

Ramulator 2.0 Summary

*Intelligent System
Laboratory*

DDR4 Summary

□ DRAM sub-system

- *PHY와 Controller는 User Logic과 함께 일반적으로 동일한 FPGA 또는 ASIC의 일부*
- User Logic이 Controller에 RD 또는 WR Request를 할 때, Logical Address를 Issue
- Controller가 logical address → physical address 변환 후 PHY에게 command를 issue
- Controller는 Request를 scheduling (ex. 이미 열려있는 Row에 Access하는 Request를 우선순위로 둠)
- PHY는 Analog Driver 등을 포함

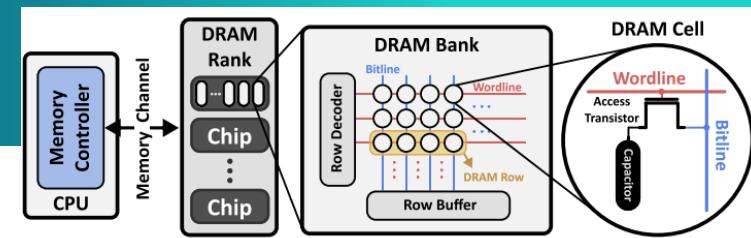
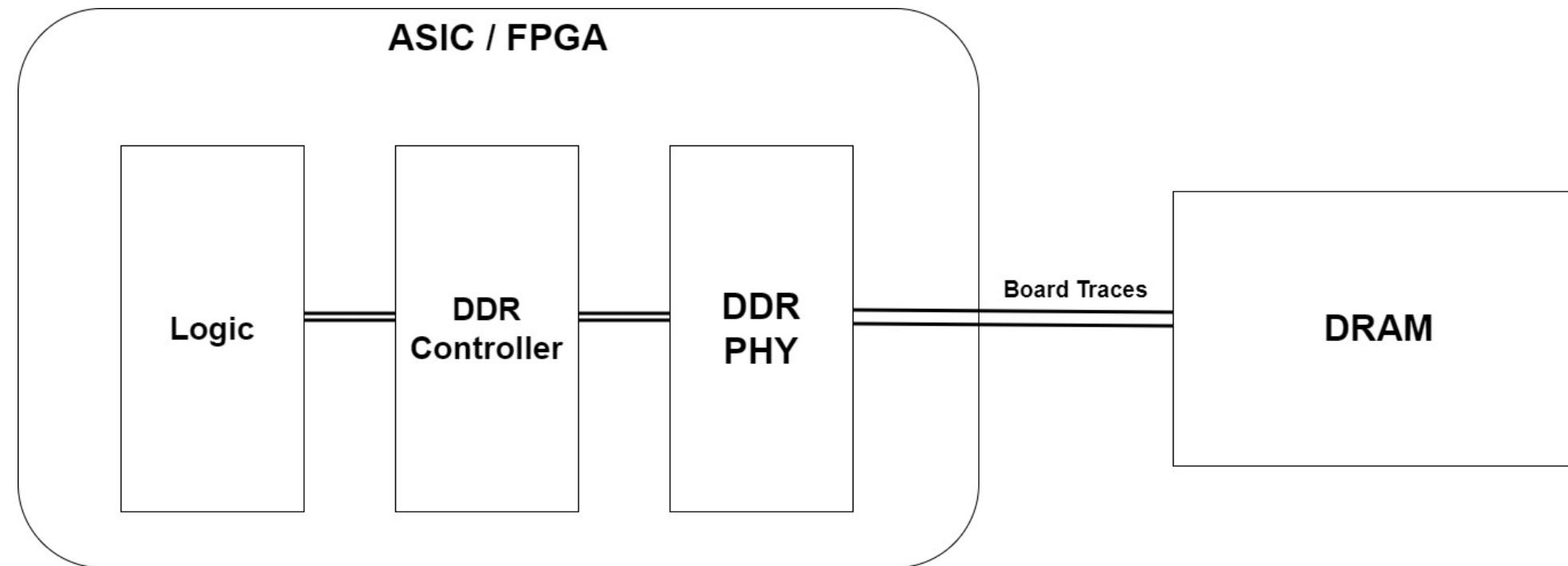


Figure 1: Structure of a typical DRAM-based system.



