

Verilog Implementation of Decision Tree Accelerator

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Side Project for 2022 Job Interviews

Outline

- Problem/ Dataset
- Software
- Conversion
 - Tree Pruning
- Hardware
 - Architecture
 - Synthesis/ Press&Route/ Evaluation

Problem Description

- **Failure in loan repayment** can be bothering for banks.
 - **Decline certain applications** to prevent repayment failure
 - **Analyze the applicant statistics** to decide who to decline.
- Use **decision tree** to learn the underlying patterns in data!
 - Decision tree can be used in various fields
 - Some of them require ***fast processing of large data***, exp: High-frequency transaction
 - To meet the need for processing speed, this work presents a **Verilog implementation of decision tree accelerator**

Dataset

- 9578 loaning application data
 - Label
 - Repayment success/fail
 - 8045 successes / 1533 fails
 - 13 Features for each application data
 - Including FICO score, interest rate...

Data Pre-process

- “Loaning Purpose” is a categorical feature (6 categories)
 - One hot encoding
 - 18 total features
- Normalize the features to 0~255, integer
 - Hardware-friendly modification
 - **Decision thresholds will also be 0~255, integer!**
 - At the cost of potential performance drop
- Training/Testing split
 - Randomly sample
 - 6704/2874

Software

Decision Tree

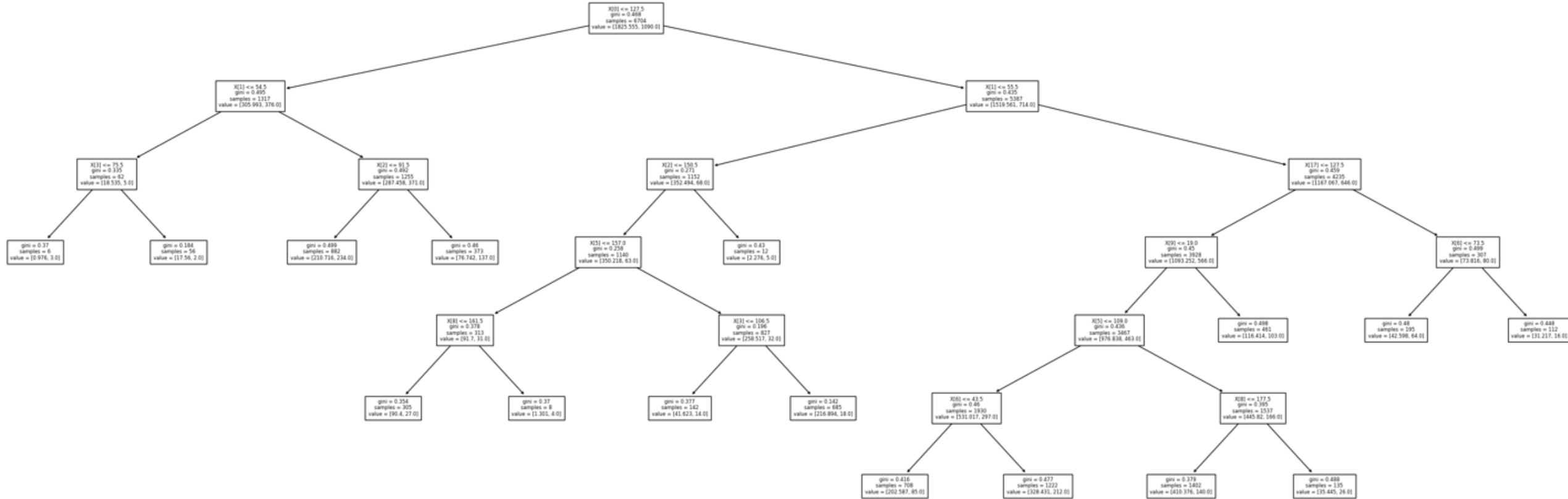
- Use the decision tree provided by scikit-learn
 - ***This work focused on the hardware implementation***
 - Fine-tuning and software analyses (exp: max-leaf-num, AUROC) are neglected
 - Confusion matrix on the test set (Before/ After converting to integers)

Ans\Pred	T	F
T	1970	461
F	284	159

Ans\Pred	T	F
T	1967	464
F	283	160

Result Tree Structure

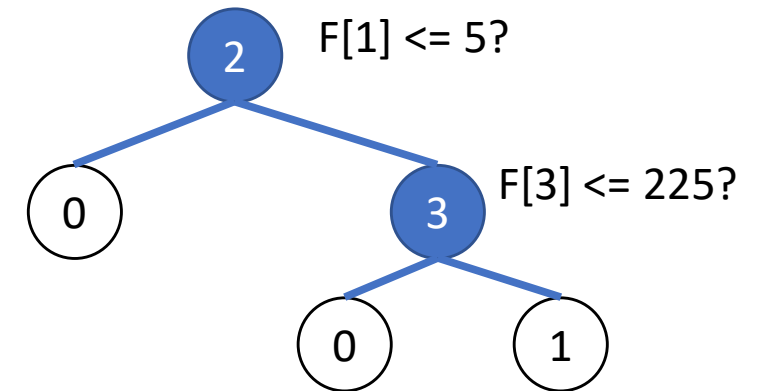
- Max Node Index: 30
- Max-depth: 6 layers



Conversion

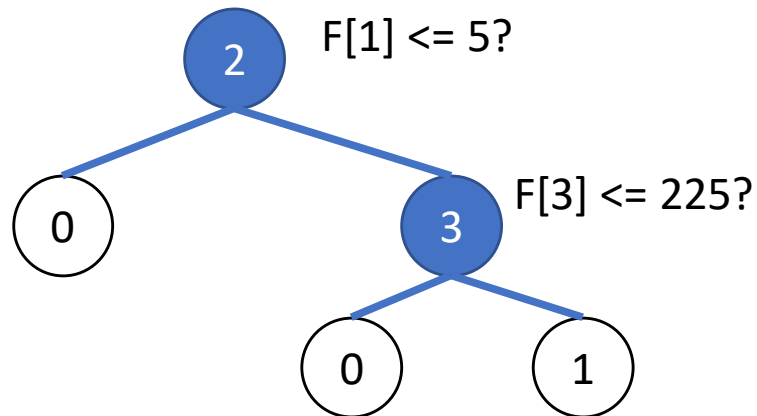
Observation

- Naïve thought
 - From the root node, iteratively moving downward, layer by layer, split by split
 - Core function is to “***move down 1 layer***”
- To move down 1 layer, we need 3 parameters:
 - The index of feature
 - The threshold
 - The index of next node
- The key decision is how to store the parameters



Conversion Strategy

- Convert python code to Verilog hardware design
 - Parse all the parameters into 3 memories



Node 0

Node 2
(root
node)

Feature Index	Threshold	Child
0	0	0
0	0	0
1	5	0
3	225	0
0	0	0
0	0	3
0	0	0
0	0	1

Feature/Node Pruning

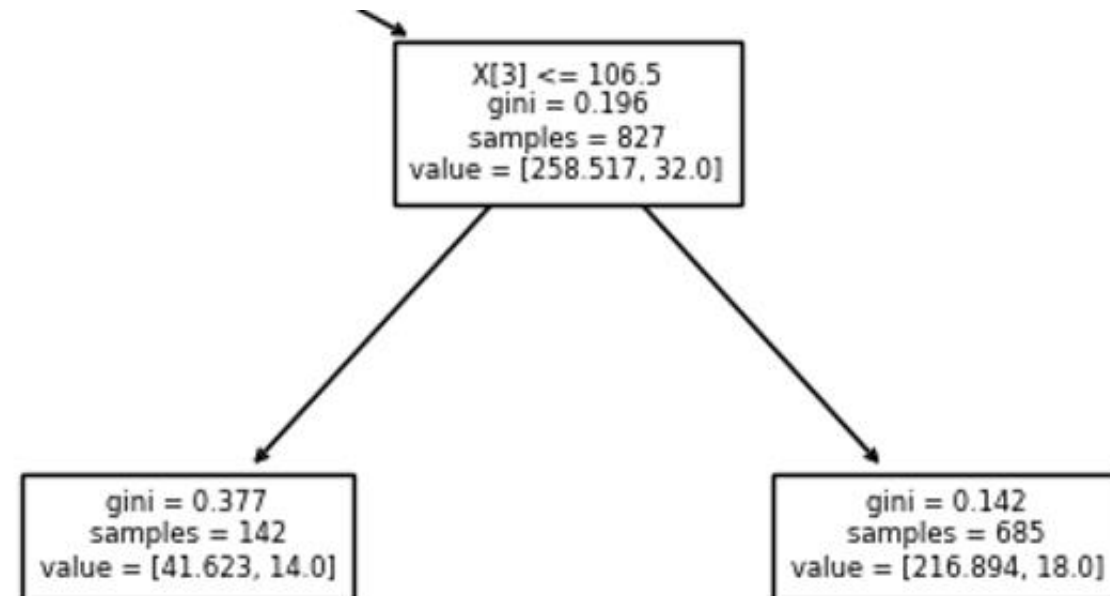
- The decision tree generated from scikit-learn can be further optimized
- Not all 18 features are used
 - Unused features cause resource waste!
 - Prune the unused ones. Re-index the features left.
- Not all 31 node indexes are occupied
 - Leaf nodes do not need a unique index!
 - Redundant node indexes cause resource waste!
 - Prune the unused ones. Re-index the nodes.

