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Computer Engineering Project | 2024

Computer Engineering Project

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Acceleration of Graph Attention Network on FPGA

Council: CE - CC05
Supervisor: Assoc. Prof. Pham Quoc Cuong
Member Secretary: Mr. Nguyen Thanh Loc

Authors:

- Hoang Tien Duc - 2152520
- Dang Hoang Gia - 2153312
- Nguyen Duc Bao Huy - 2152089

Outline

01 Introduction

Graph Neural Network

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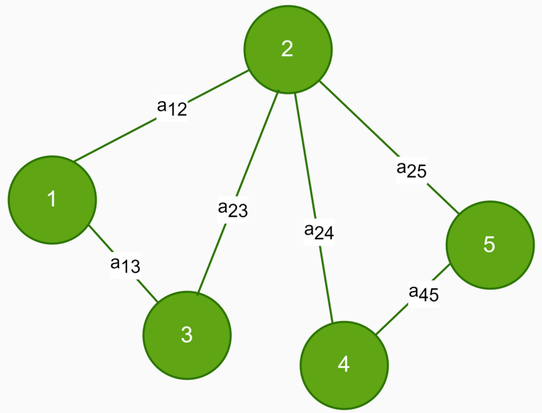
GCN:

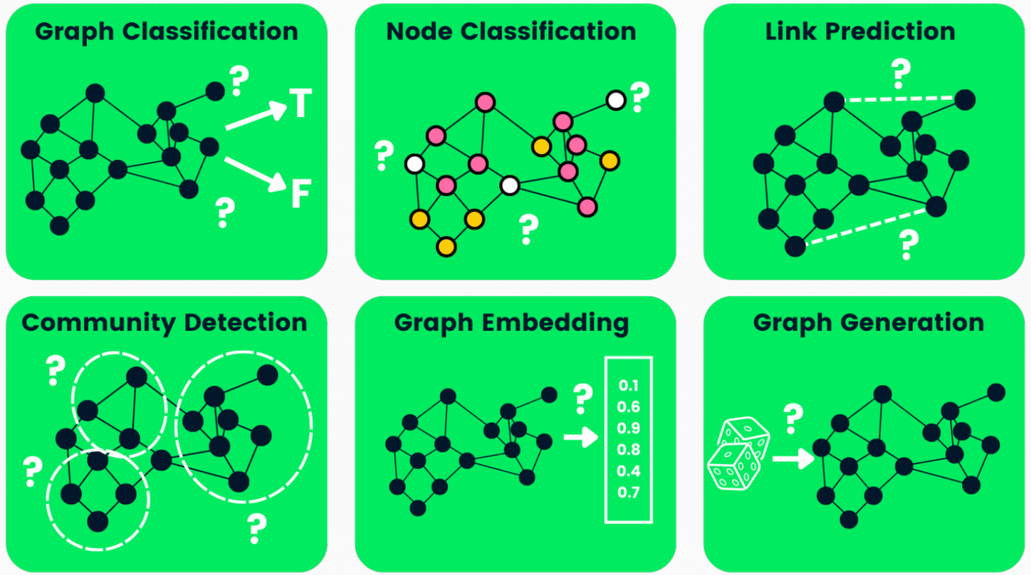
- Used in tasks like **node classification** and **link prediction**
- But **poor performance** on dynamic and inductive tasks.

GAT:

- Improves flexibility with an **attention mechanism**, focusing on **important node relationships**,
- Make it better for complex, dynamic, and real-time tasks.

==> **FPGA-based accelerators for GAT are needed to accelerate the computation of GAT operations.**





02 Background

ZCU106 Zynq SoC Ultrascale+

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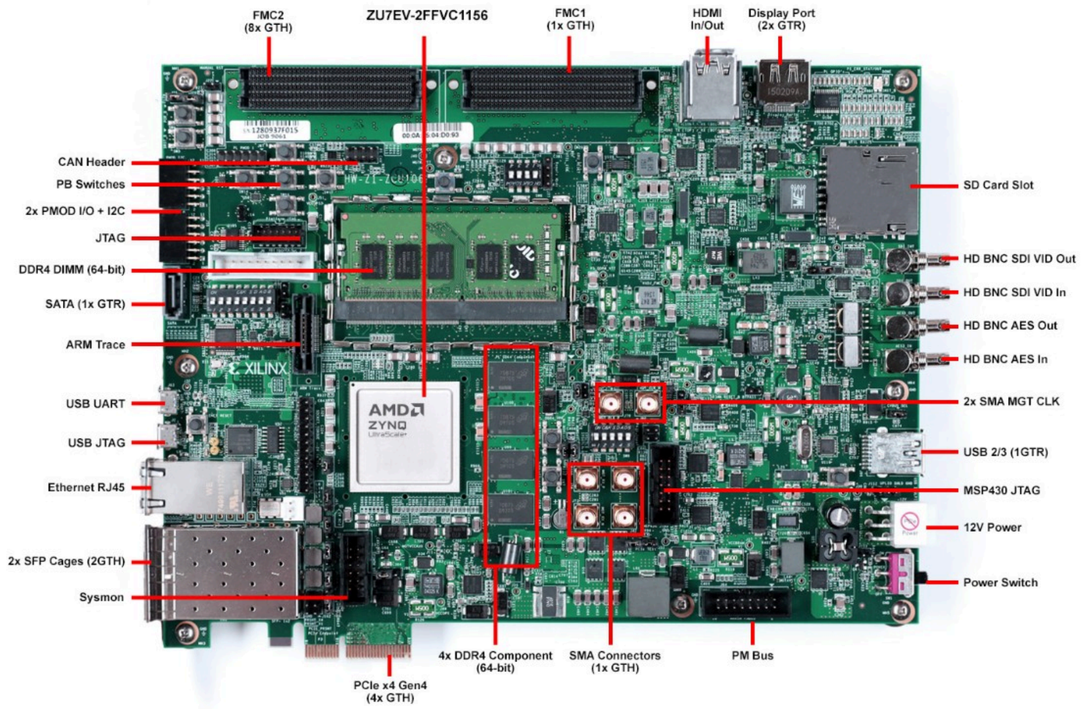

Zynq UltraScale+ MPSoC ZCU106

Resource	Information
Core Device	XCZU7EV
Available IOBs	260
LUT Elements	230,400
Flip-Flops	460,800
Block RAMs	312
Ultra RAMs	96
DSPs	1728

Resource on XCZU7EV

PYNQ Processing System

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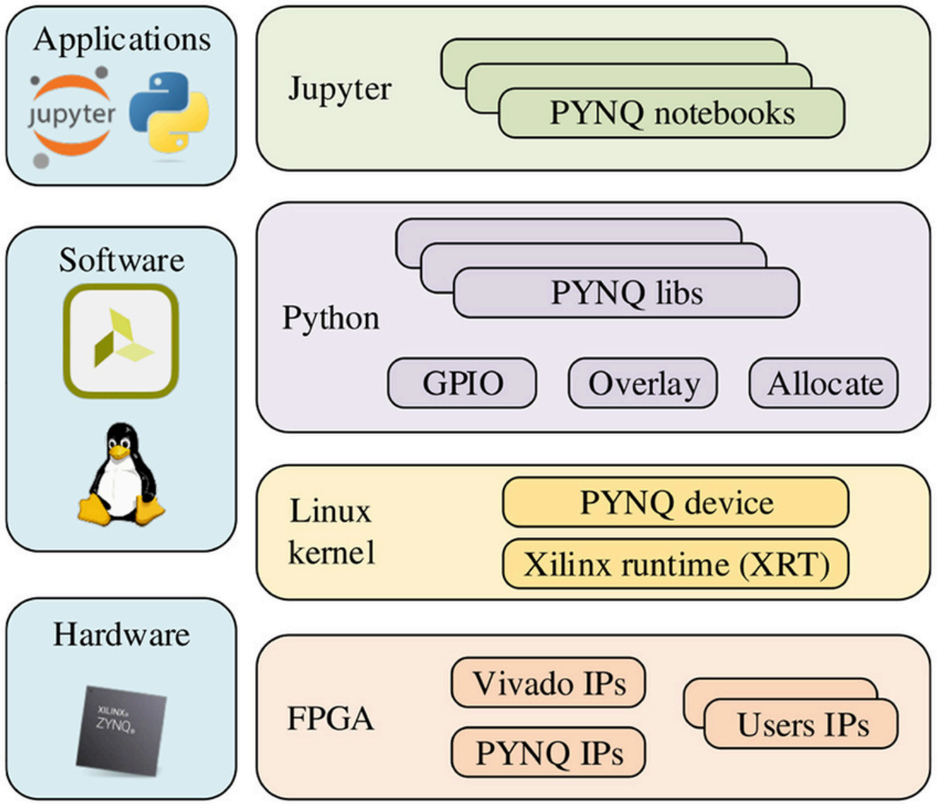
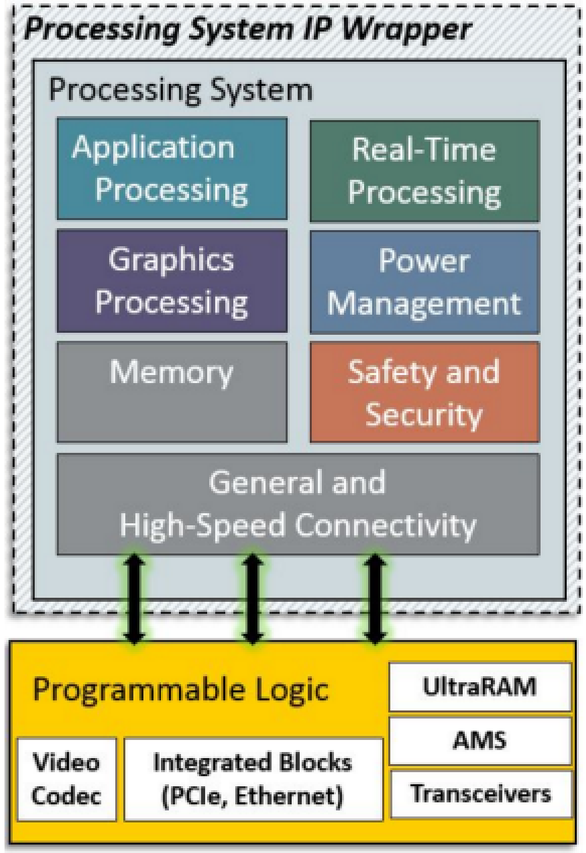


