StreamIt: A Language for Streaming Applications

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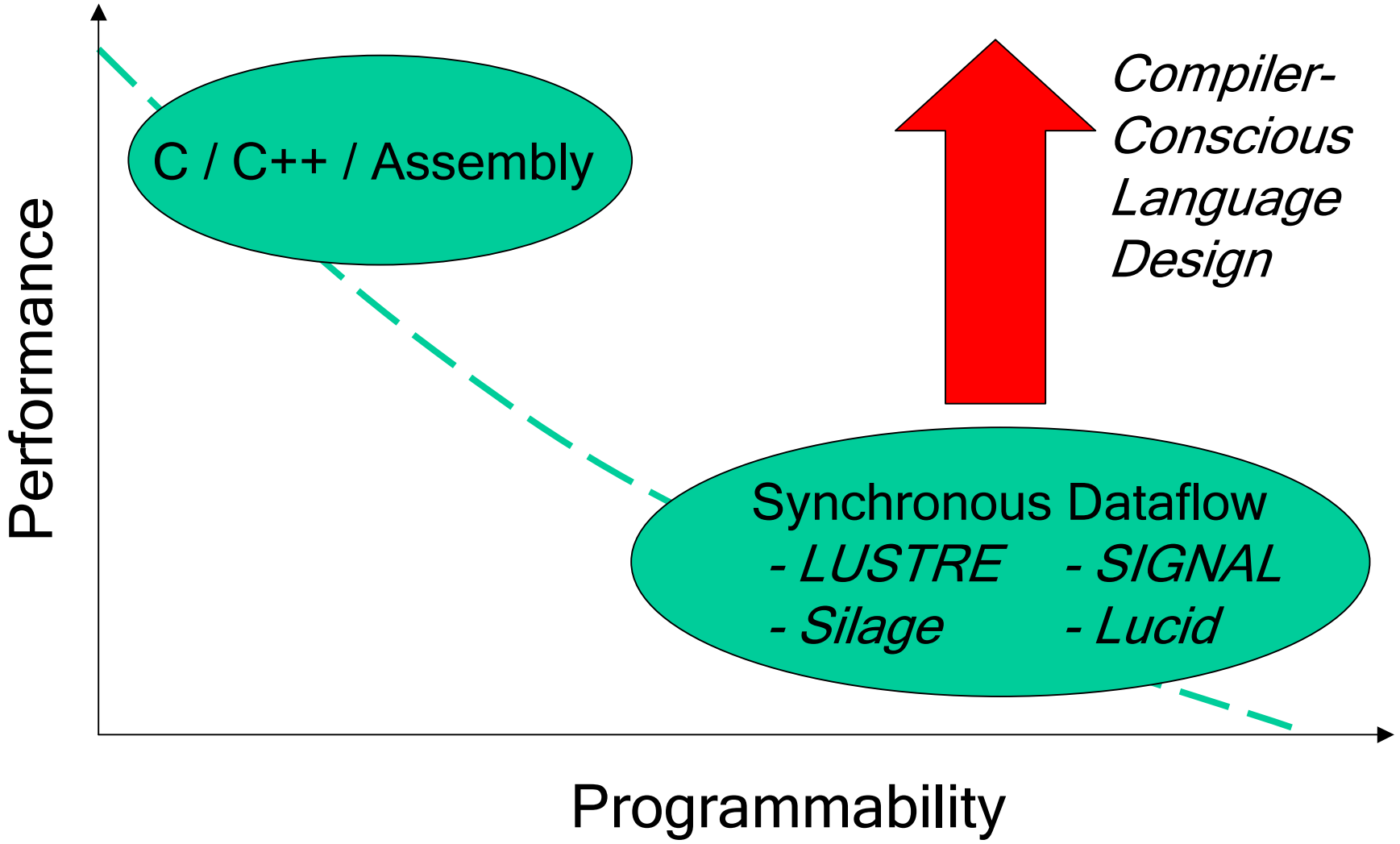
Streaming Application Domain

- Based on streams of data
- Increasingly prevalent and important
  - Embedded systems
    - Cell phones, handheld computers, DSP's
  - Desktop applications
    - Streaming media
    - Software radio
    - Real-time encryption
    - Graphics packages
  - High-performance servers
    - Software routers
    - Cell phone base stations
    - HDTV editing consoles

Developing Stream Programs



The StreamIt Language

- Also a synchronous dataflow language
  - With a few extra features
- Goals:
  - High performance
  - Improved programmer productivity
- Language Contributions:
  - Structured model of streams
  - Messaging system for control
  - Automatic program morphing

} ENABLES Compiler Analysis & Optimization

Outline

- Design of StreamIt
  - Structured Streams
  - Messaging
  - Morphing
- Results
- Conclusions

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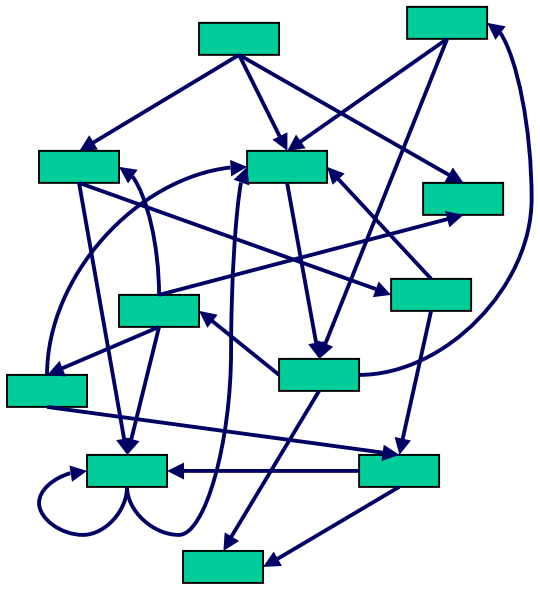
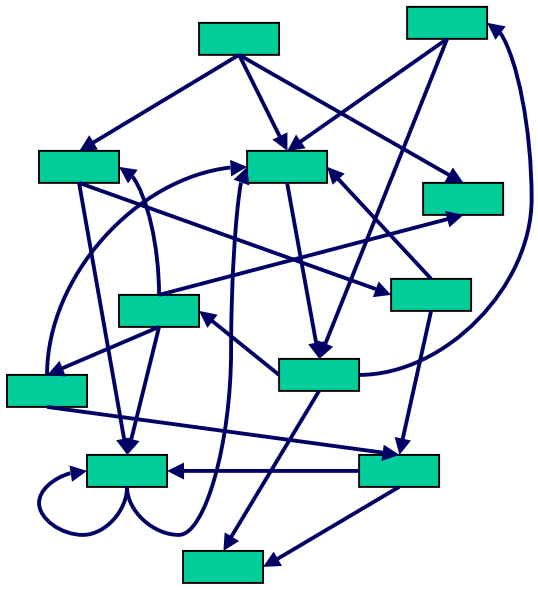
Representing Streams

- Conventional wisdom: streams are graphs
  - Graphs have no simple textual representation
  - Graphs are difficult to analyze and optimize

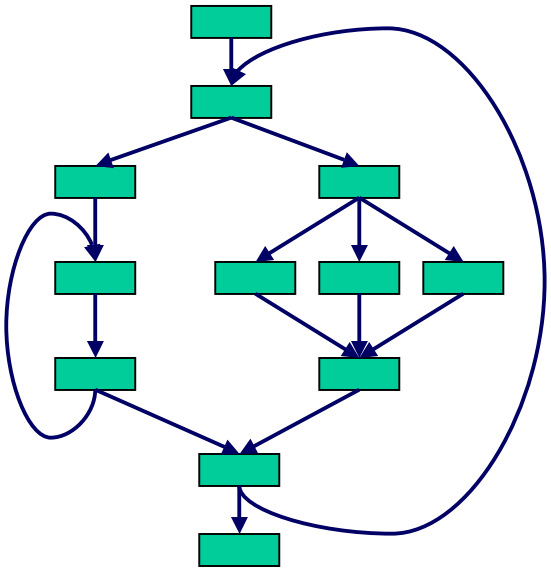


Representing Streams

- Conventional wisdom: streams are graphs
  - Graphs have no simple textual representation
  - Graphs are difficult to analyze and optimize
- Insight: stream programs have structure



unstructured

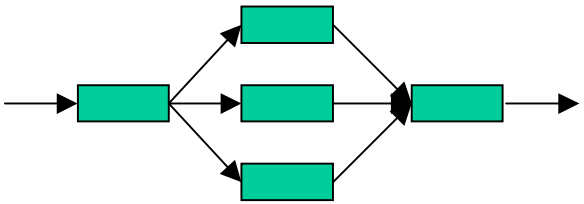


structured

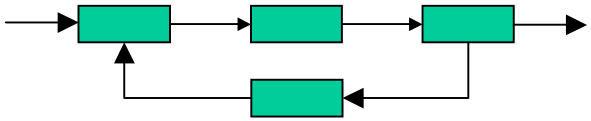
Structured Streams

- Hierarchical structures:
  - Pipeline

  - SplitJoin



  - Feedback Loop



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Structured Streams

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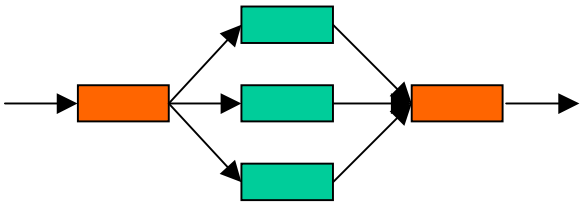

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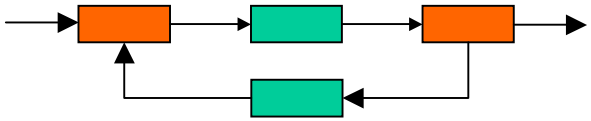

- Basic programmable unit: Filter

- Splits / Joins are compiler-defined

Representing Filters

- Autonomous unit of computation 
  - No access to global resources
  - Communicates through FIFO channels
    - input.pop() - input.peek(index) - output.push(value)
  - Peek / pop / push rates must be constant
- Looks like a Java class, with
  - An initialization function
  - A steady-state “work” function
  - Message handler functions
- Implementation has nothing to do with Java

Filter Example: LowPassFilter

```
class LowPassFilter extends Filter {
    float[] weights;

    void init(int N) {
        weights = calcWeights(N);
        setPush(1); setPop(1); setPeek(N);
        setInput(Float.TYPE); setOutput(Float.TYPE);
    }

    void work() {
        float result = 0;
        for (int i=0; i<weights.length; i++) {
            result += weights[i] * input.peek(i);
        }
        output.push(result);
        input.pop();
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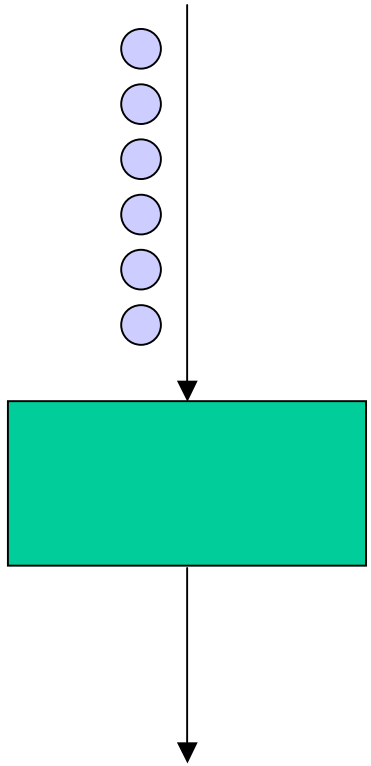

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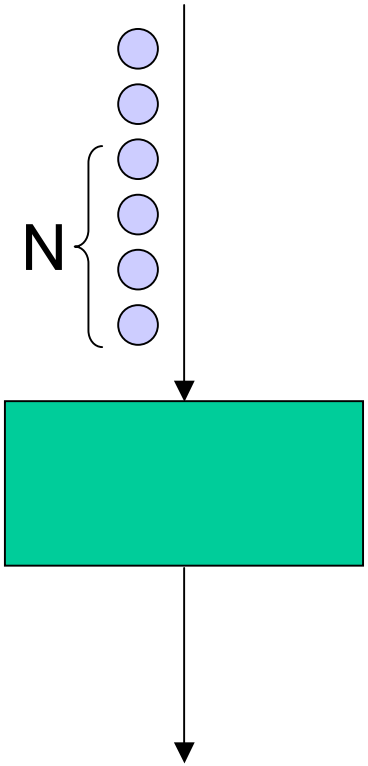

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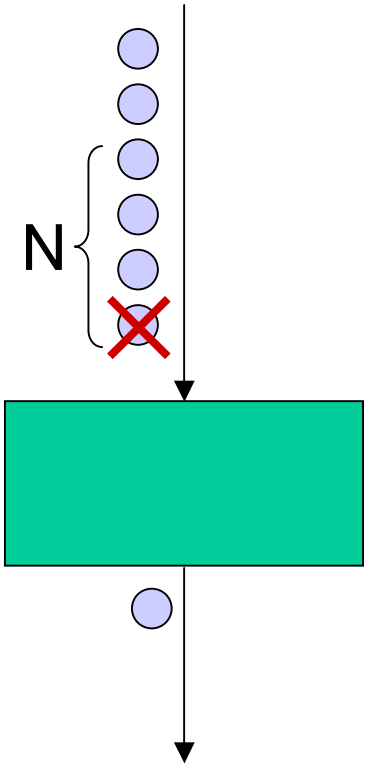

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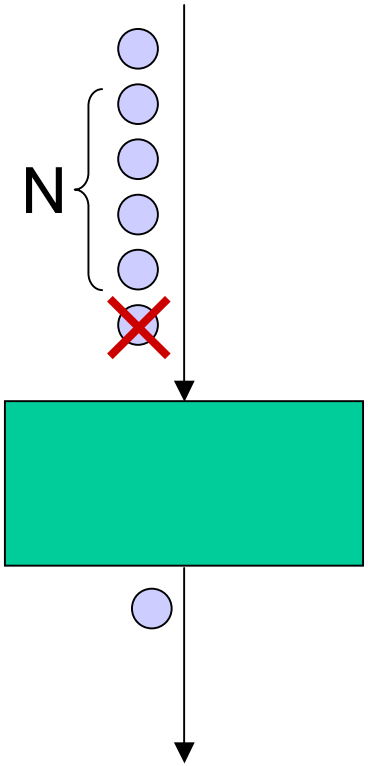

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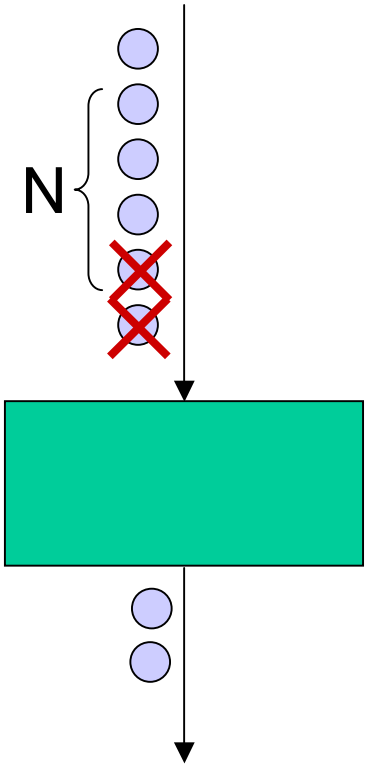
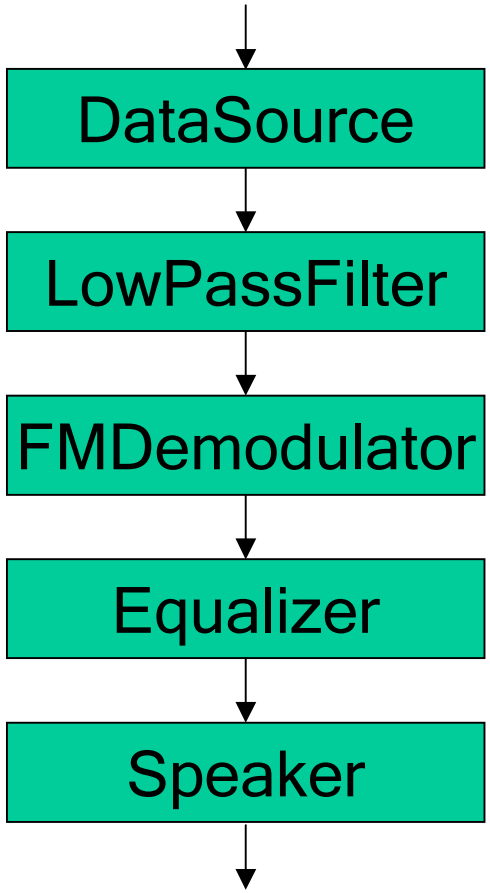


Pipeline Example: FM Radio

```
class FMRadio extends Pipeline {
  void init() {
    add(new DataSource());
    add(new LowPassFilter());
    add(new FMDemodulator());
    add(new Equalizer(8));
    add(new Speaker());
  }
}
```



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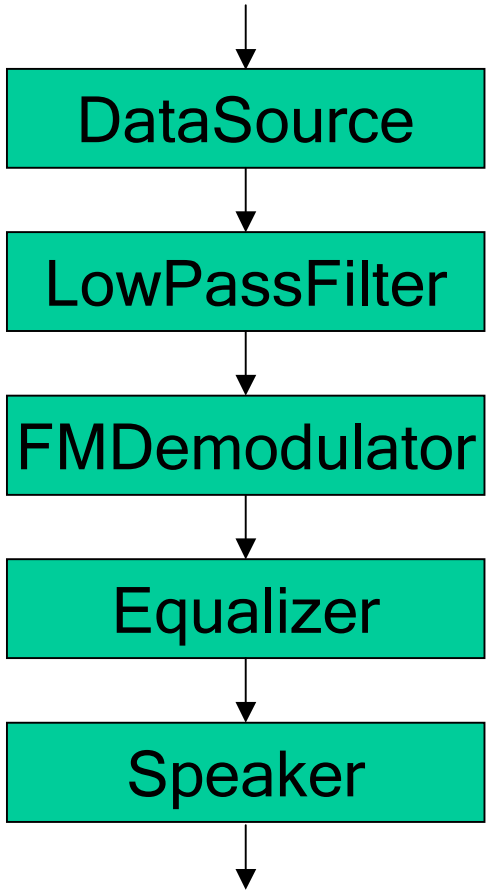
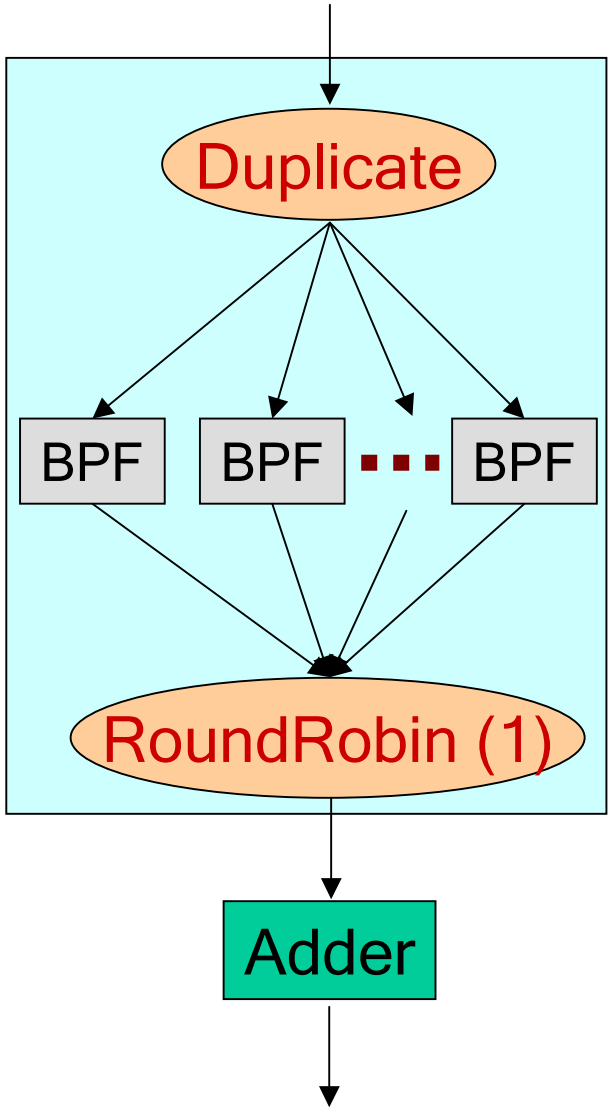


SplitJoin Example: Equalizer

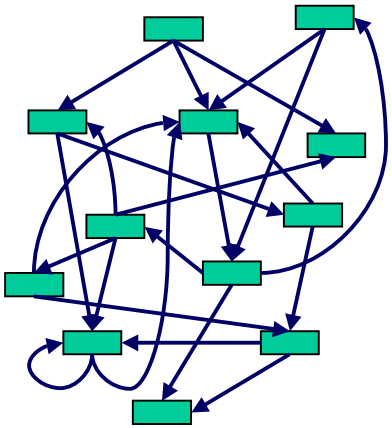
```
class Equalizer extends Pipeline {

