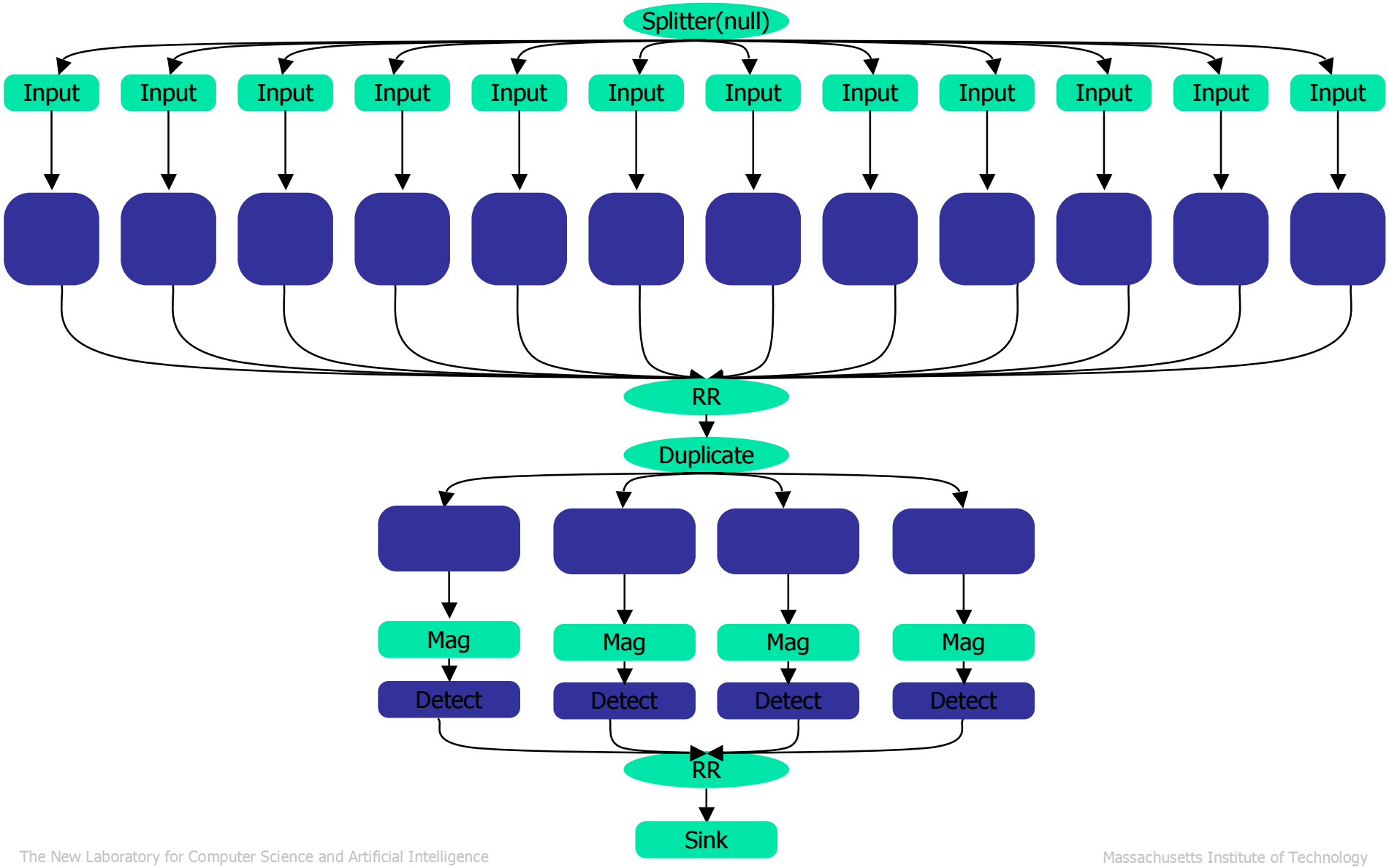
Radar (Maximal Linear Combination)



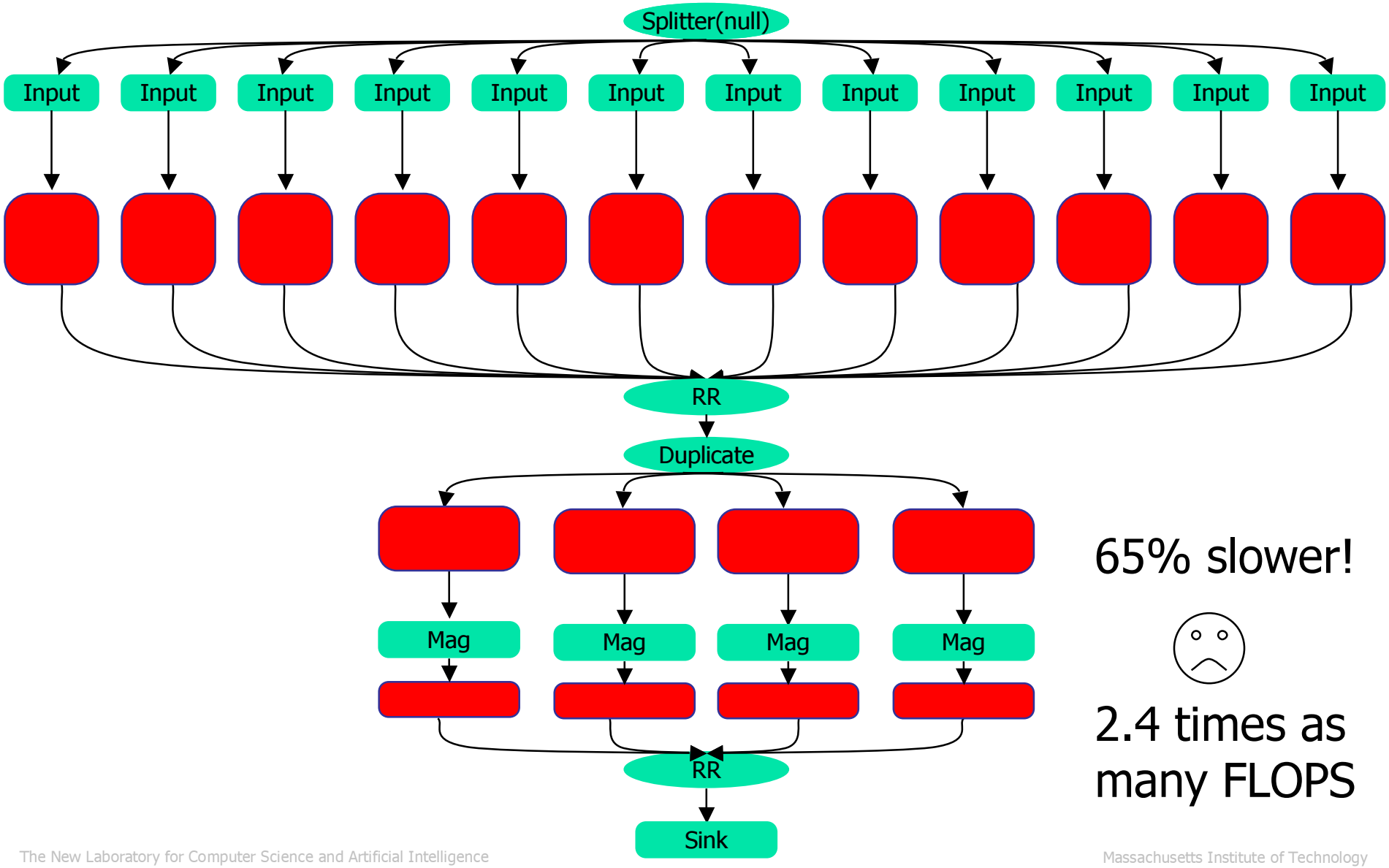
Radar (Maximal Linear Combination)



Radar (Maximal Linear Combination)



Radar (Maximal Frequency)



65% slower!

2.4 times as many FLOPS

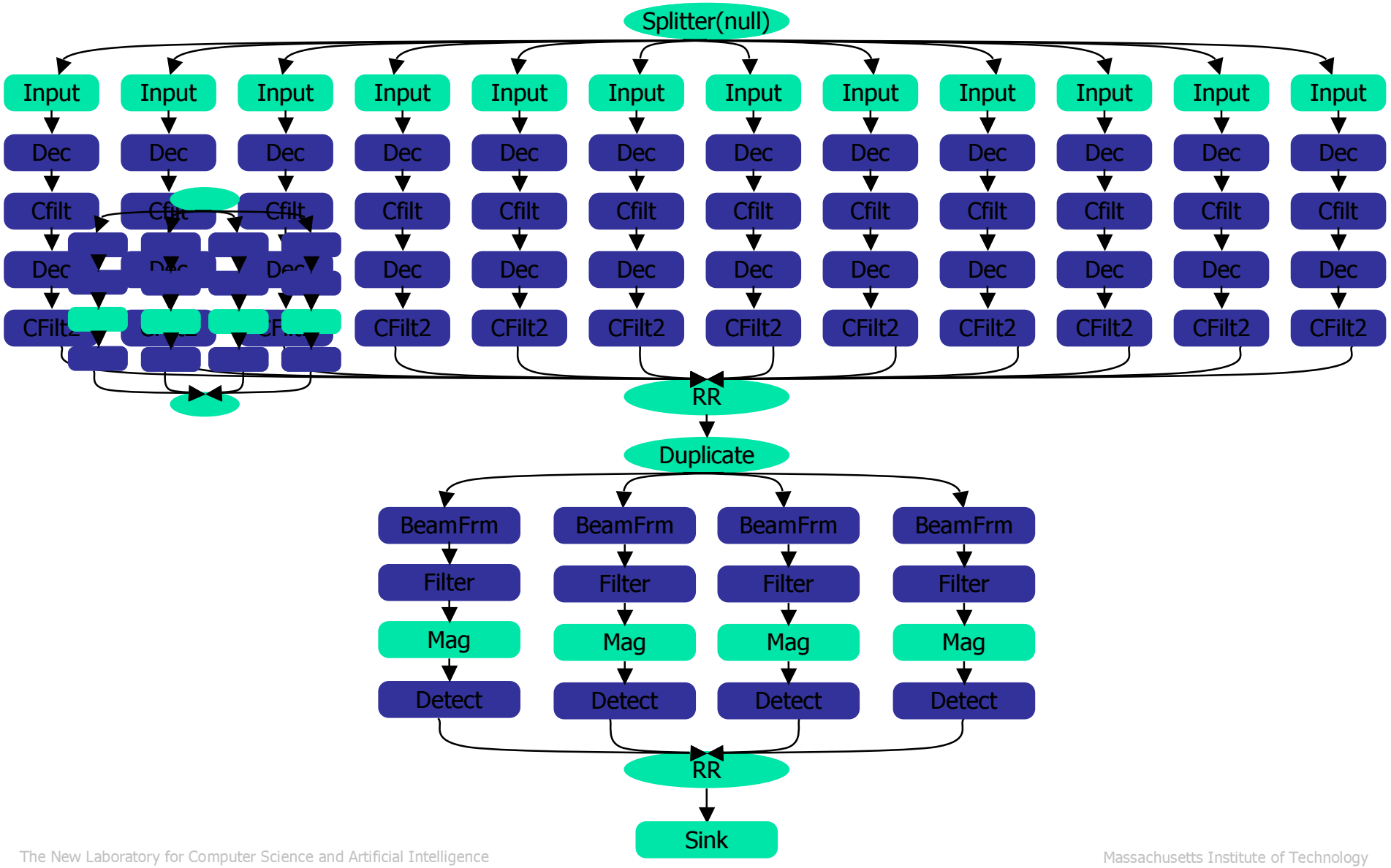
Selection Algorithm

- Estimate minimal cost for each structure:
  - Linear combination
  - Frequency translation

  } Cost function based on profiler feedback

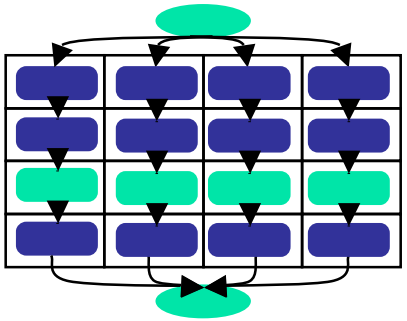
  - No transformation
    - If hierarchical, consider all possible groupings of children
- Overlapping sub-problems allows efficient dynamic programming search

Radar (Transformation Selection)



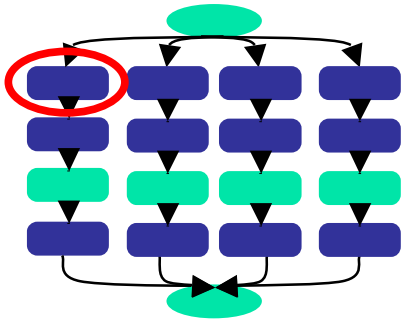
Radar (Transformation Selection)

First compute cost of individual filters:

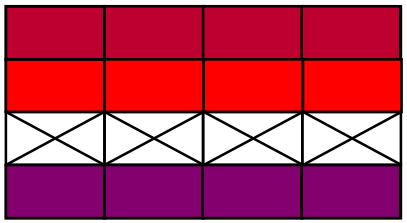


Radar (Transformation Selection)

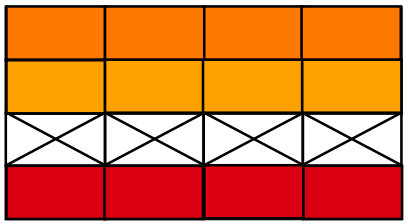
First compute cost of individual filters:



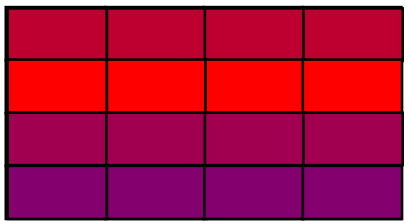
Linear Combination



Frequency

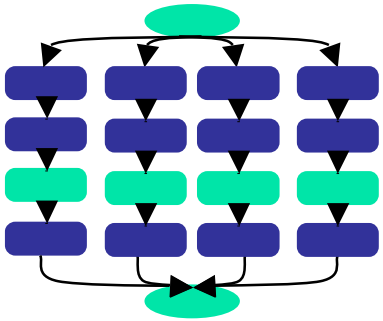


No Transform

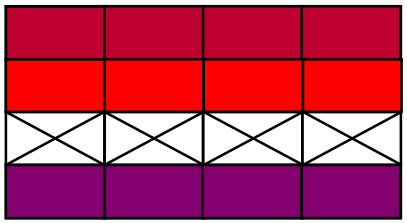


Radar (Transformation Selection)

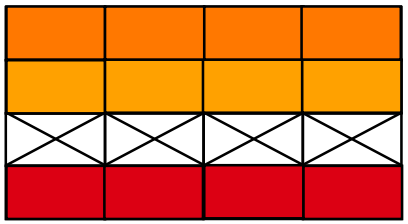
First compute cost of individual filters:



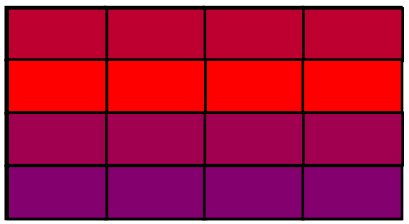
Linear Combination



Frequency



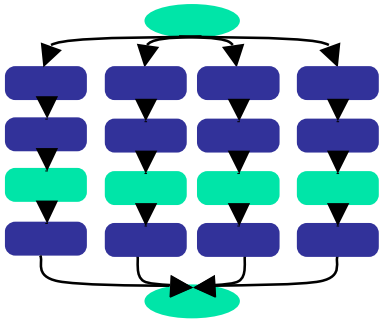
No Transform



1x1

Radar (Transformation Selection)

Then, compute cost of 1x2 nodes:

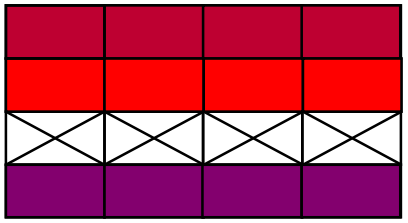


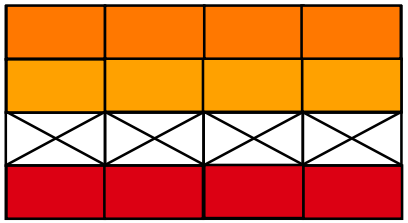
Linear Combination

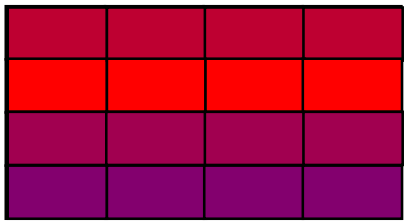
Frequency

No Transform

1x1

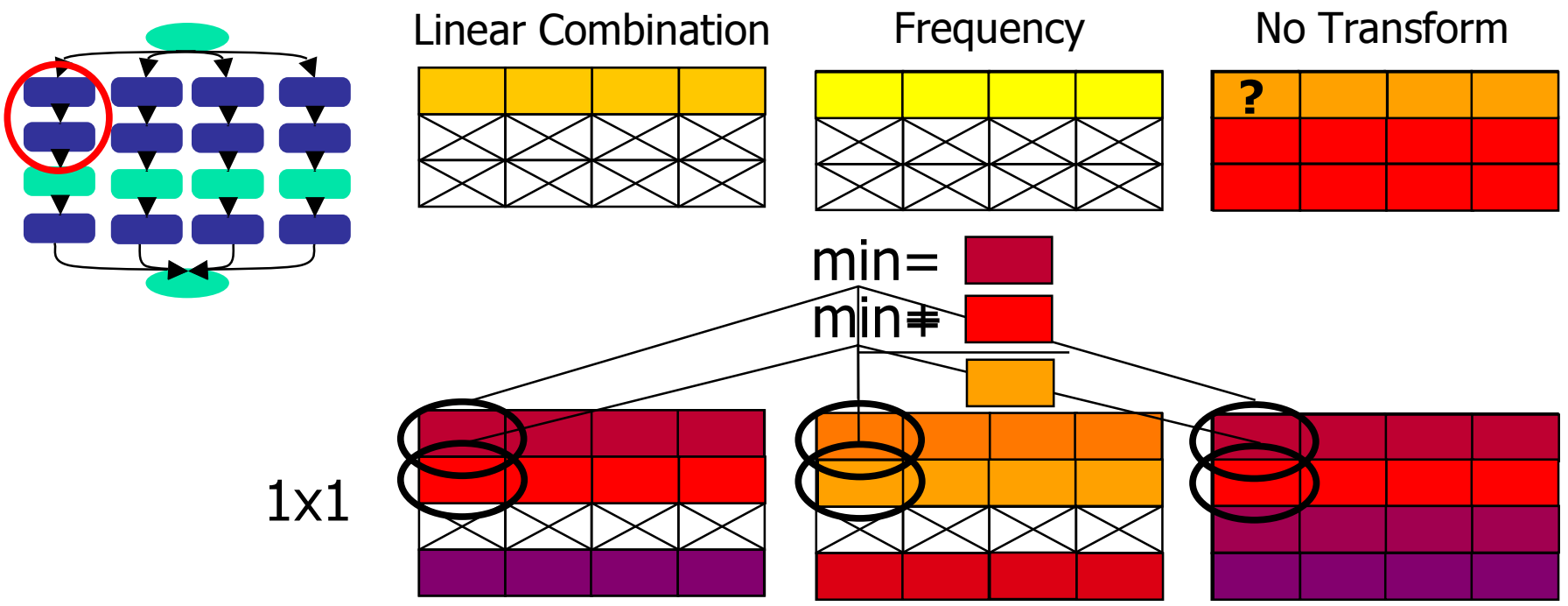






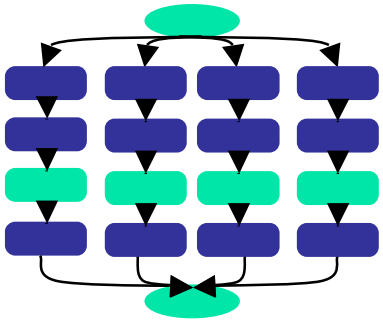
Radar (Transformation Selection)

Then, compute cost of 1x2 nodes:

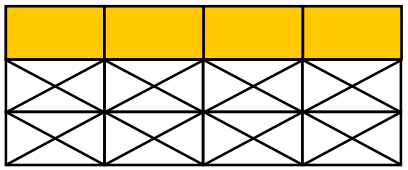


Radar (Transformation Selection)

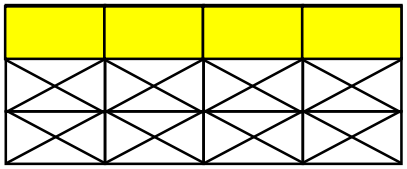
Then, compute cost of 1x2 nodes:



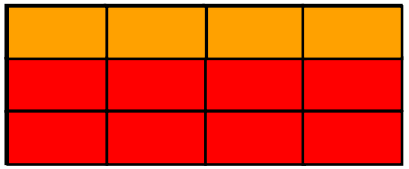
Linear Combination



Frequency

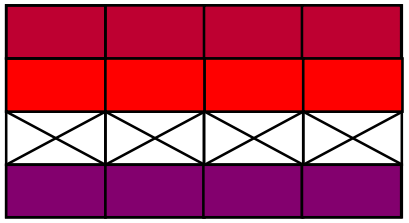


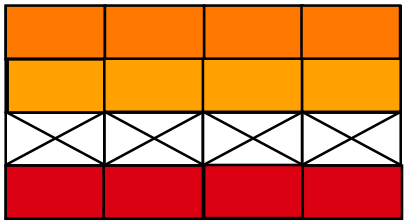
No Transform

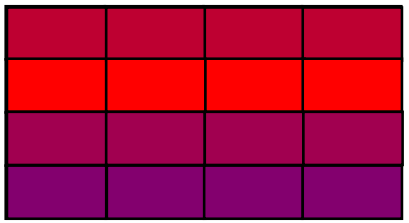


1x2

1x1

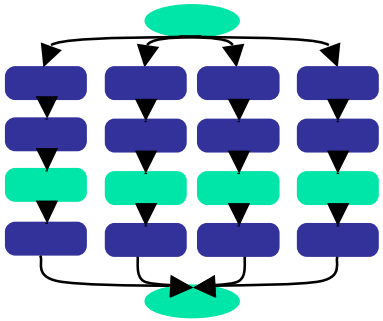




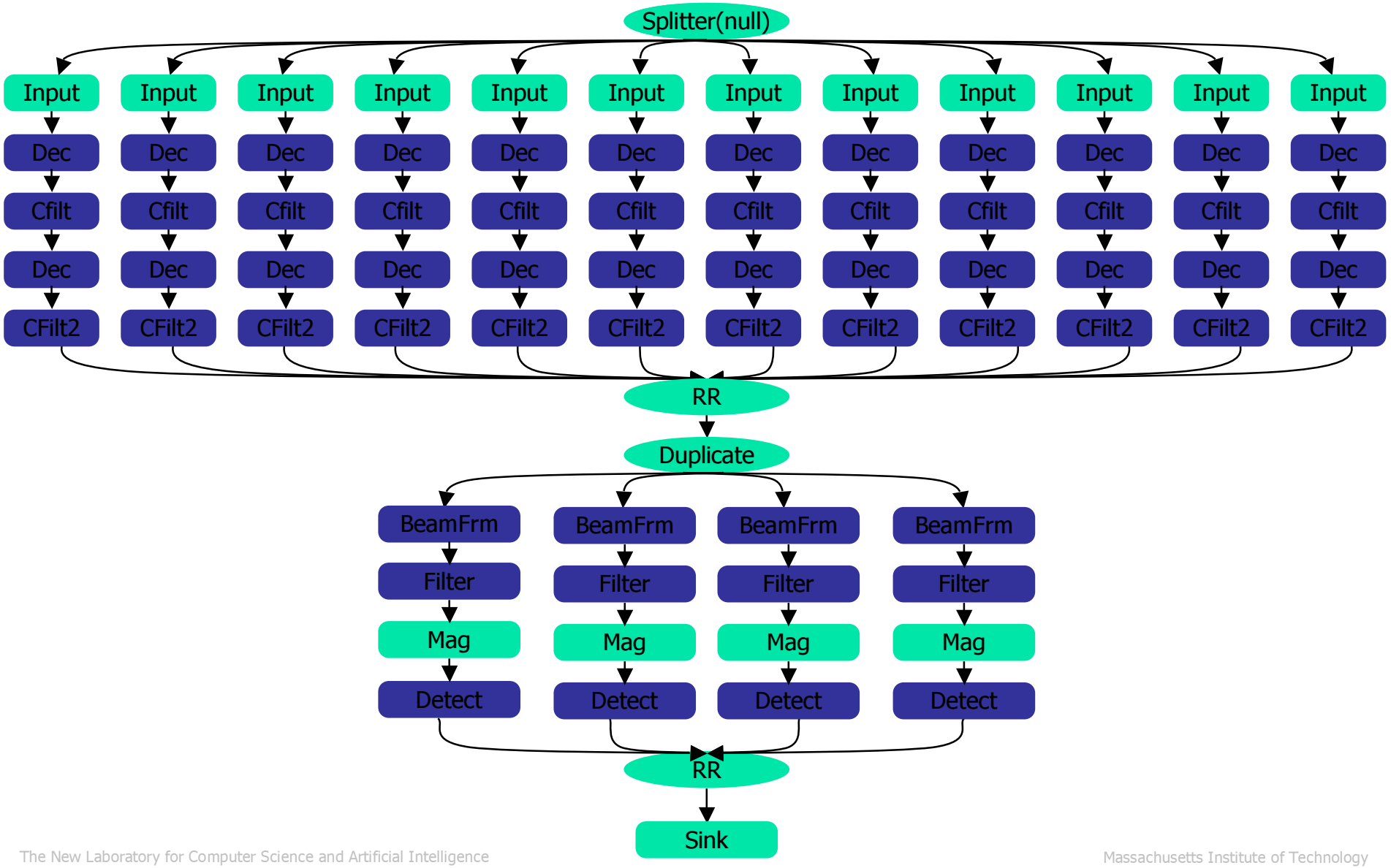


Radar (Transformation Selection)

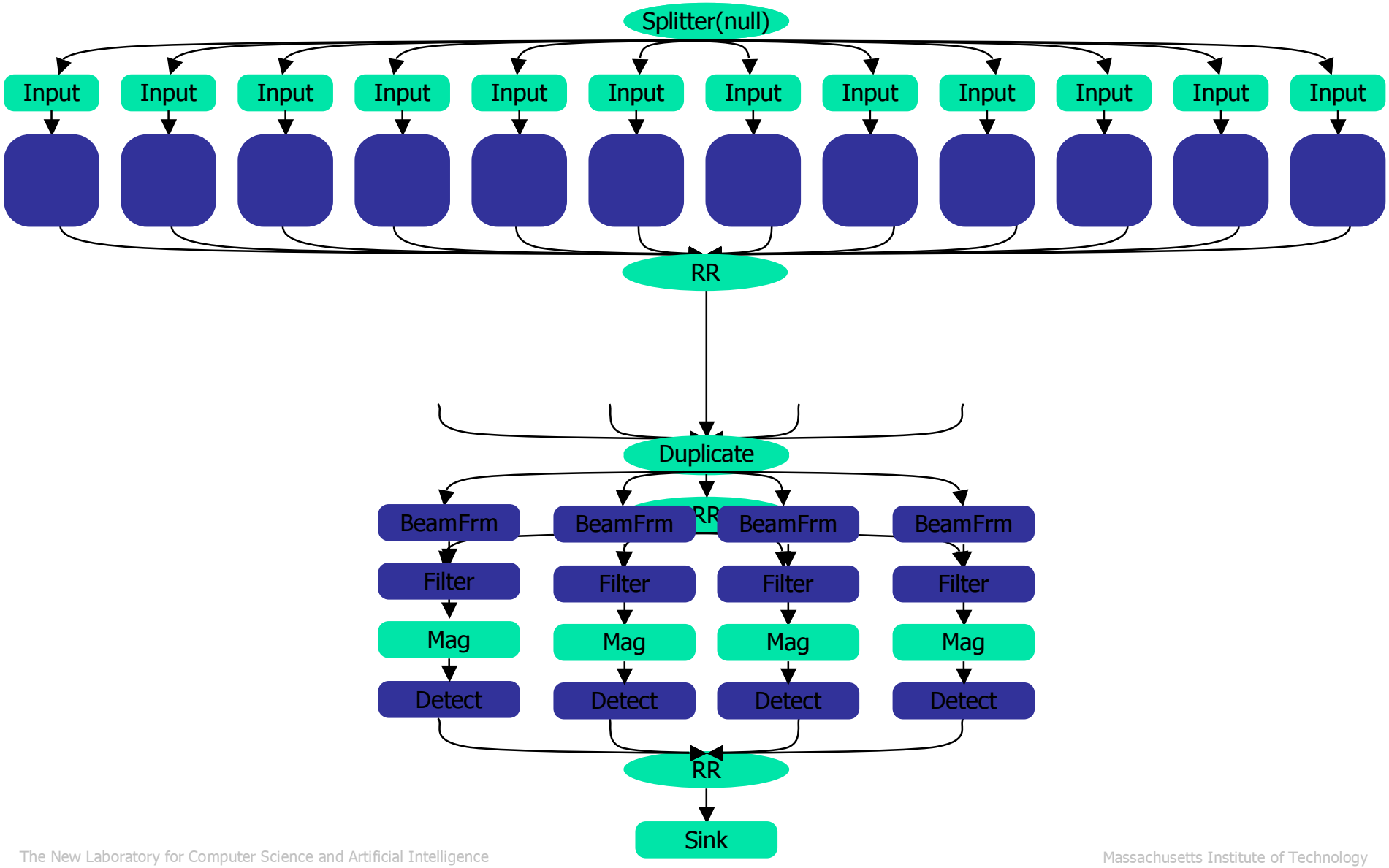
Continue with 1x3 2x1 3x1 4x1
1x4 2x2 3x2 4x2
2x3 3x3 4x3
2x4 3x4 4x4 ➡ Overall solution



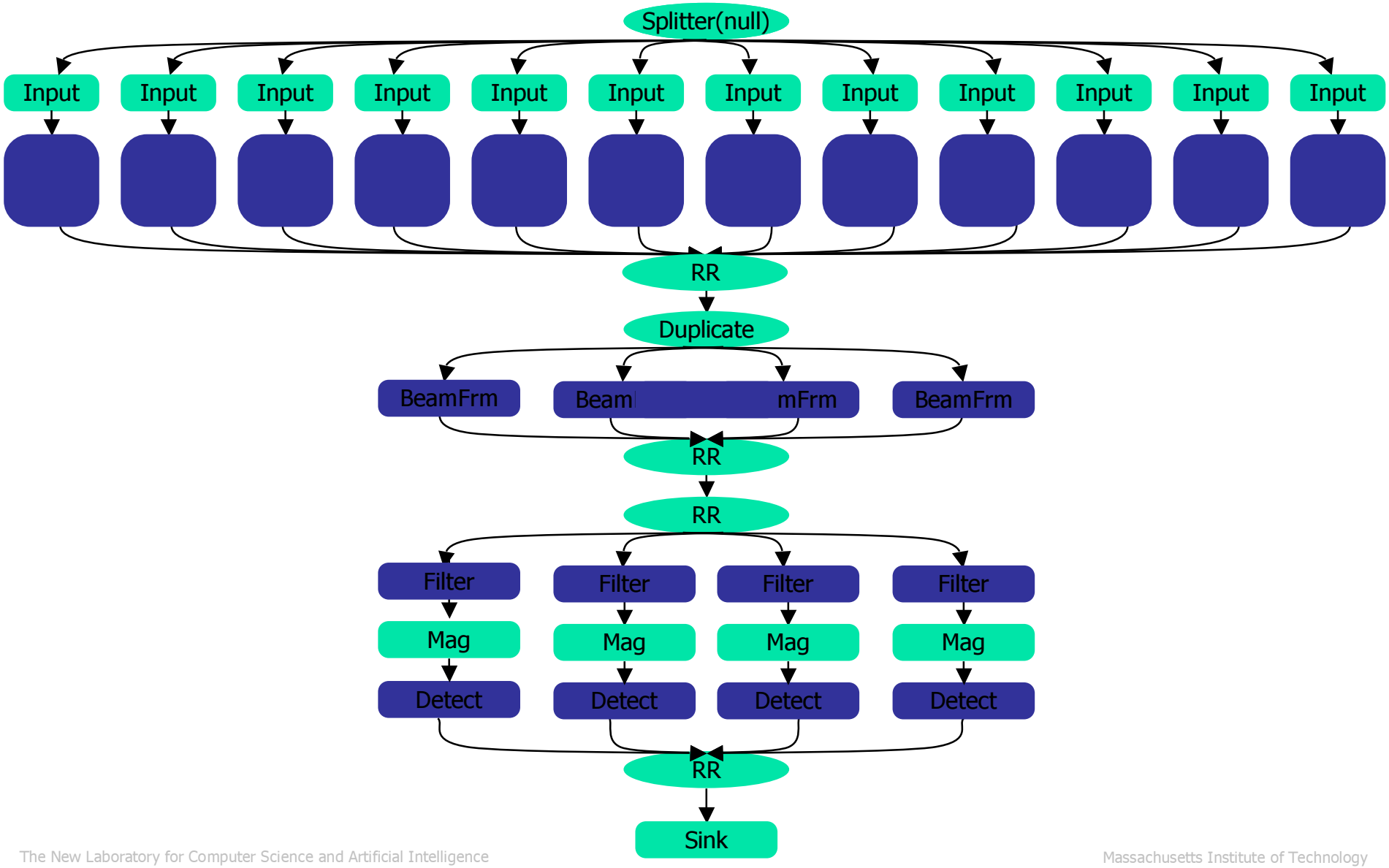
Radar (Transformation Selection)



