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EXTENDING CODELET MODEL FOR DATAFLOW SOFTWARE PIPELINING USING SOFTWARE-HARDWARE CO-DESIGN

Siddhisanket Raskar, Thomas Applencourt, Kalyan Kumaran, Guang Gao

SIDDHISANKET RASKAR
Research Aide, Argonne National Lab.
PhD Candidate, University of Delaware.

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U.S. DEPARTMENT OF ENERGY
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Outline

Background & Motivation

- Software Pipelining
- Dataflow Software Pipelining
- Codelet Model

Solution Methodology

- Extension of Codelet PXM
- Extension of CAM
- Optimizations

Problem Formulation

- Defining Class of Codelet Graph
- Challenges

Future Work

- Implementation of PXM & CAM
- Kernels & Applications

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Software Pipelining

Basics

Without Software Pipelining

Execution of loop without Software Pipelining -

- Each iteration takes 9 cycles to produce result.
- The next iteration starts after the earlier iteration finishes.
- Loop unrolling techniques can be used.

```
L  :  for (i=0 ; I < 3 ; i++)

s1:      a[i] = a[i] + 1 ;
s2:      b[i] = a[i] + 1 ;
s3:      c[i] = b[i] + 1 ;
```

C++ Code : Simple Loop

Assumption

- There is only 1 compute unit for each instruction in pipeline.
- Lets assume each instruction takes 3 cycles

Cycle	I1	I2	I3
1	s1		
2			
3			
4	s2		
5			
6			
7	s3		
8			
9			
10		s1	
11			
12			
13		s2	
14			
15			
16		s3	
⋮			

Schedule with no Software Pipelining

Software Pipelining

Basics

With Software Pipelining

Is the technique used for loop optimization where iteration of a loop is activated before its preceding iteration is complete.