  void init(int N) {
    add(new SplitJoin() {
      void init() {
        setSplitter(Duplicate());
        float freq = 10000;
        for (int i = 0; i < N; i ++, freq*=2) {
          add(new BandPassFilter(freq, 2*freq);
        }
        setJoiner(RoundRobin());
      }});
    add(new Adder(N));
  }
}
```

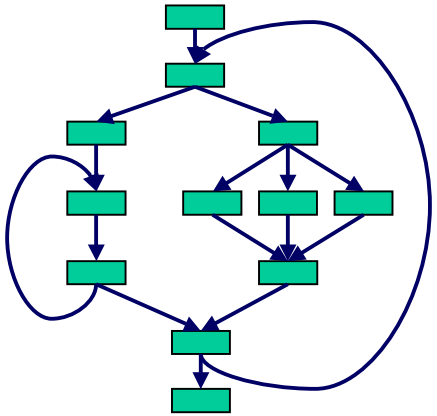


Why Structured Streams?

- Compare to structured control flow



GOTO statements



If / else / for statements

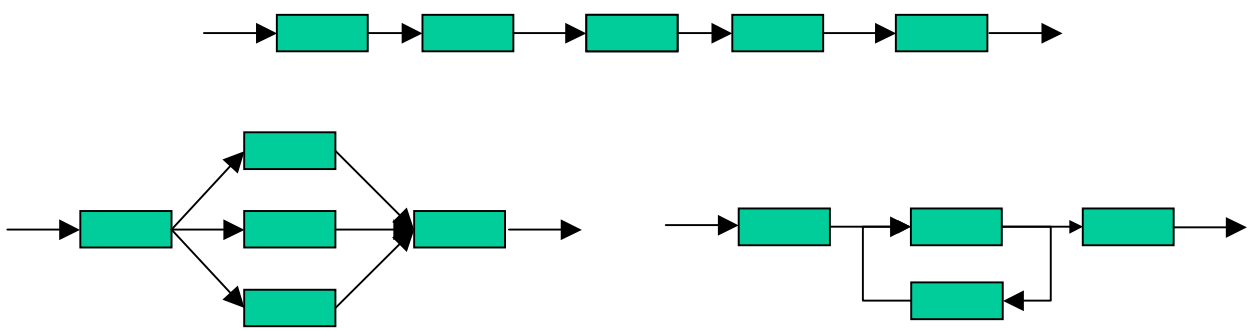
- Tradeoff:

PRO: - more robust - more analyzable

CON: - “restricted” style of programming

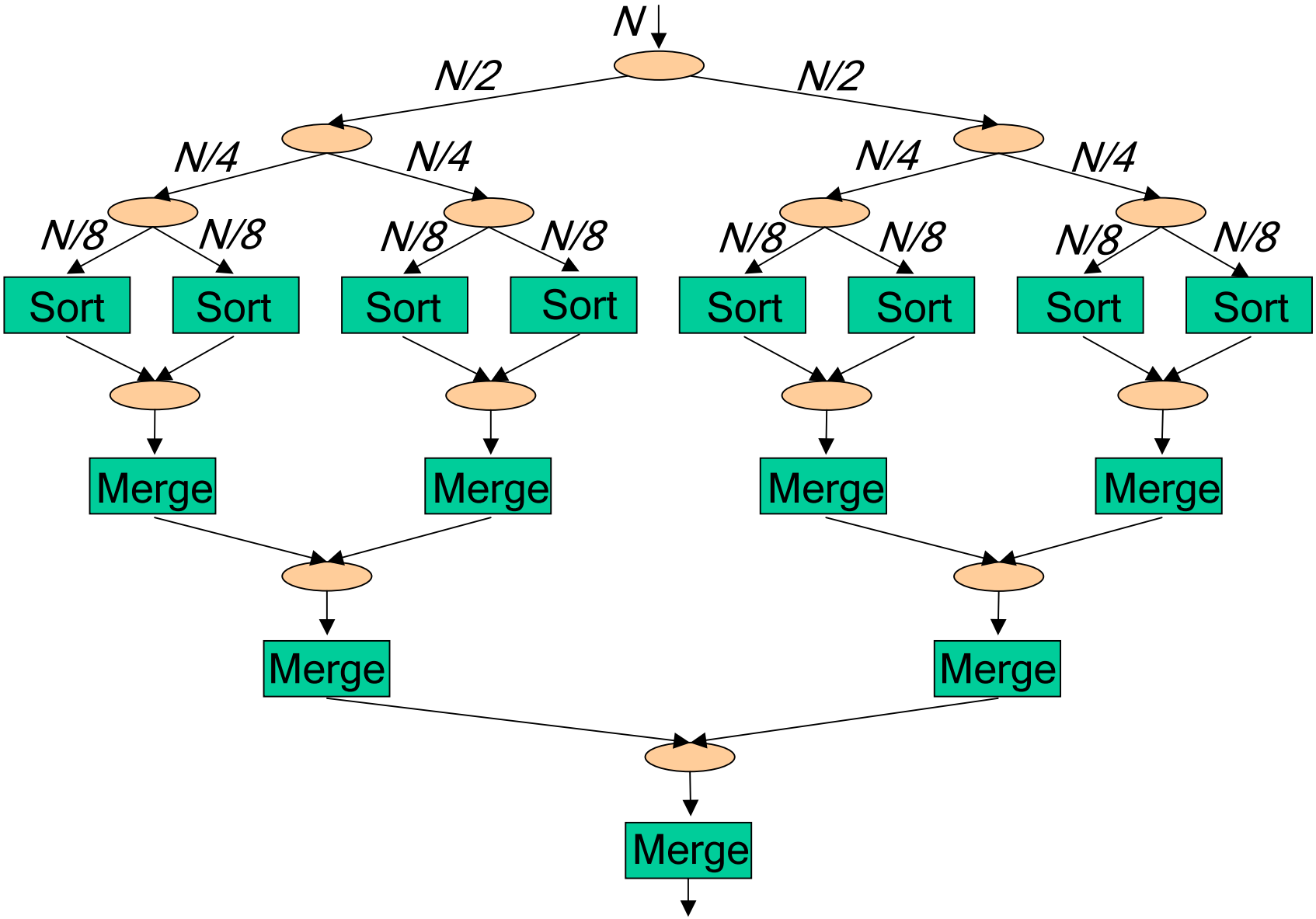
Structure Helps Programmers

- Modules are hierarchical and composable
  - Each structure is single-input, single-output



- Encapsulates common idioms
- Good textual representation
  - Enables parameterizable graphs

N-Element Merge Sort (3-level)

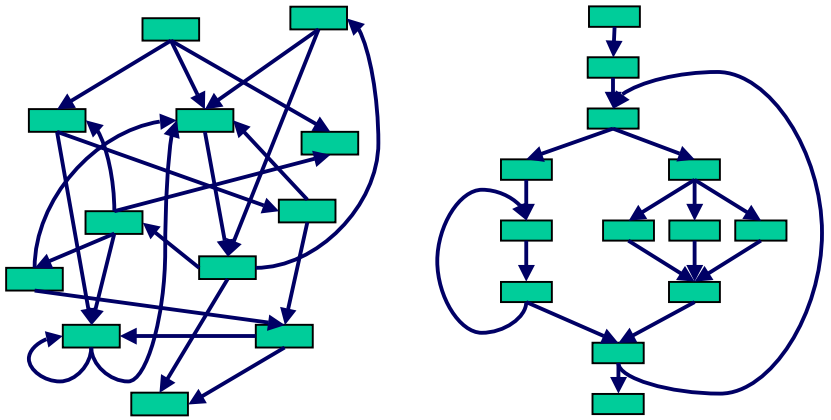


N-Element Merge Sort (K-level)

```
class MergeSort extends Pipeline {
  void init(int N, int K) {
    if (K==1) {
      add(new Sort(N));
    } else {
      add(new SplitJoin() {
        void init() {
          setSplitter(RoundRobin());
          add(new MergeSort(N/2, K-1));
          add(new MergeSort(N/2, K-1));
          setJoiner(RoundRobin());
        }});
    }
    add(new Merge(N));
  }
}
```

Structure Helps Compilers

- Enables local, hierarchical analyses
  - Scheduling
  - Optimization
  - Parallelization
  - Load balancing



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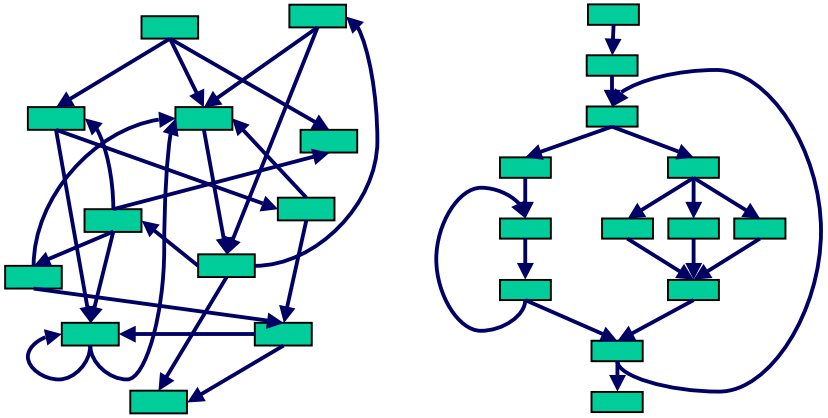
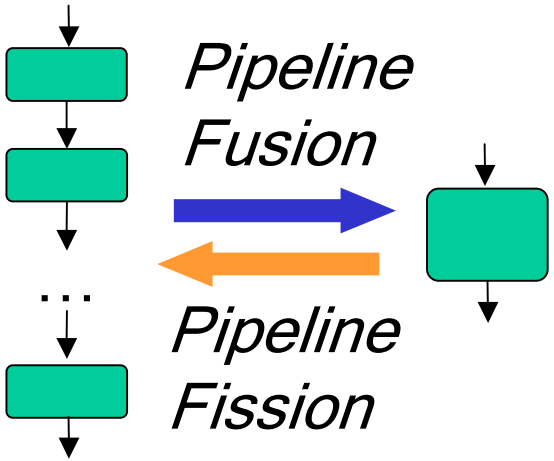
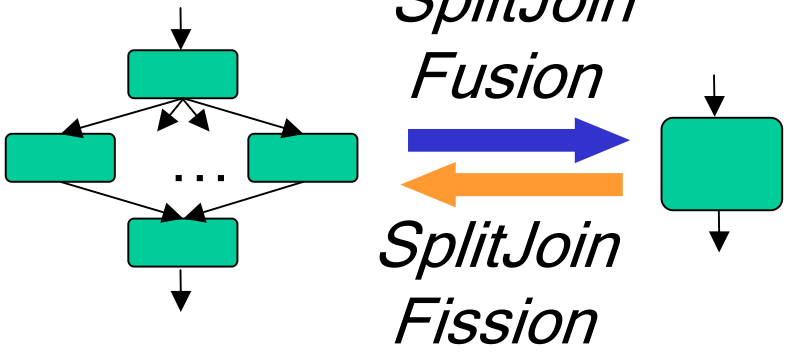


- Examples:





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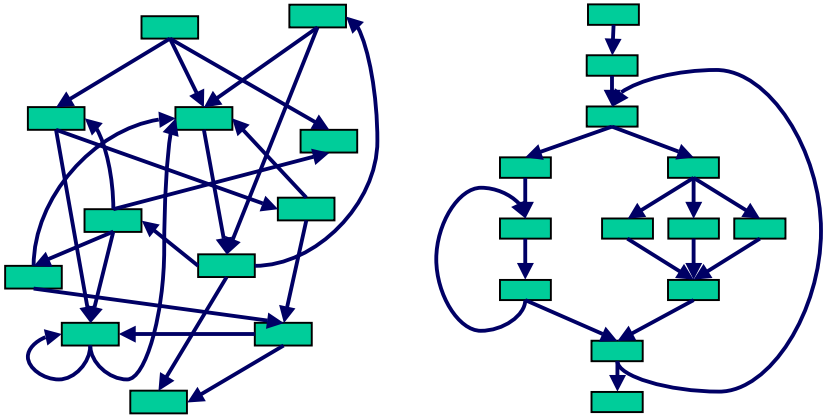

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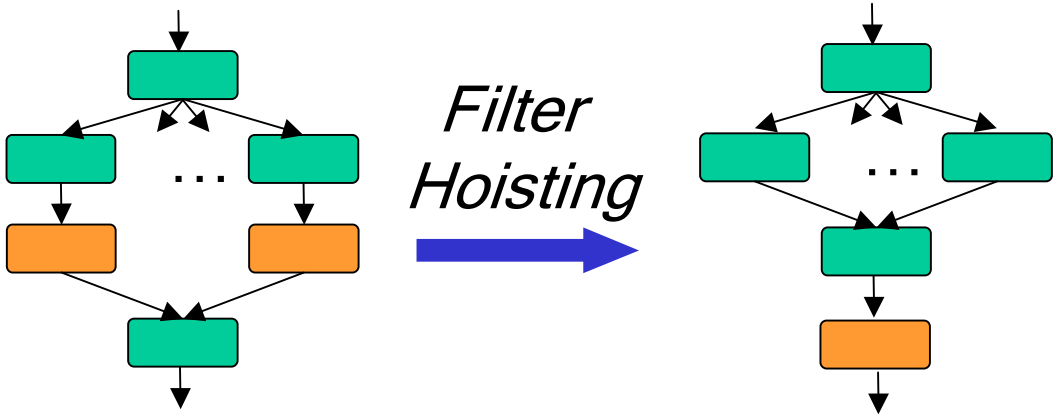

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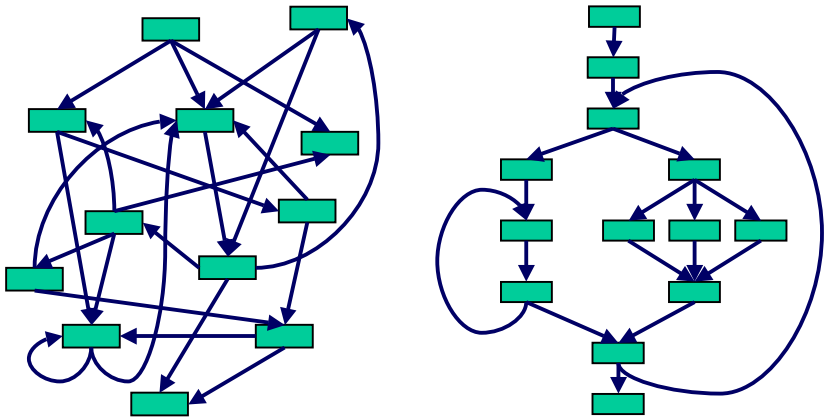


- Disallows non-sensical graphs
- Simplifies separate compilation
  - All blocks single-input, single-output

CON: Restricts Coding Style

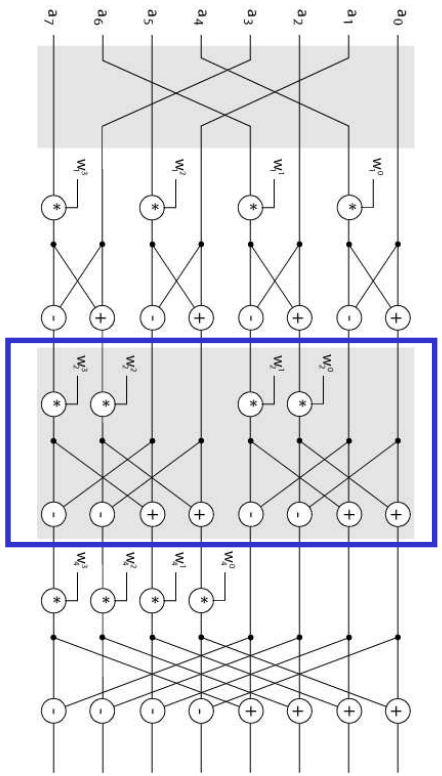
- Some graphs need to be re-arranged
- Example: FFT

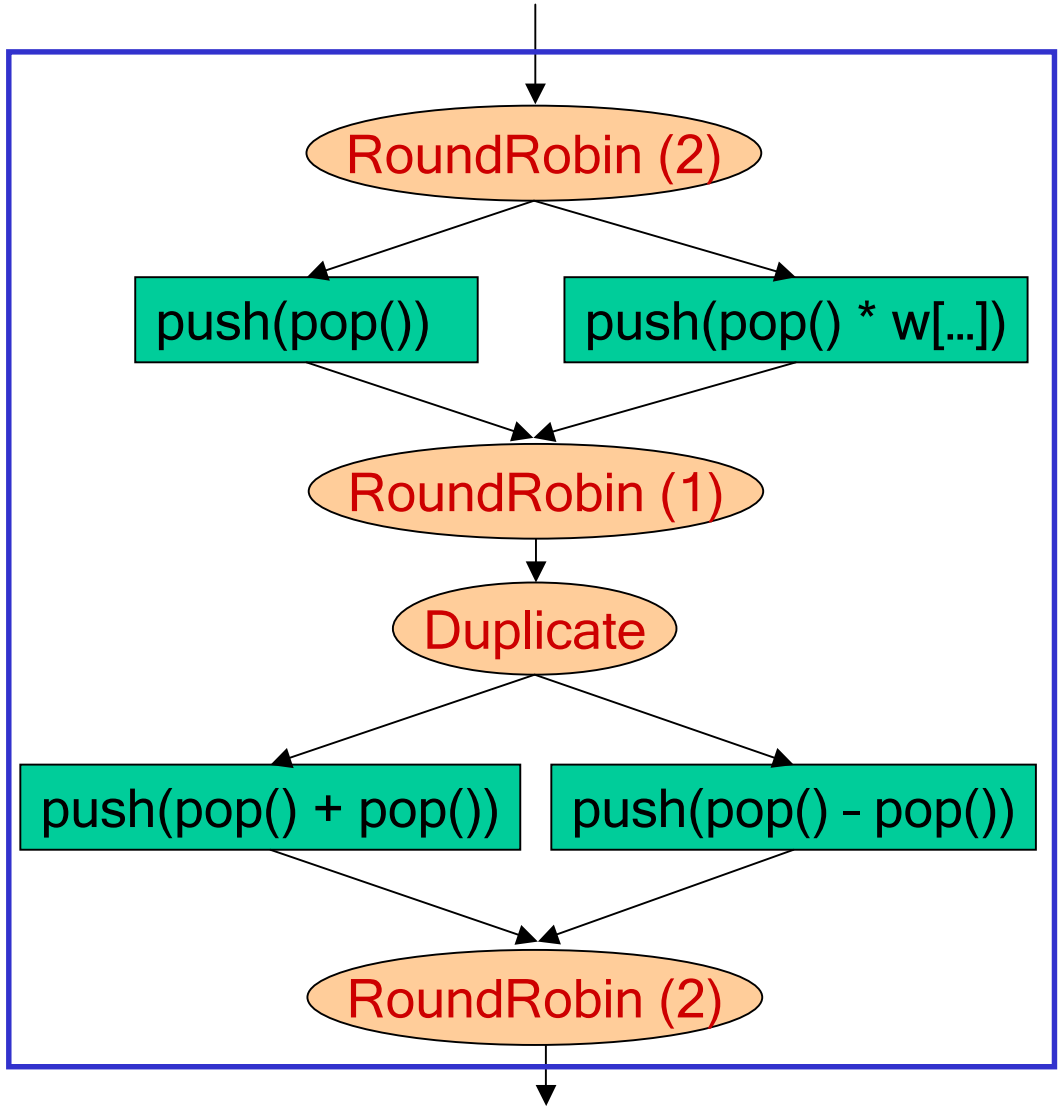
Bit-reverse order

Butterfly (2 way)

Butterfly (4 way)

Butterfly (8 way)





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  - Morphing
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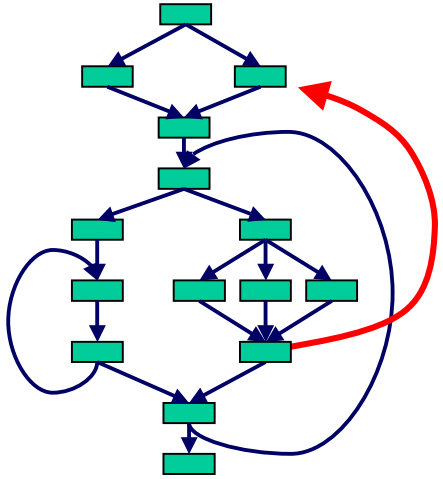
Control Messages

- Structures for regular, high-bandwidth data
- But also need a control mechanism for irregular, low-bandwidth events



  - Change volume on a cell phone
  - Initiate handoff of stream
  - Adjust network protocol

Supporting Control Messages

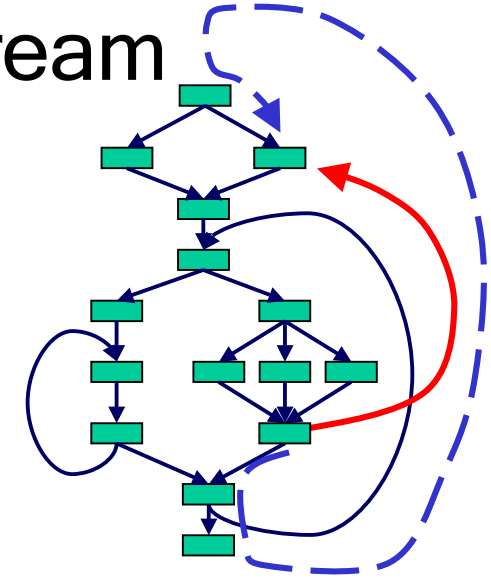
- Option 1: Embed message in stream

  PRO: - message arrives with data

  CON: - complicates filter code

  - complicates structure

  - runtime overhead

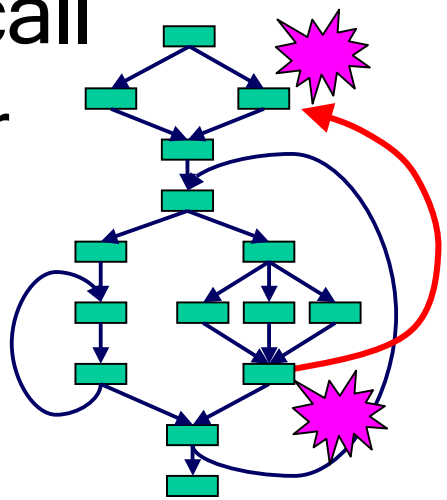


- Option 2: Synchronous method call

  PRO: - delivery transparent to user

  CON: - timing is unclear

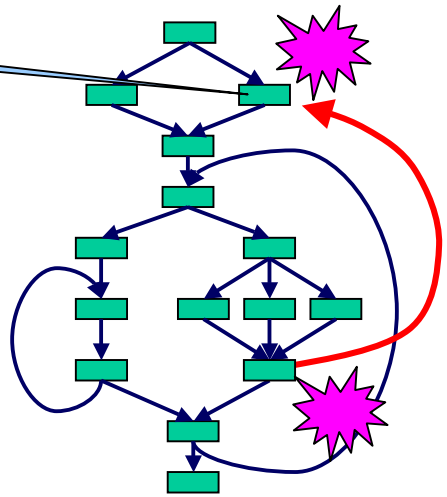
  - limits parallelism



StreamIt Messaging System

- Looks like method call, but semantics differ