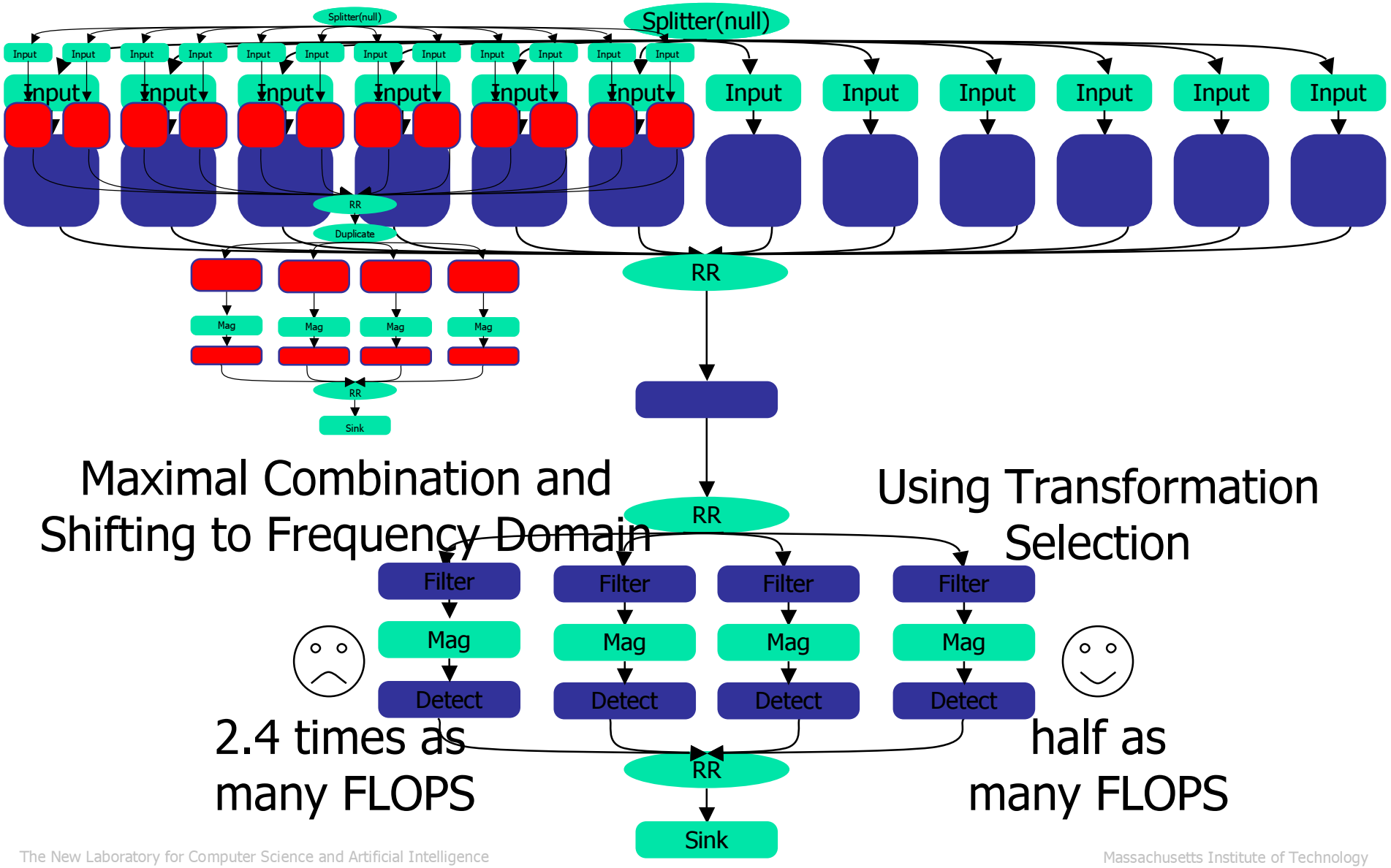
Radar (Transformation Selection)



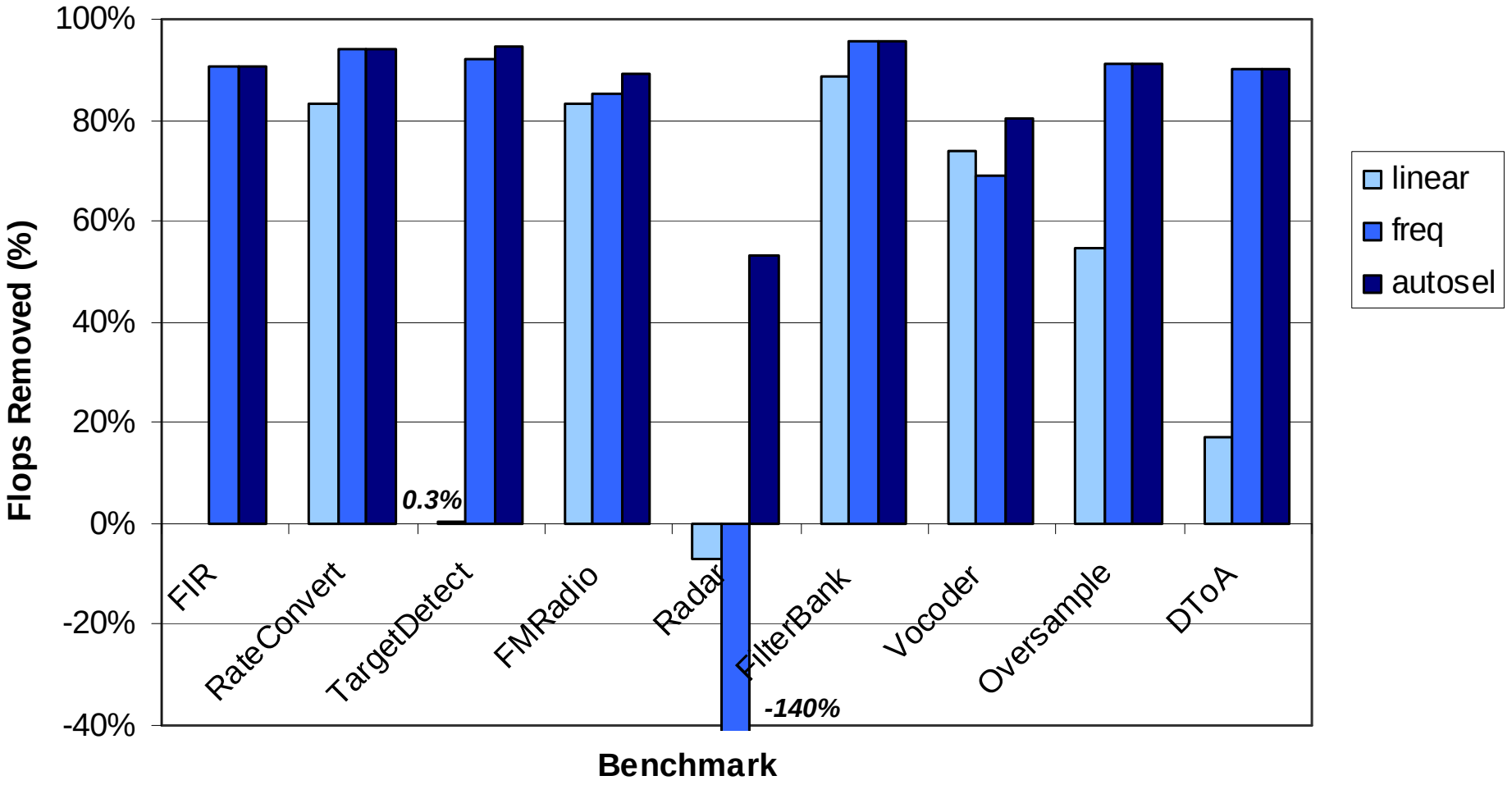
Radar (Transformation Selection)



Radar


Splitter(null)
Input
RR
Duplicate
Mag
Sink
Maximal Combination and Shifting to Frequency Domain
Using Transformation Selection
Filter
Detect
2.4 times as many FLOPS
half as many FLOPS

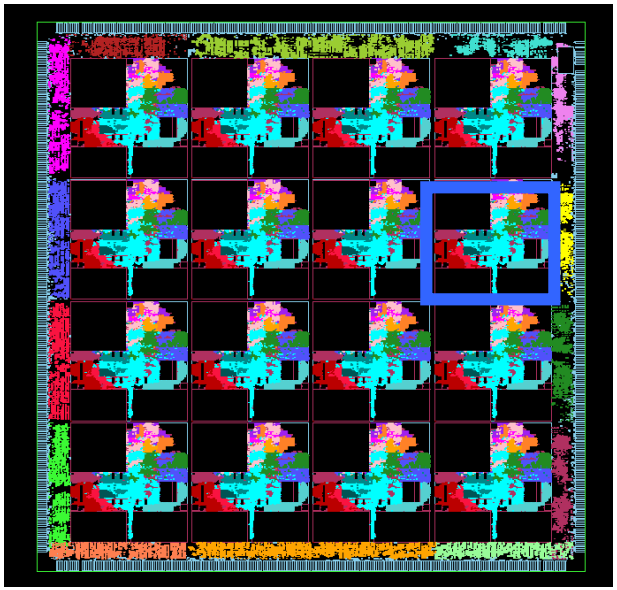
Floating-Point Operations Reduction

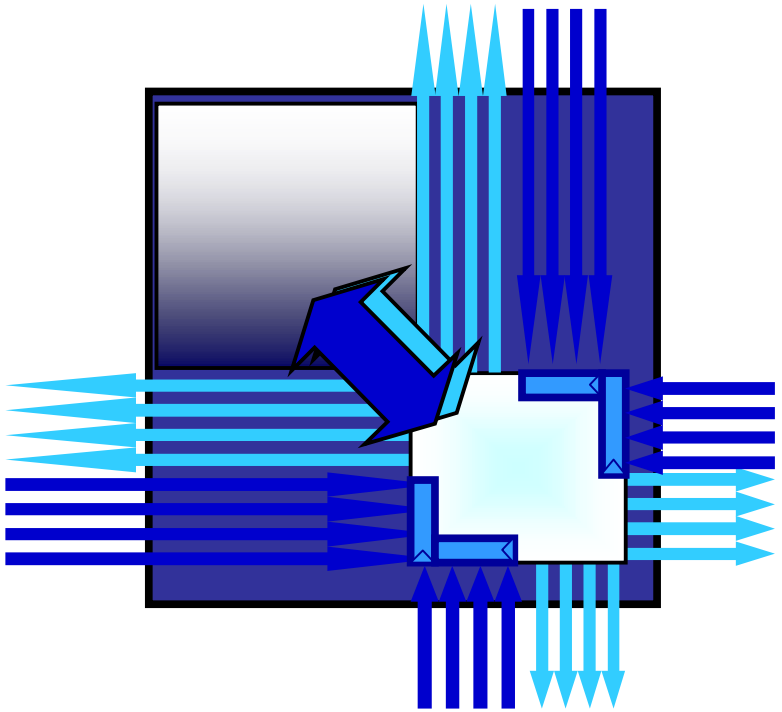


Outline

- Historical timeline of Stream Programming
- The StreamIt Language
- DSP Domain Specific Optimizations
- Architecture Specific Optimizations

RAW: A Wire Exposed Architecture





- A wire can cross a tile in a single clock cycle
  - Wire delay is not a issue in the processor design
- Ultra fast interconnect network
  - Exposes the wires to the compiler
  - Compiler orchestrate the communication → hide wire delay

Raw Chip

IBM SA-27E .15u 6L Cu

18.2 mm x 18.2 mm

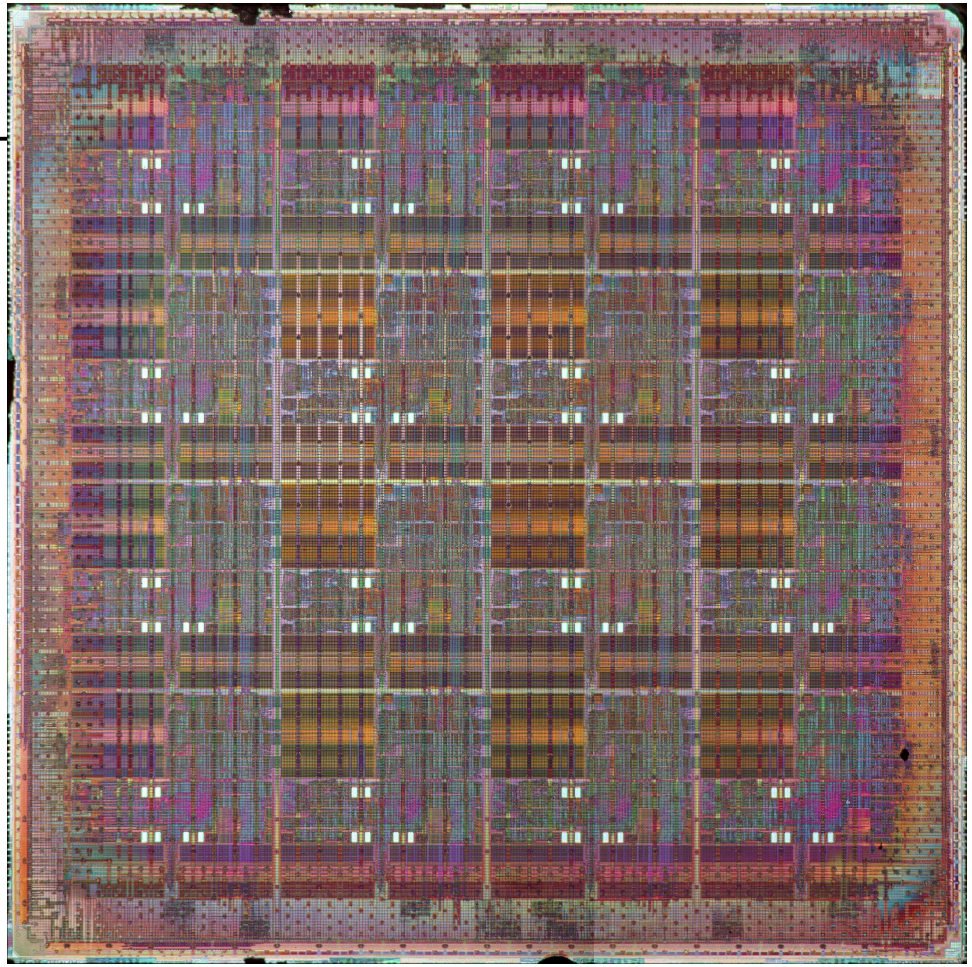
16 Flops/ops per cycle

208 Operand Routes / cycle

2048 KB L1 SRAM

1657 Pin CCGA Package

1080 HSTL core-speed signal I/O



Core Tested @ 420 MHz!!

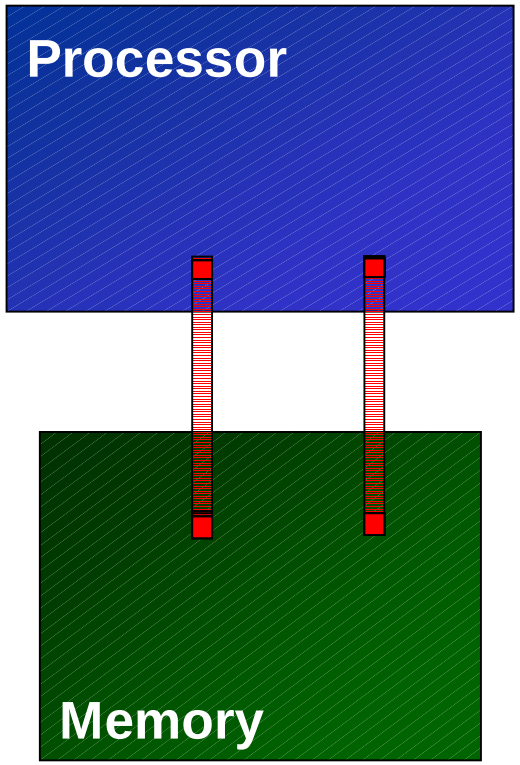
@ 260 MHz Worst Case (Temp, Vdd, process):

3.6 Peak GFLOPS (without FMAC!)
225 Gb/s on-chip bisection bandwidth
201 Gb/s off-chip I/O bandwidth

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

- Run one filter at a time

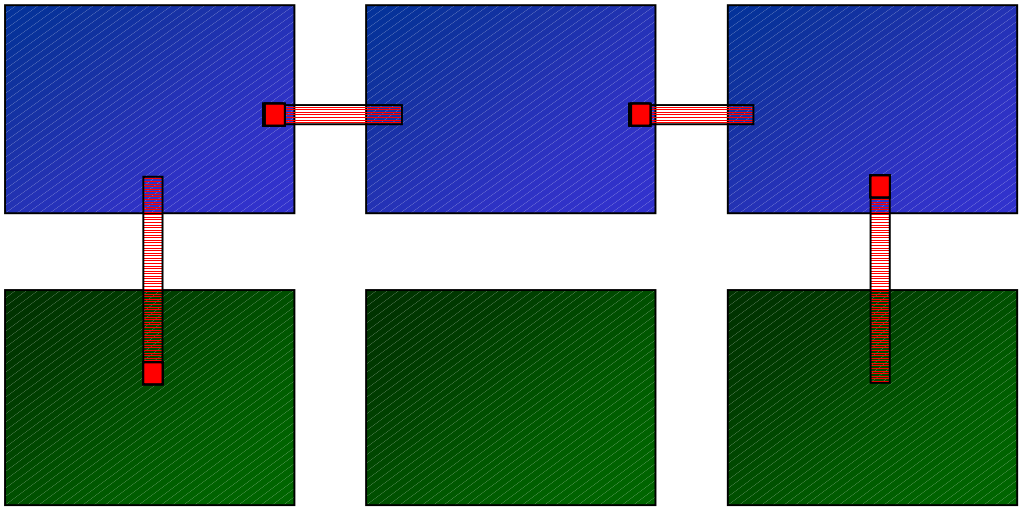
- Pros:
  - Scheduling is easy
  - Synchronization from Memory
- Cons:
  - If a filter run is too short
    - Filter load overhead is high
  - If a filter run is too long
    - Data spills down the cache hierarchy
    - Long latency
  - Lots of memory traffic
    - Bad cache effects
  - Does not scale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