- Instructions are reordered as long as they satisfy the dependencies.
- It's a static, compile time technique.
- It uses dependence graph to compute schedule statically.

```
L  :  for (i=0 ; I < 3 ; i++)

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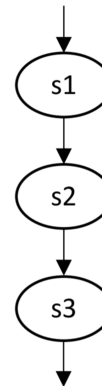
C++ Code : Simple Loop

Assumption

- There is only 1 functional unit for each task in pipeline.
- Lets assume each instruction takes 3 cycles



Dependence Graph

Cycle	I1	I2	I3
1	s1		
2		s1	
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4	s2		
5		s2	
6			s2
7	s3		
8		s3	
9			s3
10			
11			
⋮			

Schedule with Software Pipelining

Software Pipelining
Advantages

Advantages

- Throughput of the system is improved with schedule with software pipelining.

Rau et al.81 (MICRO14)
Modulo Scheduling

Rau et al.94 (MICRO27)
Iterative Modulo Scheduling

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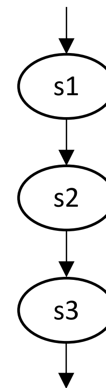

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Schedule with no Software Pipelining

Dataflow Software Pipelining

Basics

Dataflow Software Pipelining

- Dataflow Software Pipelining is compile time as well as runtime technique.
- The naturally available information about dependencies is used at runtime for scheduling.
- Tokens from various iterations of the loop are executed.

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C++ Code : Simple Loop

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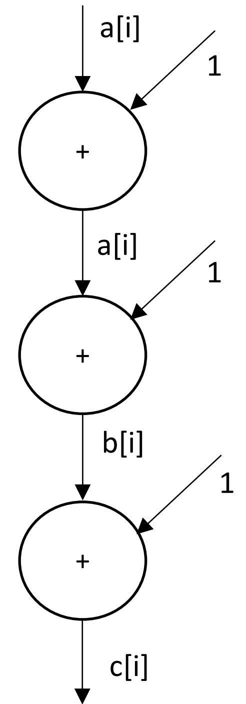
- There are 3 PEs.
- Lets assume each instruction takes 1 cycle.



Only Loop Body

	Tokens Iteration 1
	Tokens Iteration 2
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G. R. Gao, “Algorithmic aspects of balancing techniques for pipelined data flow code generation,” *J. Parallel Distrib. Comput.*, vol. 6, pp. 39– 61, Feb. 1989.

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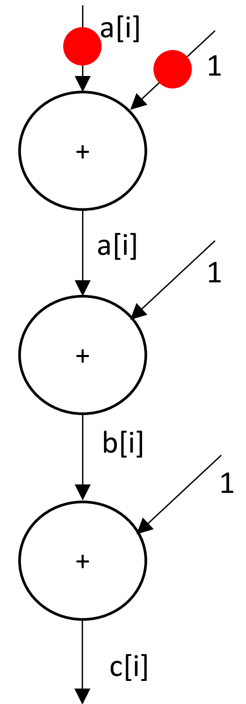

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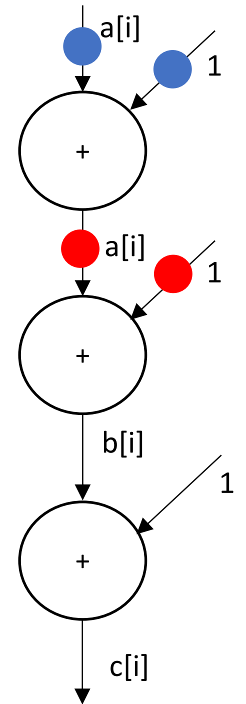

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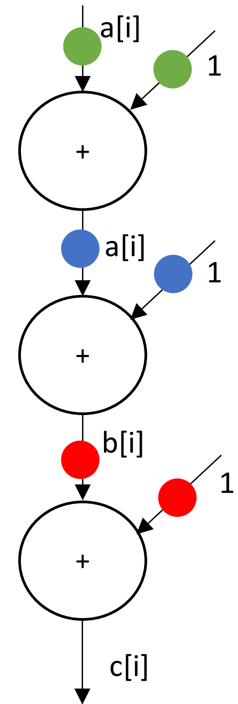

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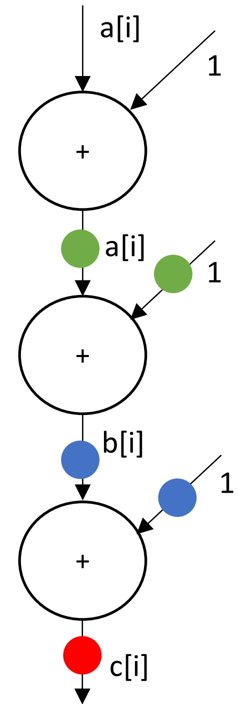

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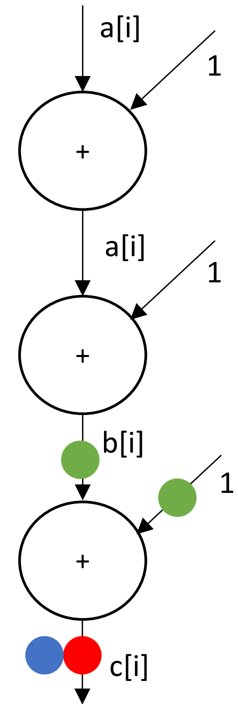