Redundant Splits Pruning

- Reason: Decision tree training target
 - Minimizing the weighted entropy sum after split
 - ***Does not guarantee the split produces different predictions!***
 - Redundant splits are sometimes generated
 - Recursively prune the redundant splits

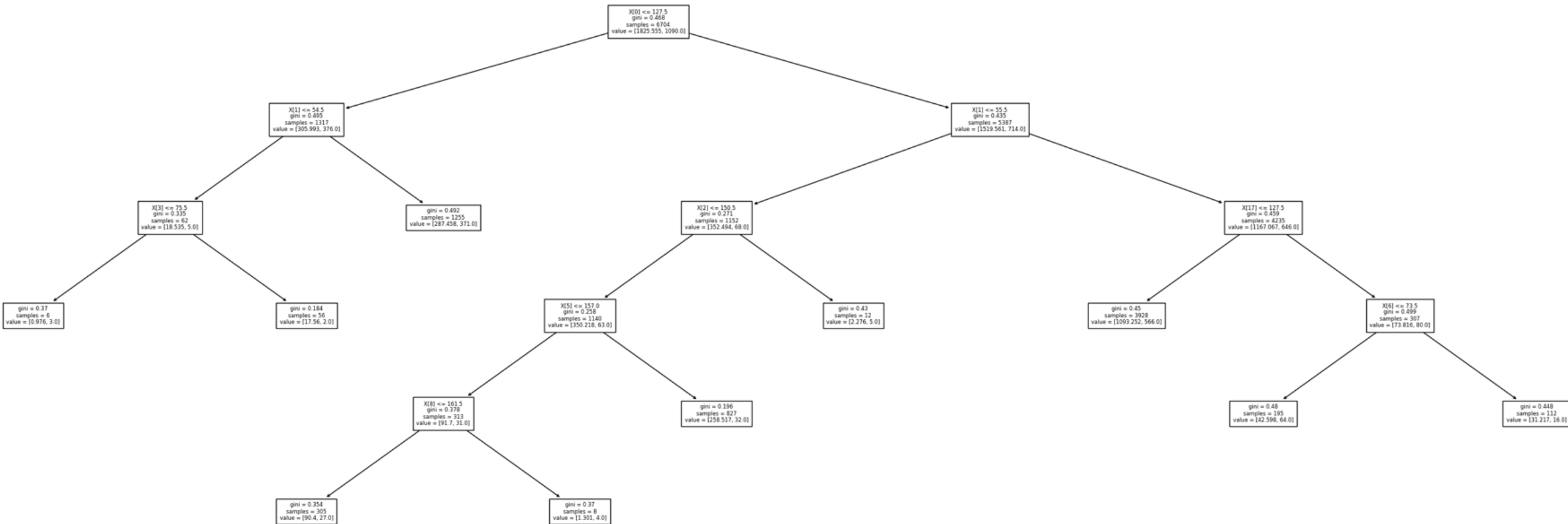
$$0.377 * 142 + 0.142 * 685 < 0.196 * 827$$

But both leaf nodes predict class 0!



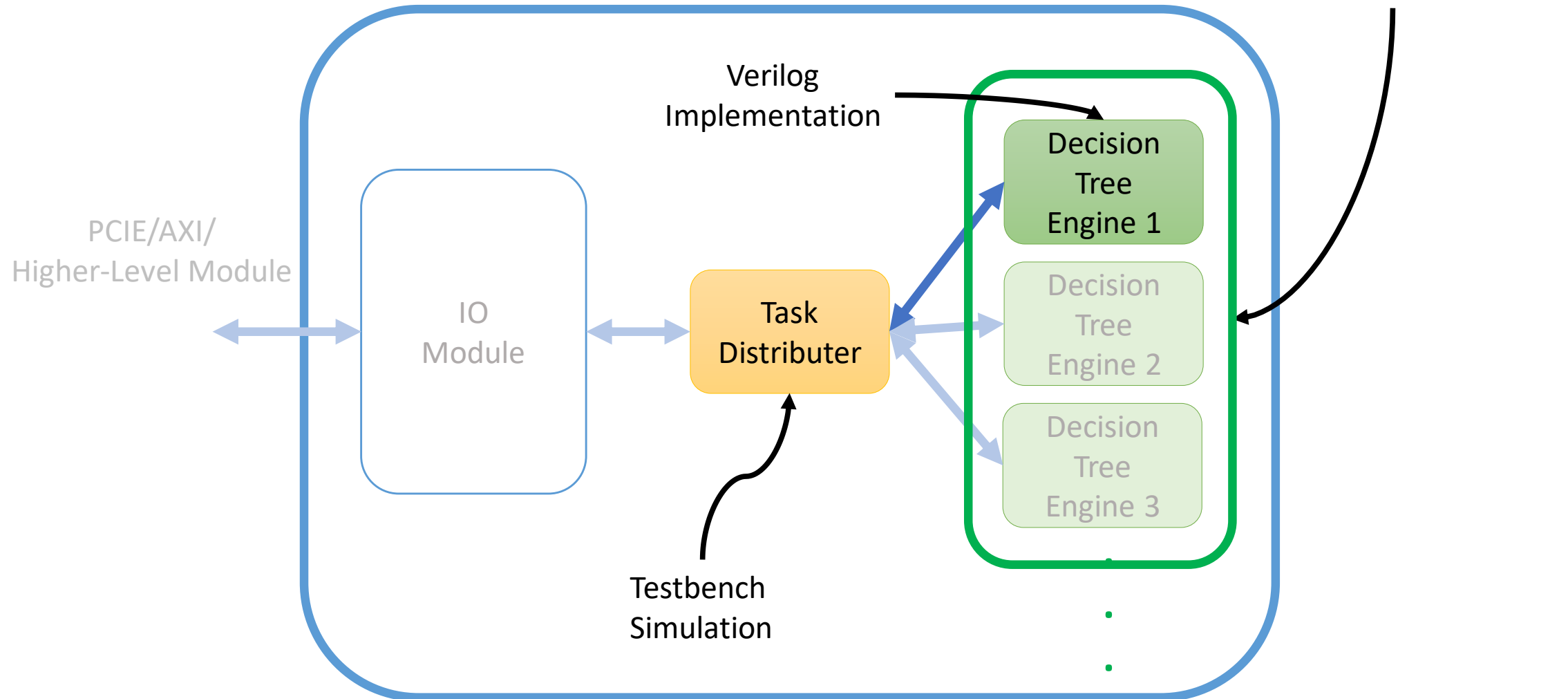
Final Tree Structure

- Max node index: 10
- Max-depth: 5 layers



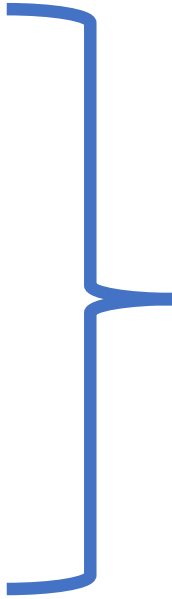
Hardware

Top-Level View / Project Scope



Architecture – Core Function

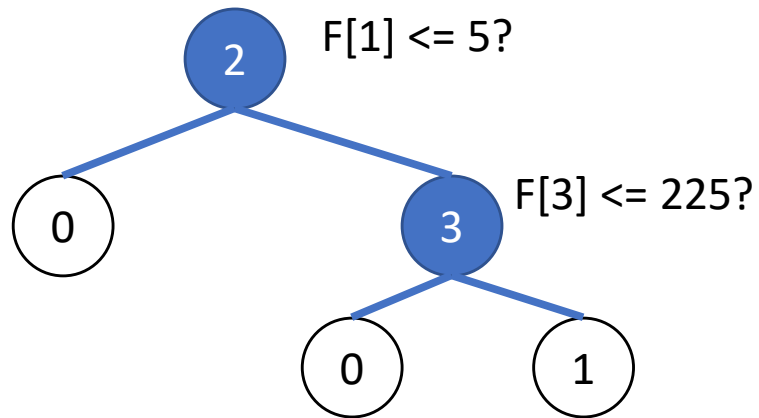
- 3-stage pipeline for the decision tree engine
 - 1st:
 - Retrieve the feature index by the node index
 - 2nd:
 - Retrieve the feature by feature index
 - Retrieve the threshold used
 - 3rd:
 - Comparing the selected feature with the threshold
 - Retrieve the next node index



