Phased Scheduling of Stream Programs

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MIT LCS

Streaming Application Domain

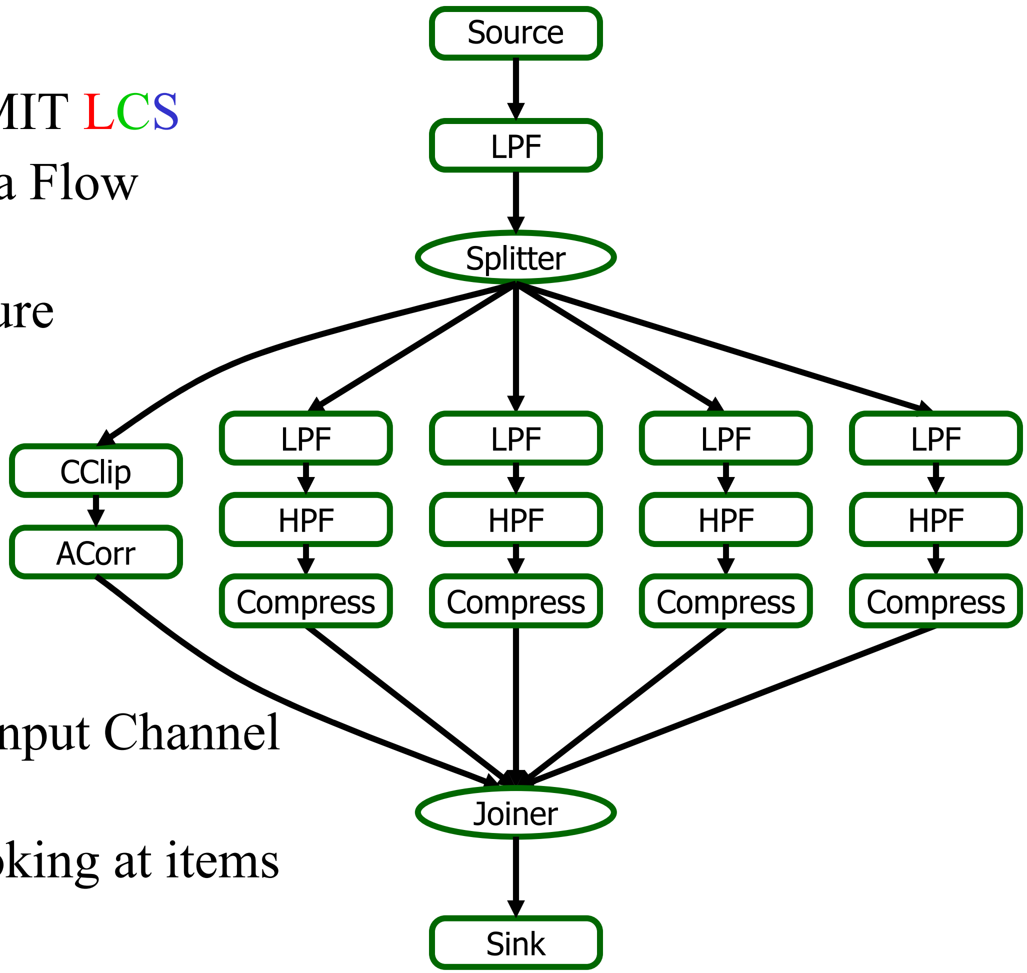
- Based on audio, video and data streams
- Increasingly prevalent
  - Embedded systems
    - Cell phones, handheld computers, etc.
  - Desktop applications
    - Streaming media
    - Software radio
    - Real-time encryption
  - High-performance servers
    - Software Routers (ex. Click)
    - Cell phone base stations
    - HDTV editing consoles

Properties of Stream Programs

- A large (possibly infinite) amount of data
  - Limited lifespan of each data item
  - Little processing of each data item
- A regular, static computation pattern
  - Stream program structure is relatively constant
  - A lot of opportunities for compiler optimizations

StreamIt Language

- Streaming Language from MIT LCS
- Similar to Synchronous Data Flow (SDF)
- Provides hierarchy & structure
- Four Structures:
  - Filter
  - Pipeline
  - SplitJoin
  - FeedbackLoop
- All Structures have Single-Input Channel Single-Output Channel
- Filters allow ‘peeking’ – looking at items which are not consumed



Our Contributions

New scheduling technique called Phased Scheduling

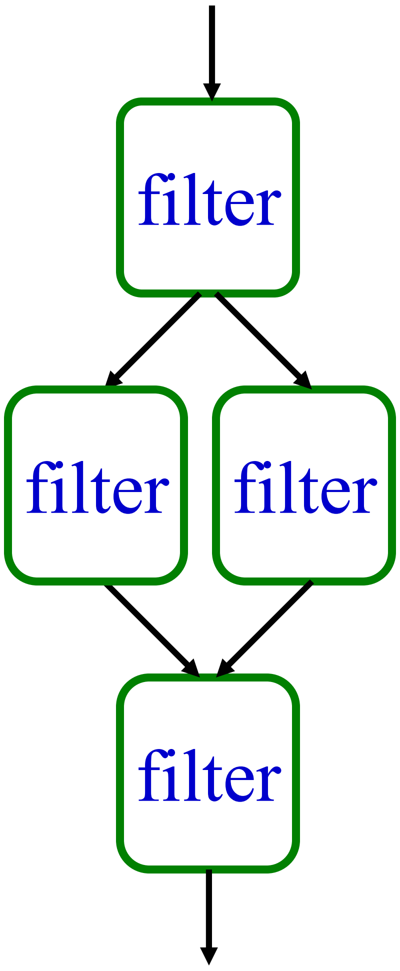
- Small buffer sizes for hierarchical programs
- Fine grained control over schedule size vs buffer size tradeoff
- Allows for separate compilation by always avoiding deadlock
- Performs initialization for peeking Filters

Overview

- General Stream Concepts
- StreamIt Details
- Program Steady State and Initialization
- Single Appearance and Pull Scheduling
- Phased Scheduling
  - Minimal Latency
- Results
- Related Work and Conclusion

Stream Programs

- Consist of Filters and Channels
- Filters perform computation
- Channels act as FIFO queues for data between Filters



Filters

- Execute a work function which:
  - Consumes data from their input
  - Produces data to their output
- Filters consume and produce constant amount of data on every execution of the work function
  - Rates are known at compilation time
- Filter executions are atomic

Stream Program Schedule

- Describes the order in which filters are executed
- Needs to manage grossly mismatched rates between filters
- Manages data buffered up in channels between filters
- Controls latency of data processing

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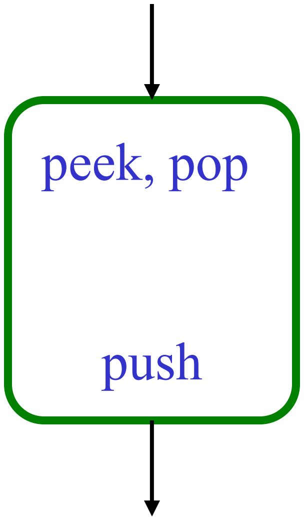
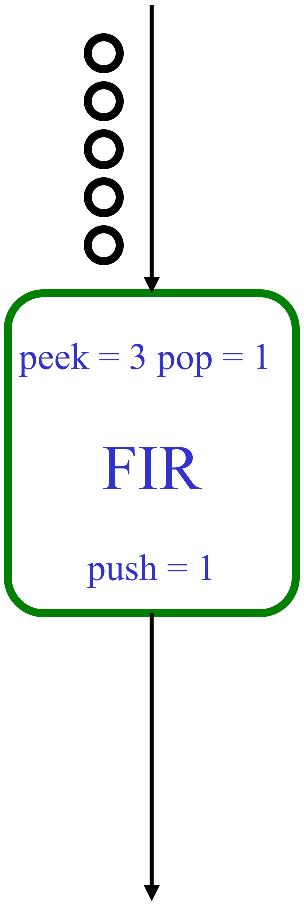
StreamIt - Filter

- Performs the computation
- Consumes pop data items
- Produces push data items
- Inspects peek data items



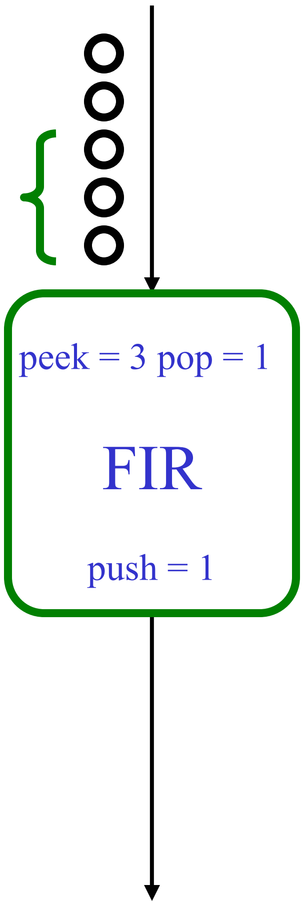
StreamIt - Filter

- Example:
  - FIR filter



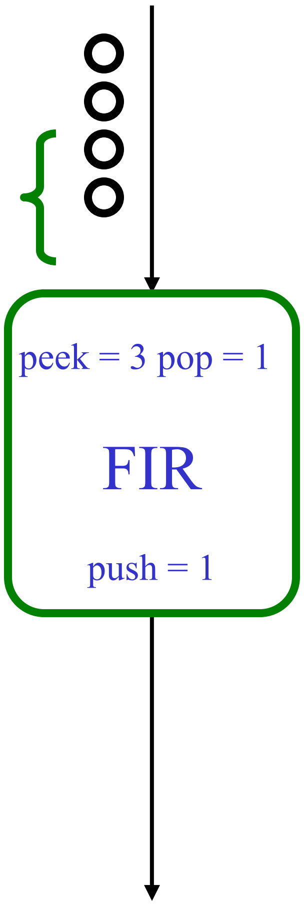
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items



StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item



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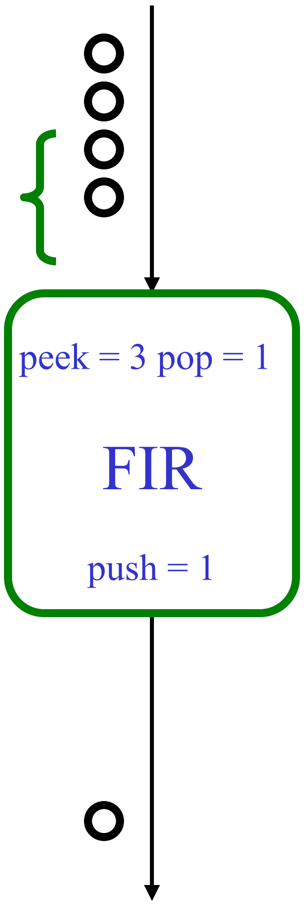

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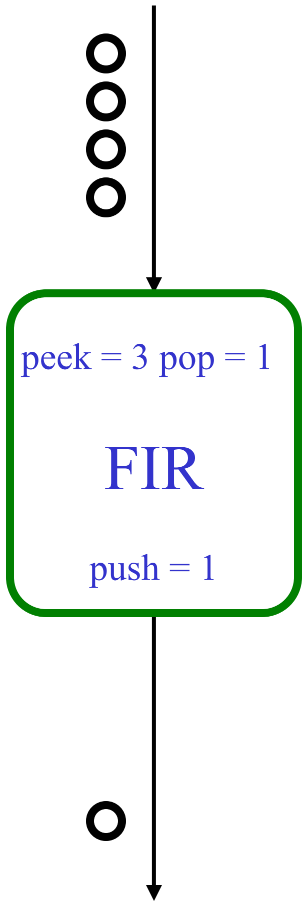

StreamIt - Filter

- Example:
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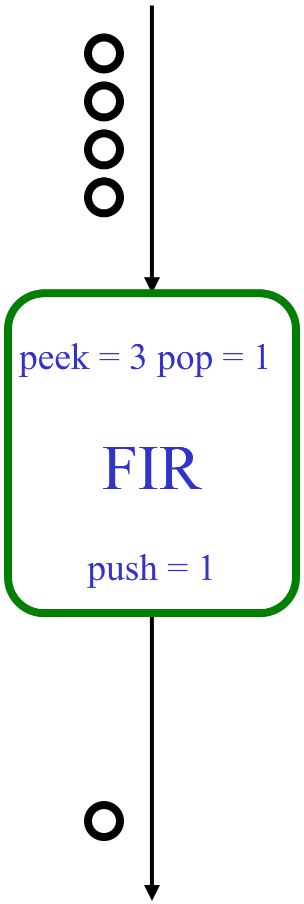
  - And again…



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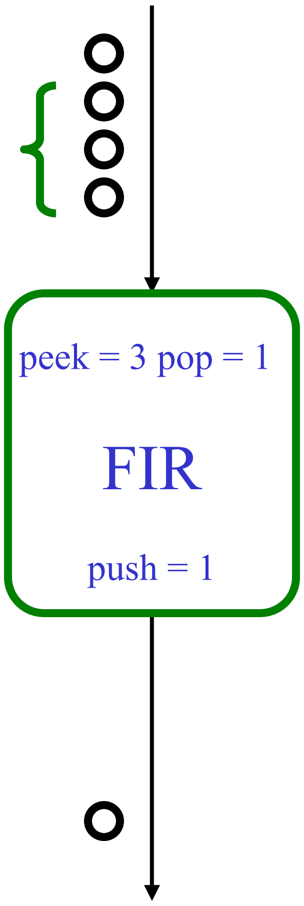

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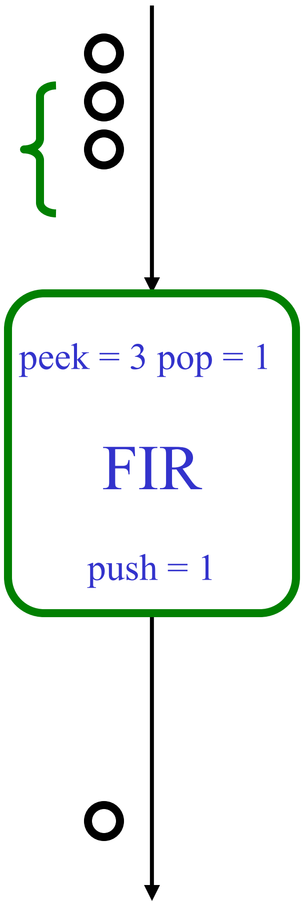

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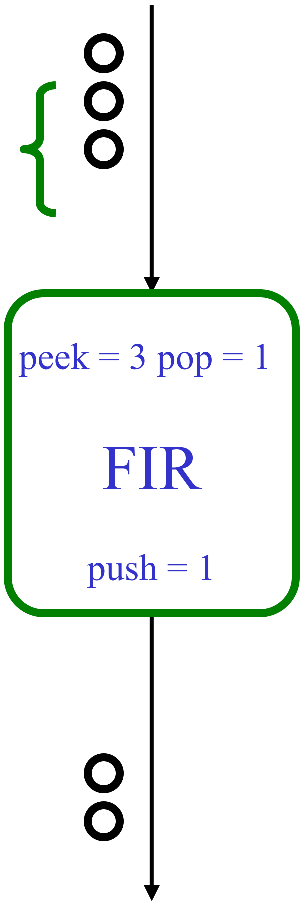

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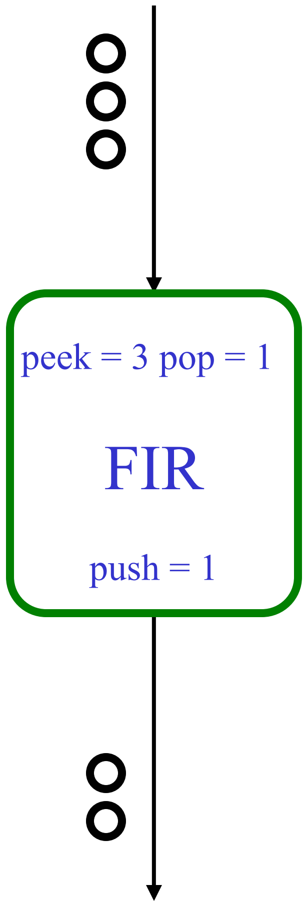
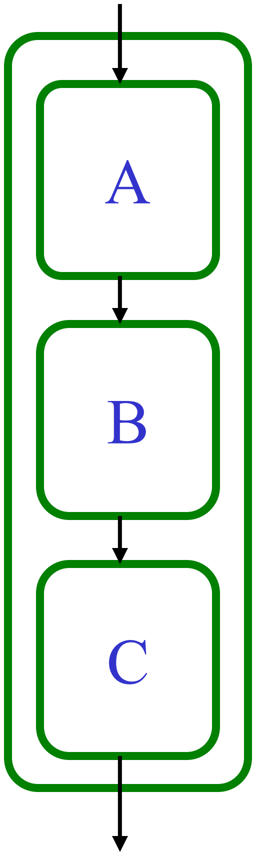