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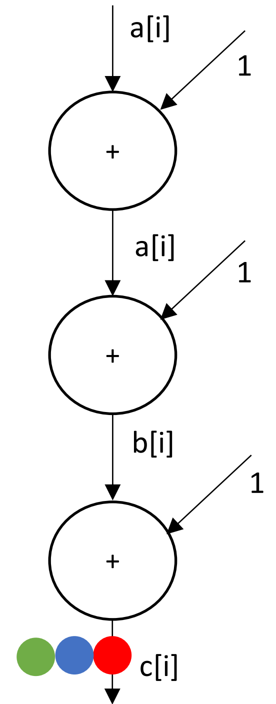

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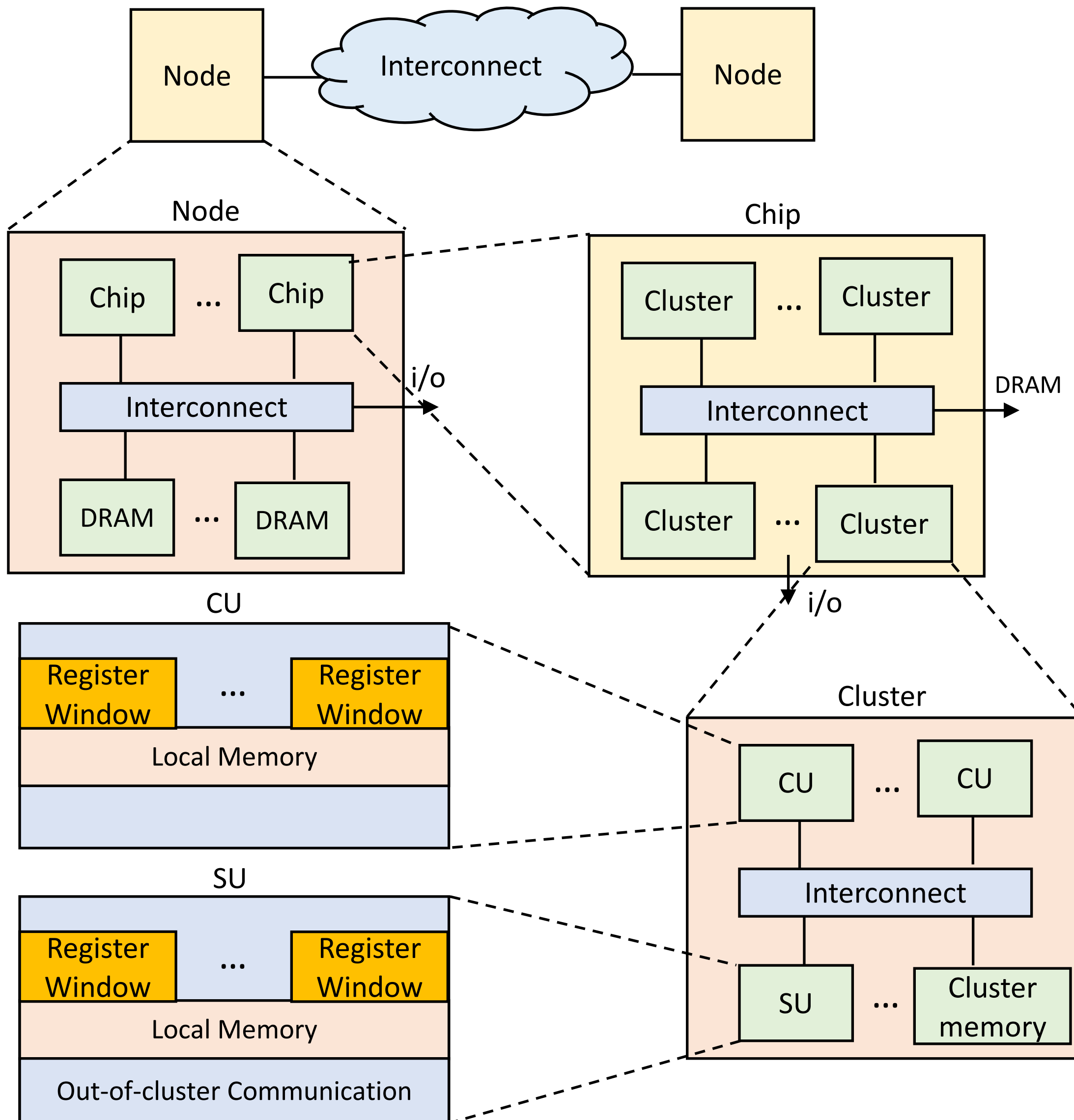
Original Codelet Model
Abstract Machine



Firing Rules

- A codelet becomes enabled once tokens (events) are present on each of its input arcs.
- An enabled actor can be fired if it has acquired all its required resource and is scheduled for execution.
- A codelet actor fires by consuming tokens on its input arcs, performing the operations within the codelet, and producing a token (event) on each of its output arcs.

S. Zuckerman, J. Suetterlein, R. Knauerhase, and G. R. Gao, "Using a "codelet" program execution model for exascale machines: Position paper," in *Proceedings of the 1st International Workshop on Adaptive Self-Tuning Computing Systems for the Exaflop Era*, EXADAPT '11, (New York, NY, USA), pp. 64–69, ACM, 2011.

Motivation

Software Pipelining is one of the most successful technology in the exploitation of *Instruction Level Parallelism*

How should the success of software pipelining be exploited under the new many core architecture area?

Unsolved Challenges

Nested Loops

- Numerous techniques exist for single loops (innermost loop) but only few address software pipelining of loop nests.

Multiple Cores

- Traditional software pipelining techniques relied on good static hardware & scheduling techniques which satisfied uniprocessor architectures.
- Challenges to extend this for multiple cores
  - Variability of instruction timing between cores
  - Loop carried dependencies must be realized across different cores.
  - Variable runtime traffic in the on-chip network.

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Problem Formulation

Defining Class of Codelet Graphs

A programming model which will leverage
coarse grain parallelism at Codelet graph level &
fine grain parallelism at Codelet level.

At Codelet Graph Level

Class of Codelet graphs for which software pipelining advantages can be clearly demonstrated.

- No Loops.
- Self Loops are allowed.

At Codelet Level

Leverage upon all the work done on the instruction level parallelism & dataflow software pipelining.

- Dependency analyzable loops
- Dependency restricted to affine functions.

Motivating Example
Producer – Consumer Problem