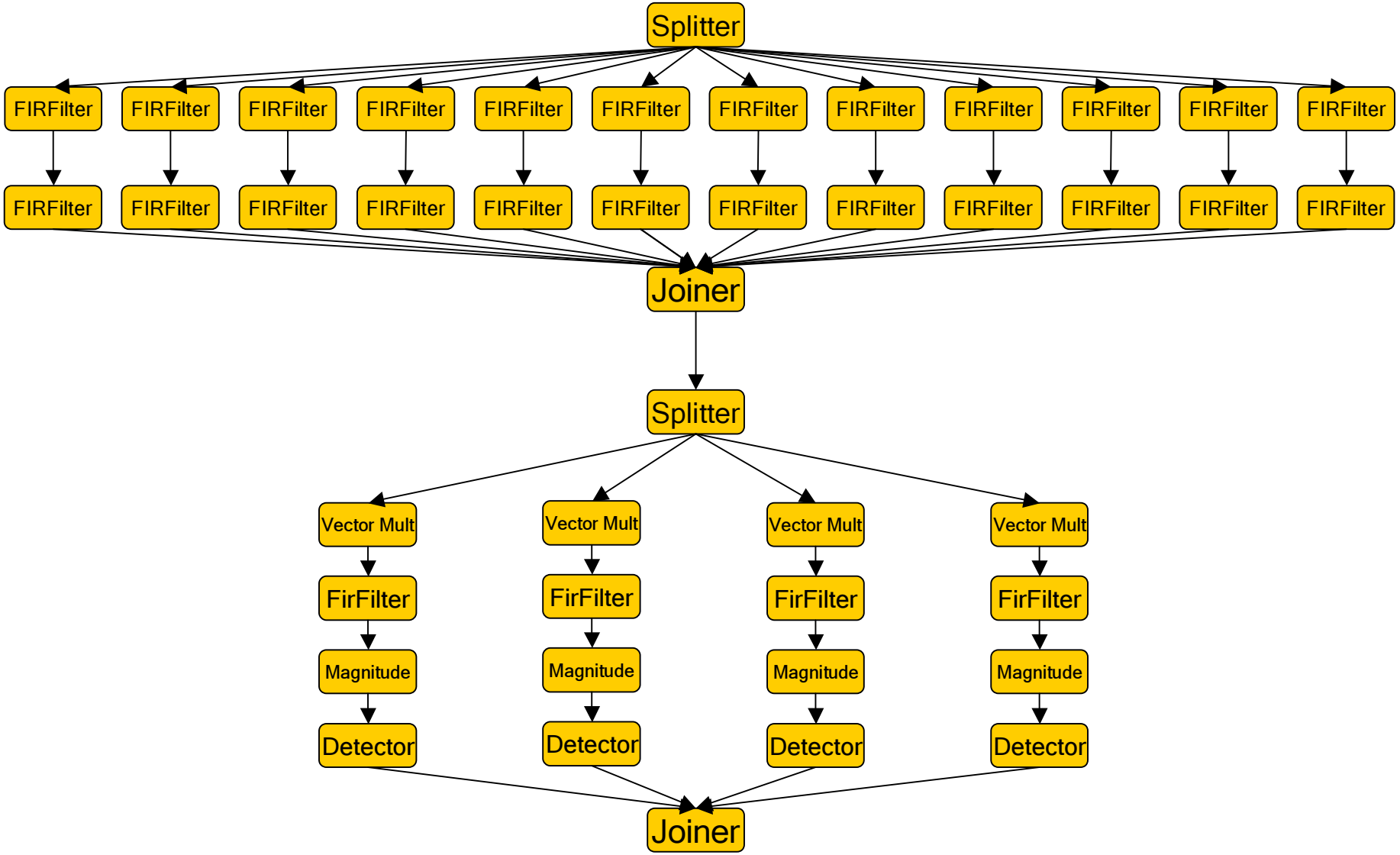
How to execute a Stream Graph? Method 2: Space Multiplexing

- Map filter per tile and run forever

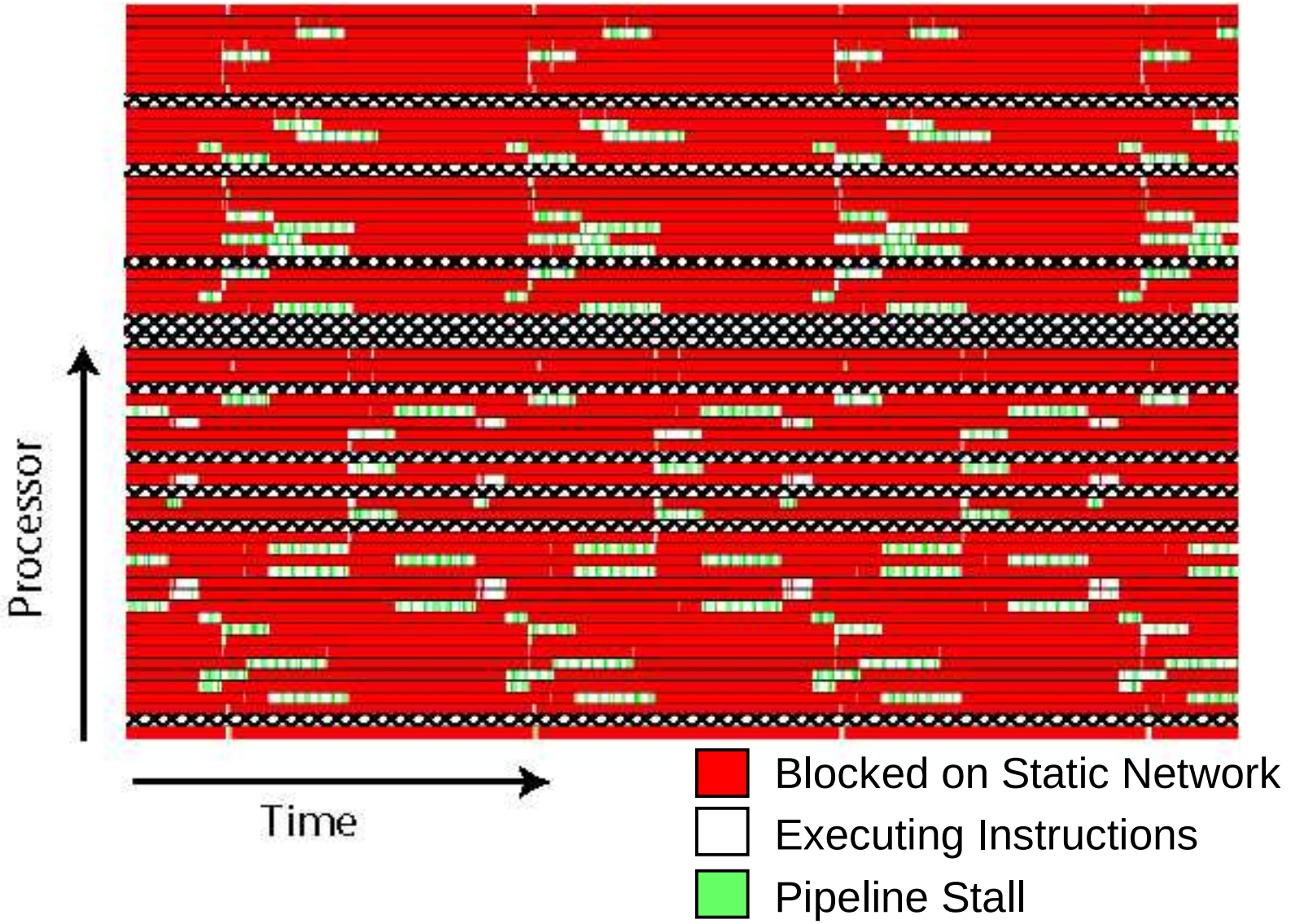
- Pros:
  - No filter swapping overhead
  - Exploits spatially-aware architectures
    - Scales well
  - Reduced memory traffic
  - Localized communication
  - Tighter latencies
  - Smaller live data set
- Cons:
  - Load balancing is critical
  - Not good for dynamic behavior
  - Requires # filters ≤ # processing elements



Example: Radar Array Front End



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

Bridging the Abstraction layers

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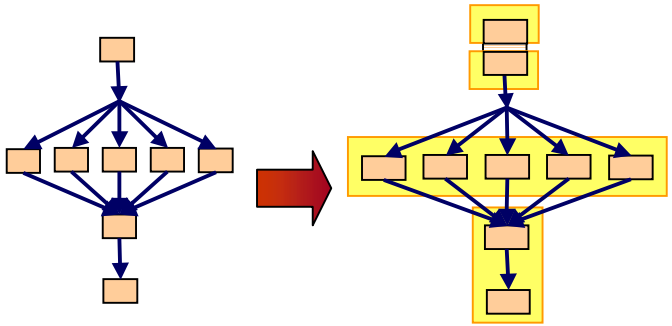
- Each architecture is different in granularity and topology
  - Communication is exposed to the compiler
- The compiler needs to efficiently bridge the abstraction
  - Map the computation and communication pattern of the program to the PE's, memory and the communication substrate
- The StreamIt Compiler
  - Partitioning
  - Placement
  - Scheduling
  - Code generation

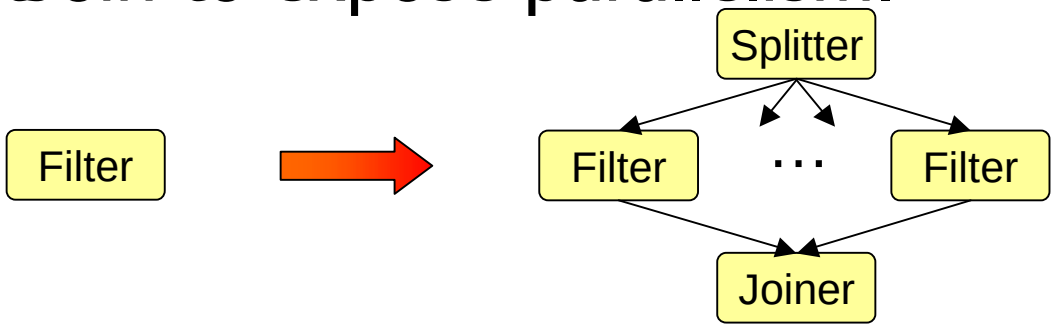
Partitioning: Choosing the Granularity



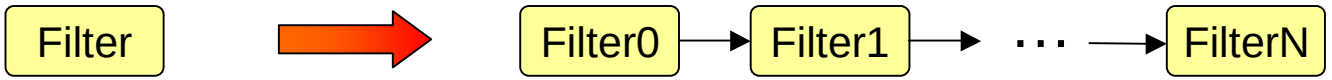
- Mapping filters to tiles
  - # filters should equal (or a few less than) # of tiles
  - Each filter should have similar amount of work
    - Throughput determined by the filter with most work
- Compiler Algorithm
  - Two primary transformations
    - Filter fission
    - Filter fusion
  - Uses dynamic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

Partitioning - Fission

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

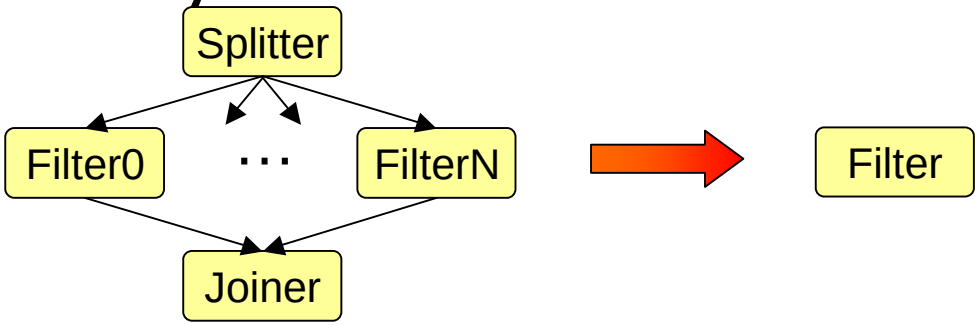


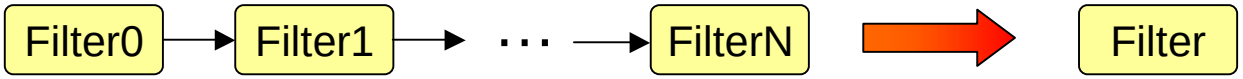
-Split a filter into a pipeline for load balancing