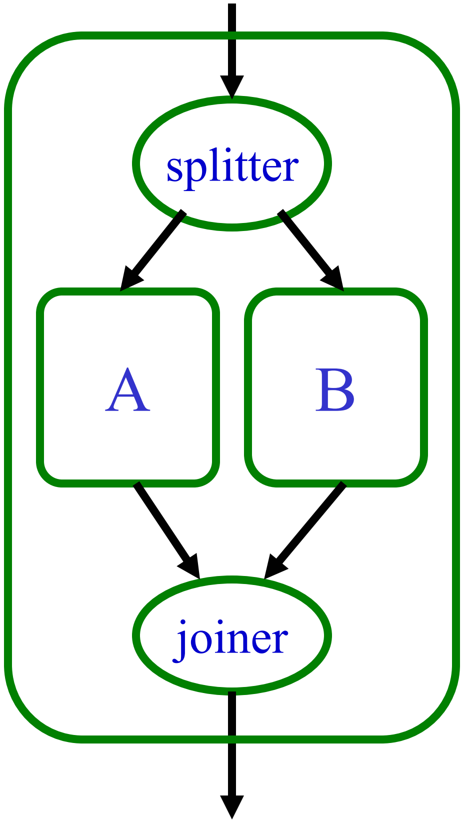
StreamIt Pipeline

- Connects multiple components together
- Sequential (data-wise) computation
- Inserts implicit buffers between them



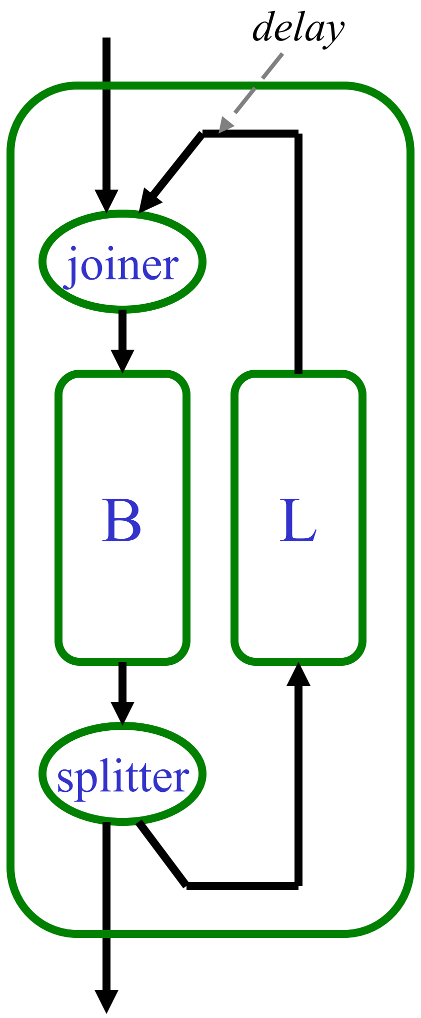
StreamIt SplitJoin

- Also connects several components together
- Parallel computation construct
- Allows for computation of same data (DUPLICATE splitter) or different data (ROUND_ROBIN splitter)



StreamIt FeedbackLoop

- ONLY structure to allow data cycles
- Needs initialization on feedbackPath
- Amount of data on feedbackPath is *delay*



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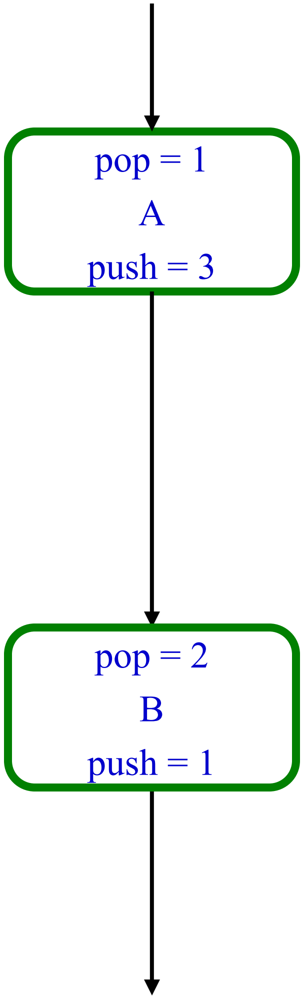
Scheduling – Steady State

- Every valid stream graph has a Steady State
- Steady State does not change amount of data buffered between components
- Steady State can be executed repeatedly forever without growing buffers

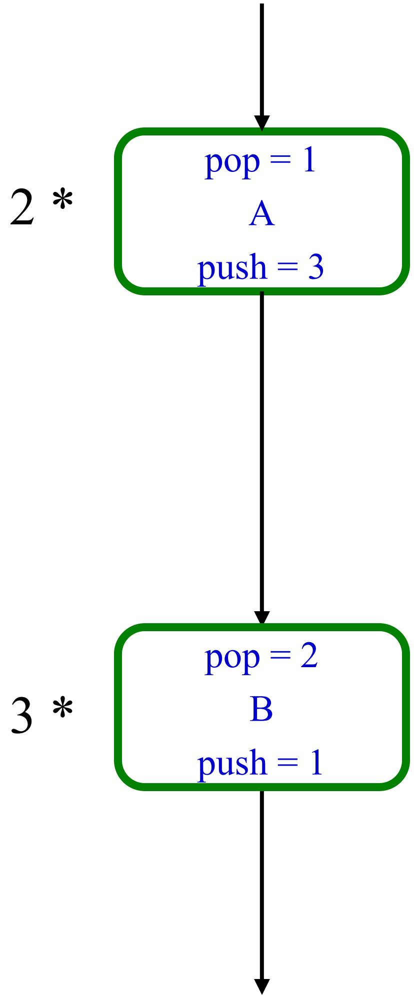
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of 2



Steady State Example

- A executes 2 times
  - pushes 2 * 3 = 6 items
- B executes 3 times
  - pops 3 * 2 = 6 items
- Number of data items stored between Filters does not change



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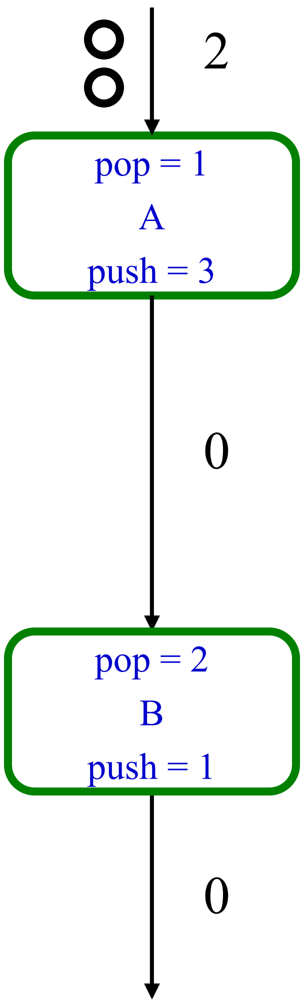
- Schedule:
  -



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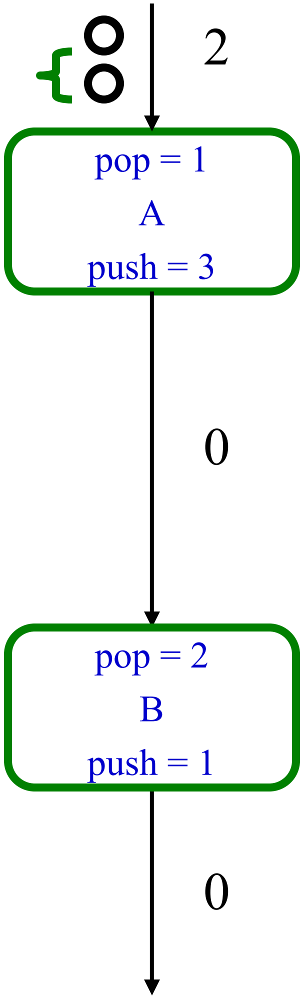
- Schedule:
  - A



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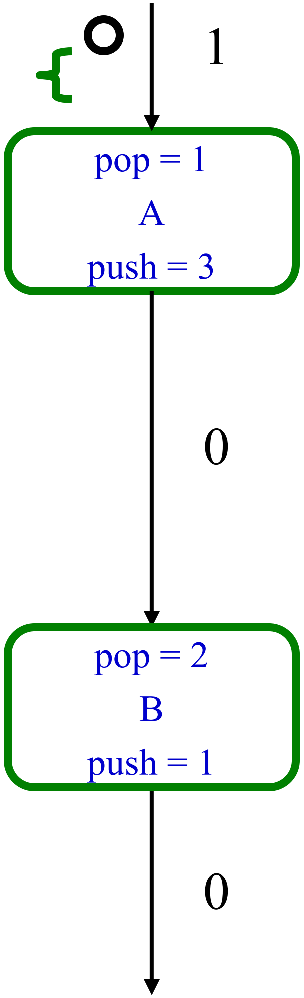

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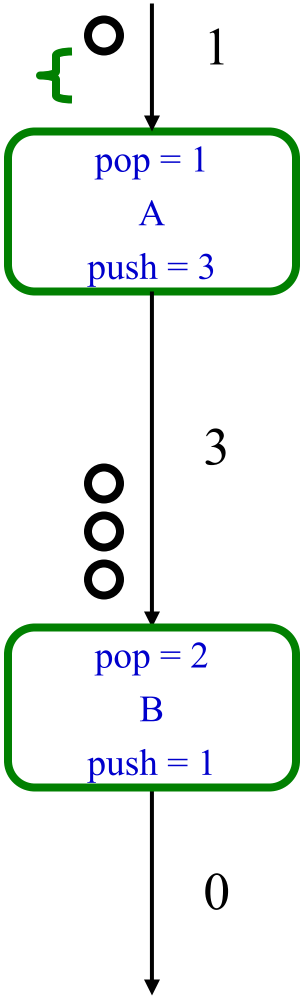

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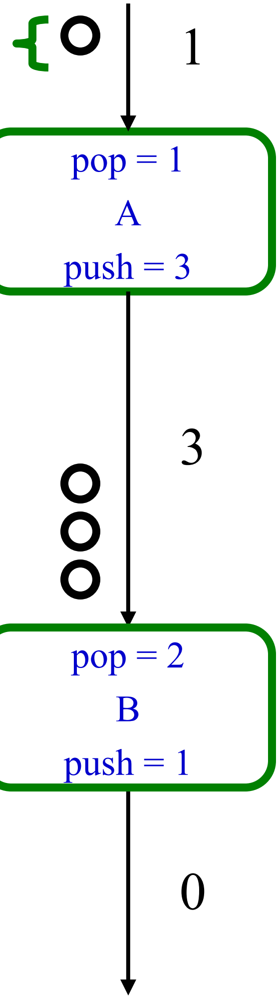
- Schedule:
  - AA



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- Schedule:
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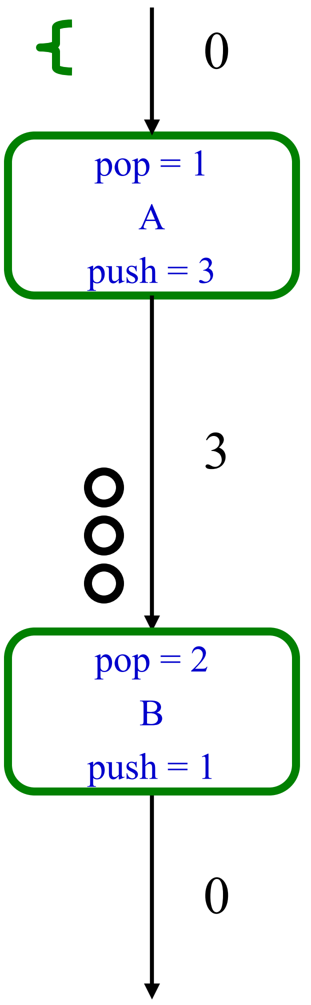

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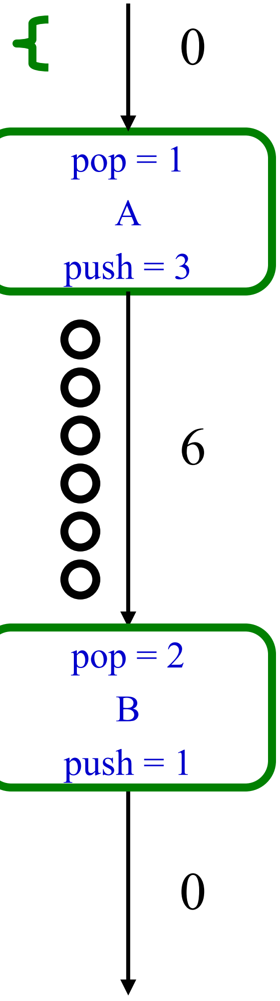

Steady State Example

- 3:2 Rate Converter
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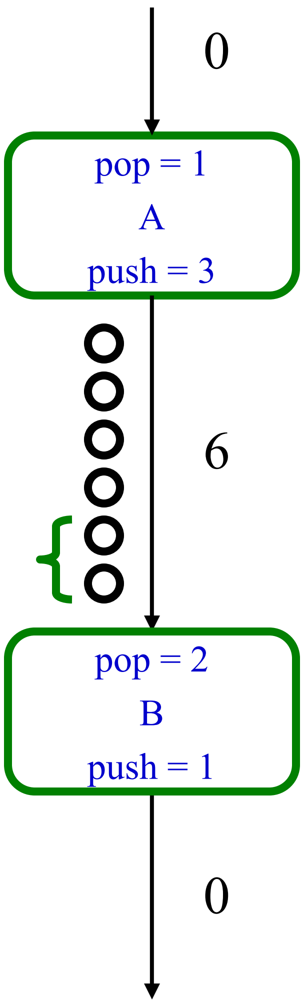
- Schedule:
  - AAB



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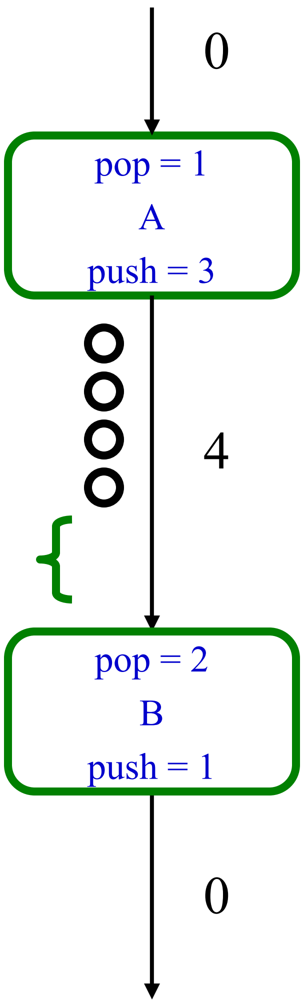

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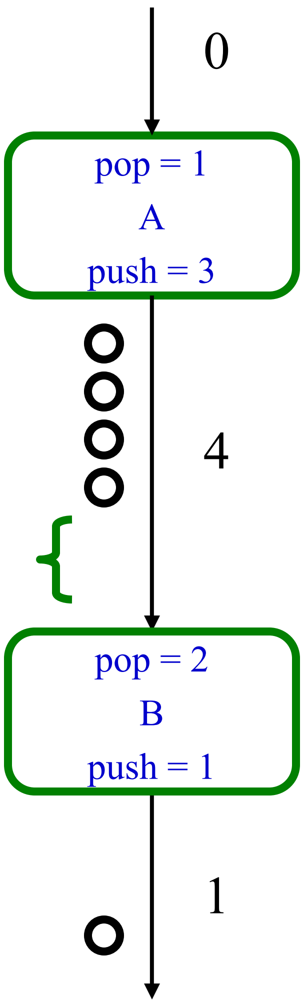