DDR4 Summary

□ DDR4 Hierarchy – Overview

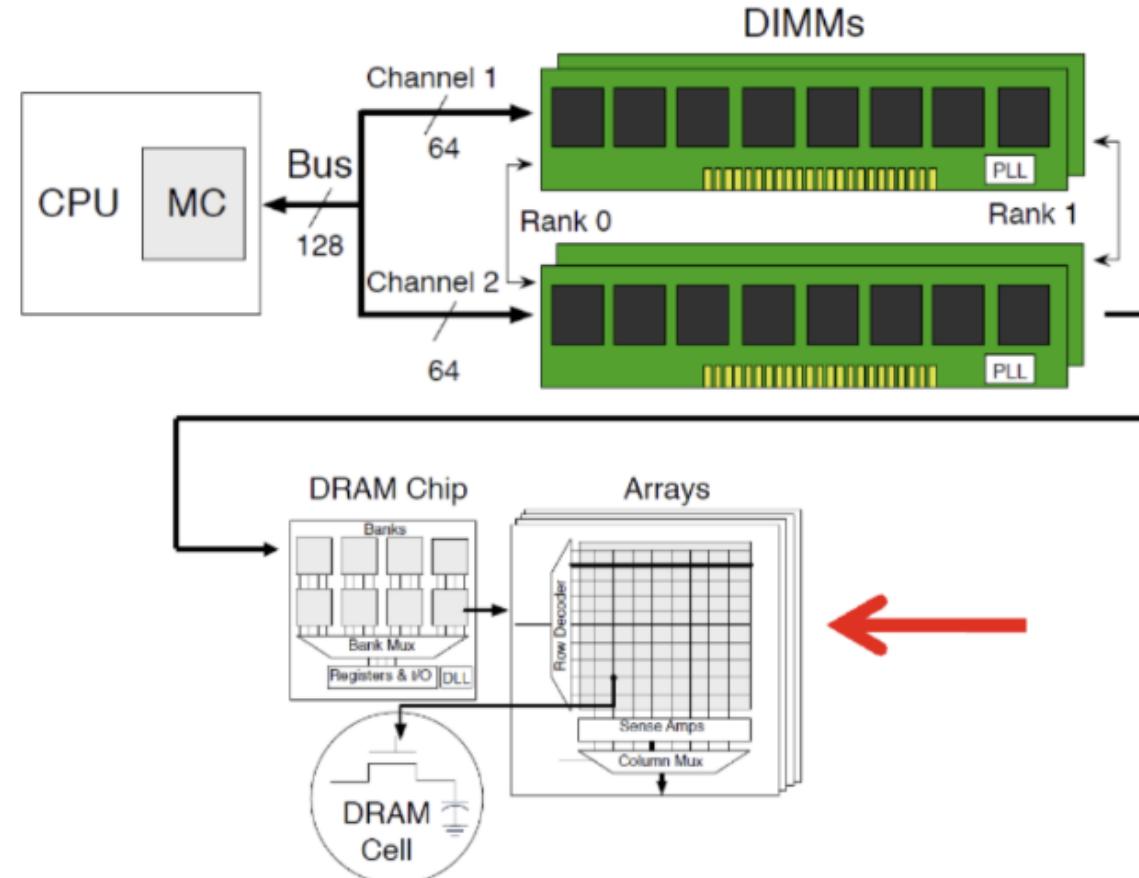


Fig 3. Main memory system 요약 [1]

DDR4 Summary

□ DDR4 Hierarchy - Channel level

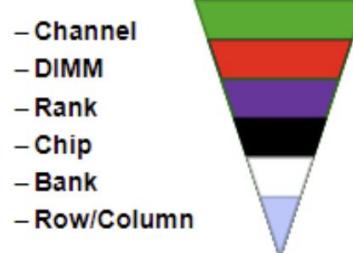


Fig 2. Memory subsystem organization [1]

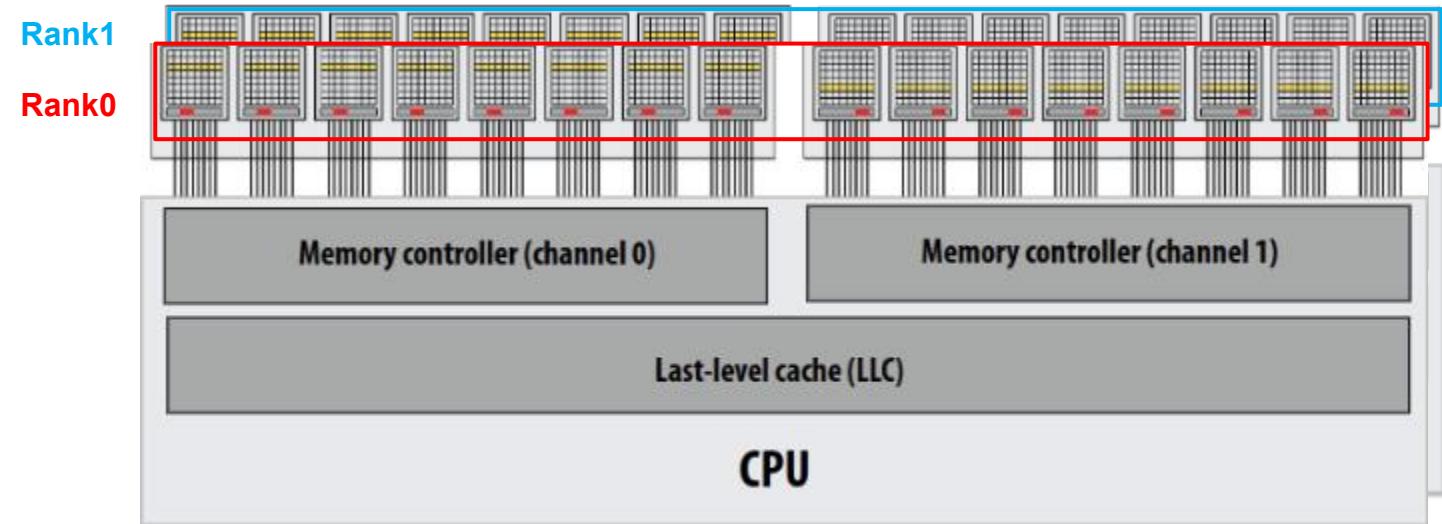


Fig 6. DRAM multi-channel 구조 [2]

- DRAM Channel는 각각 독립적인 Memory Controller에 할당됨
- 한 channel에 여러 개의 DIMM이 꽂혀 있으며, 1개의 DIMM도 여러 개의 rank(DIMM의 앞, 뒤)들로 구성
- 여러 Rank는 Data Bus를 공유 → CAS to CAS latency (timing Constraints 유발)

