

# NCTU-EE IC LAB – Fall 2023

## Midterm Project

### Design: Maze Router Accelerator (MRA)

#### Data Preparation

1. Extract test data from TA's directory:

```
% tar xvf ~iclabTA01/Midterm_Project.tar
```

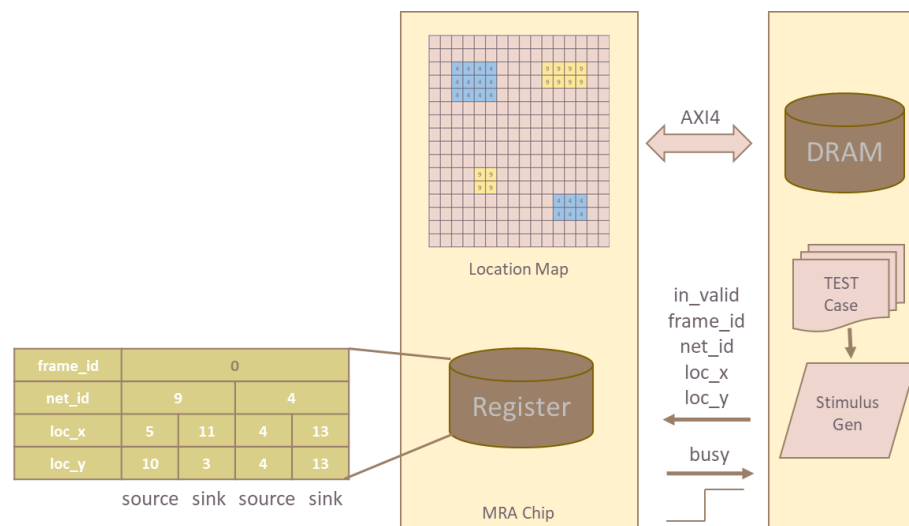
#### Design Description

Wire routing, often referred to simply as "routing", is a pivotal stage in IC (Integrated Circuit) design. Following the placement phase, the routing process introduces the necessary wires to connect the components in accordance with the IC's design rules. All routing tools share a fundamental objective: they begin with predefined polygons representing terminals on cells. Each polygon is linked to a specific net, either by name or number. The router's main responsibility is to generate geometries that ensure terminals linked to the same net are connected. At the same time, terminals from different nets should remain unconnected, while adhering to all design guidelines.

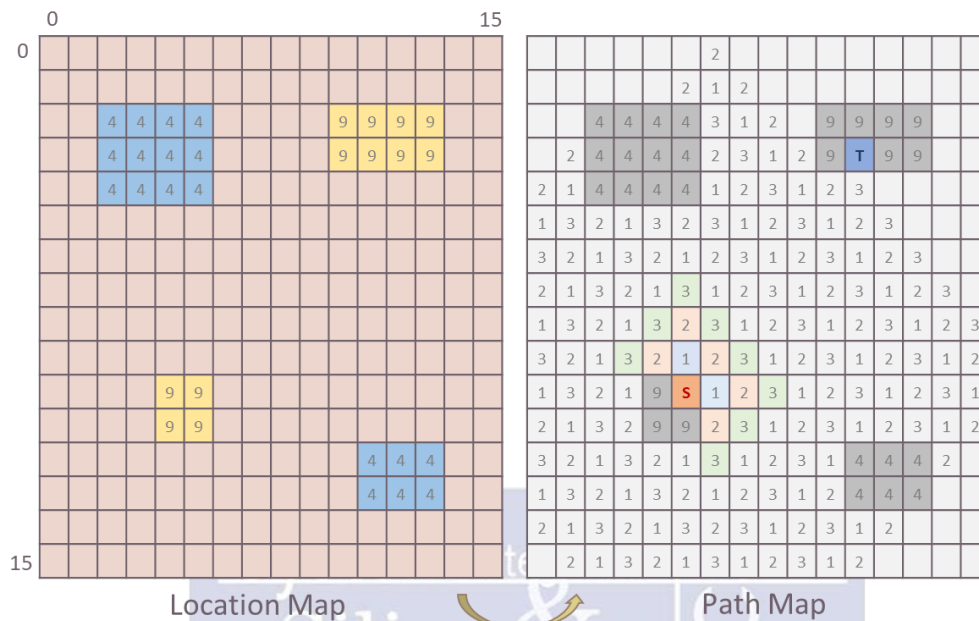
In this project, you'll be developing a robust router called the "Maze Router". This router will handle multiple un-routed targets stored in DRAM. Your primary objective is to ensure that all terminals linked to a specific net are interconnected. Let's delve deeper into how the Maze Router operates.

Here is step by step illustration:

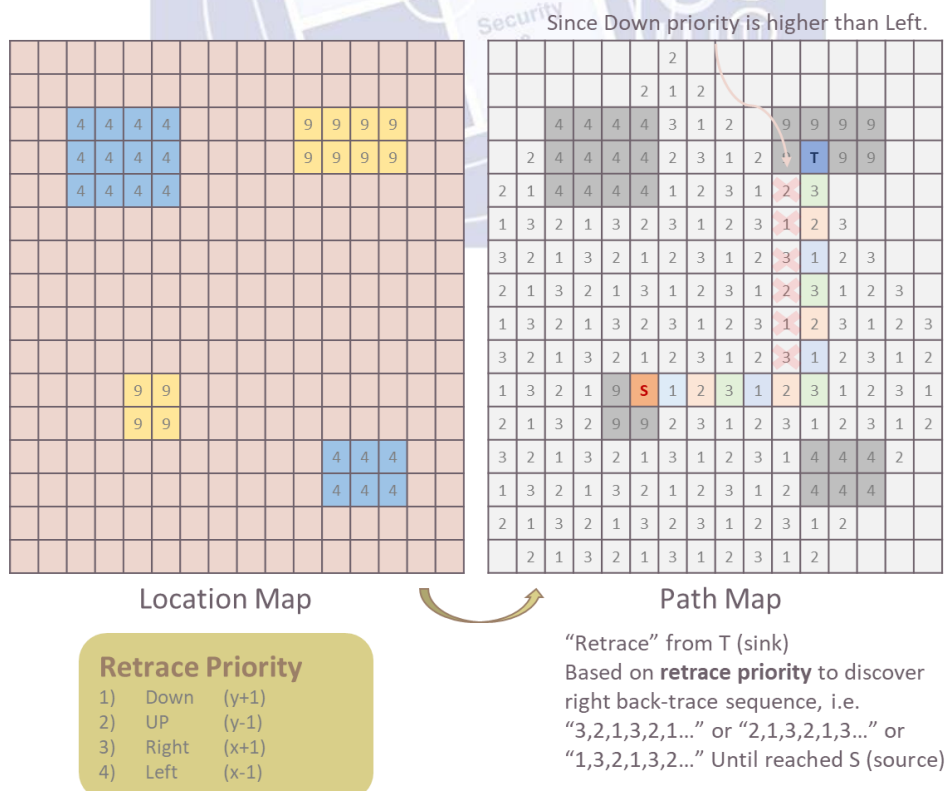
**Step 0: Get Input & Fetch DRAM**



## Step 1: Filling Path Map

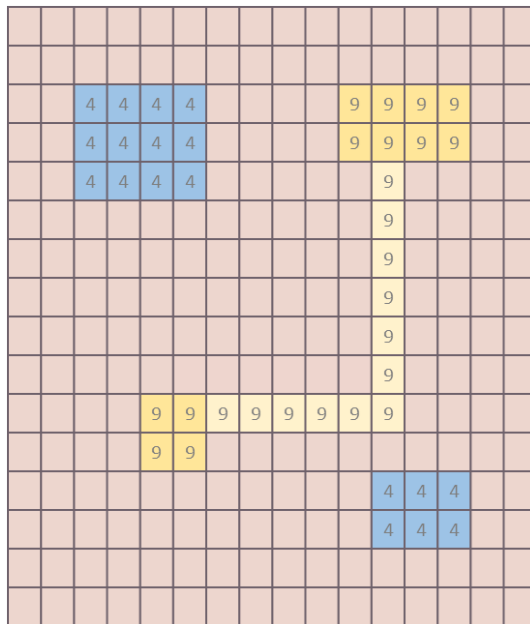


## Step 2: Retrace Path Map



### Step 3: Update Location Map

**Loop:** Until all targets routed



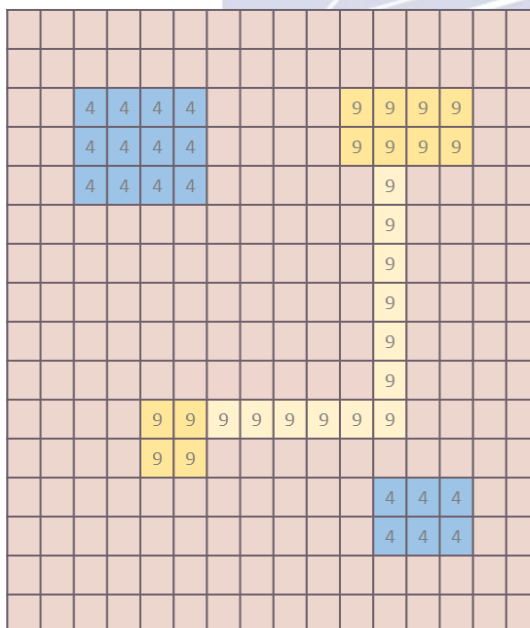
**Repeat**  
**Step.1 ~ Step.4**

frame_id	0			
net_id	9		4	
loc_x	5	11	4	13
loc_y	10	3	4	13

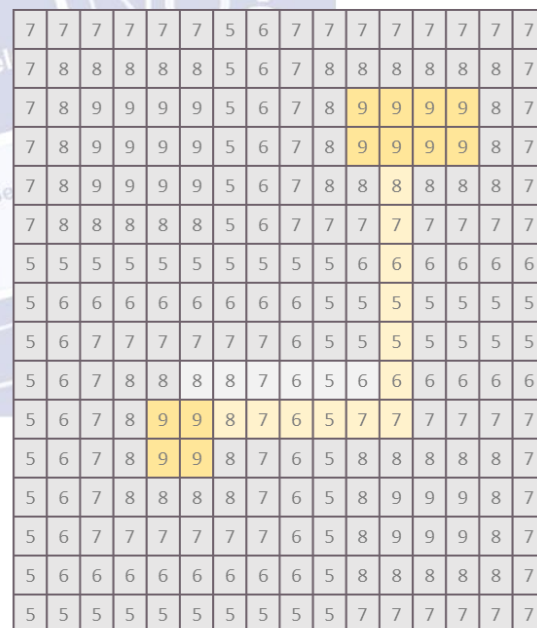
source sink

Do it again for another target  
until all targets find the path.