```
#include<iostream>
using namespace std;

int main()

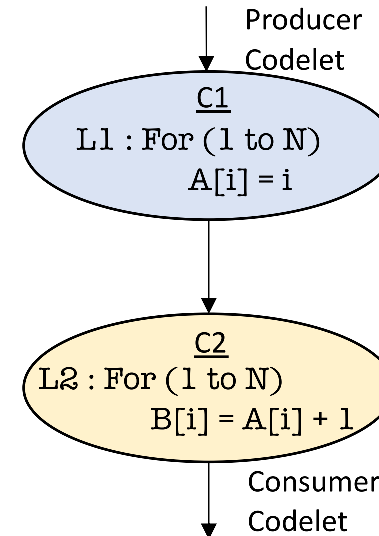
{
    int A[10], B[10];
    int i;

    for(i=0;i<10;i++)
        A[i]=i;

    for(i=0;i<10;i++)
        B[i]=A[i]+1;

    return 1;
}
```

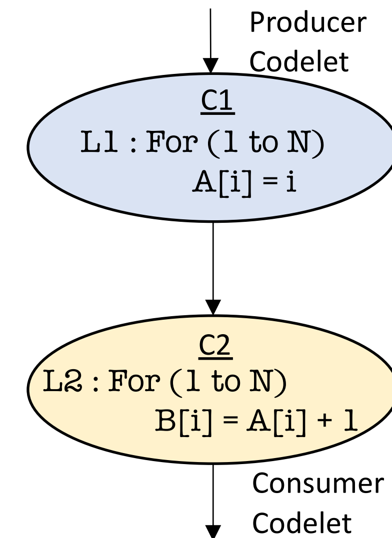
Memory Copy Example



Producer – Consumer Codelets

Motivating Example
Original Codelet Model

- Codelet 1 :
  - Loop with N iterations
- Codelet 2 :
  - loop with N iteration
- Execution :
  - Codelet 1 finishes its execution, sends signal to Codelet 2.
- Output :
  - It will take time required for N + N iterations.
  - We also need to store output of Codelet 1 somewhere and then load it for Codelet 2.

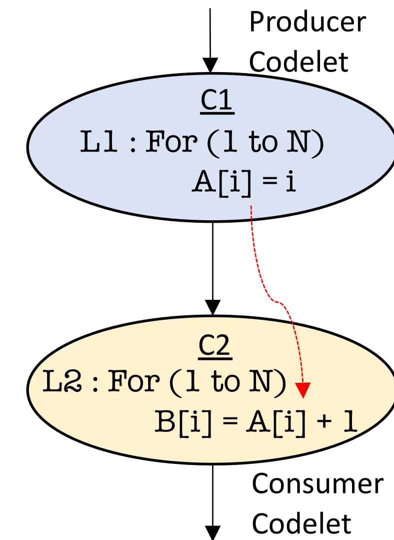


Producer-Consumer Codelets

Motivating Example
Extended Codelet Model with Dataflow Software Pipelining

- Codelet 1 :
  - Loop with N iterations
- Codelet 2 :
  - loop with N iteration
- Execution :
  - With Dataflow Software Pipelining,
    we can start execution of Codelet 2 while Codelet 1 execution is still not finished.

- Output :
  - We can start iteration 1 of Codelet 2 after iteration 1 of Codelet 1 finishes.