Steady State Example

- 3:2 Rate Converter
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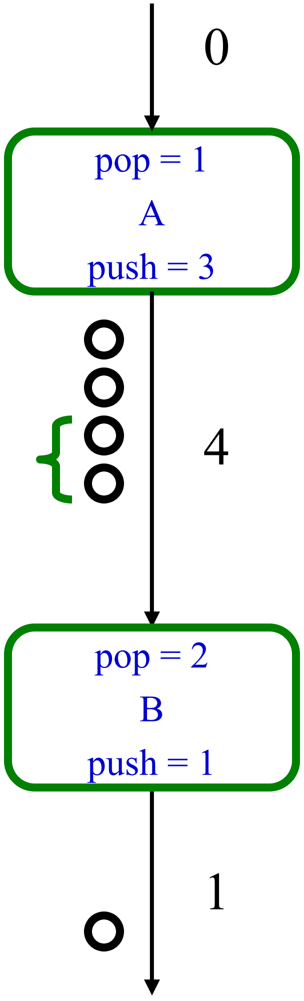
- Schedule:
  - AABB



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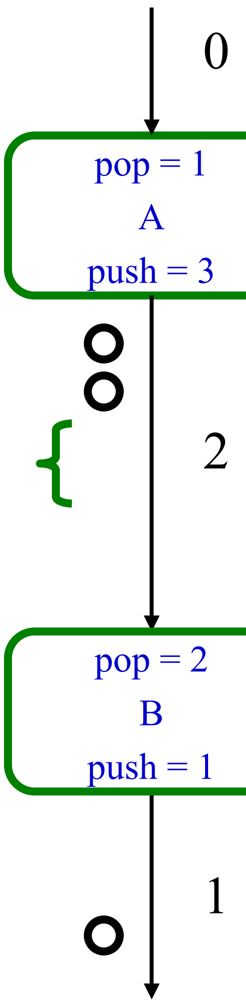

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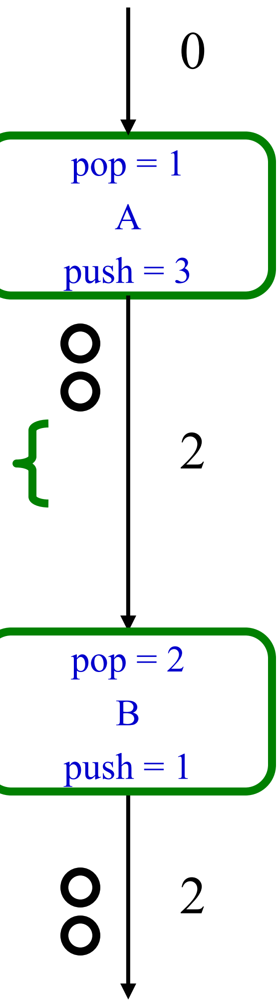

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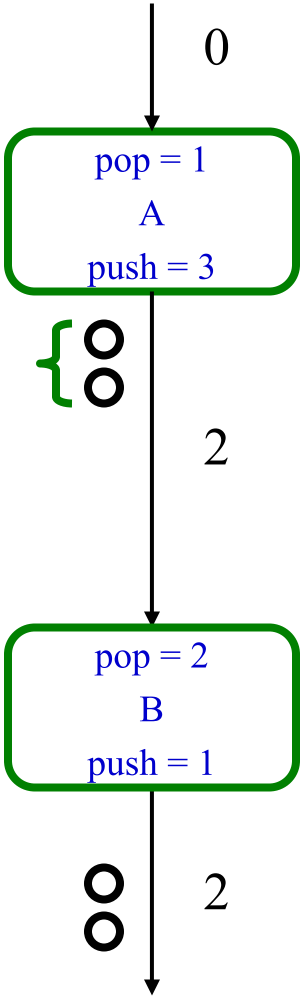

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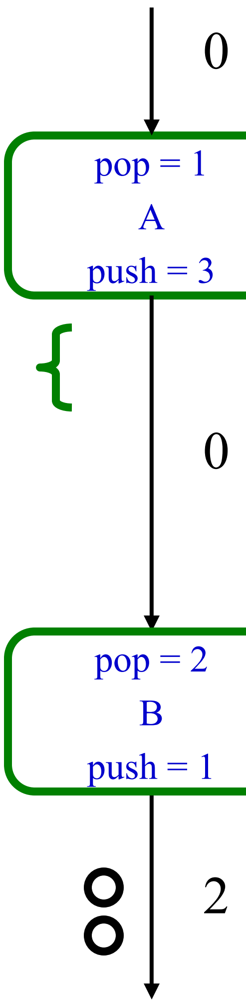

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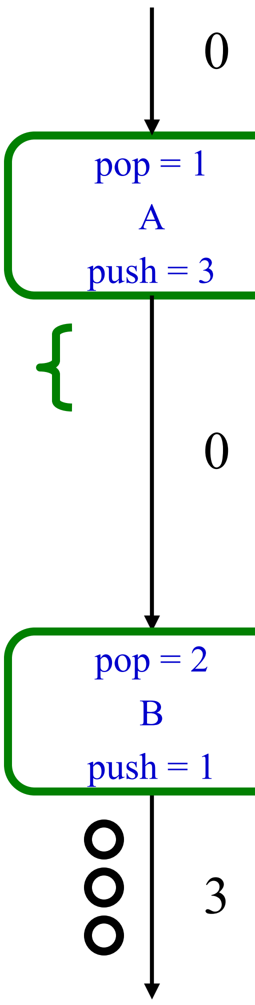

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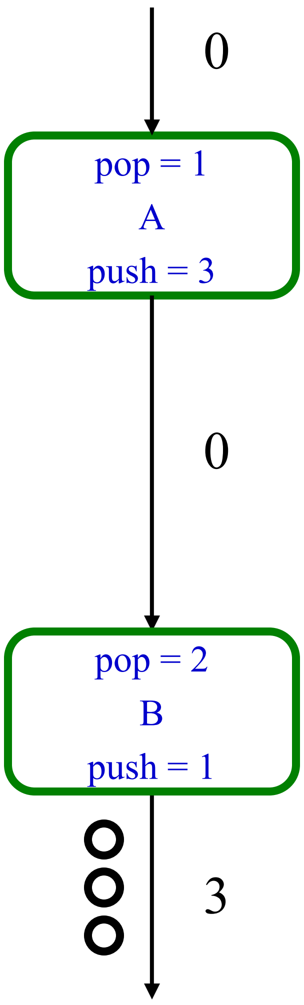

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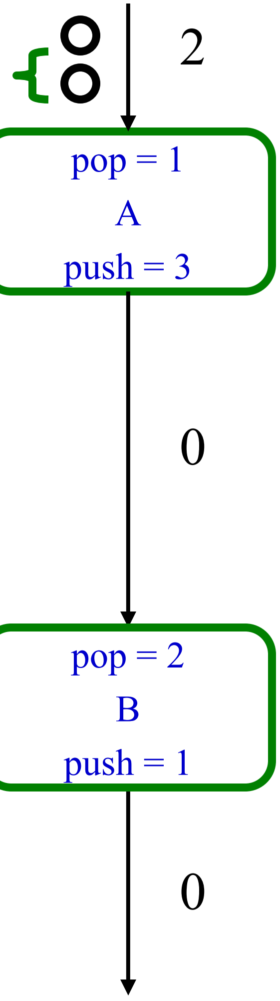

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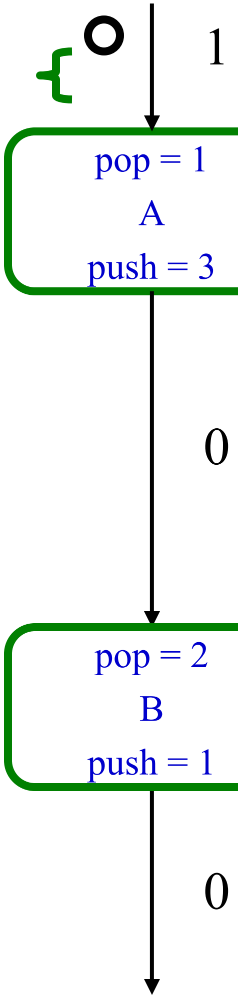

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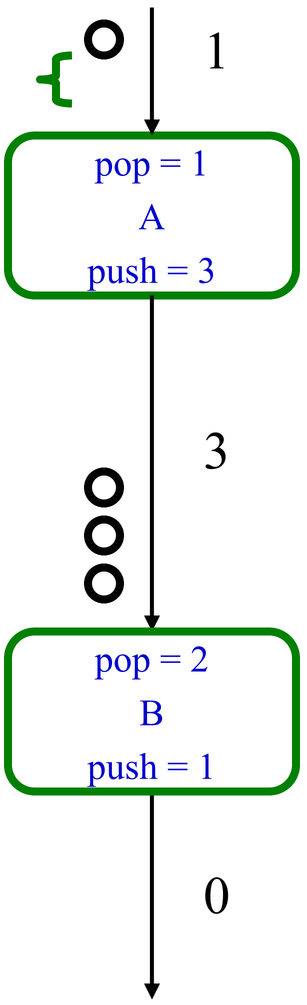

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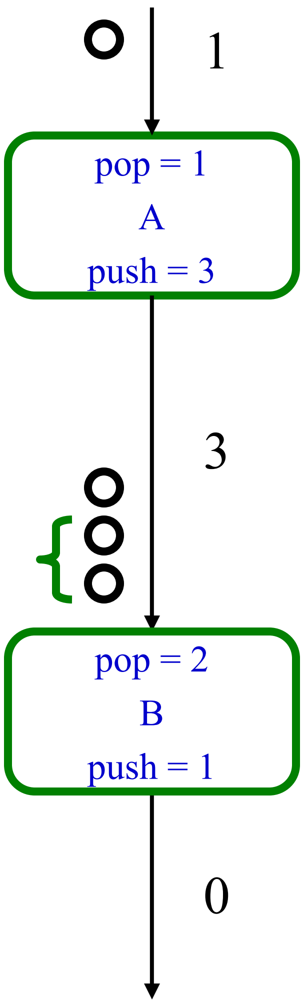

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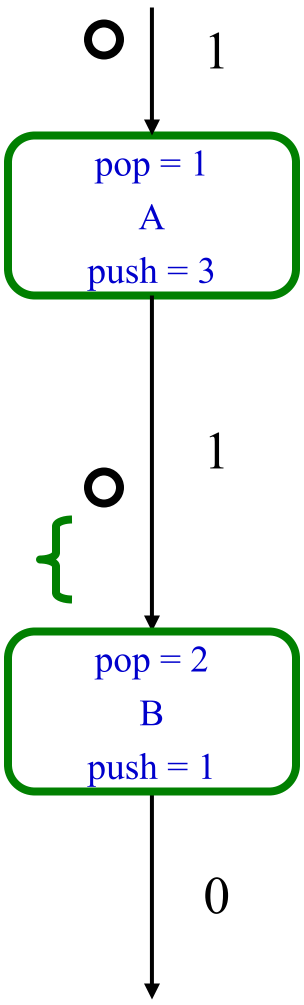

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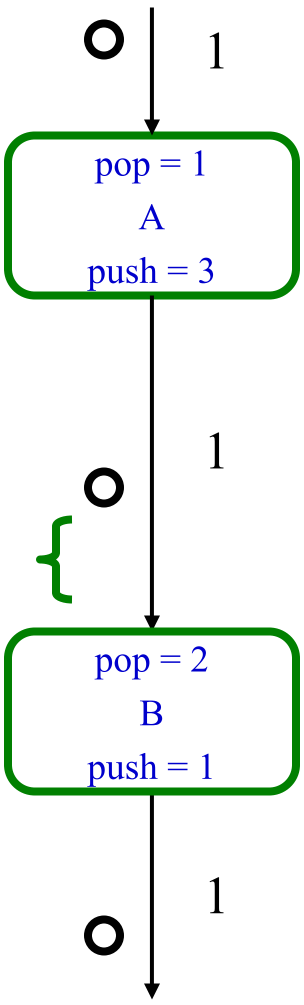

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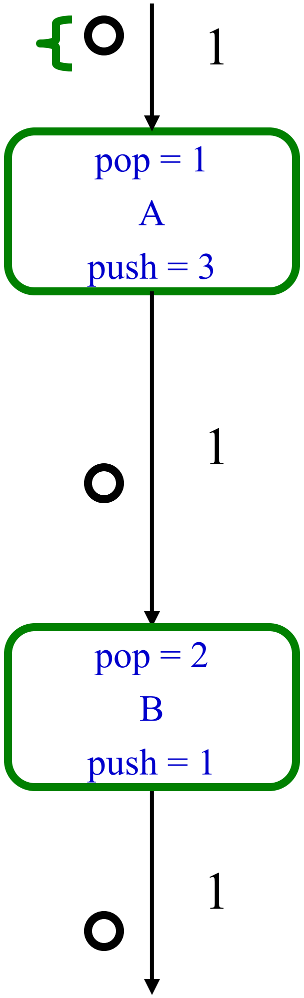

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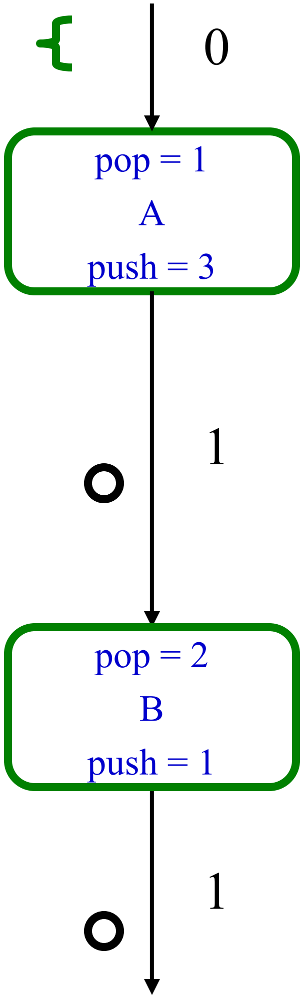

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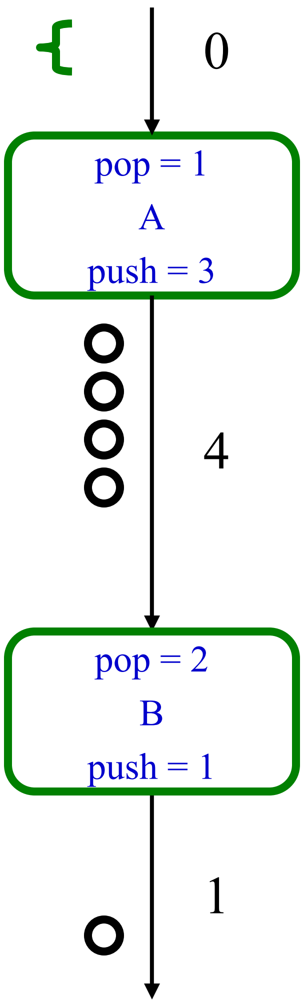

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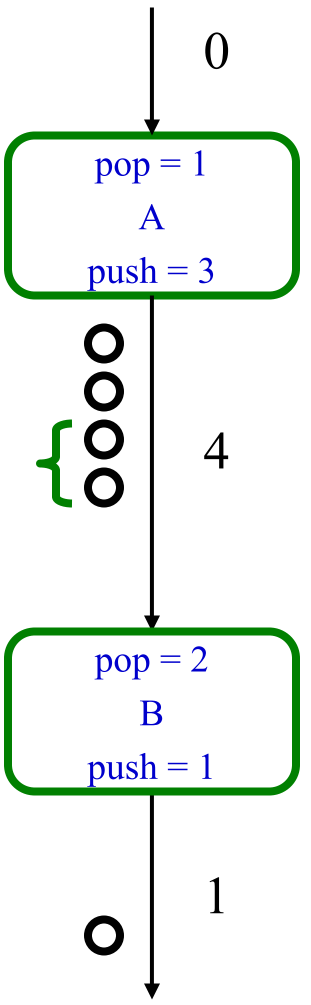