```
void raiseVolume(int v)
  myVolume += v;
}
```

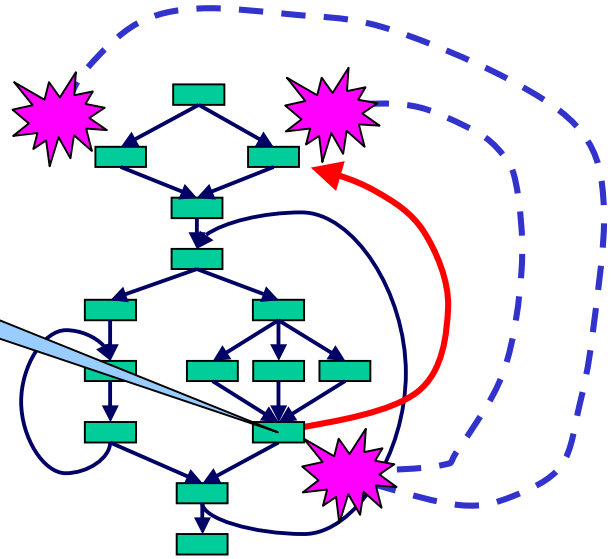


  - No return value
  - Asynchronous delivery
  - Can broadcast to multiple targets

StreamIt Messaging System

- Looks like method call, but semantics differ

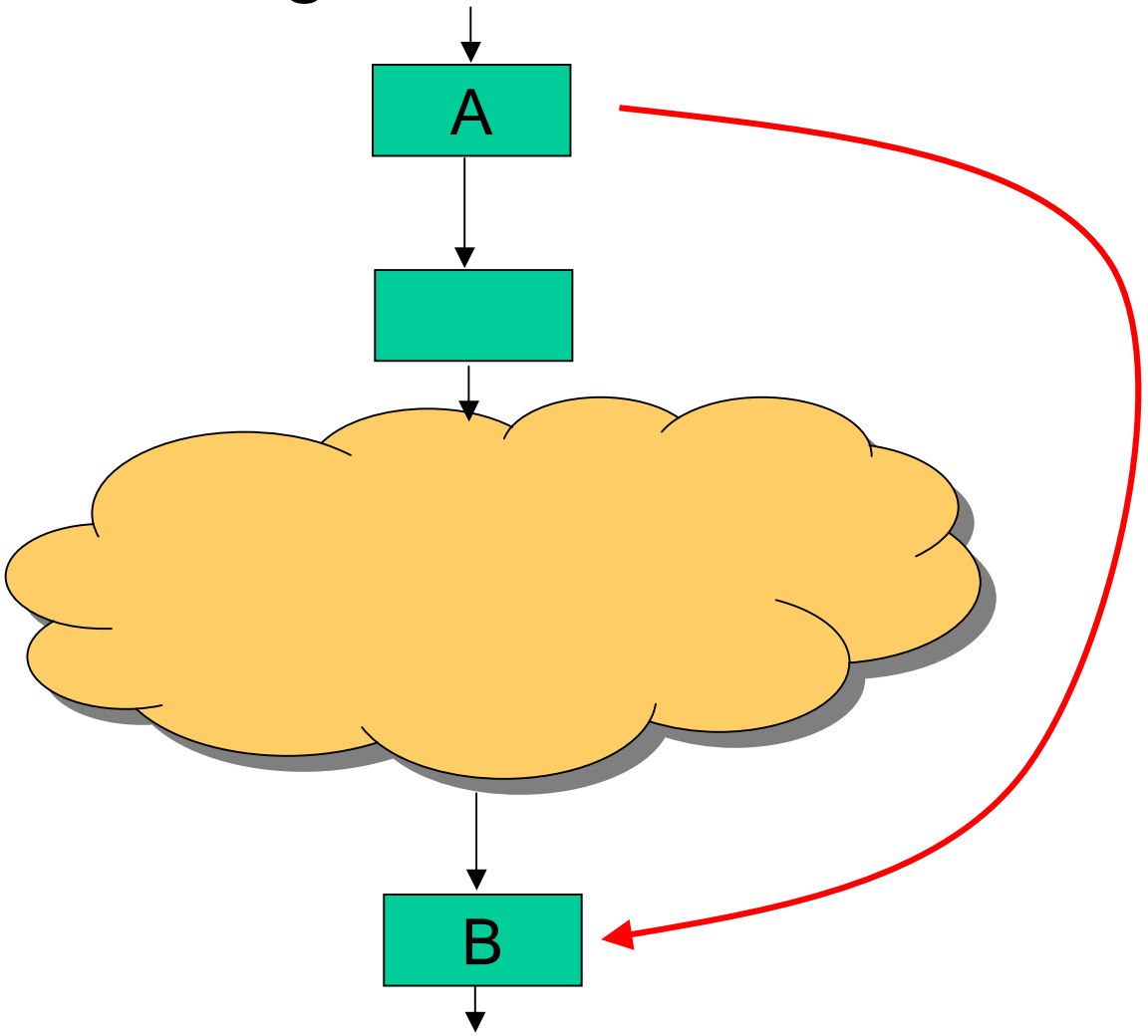
```
void work () {
  TargetFilter x;
  …
  if (lowVolume())
     x.raiseVolume(10);
}
```



  - No return value
  - Asynchronous delivery
  - Can broadcast to multiple targets
- Timed relative to data
  - User gains precision; compiler gains flexibility

Message Timing

- A sends message to B with zero latency



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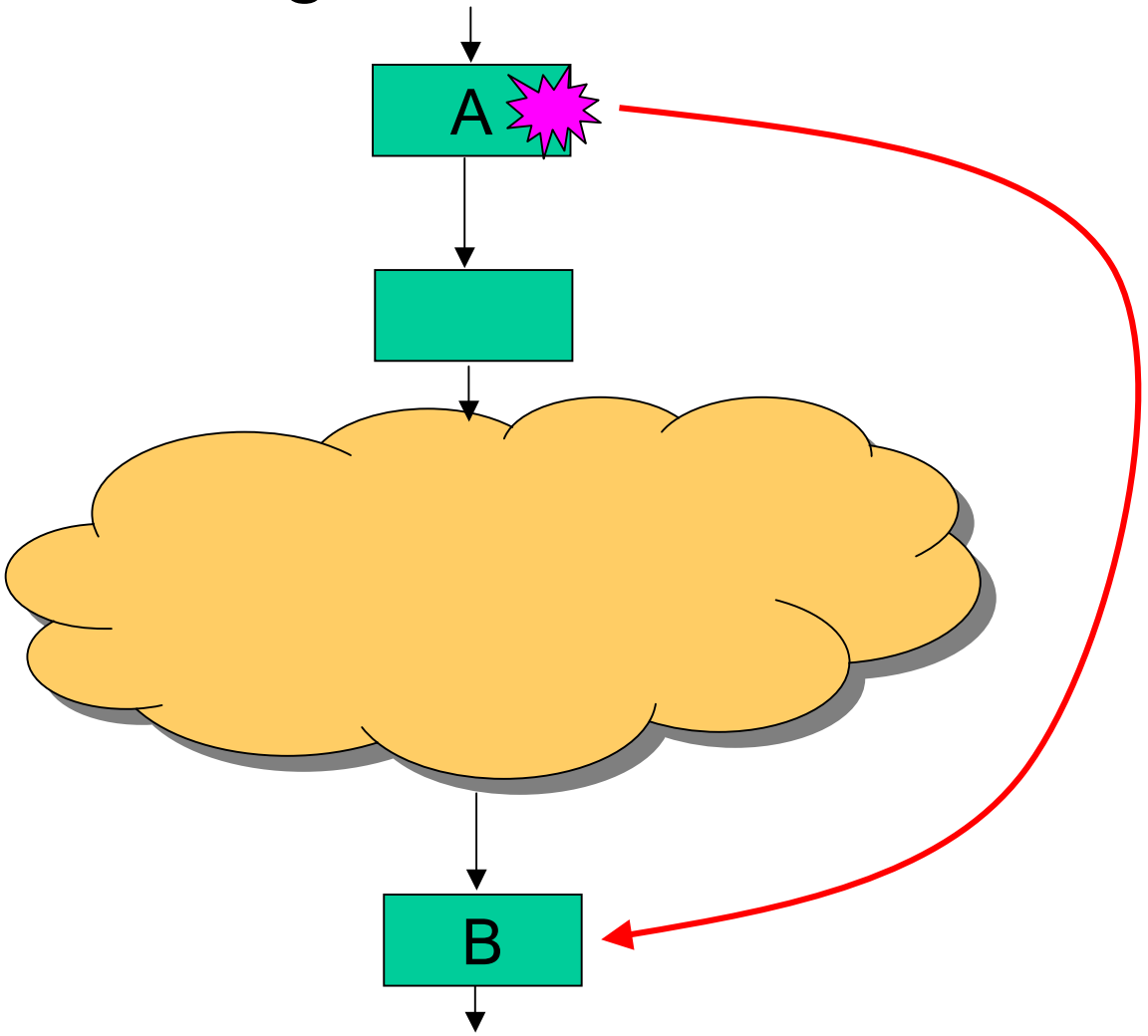

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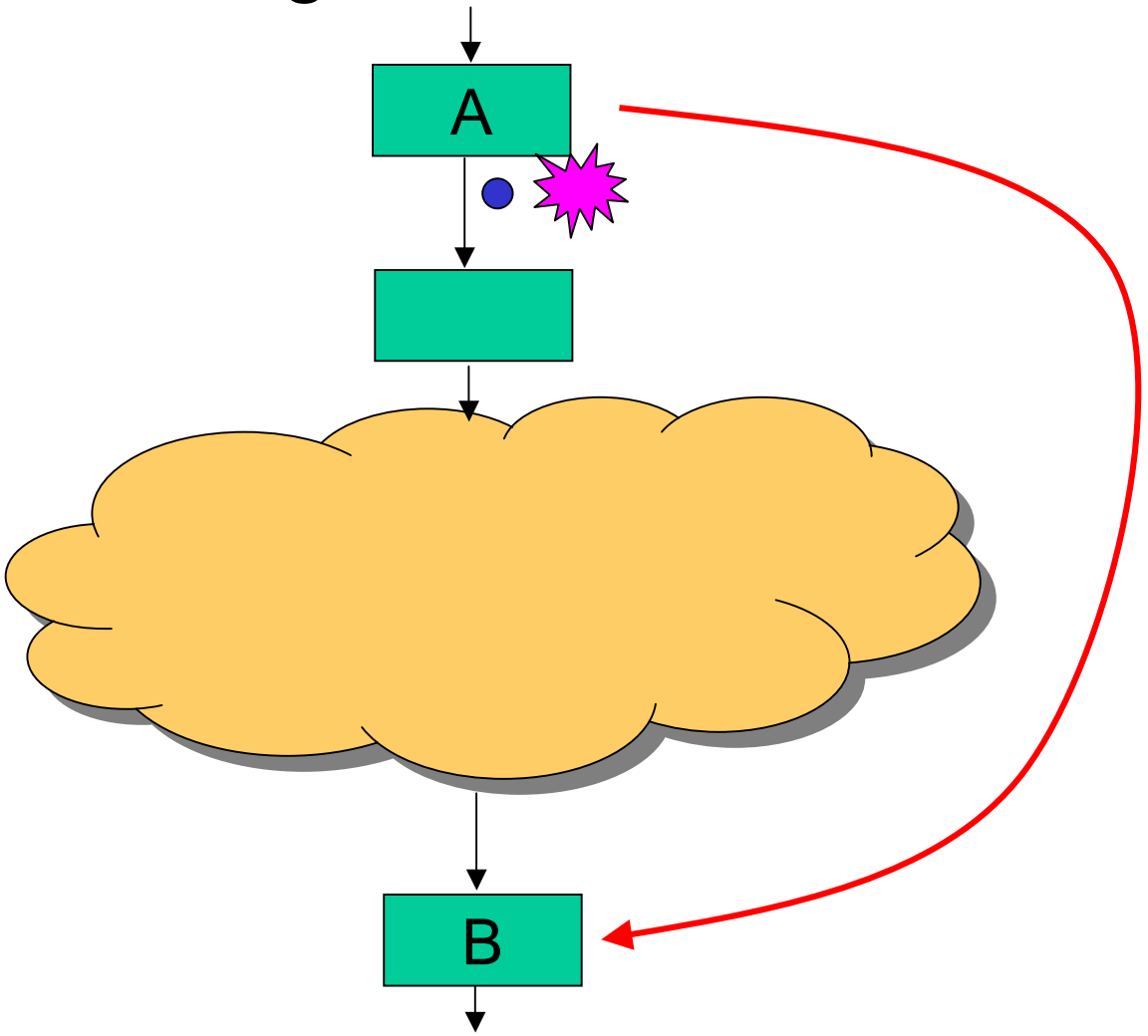

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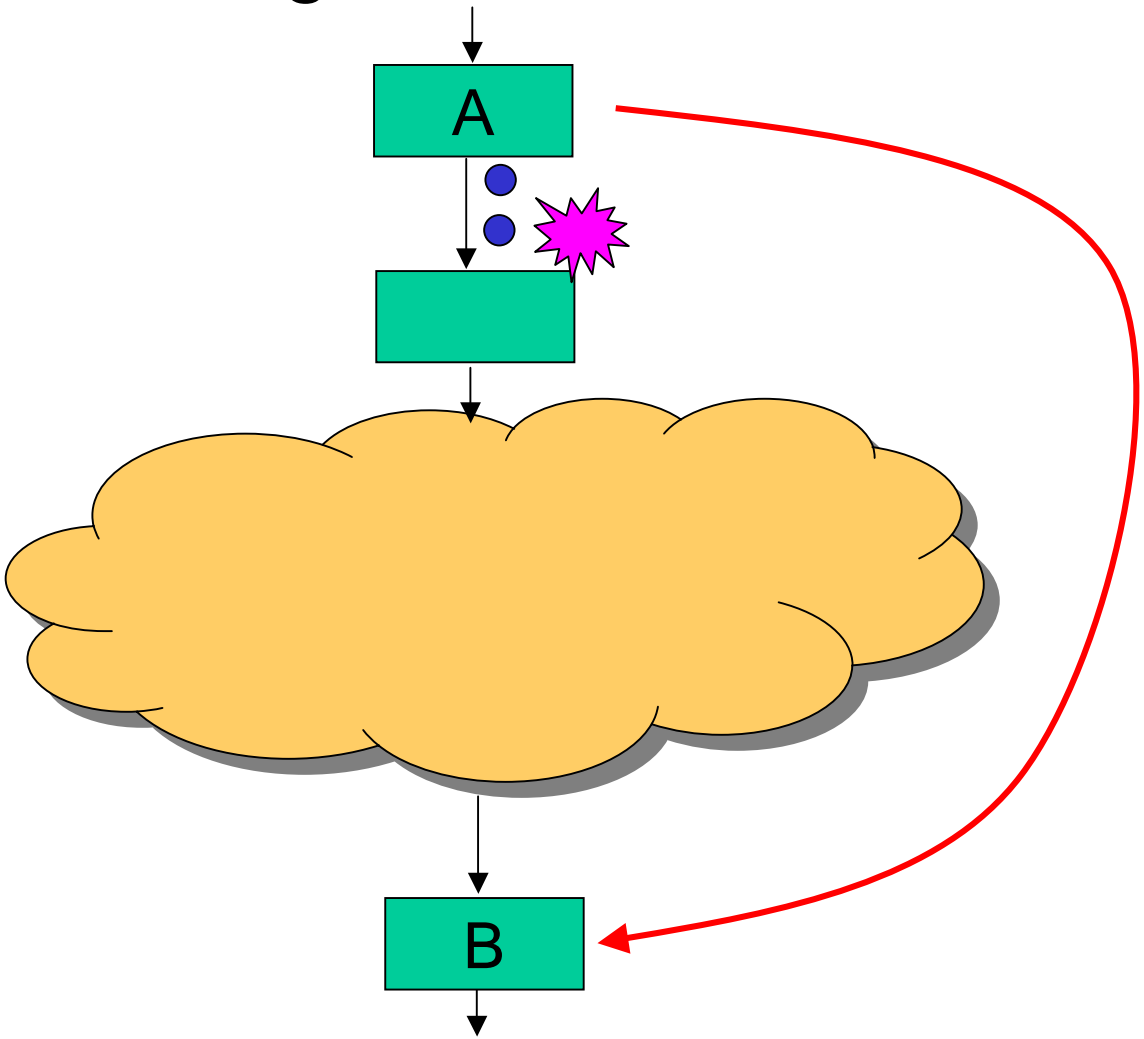

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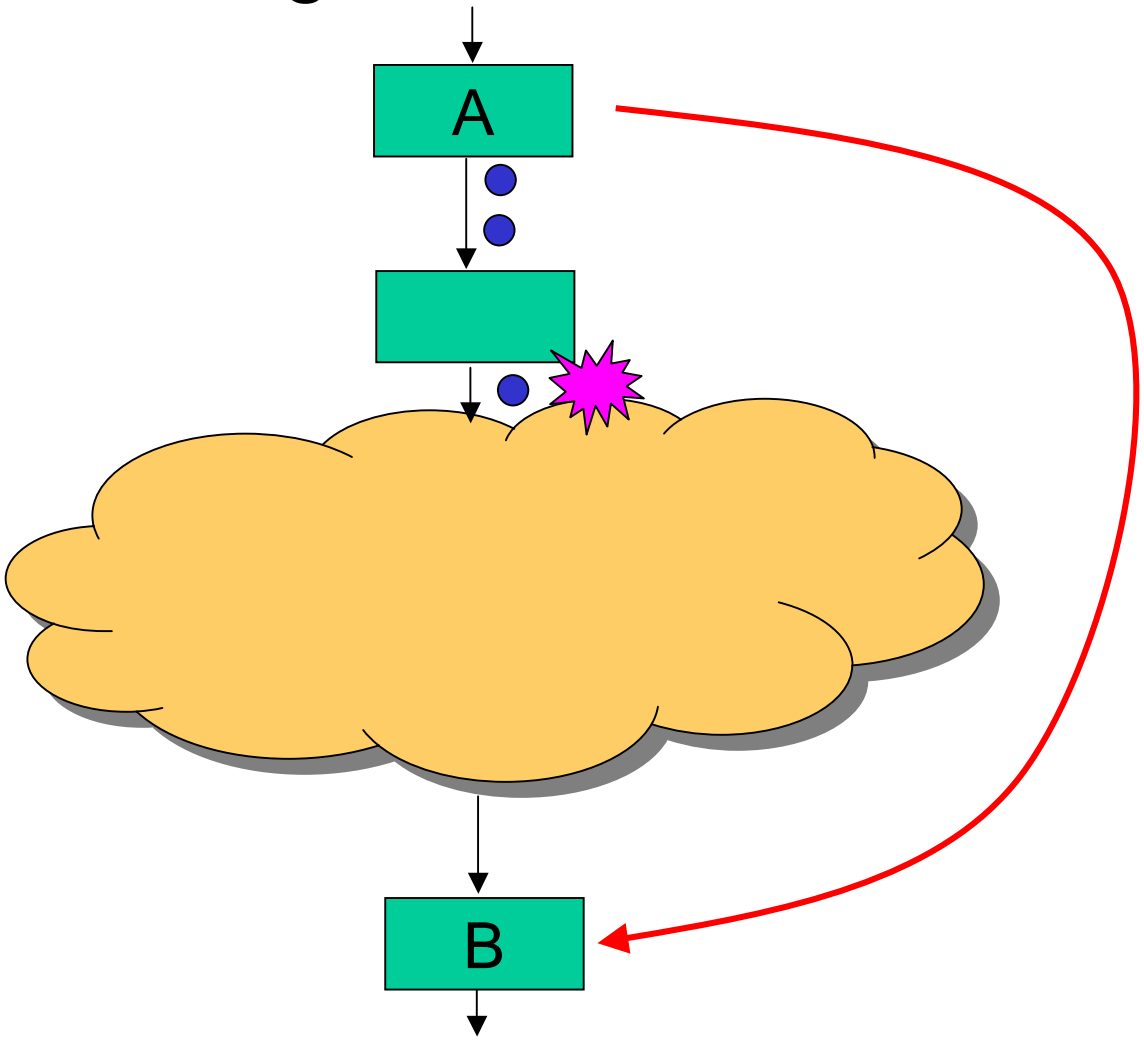

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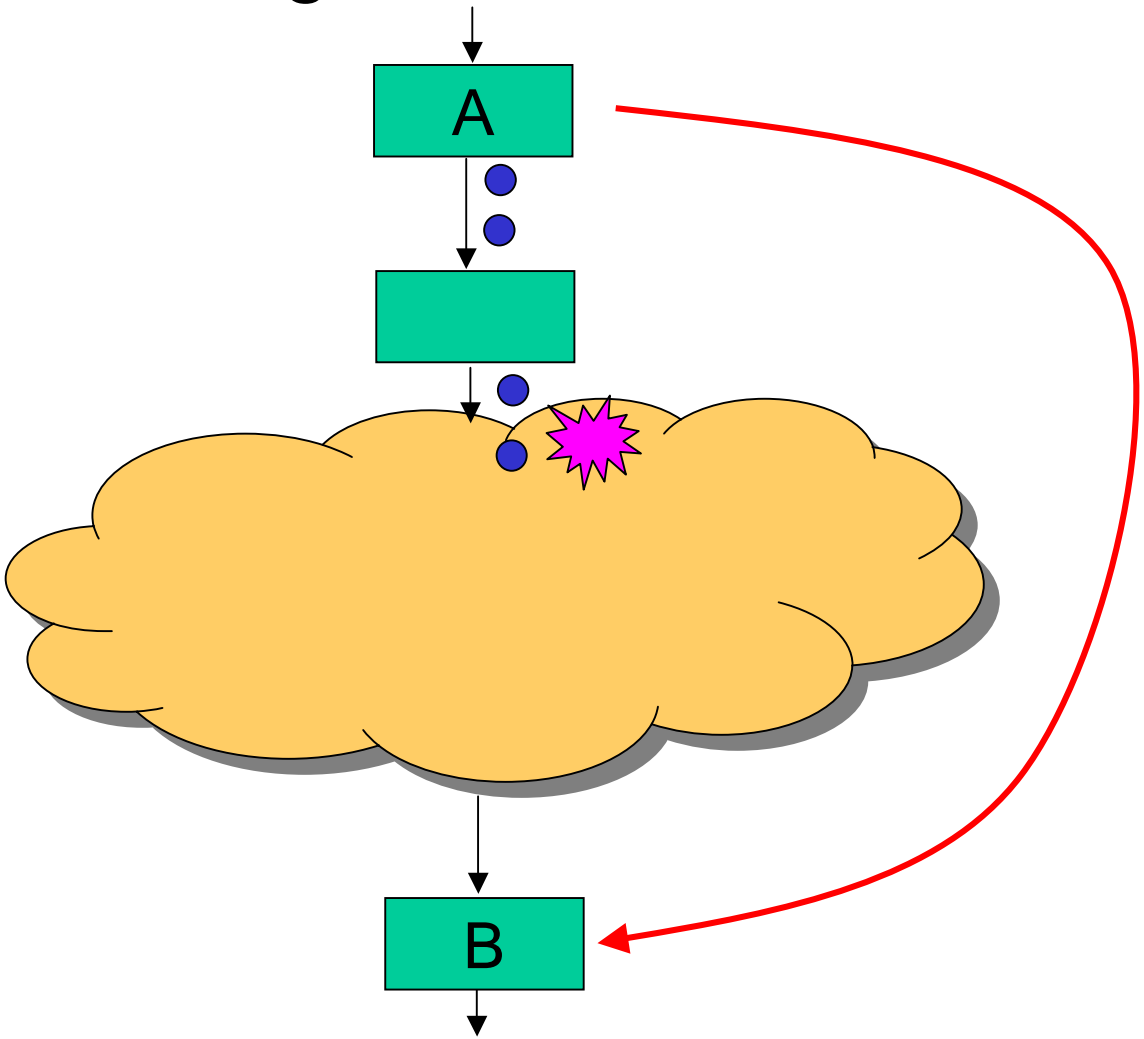