  - The first output will be produced at unit time 3.
  - Output will be produced at each iteration after that.



Producer-Consumer Codelets

Challenges
Dataflow Software Pipelining for Codelet Model

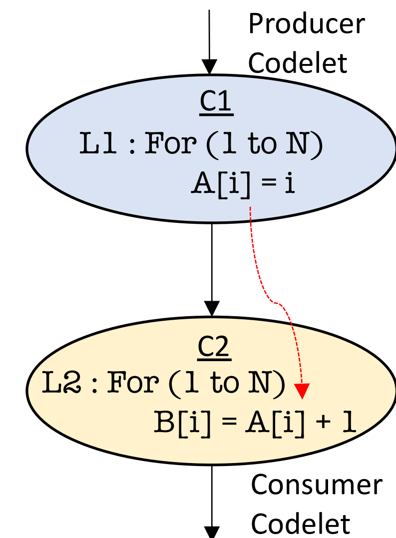
Challenge 1

- Dataflow Software Pipelining behavior described above is ***not*** possible with Original Codelet Model.
  - ***Firing rules*** will not allow Consumer Codelet to fire before Producer Codelet finishes its execution.

- Such a behavior will be very useful for ***Streaming*** applications.

- Solution Methodology
  - Extension to kinds of *events*
  - Extension to *firing rules*.

Extended Codelet Program Execution Model



Producer-Consumer Codelets

Challenges

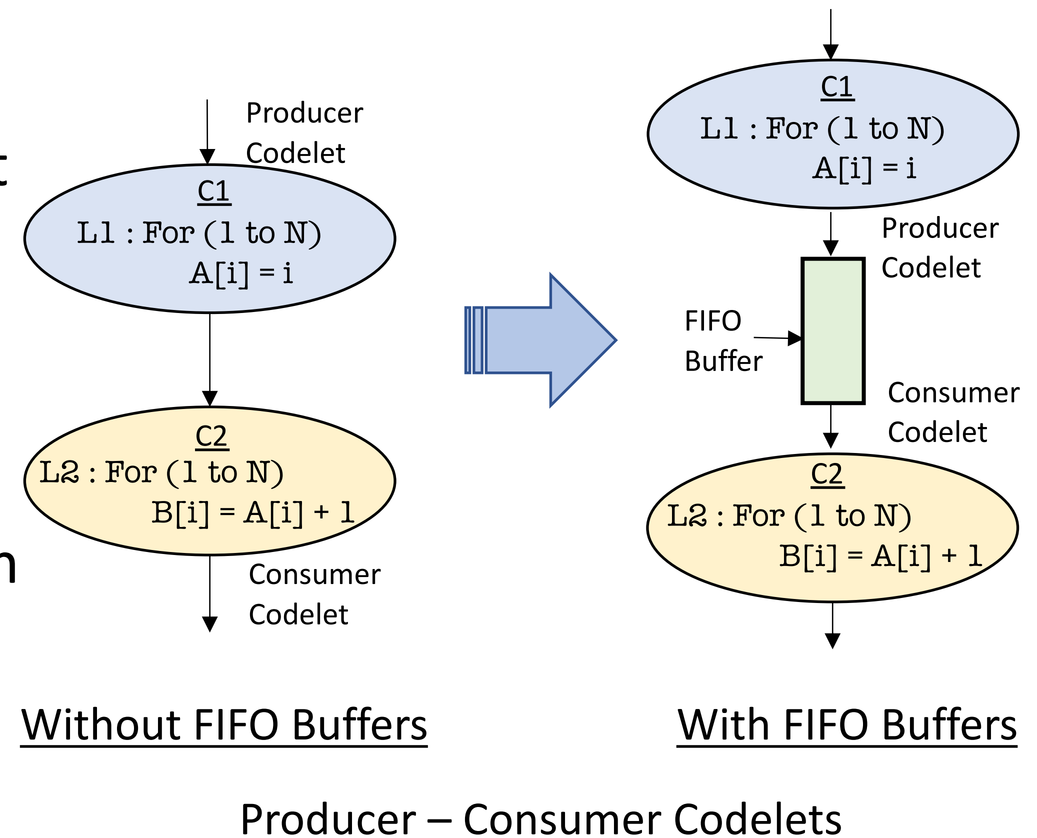
Dataflow Software Pipelining for Codelet Model

Challenge 2

- Software implementation of these extension to support Dataflow Software Pipelining in Codelet Program Execution Model will incur some additional *cost*.

- ***Hardware-Software Co-Design*** to efficiently support extension to Codelet Program Execution Model.

Extended Codelet Abstract Machine Model



Producer – Consumer Codelets