### Step 4: Calculate Path Cost



Location Map



Weight Map (store in DRAM)

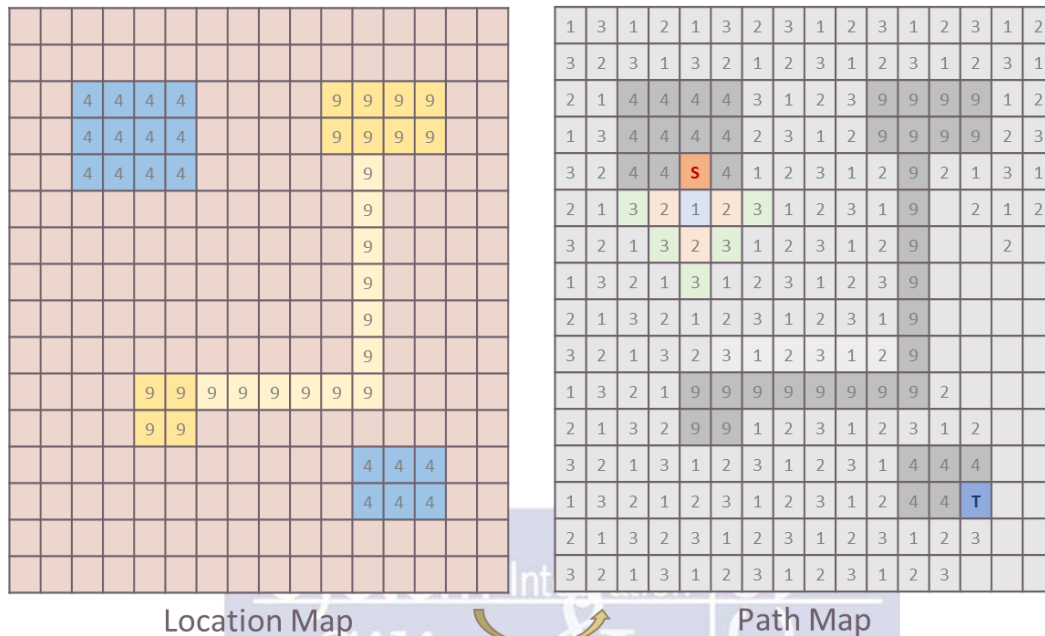
Accumulate weight on the path from  
Source to Sink.

Ex:  $8+7+6+5+7+7+6+5+5+6+7+8 = 77$

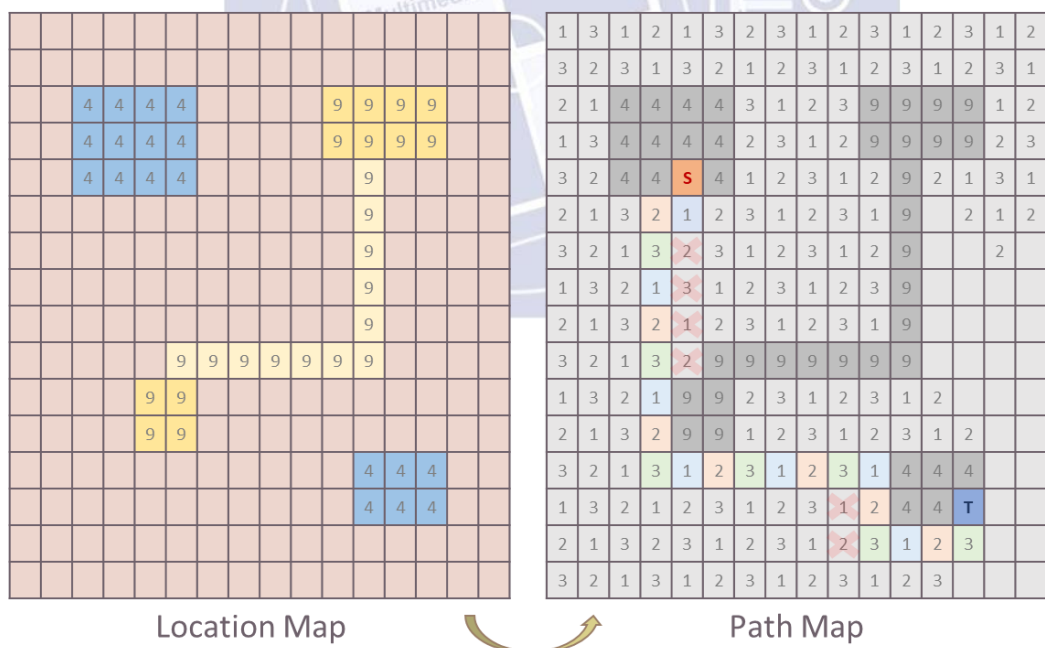
Record it as target #1 path cost.

(Total cost += target #1 cost )

## Loop2 >> Step 1: Filling Path Map



## Loop2 >> Step 2: Retrace Path Map



### Retrace Priority

- 1) Down (y+1)
- 2) UP (y-1)
- 3) Right (x+1)
- 4) Left (x-1)

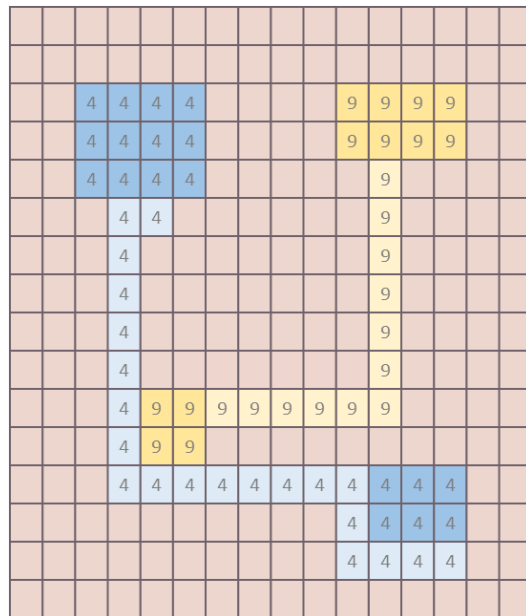
“Retrace” from T (sink)

Based on **retrace priority** to discover right back-trace sequence, i.e.