DDR4 Summary

□ DDR4 Hierarchy - Rank level

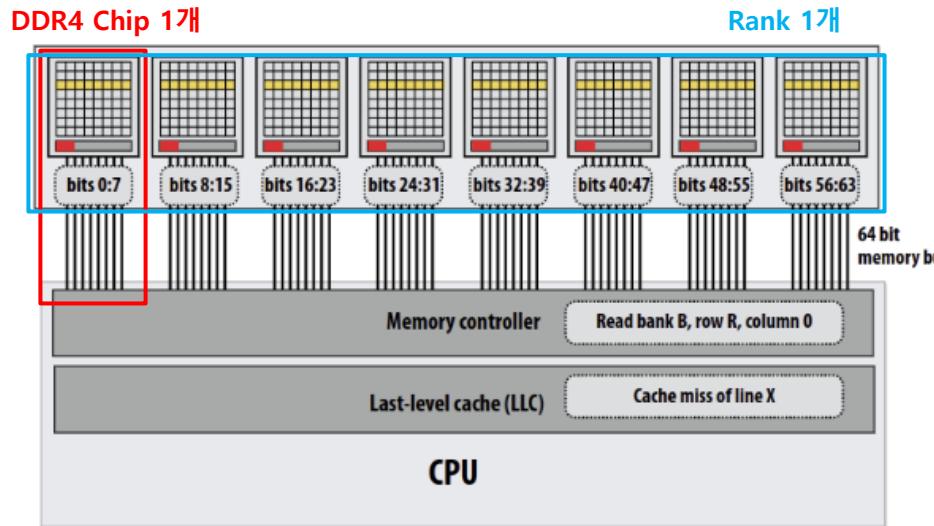
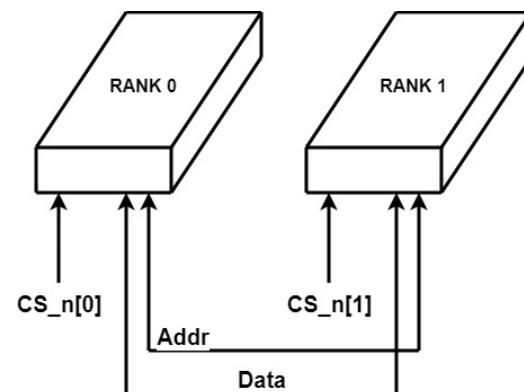


Fig 5. DRAM multi-chip 구조 [2]



DRAM Rank는 여러 Chip을 가지는 Level

- 이 여러 Chip들을 논리적으로 묶은 단위가 Rank
- Rank 1개당 1개의 Chip Select 신호가 할당

오른쪽 위의 그림은 64bit Transfer하는 Rank

- 8개의 chip(x8)으로 구성
- 해당 Rank는 1번의 memory operation에 64bit를 전송

오른쪽 아래 그림은 Dual Rank를 보여줌

- 2개의 Device는 동일한 Addr 및 Data Bus에 연결
- 각 Device를 별도로 지정하기 위해 2개의 ChipSelect가 필요
- 2개의 ChipSelect가 필요하므로, 이 설정을 Dual-Rank라고 함