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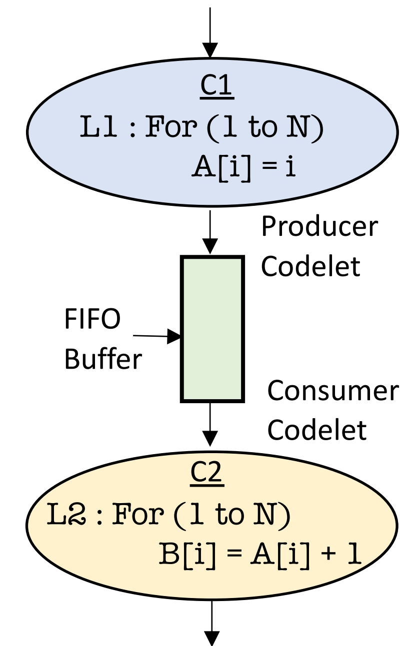
Solution Methodology
Step 1: Extending Codelet Program Execution Model.

Extending Firing Rules

- Under certain cases, We will allow next Codelet to begin its execution before the current Codelet has finished its execution.
  - *Producer-consumer* behavior
  - *forall* loop
- Codelet level API to support FIFO operations.
- Decided by compiler or explicitly indicated by programmer.

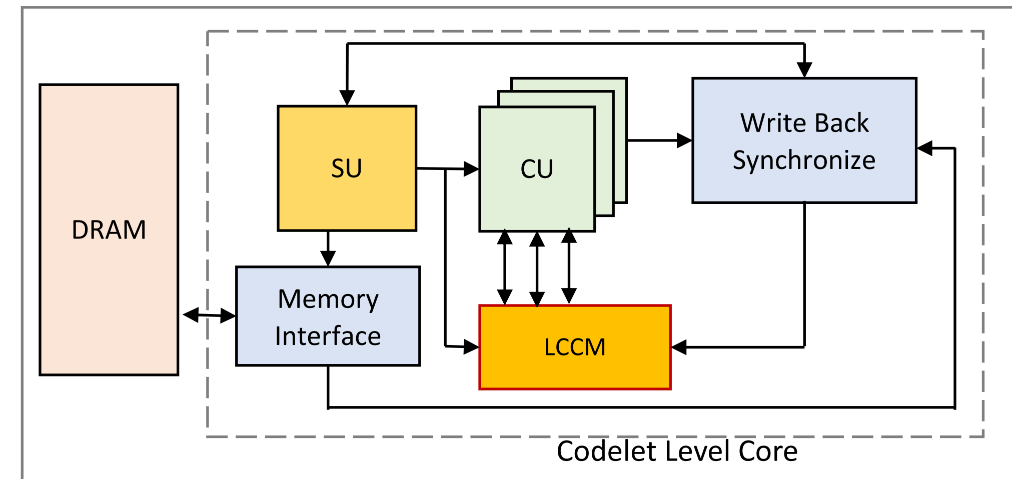


Producer-Consumer Codelets

Solution Methodology
Step 2 : Extending Codelet Abstract Machine

- Ongoing work on *Sequential Codelet Model (SCM) for parallel code execution.* [Monsalve et. al 2019]

- Focus on ***Codelet Level Core***
  - FIFO buffers can be envisioned in the *Local Codelet Level Core Memory* (LCCM)
  - Dataflow Software Pipelining at Threaded Procedure (TP) level.



[Monsalve et. al 201] "Sequential Codelet Model for Parallel Execution" , Jose M Monsalve Diaz, and Guang R Gao , CAPSL Technical Memo 132, June 2019.

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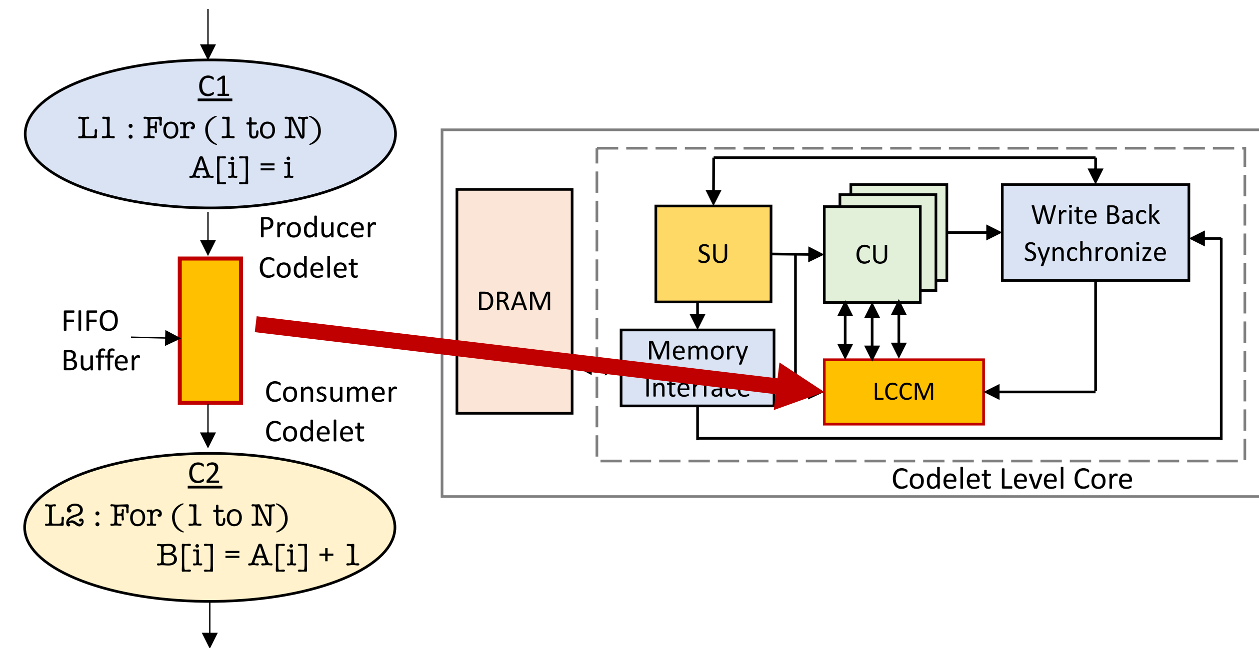