“3,2,1,3,2,1...” or “2,1,3,2,1,3...” or

“1,3,2,1,3,2...” Until reached S (source)

### Loop2 >> Step 3: Update Location Map



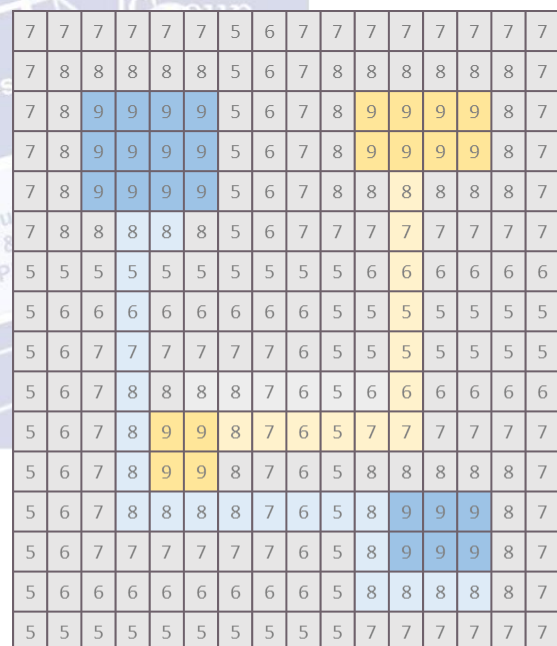
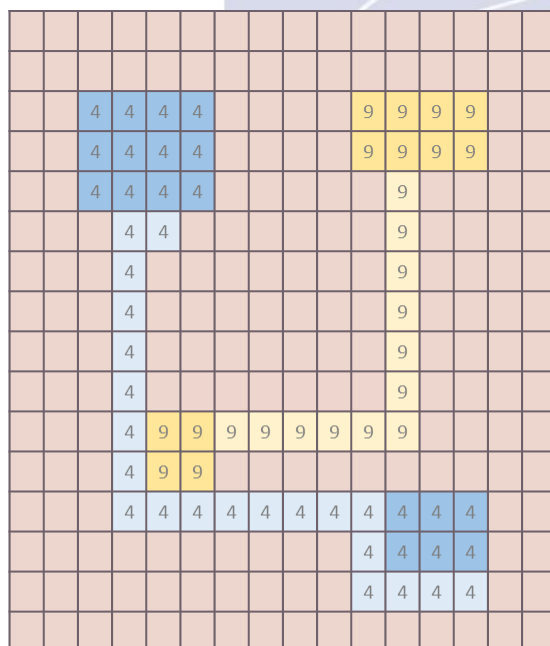
All targets find path



frame_id	0			
net_id	9		4	
loc_x	5	11	4	13
loc_y	10	3	4	13

### Loop2 >> Step 4: Calculate Path Cost

Source Sink Source Sink



Location Map



Weight Map (store in DRAM)

Accumulate weight on the path from Source to Sink.

Ex:  $8+8+5+6+7+8+8+8+8+8+8+7+6+5+8+8+8+8+8+8 = 156$

Record it as target #2 path cost.

(Total cost += target #2 cost )

The diagram illustrates the Pattern architecture, showing the interaction between the MRA Chip and the PATTERN unit.

**MRA Chip:**

- Location Map:** A 16x16 grid of numbers (0-9) representing the location map. Some cells are highlighted in blue (e.g., (4,4), (4,5), (4,6), (5,4), (5,5), (5,6), (6,4), (6,5), (6,6), (7,4), (7,5), (7,6), (8,4), (8,5), (8,6), (9,4), (9,5), (9,6)).
- Target #1 Cost:** A stack of three pink rectangles representing the target cost.
- Total Cost:** A pink cylinder representing the total cost.

**PATTERN:**

- Functional Check:** A pink parallelogram representing the functional check.
- DRAM:** A brown cylinder representing the DRAM.
- frame #id:** A label above the DRAM.

**Data Flow:**

- AXI4:** A double-headed arrow connecting the MRA Chip and the PATTERN unit.
- cost:** A single-headed arrow pointing from the MRA Chip to the PATTERN unit.
- busy:** A single-headed arrow pointing from the PATTERN unit to the MRA Chip.

**Pattern will check:**

- (1) Check original target is consistent with original location map store in DRAM. (**consistent check**)
- (2) Check routed location map store in DRAM to see if source can reach sink or not. (**connectivity check**)
- (3) Check weight output is correct with your routed location map in DRAM (**cost check**)

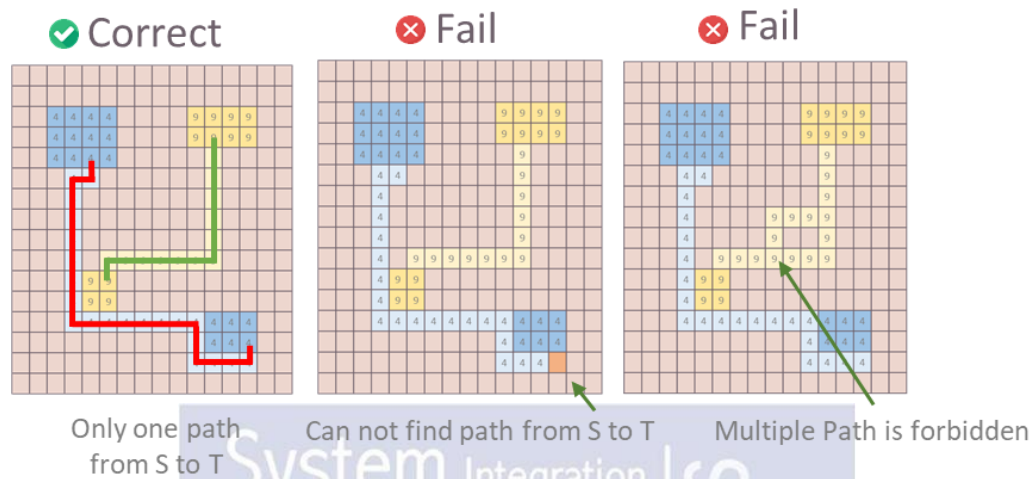
Here is some check point in routed result:

Check original target is consistent with original location map store in DRAM.