DDR4 Summary

□ DDR4 Hierarchy – Bank Group Level

1개 Chip 안에 여러 Bank Group

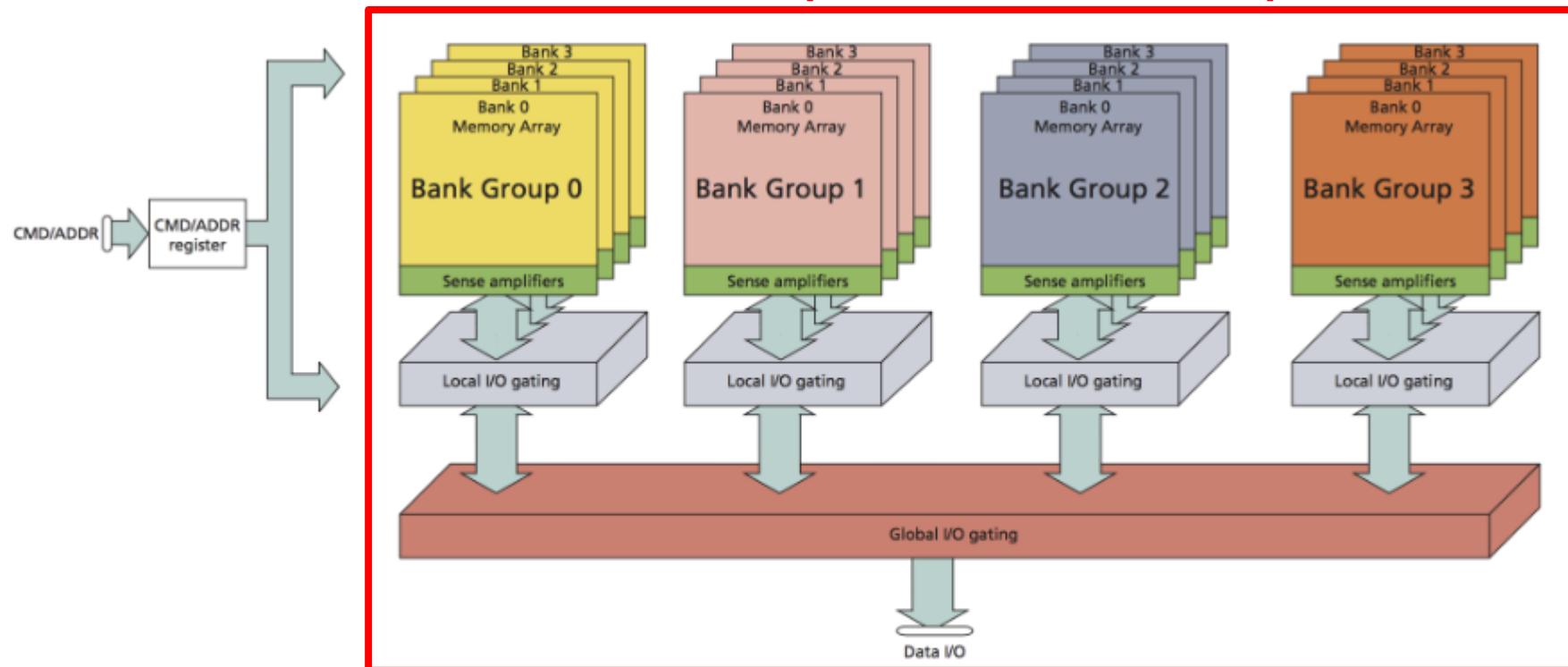
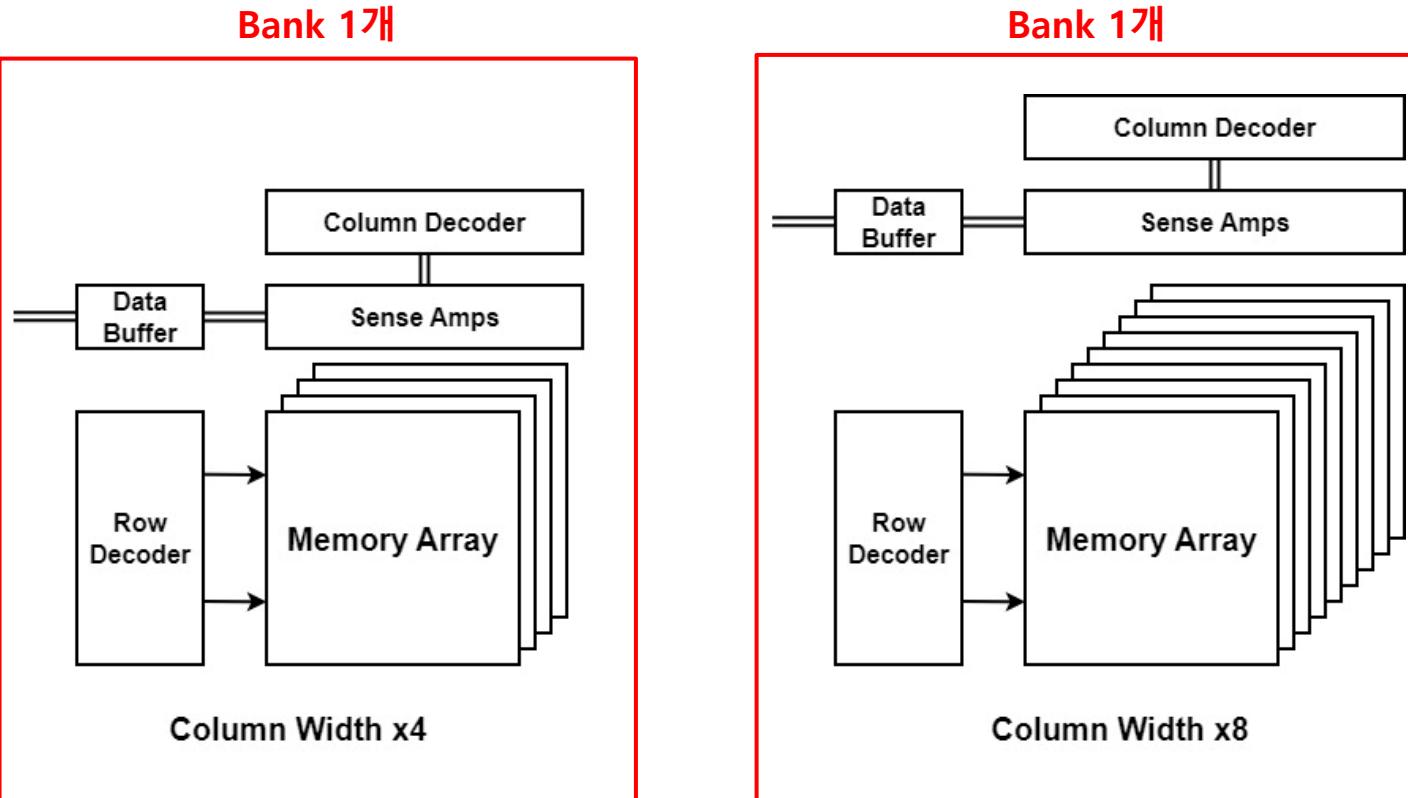


Figure 2: BankGroup & Bank (Source: Micron Datasheet)

DDR4 Summary

□ DDR4 Hierarchy – Each Bank (Bank Level)



Column Address

- Sense Amp로 load된 Word의 일부를 Read
- Column의 Width = Bit Line
- Column Width은 표준
 - 4bit, 8bit 또는 16bit Width
 - DRAM은 이에 따라 x4, x8, x16으로 분류
 - DQ Data Bus Width = Column Width
 - x4 → 4 data pins DQ[3:0]
 - x8 → 8 data pins DQ[7:0]