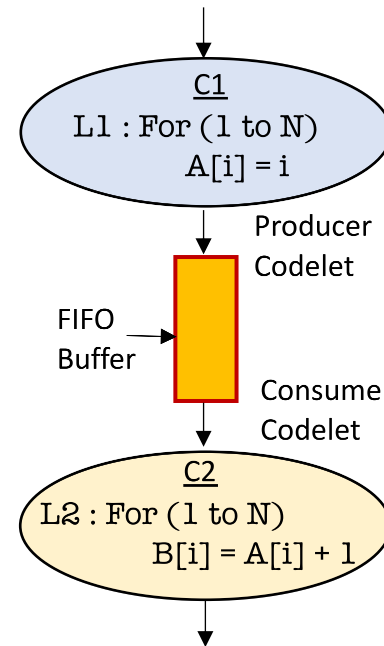
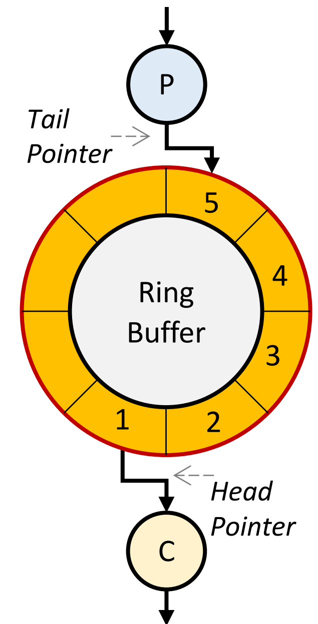


Solution Methodology
Step 3: Optimizations

- A *circular buffer* or a *ring buffer* is efficient data structure for *implementation* of FIFO buffer.
- elements are NOT shifted when one is consumed.
- Only *head* & *tail* pointers are updated every time data is added/ removed.





FIFO Ring Buffers

All Codelet graphs are not simplistic like Single producer – Single Consumer

Single Producer – Multiple Consumer

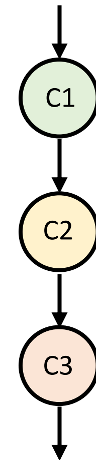
- ***Chain of Codelets.***
  - C1 is the only *producer* codelet.
  - C2 producer as well as consumer Codelet.
  - C3 is consumer Codelet.
- ***Tree of Codelets.***
  - P is the only *producer* codelet.
  - C1, C2 & C3 are consumer codelets.
  - They consume the same data tokens produced by codelet P.

Do you duplicate tokens & allocated separate FIFO buffer for each arc?

Or

You can find mechanism to share FIFO buffers?

Chain of Codelets



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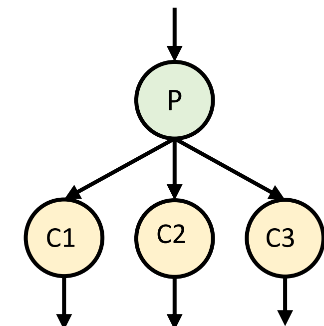
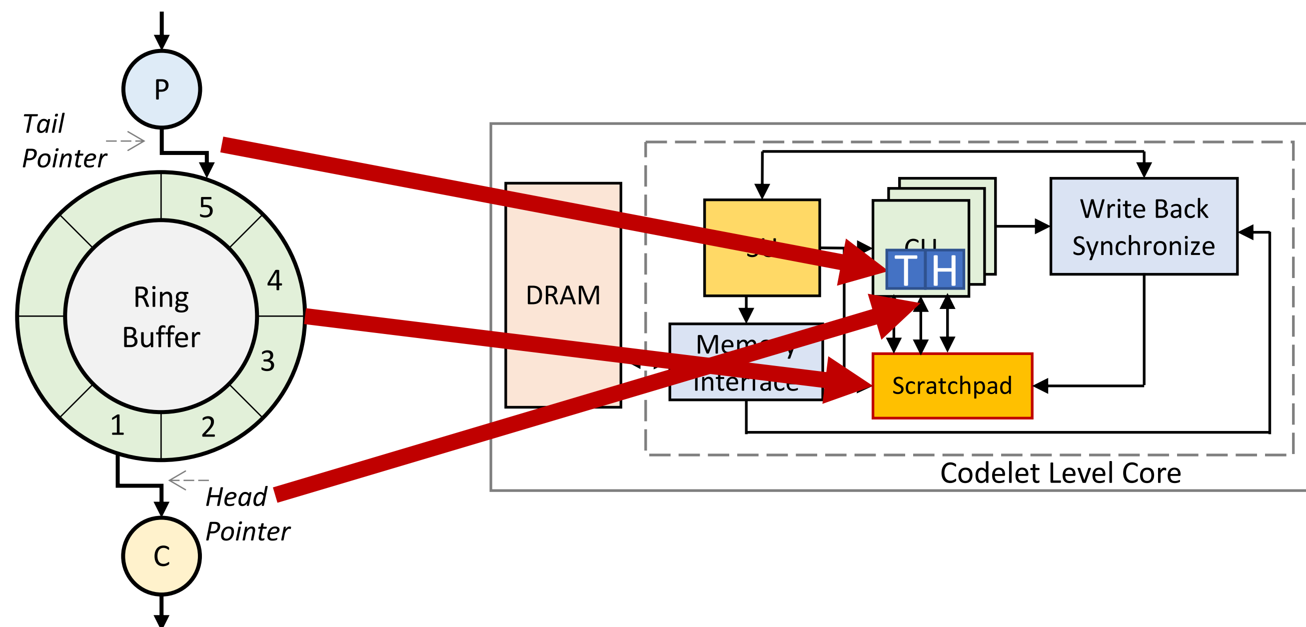