Pynq Framework



Xilinx PS-PL Connectivity

Graph Attention Network

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GAT Algorithms:

Linear transformation: $$\vec{z_{ij}} = W\vec{h}_{ij}$$

Attention coefficient: $$e_{ij} = a(W\vec{h_i}, W\vec{h_j})$$

Softmax: $$\alpha_{ij} = \frac{\exp(\text{LeakyReLU}(e_{ij}))}{\sum_{k\in\mathcal{N}_i}\exp(\text{LeakyReLU}(e_{ik}))}$$

Aggregation: $$\vec{\mathbf{h}'_i} = \sigma\left(\sum_{j\in\mathcal{N}(i)}\alpha_{ij}W\vec{\mathbf{h}_j}\right)$$

Graph Attention Network

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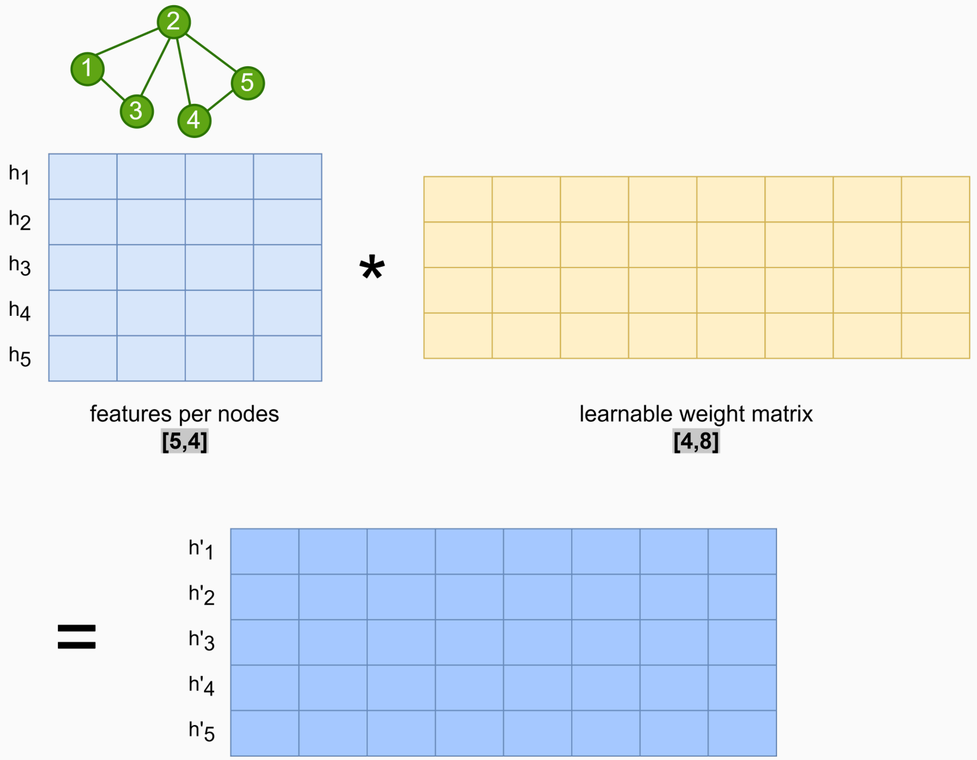
Weight and feature linear transformation

$$\vec{z_{ij}} = W\vec{h}_{ij}$$



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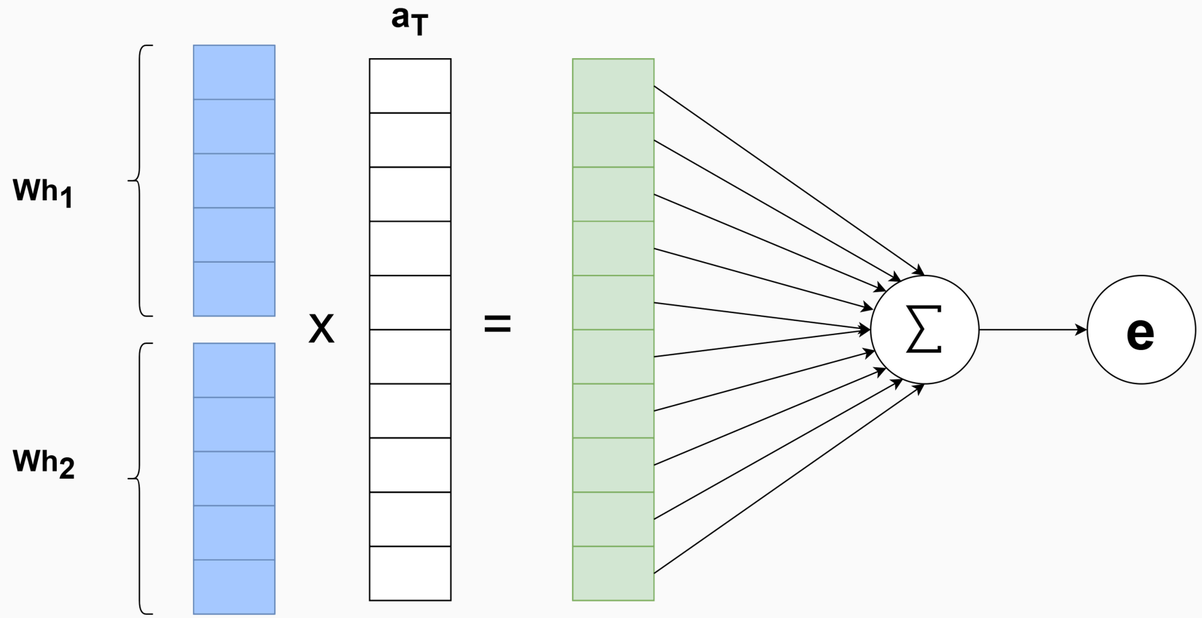
Attention coefficient

$$e_{ij} = a(W\vec{h_i}, W\vec{h_j})$$



Graph Attention Network

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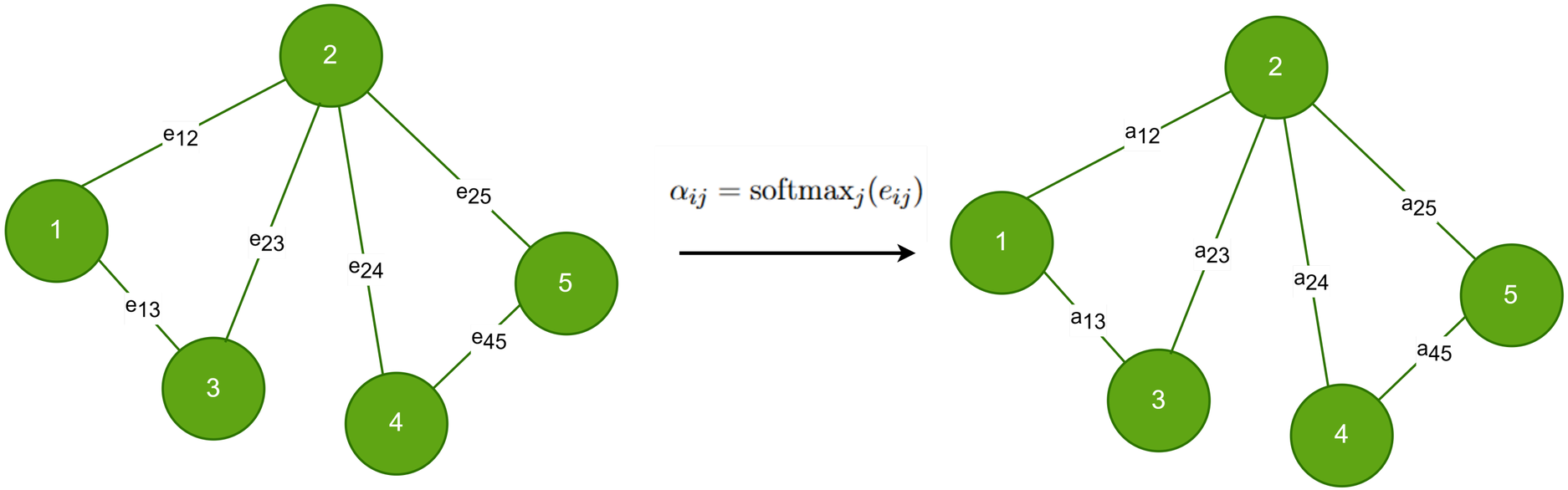
Softmax

$$\alpha_{ij} = \frac{\exp(\text{LeakyReLU}(e_{ij}))}{\sum_{k \in \mathcal{N}_i} \exp(\text{LeakyReLU}(e_{ik}))}$$