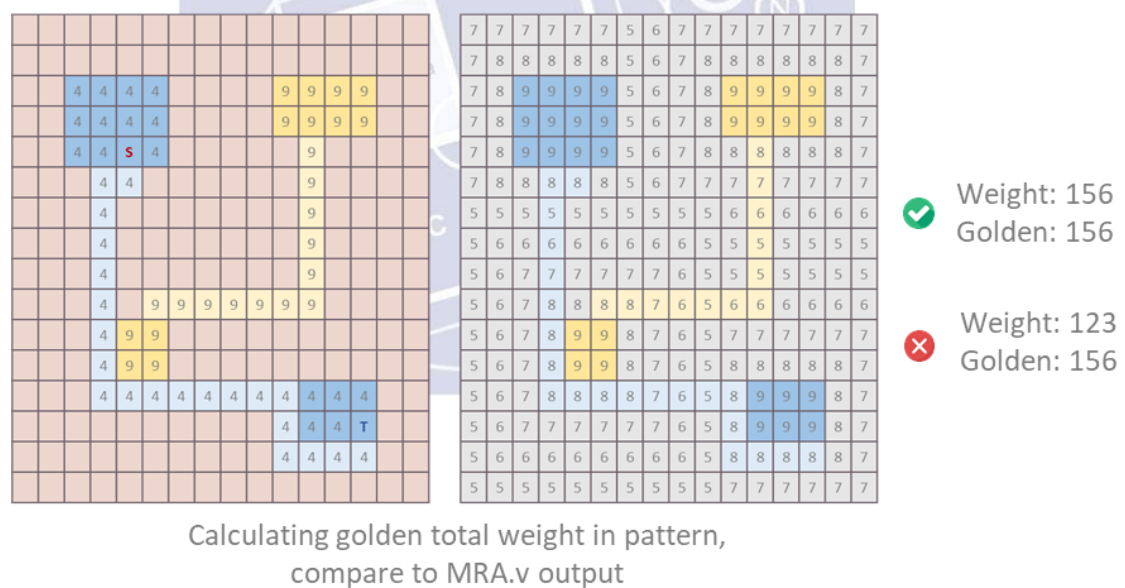
## (2) Connectivity Check

Check routed location map store in DRAM to see if source can reach sink or not.



## (3) Cost Check

Check weight output is correct with your routed location map in DRAM



Note that only if (1) pass, then will check (2), then (3). Any of violation of rules will fail this Midterm.

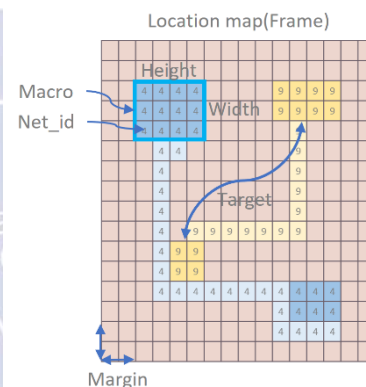


Now, we need to formulate this problem more specifically with well-defined SPEC. Hence, let me introduce definition/SPEC precisely for in this midterm project.

### SPEC for Test Case Generation

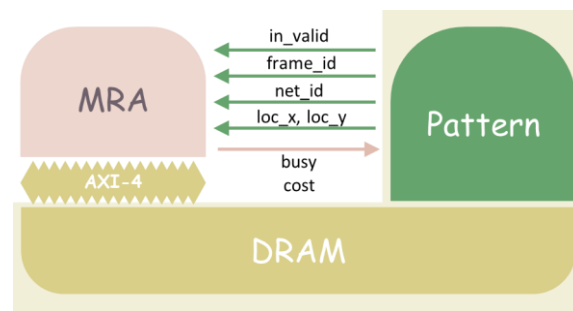
---

1. One Location map called a Frame, with 64 by 64 4-bit array
2. Each Frame has its Frame\_id, identify the address store in DRAM
3. Location map include several routing Target, # of targets would range in 1~15
4. Each Target owns its NET\_ID, NET\_ID would range from 1~15
5. One Target consisted of 2 Macro, one is Source, the other is Sink
6. Macro height and width would be ranged in 2~6 if # of targets less than 11, otherwise would be 2~4
7. Macro has one Terminal, which must be located at the outermost region of the Macro
8. Location of Terminal would be send by input loc\_x and loc\_y, first is Source, followed by Sink
9. Location map record all Macro location, identified by a 4-bit value NET\_ID, while 0 represent empty region
10. Margin of Location map would be outermost 2 rows and 2 columns
11. Macro would never place at the Margin area
12. Target is routed means only one path is highlighted with NET\_ID from Source Terminal to Sink Terminal in Location map
13. Length means path grid number from Source Terminal to Sink Terminal exclusive itself when Target is routed
14. Length of each Target is limited within 1000 units, i.e. no case over 1000 units
15. Weight means path weighted sum from Source Terminal to Sink Terminal exclusive itself when Target is routed
16. Location map routing success means all Target is routed in Location map (not unique solution)
17. Location map must be routing success with given approach
18. Cost of routing result means the accumulation Weight when Location map routing success





## System Architecture



First, pattern will give the **frame\_id** of Location Map and Weight in DRAM, also send the corresponding **net\_id**, source location and sink location with the **loc\_x, loc\_y** in a row when **in\_valid** is high. Note that the number of targets will not be provided. It depends on how

many **net\_id** you get when **in\_valid** is high. Then, your chip should fetch frame data stored in DRAM via AXI-4. While your design is dealing with current task, **busy** should be high. After all processing is done, and all data is written back to DRAM, **busy** should be pull low so that pattern could check the answer in DRAM and output cost is consistent with golden one. On the other hand, pattern can directly access DRAM for data checking and overwriting without any constrain. In this project, all frames are 64 x 64, 4-bit net id location map, and all Weight Maps are 64 x 64, 4-bit integer. The DRAM behavior model (pseudo\_DRAM.v) is provided by TA.