Move 1 layer
down in the tree

Architecture – Core Function

- Parameter storage option
 - SRAM: Better generalizability for larger trees!
 - Flip-Flop array



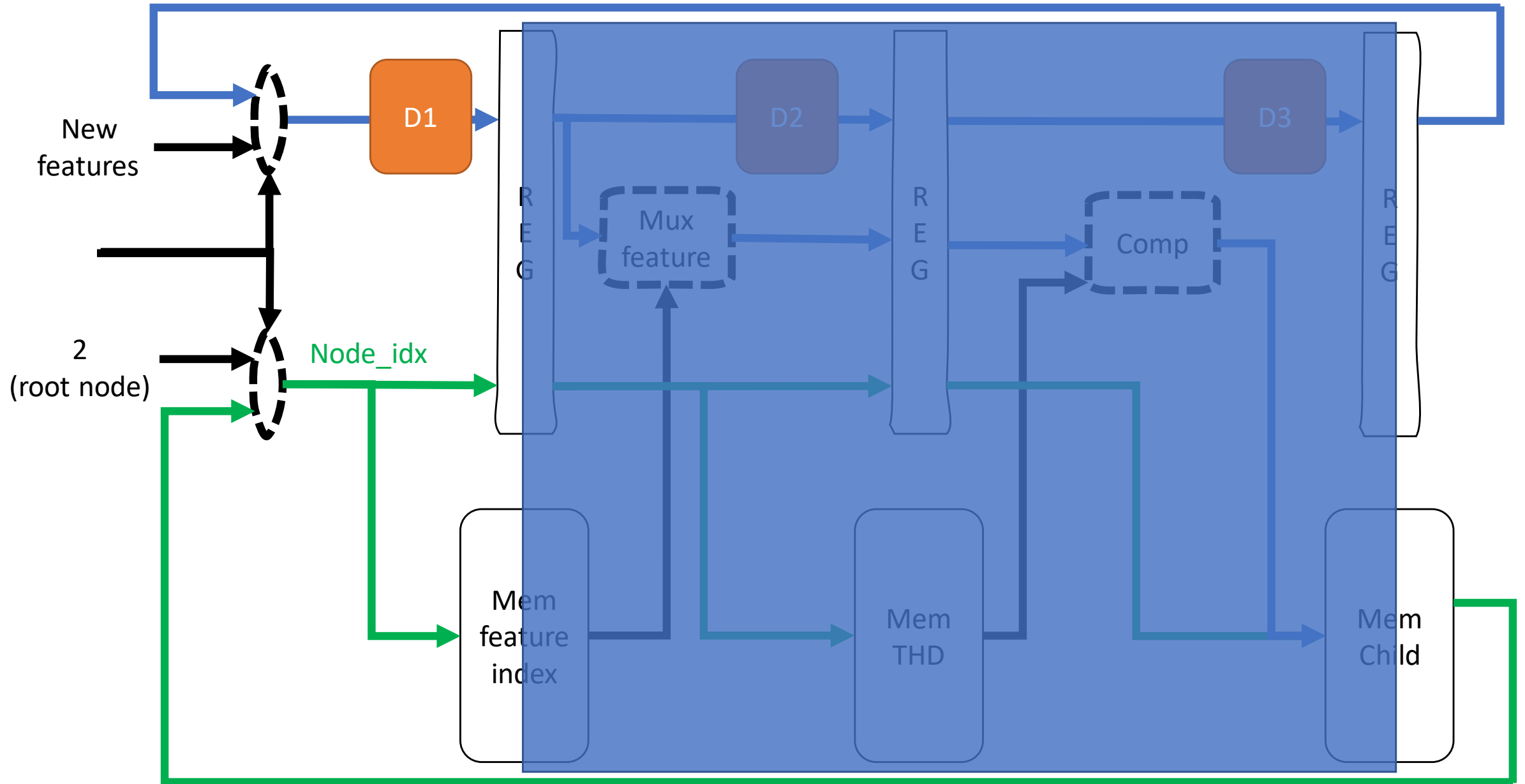
Node 0

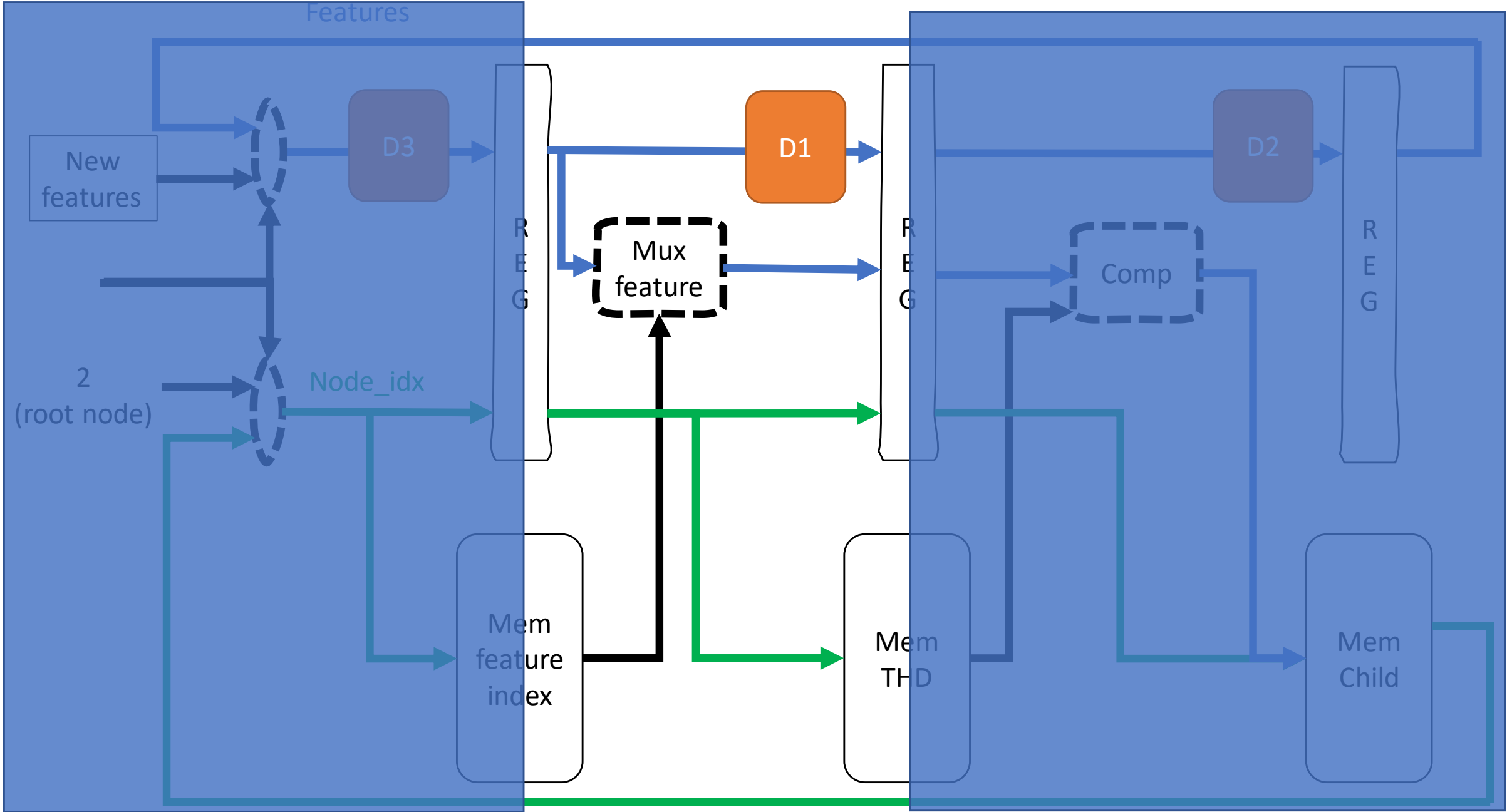
Node 2
(root
node)