DDR4 Summary

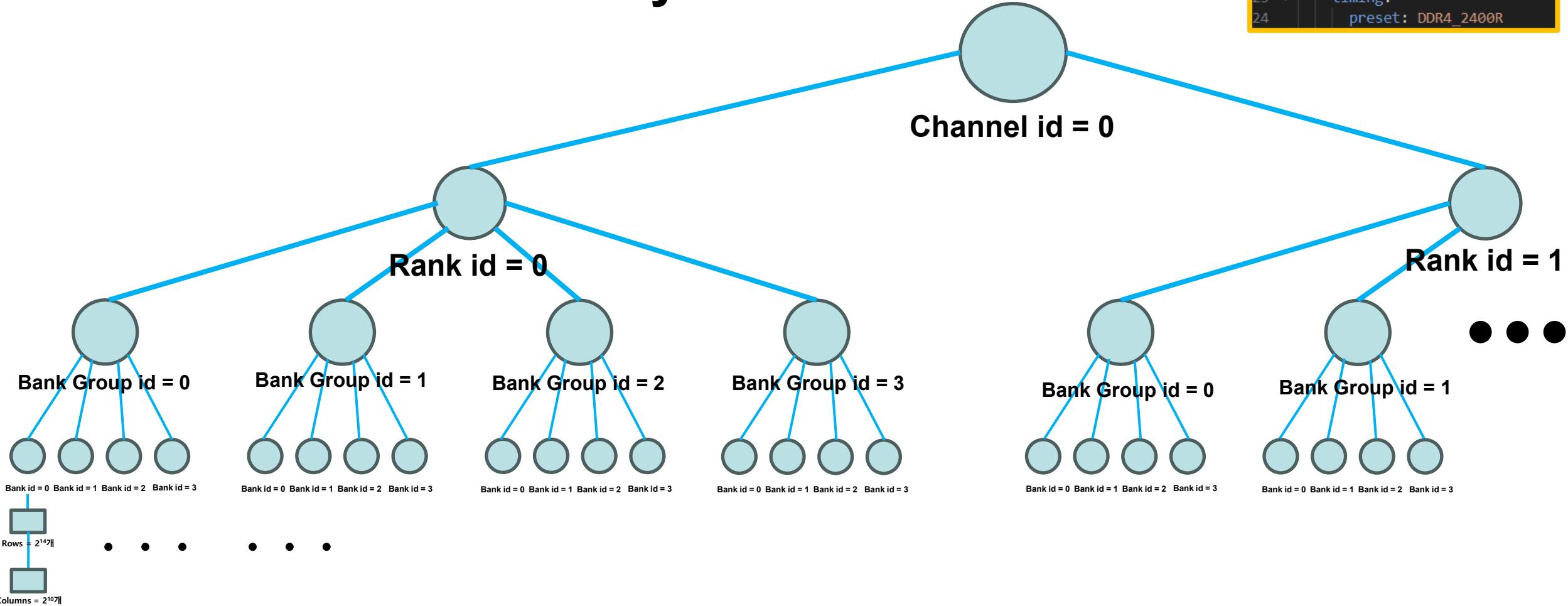
□ How Ramulator Models DDR4 Hierarchy

DDR4.cpp

```
6   class DDR4 : public IDRAM, public Implementation {
7     RAMULATOR_REGISTER_IMPLEMENTATION(IDRAM, DDR4, "DDR4", "DDR4 Device Model")
8
9   public:
10    inline static const std::map<std::string, Organization> org_presets = {
11      //  name      density  DQ  Ch Ra Bg Ba  Ro    Co
12      {"DDR4_2Gb_x4", {2<<10, 4, {1, 1, 4, 4, 1<<15, 1<<10}}}, // Red box highlights row
13      {"DDR4_2Gb_x8", {2<<10, 8, {1, 1, 4, 4, 1<<14, 1<<10}}}, // Yellow box highlights column
14      {"DDR4_2Gb_x16", {2<<10, 16, {1, 1, 2, 4, 1<<14, 1<<10}}}, // Blue box highlights column
15      {"DDR4_4Gb_x4", {4<<10, 4, {1, 1, 4, 4, 1<<16, 1<<10}}}, // Red box highlights row
16      {"DDR4_4Gb_x8", {4<<10, 8, {1, 1, 4, 4, 1<<15, 1<<10}}}, // Yellow box highlights column
17      {"DDR4_4Gb_x16", {4<<10, 16, {1, 1, 2, 4, 1<<15, 1<<10}}}, // Blue box highlights column
18      {"DDR4_8Gb_x4", {8<<10, 4, {1, 1, 4, 4, 1<<17, 1<<10}}}, // Red box highlights row
19      {"DDR4_8Gb_x8", {8<<10, 8, {1, 1, 4, 4, 1<<16, 1<<10}}}, // Yellow box highlights column
20      {"DDR4_8Gb_x16", {8<<10, 16, {1, 1, 2, 4, 1<<16, 1<<10}}}, // Blue box highlights column
21      {"DDR4_16Gb_x4", {16<<10, 4, {1, 1, 4, 4, 1<<18, 1<<10}}}, // Red box highlights row
22      {"DDR4_16Gb_x8", {16<<10, 8, {1, 1, 4, 4, 1<<17, 1<<10}}}, // Yellow box highlights column
23      {"DDR4_16Gb_x16", {16<<10, 16, {1, 1, 2, 4, 1<<17, 1<<10}}}], // Blue box highlights column
24  };
25
        DRAM Size DQ pins  Channel, Rank, Bank Group, Bank, Row, Column
        • 16GB   • DQ[15:0] • addr_vec = [1, 1, 2, 4, 217, 210]
```