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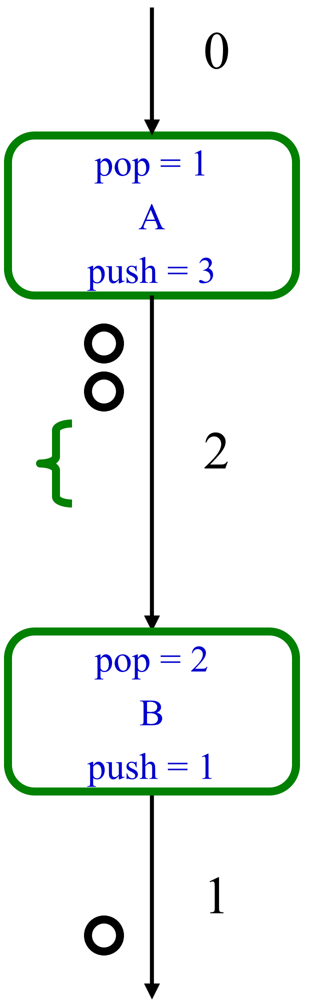

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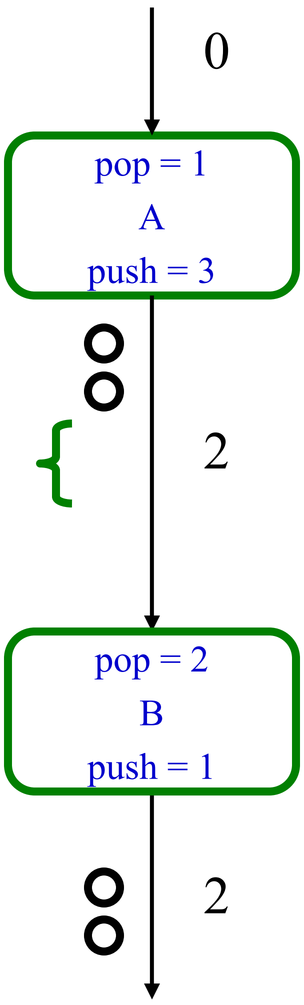

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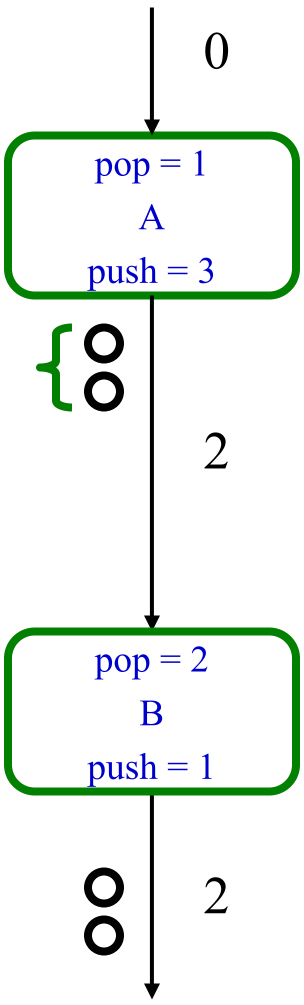

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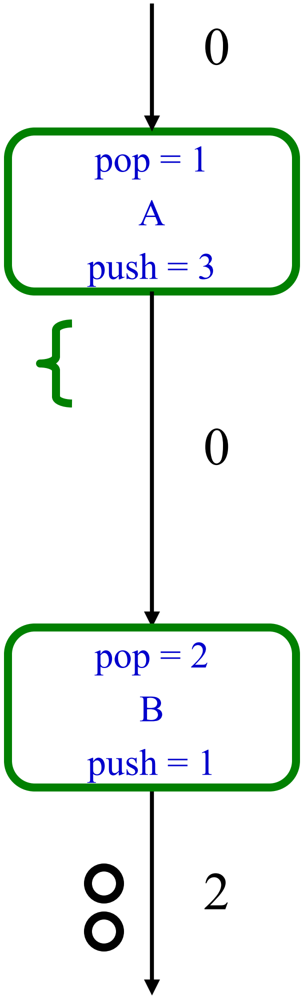
- Schedule:
  - AABBB
  - ABABB



Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
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- Schedule:
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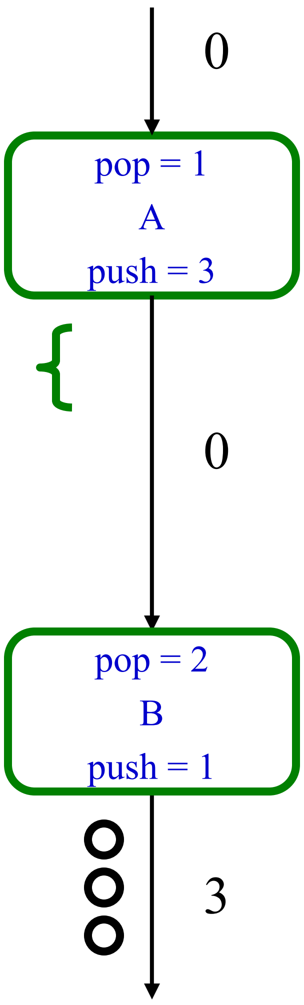
  - ABABB



Steady State Example

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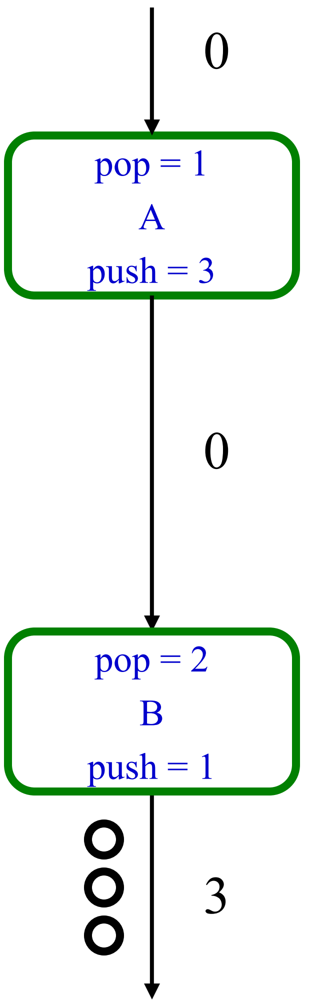
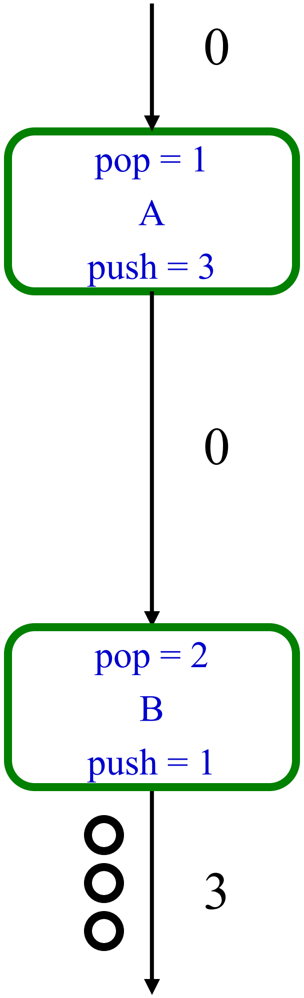


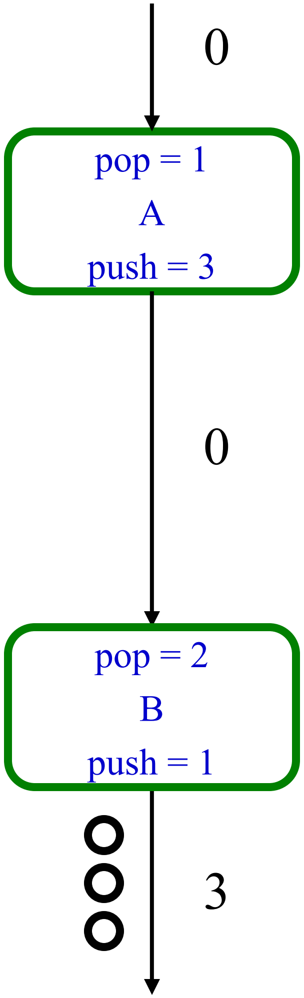
Steady State Example - Buffers

- AABBB requires 6 data items of buffer space between filters A and B
- ABABB requires 4 data items of buffer space between filters A and B



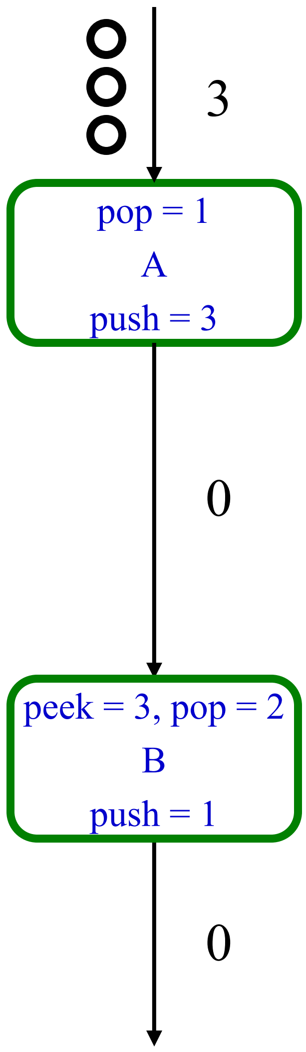
Steady State Example - Latency

- AABBB – First data item output after third execution of an filter
  - Also A already consumed 2 data items
- ABABB – First data item output after second execution of an filter
  - A consumed only 1 data item



Initialization

- Filter Peeking provides a new challenge
- Just Steady State doesn't work:
  -



Initialization

- Filter Peeking provides a new challenge
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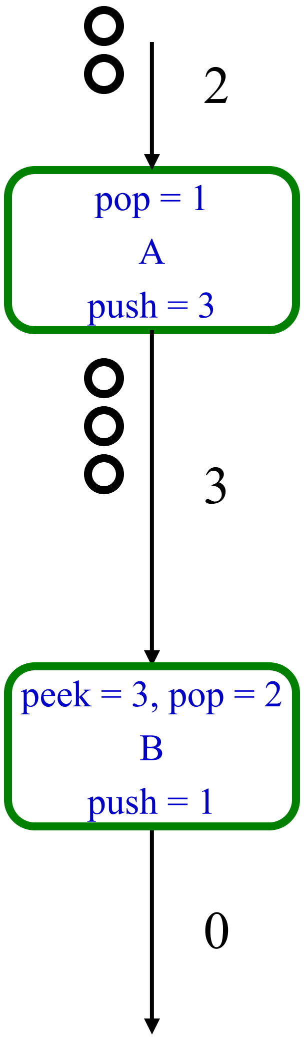
  - A



Initialization

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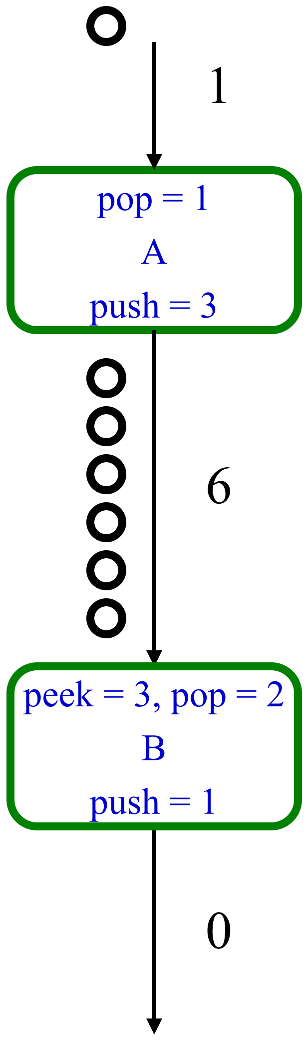
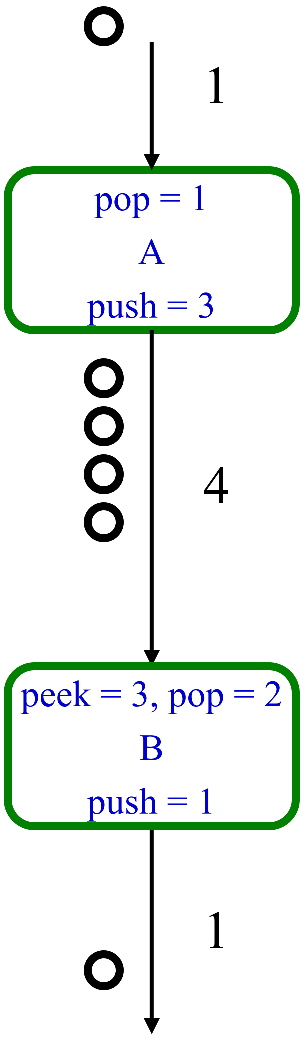


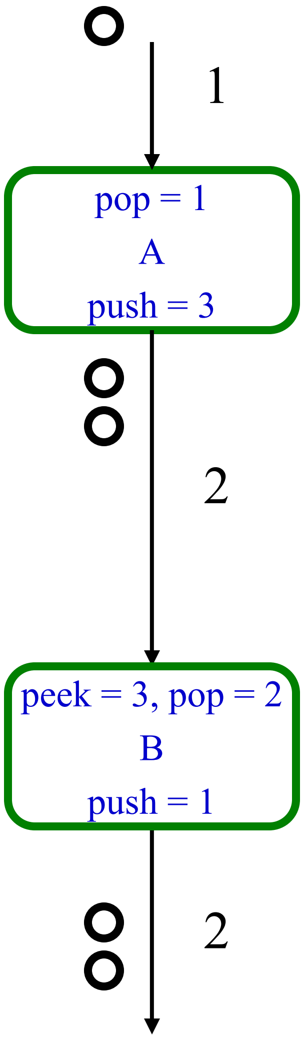
Initialization

- Filter Peeking provides a new challenge
- Just Steady State doesn't work:
  - AAB



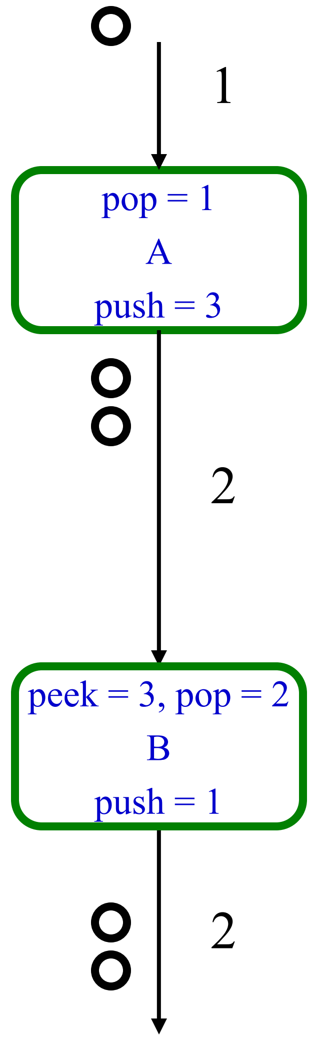
Initialization

- Filter Peeking provides a new challenge
- Just Steady State doesn't work:
  - AABB
  - Can't execute B again!