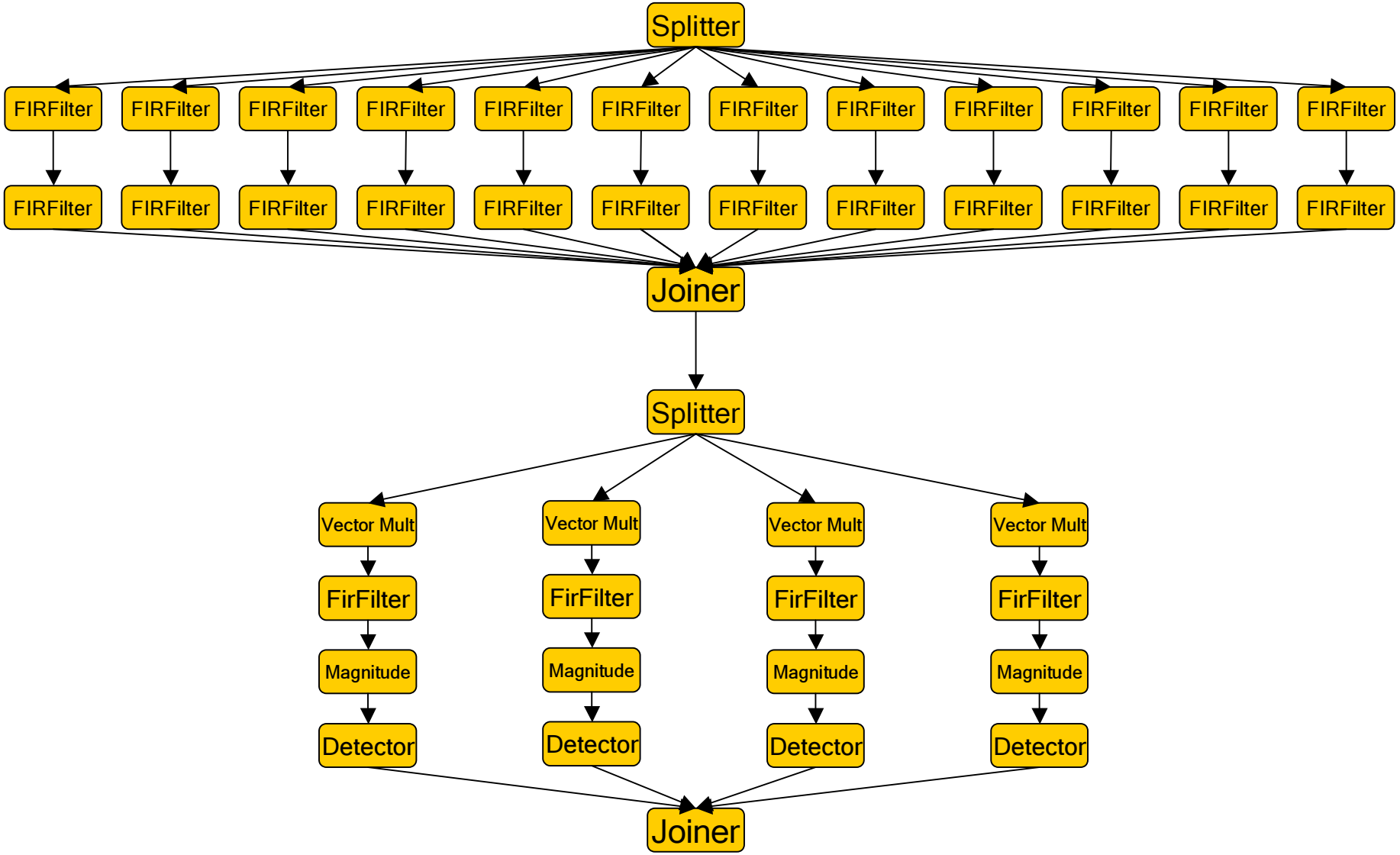
Partitioning - Fusion

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

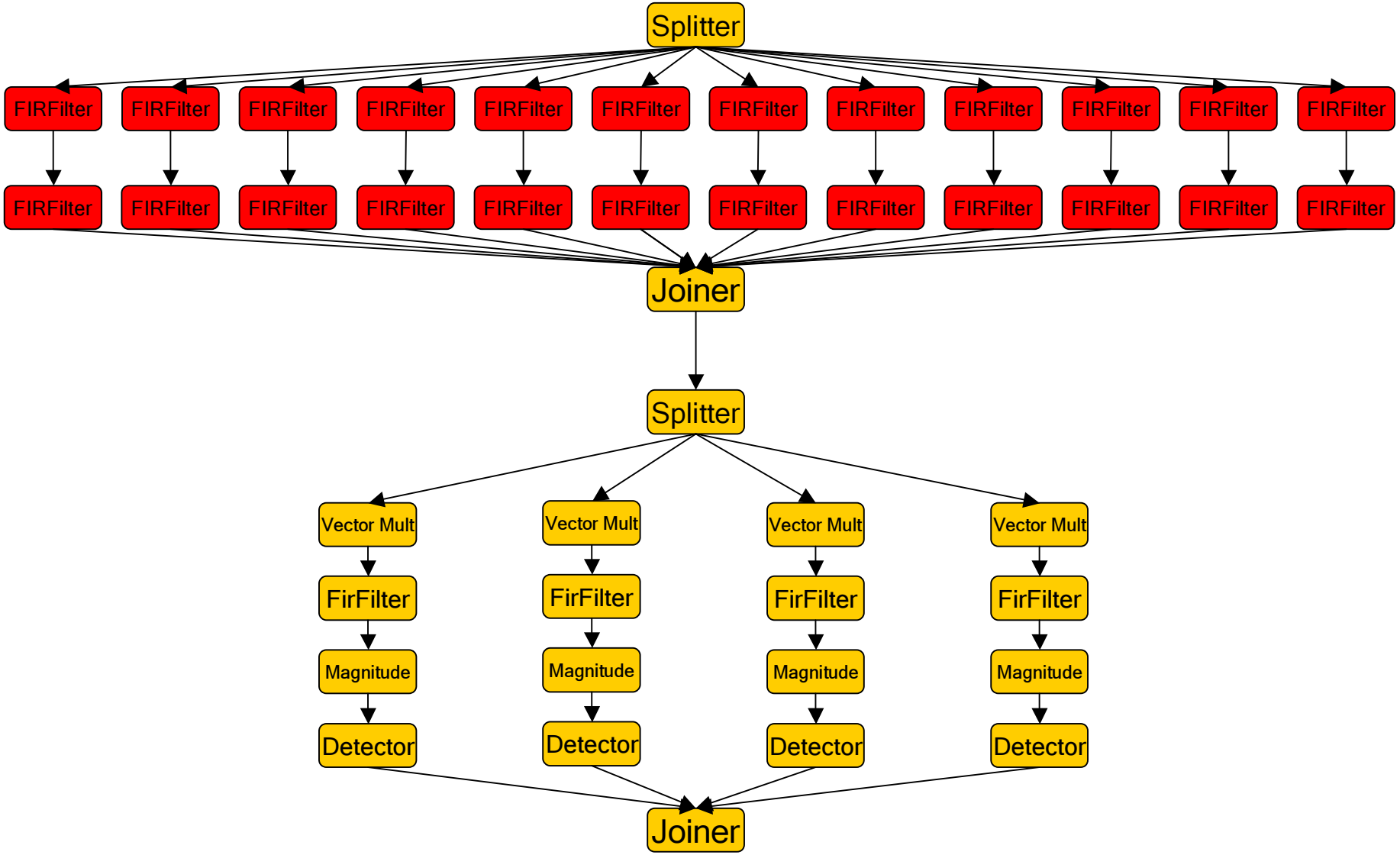




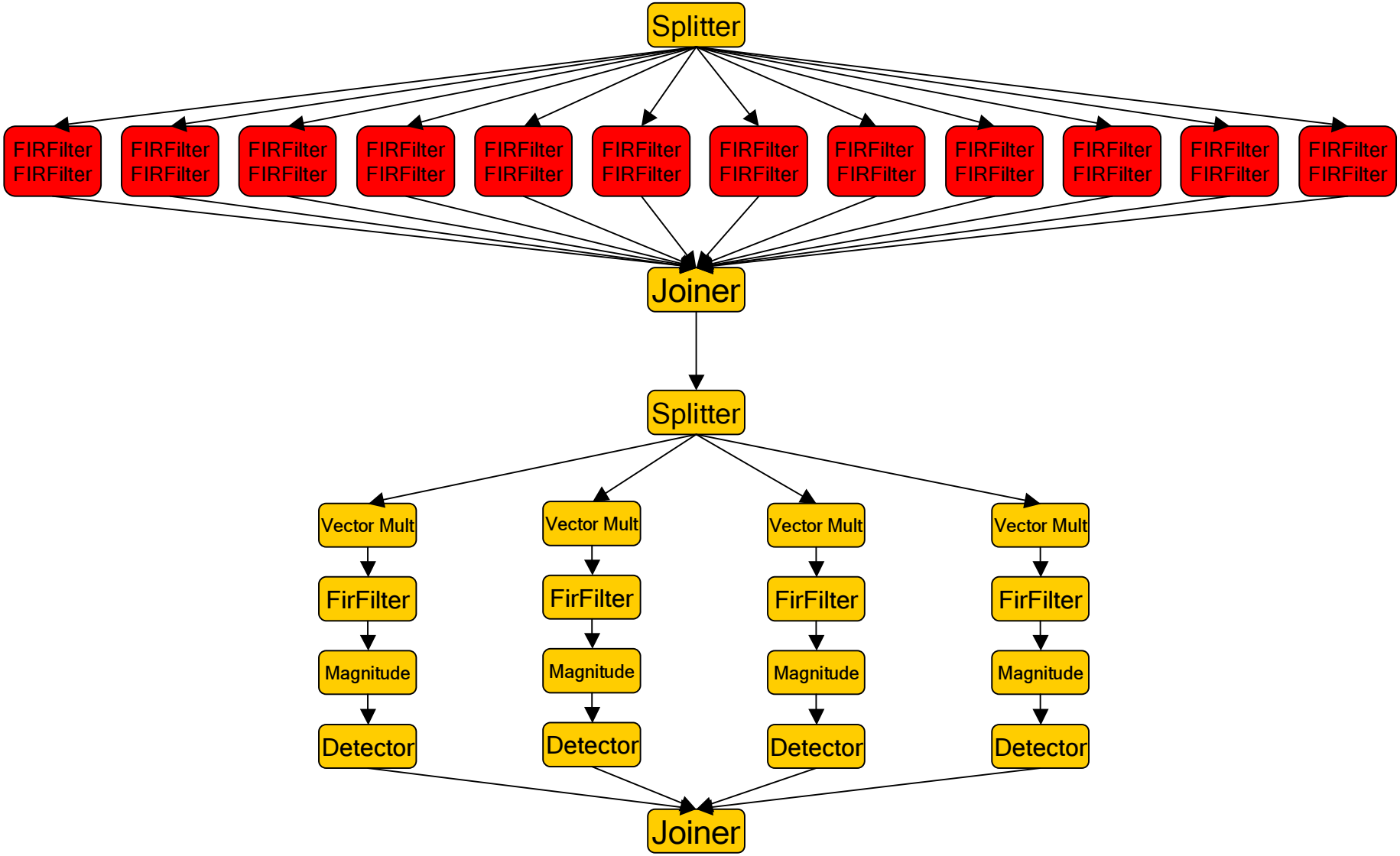
Example: Radar Array Front End (Original)