## Memory Mapping

Example of data in memory:



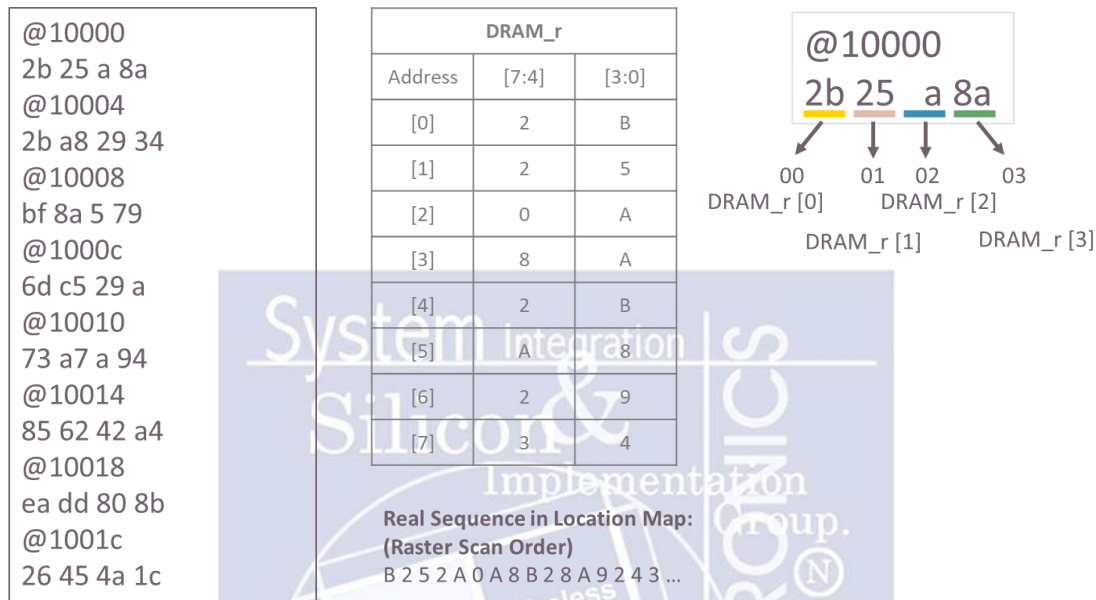
Since all 16 frames are 64 x 64, 4-bit location map, we need 2048 bytes to store single frame. Each address in DRAM can store 1 byte (8 bits). Thus, the address of frame No.0 is range from 0x0001\_0000 to 0x0001\_07FF, No.1 is ranged from 0x0001\_0800 to 0x0001\_0FFF and so on. Every frame is **in raster scan order** in DRAM, each byte in DRAM represent 2 position value, where [3:0] means 1<sup>st</sup> element, and [7:4] means 2<sup>nd</sup> element.

## Mapping Example:

For example, 0x0001\_0000 stores the (0, 0) [3:0] and (1,0) [7:4] value of Frame NO.0, 0x0001\_0001 stores the (0, 2) [3:0] and (0, 3) [7:4] of Frame NO.0.

### Variable in pseudo\_DRAM.v

```
reg [7:0] DRAM_r [0:196607]; (Address from 00000000 to 0002FFFF)
```



As for Weight Map, all of them are 64 x 64, 4-bit integer, and also **in raster scan order** in DRAM. The address of Weight No.0 is range from 0x0002\_0000 to 0x0002\_07FF, No.1 is ranged from 0x0002\_0800 to 0x0002\_0FFF and so on.

## Fetch DRAM:

Given **frame\_id** = 5, that means your need to fetch DRAM 0x0001\_2800 ~ 0x0001\_2FFF for Location map and 0x0002\_2800 ~ 0x0002\_2FFF for Weight map with AXI4 protocol.

Note that Memory Address is Byte Offset as shown in above example. Each address is mapped to single byte.

Please refer to NOTE\_2023\_FALL for more detail information of DRAM.

You should **generate the SRAM** to store the required data. TA will check if you truly use memory, and if **NOT**, you will **Fail** the demo.

## Control Interface

### Inputs

1. You will receive 1 number **frame\_id** [4:0] which is the index of both Location Map and Weight Map.
2. You will receive several numbers of **net\_id** [3:0] which identify (1) NET\_ID of target that stores in Location Map, (2) Routing Sequence. One **net\_id** will show up 2 cycles.
3. Numbers targets would not be given. It is based on how many **net\_id** you received when **in\_valid** is high.
4. For each target, you will receive 2 numbers of **loc\_x**, **loc\_y** [5:0] which identify (1) Source location of target at 1<sup>st</sup> cycle, (2) Sink location of target at 2<sup>nd</sup> cycle.
5. Input signal **frame\_id**, **net\_id**, **loc\_x**, **loc\_y** are valid when **in\_valid** is high, otherwise would be unknown value.
6. There is **only 1 reset** before the first pattern, thus, your design must be able to reset automatically.
7. All inputs will be changed at clock **negative** edge.
8. The next input pattern will come in 3 cycles after **busy** falls.