src/memory_system folder

□ DRAM Node Hierarchy

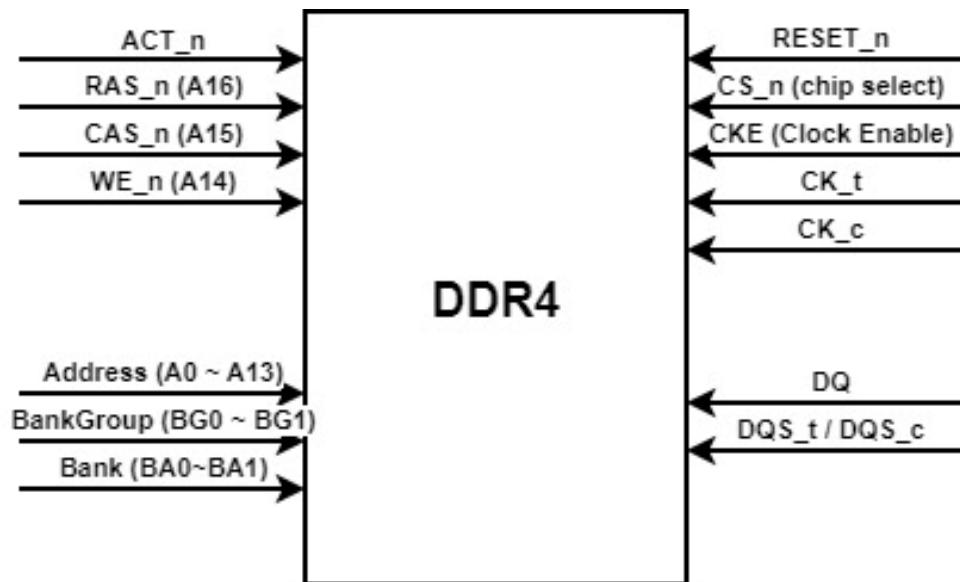


yaml file DRAM 설정

```
17 v DRAM:  
18   impl: DDR4  
19 v org:  
20     preset: DDR4_8Gb_x8  
21     channel: 1  
22     rank: 2  
23 v timing:  
24     preset: DDR4_2400R
```

DDR4 Summary

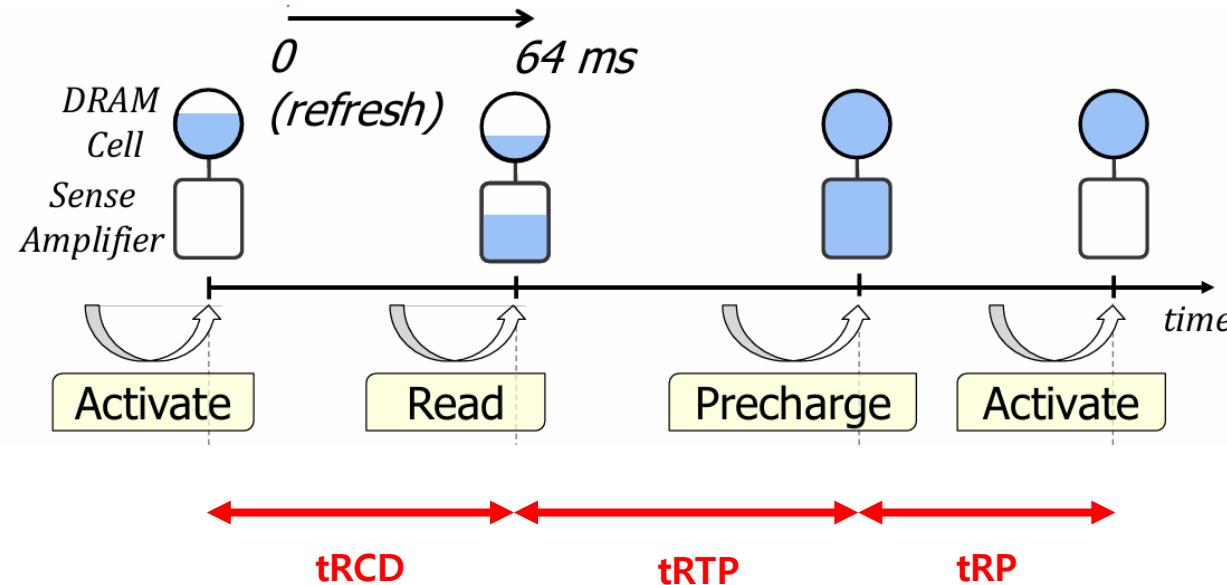
□ DDR4 basic signals



Symbol	Type	Function
RESET_n	Input	DRAM is active only when this signal is HIGH
CS_n	Input	The memory looks at all the other inputs only if this is LOW.
CKE	Input	Clock Enable. HIGH activates internal clock signals and device input buffers and output drivers.
CK_t/CK_c	Input	Differential clock inputs. All address & control signals are sampled at the crossing of posedge of CK_t & negedge of CK_n.
DQ/DQS	Inout	Data Bus & Data Strobe. This is how data is written in and read out. The strobe is essentially a data valid flag.
RAS_n/A16 CAS_n/A15 WE_n/A14	Input	These are dual function inputs. When ACT_n & CS_n are LOW, these are interpreted as Row Address Bits. When ACT_n is HIGH, these are interpreted as command pins to indicate READ, WRITE or other commands.
ACT_n	Input	Activate command input
BG0-1 BA0-1	Input	Bank Group, Bank Address
A0-13	Input	Address inputs