Graph Attention Network

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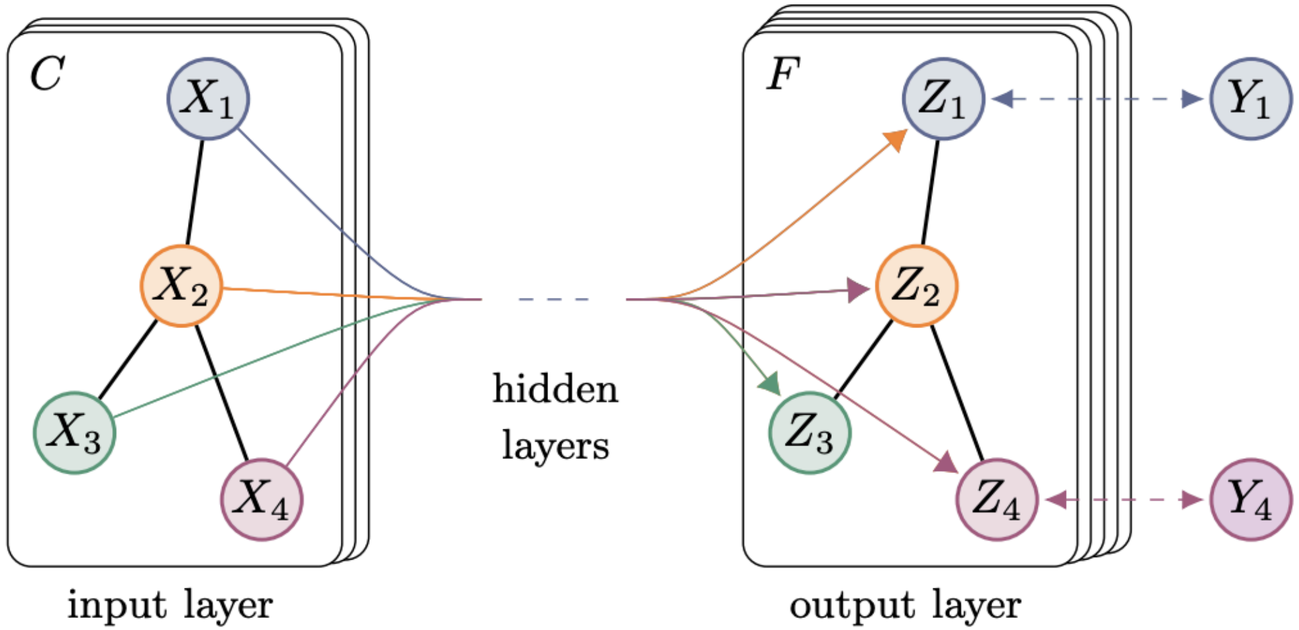
Aggregation

$$\vec{\mathbf{h}}_i' = \sigma\left(\sum_{j \in \mathcal{N}(i)} \alpha_{ij} W \vec{\mathbf{h}}_j\right)$$



Related Work

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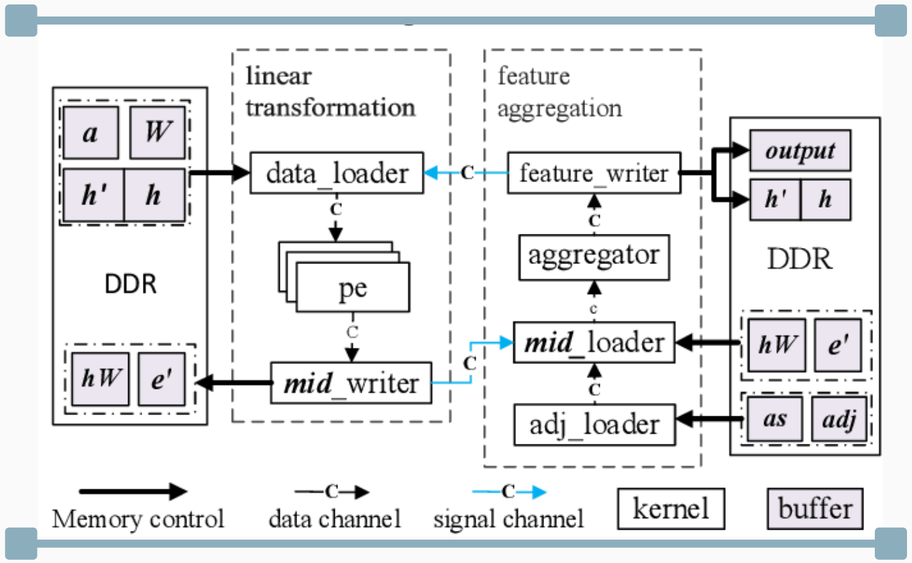
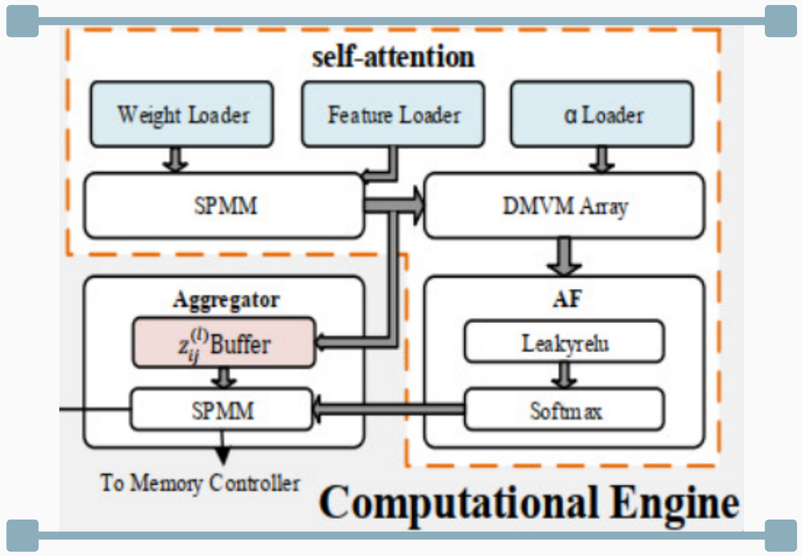
S-GAT: (W. Yan, W. Tong and X. Zhi)

- Model compression, feature quantization, shift-based multiplication.
- Performance: 593x CPU, 7.34x Nvdia Tesla V100



SH-GAT: (Wang. et.al)

- Split weights, softmax approximation, load-balanced SPMM, pre-fetching to address memory irregularities.
- Performance: 3283x CPU. 13x GPU



03 Methodological Approach

Algorithm Optimization

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Original GAT Calculation

$$\vec{z_{ij}} = W\vec{h}_{ij}$$

$$e_{ij} = \text{LeakyReLU}\left(\vec{a}^{\top}[\vec{z}_i \| \vec{z}_j]\right)$$

$$\alpha_{ij} = \frac{\exp\left(e_{ij}\right)}{\sum_{k\in\mathcal{N}(i)}\exp\left(e_{ik}\right)}$$

$$\vec{h}_i = \sigma\left(\sum_{j\in\mathcal{N}(i)}\alpha_{ij}\vec{z}_j\right)$$

Proposed GAT Calculation

$$\vec{z_{ij}} = W\vec{h}_{ij}$$

$$e_{ij} = \text{ReLU}\left(\vec{a}_1^{\top}\vec{z}_i + \vec{a}_2^{\top}\vec{z}_j\right)$$

$$\alpha_{ij} = \frac{2^{e_{ij}}}{\sum_{k\in\mathcal{N}(i)}2^{e_{ik}}}$$

$$\vec{h}_i = \text{ReLU}\left(\sum_{j\in\mathcal{N}(i)}\alpha_{ij}\vec{z}_j\right)$$

Data pre-processing

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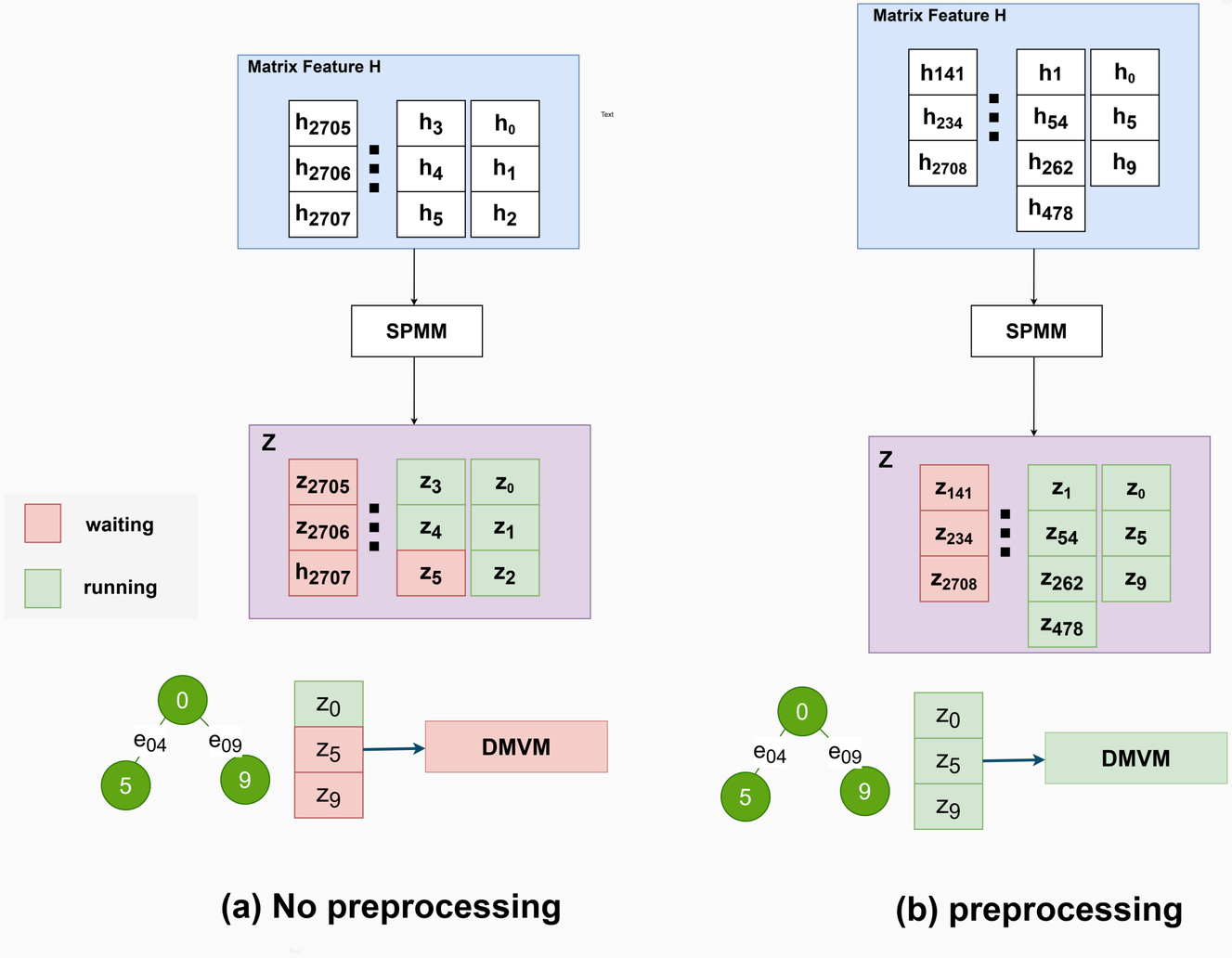
Pipeline stalls occur due to **unorganized data** flow through computational modules.