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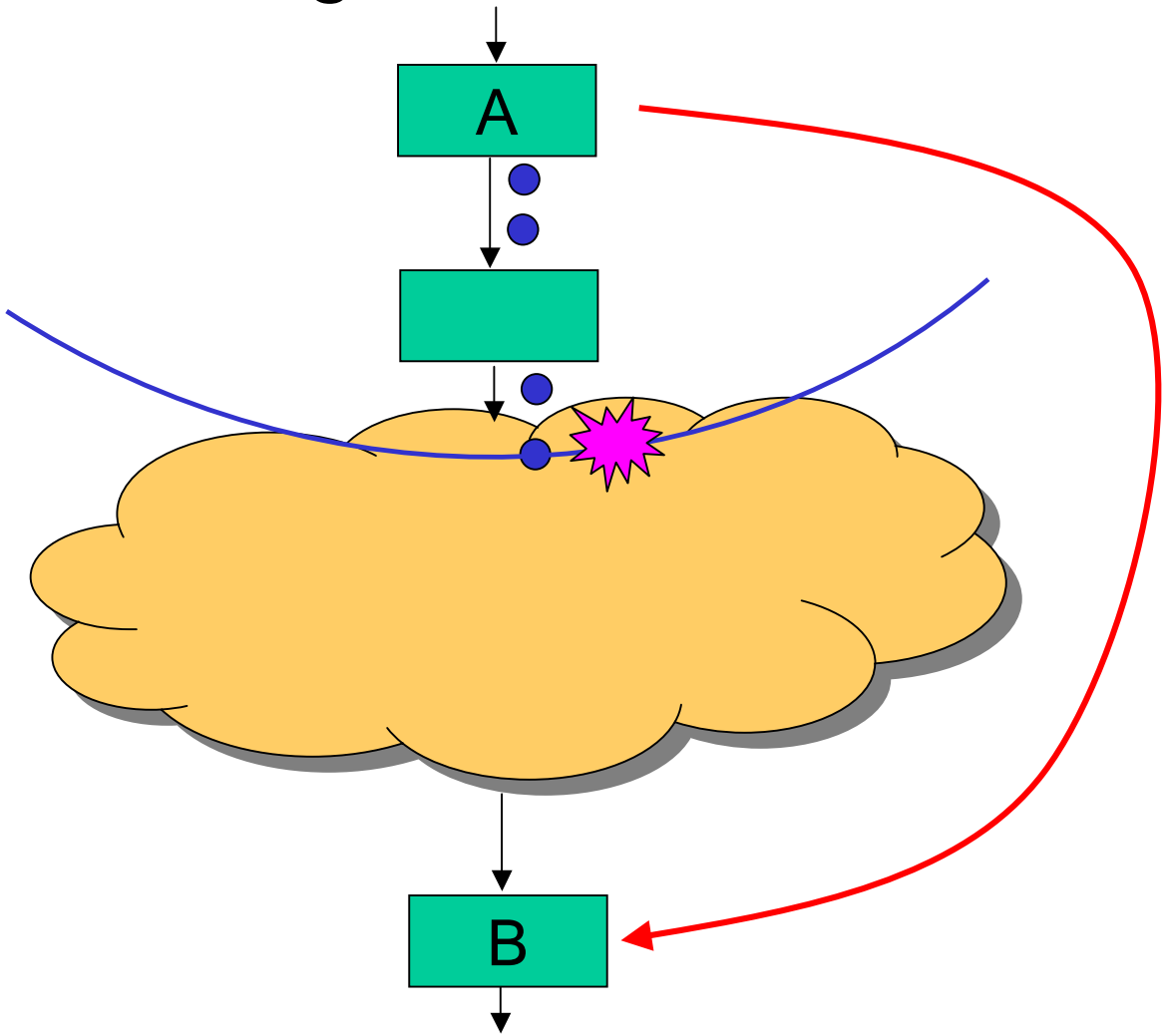

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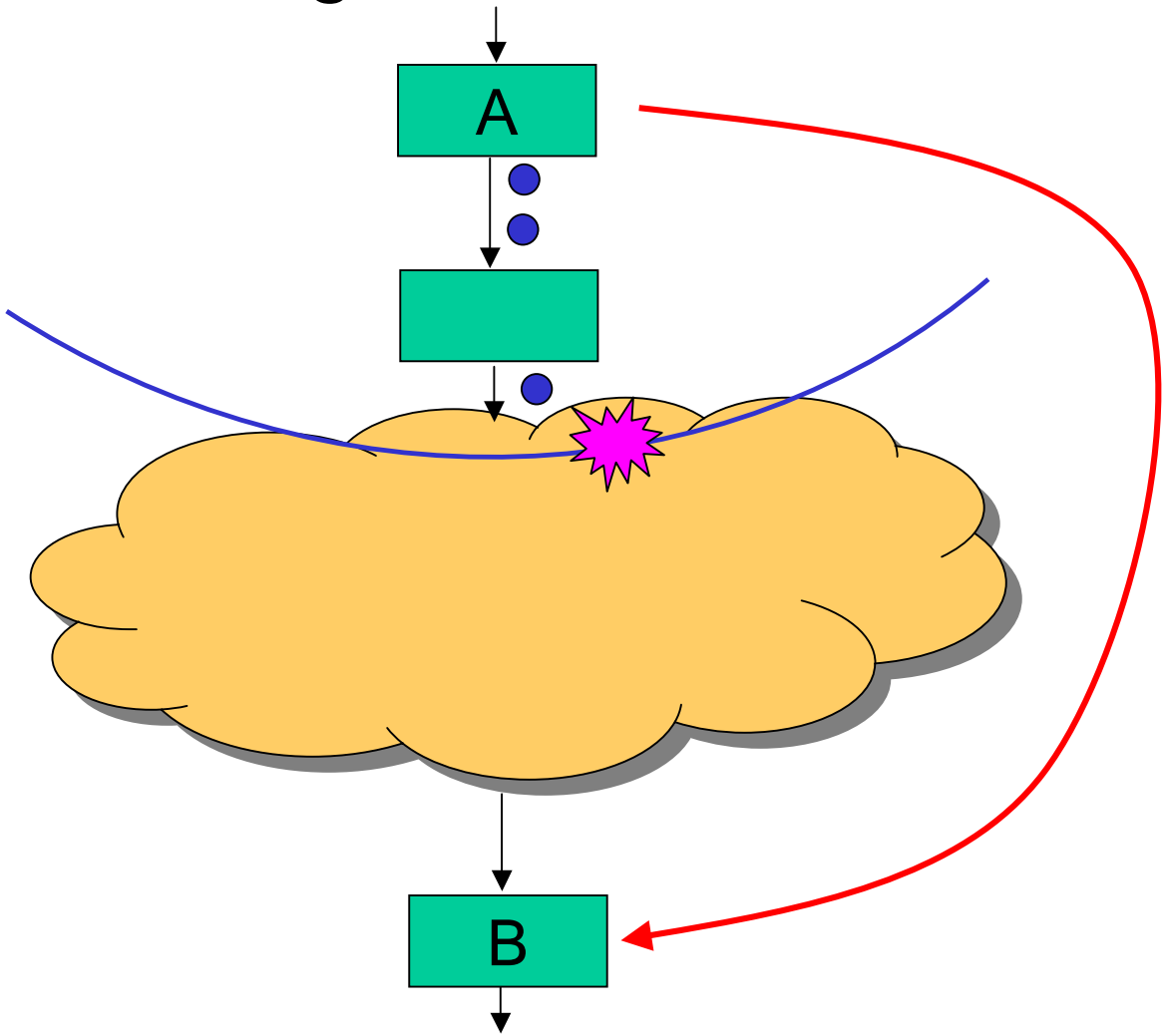

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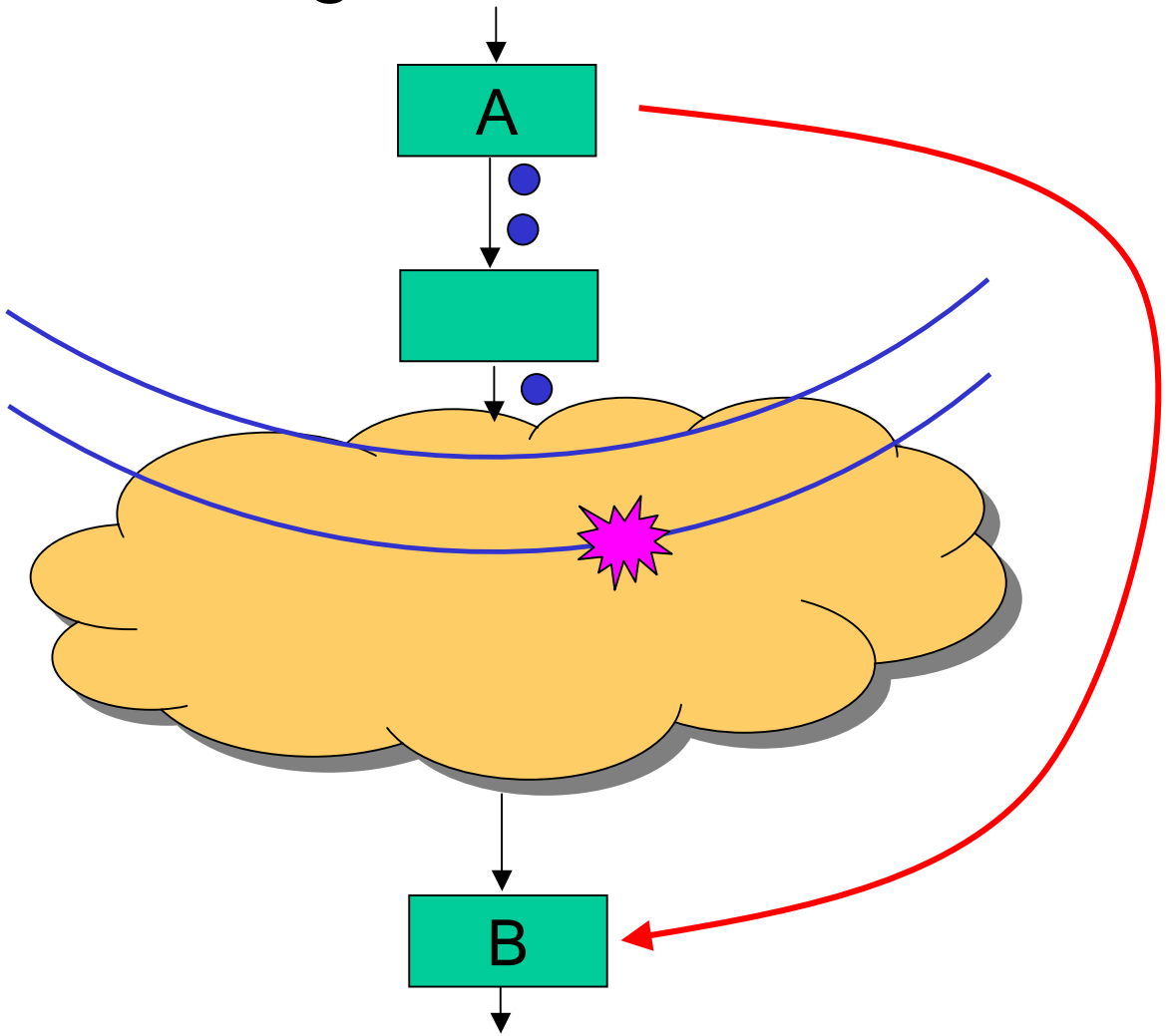

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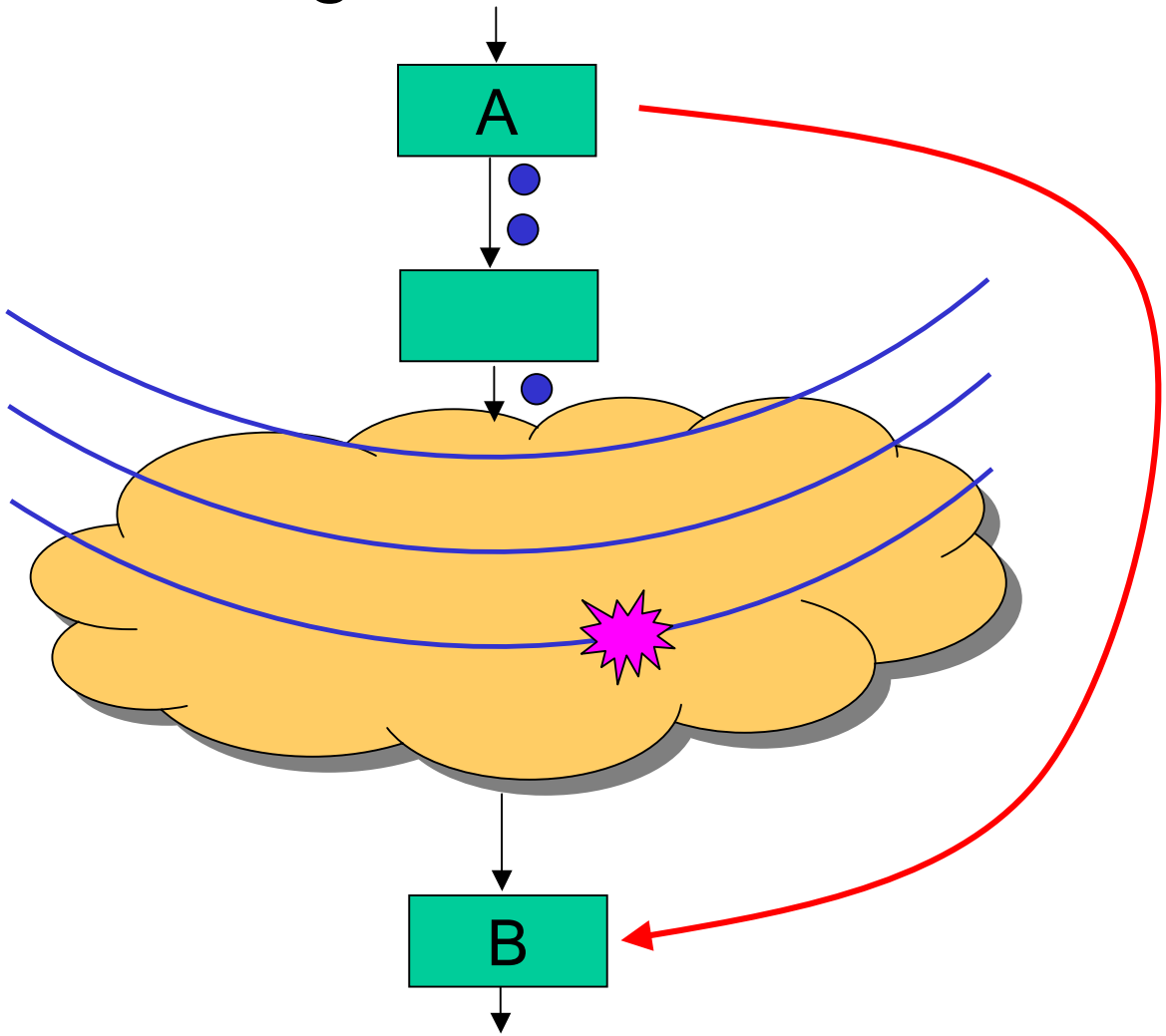

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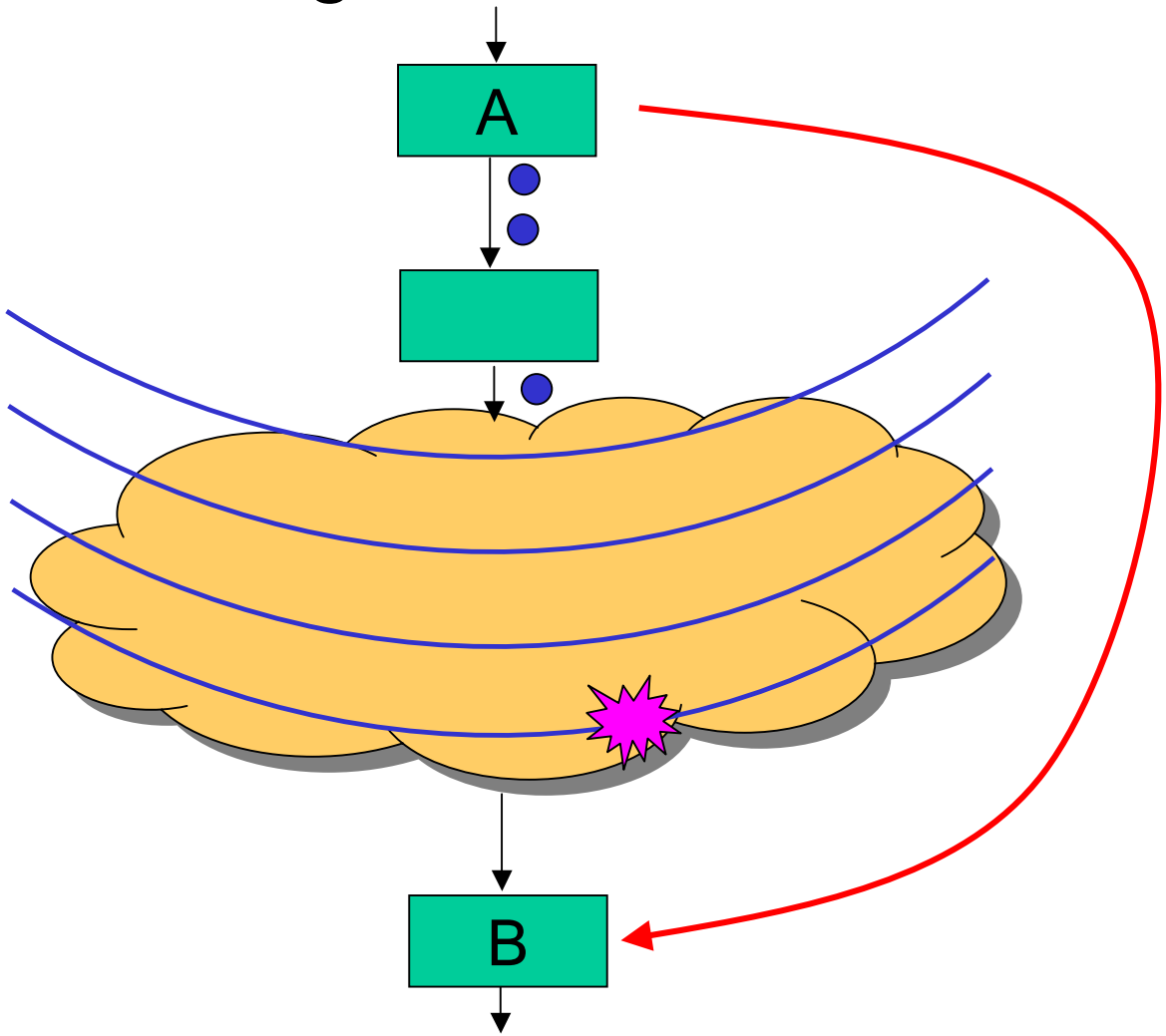

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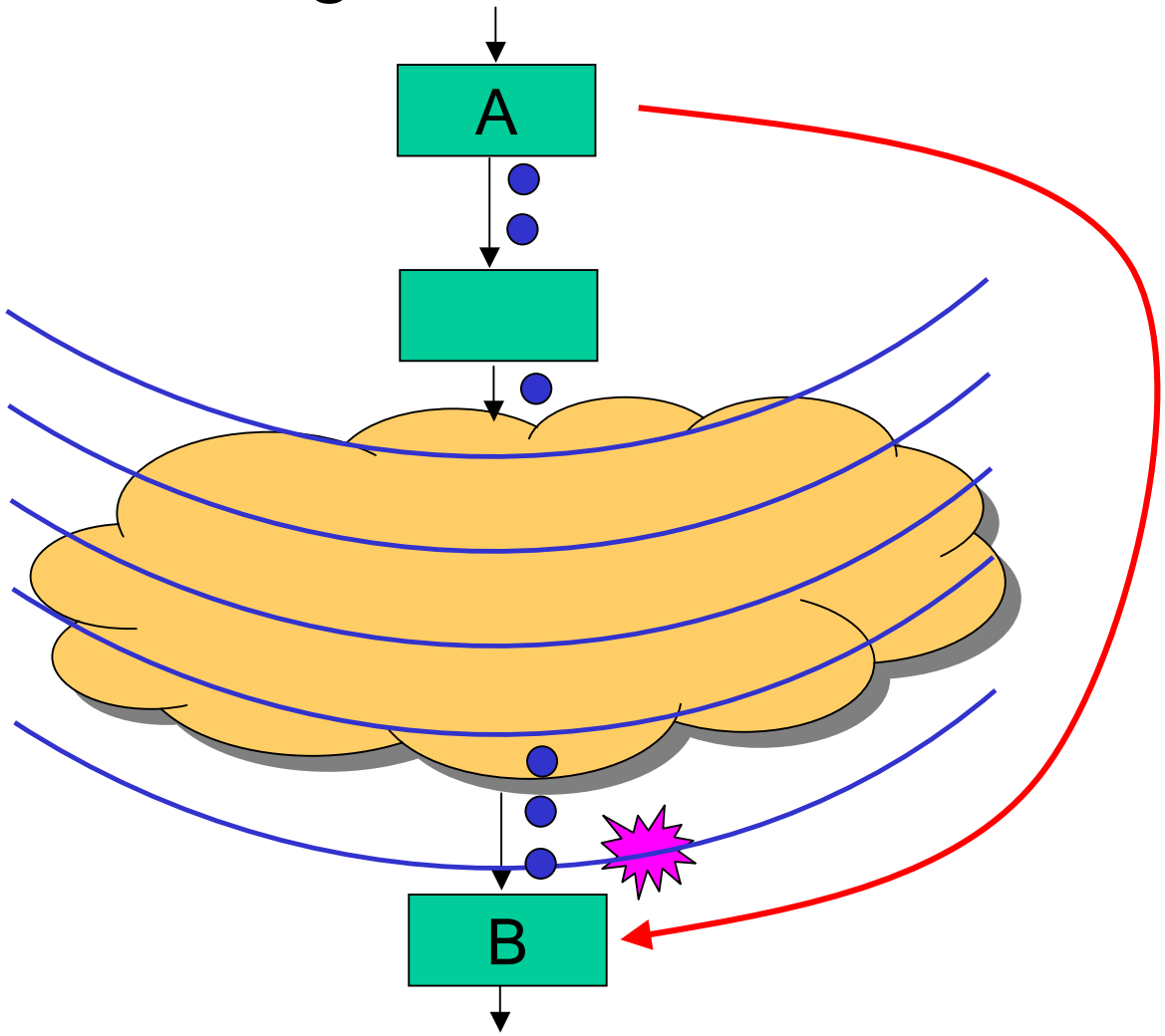

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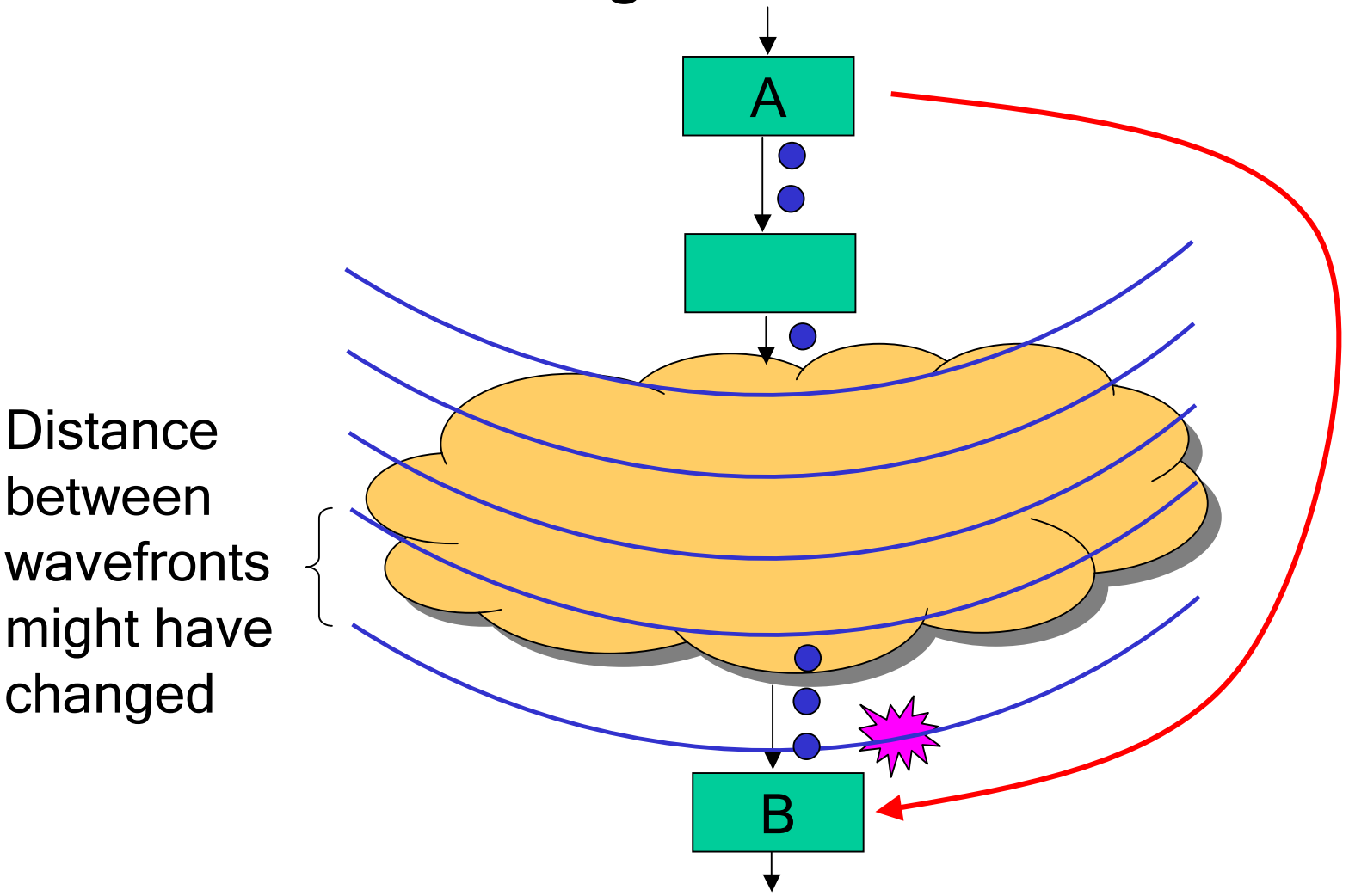

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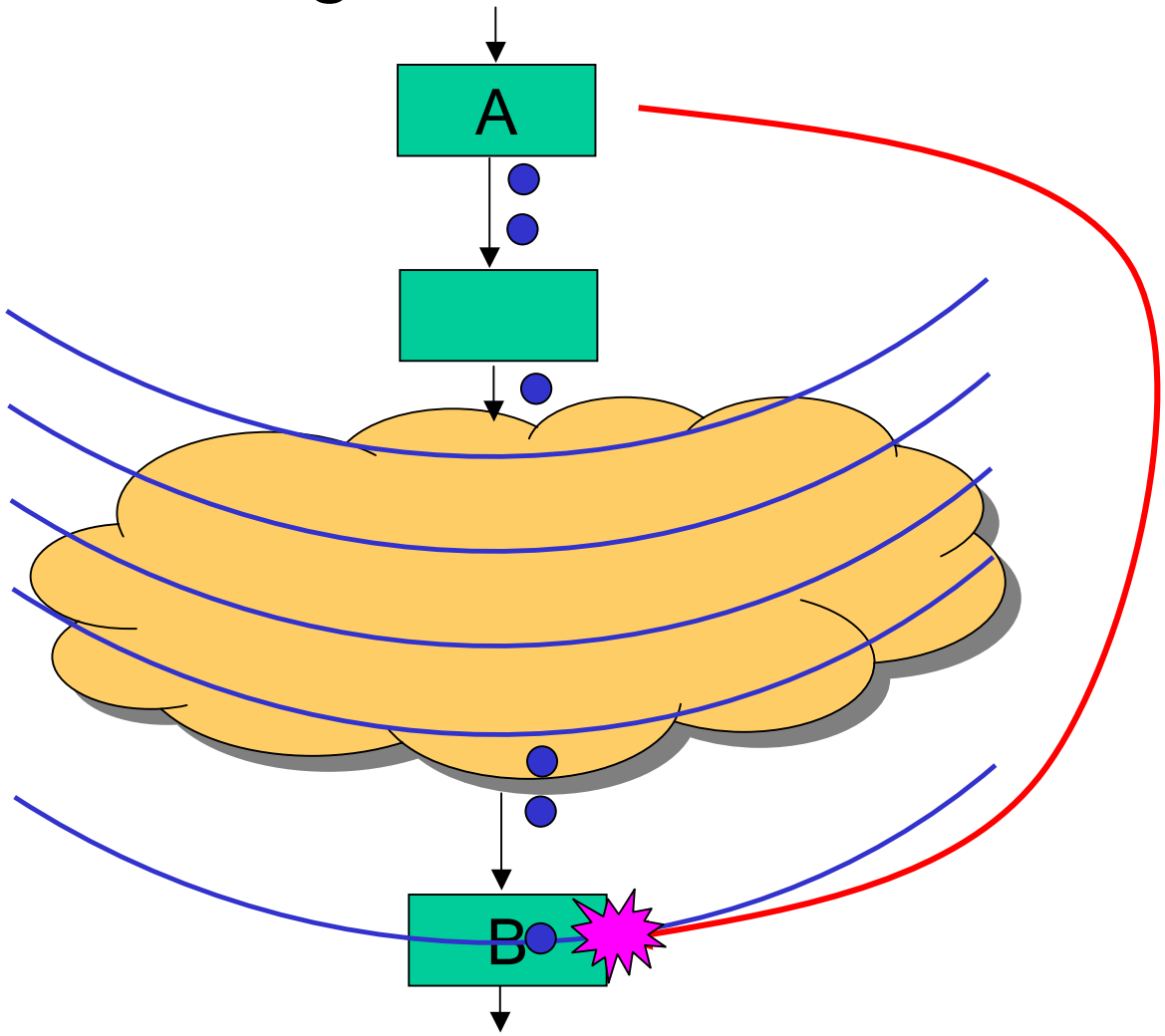
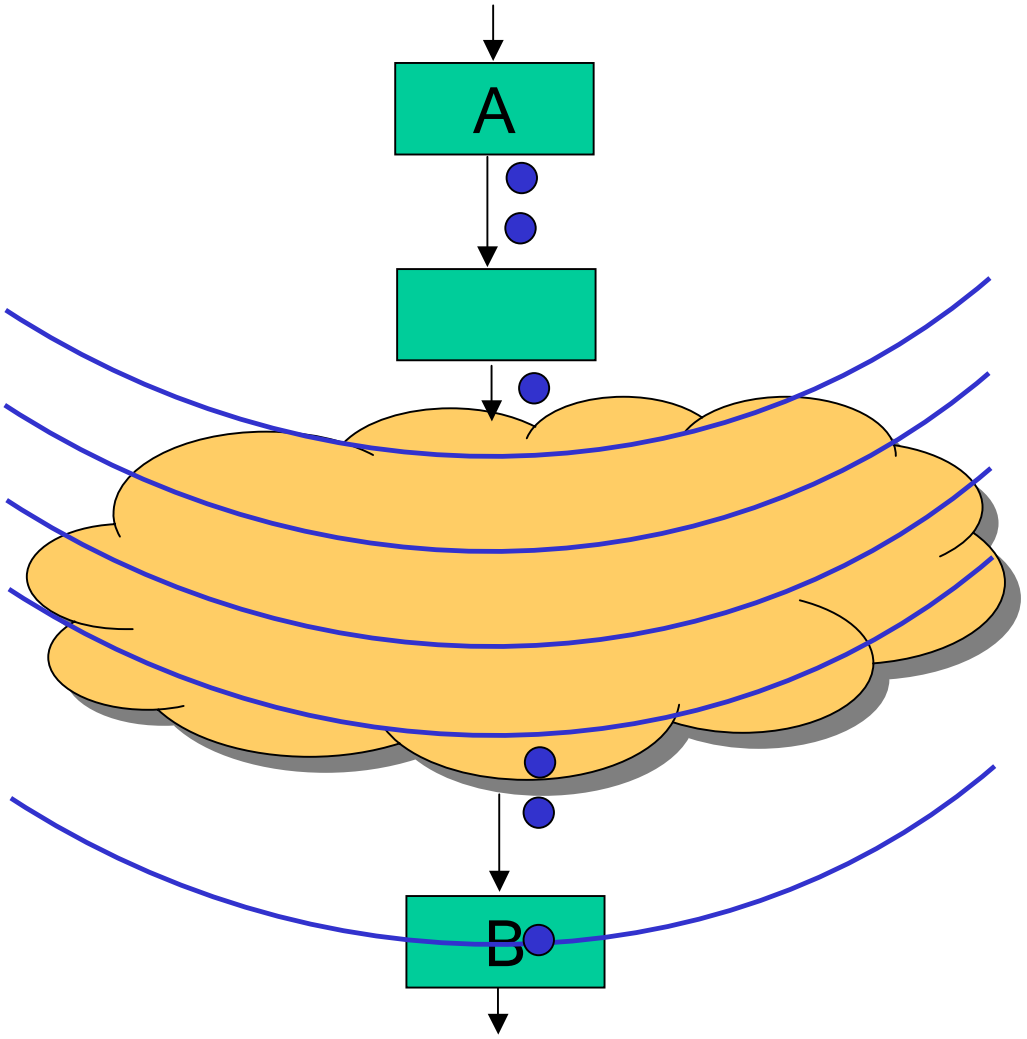


General Message Timing

- Latency of N means:
  - Message attached to wavefront that *sender* sees in N executions



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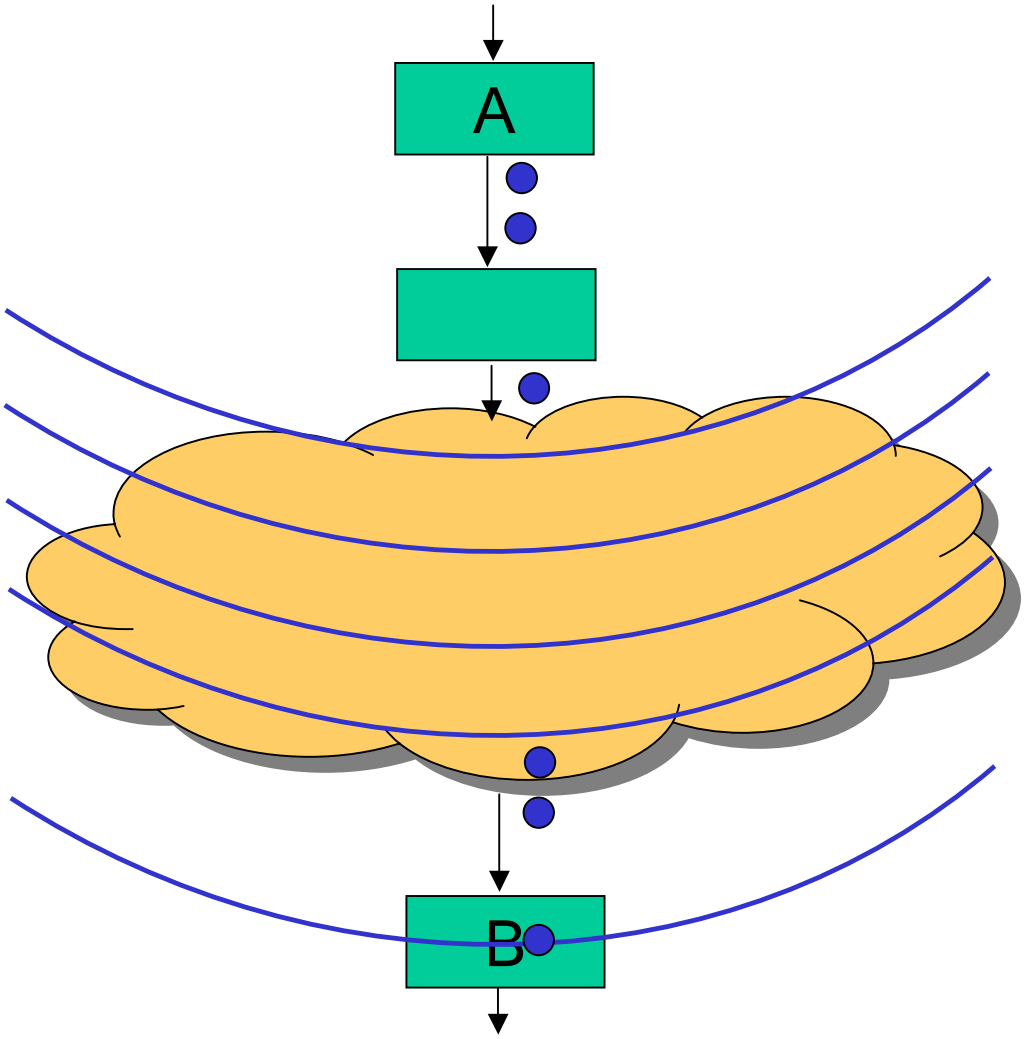

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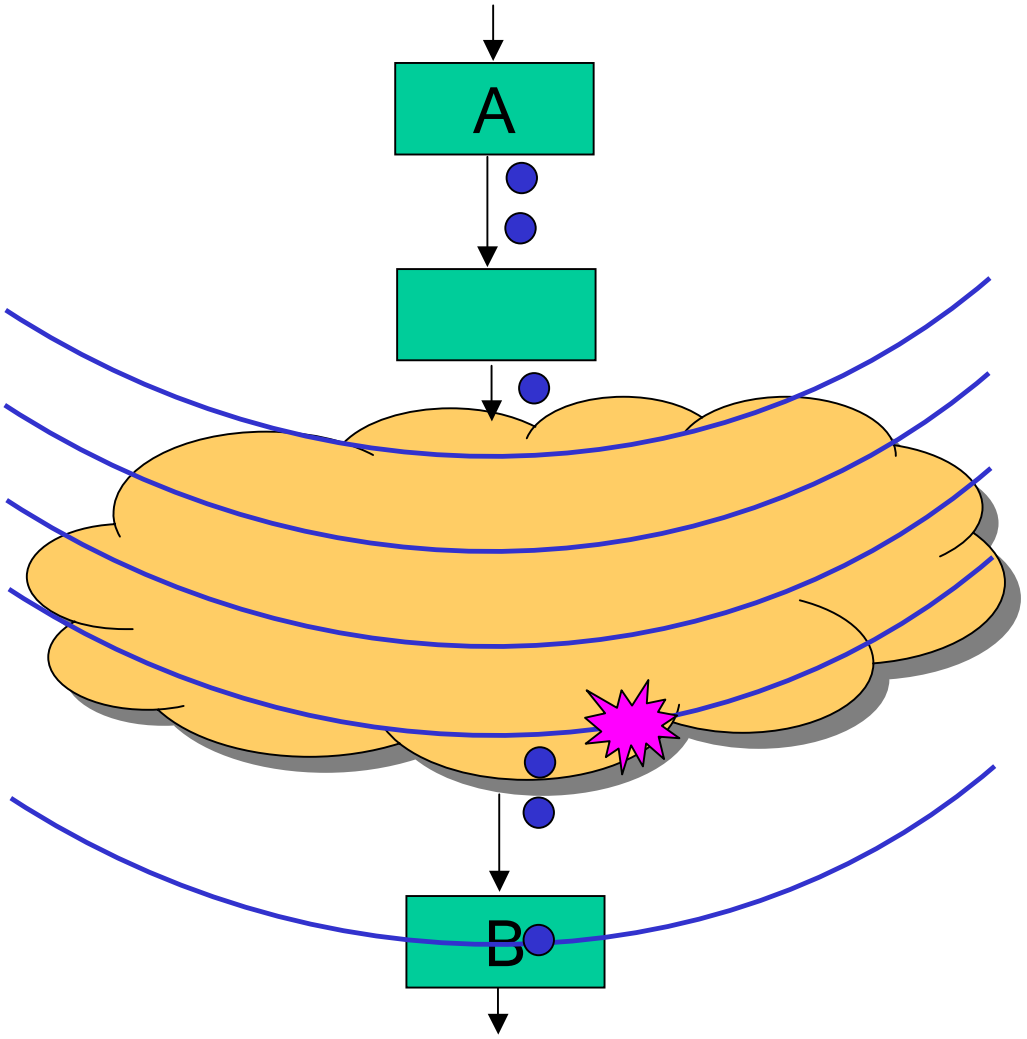