Name	Width	Functional Description
<b>rst_n</b>	1	Asynchronous reset and active-low
<b>clk</b>	1	Clock for MRA chip
<b>in_valid</b>	1	When <b>in_valid</b> is high, all the other three input is valid.
<b>frame_id</b>	5	Index of Location/Weight map, range in No. 0 ~ No. 31
<b>net_id</b>	4	NET ID that stores in Location map, one location map may contain 1~15 targets, so <b>net_id</b> will range in 1~15
<b>loc_x</b>	6	Indicate location (x coordinate) of either source or sink terminal for routing target, range in 0~63
<b>loc_y</b>	6	Indicate location (y coordinate) of either source or sink terminal for routing target, range in 0~63

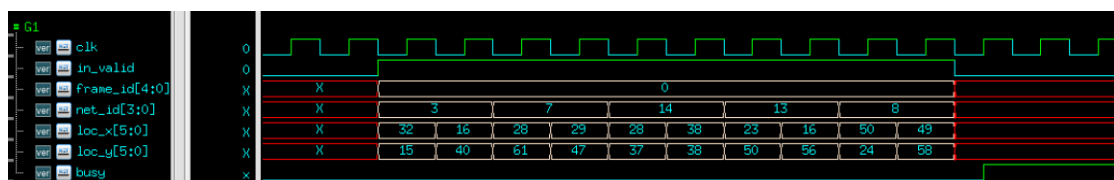


Fig 1. Input waveform example

## Outputs

1. Your routed result should be written back to DRAM. After **busy** is pulled low, **pattern** will check the correctness of the value inside DRAM.
2. All outputs are synchronized at clock **positive** edge.
3. **busy** should be low after initial reset.
4. **busy** should not be raised when **in\_valid** is high.

The test pattern will check whether your data in DRAM and **cost** is correct or not at the first clock **negative** edge after busy pulled low.

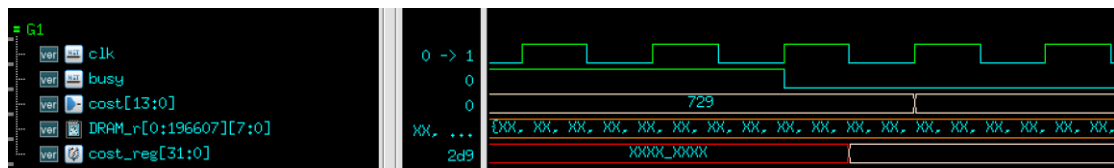


Fig 2. Output waveform example

## AXI4 IO

Please refer to Midterm\_Project\_Pre-Released\_2023\_FALL

## Specifications

1. Top module name: **MRA**(File name: **MRA.v**)
2. It is **asynchronous** reset and **active-low** architecture.
3. All the data are in **unsigned** format.
4. The total cell area should not larger than **2,500,000  $\mu m^2$** . The latency of your design in each pattern should not be larger than **1,000,000 cycles**.
5. The maximum clock period is set to **15 ns**, and **you can determine the clock period by yourself**.
6. The input delay and the output delay should be **half** of the clock period. For example, if clock period is 10ns, the input delay and the output delay will be 5ns.
7. The output loading is set to 0.05.
8. The synthesis result of data type cannot include any **LATCH** (check in syn.log).
9. The slack in the end of MRA.timing should be **non-negative** and the result should be **MET**.
10. Since memories are used in this project, the syn.tcl and .synopsys\_dc.setup in Lab05 may be a good reference one.

```
set target_library "fsa0m_a_generic_core_ss1p62v125c.db \
SUMA180_128X128X1BM1_WC.db \
SUMA180_2048X6X1BM4_WC.db"
```

11. **Note that maximum synthesis time could not be over 3 hours (Normally, this design would not over 3 hours)**
12. No **ERROR** is allowed in every simulation/synthesis.

## Grading Policy

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1. The performance is determined by latency and cycle time of your design. The smaller the performance index is, the higher score you can get.

$$\text{Score} = \text{SampleCase}(20\%) + \text{Functionality}(50\%) + \text{Performance}(30\%)$$

**SampleCase (20%):** 2 simple case, 2 medium case and 2 hard case

**Functionality(50%):** Random test

**Performance(30%):** Total Latency x Cycle Time

2. **Note that cell area must within 2,500,000  $\mu\text{m}^2$ , or you will fail**
3. Performance points can be obtained when both Sample Case and Functionality pass
4. 2<sup>nd</sup> demo will get 30% off of total score.

TA will demo your design with the DRAM latency ranged from 300 to 500, not fixed.

## Note

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1. Please submit your files under 09\_SUBMIT before 12:00 at noon:  
**Due Day :**      **1<sup>st</sup> Demo : 11/15**      **2<sup>nd</sup> Demo : 11/17**  
If uploaded files **violate the naming rule**, you will get **5 deduct points**
- In this lab, you can adjust your clock cycle time. Consequently, make sure to key in your clock cycle time after the command like the figure below. It means that the TA will demo your design under this clock cycle time:

```
[Exercise/09_SUBMIT]$ ./00_tar 15.0
```

- After that, you should check the following files under 09\_SUBMIT/Midterm\_Project\_iclabXXX/

**RTL design :**    **MRA\_iclab???.v**, (??? is your account number)

**Memory File :**    **MEMORY\_NAME\_iclab???.v**

**MEMORY\_NAME\_iclab???.db**

**File List for Customized SRAM:**    **filelist\_iclab???.f**

**Clock period:**    **clock\_period\_iclab???.txt**    (ex: 20.0\_iclab099.txt)

If you miss any files on the list, you will fail this lab.