==> Group **source node** and **neighboring nodes** into a **subgraph** to streamline data flow and prevent stalls.



Data pre-processing

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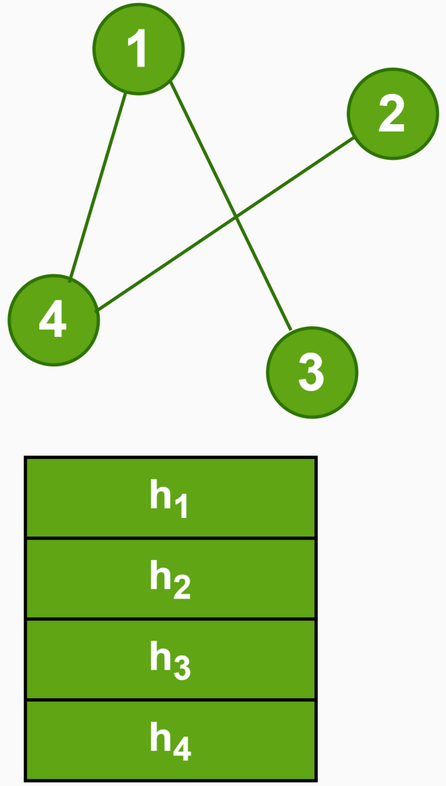
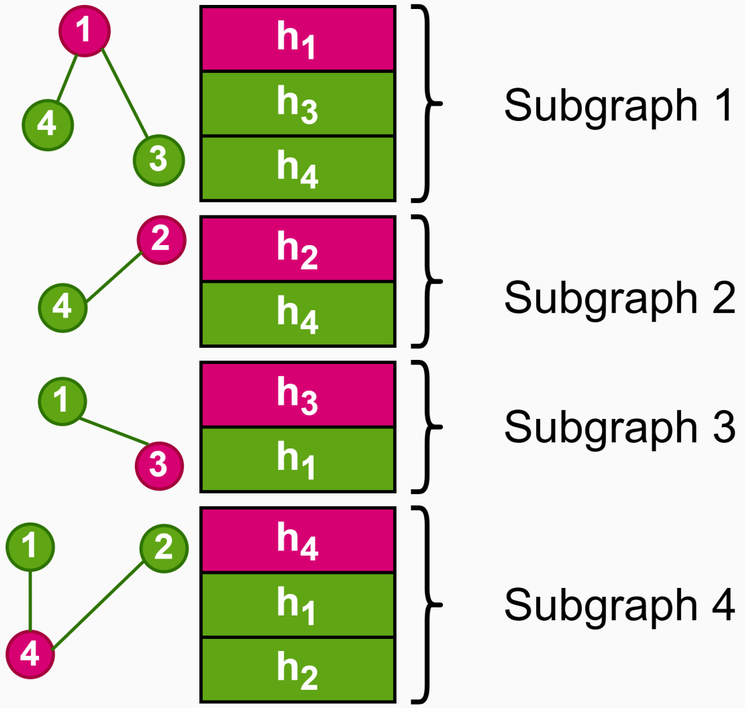
A 4-node graph can represent as 4 subgraphs.

Source node: header of each subgraph.
Neighbor node: node adjacent to source node.



Original Graph and H matrix



Proposed subgraphs

GCSR Format

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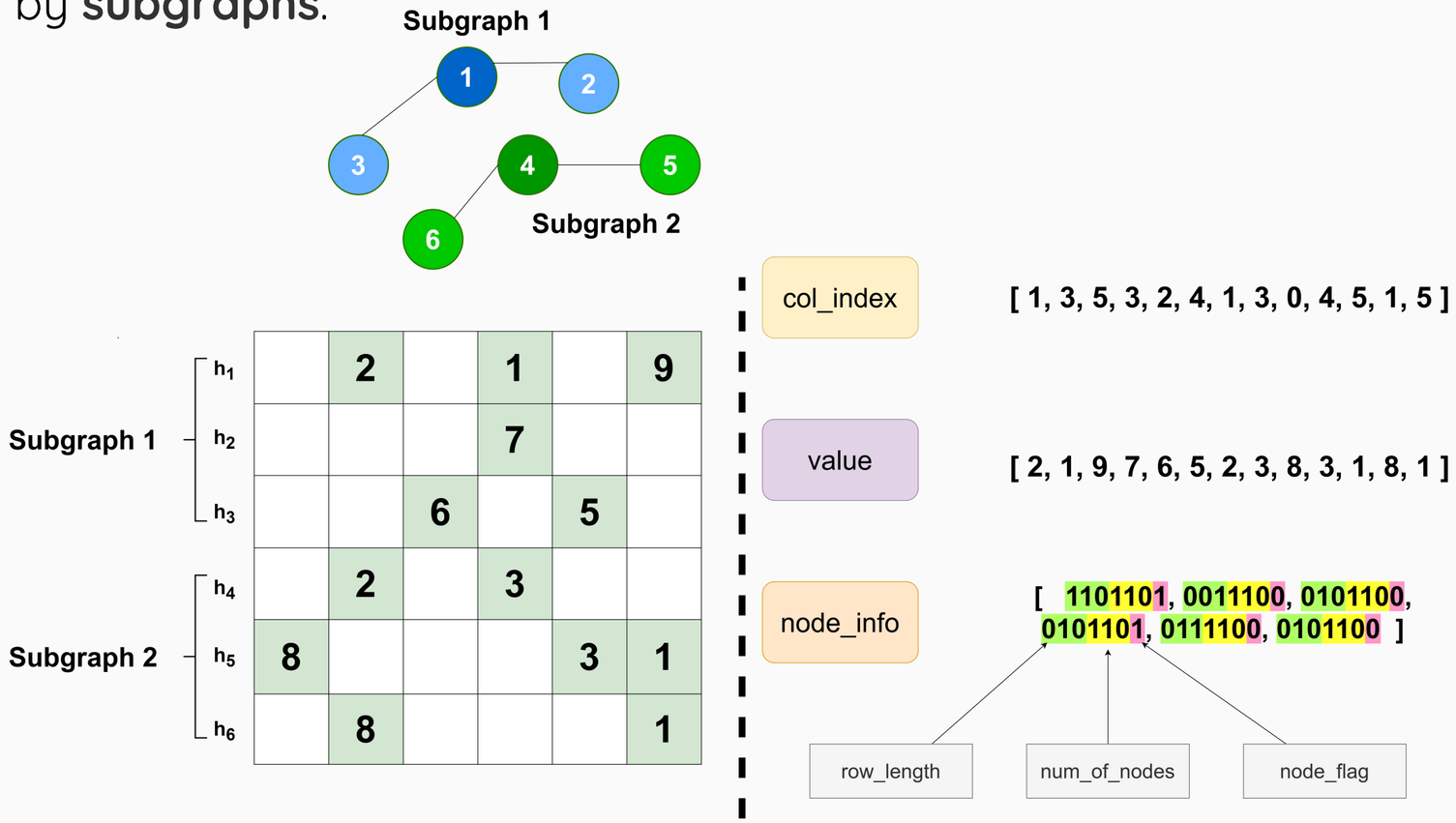
GCSR stands for **Graph Compressed Sparse Row.**

- Collect information of **index and value,** compressed it into 3 components.
- Organized by **subgraphs**.



04 Overall Architecture

General Architecture

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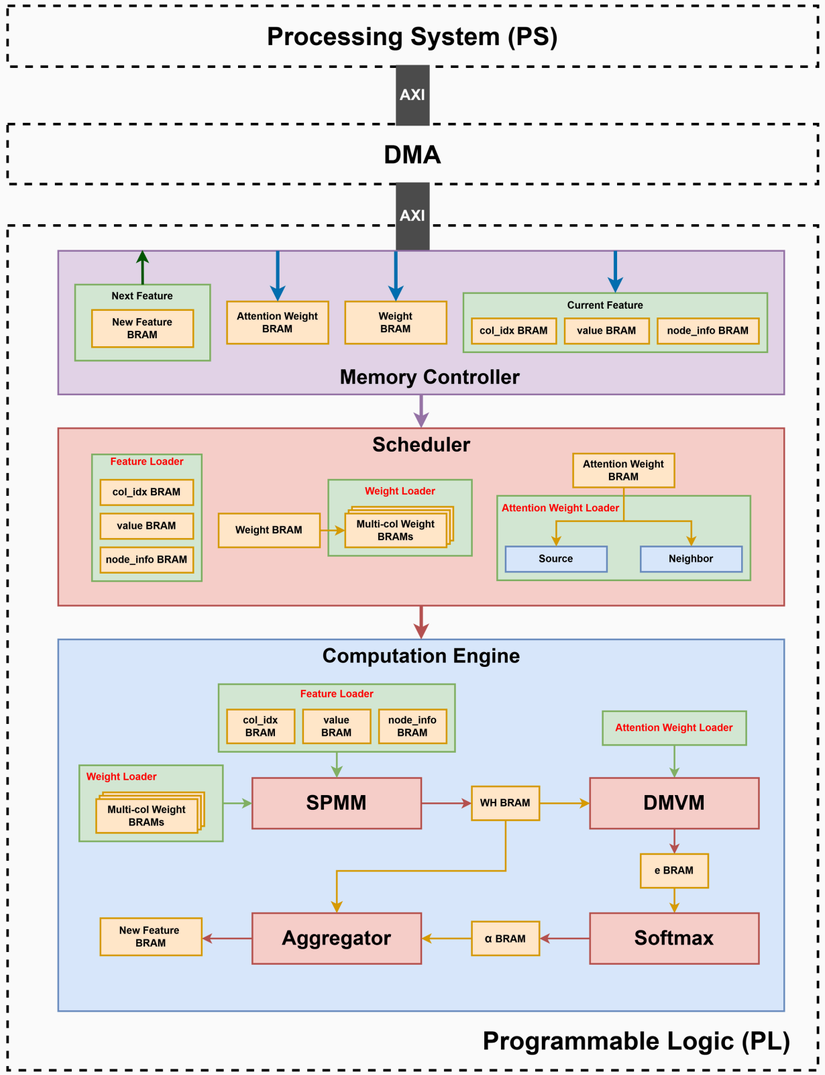

PS is responsible for **running software application** (training GAT model and transferring input data).