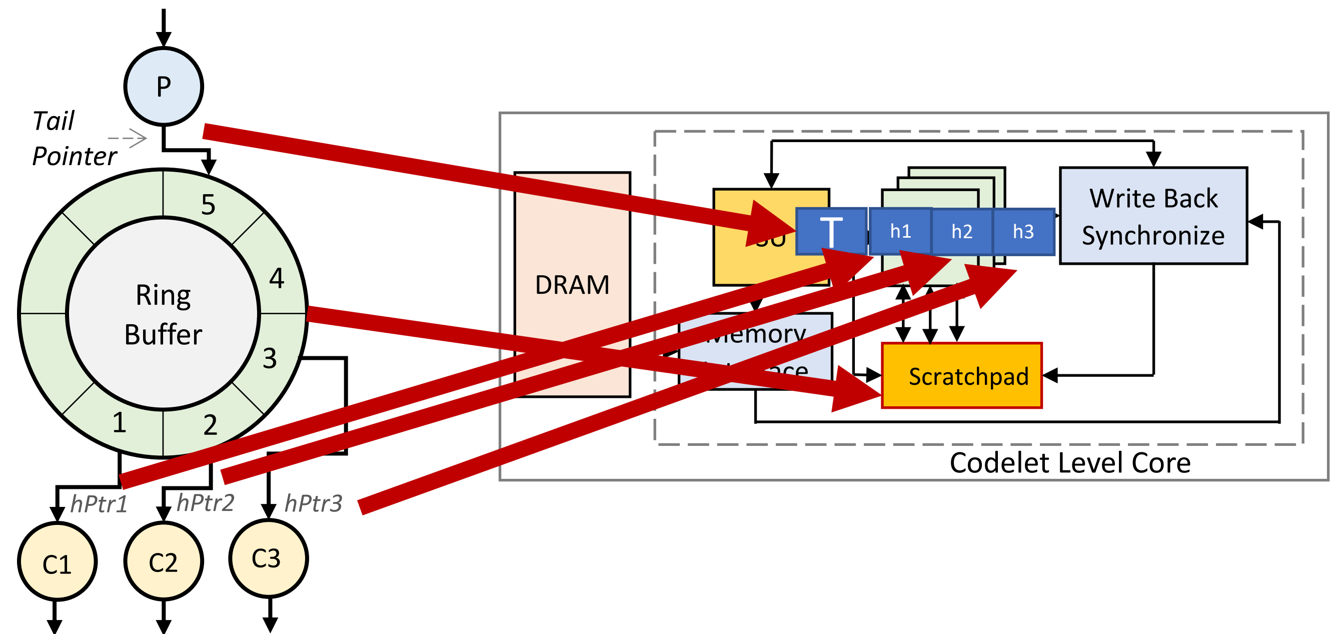
FIFO Ring Buffer

- Ring Buffer will be allocated in the LCCM (Scratchpad)
- The *tail* and *head* pointers will be maintained in the specific registers



Multiple-Head FIFO Ring Buffers

- Share FIFO Ring Buffer with all consumers of same producer
- Each Codelet will maintain head pointers in registers in their respective CUs.
- There will be only 1 tail pointer for 1 producer.



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Future Work

Implementation : Software

- Codelet Level Instruction Set Architecture (ISA) to leverage FIFO buffers.
- Extension to DARTS to support Dataflow Software Pipelining.

Implementation : Hardware-Software

- FPGA Implementation
  - DEMAC cluster [Roa et al. 2018]

Kernels & Applications

- Cannons algorithm for Matrix Multiplication.

[Roa et al. 2018] Diego Roa, Jose Monsalve, Ryan Kabrick, Xu Tan, and Guang Gao (2018). *Landing Codelets PXM on DARTS, DEMAC - Towards a Hardware/Software, Codesign/Evaluation Platform*. University of Delaware booth, Supercomputing 2018, November 2018, Dallas, Texas.

THANK YOU.

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