DRAM Operations & States

□ DRAM Operations & States

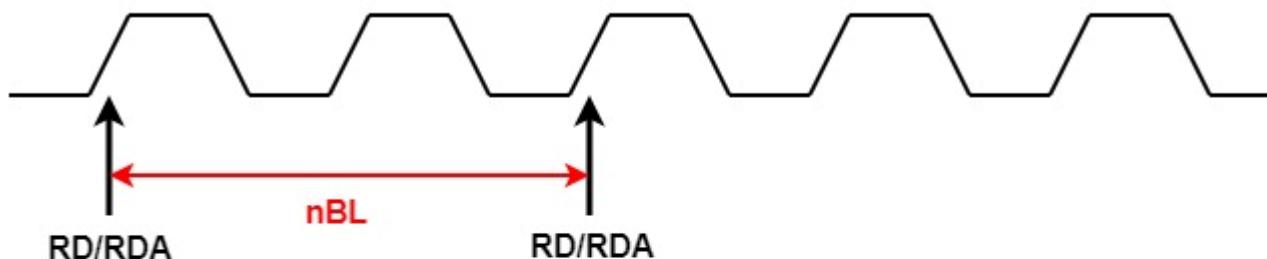


- **Main DRAM states**
 - **Activate**
 - **Read/Write**
 - **Precharge**

DDR4 Summary

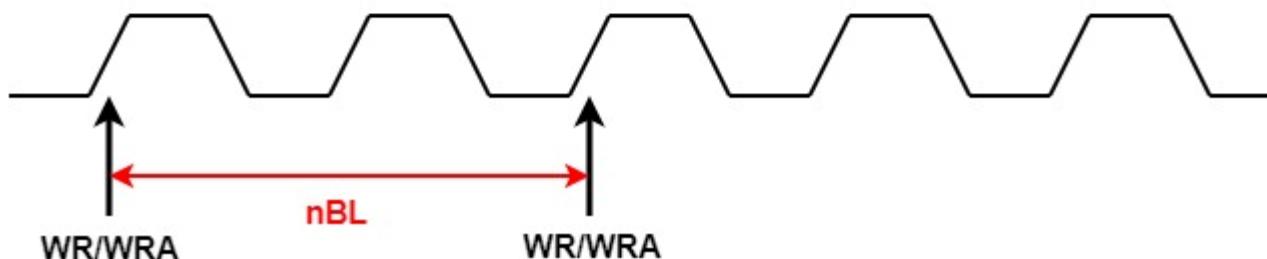
□ DRAM Timings – Channel level

Level: Channel
- CAS <-> CAS, Data bus occupancy



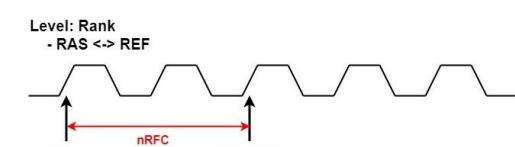
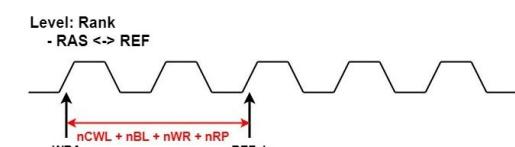
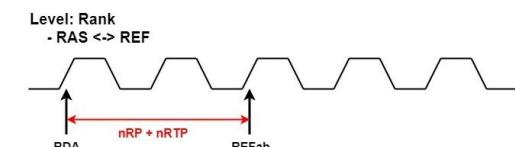
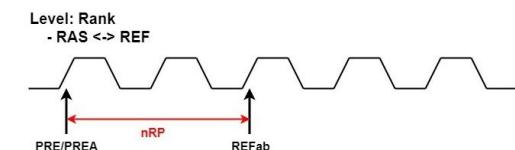
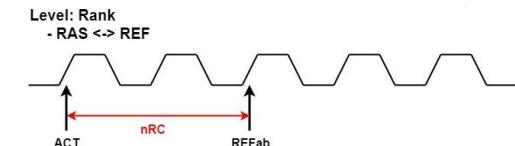
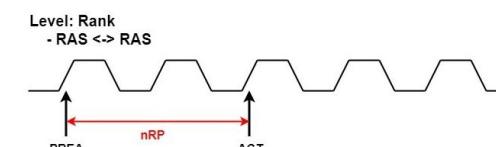
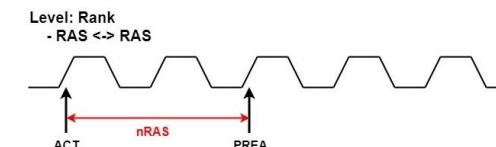
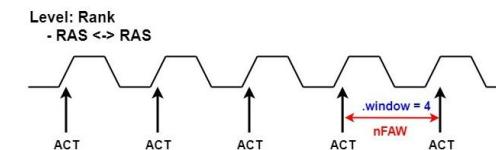
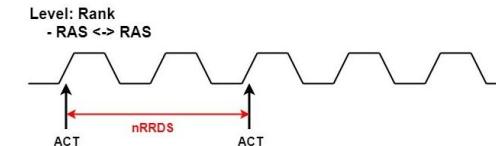
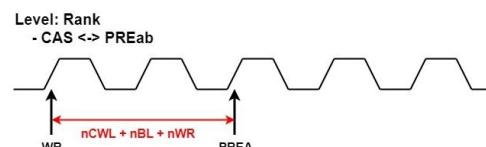
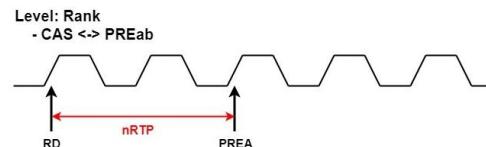
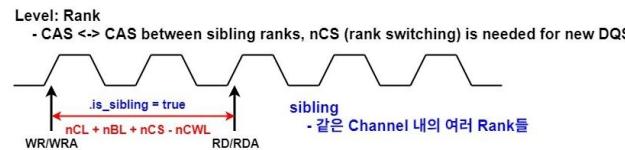
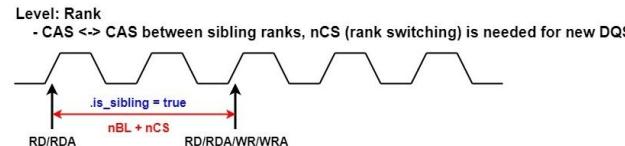
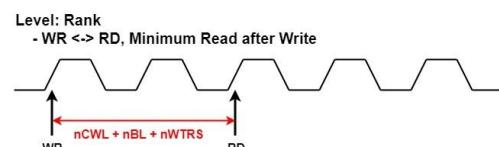
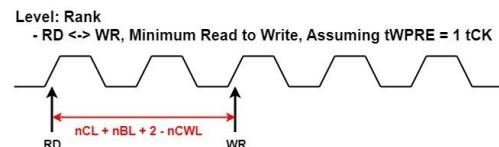
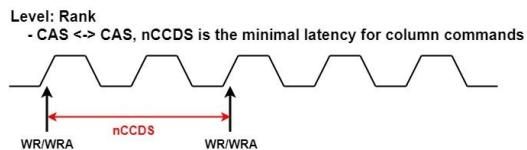
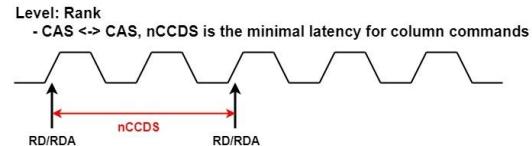
- 서로 같은 Channel에서의 Column Access
- 같은 Channel은 Data Bus 공유함