PL is responsible for **operating GAT algorithm.**

- Memory Controller (**6** BRAMs).
- Scheduler (**3** Loaders).
- SPMM (Sparse Matrix Multiplication).
- DMVM (Dense Matrix Vector Multiplication).
- Softmax.
- Aggregator.

SPMM/SP-PE

(Sparse Matrix Vector Multiplication/Sparse Processing Element)

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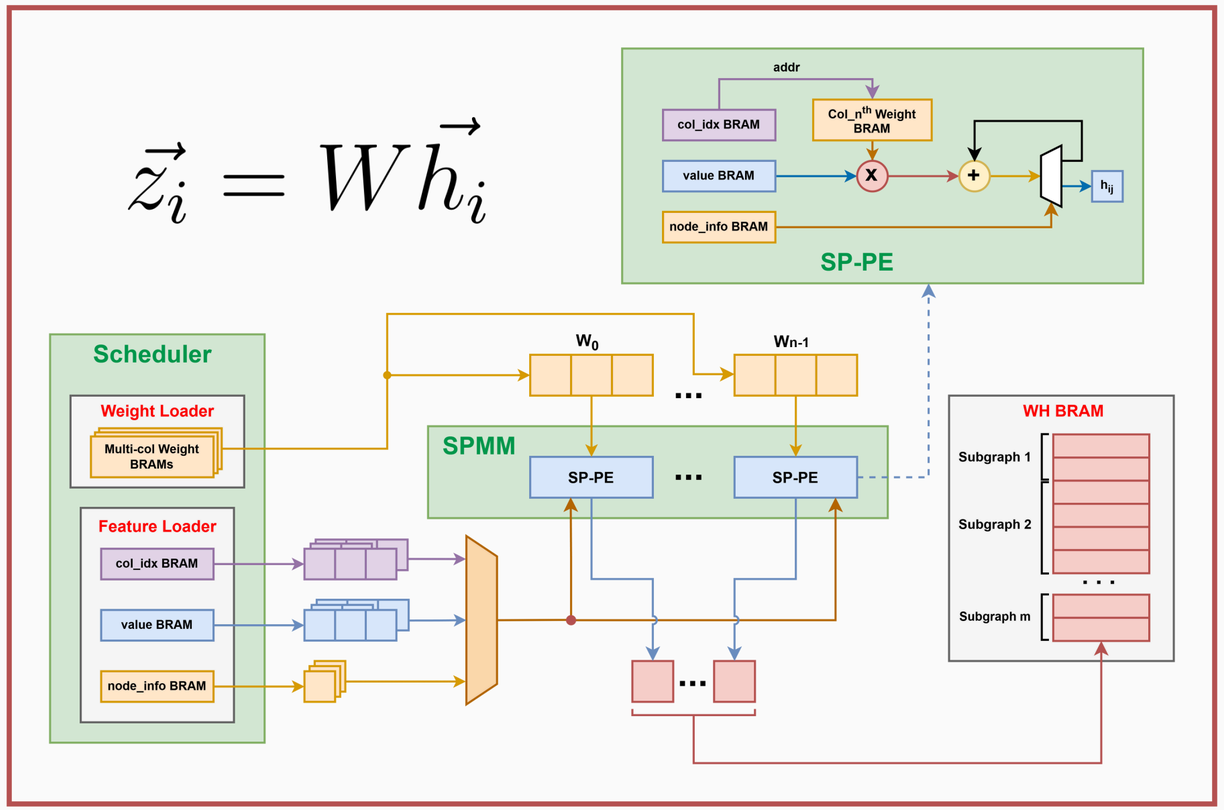
Each **SP-PE** contains a **column-specific Weight BRAM**.

col_idx is used as **read address** to retrieve the corresponding **weight value** from BRAM.

When the number of non-zero feature values reaches **row_length**, **pe_ready_o** will be asserted.



DMVM

(Dense Matrix Vector Multiplication)

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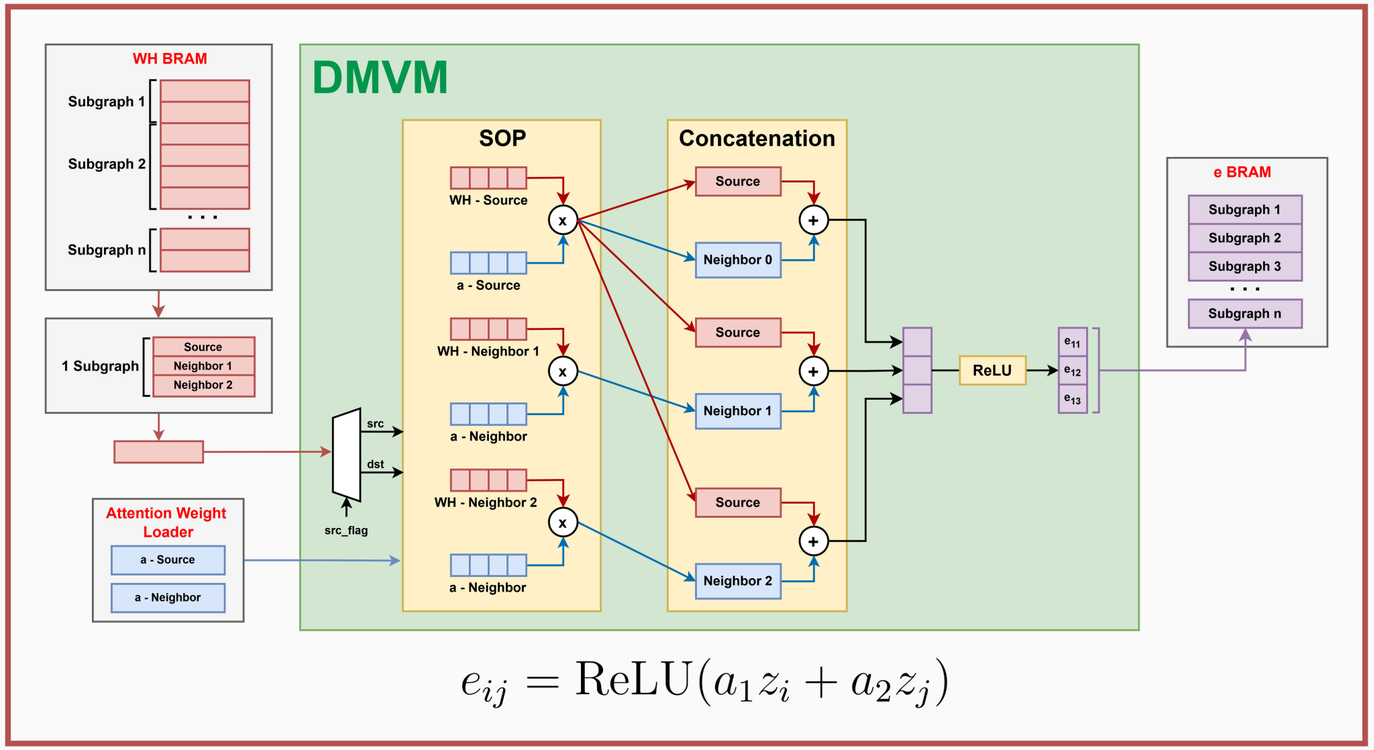

$$e_{ij} = \mathrm{ReLU}(a_1 z_i + a_2 z_j)$$

Each **WH entry** is multiplied with either **a_source** or **a_neighbor** based on **src_flag**.

The result is then concatenated with the **source node's product**.

Finally, it passes through the **ReLU** function to retrieve **Attention Cofficient e**.

Softmax

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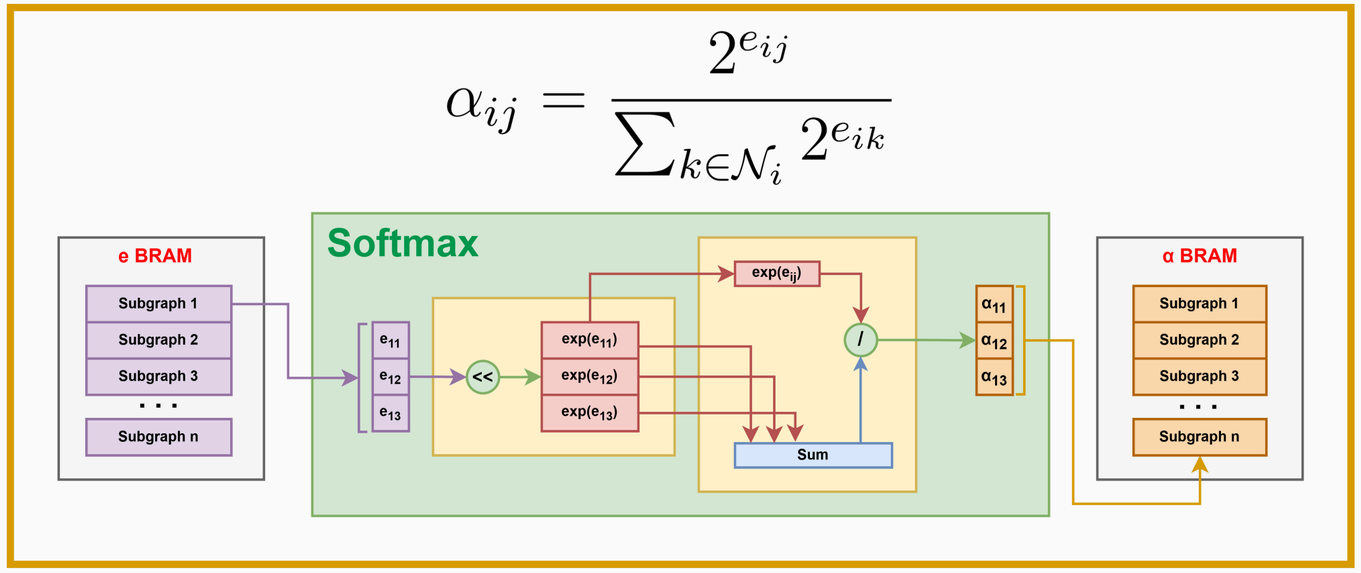
$$\alpha_{ij} = \frac{2^{e_{ij}}}{\sum_{k \in \mathcal{N}_i} 2^{e_{ik}}}$$



Each entry from **e BRAM** contains **attention coefficients** of a **subgraph**.