Feature Index	Threshold	Child
0	0	0
0	0	0
1	5	0
3	225	0
0	0	0
0	0	3
0	0	0
0	0	1

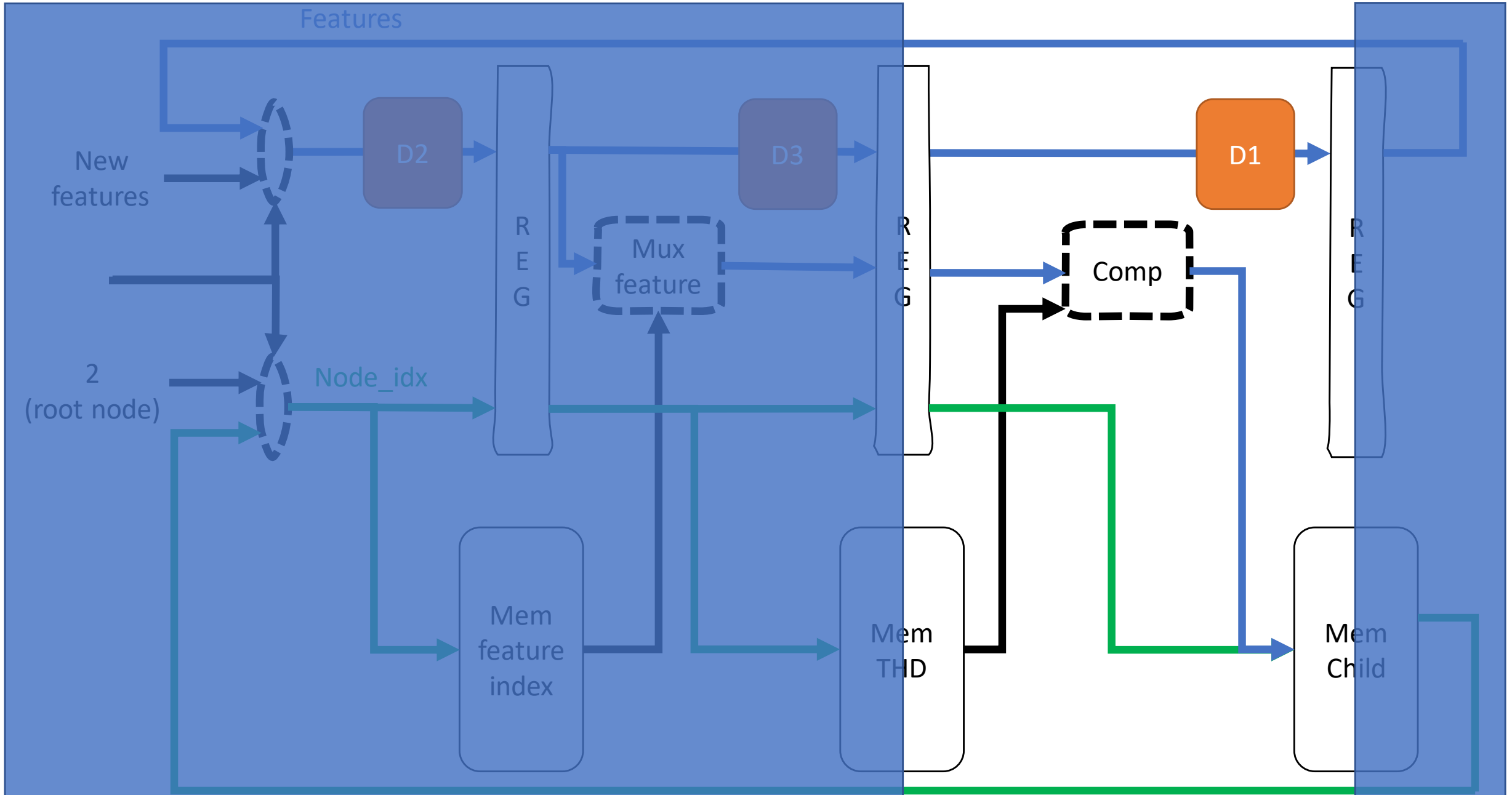
Stage 1

Features



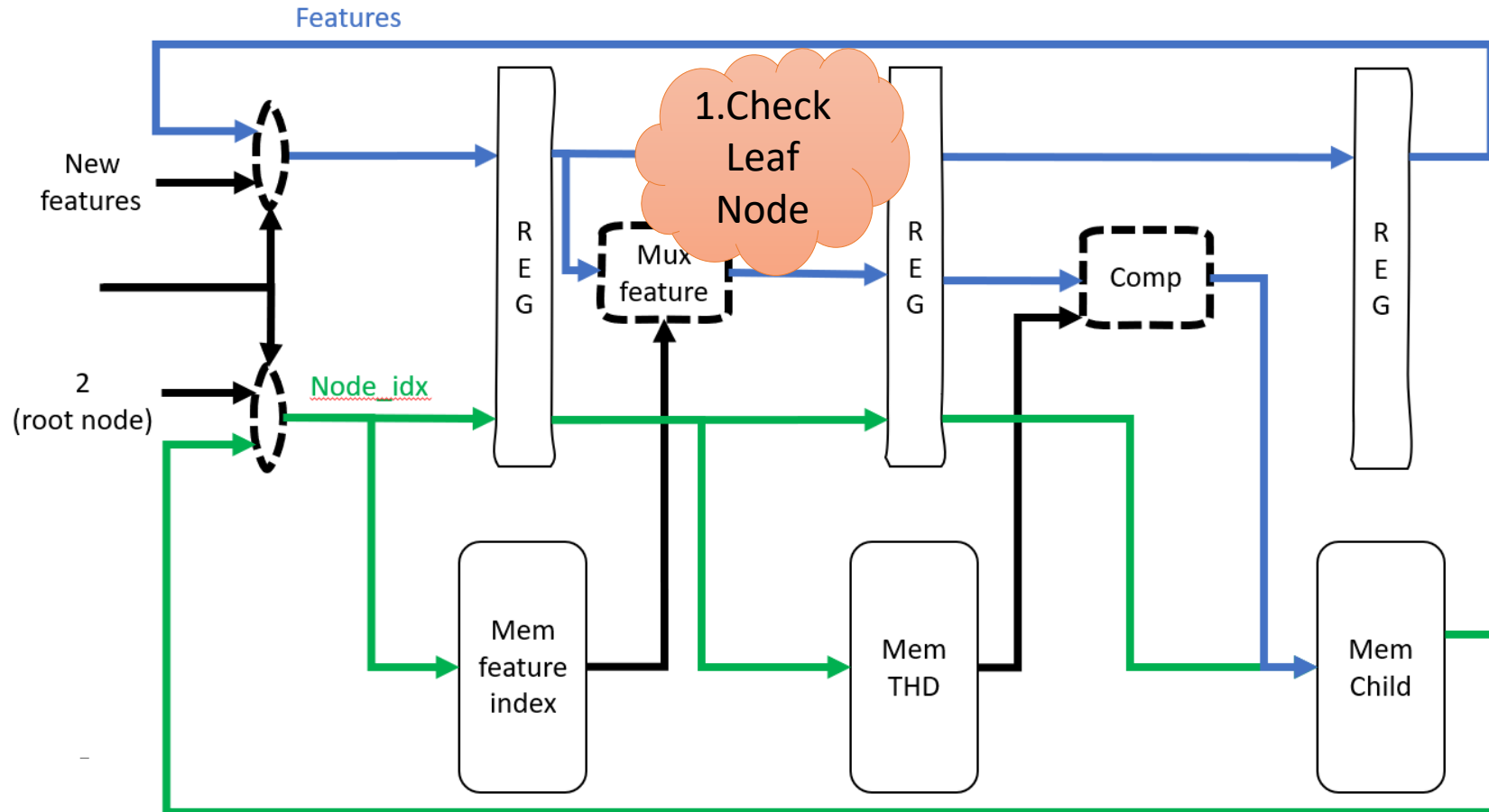


Stage 3



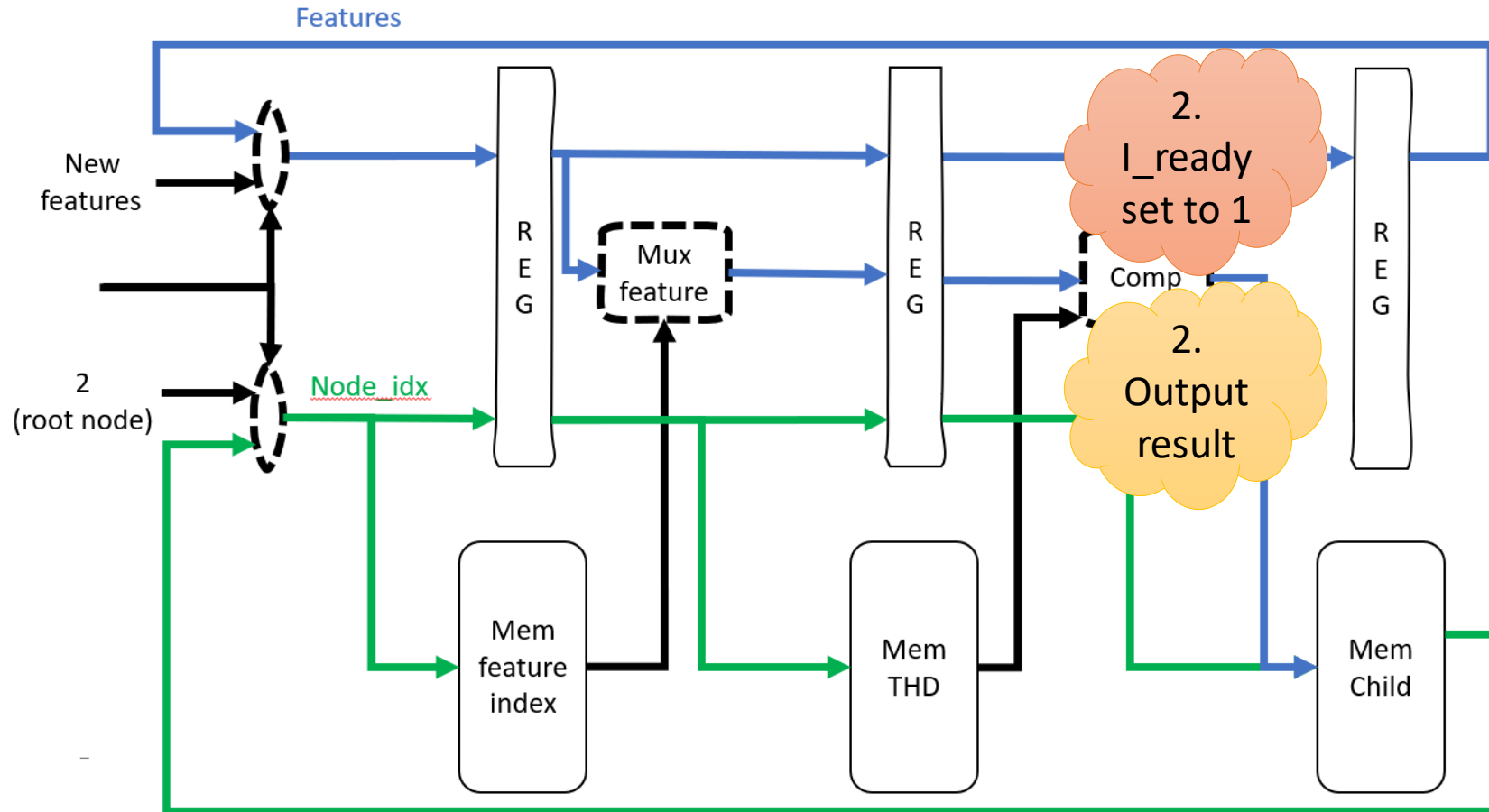
