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 \textit{pop} data items
- Produces \textit{push} data items
- Inspects \textit{peek} data items
StreamIt - Filter

- Example:
  - FIR filter

- peek = 3
- pop = 1

- push = 1
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items

FIR

peek = 3 pop = 1
push = 1
StreamIt - Filter

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

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

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

```
peek = 3 pop = 1
push = 1
```
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item
  - Produces 1 data item
  - And again…
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item
  - Produces 1 data item
  - And again…

FIR
peek = 3 pop = 1
push = 1
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item
  - Produces 1 data item
  - And again…
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item
  - Produces 1 data item
  - And again…

\[
\begin{align*}
\text{peek} &= 3 \\
\text{pop} &= 1 \\
\text{push} &= 1
\end{align*}
\]
StreamIt - Filter

- Example:
  - FIR filter
  - Inspects 3 data items
  - Consumes 1 data item
  - Produces 1 data item
  - And again…
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 Feedback Loop

- ONLY structure to allow data cycles
- Needs initialization on feedbackPath
- Amount of data on feedbackPath is \textit{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 $2 \times 3 = 6$ items
- B executes 3 times
  - pops $3 \times 2 = 6$ items
- Number of data items stored between Filters does not change
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - pop = 1
  - A
  - push = 3
  - pop = 2
  - B
  - push = 1
Steady State Example

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

```
pop = 1
A
push = 3

pop = 2
B
push = 1
```
Steady State Example

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

```
pop = 1
A
push = 3

0
1

pop = 2
B
push = 1
```
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - A
Steady State Example

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

```plaintext
pop = 1
A
push = 3

pop = 2
B
push = 1
```
Steady State Example

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

```
{c}
pop = 1
A
push = 3

0
--->
3

0
--->
0
```

pop = 2
B
push = 1
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AA
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AAB
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AAB
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AAB
Steady State Example

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

Schedule:
- pop = 1
- A
- push = 3

Schedule:
- pop = 2
- B
- push = 1

Diagram:
- 0
- 4
- 1
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AABB
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
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- Schedule:
  - AABB
Steady State Example

- 3:2 Rate Converter
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- Schedule:
  - AABBB
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
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- Schedule:
  - AABBB
Steady State Example

- 3:2 Rate Converter
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  - AABBB
Steady State Example

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Steady State Example

- 3:2 Rate Converter
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- Second filter (B) downsamples by factor of two
- Schedule:
  - AABBB
  - A
Steady State Example

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- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AABBB
  - A
Steady State Example

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- Second filter (B) downsamples by factor of two
- Schedule:
  - AABBB
  - A
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AABBB
  - AB
Steady State Example

- 3:2 Rate Converter
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  - AB
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  - ABA
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  - AABBB
  - ABAB
Steady State Example

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  - AABBB
  - ABABB
Steady State Example

- 3:2 Rate Converter
- First filter (A) upsamples by factor of 3
- Second filter (B) downsamples by factor of two
- Schedule:
  - AABBB
  - ABABB
Steady State Example - Buffers

- AABBB requires 6 data items of buffer space between filters A and B
- ABABBB 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:
  - pop = 1
  - push = 3
  - peek = 3, pop = 2
  - push = 1
Initialization

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

```
pop = 1
push = 3
```

```
2
```

```
3
```

```
peek = 3, pop = 2
push = 1
```

```
0
```
Initialization

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

- 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:
  - 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:
  - pop = 1
  - push = 3
  - peek = 3, pop = 2
  - push = 1
Initialization

- Initialization Schedule:
  - A

```
pop = 1
A
push = 3
```

```
peek = 3, pop = 2
B
push = 1
```

```
0
```
Initialization

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

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

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

- Steady State Schedule:
  - AA
Initialization

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

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

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

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

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

- Steady State Schedule:
  - AABBB
  - 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!
SAS Example – Buffer Size

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

- Optimal SAS CD-DAT schedule:
  - 49{3A 2B} 4{7C 8D}
  - Required Buffer size: 258
SAS Example – Buffer Size

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

- Optimal SAS CD-DAT schedule:
  - 49{3A 2B} 4{7C 8D}
  - Required Buffer size: 258
SAS Example – Buffer Size

- Naïve SAS schedule:
  - 147A 98B 28C 32D
  - Required Buffer Size: 714
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- Optimal SAS CD-DAT schedule:
  - 49\{3A 2B\} 4\{7C 8D\}
  - Required Buffer size: 258
SAS Example – Buffer Size

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  - 49{3A 2B} 4{7C 8D}
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SAS Example – Buffer Size

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  - 147A 98B 28C 32D
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  - 49{3A 2B} 4{7C 8D}
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SAS Example – Buffer Size

- Naïve SAS schedule:
  - 147A 98B 28C 32D
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SAS Example – Buffer Size

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

- Optimal SAS CD-DAT schedule:
  - 49{3A 2B} 4{7C 8D}
  - Required Buffer size: 258
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

<table>
<thead>
<tr>
<th></th>
<th>Buffer Size</th>
<th>Schedule Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAS</td>
<td>258</td>
<td>4</td>
</tr>
<tr>
<td>Pull Schedule</td>
<td>26</td>
<td>251</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
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</tr>
</thead>
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<td>4</td>
</tr>
<tr>
<td>Pull Schedule</td>
<td>26</td>
<td>251</td>
</tr>
<tr>
<td>Phased Schedule</td>
<td>35</td>
<td>52</td>
</tr>
</tbody>
</table>
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 Feedback Loop with a tight *delay* constraint
- Not possible to schedule using SAS
- Can schedule using Phased Scheduling
  - Use Minimal Latency Scheduling

Delay: 10
Minimal Latency Scheduling

- Minimal Latency Phased Schedule:
Minimal Latency Scheduling

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

![Diagram showing a minimal latency phased schedule with nodes labeled 1, 2, 3, 4, 5, 6 and delay = 10]
Minimal Latency Scheduling

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

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

\[ \text{delay} = 10 \]
Minimal Latency Scheduling

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

[Diagram showing a network with labels 1, 2, 3, 4, 5, 6, 10, 0, delay = 10]
Minimal Latency Schedule

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

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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