After calculating the **base-2 exponentials** for each coefficient, their **sum** is computed sequentially.

Finally, each base-2 exponential coefficient is **divided** by the sum to obtain the **normalized coefficient**.

Aggregator

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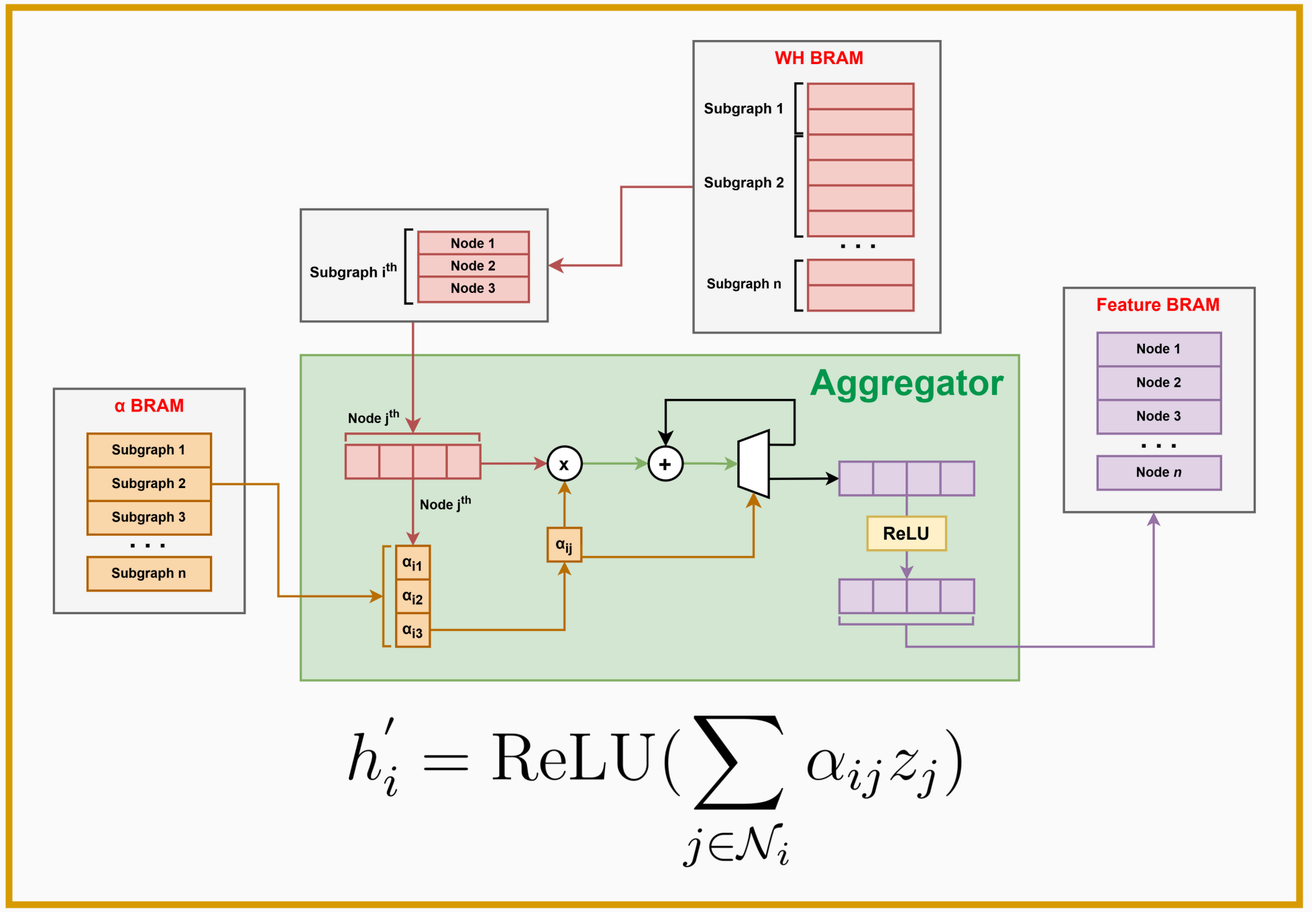
Each vector from **WH BRAM** is **multiplied** with corresponding normalized coefficient from **α BRAM**.

The results are **accumulated** until all nodes in the subgraph are processed.

Finally, the accumulated values pass through the **ReLU** function to produce the **feature vector** for the **next layer**.



05 Implementation

System Implementation

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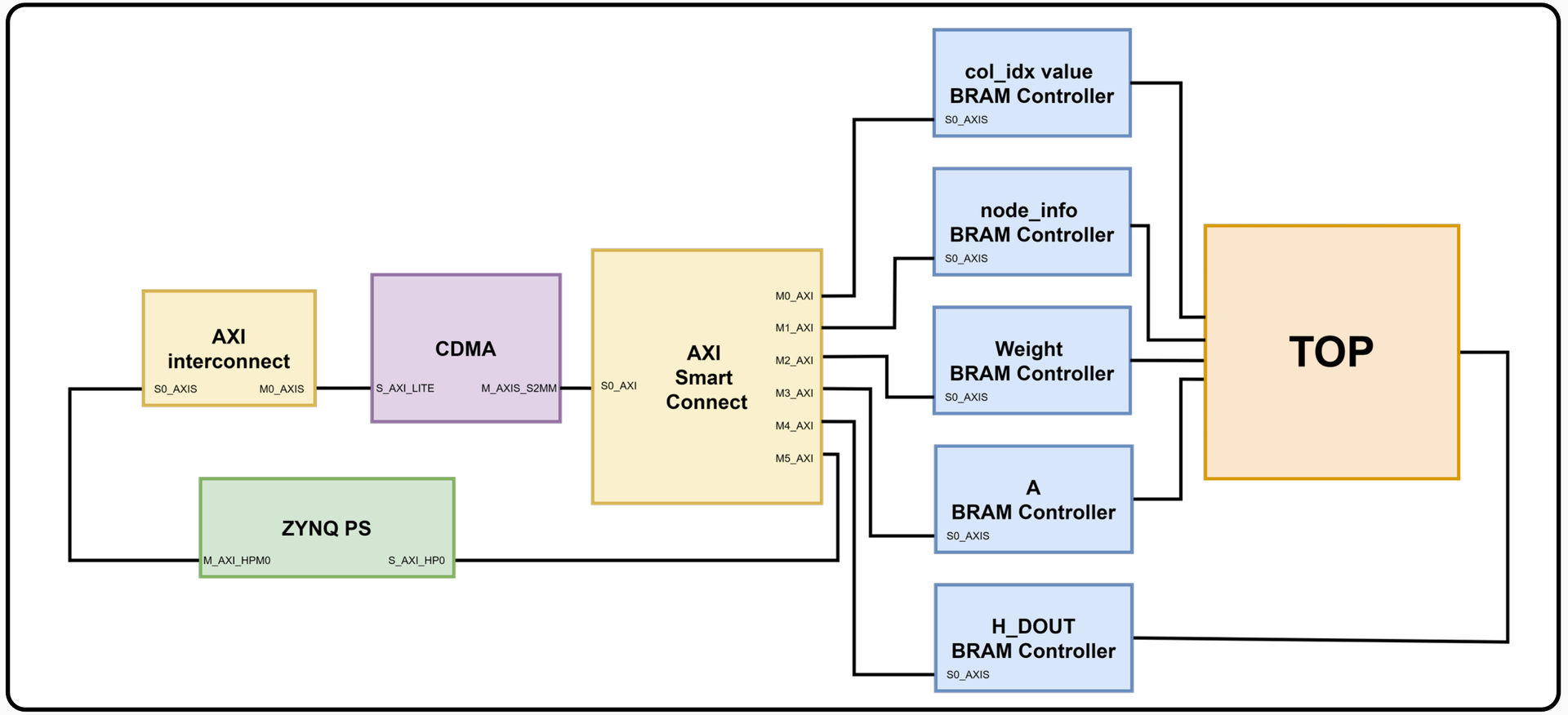

System Block Design (Vivado)

06 Results

SPMM Simulation

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11	0	0	0	3
0	3	0	0	1
2	9	4	0	0
0	13	8	0	5

X

24	14	7	3	28	-28
14	21	16	2	2	-29
20	9	22	-9	-22	19
16	13	18	13	2	-3
-26	20	31	11	1	2

=

186	214	170	66	311	-302
16	83	79	17	7	-85
254	253	246	-12	-14	-241
212	445	539	9	-145	-215