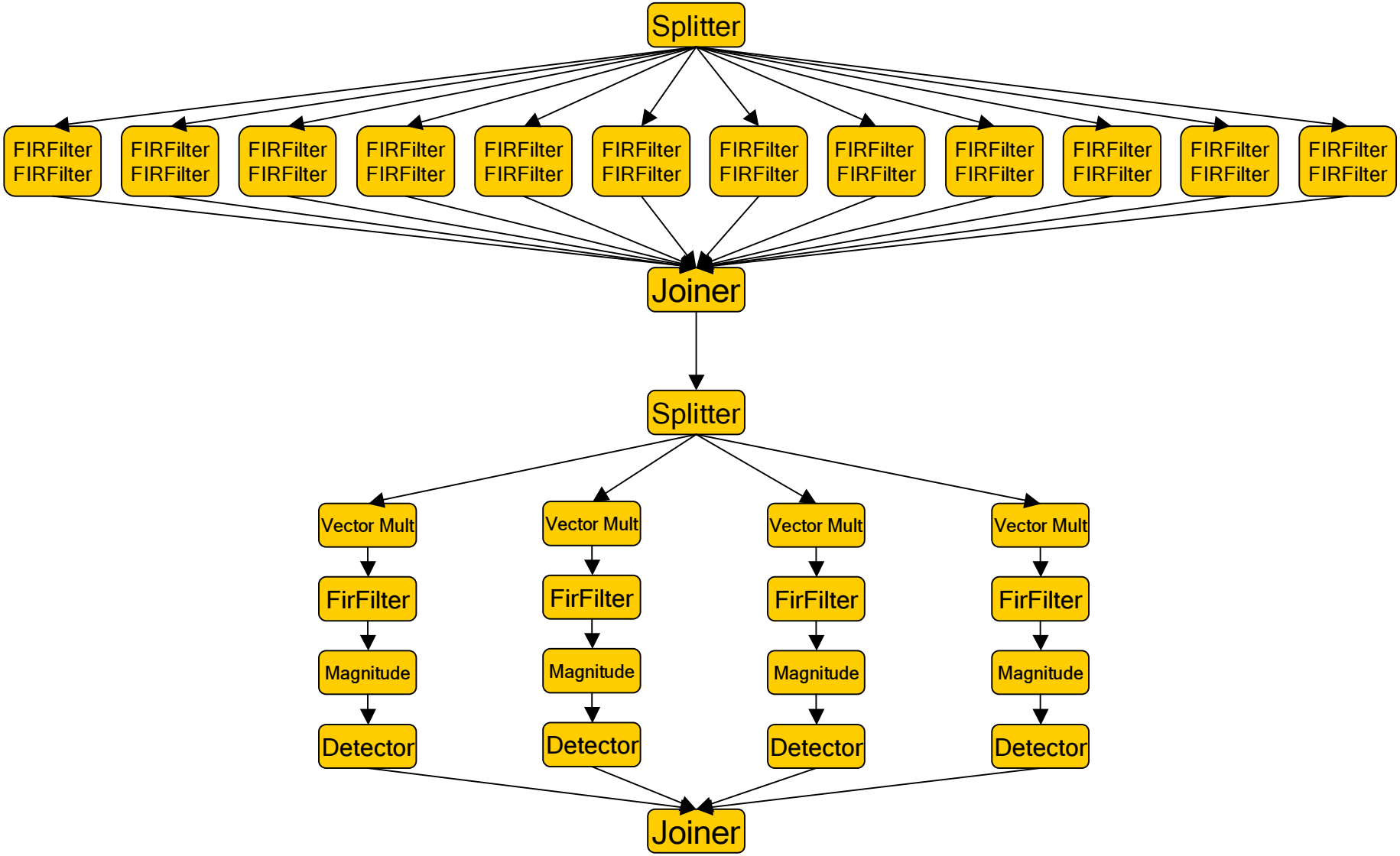
Example: Radar Array Front End



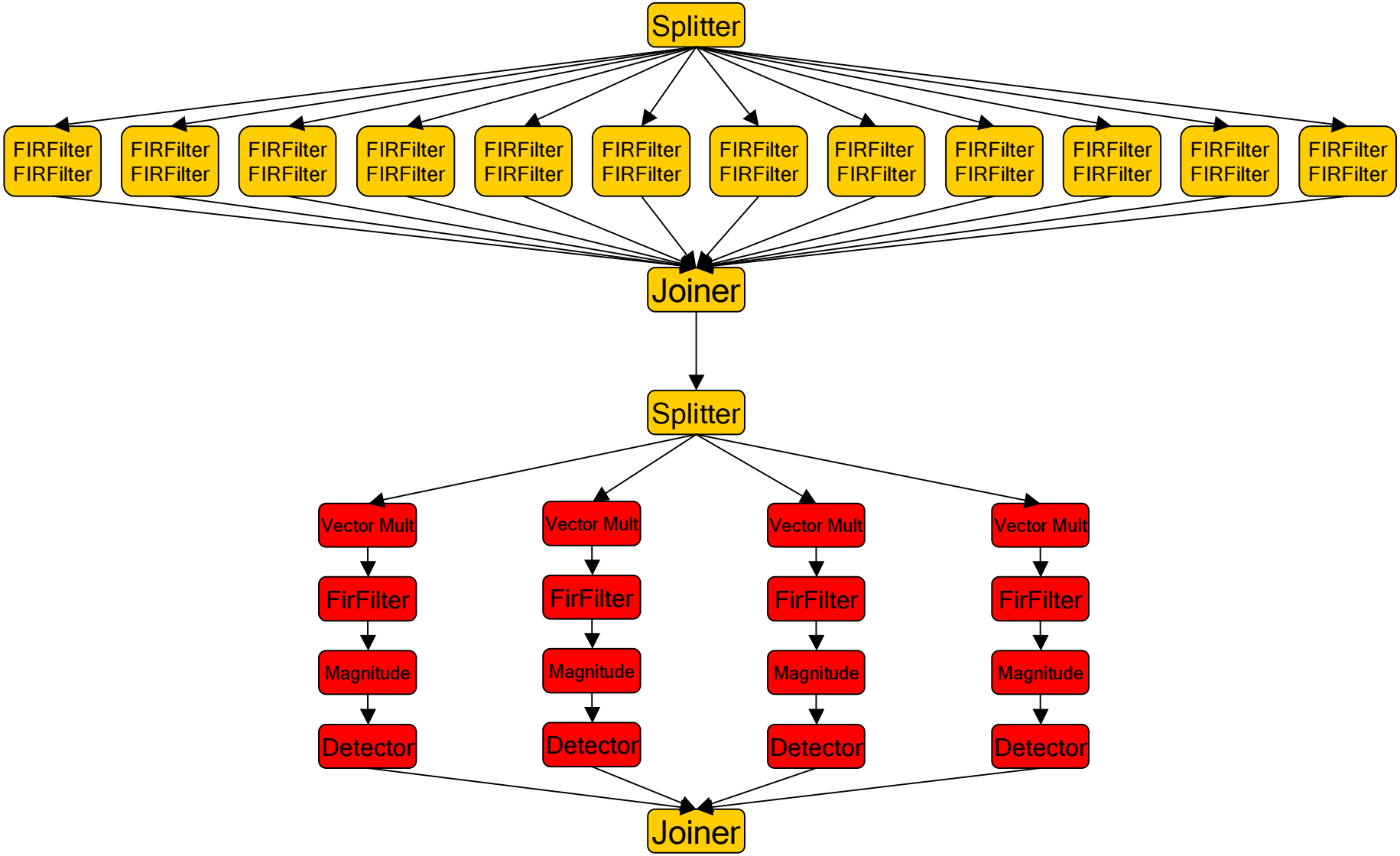
Example: Radar Array Front End



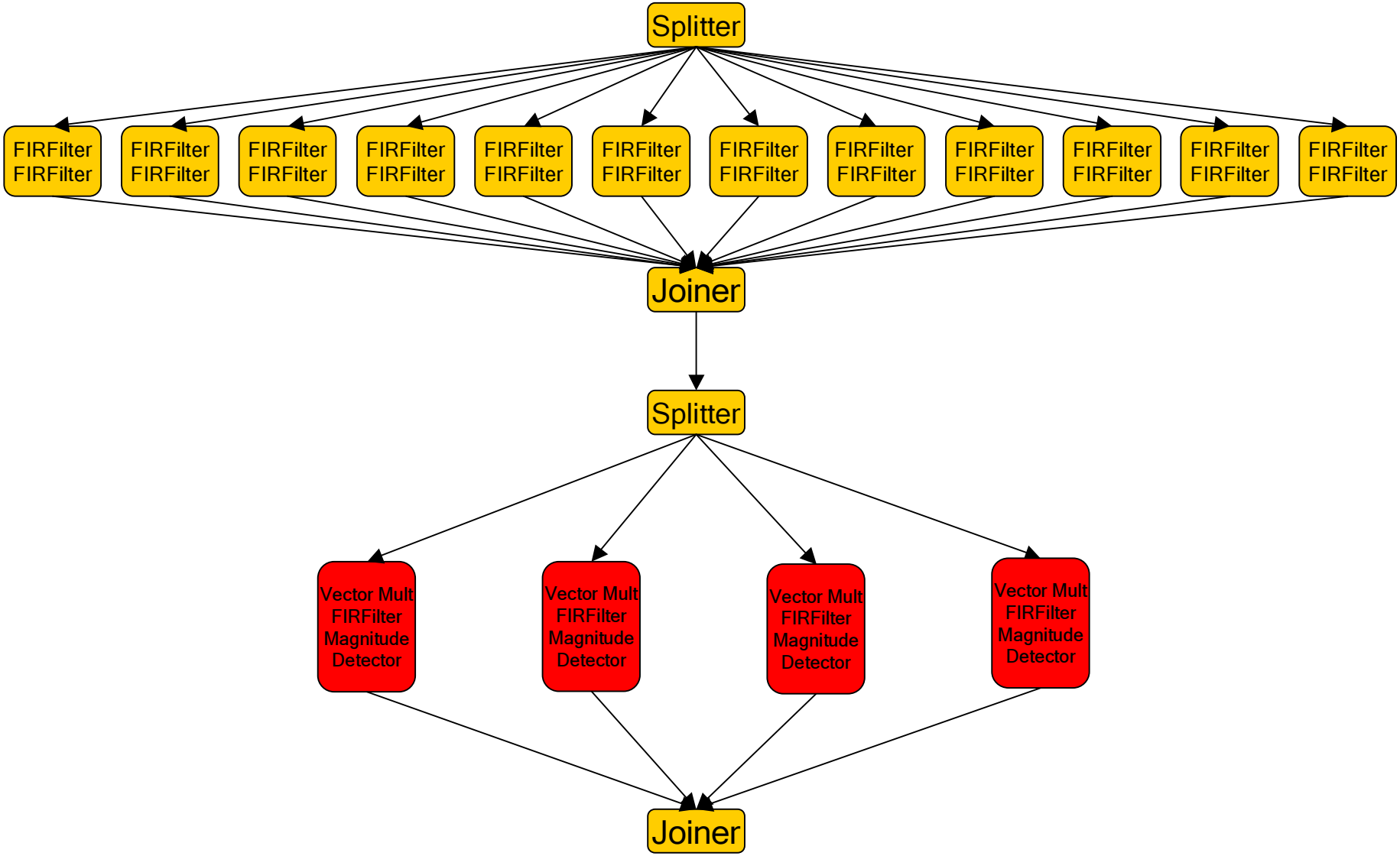
Example: Radar Array Front End



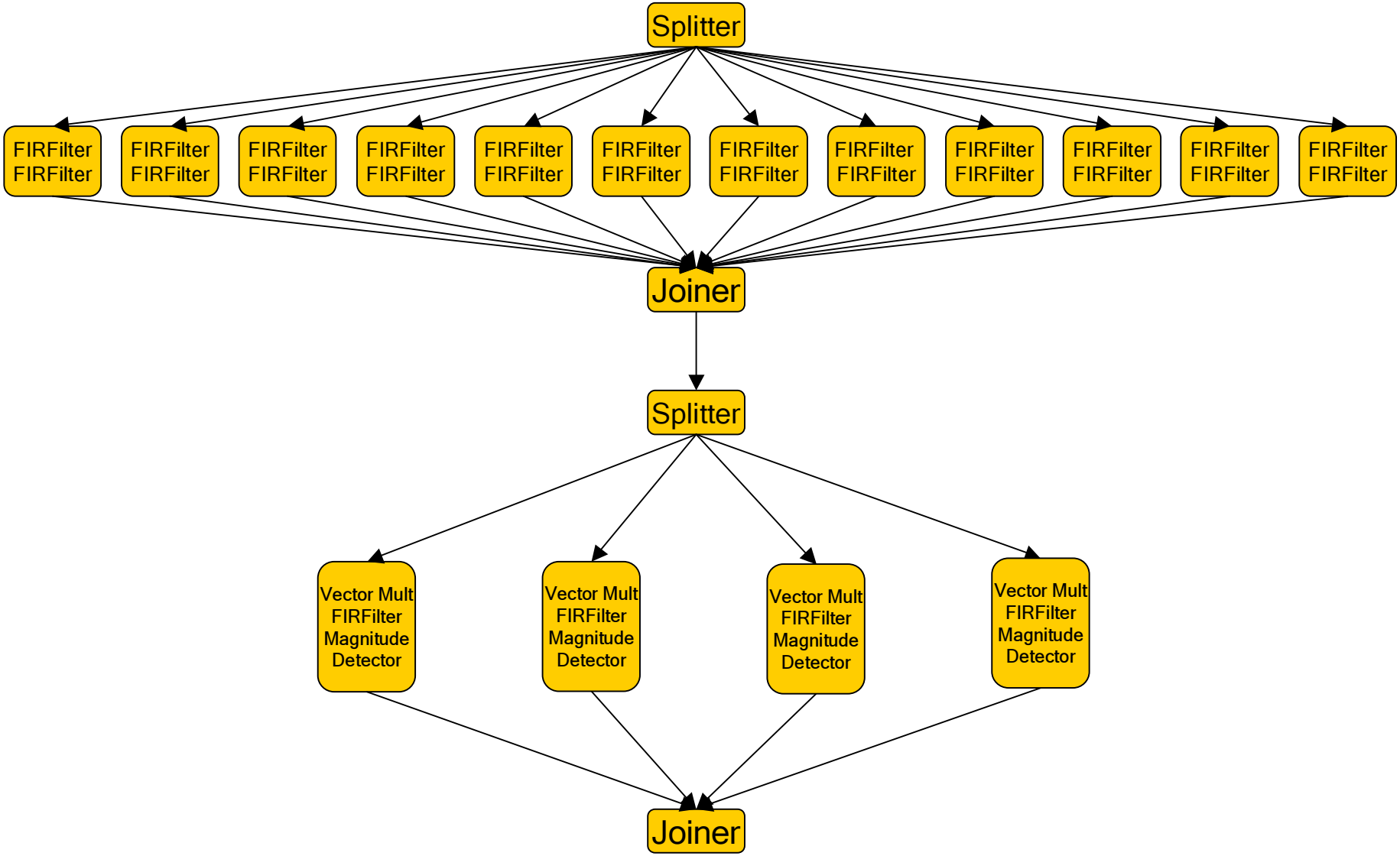
Example: Radar Array Front End



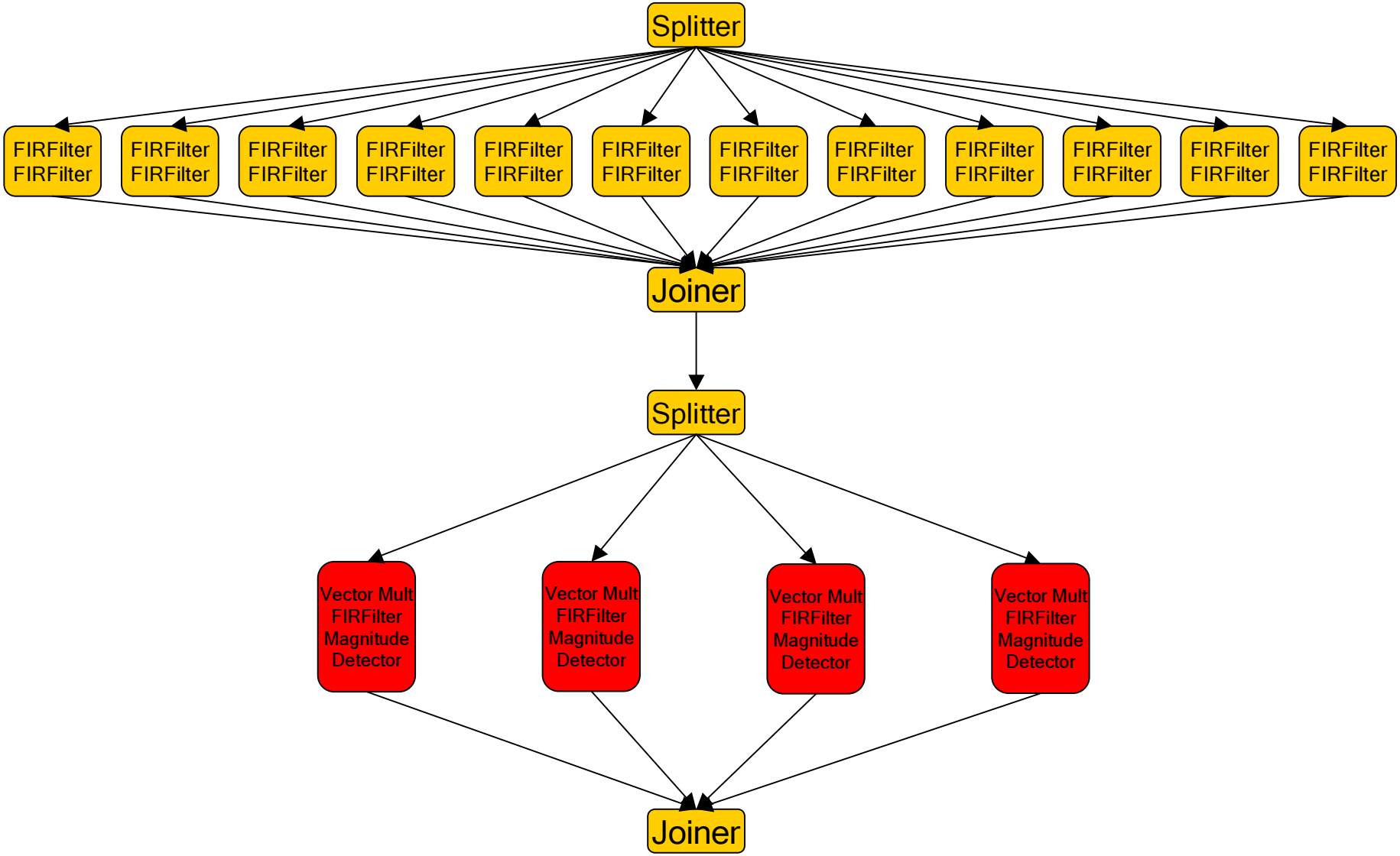
Example: Radar Array Front End



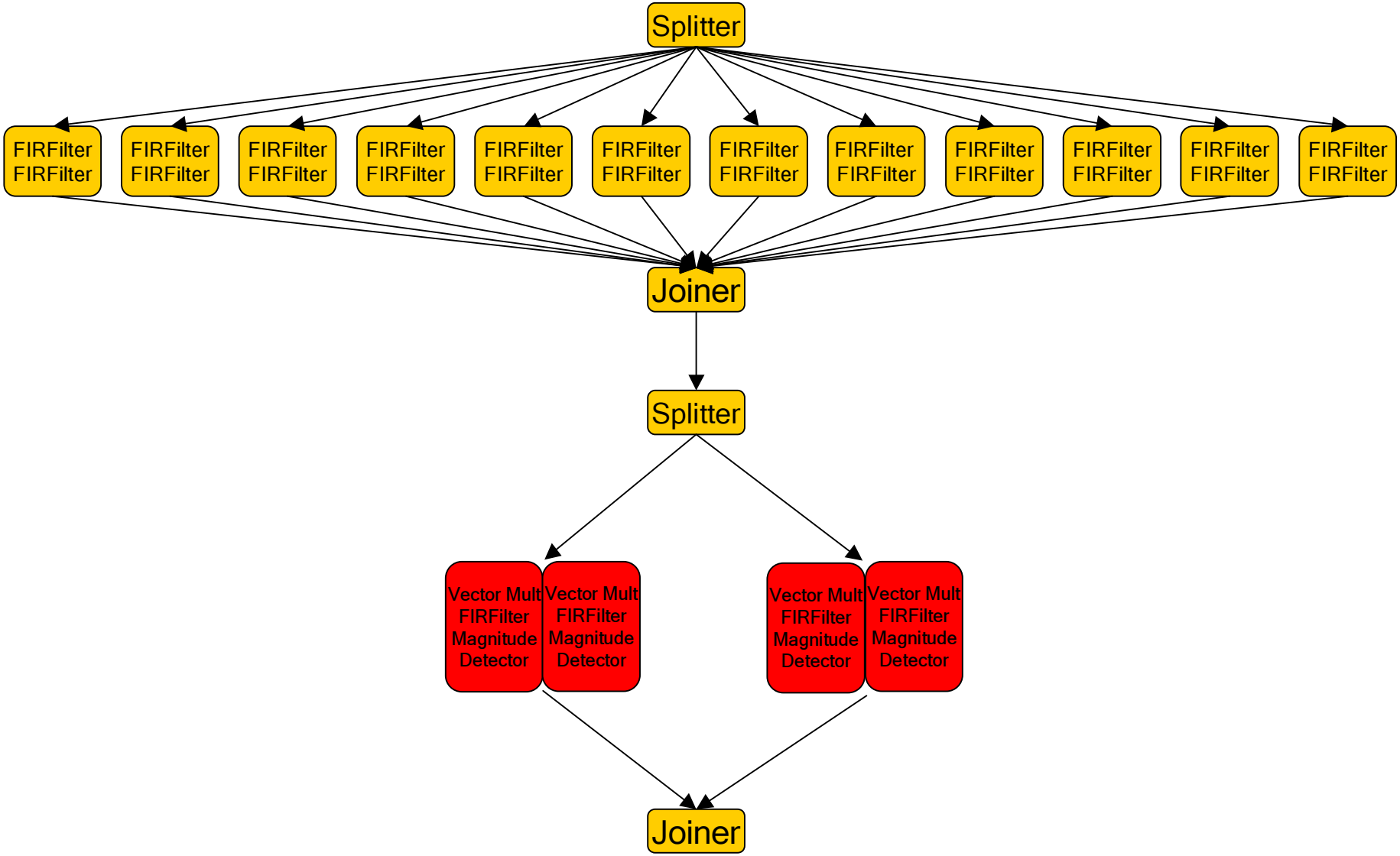
Example: Radar Array Front End



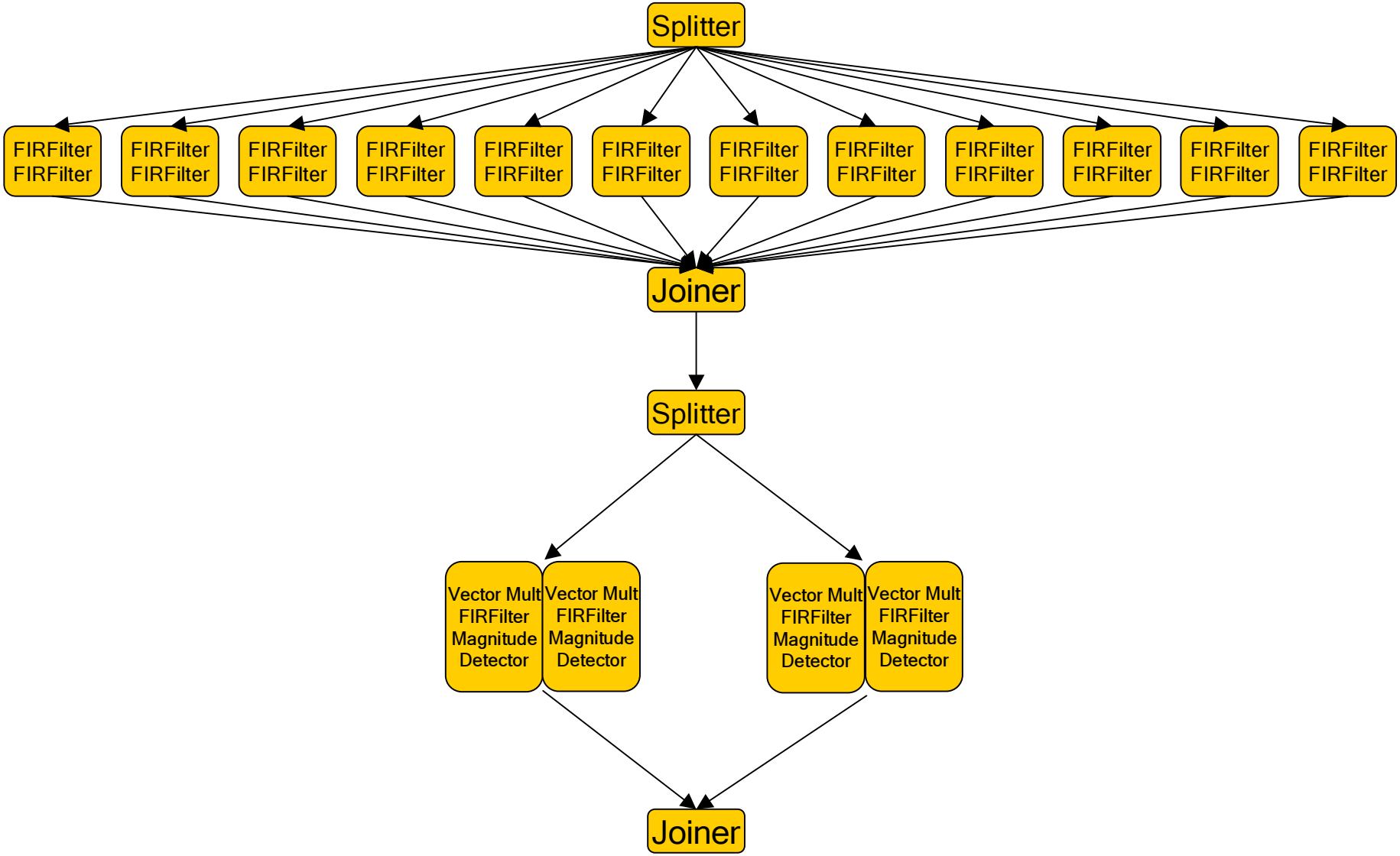
Example: Radar Array Front End



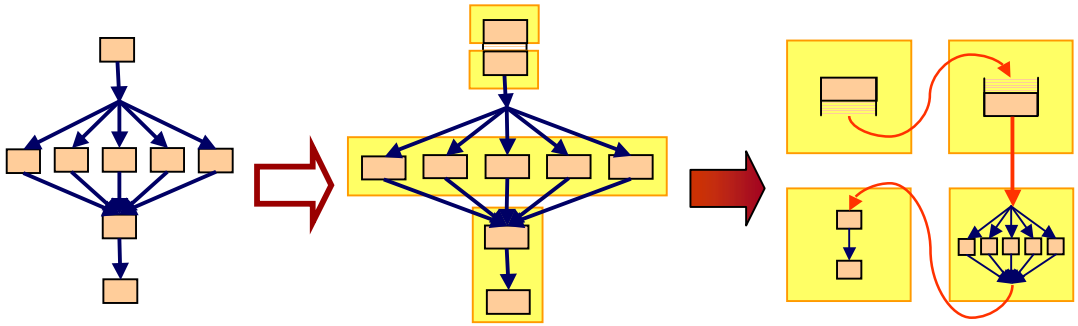
Example: Radar Array Front End



Example: Radar Array Front End (Balanced)