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- Latency of N means:
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- Examples:
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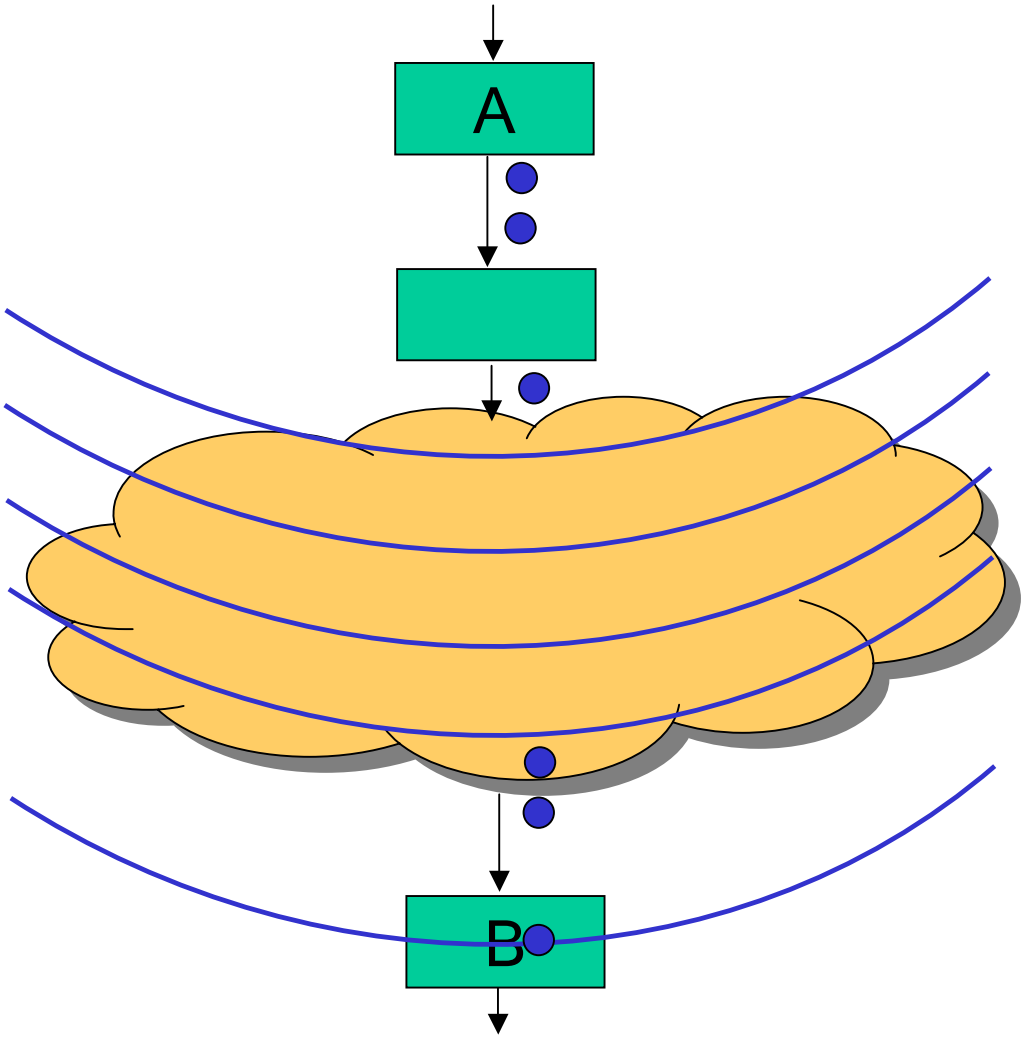
  - B → A, latency 25



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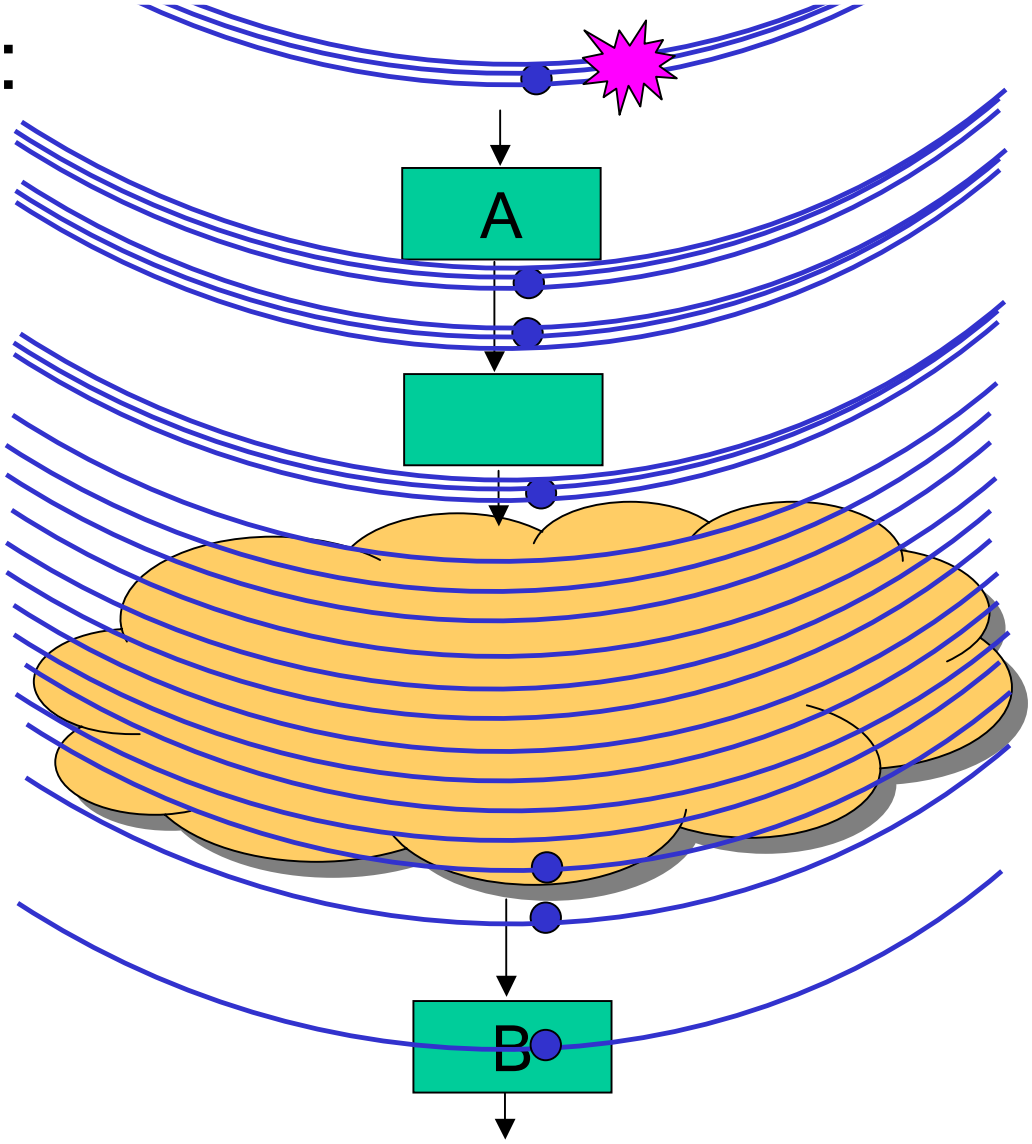


Rationale

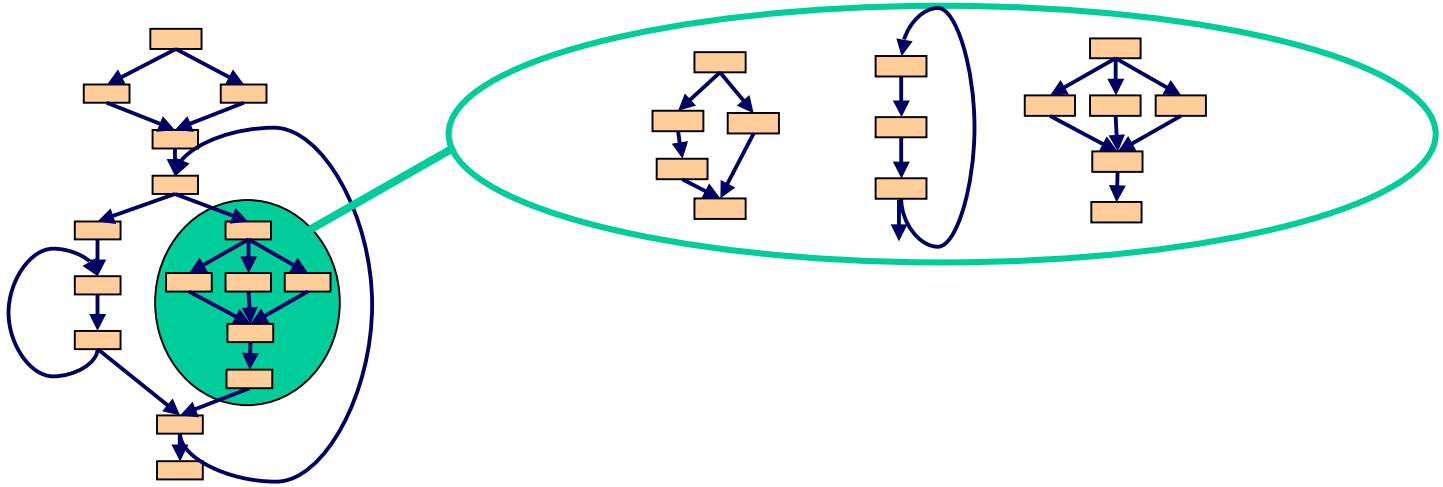
- Better for the programmer
  - Simplicity of method call
  - Precision of embedding in stream
- Better for the compiler
  - Program is easier to analyze
    - No code for timing / embedding
    - No control channels in stream graph
  - Can reorder filter firings, respecting constraints
  - Implement in most efficient way

Outline

- Design of Streamlt
  - Structured Streams
  - Messaging
  - Morphing
- Results
- Conclusions

Dynamic Changes to Stream

- Stream structure needs to change

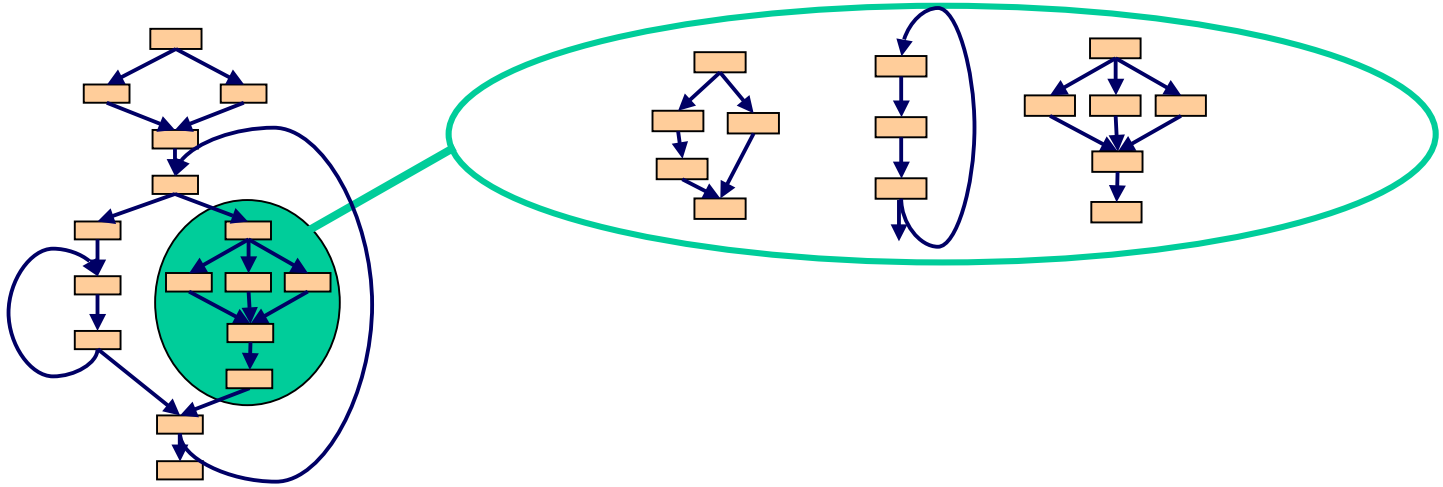


- Examples
  - Switch radio from AM to FM
  - Change from Bluetooth to 802.11

Program "Morphing"

Dynamic Changes to Stream

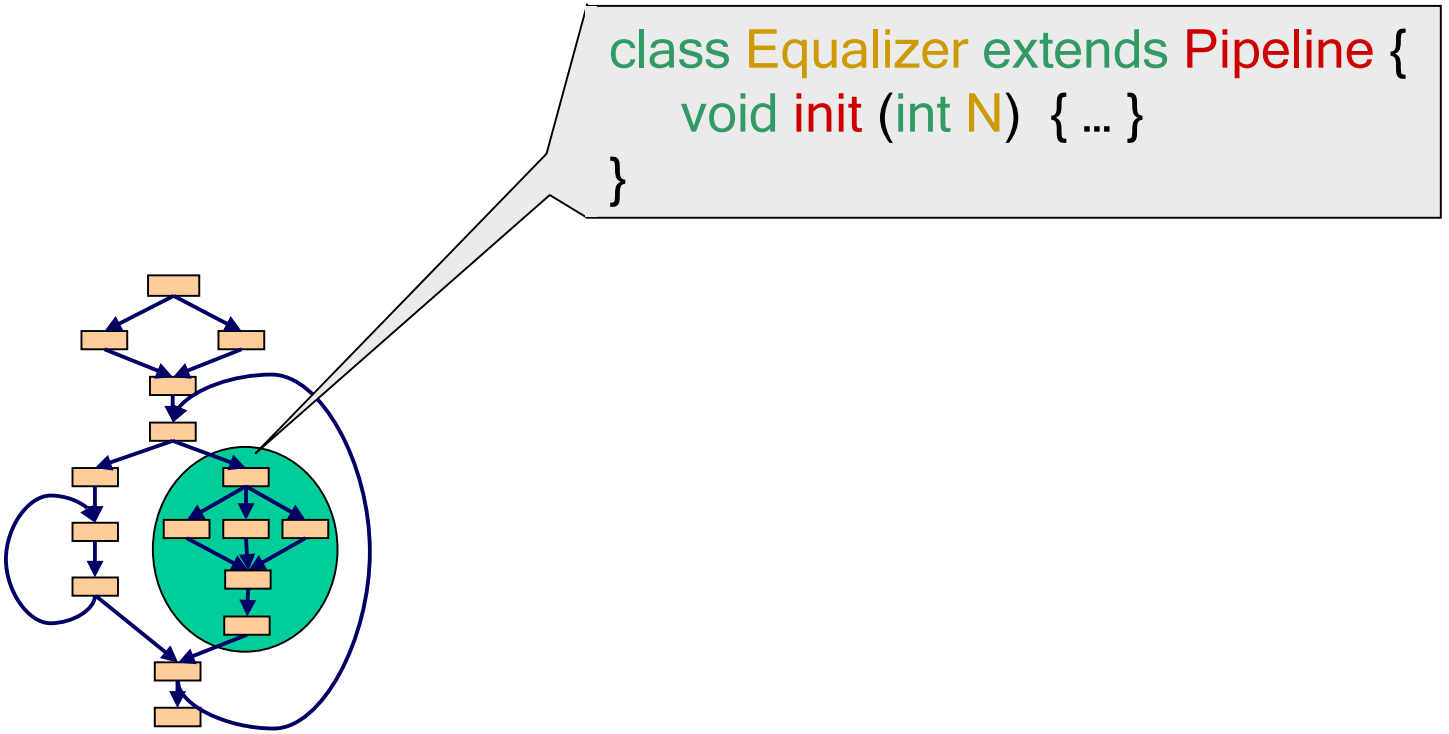