Feature (4x5) Weight (5x6) WH (4x6)

col_idx	0	4	1	4	0	1	2	1	2	4
value	11	3	3	1	2	9	4	13	8	5

node_info	2 || 4 || 1	2 || 4 || 0	3 || 4 || 0	3 || 4 || 0

SPMM Simulation

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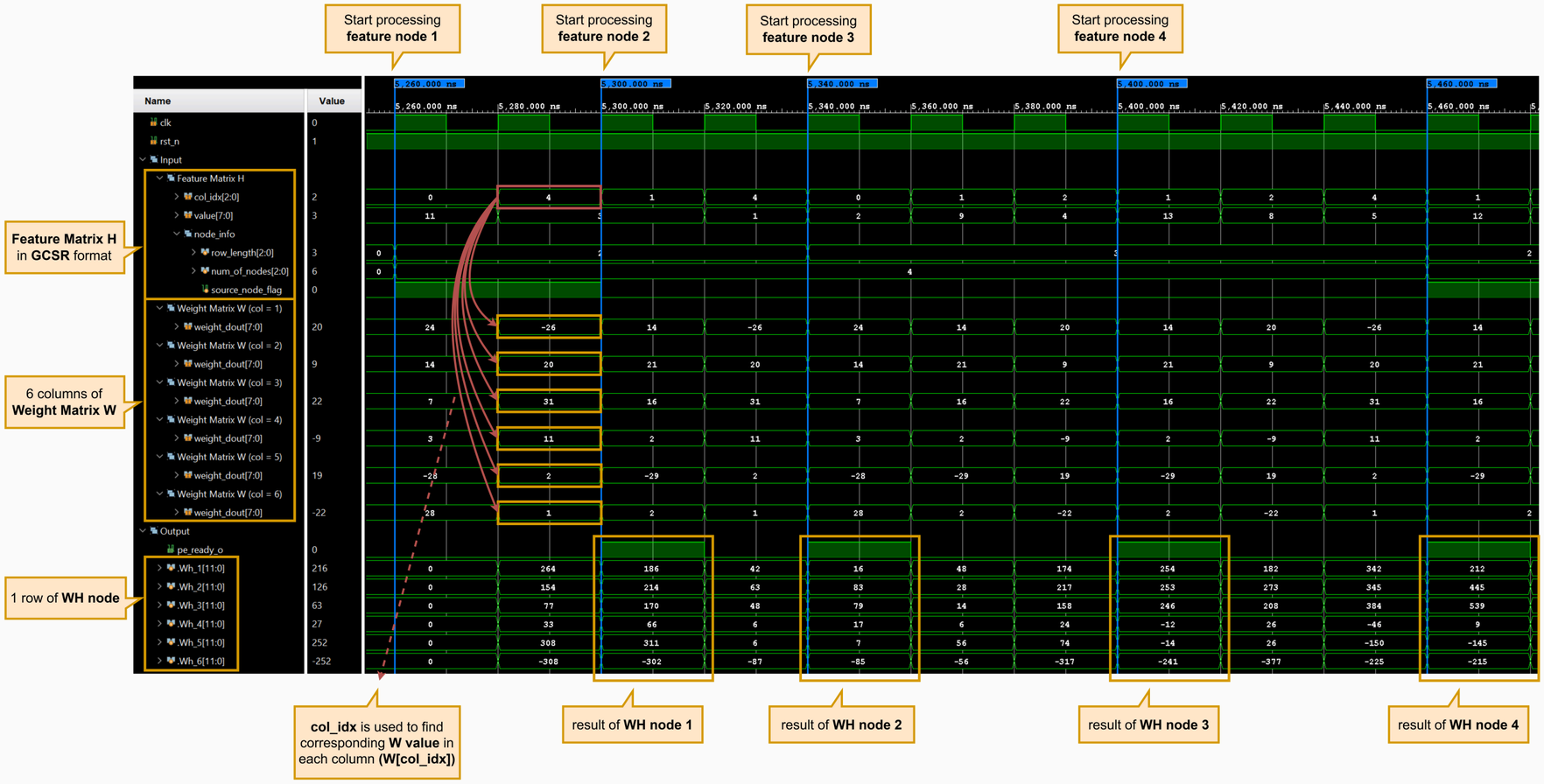
186	214	170	66	311	-302
16	83	79	17	7	-85
254	253	246	-12	-14	-241
212	445	539	9	-145	-215

WH (4x6)



SPMM Simulation

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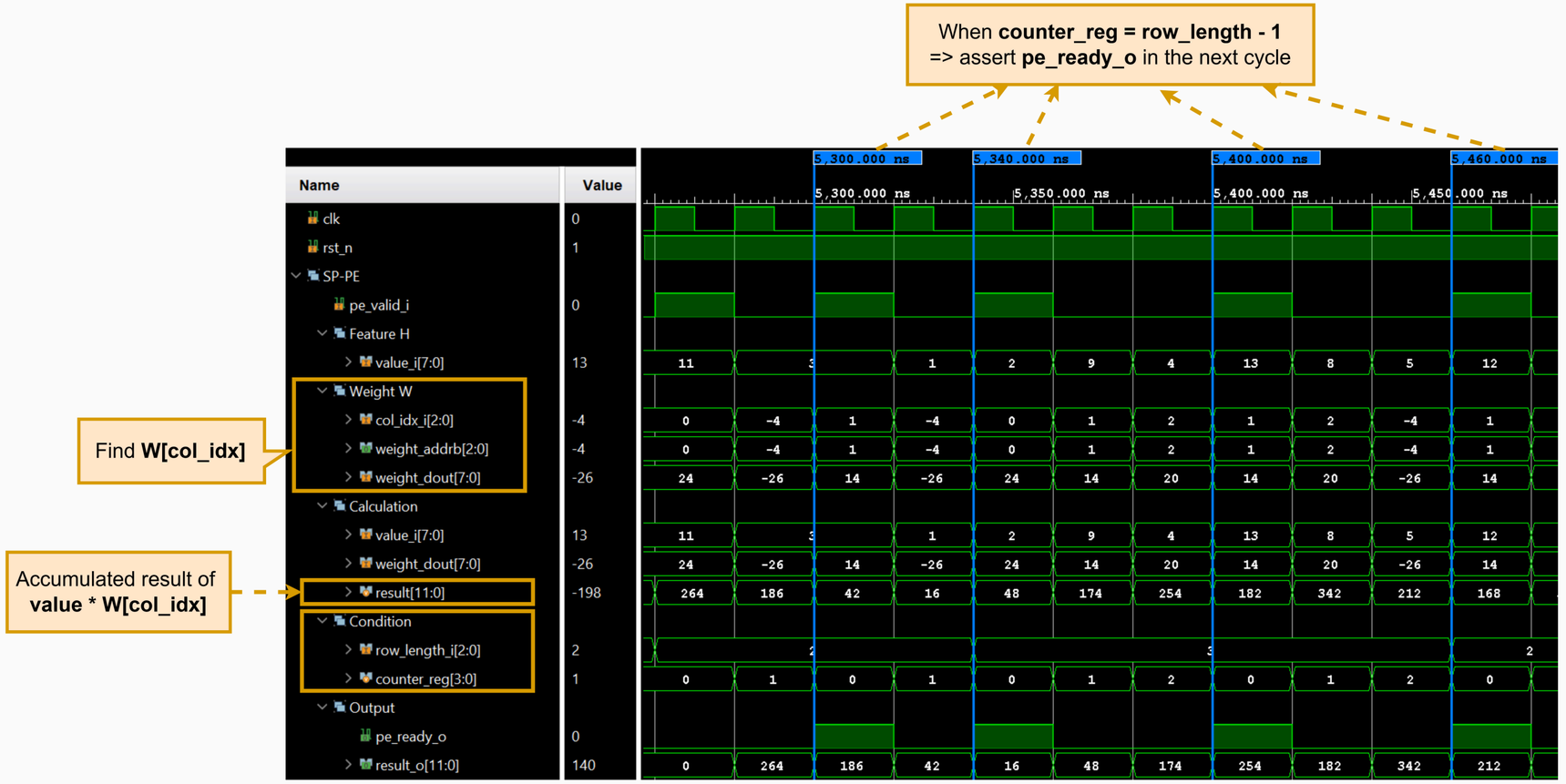

Calculation operation in one SP-PE module

Model Training

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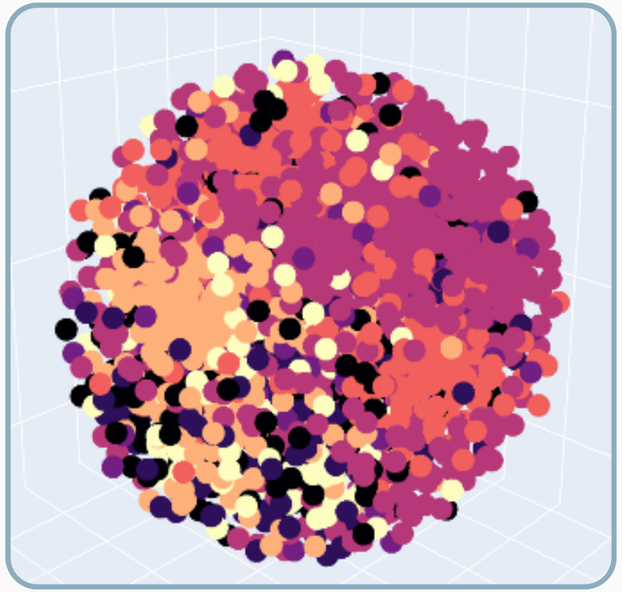
Visualize Cora Dataset (Without Training)