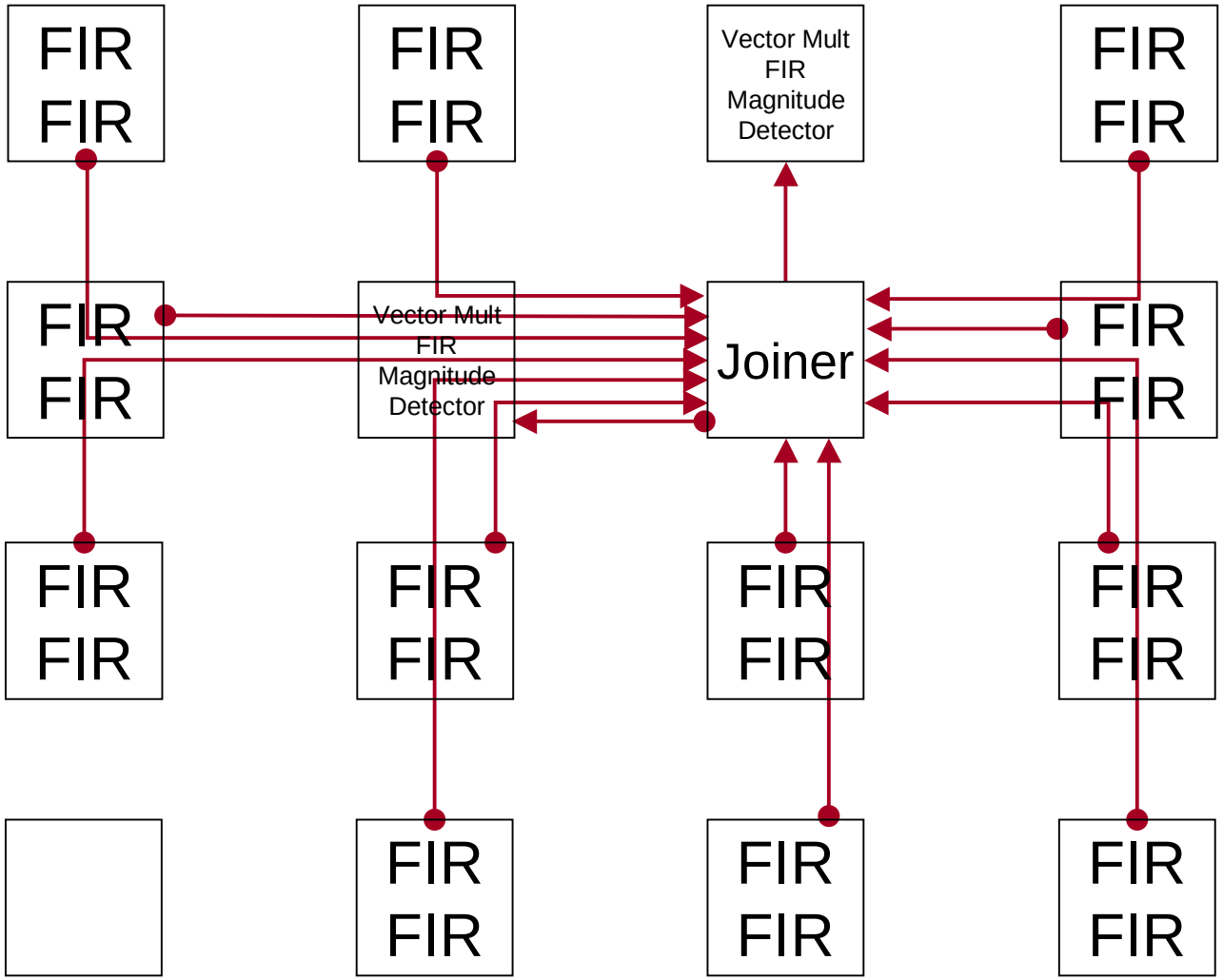


Placement: Minimizing Communication

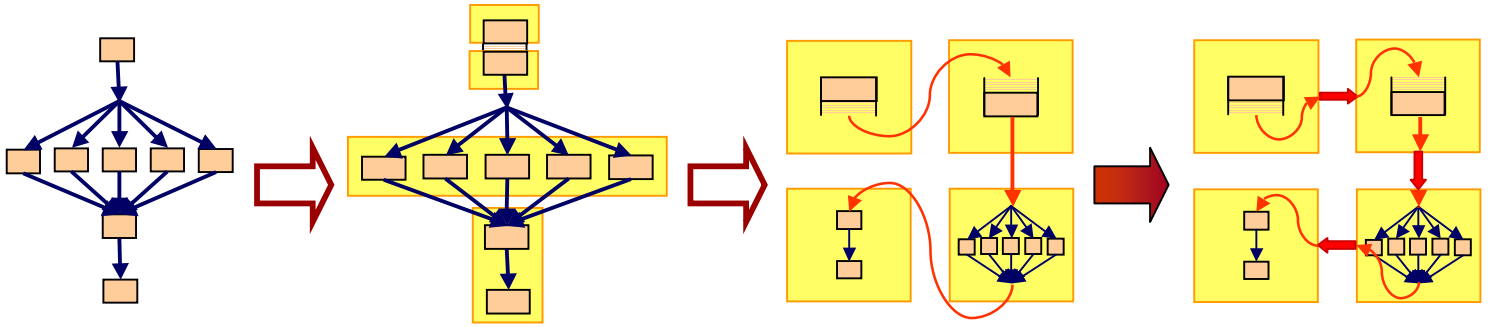


- Assign filters to tiles
  - Communicating filters → try to make them adjacent
  - Reduce overlapping communication paths
  - Reduce/eliminate cyclic communication if possible
- Compiler algorithm
  - Uses Simulated Annealing

Placement for Partitioned Radar Array Front End



Scheduling: Communication Orchestration



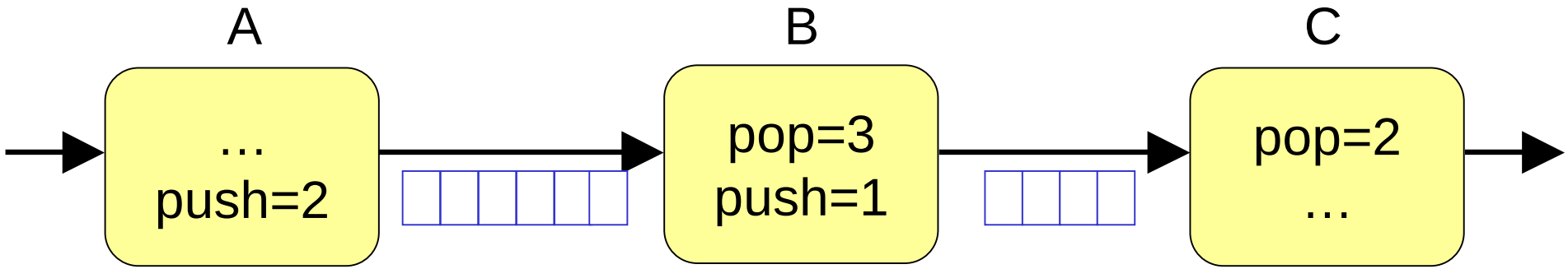
- Create a communication schedule

- 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

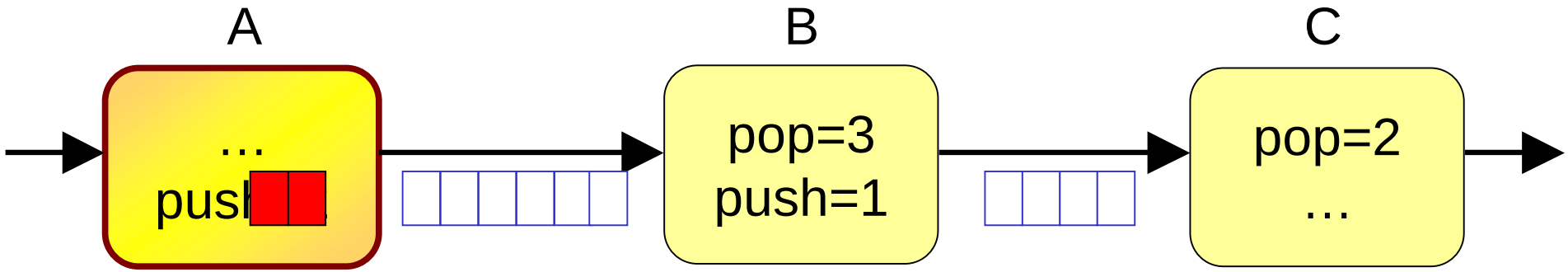
- Schedule = { }



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 = { A }



Steady-State Schedule

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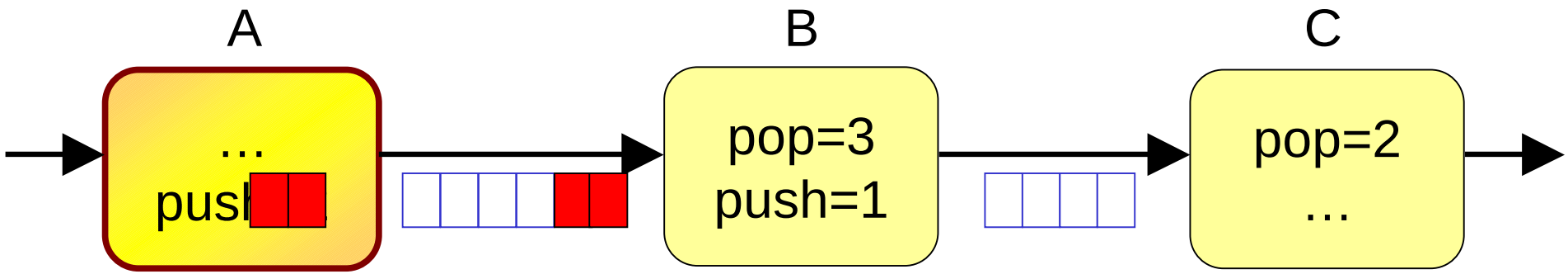
  - # of items in the buffers are the same before and the after executing the schedule
  - There exist a unique minimum steady state schedule

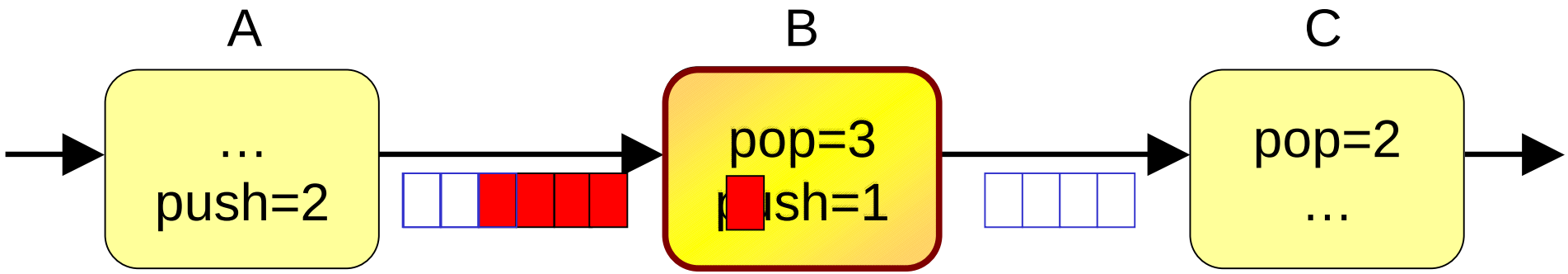
- Schedule = { A, A }



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

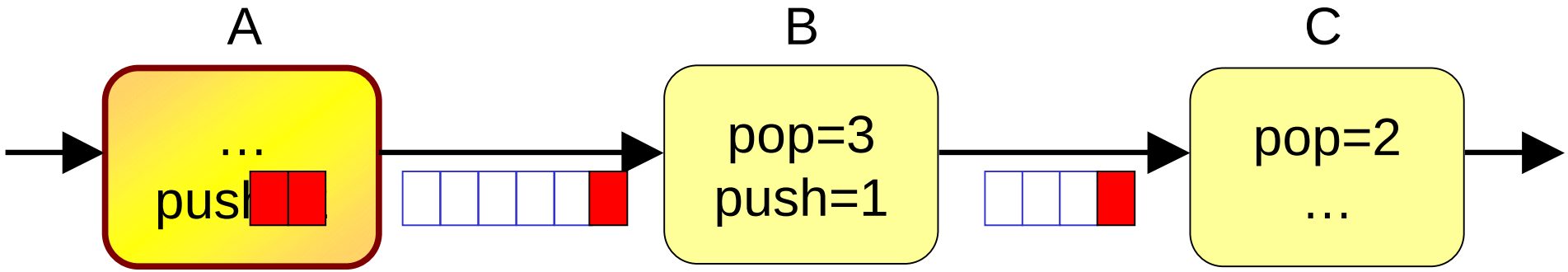
- Schedule = { A, A, B }



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

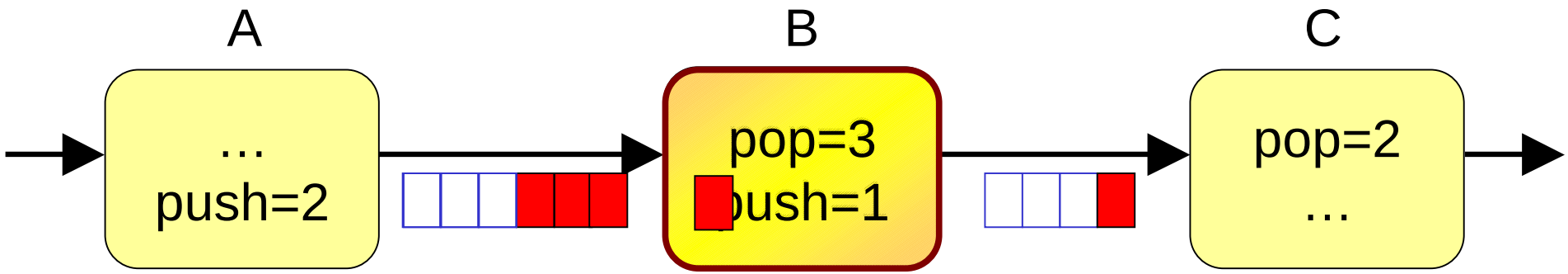
- Schedule = { A, A, B, A }



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

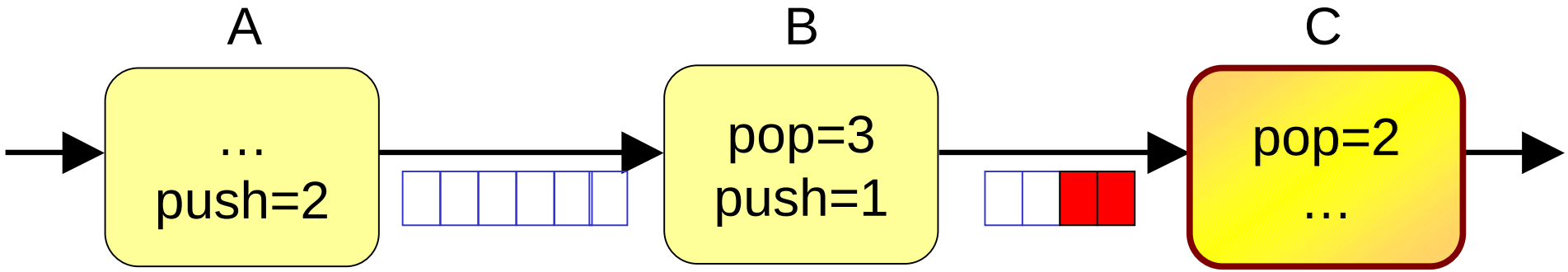
- Schedule = { A, A, B, A, B }



Steady-State Schedule

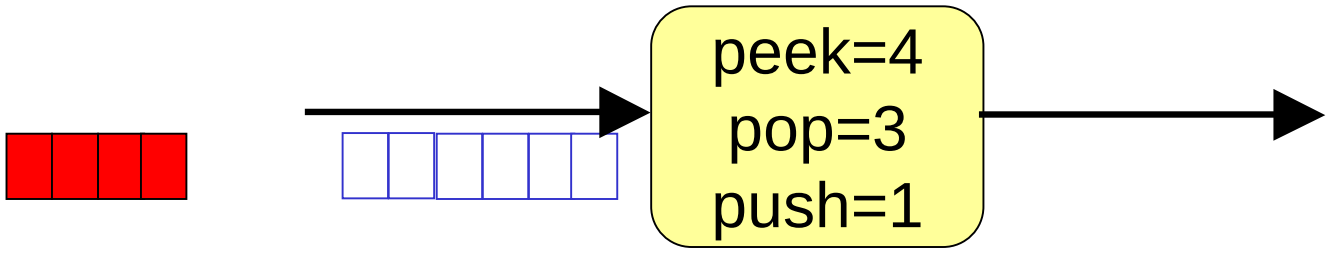
- All data pop/push rates are constant
- Can find a Steady-State Schedule
  - # of items in the buffers are the same before and the after executing the schedule
  - There exist a unique minimum steady state schedule

- Schedule = { 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



Initialization Schedule

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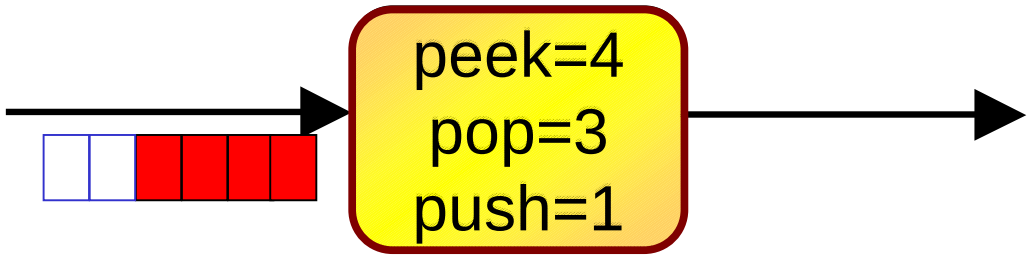
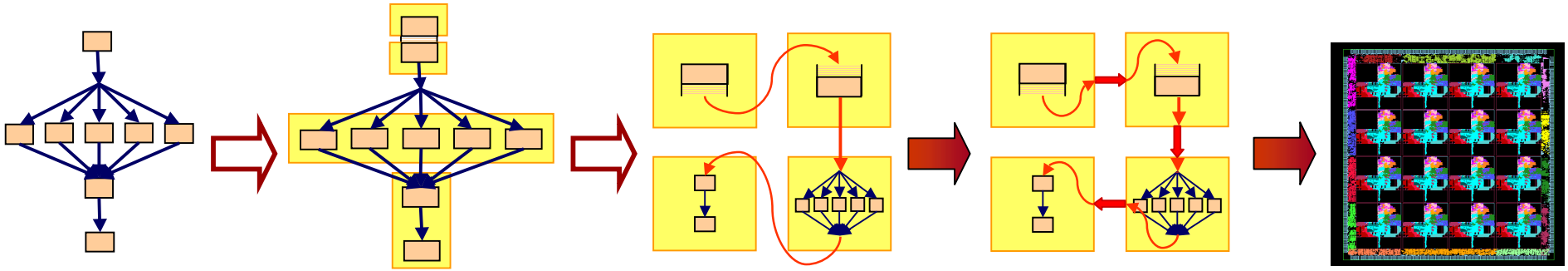
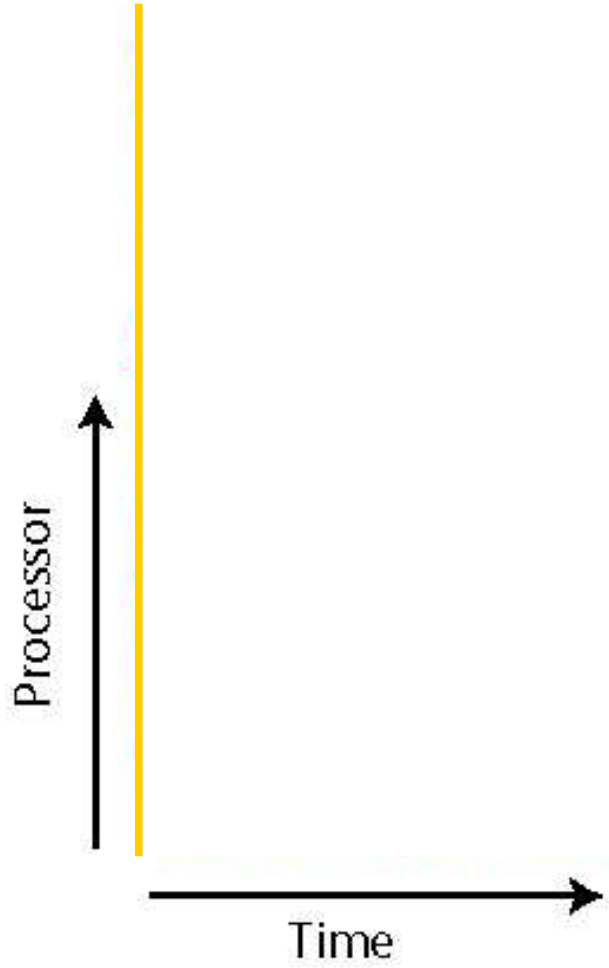