Architecture – A deeper look

- Input / Output
 - Assume the task distributor takes 1 cycle to respond



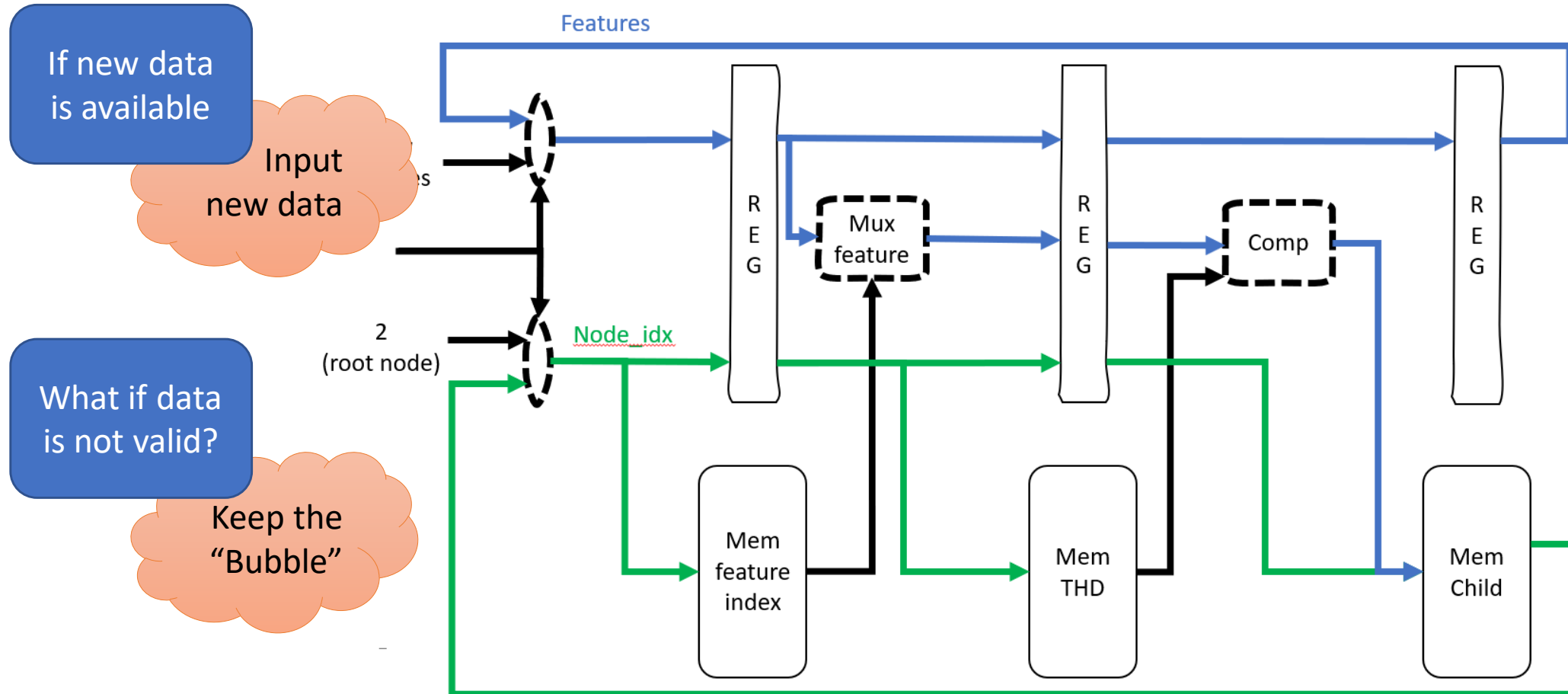
Architecture – A deeper look

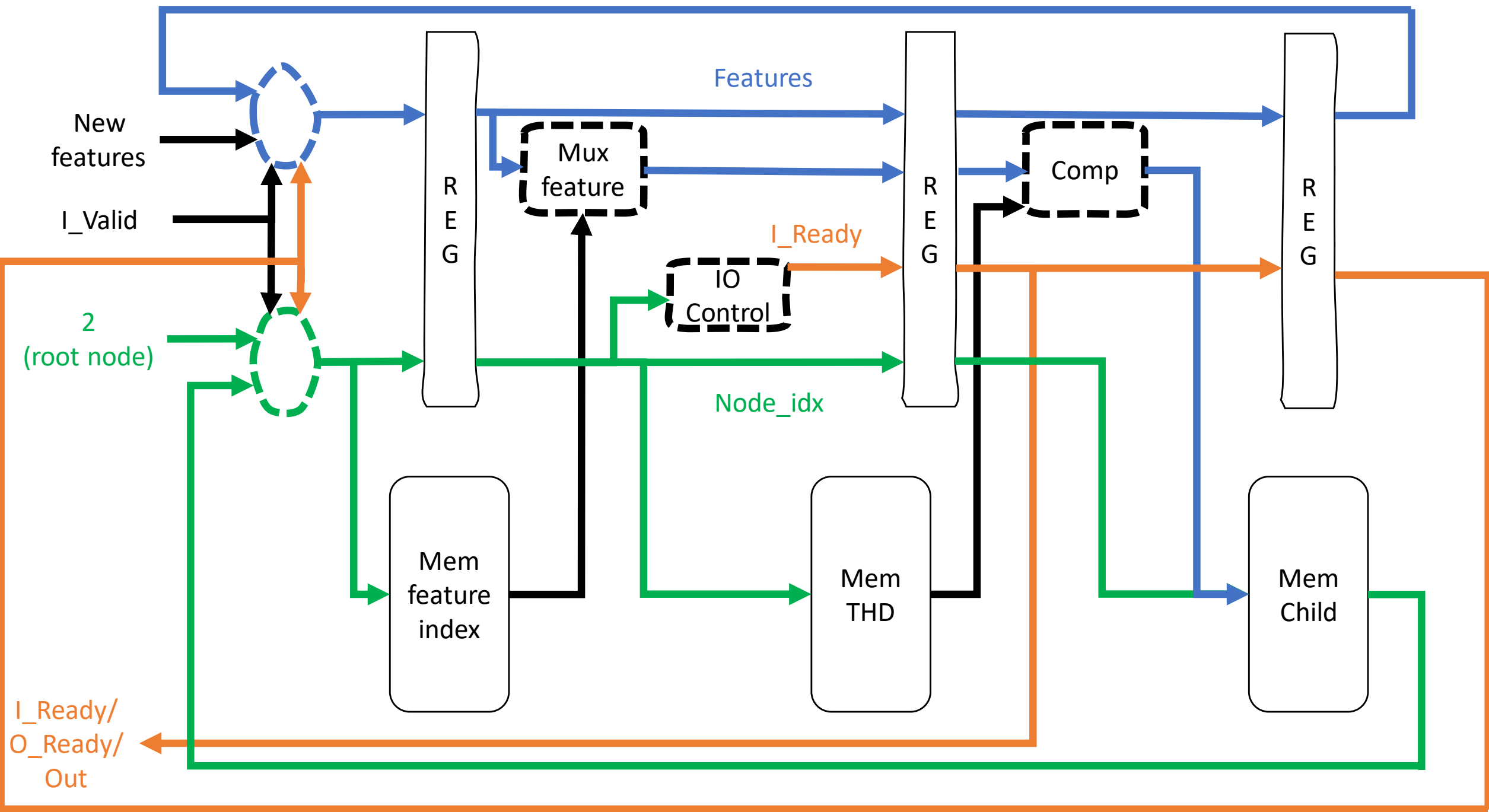