- Stream structure needs to change



- Challenges for programmer:
  - Synchronizing the beginning, end of morphing
  - Preserving live data in the system
  - Efficiency

Morphing in StreamIt

- Send message to “init” to morph a structure



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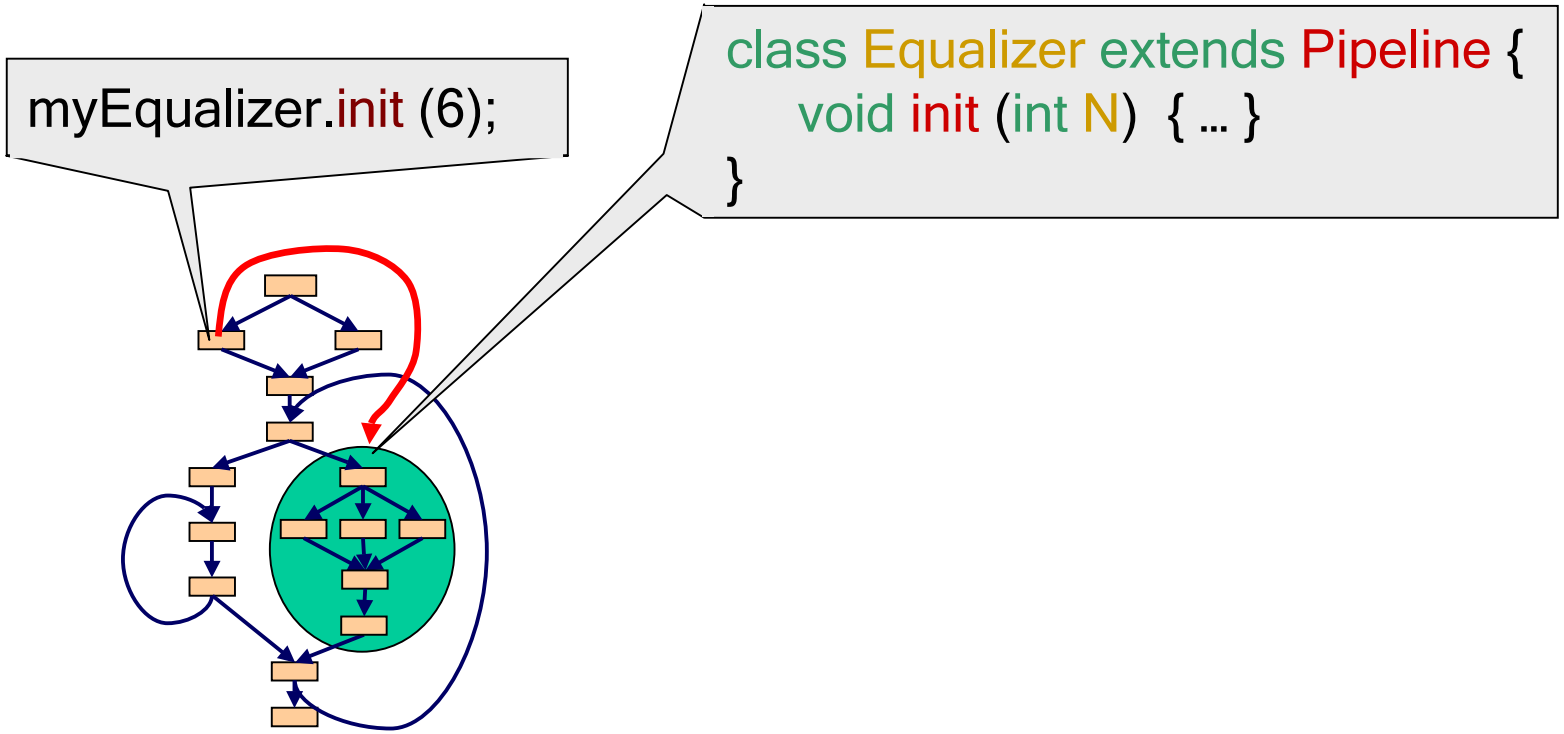

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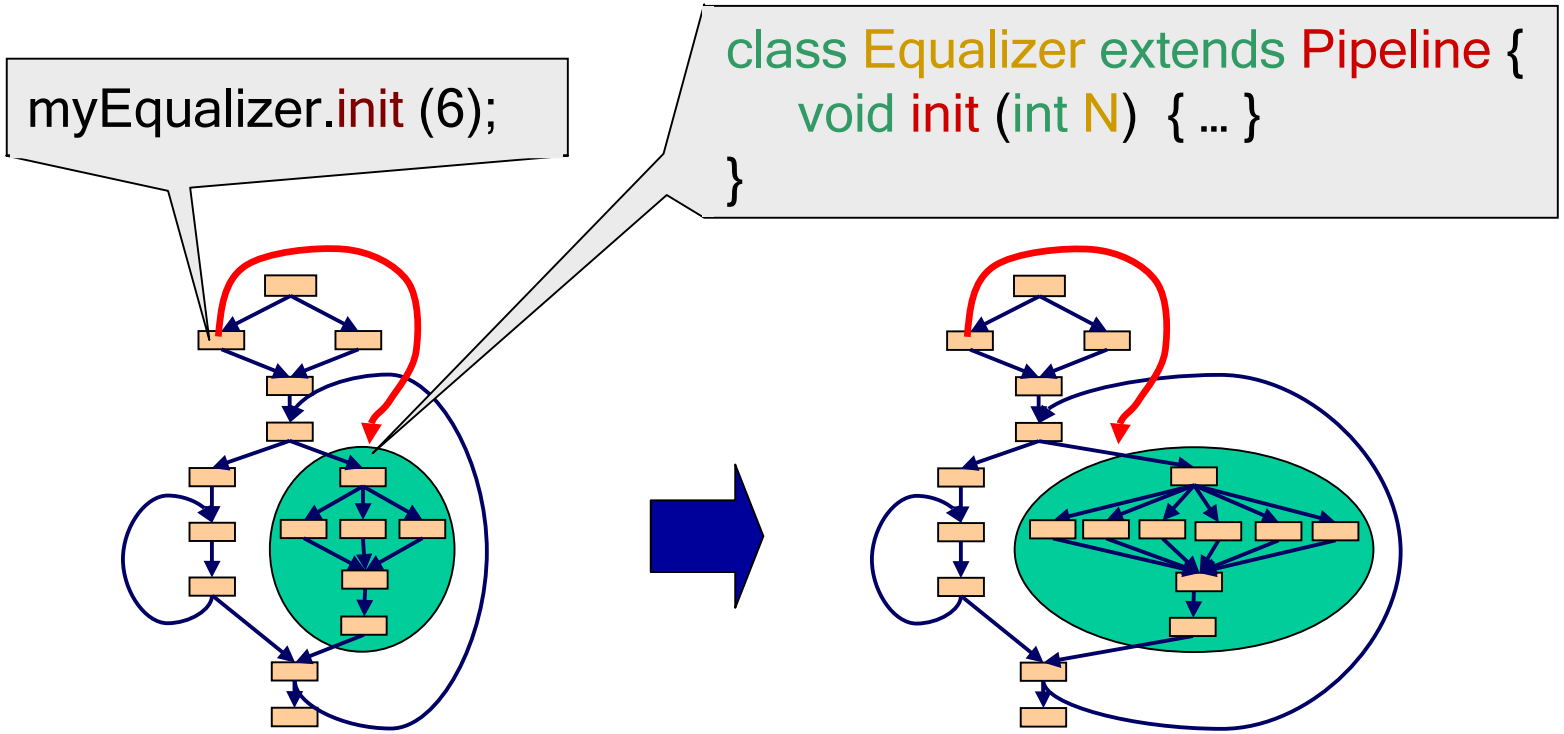

  - When message arrives, structure is replaced
  - Live data is automatically drained

Rationale

- Programmer writes “init” only once
  - No need for complicated transitions
- Compiler optimizes each phase separately
  - Benefits from anticipation of phase changes

Outline

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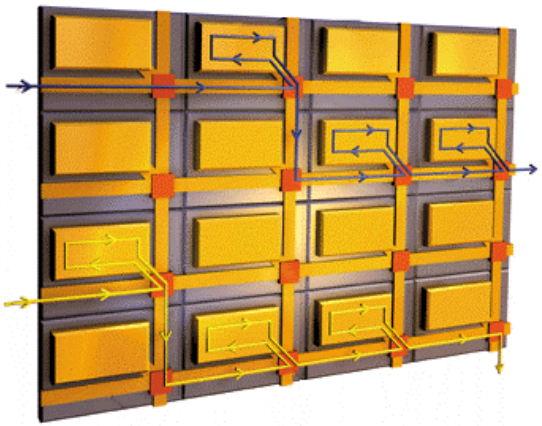
Implementation

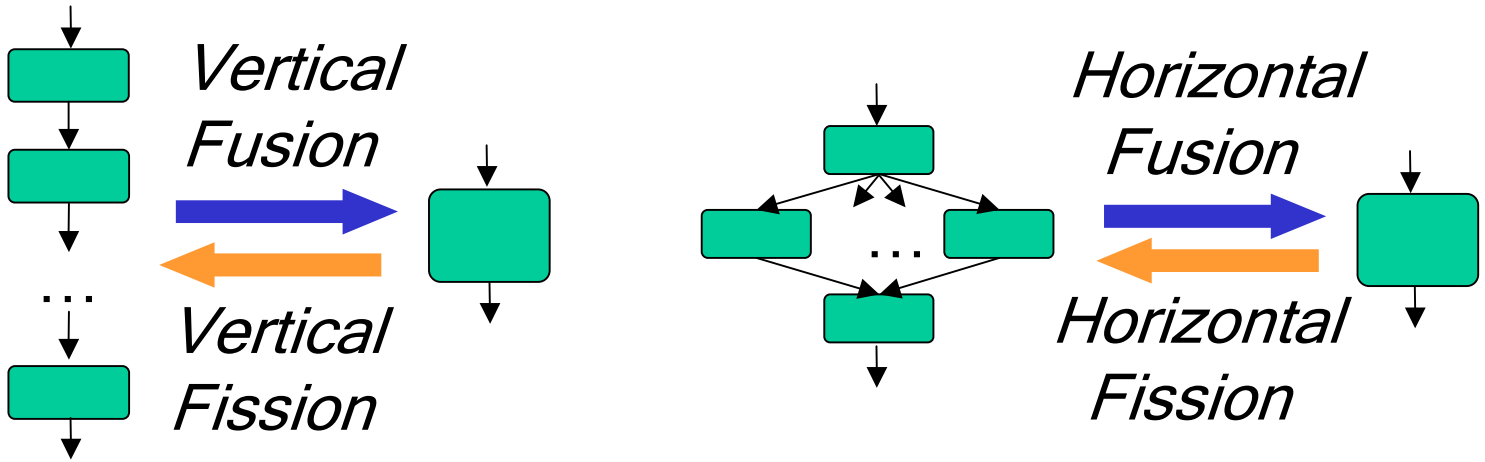
- Prototype StreamIt compiler complete
- Backends:
  - Uniprocessor
  - RAW: A tiled architecture with fine-grained, programmable communication



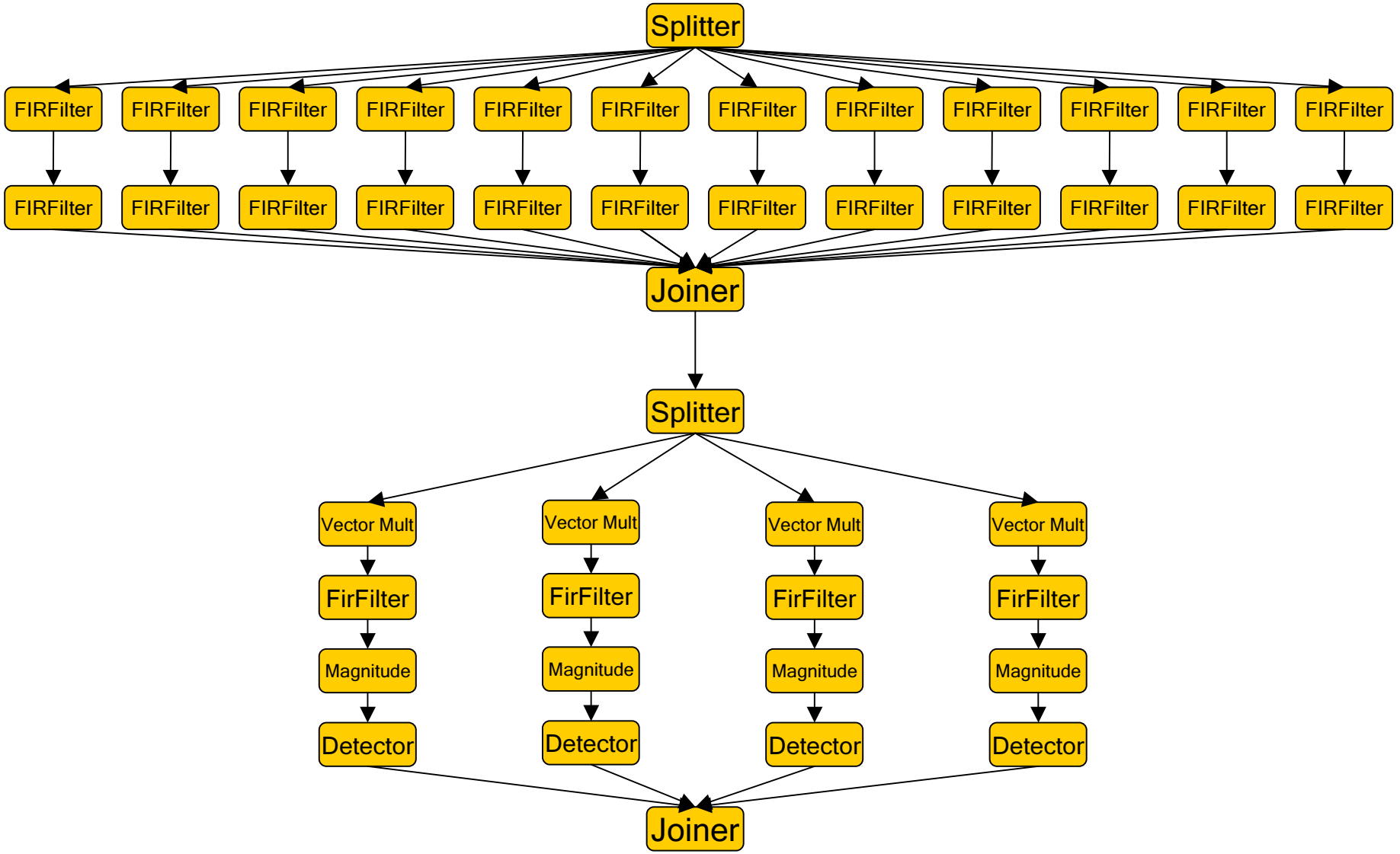
- Extended KOPI, open-source Java compiler

Results