Initialization

- Filter Peeking provides a new challenge
- Just Steady State doesn't work:
  - AABB
  - Can't execute B again!
- Can't execute A one extra time:
  - AABB



Initialization

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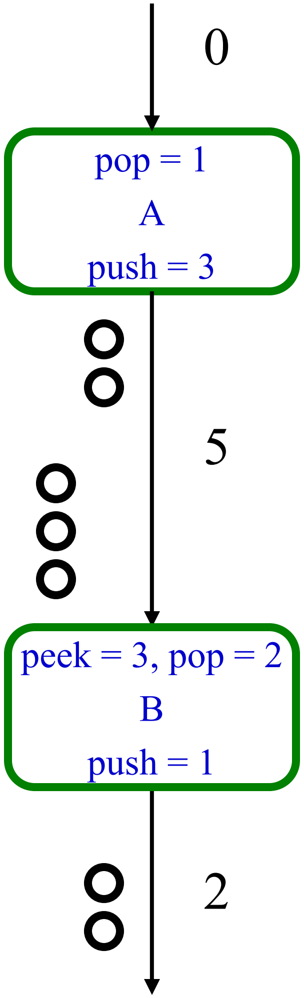
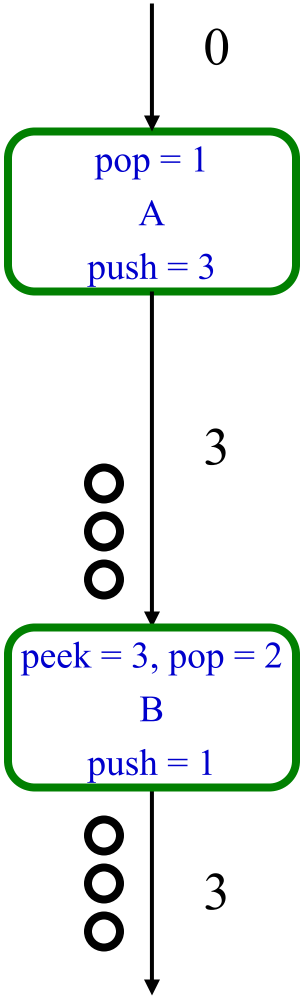
  - Can't execute B again!
- Can't execute A one extra time:
  - AABBA



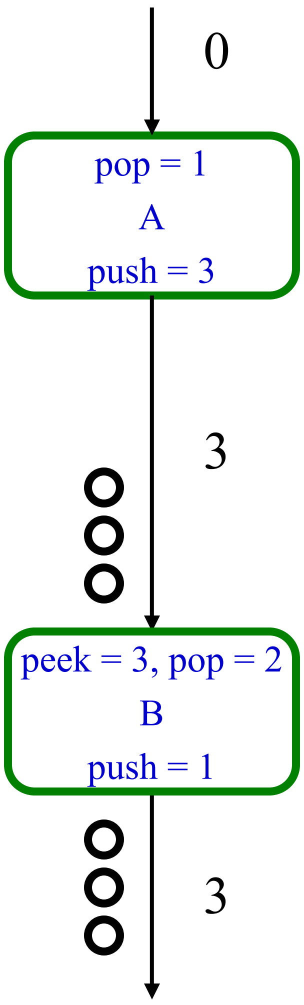
Initialization

- Filter Peeking provides a new challenge
- Just Steady State doesn’t work:
  - AABB
  - Can’t execute B again!
- Can’t execute A one extra time:
  - AABBAB
  - Left 3 items between A and B!



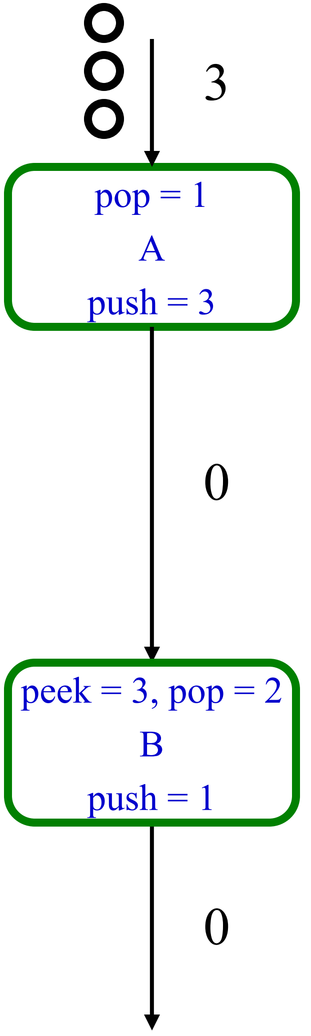
Initialization

- Must have data between A and B before starting execution of Steady State Schedule
- Construct two schedules:
  - One for Initialization
  - One for Steady State
- Initialization Schedule leaves data in buffers so Steady State can execute



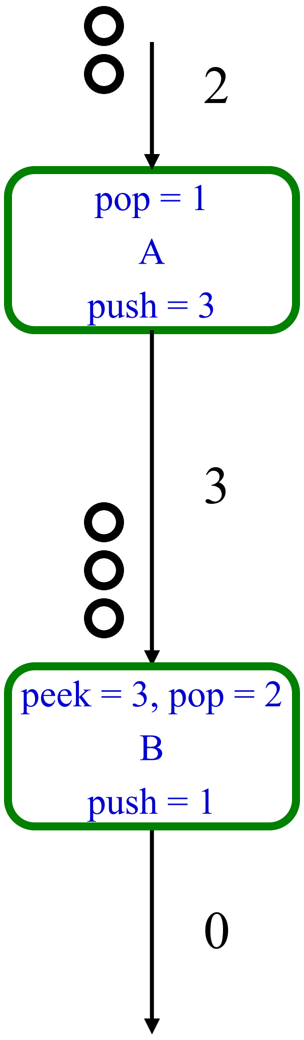
Initialization

- Initialization Schedule:
  -



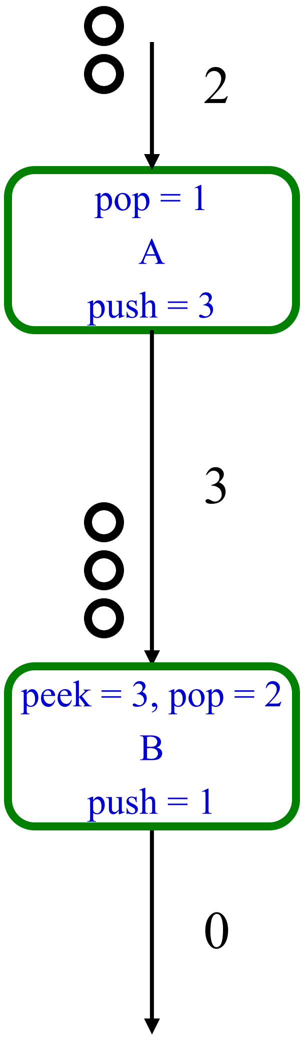
Initialization

- Initialization Schedule:
  - A



Initialization

- Initialization Schedule:
  - A
  - Leave 3 items between A and B
- Steady State Schedule:
  -



Initialization

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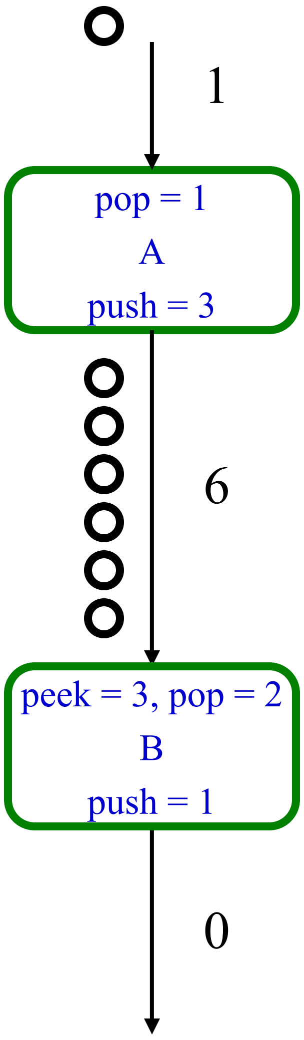
- Steady State Schedule:
  - A



Initialization

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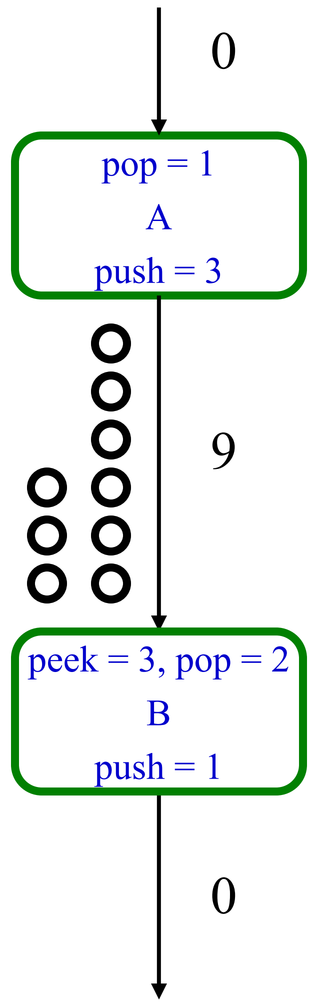
  - AA



Initialization

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  - A
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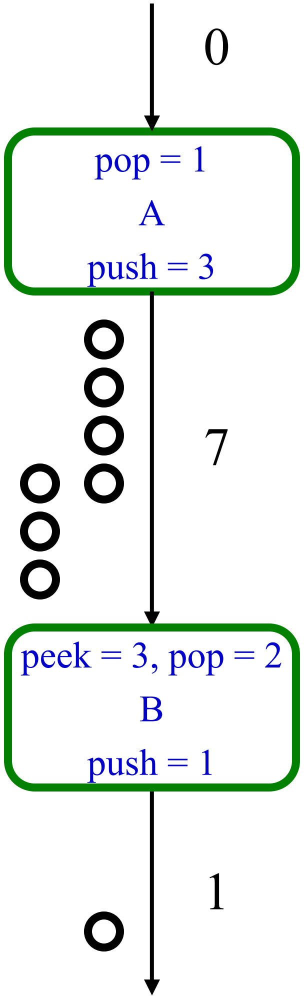
  - AAB



Initialization

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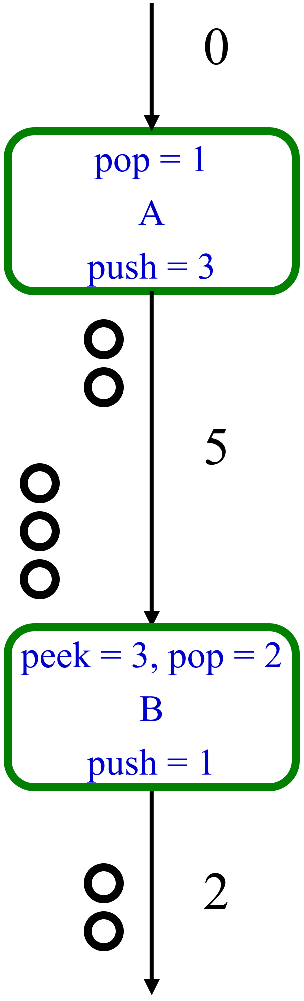

Initialization

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- Steady State Schedule:
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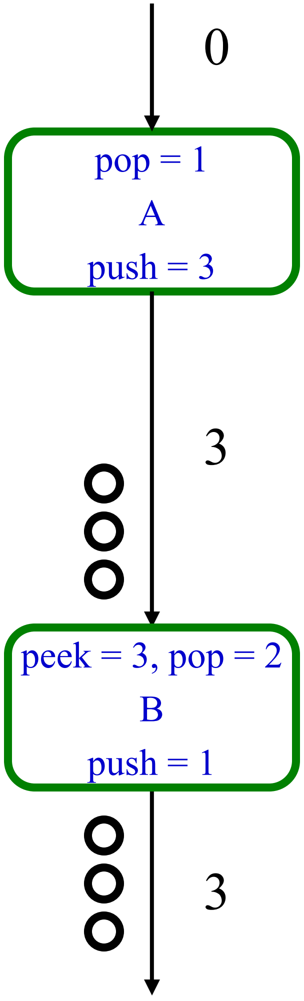

Initialization

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- Steady State Schedule:
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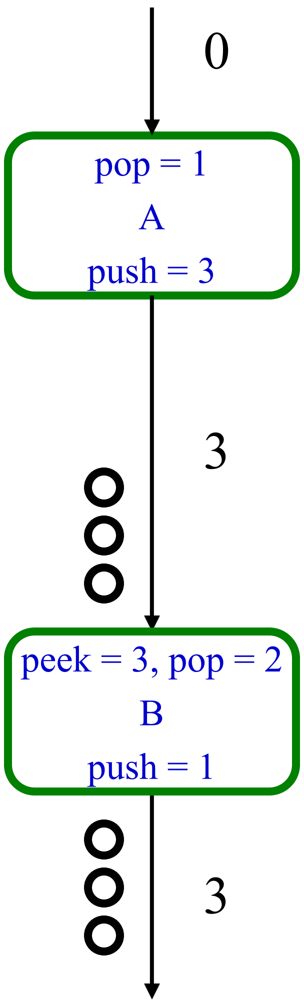
  - Leave 3 items between A and B



Initialization

- Initialization Schedule:
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  - Leave 3 items between A and B
- Steady State Schedule:
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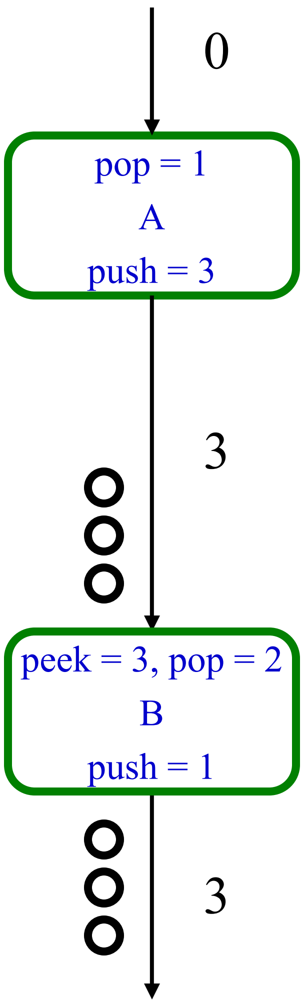
  - Leave 3 items between A and B
- See paper for more details



Overview

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Scheduling

- Steady State tells us how many times each component needs to execute
- Need to decide on an order of execution
- Order of execution affects
  - Buffer size
  - Schedule size
  - Latency

Single Appearance Scheduling (SAS)

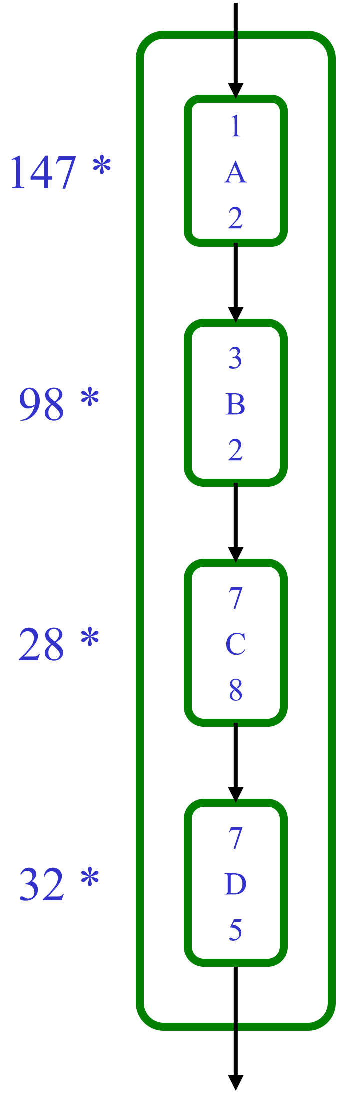
- Every Filter is listed in the schedule only once
- Use loop-nests to express the multiplicity of execution of Filters
- Buffer size is not optimal
- Schedule size is minimal

Schedule Size

- Schedules can be stored in two ways
  - Explicitly – in a schedule data structure
  - Implicitly – as code which executes the schedule's loop-nests
- Schedule size = number of appearances of nodes (filters and splitters/joiners) in the schedule
  - Single appearance schedule size is same as number of nodes in the program
  - Other scheduling techniques can have larger size
  - SAS schedule size is minimal: all nodes must appear in every schedule at least once

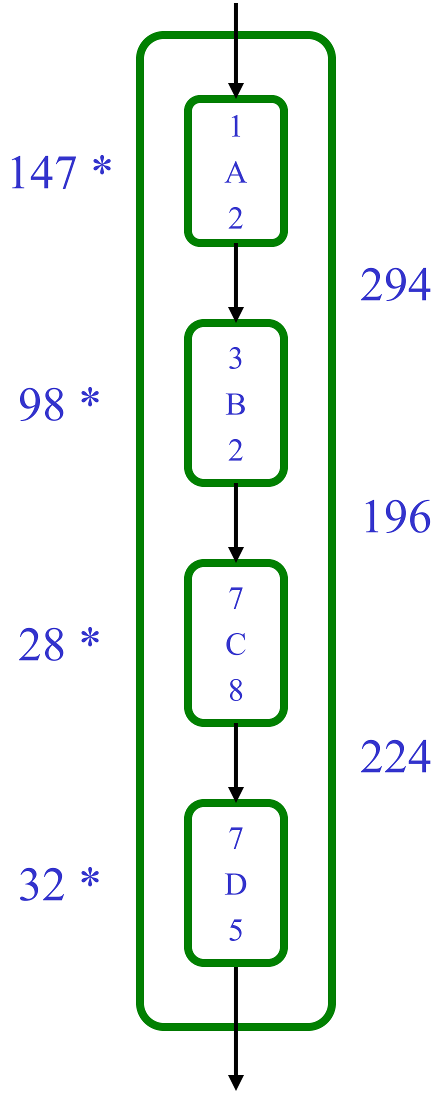
SAS Example – Buffer Size

- Example: CD-DAT
- CD to Digital Audio Tape rate converter
- Mismatched rates cause large number of executions in Steady State



SAS Example – Buffer Size

- Naïve SAS schedule:
  - 147A 98B 28C 32D
  - Required Buffer Size: 714
  - Unnecessarily large buffer requirements!