- Input / Output
 - Assume the task distributor takes 1 cycle to respond



Architecture – A deeper look

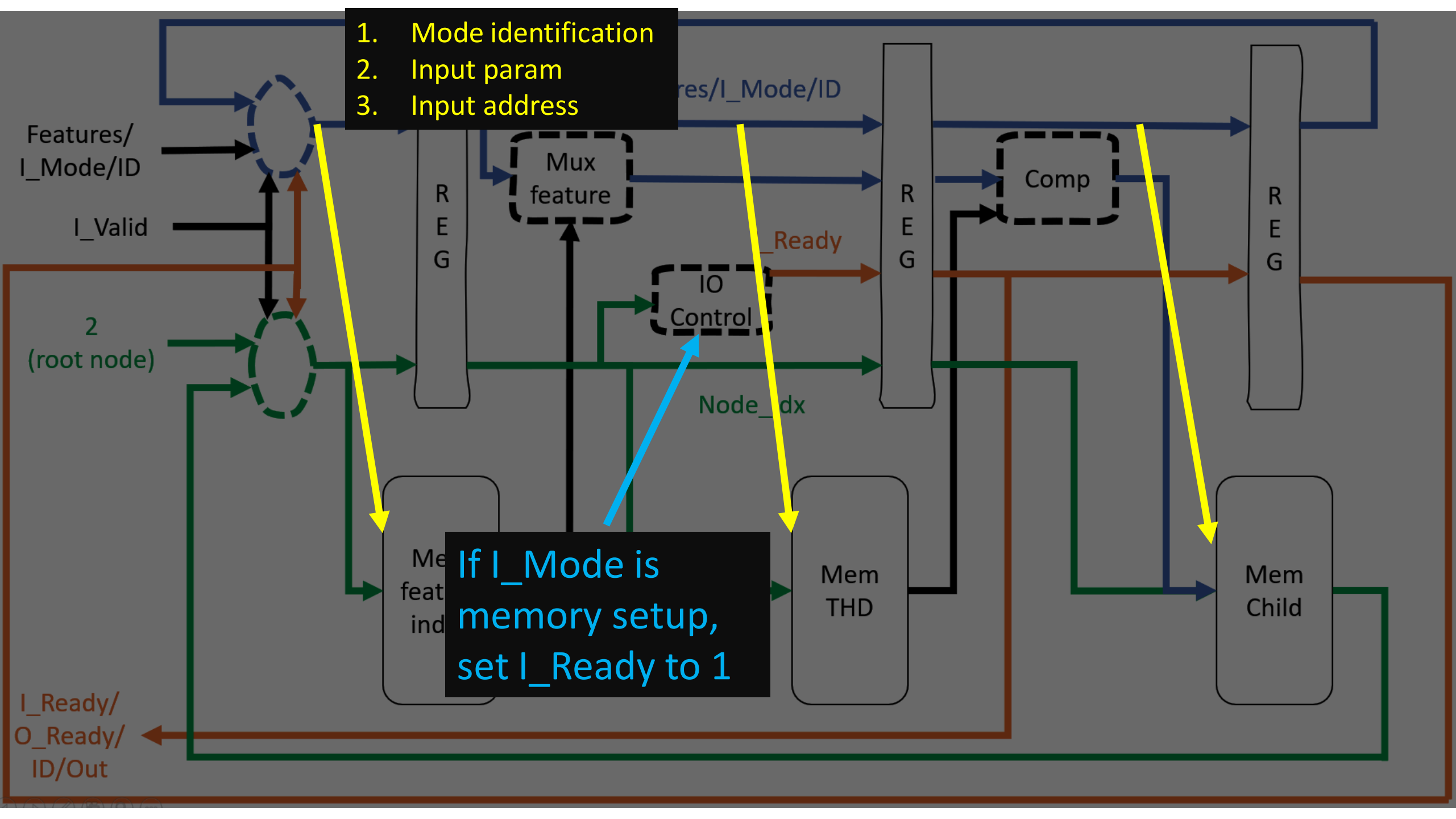
- Input / Output
 - Assume the task distributor takes 1 cycle to respond