- Developed applications in StreamIt
  - GSM Decoder
  - FM Radio
  - BeamFormer
  - FFT
  - Matrix multiply
  - CRC Encoder/Decoder
- Load-balancing transformations improve performance on RAW



Example: BeamFormer (Original)



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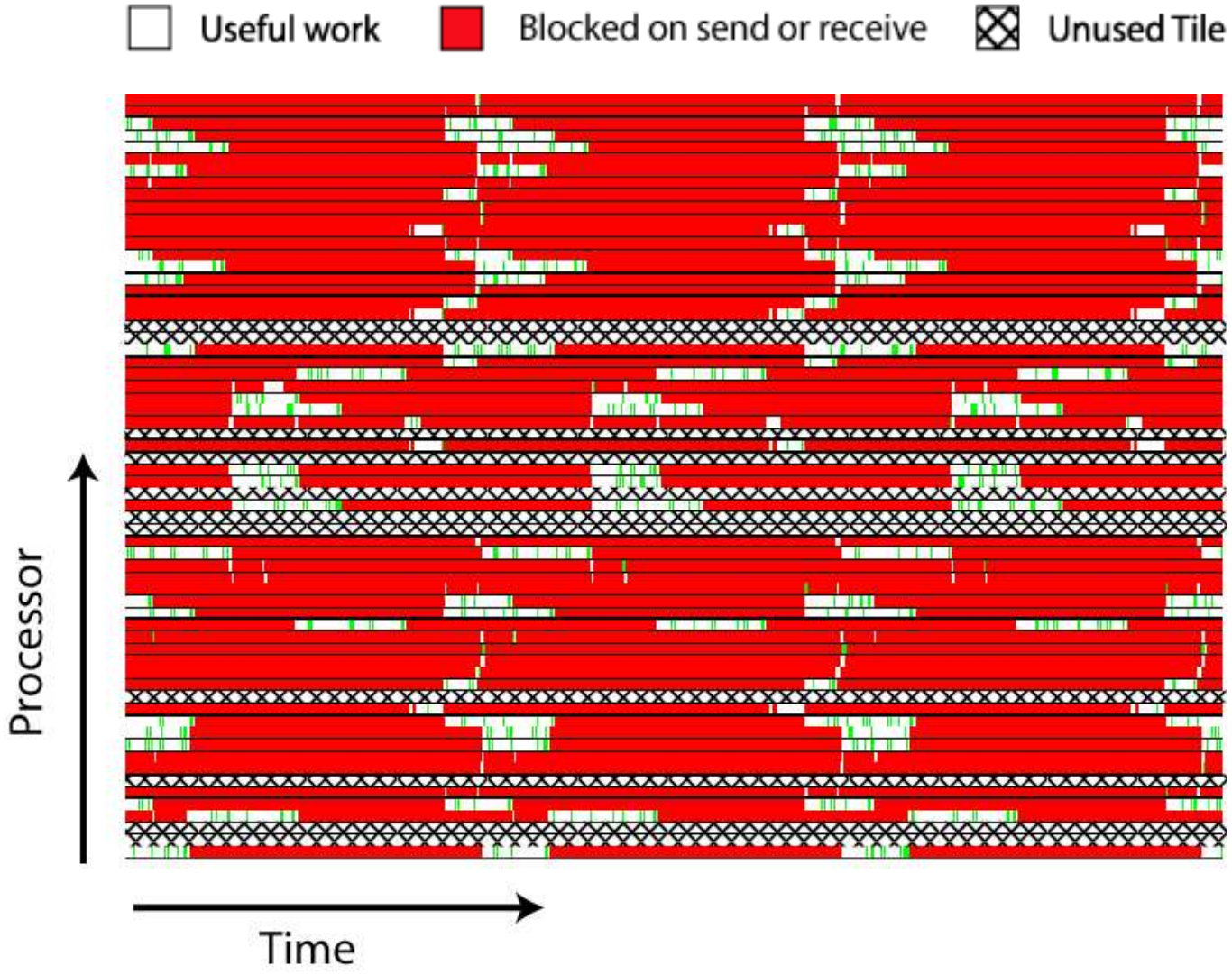

570 MFLOPS

110,000 $\frac{\text{cycles}}{\text{item}}$

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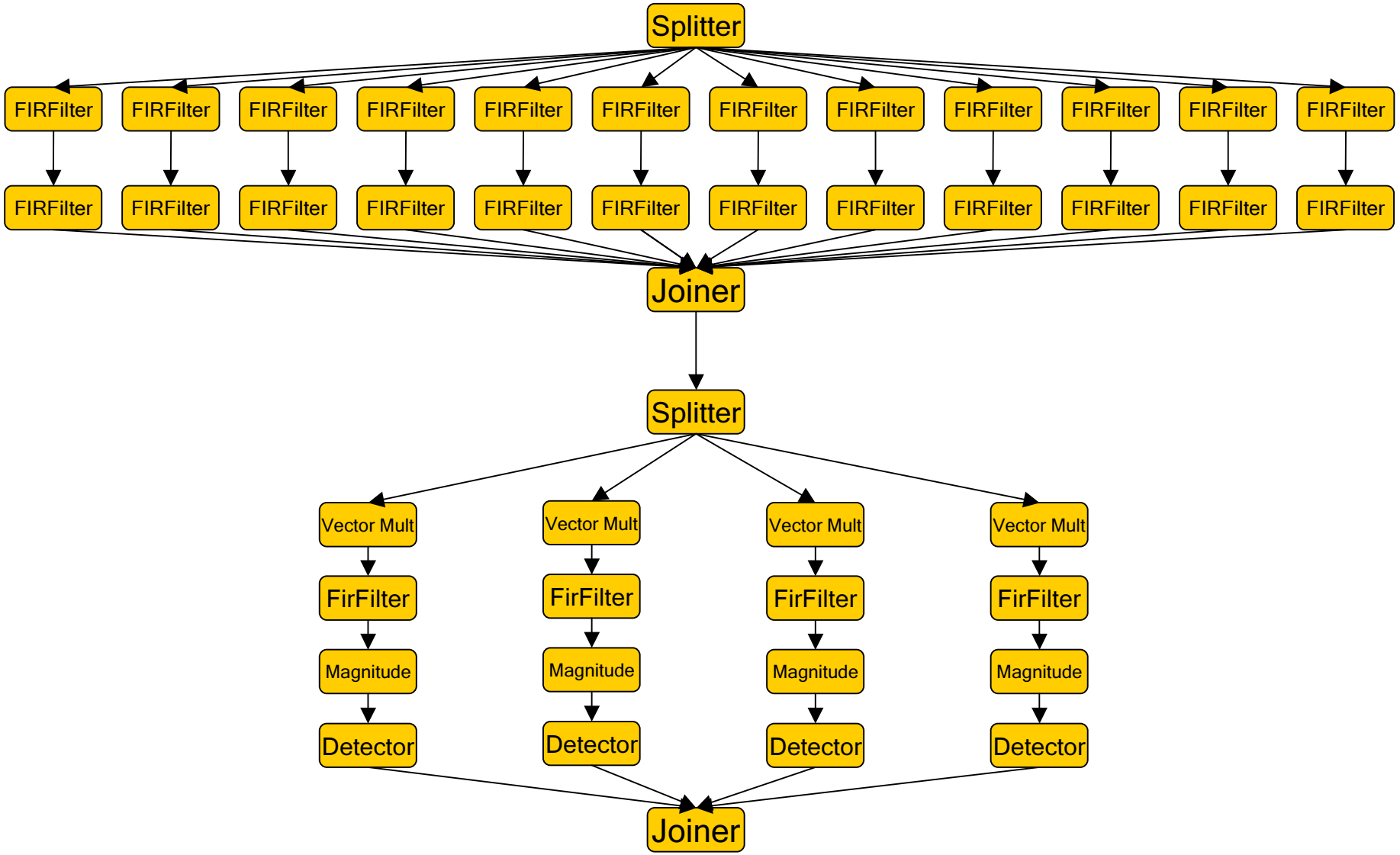

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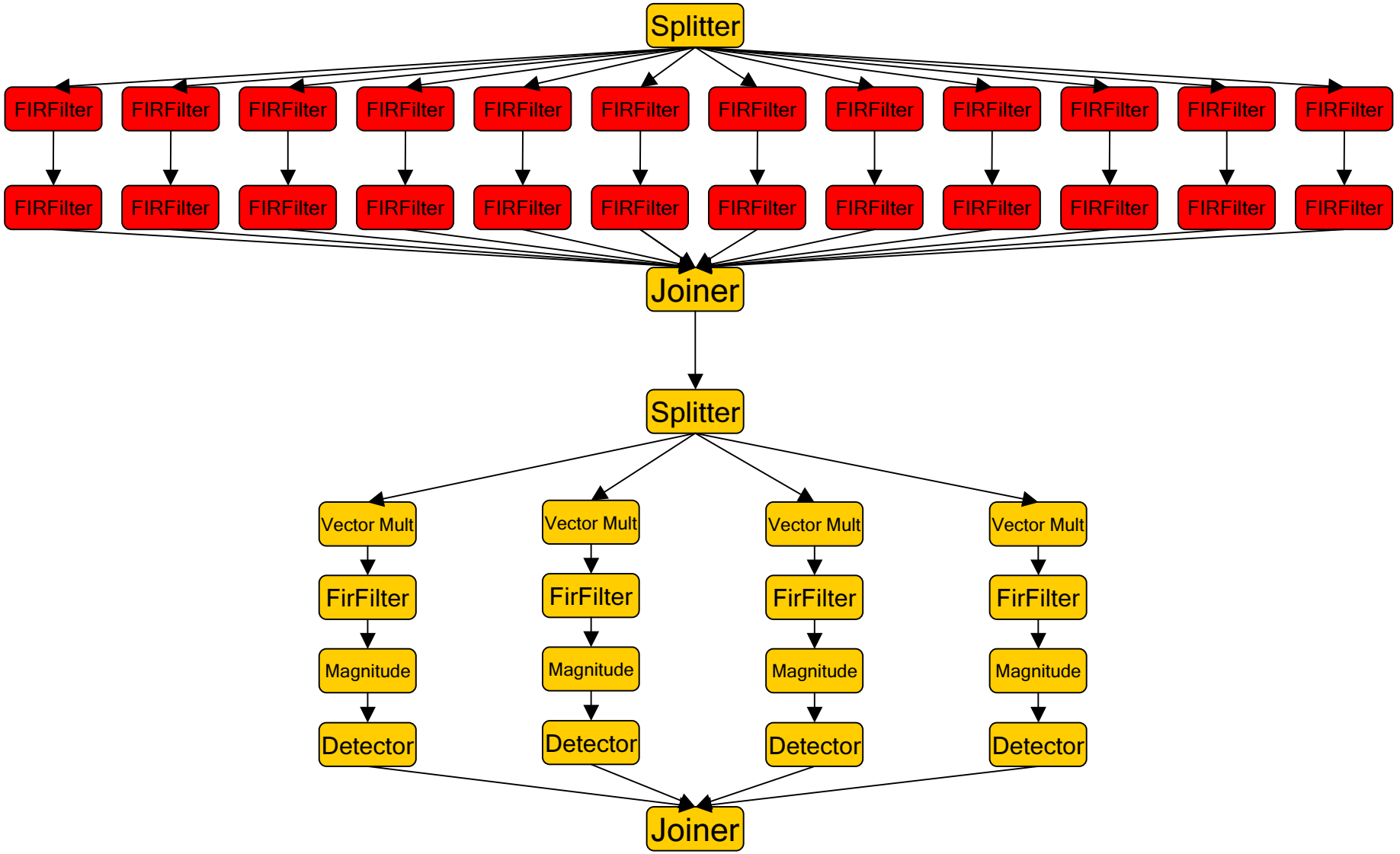

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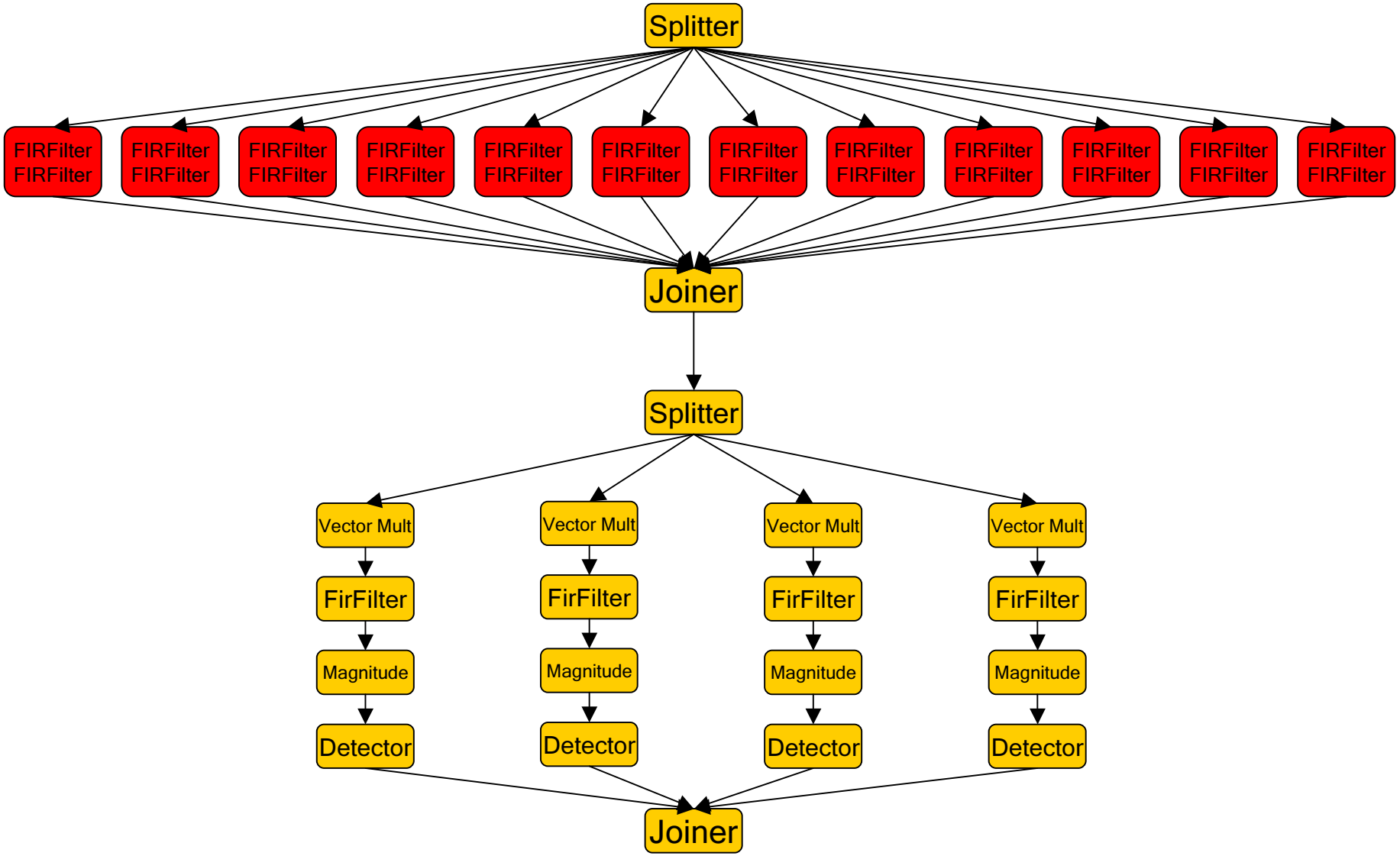

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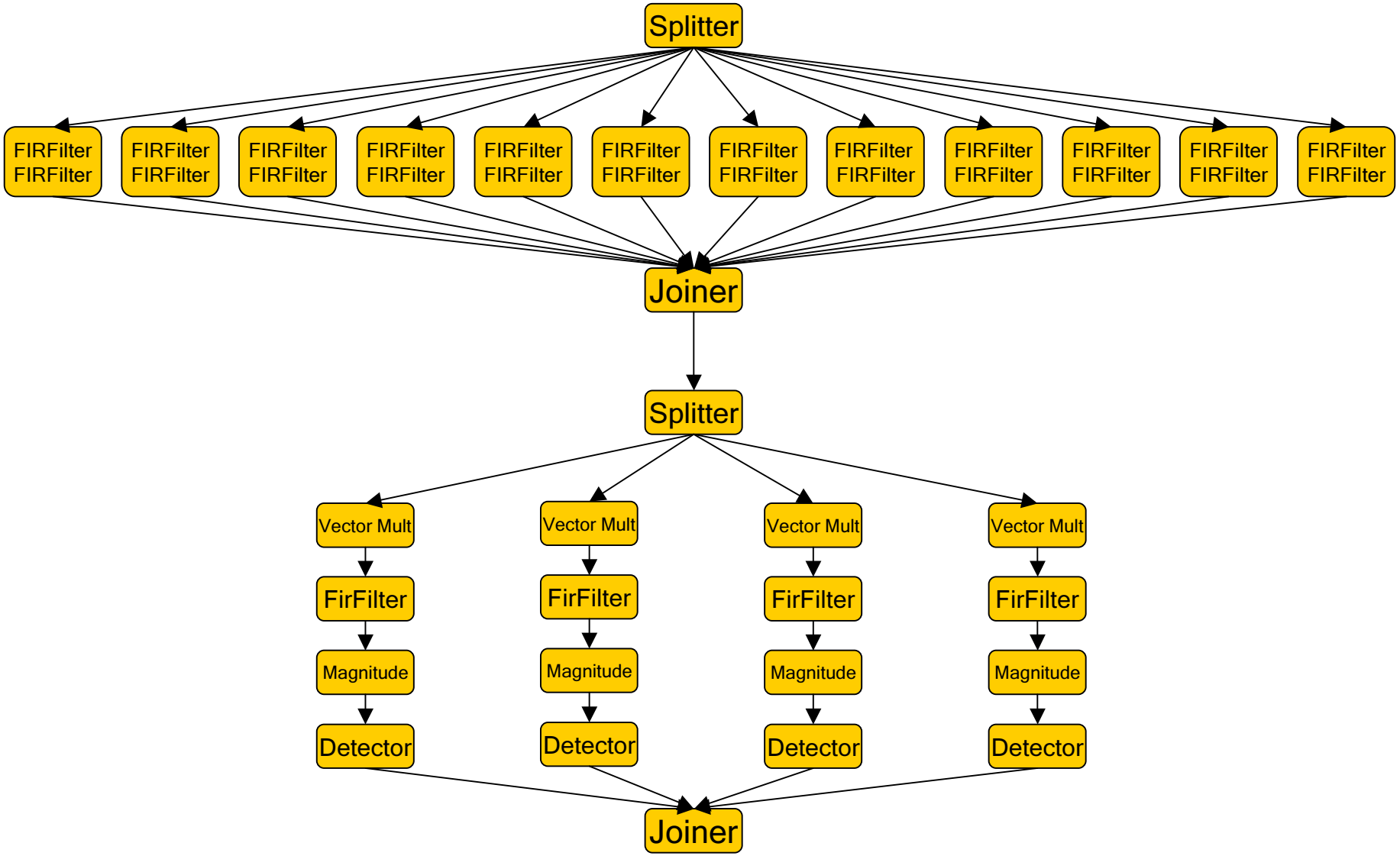

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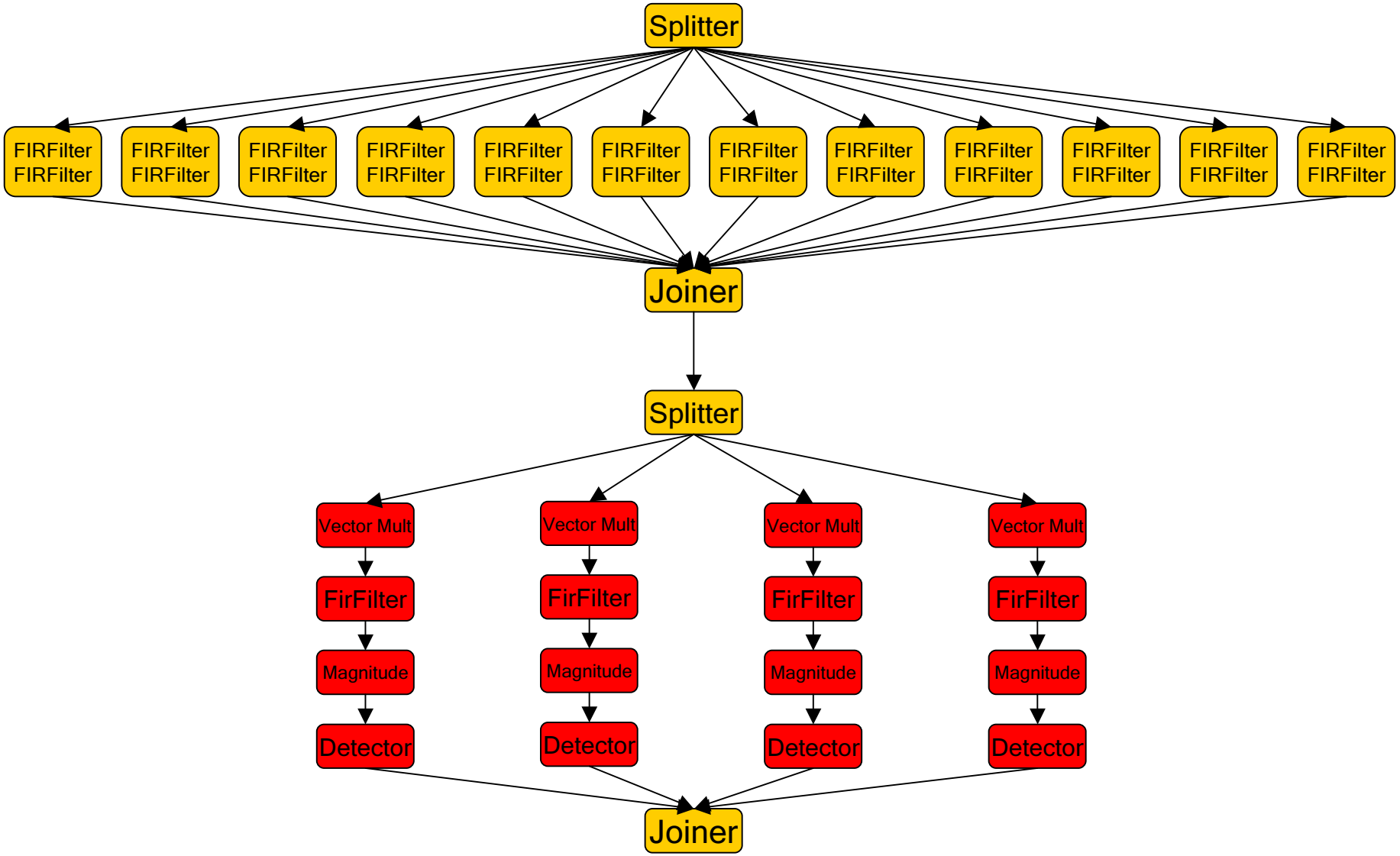

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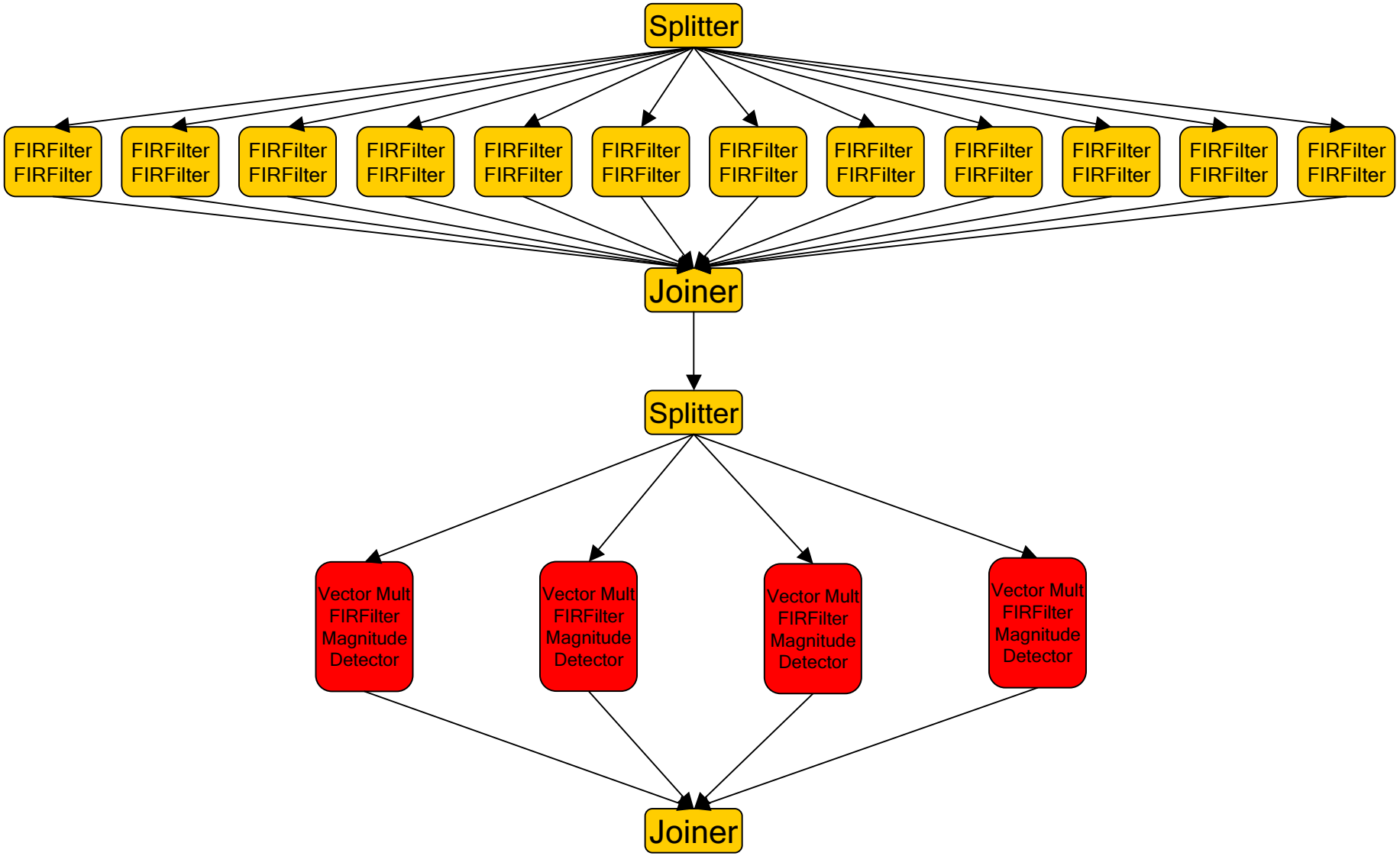

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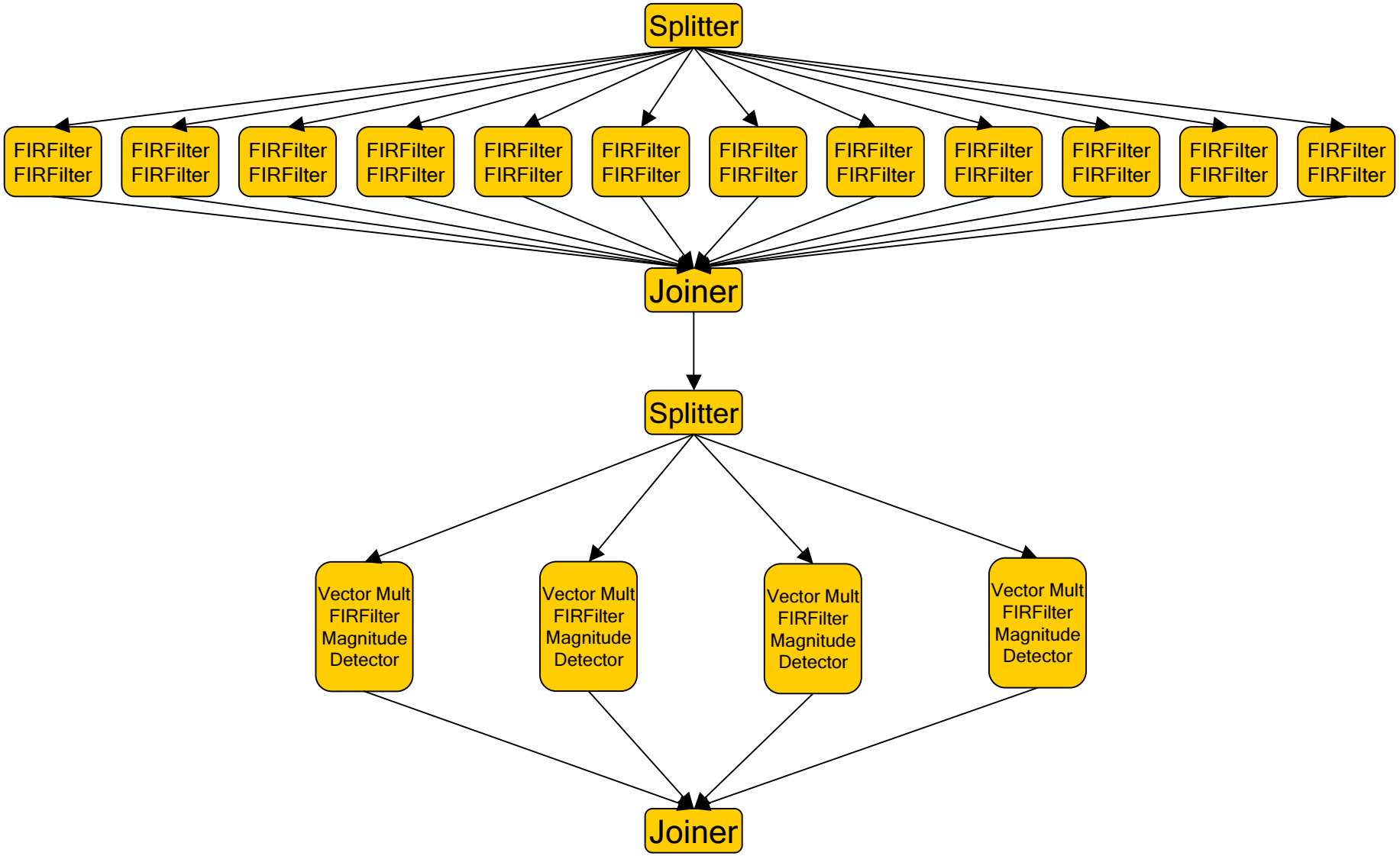

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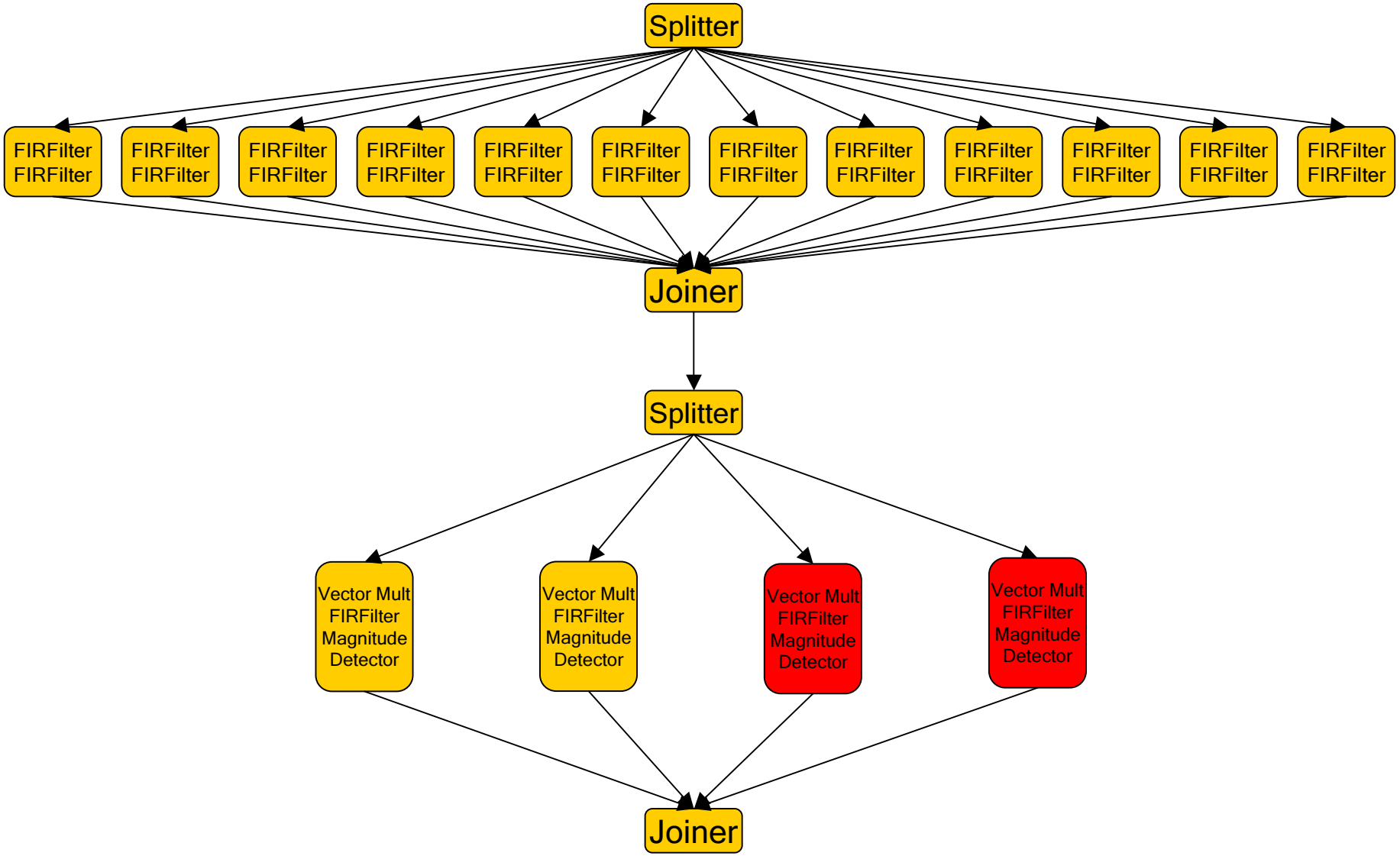