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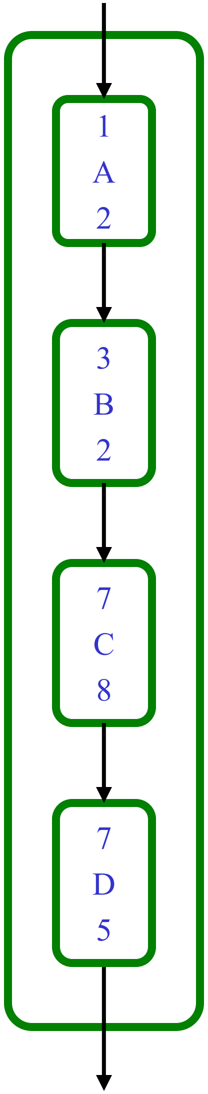

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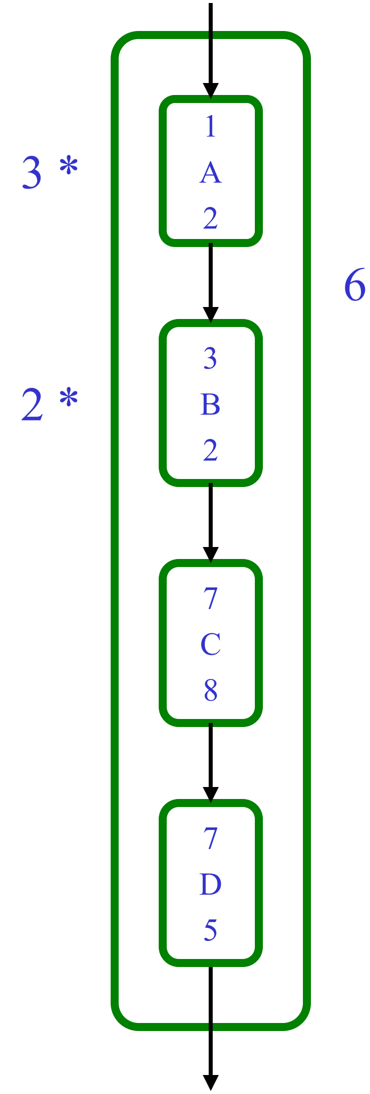

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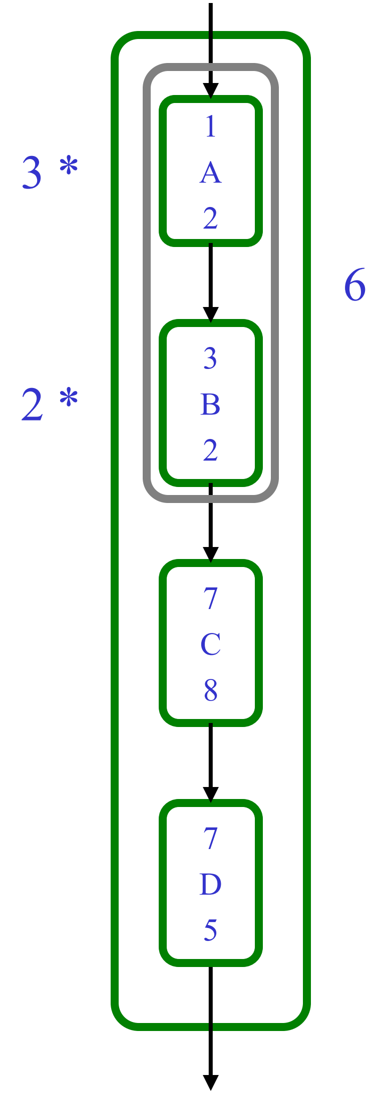

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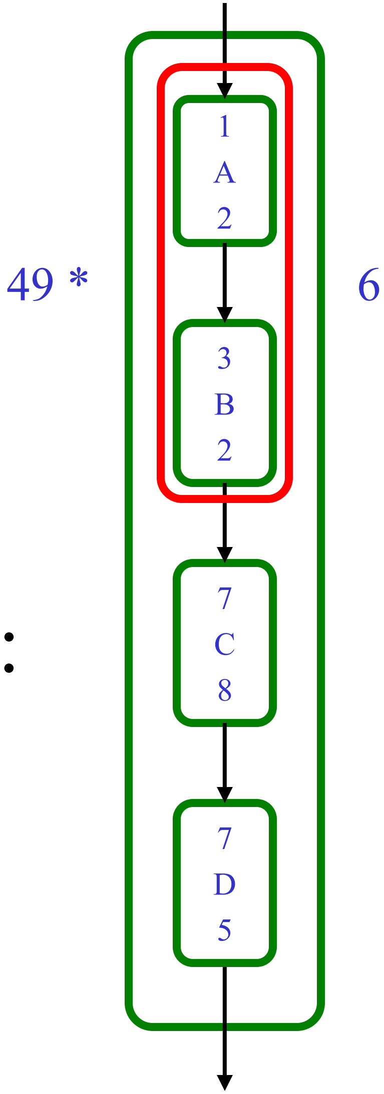

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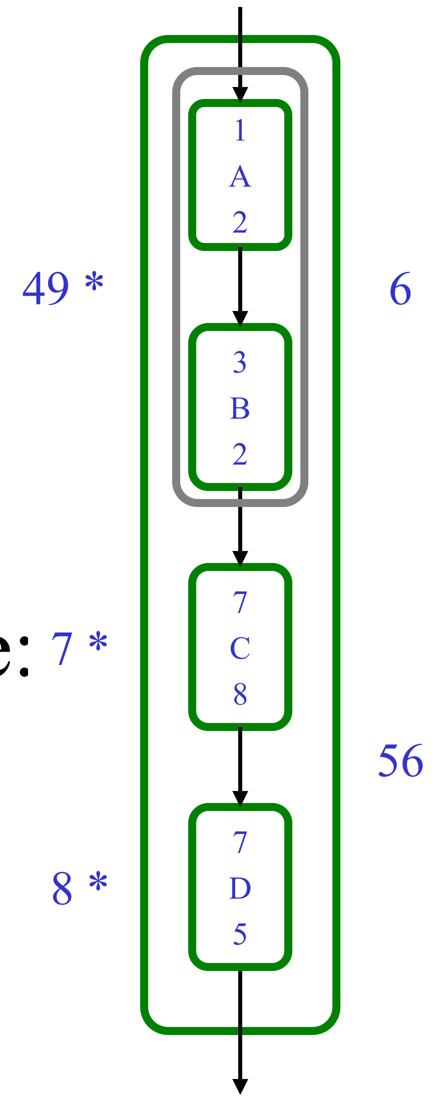

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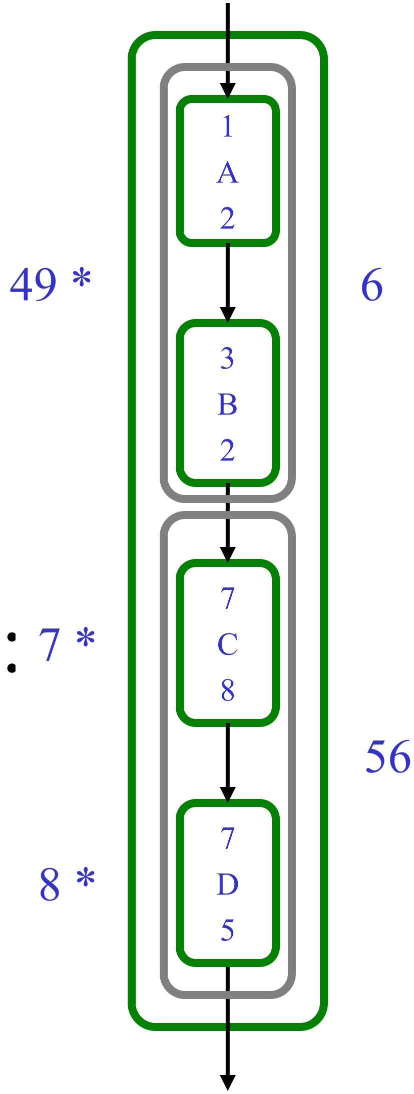

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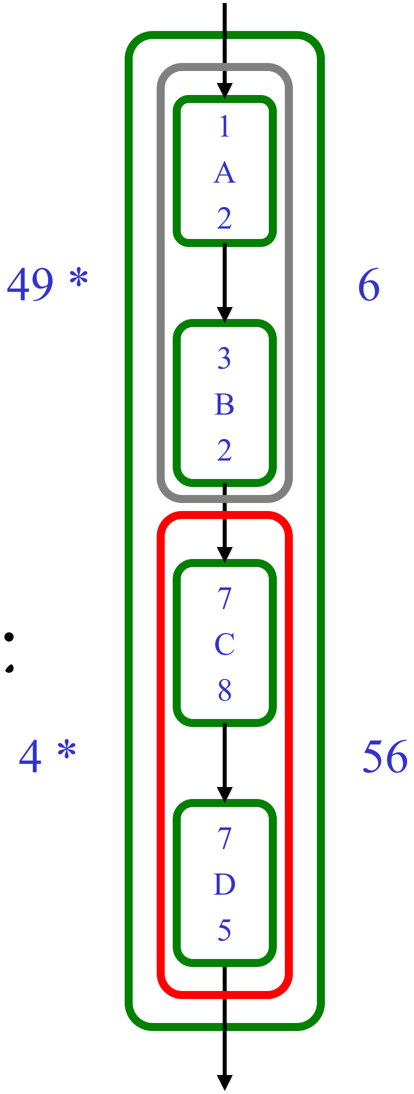

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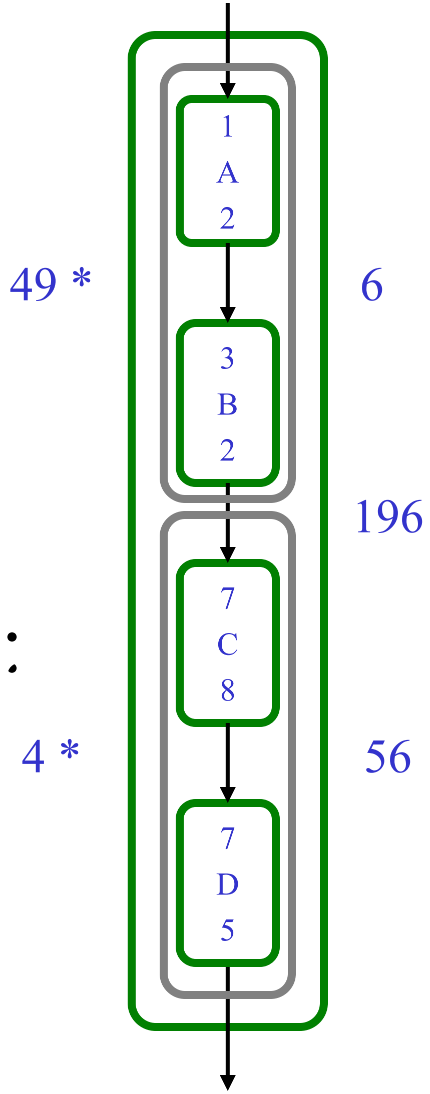

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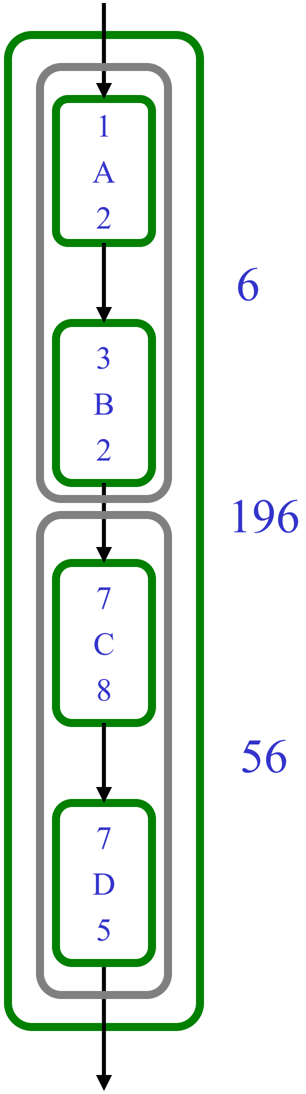
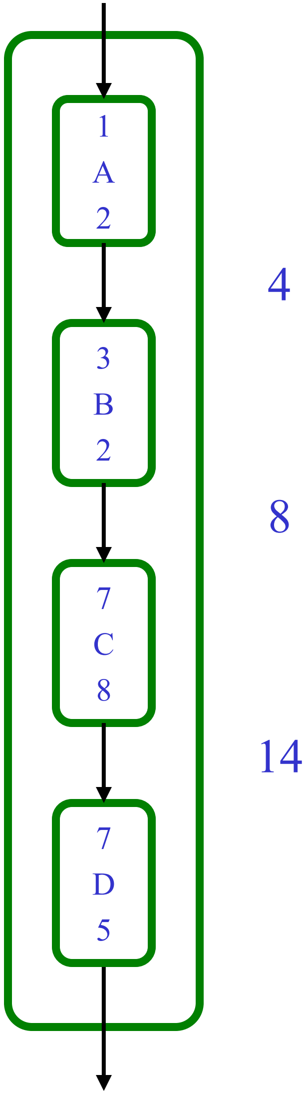


Pull Schedule Example – Buffer Size

- Pull Scheduling:
  - Always execute the bottom-most element possible
- CD-DAT schedule:
  - 2A B A B 2A B A B C D … A B C 2D
  - Required Buffer Size: 26
  - 251 entries in the schedule
- Hard to implement efficiently, as schedule is VERY large



SAS vs Pull Schedule

	Buffer Size	Schedule Size
SAS	258	4
Pull Schedule	26	251

Need something in between SAS and Pull Scheduling

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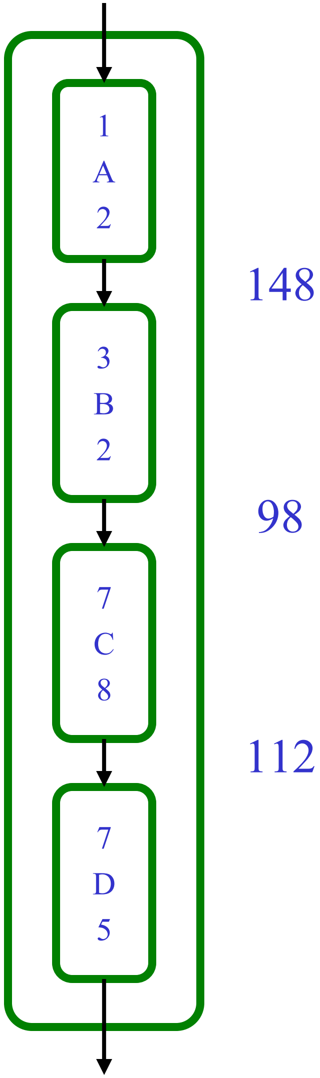
Phased Scheduling

- Idea:
  - What if we take the naïve SAS schedule, and divide it into n roughly equal phases?
- Buffer requirements would reduce roughly by factor of n
- Schedule size would increase by factor of n
- May be OK, because buffer requirements dominate schedule size anyway!