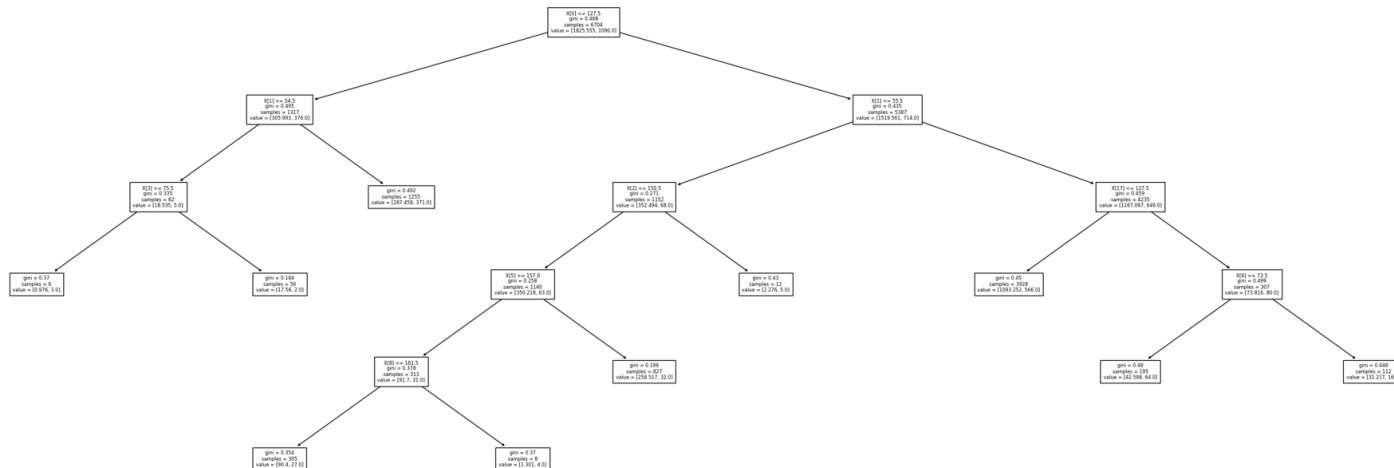
Architecture – A deeper look

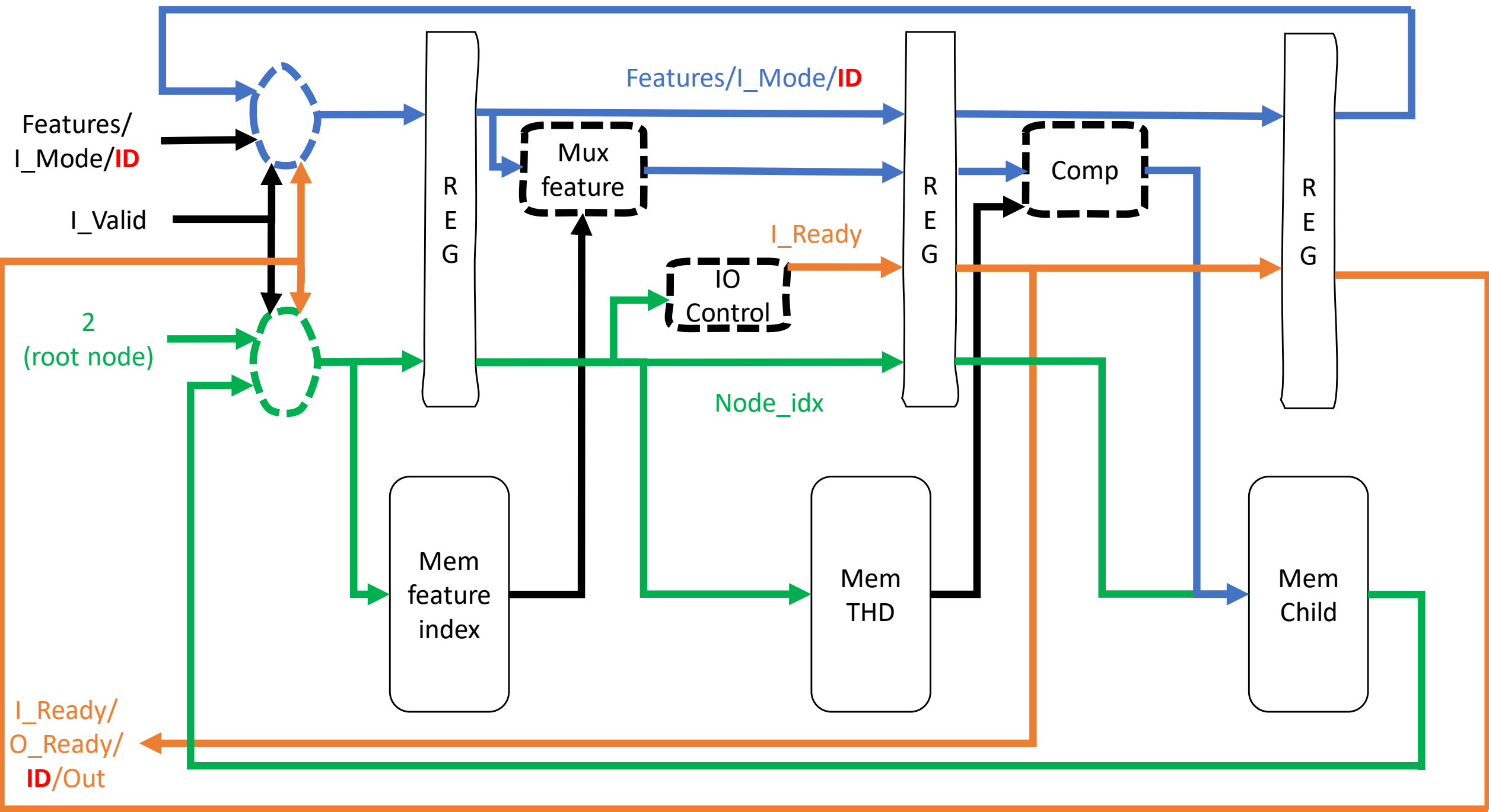
- Memory Initialization
 - Pass the params and addresses one by one
 - Re-using existing input ports
 - How to identify the correct instruction?
 - Add a new input port, I_Mode
 - 00: Initialize feature index memory
 - 01: Initialize threshold memory
 - 10: Initialize child node memory
 - 11: Computation
 - ***Allows parameter modification at run time!***



Architecture – Final thoughts

- Processing latency varies between data
 - IO does not follow first-in-first-out
 - Naïve solution:
 - Track the data ID in each stage





Synthesis

- Using Synopsys Design Vision
 - Process node: TSMC 0.13um
 - Clock Cycle: 3.6ns
 - Memory: 86% of the cell area

```
Number of ports:          92
Number of nets:          675
Number of cells:         556
Number of combinational cells: 294
Number of sequential cells: 259
Number of macros/black boxes: 3
Number of buf/inv:       44
Number of references:     58

Combinational area:      2946.686373
Buf/Inv area:           417.560399
Noncombinational area:   8352.905128
Macro/Black Box area:   72567.695312
Net interconnect area:   74480.587451

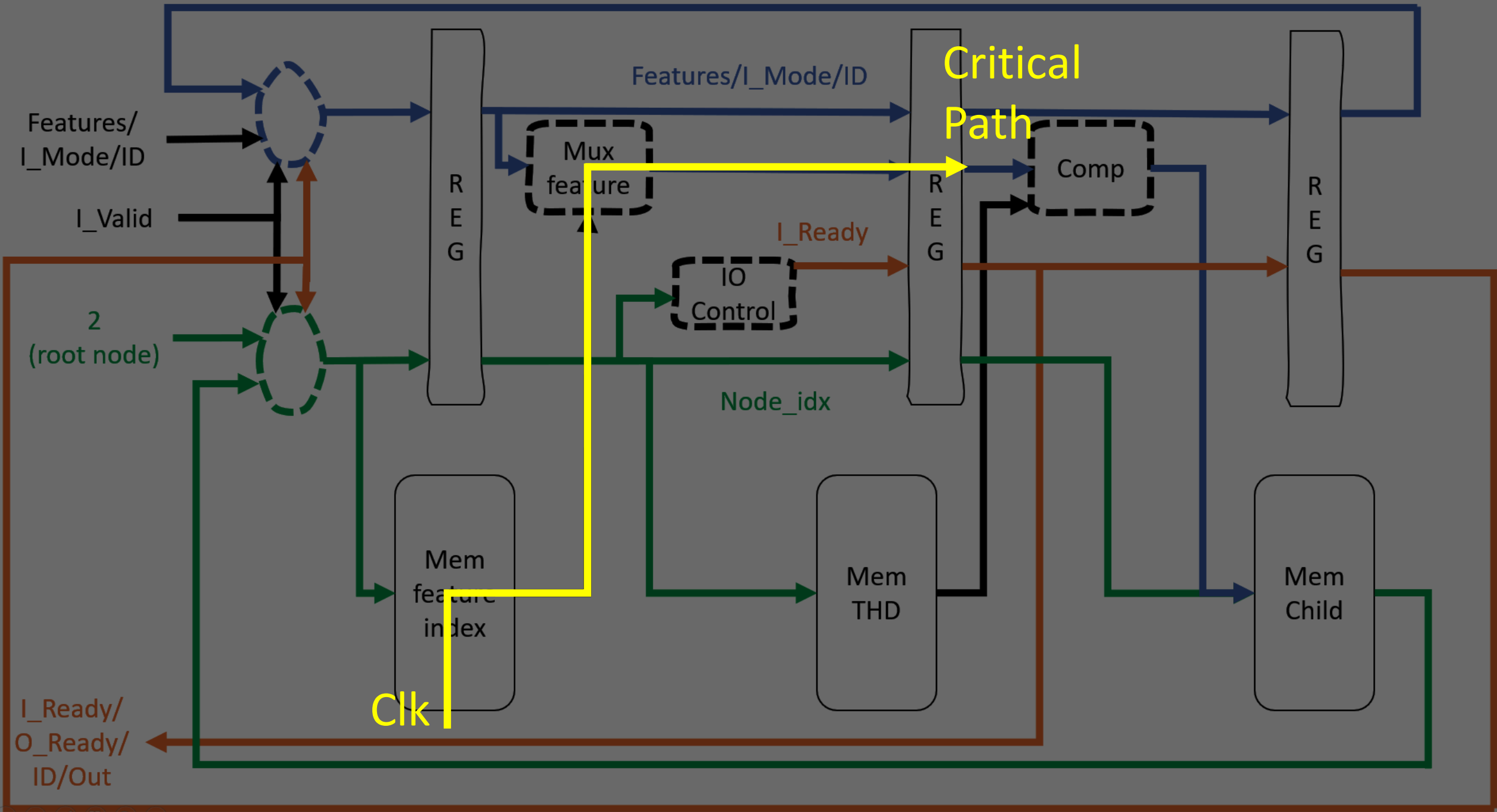
Total cell area:         83867.286814
Total area:              158347.674265
```

```
Startpoint: fea_idx_sram
              (rising edge-triggered flip-flop clocked by clk)
Endpoint: selected_feature_s2_r_reg_0_
              (rising edge-triggered flip-flop clocked by clk)
```

```
Path Group: clk
Path Type: max
```