Then use the command like the figure below to check if the files are uploaded or not.

```
[Exercise/09_SUBMIT]$ ./02_check 1st_demo
```



**Example:**

You will submit `MRA_iclab099.v`, `20.0_iclab099.txt`

Given your memory name is RA1SH512, and your submitted memory file

`RA1SH512_iclab099.v`, `RA1SH512_iclab099.db`, `filelist_iclab099.f`

And you modified in `filelist_iclab099.f`

`../04_MEM/RA1SH512.v`

(Note that in `filelist_iclab099.f`, no `_iclab099` after your module name)

Besides, you can provide **multiple** memory specs in this lab.

If the uploaded files violating the naming rule, you will get **5 deduct points**.

**If you omit any file, you will fail demo.**

## 2. Template folders and reference commands:

01\_RTL/ (for RTL simulation) `./01_run_vcs_rtl`

`./01_run_vcs_rtl FUNC`

`./01_run_vcs_rtl SAMPLE`

02\_SYN/ (for Synthesis) `./01_run_dc_shell`

**Remember modify .tcl to fit your memory db name (refer to Lab05)**

(Check the design which contains **Latch** and **Error** or not in `syn.log`)

(Check the design's timing in `/Report/MRA.timing` to see if the slack is **MET**)

03\_GATE\_SIM/ (Gate Level simulation) `./01_run_vcs_gate`

You can key in `./09_clean_up` to clear all log files and dump files in each folder

04\_MEM/ (Memory location)

You should generate your memories and put the required files (.v and .db) here.

09\_SUBMIT/ (submit your files) `./00_tar ./01_submit ./02_check`

You should make sure the clock period values identical in

`00_TESTBED/PATTERN.v` and `02_SYN/syn.tcl`

## Sample Case

### 3 Cases: Simple, Medium, Hard

\_0: Simple

\_1: Medium

\_2: Hard

00\_TESTBED/DRAM/

**dram.dat**

You can write a pattern to read this file and send to chip

00\_TESTBED/TEST\_CASE/

**Input.txt**

You can write a pattern to read this file and send to chip

## Map.txt, Output.txt, Weight.txt

Provide for you to debug

00\_TESTBED/Picture/

\*.png

Provide for you to debug

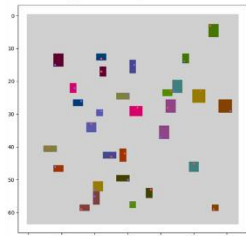
### Sample Case

File Description

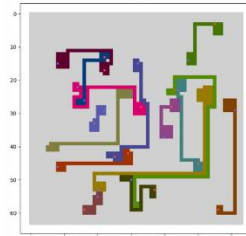
Input data  
(input.txt)

```
1 # Pattern
6 15 No. Pattern / # Macro
15 Net id (target1)
16 59 Source loc_x / Source loc_y
20 55 Sink loc_x / Sink loc_y
4 Net id (target2)
6 40 Source loc_x / Source loc_y
30 24 Sink loc_x / Sink loc_y
5 Net id (target3)
50 45 Source loc_x / Source loc_y
44 23 Sink loc_x / Sink loc_y
3
19 33 ...
22 29
30
42 28
40 37
14
29 42
8 46
```

Original map in DRAM



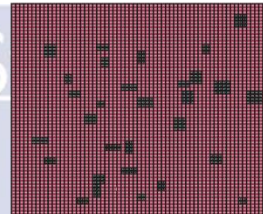
Routed map in DRAM



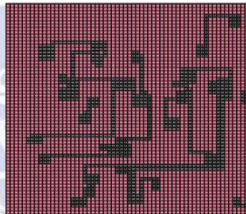
DRAM data  
Map / Weight (drum.dat)

```
d10000 00 00 00 00
d10004 00 00 00 00
d10008 00 00 00 00
d1000c 00 00 00 00
d10010 00 00 00 00
d10014 00 00 00 00
d10018 00 00 00 00
d1001c 00 00 00 00
d10020 00 00 00 00
d10024 00 00 00 00
d10028 00 00 00 00
d1002c 00 00 00 00
```

Location map in DRAM (map.txt)



Routed map in DRAM (output.txt)



Weight data in DRAM (weight.txt)



### Hint

1. **Recommend development flow:**
  - I. Establish a PATTERN for testing your circuit
  - II. Ensure your design can fetch data from DRAM with AXI4
  - III. Ensure your design can write back to DRAM with AXI4
  - IV. Design the Memory usage of whole algorithm
  - V. Design the Architecture of circuit and FSM for each part
  - VI. Implementation of algorithm (01 → 02 → 03)
  - VII. Verify circuit functionality with more test case
  - VIII. Find out bottleneck and do some optimization
  - IX. Optimize latency – Algorithm and Architecture
  - X. Optimize area – Memory and Circuit Design
  - XI. Optimize routed cost – Algorithm (optional)
2. **TA provide a pseudo code for those not familiar with this algorithm**



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**Algorithm 1** Filling Path Map

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```
1: Traverse Sequence = 1,2,3,1,2,3,...
2: CLEAN node list
3: PUSH source into node list
4: while node list is not empty do
5:   POP node list as current node
6:   for neighbor is Down, Up, Right, Left Node do
7:     if neighbor is sink then
8:       current node = neighbor
9:       break while loop
10:    else if neighbor is inside region, not block, not traversed then
11:      TRAVERSED neighbor (Update Path Map)
12:      PUSH neighbor into node list
13:    end if
14:  end for
15: end while
16: if current node is not sink then
17:   ERROR
18: end if
```

---

---

**Algorithm 2** Retrace Path Map

---

```
1: Traverse Sequence = 3,2,1,3,2,1,...
2: current node = sink
3: while current node is not source do
4:   for neighbor is Down, Up, Right, Left Node do
5:     if neighbor is right Traverse Sequence and inside region then
6:       Update Location Map
7:       current node = neighbor
8:       break For loop
9:     end if
10:  end for
11: end while
```

---