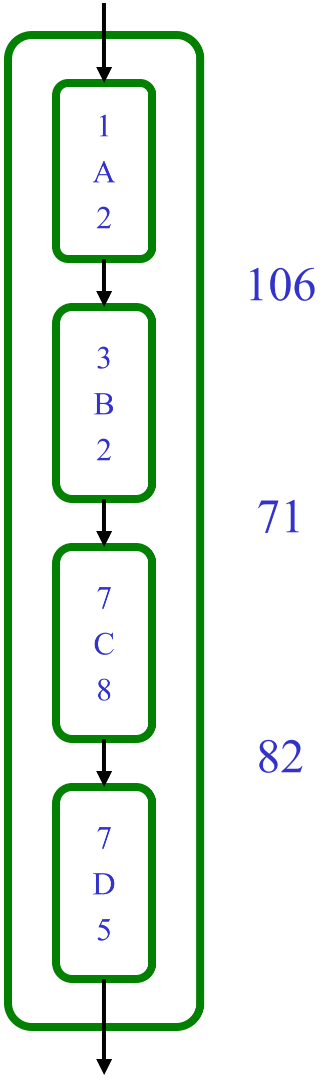
Phased Scheduling

- Try n = 2:
- Two phases are:
  - 74A 49B 14C 16D
  - 73A 49B 14C 16D
- Total Buffer Size: 358
- Small schedule increase
- Greater n for bigger savings



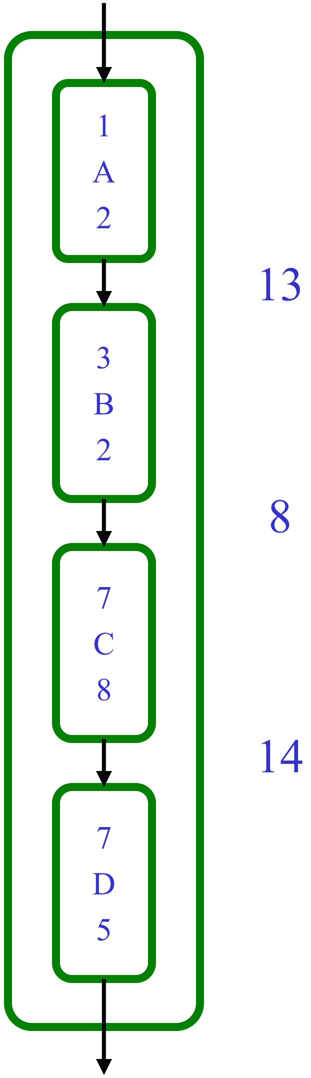
Phased Scheduling

- Try n = 3:
- Three phases are:
  - 48A 32B 9C 10D
  - 53A 35B 10C 11D
  - 46A 31B 9C 11D
- Total Buffer Size: 259
- Basically matched best SAS result
  - Best SAS was 258



Phased Scheduling

- Try n = 28:
- The phases are:
  - 6A 4B 1C 1D
  - 5A 3B 1C 1D
  - …
  - 4A 3B 1C 2D
- Total Buffer Size: 35
- Drastically beat best SAS result
  - Best SAS was 258
- Close to minimal amount (pull schedule)
  - Pull schedule was 26

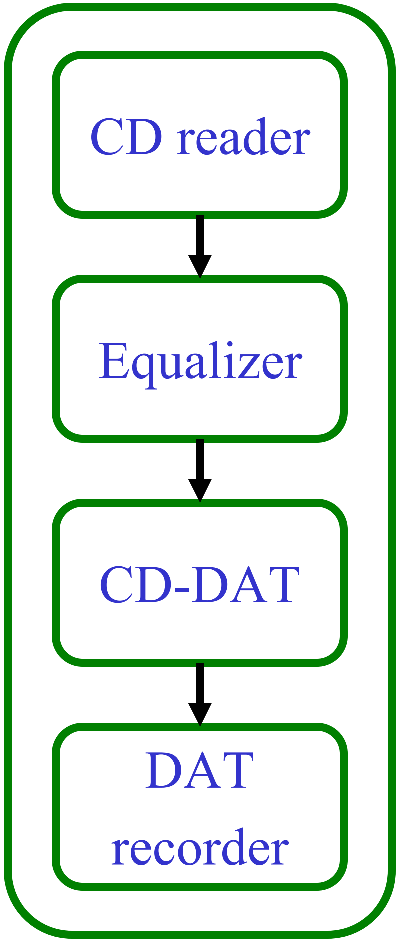


CD-DAT Comparison: SAS vs Pull vs Phased

	Buffer Size	Schedule Size
SAS	258	4
Pull Schedule	26	251
Phased Schedule	35	52

Phased Scheduling

- Apply technique hierarchically
- Children have several phases which all have to be executed
- Automatically supports cyclo-static filters
- Children pop/push less data, so can manage parent's buffer sizes more efficiently



Phased Scheduling

- What if a Steady State of a component of a FeedbackLoop required more data than available?
- Single Appearance couldn't do separate compilation!
- Phased Scheduling can provide a fine-grained schedule, which will always allow separate compilation (if possible at all)

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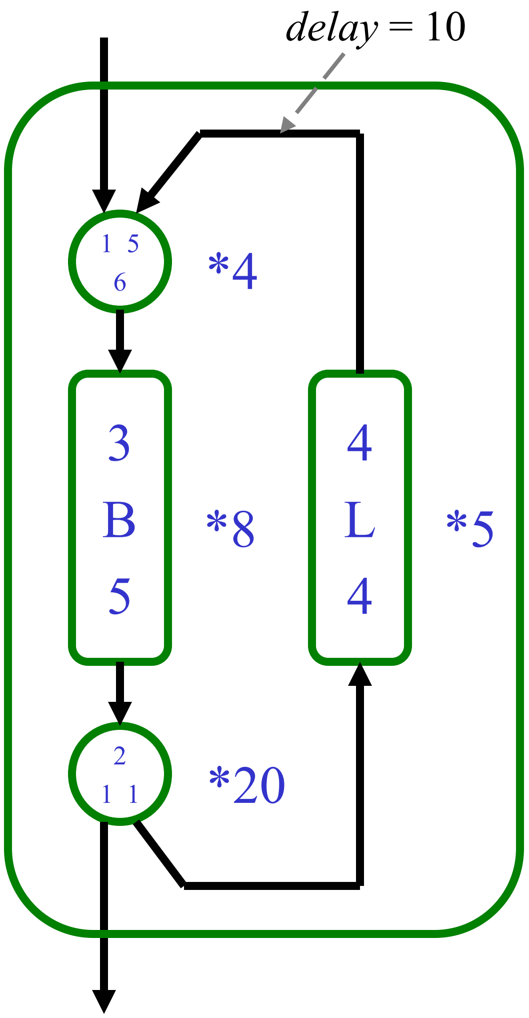
Minimal Latency Schedule

- Every Phase consumes as few items as possible to produce at least one data item
- Every Phase produces as many data items as possible
- Guarantees any schedulable program will be scheduled without deadlock
- Allows for separate compilation
- For details, see our paper

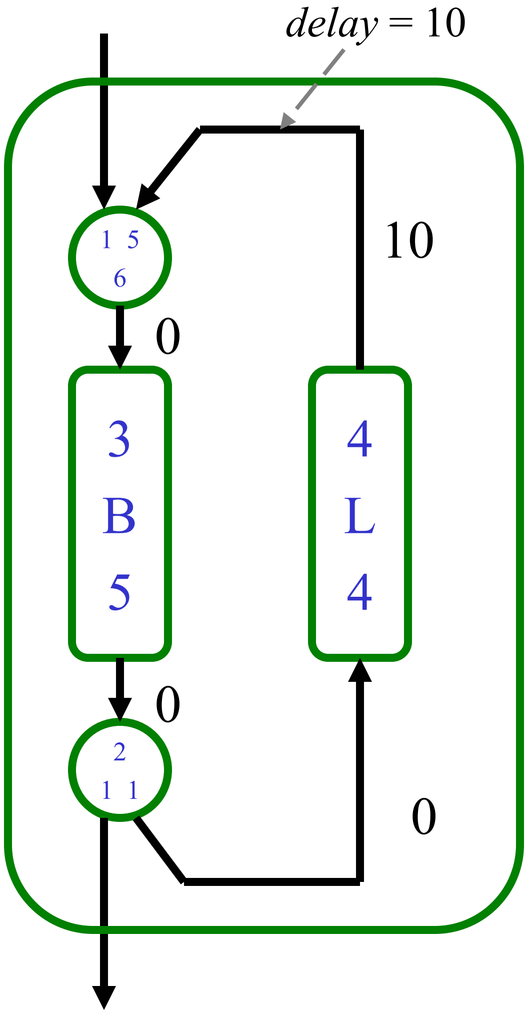
Minimal Latency Scheduling

- Simple FeedbackLoop with a tight *delay* constraint
- Not possible to schedule using SAS
- Can schedule using Phased Scheduling
  - Use Minimal Latency Scheduling



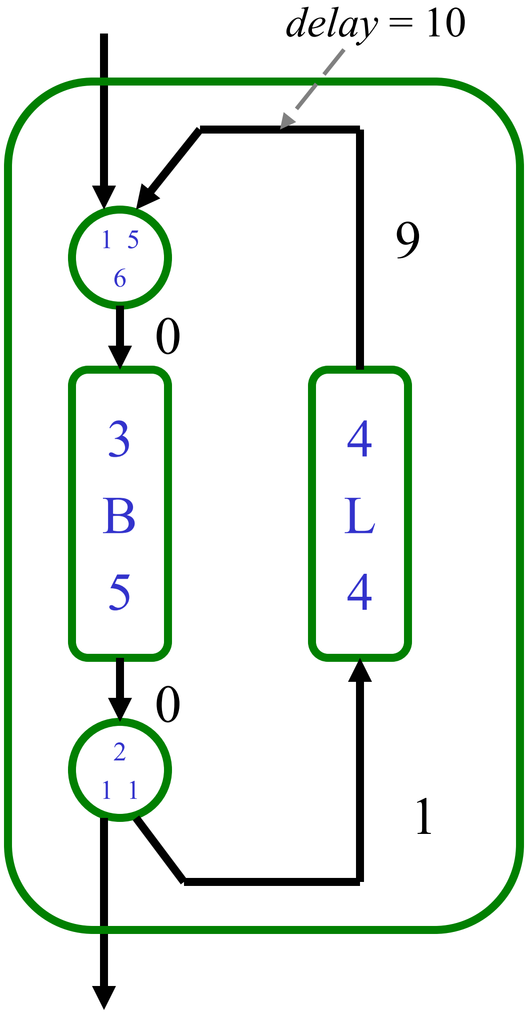
Minimal Latency Scheduling

- Minimal Latency Phased Schedule:



Minimal Latency Scheduling

- Minimal Latency Phased Schedule:
  - join 2B 5split L



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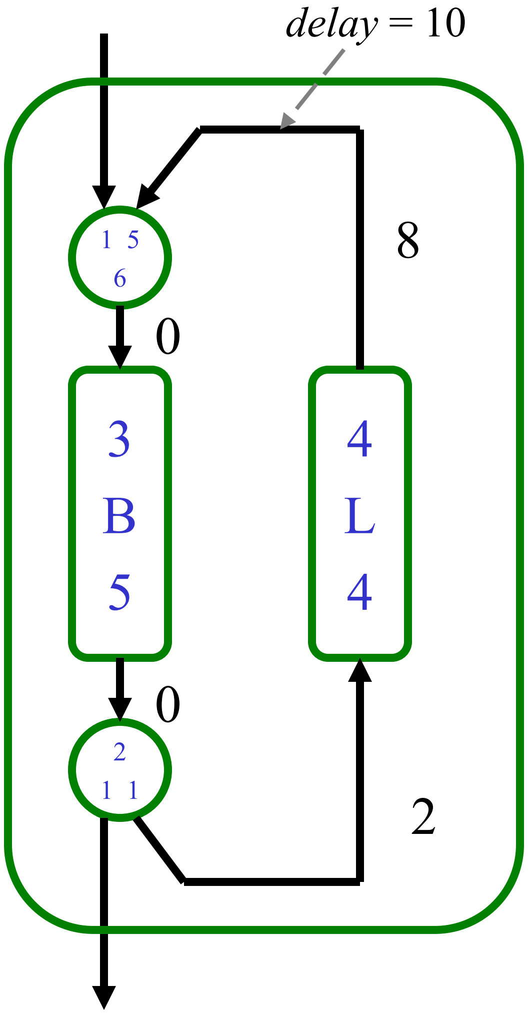

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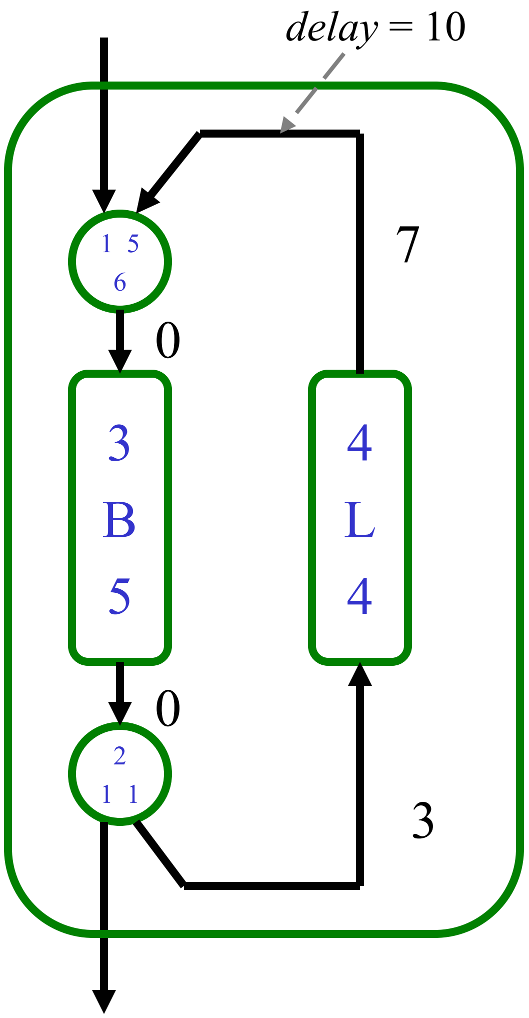

Minimal Latency Scheduling

- Minimal Latency Phased Schedule:
  - join 2B 5split L
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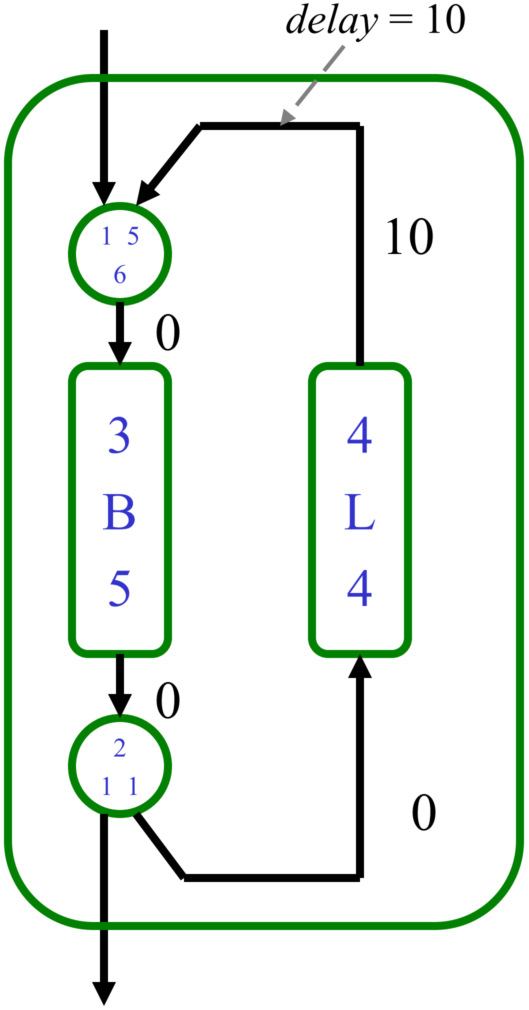
  - join 2B 5split 2L