Code Generation: Optimizing tile performance



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

Performance Results for Radar

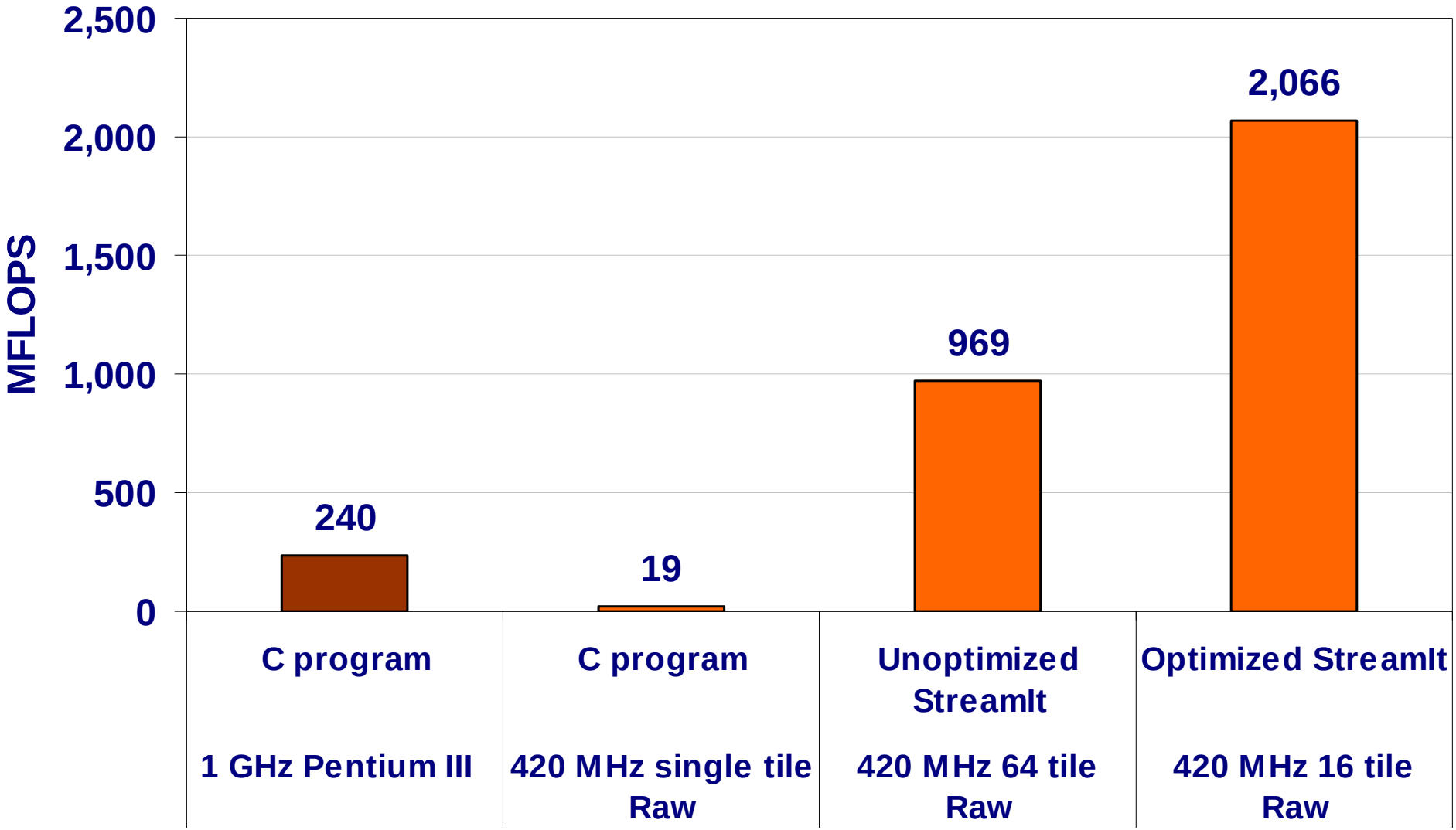


Blocked on Static Network

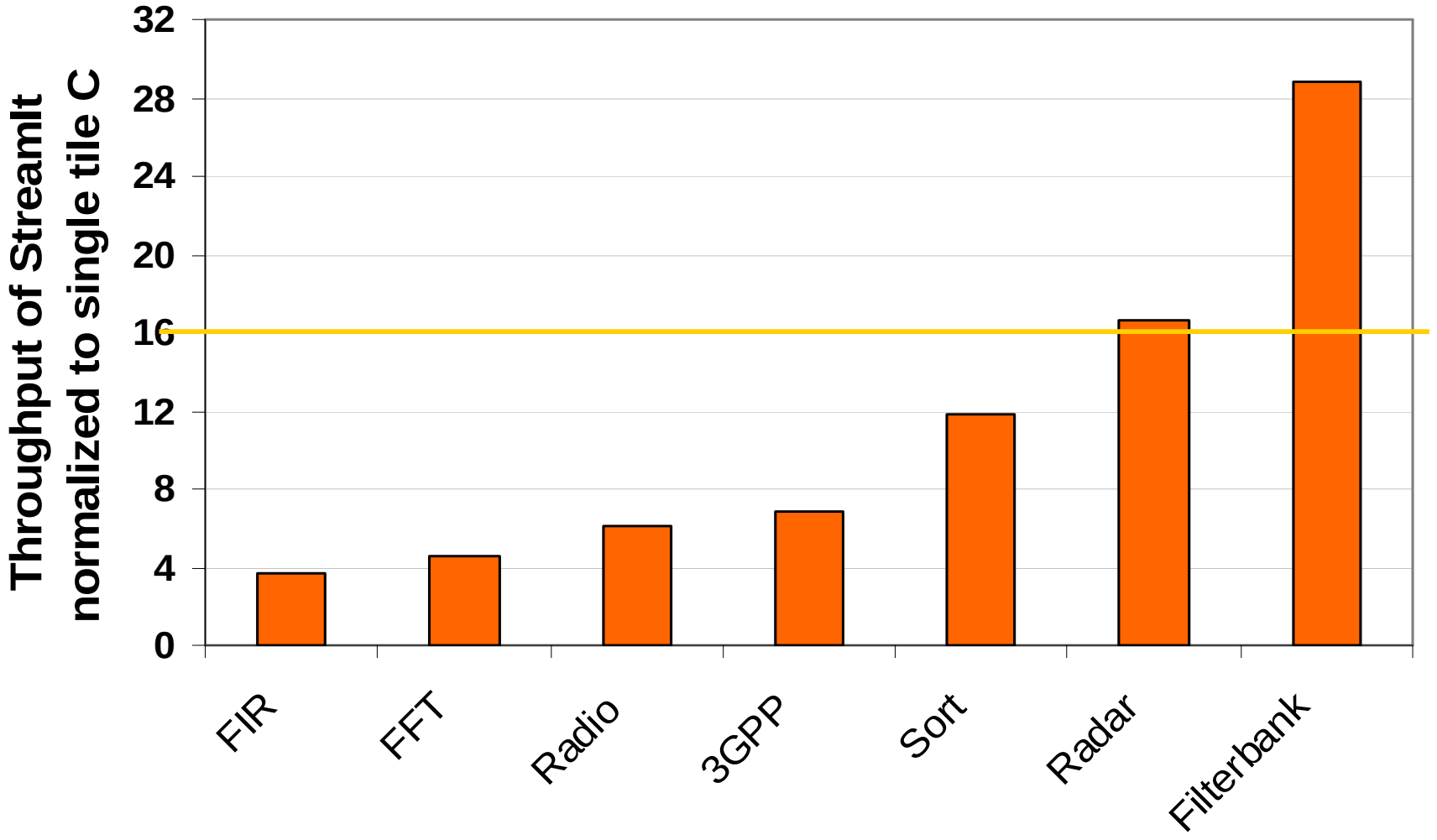
Executing Instructions

Pipeline Stall

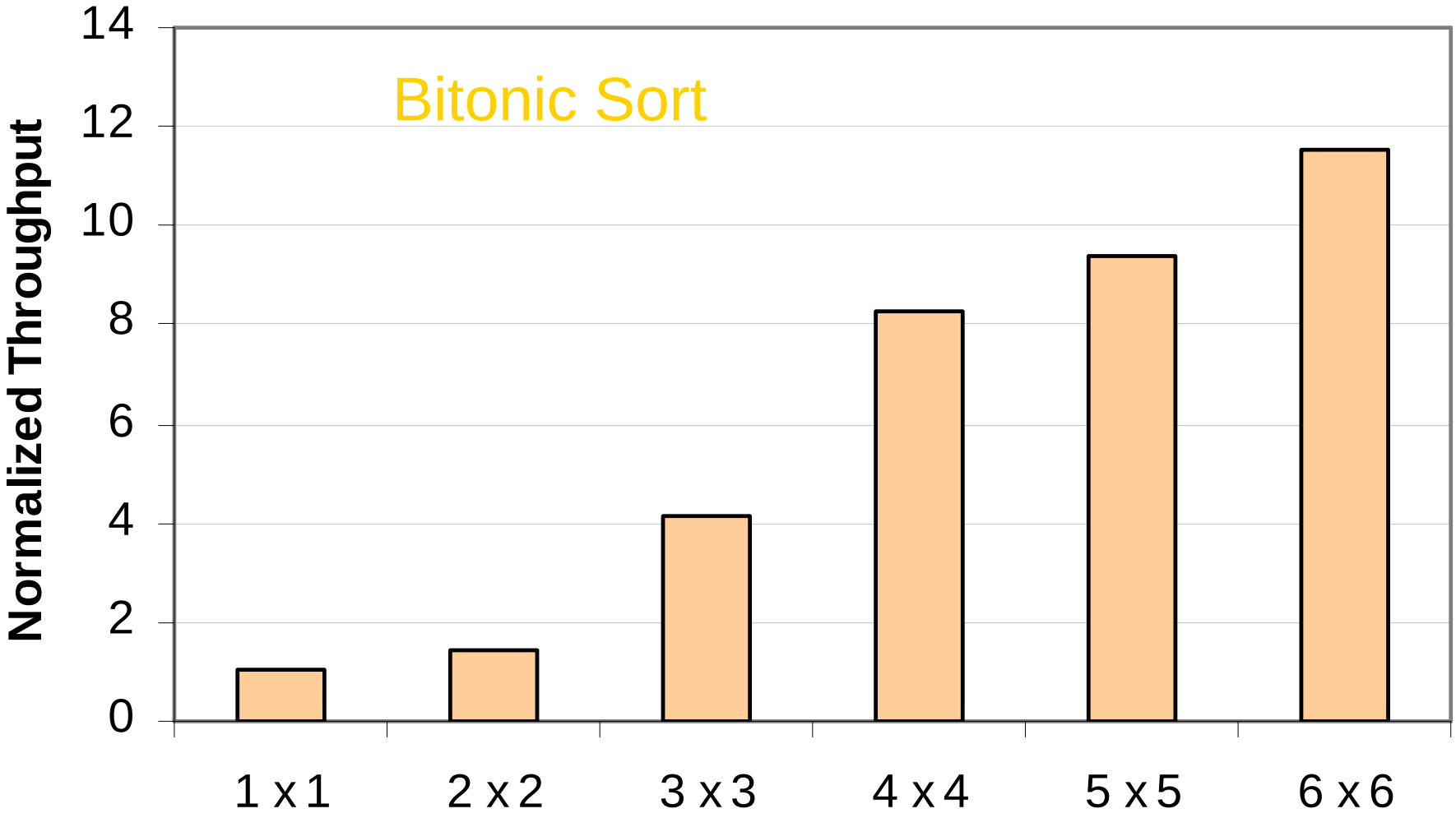
Performance of Radar



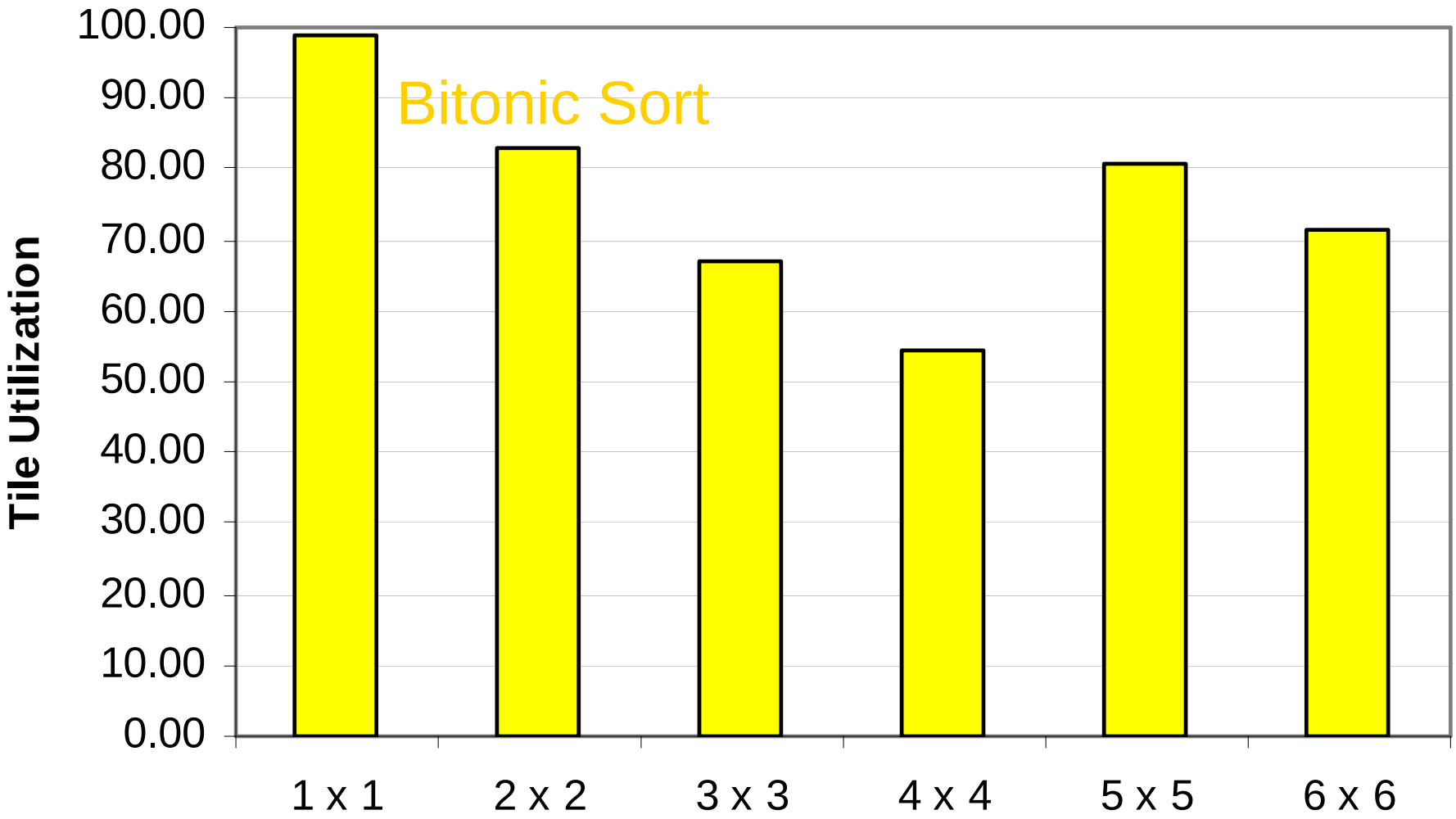
Application Performance



Scalability of StreamIt



Scalability of StreamIt



Conclusions

- Streaming Programming Model
  - Can break the von Neumann bottleneck
  - A natural fit for a large class of applications
  - An ideal model for communication-exposed architectures.
- Can we replace the DSP engineer from the design flow?
  - On the average 90% of the FLOPs eliminated
  - Average performance speedup of 450%
- Increased abstraction does not have to sacrifice performance
- The hardware is ready for the stream programming model

http://cag.lcs.mit.edu/commit/