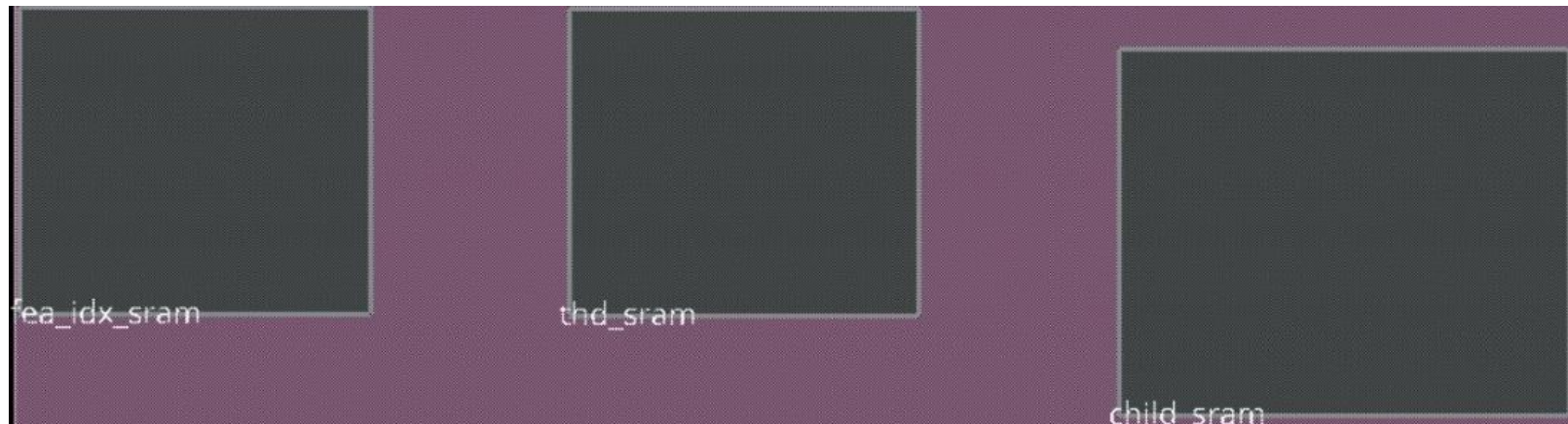
Des/Clust/Port	Wire Load Model	Library
DEC	tsmc13_wl10	slow

Point	Incr	Path
clock clk (rise edge)	0.00	0.00
clock network delay (ideal)	0.50	0.50
fea_idx_sram/CLK (sram_256x8)	0.00	0.50 r
fea_idx_sram/Q[1] (sram_256x8)	2.06	2.56 f
U400/Y (NOR2BX4)	0.17	2.73 f
U401/Y (BUFX12)	0.19	2.92 f
U414/Y (AOI22X1)	0.29	3.21 r
U415/Y (OAI211X1)	0.23	3.44 f
U416/Y (NAND2X1)	0.22	3.66 r
U371/Y (OAI21X2)	0.12	3.78 f
selected_feature_s2_r_reg_0_/D (DFFRX1)	0.00	3.78 f
data arrival time		3.78

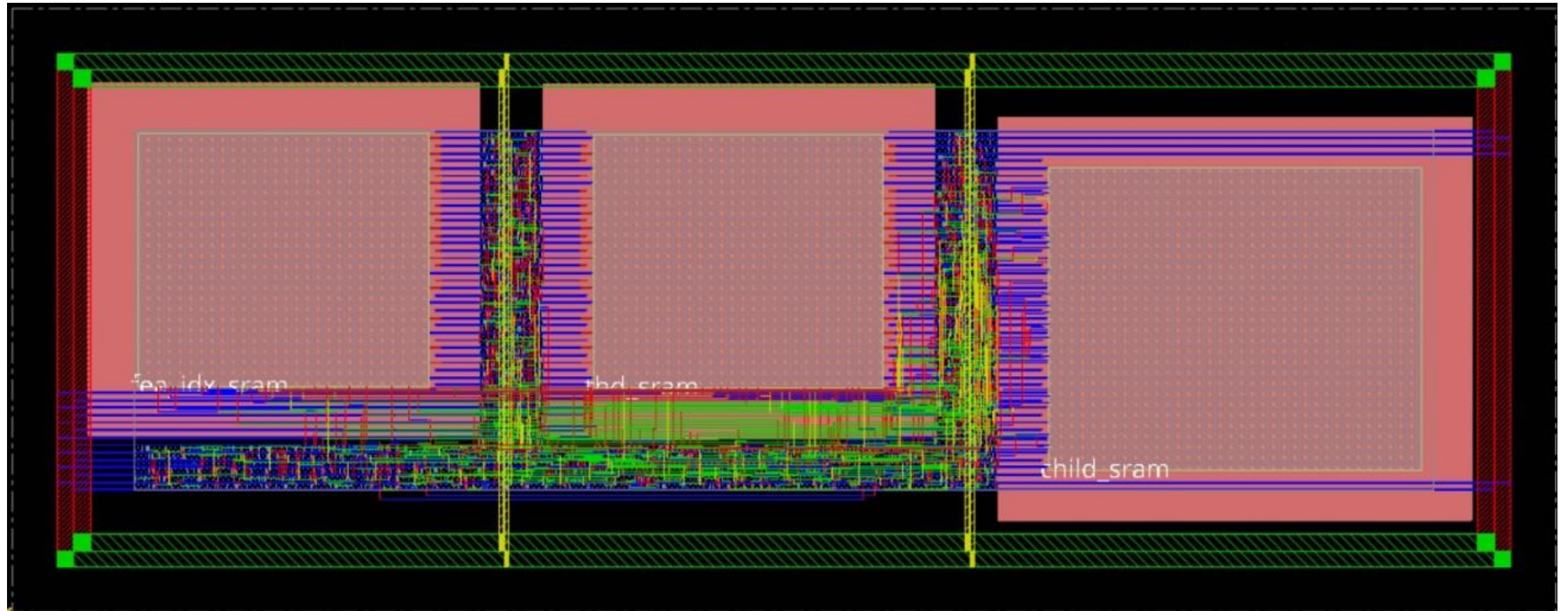


Press and Route

- Using Cadence Innovus
 - Following the steps taught in COMPUTER-AIDED VLSI SYSTEM DESIGN, National Taiwan University
 - Utilization Rate: 0.65
 - Memory dominating layout
 - **Floorplan, memory placement, power plan** are critical to avoid violations!
 - Pass P&R testbench simulation at clock cycle 3.6 ns



Press and Route



Accelerator Performance

- The evaluation metric is the inference time of all 2874 testing data.
- The baseline inference time of scikit-learn decision tree, using CPU, is 1.58 ms
 - Intel(R) Core(TM) i7-7700 CPU @ 3.60GHz

```
Total inference time using cpu: 0.0015842914581298828
```

- The presented decision tree accelerator only requires 42.5 us!
 - Including memory setup
 - ~37 times faster!

```
PASS  
Simulation complete via $finish(1) at time 42508800 PS + 0  
./tb_v3.v:226 $finish;
```

References

- <https://stackoverflow.com/questions/51397109/prune-unnecessary-leaves-in-sklearn-decisiontreeclassifier>
- <https://stackoverflow.com/questions/56334210/how-to-extract-sklearn-decision-tree-rules-to-pandas-boolean-conditions>
- <https://github.com/Shayan-Asgari/ClassificationTrees>
- Course material of COMPUTER-AIDED VLSI SYSTEM DESIGN, National Taiwan University

About me

- Bo-Fan, Chen
- Nationality: Taiwan
- Language
 - Mandarin
 - English
- Education
 - National Taiwan University
 - Electric Engineering, graduated in 2019.07
 - Graduate Institute of Electronics Engineering, Integrated Circuits & Systems Group, Laboratory for Data Processing Systems, expect to graduate in 2022.09
 - Aarhus University, Denmark
 - Exchange student, from 2021.09 to 2022.07
 - Software Engineering, Electric Engineering
- Academic Work
 - CF-NET: Complementary Fusion Network for Rotation Invariant Point Cloud Completion, ICASSP 2022
- Skills
 - Digital Circuit Design, Verilog, Synopsys Design Vision, Cadence Innovus
 - Machine Learning, Python, Numpy, Pytorch, Tensorflow
- Objective
 - Looking for a position as digital circuit RTL engineer. Preferred locations are: United States, Europe, Taipei.



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