Minimal Latency Schedule

- Minimal Latency Phased Schedule:
  - join 2B 5split L
  - join 2B 5split L
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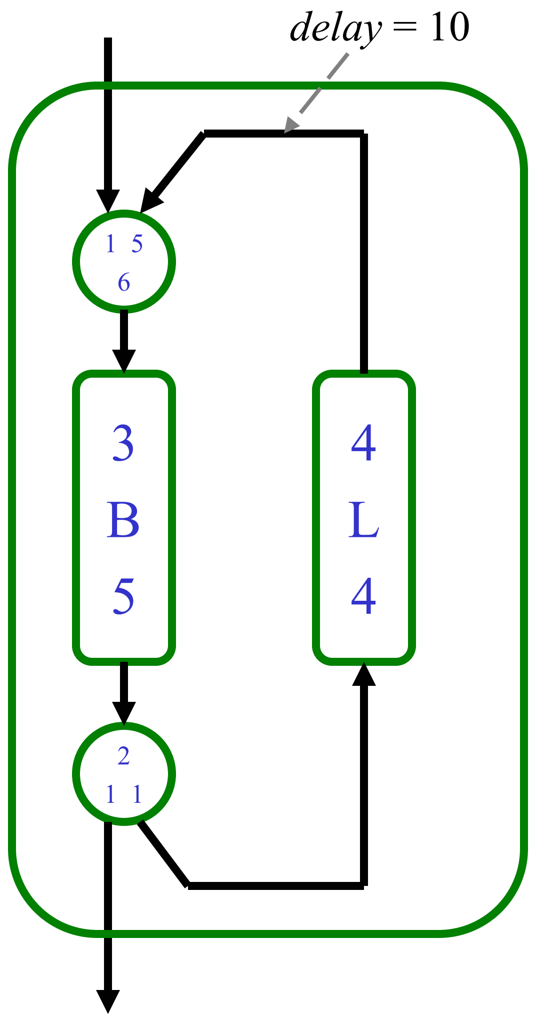
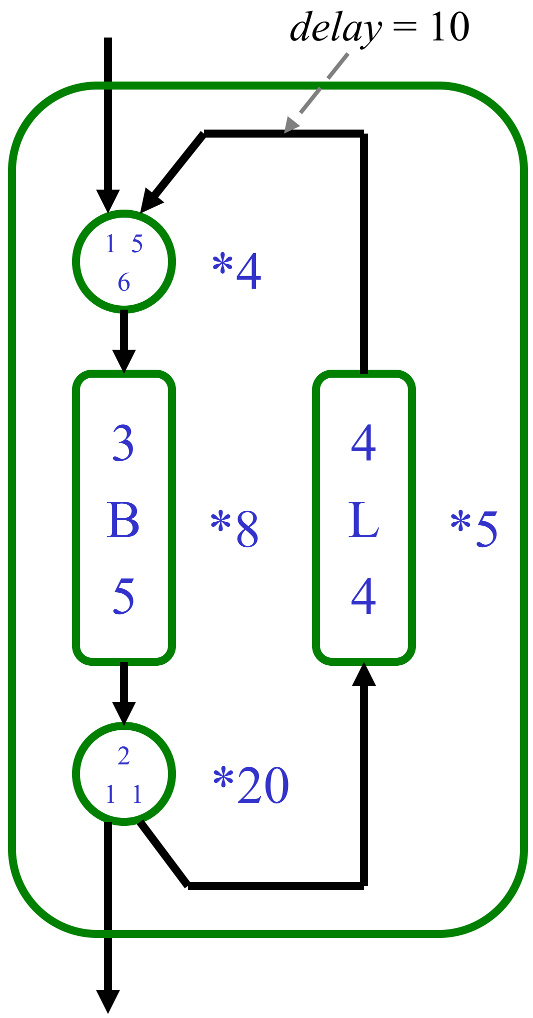
  - join 2B 5split 2L
- Can also be expressed as:
  - 3 {join 2B 5split L}
  - join 2B 5split 2L
- Common to have repeated Phases



Why not SAS?

- Naïve SAS schedule
  - 4join 8B 20split 5L:
  - Not valid because 4join consumes 20 data items
- Would like to form a loop-nest that includes join and L
- But multiplicity of executions of L and join have no common divisors



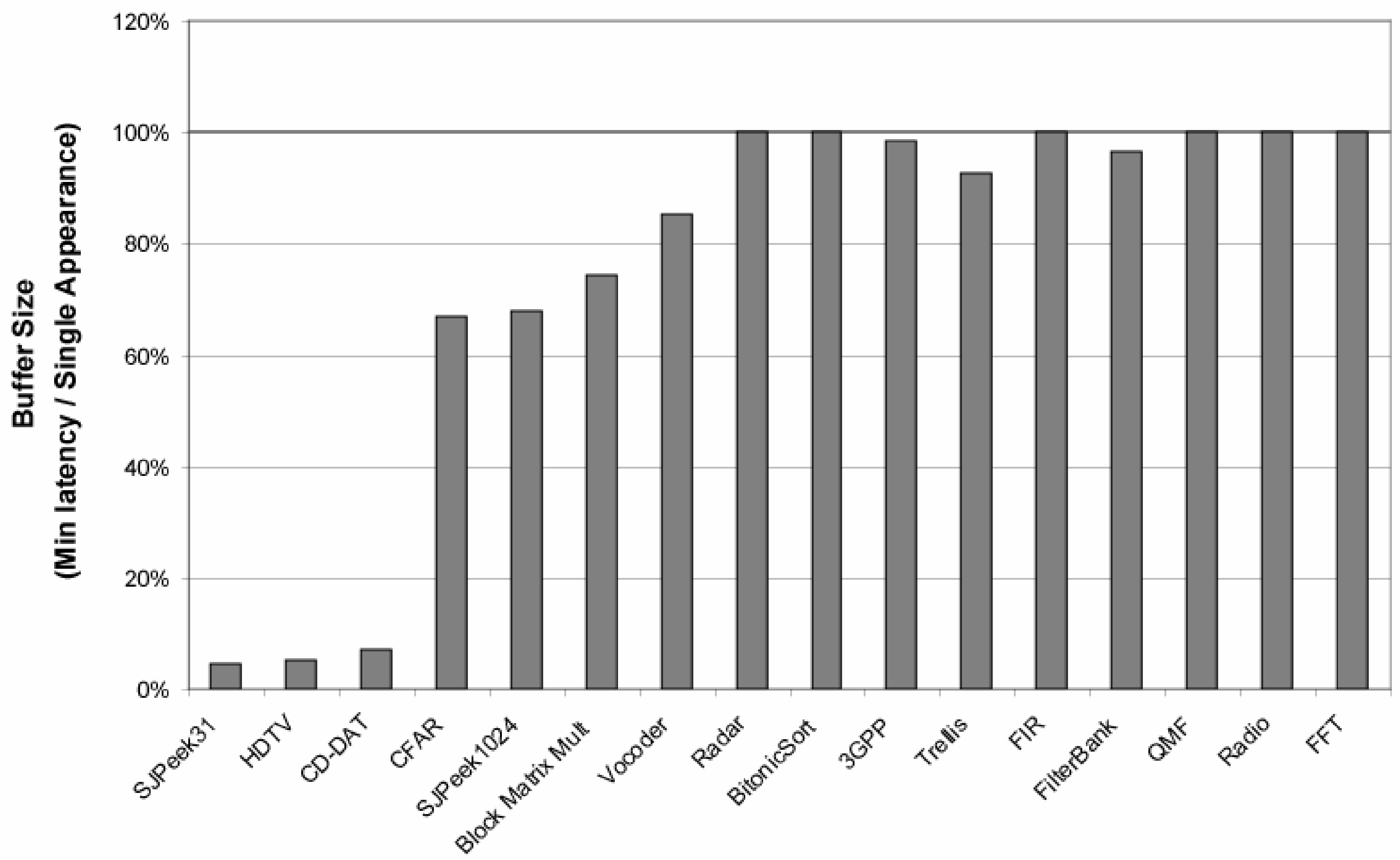
Overview

- General Stream Concepts
- StreamIt Details
- Program Steady State and Initialization
- Single Appearance and Pull Scheduling
- Phased Scheduling
  - Minimal Latency
- Results
- Related Work and Conclusion

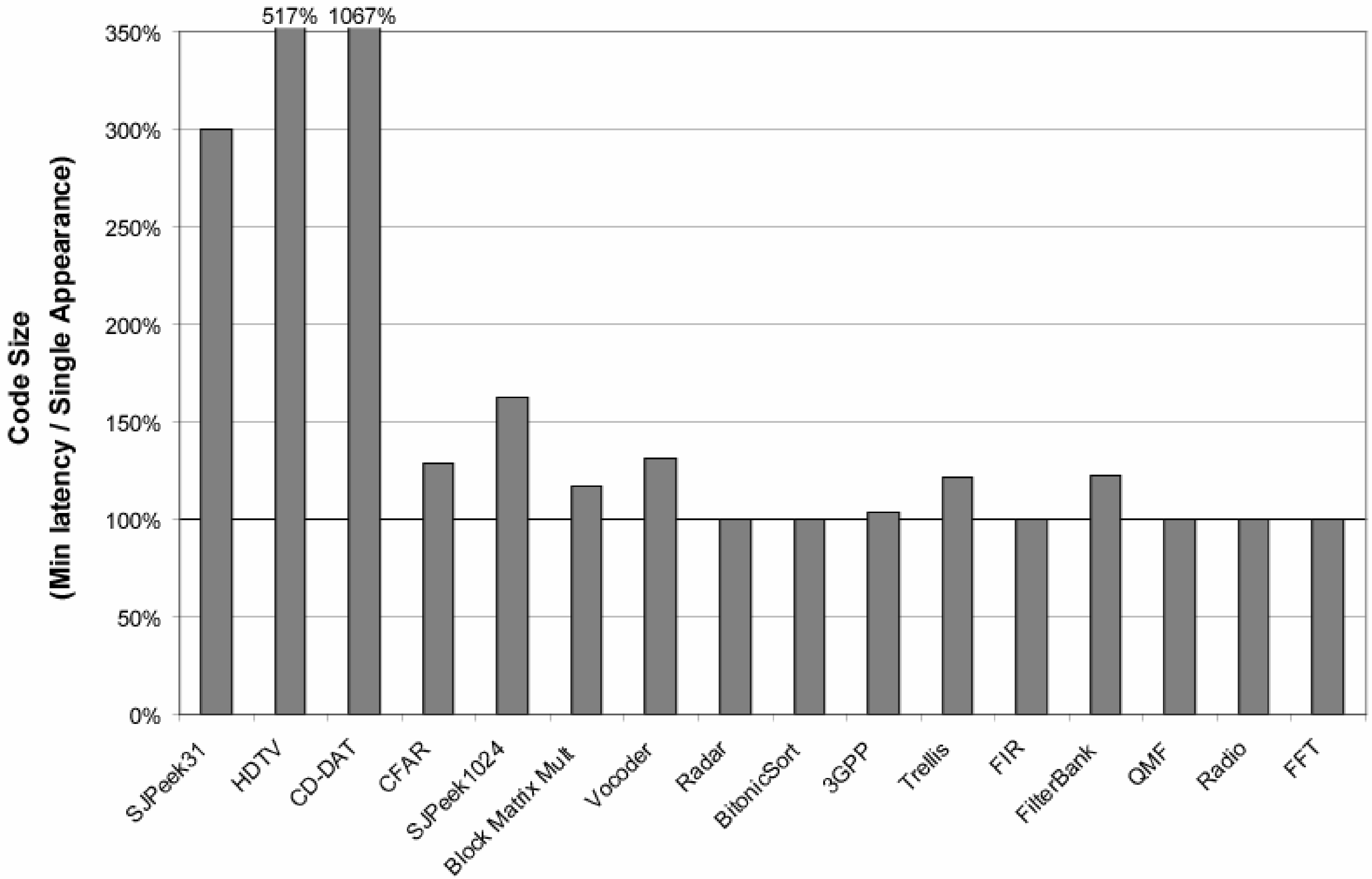
Results

- SAS vs Minimal Latency
- Used 17 applications
  - 9 from our ASPLOS paper
  - 2 artificial benchmarks
  - 2 from Murthy99
  - Remaining 4 from our internal applications

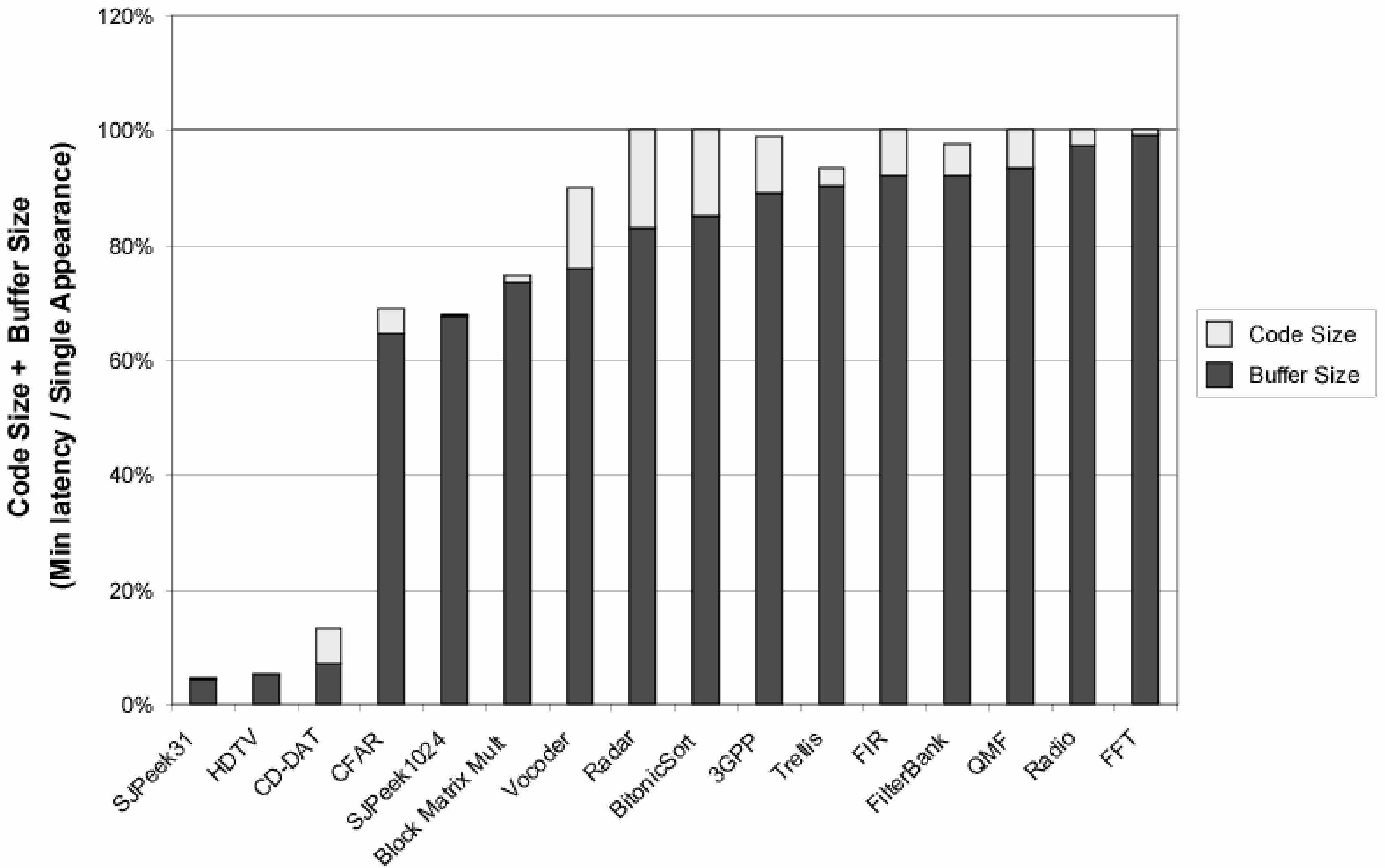
Results - Buffer Size



Results – Schedule Size



Results - Combined



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Related Work

- Synchronous Data Flow (SDF)
- Ptolemy [Lee et al.]
- Many results for SAS on SDF
  - Memory Efficient Scheduling [Bhattacharyya97]
  - Buffer Merging [Murthy99]
- Cyclo-Static [Bilsen96]
- Peeking in US Navy Processing Graph Method [Goddard2000]
- Languages: LUSTRE, Esterel, Signal

Conclusion

Presented Phased Scheduling Algorithm

- Provides efficient interface for hierarchical scheduling
- Enables separate compilation with safety from deadlock
- Provides flexible buffer / schedule size trade-off
- Reduces latency of data throughput

Step towards a large scale hierarchical stream programming model

Phased Scheduling of Stream Programs

StreamIt Homepage

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