2-D Visualization



3-D Visualization

Model Training

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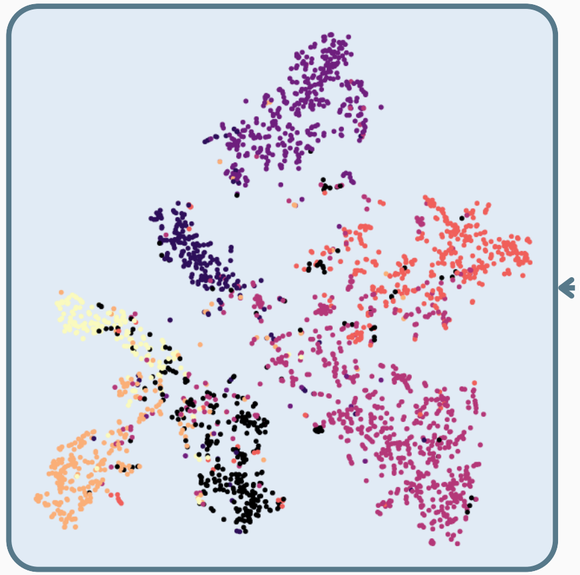
Visualization (Training GAT Model + Without Quantization)



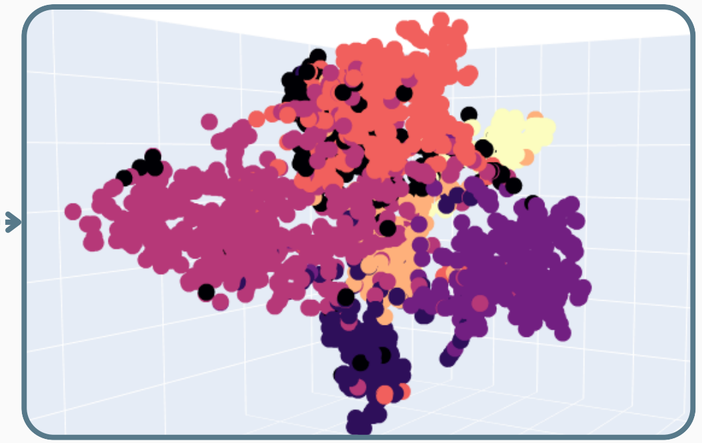
2-D Visualization

82.5%

```
test_accuracy = buildGATModel.test()
print(f'Test Accuracy without Quantization:

Test Accuracy without Quantization: 0.825
```

Accuracy



3-D Visualization

Model Training

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Visualization (Training GAT Model + Quantization)

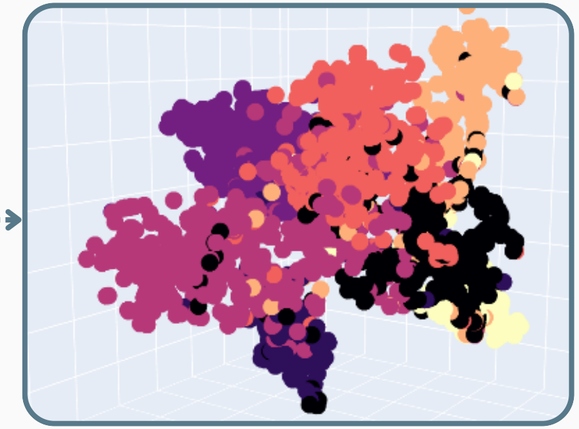
2-D Visualization

82.2%

```
test_accuracy = buildGATModel.test()
print(f'Test Accuracy with Quantization Aware Training (QAT):
```

```
Test Accuracy with Quantization Aware Training (QAT): 0.822
```

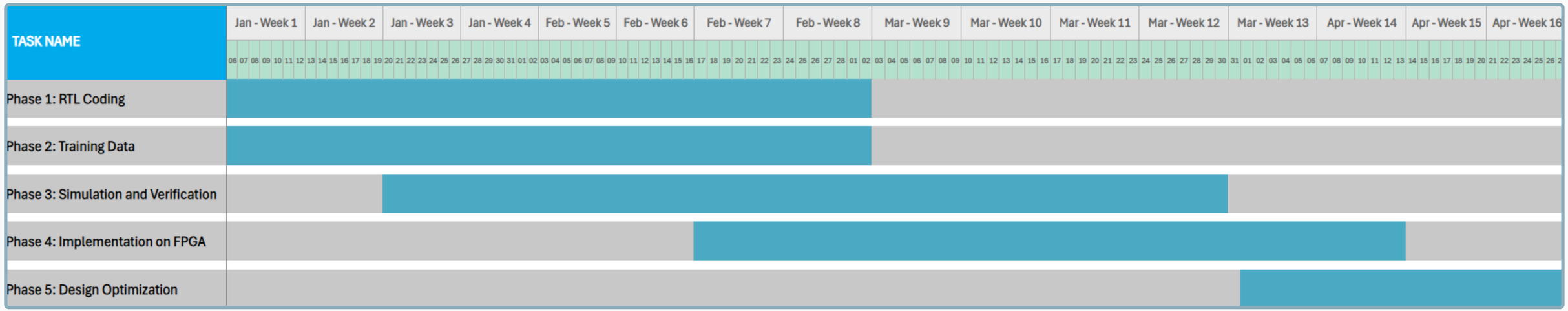
Accuracy



3-D Visualization

Future Plan

Future Plan



Proposed Timeline And Goals

Thank you for your Attention

System Accuracy

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Visualization (Full Flow Simulation On Software)

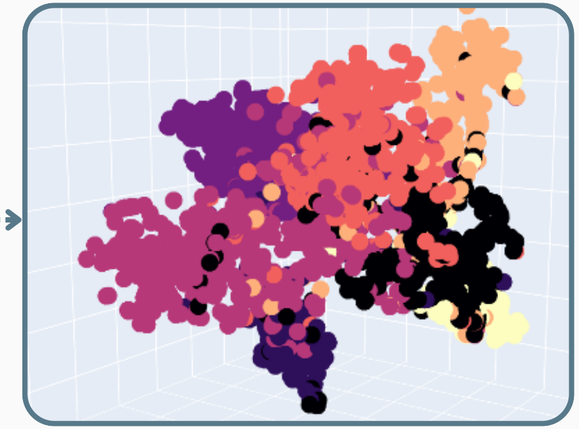
2-D Visualization

82.2%

```
test_accuracy = buildGATModel.test()
print(f'Test Accuracy with Quantization Aware Training (QAT):
```

```
Test Accuracy with Quantization Aware Training (QAT): 0.822
```

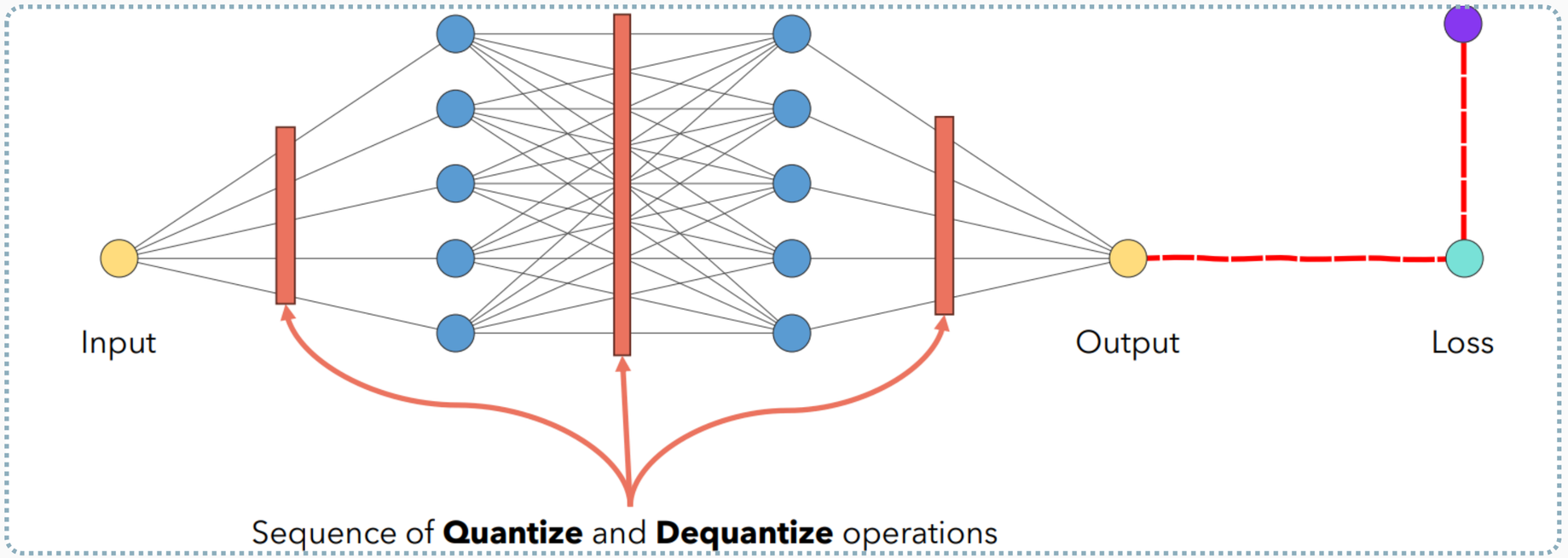
Accuracy



3-D Visualization

Quantization Process

- Convert parameters from Float32 to Int8
- Apply Quantization Aware Training (QAT) technique
- Detailed Flow



Softmax Accuracy Loss

Dataset	Cora	Citeseer	Pubmed
Accuracy Loss	0.15	0.006	0.012

Accuracy loss across datasets

Latency Comparison

Datasets	Latency (us)				
	SH-GAT (Ours)	FTW-GAT [10]	FP-GNN [9]	H-GAT [8]	S-GAT [7]
Cora	19.4	44.9	46.3	600	6400
CiteSeer	22.1	50.8	71.4	800	N/A
PubMed	150.2	339	616	5700	N/A

Comparison with FPGA-based accelerators on latency

GAT With Dataset

- Cora (Previous Slide)
- CiteSeer
- PubMed

Dataset	Nodes	Edges	Input Feature	Classes	Feature Density	Edge Density	Weight Density
Cora	2708	10,556	1433	7	1.3%	0.14%	100%
CiteSeer	3327	9104	3703	6	0.8%	0.08%	100%
PubMed	19,717	88,648	500	3	10.4%	0.02%	100%

Dataset information with Nodes, Edges and Features