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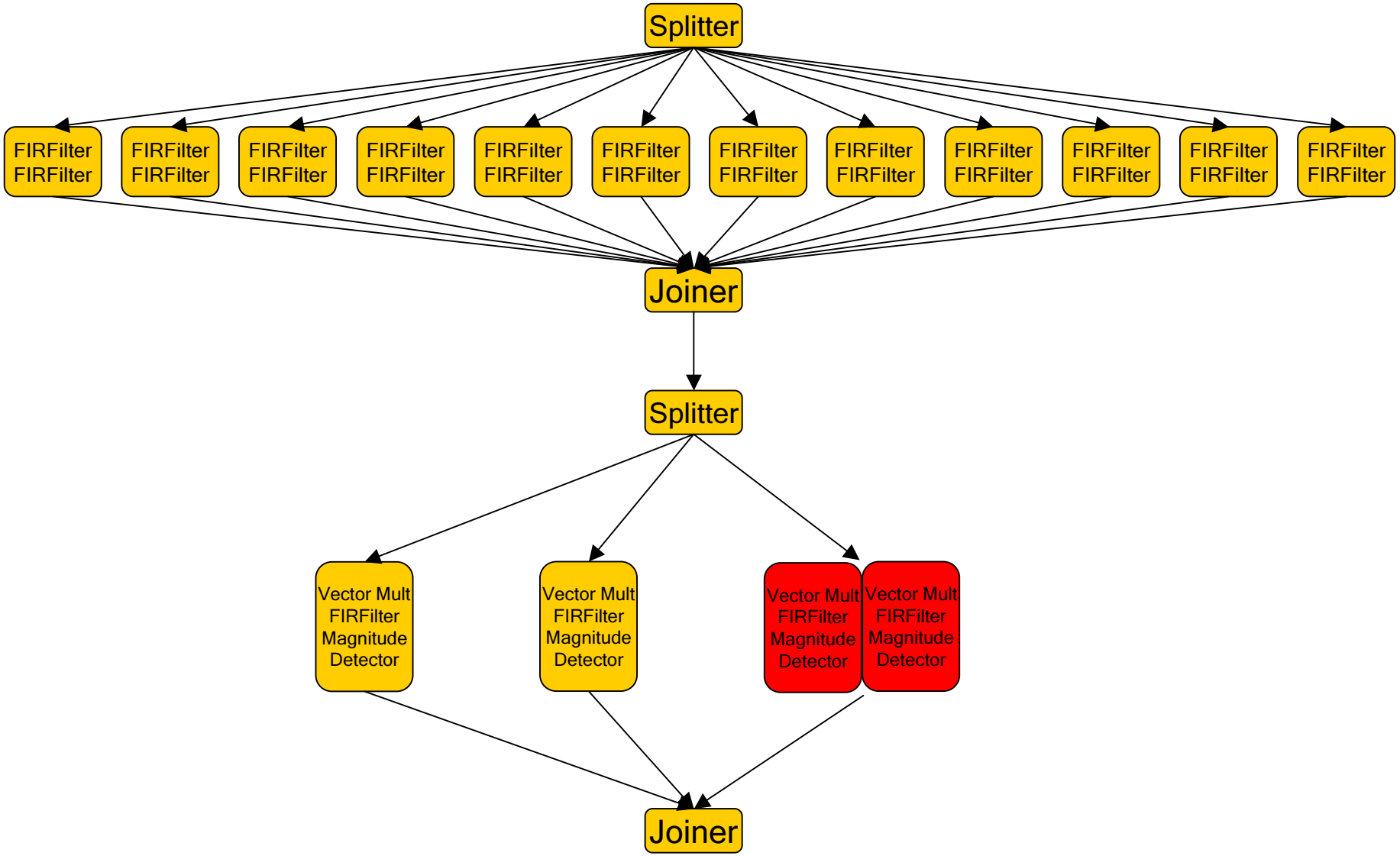

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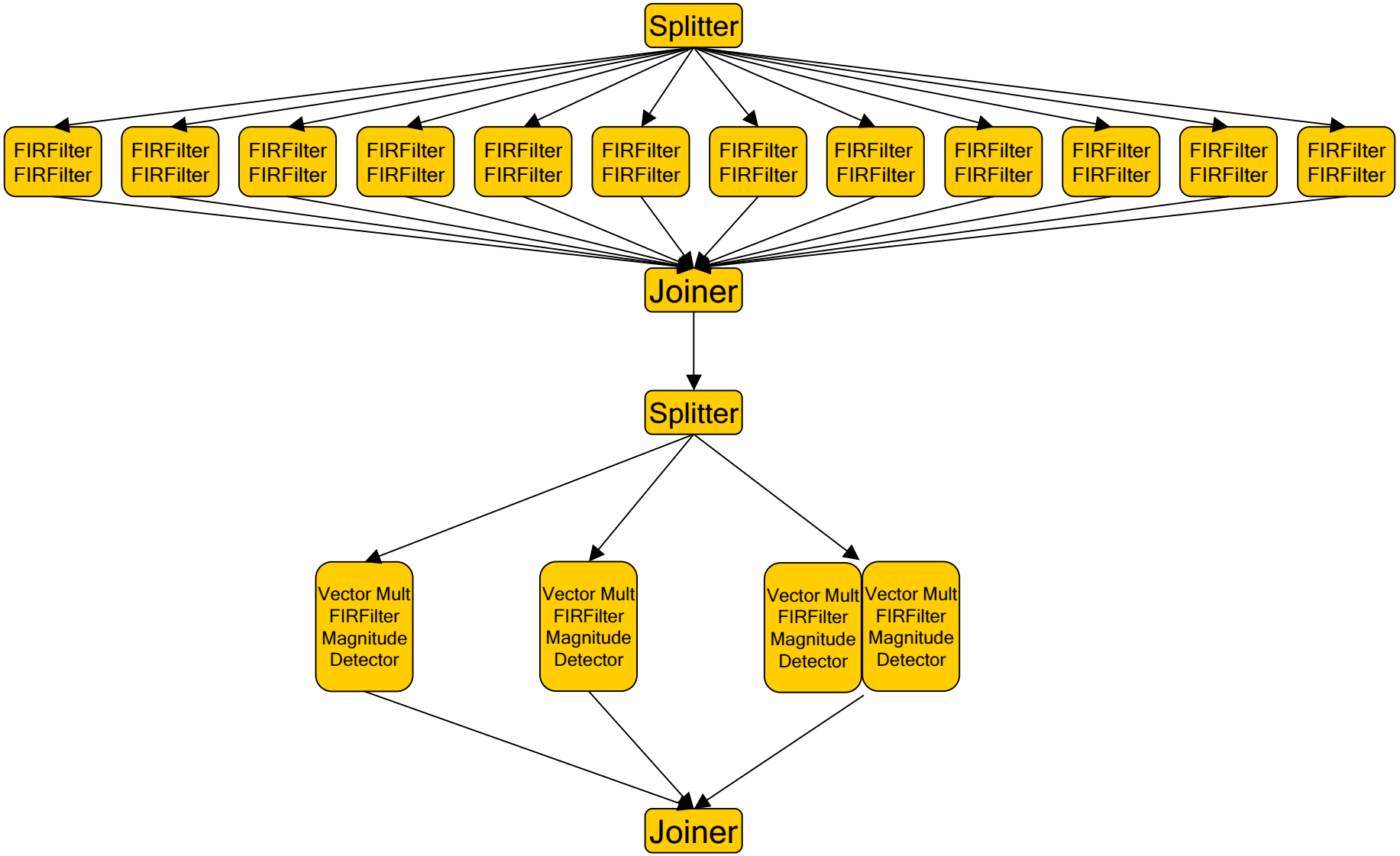

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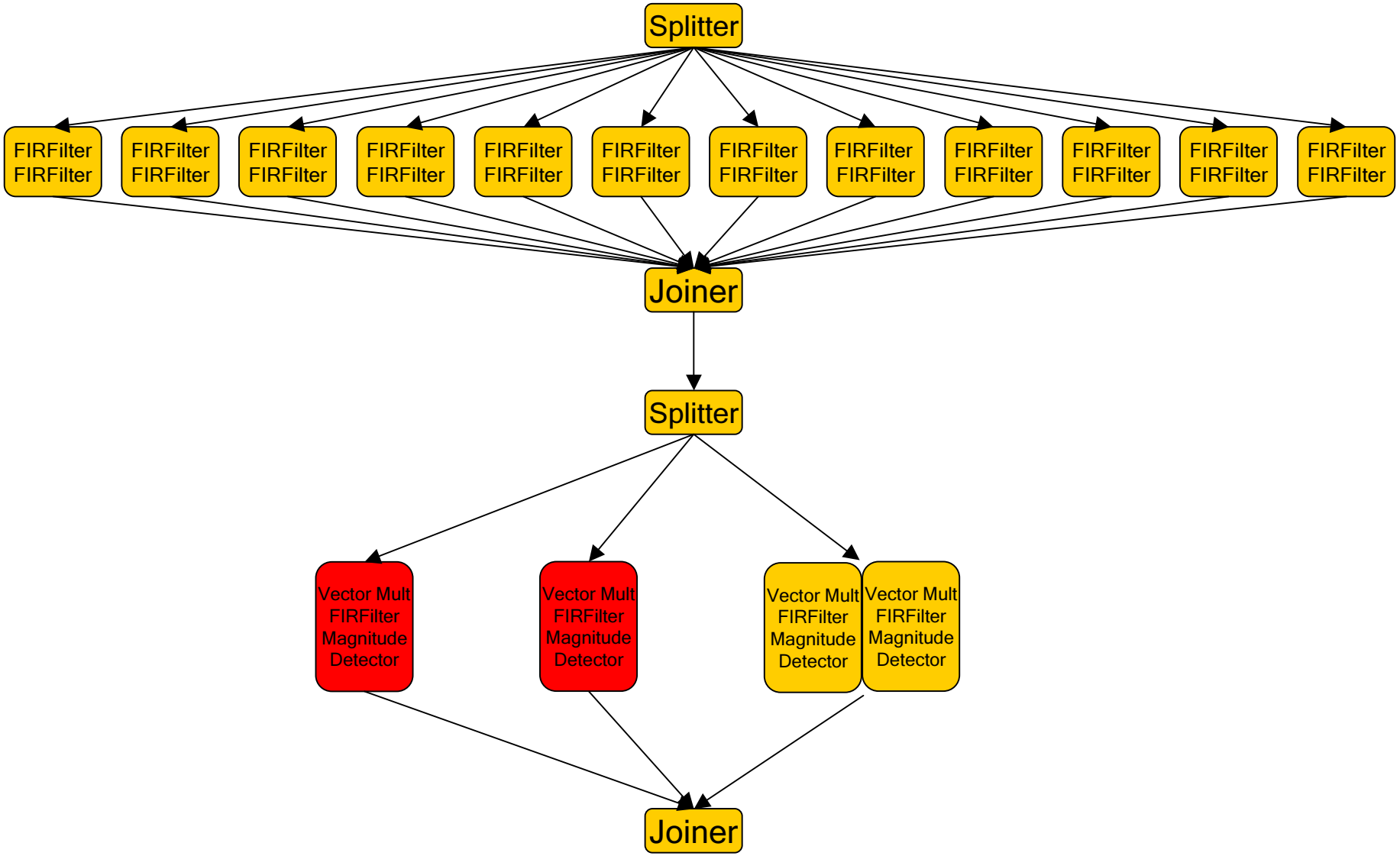

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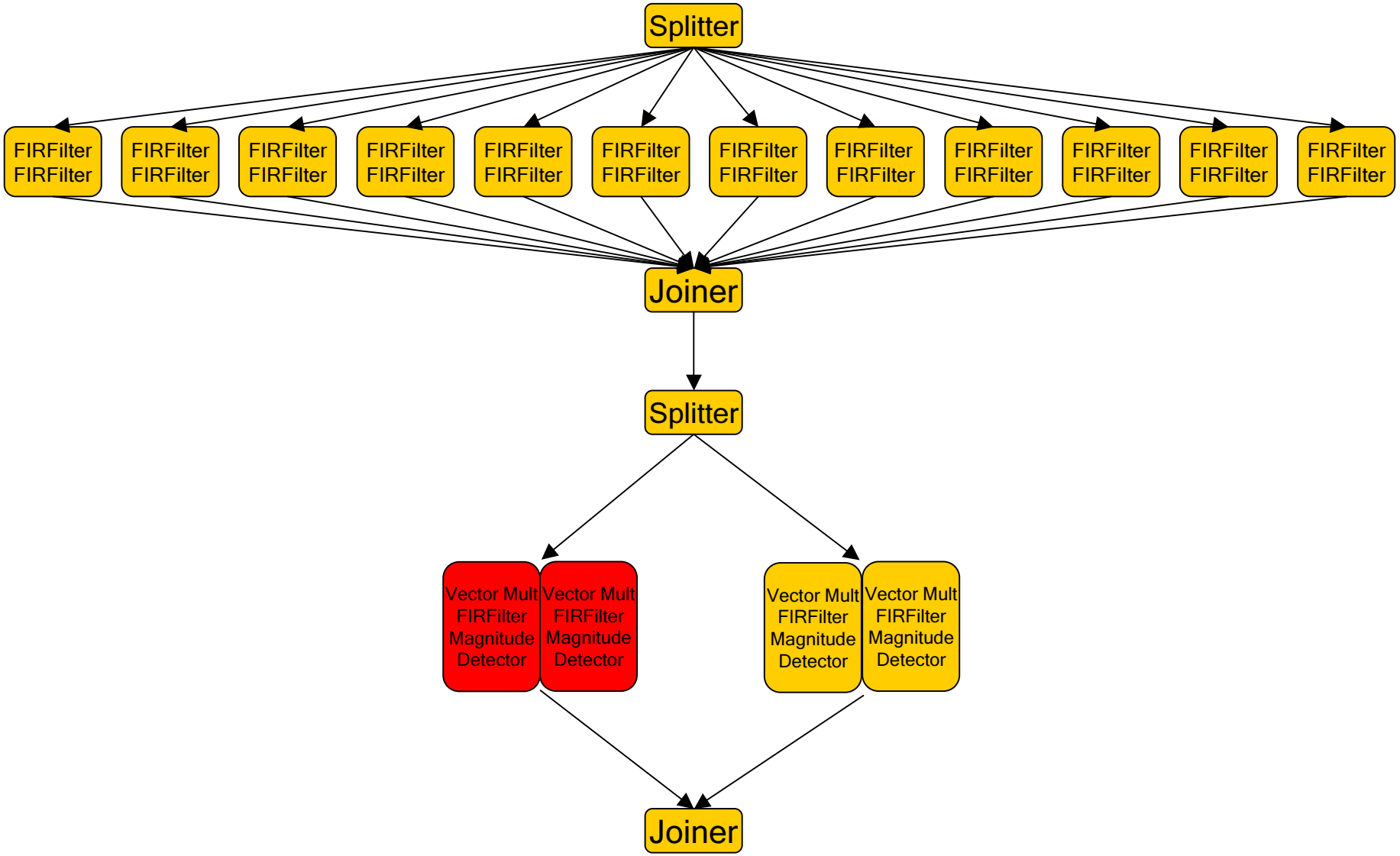
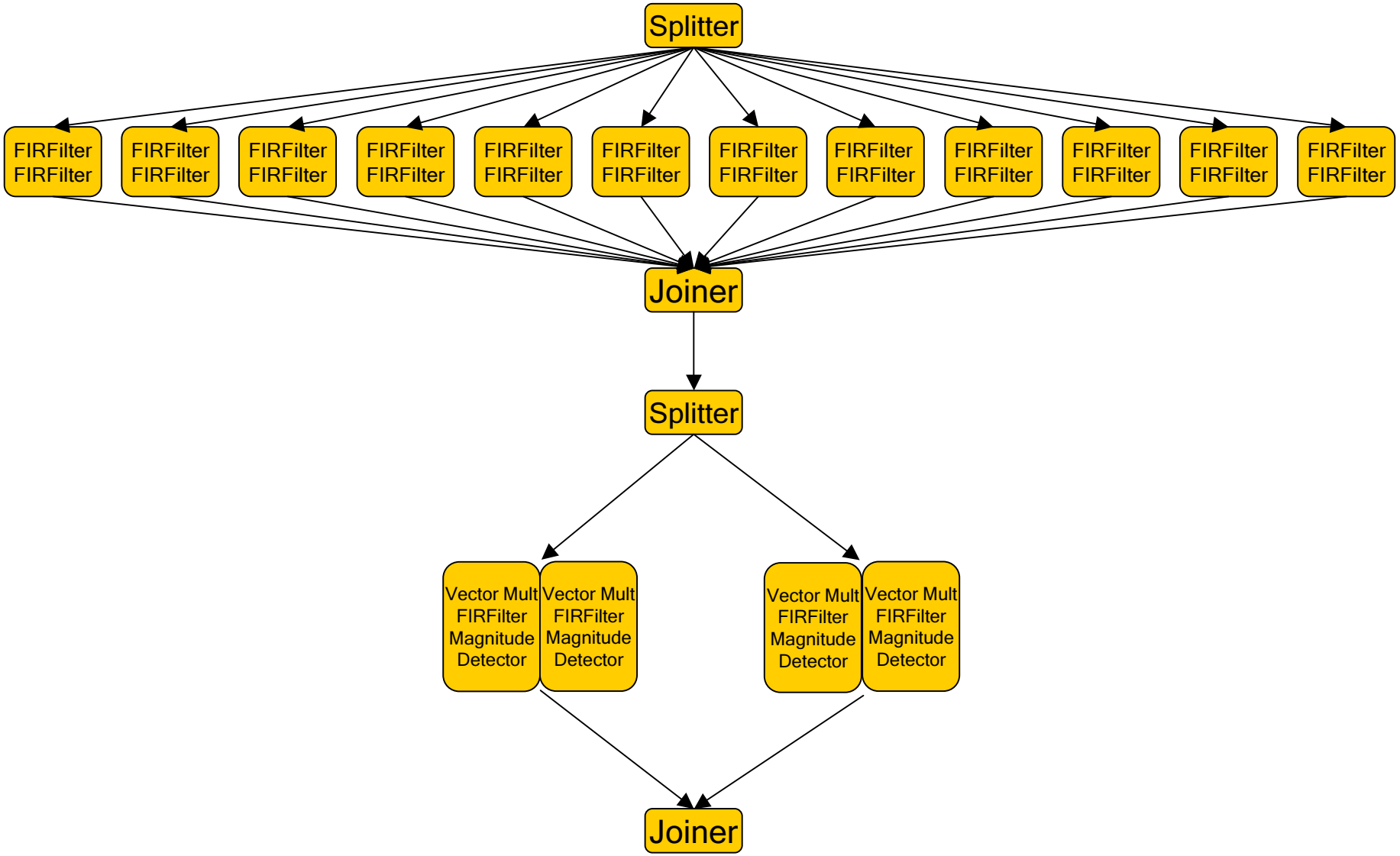


Example: BeamFormer (Balanced)



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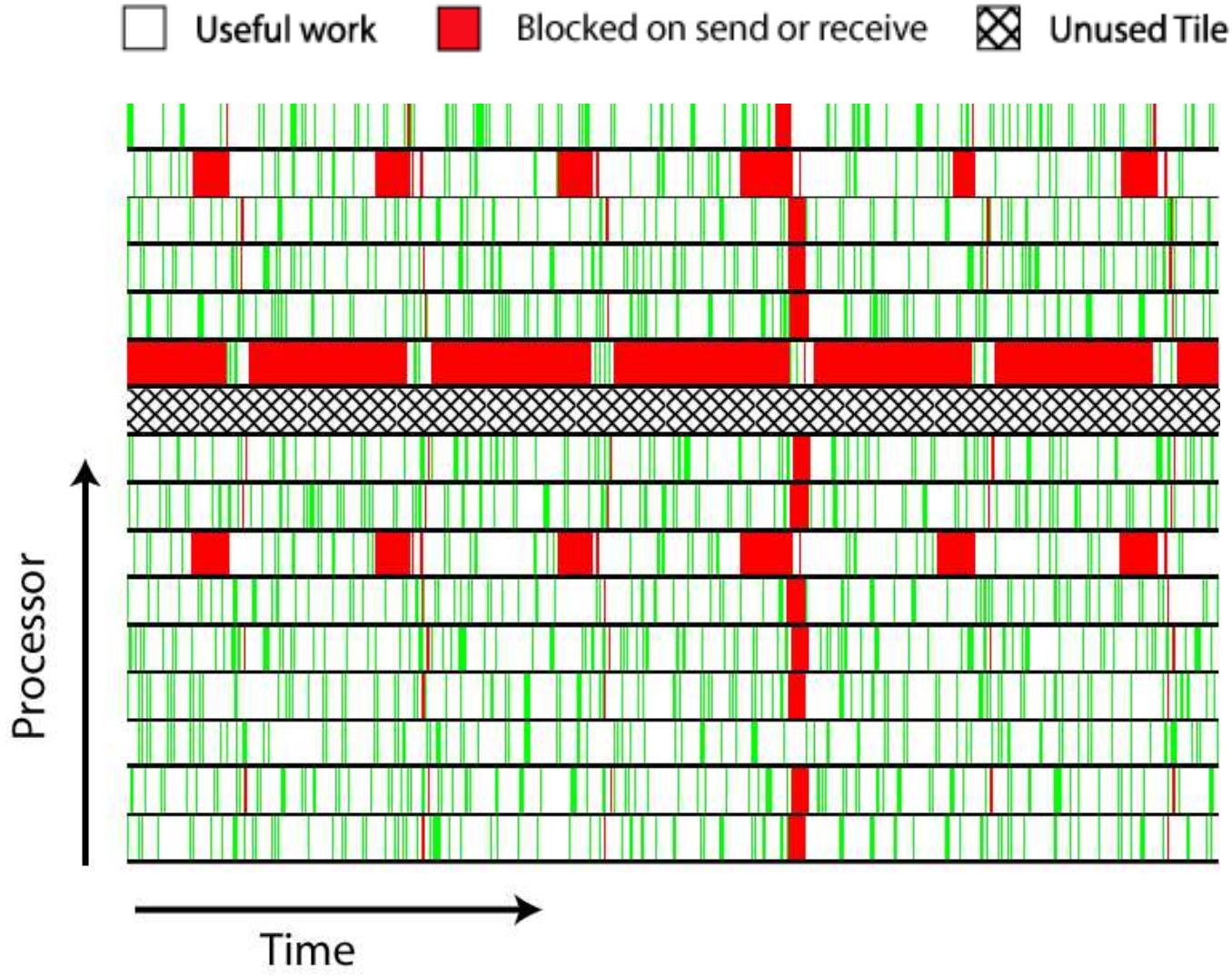

1120 MFLOPS

55,000 $\frac{\text{cycles}}{\text{item}}$

Outline

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Conclusions

- Compiler-conscious language design can improve both programmability and performance
  - Structure enables local, hierachical analyses
  - Messaging simplifies code, exposes parallelism
  - Morphing allows optimization across phases

- Goal: Stream programming at high level of abstraction without sacrificing performance

For More Information

StreamIt Homepage

http://compiler.lcs.mit.edu/streamit