Level: Channel
- CAS <-> CAS, Data bus occupancy



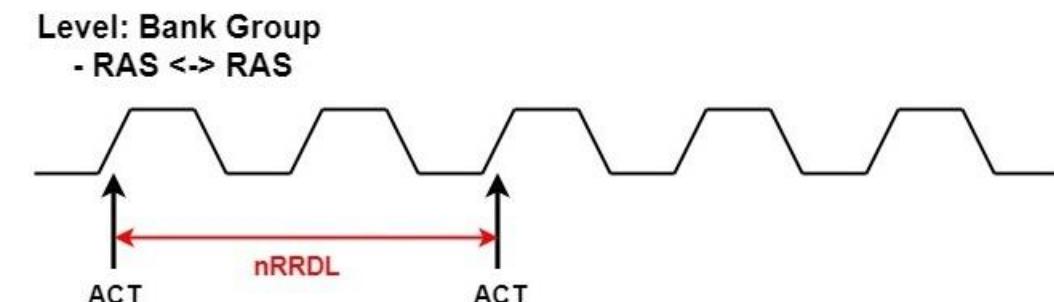
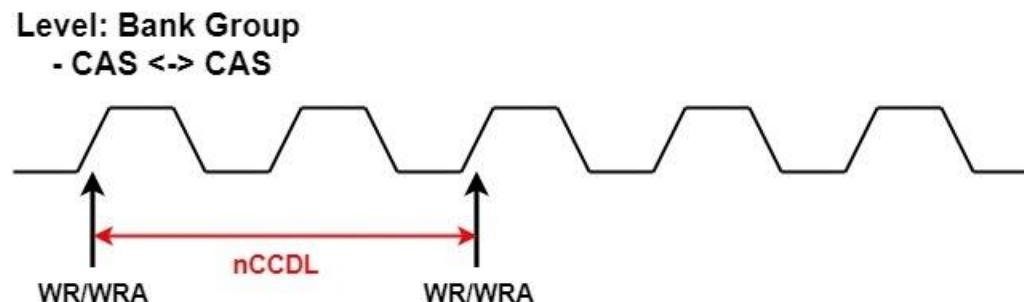
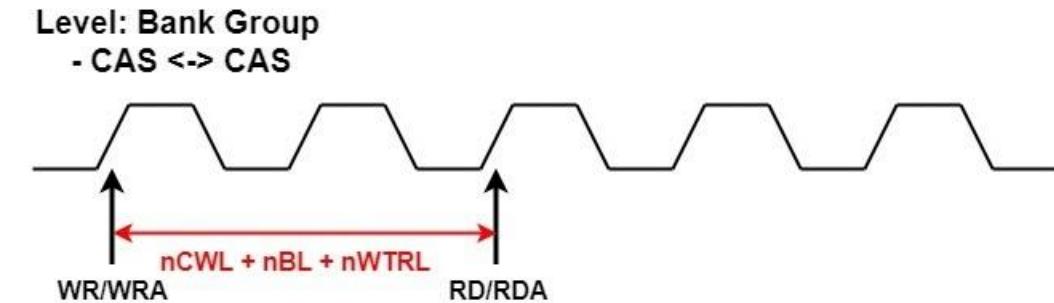
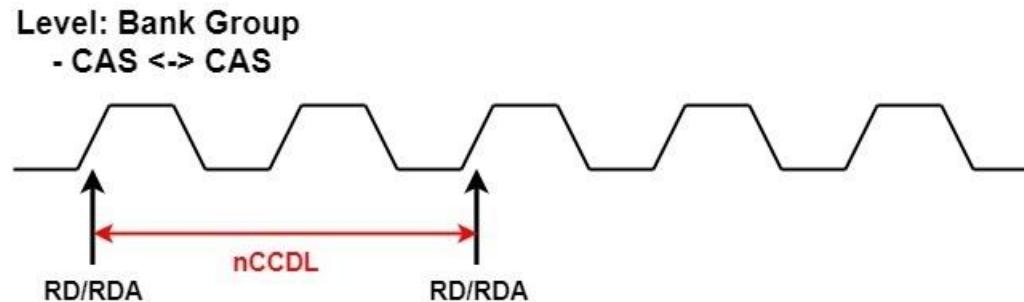
DDR4 Summary

□ DRAM Timings – Rank level



DDR4 Summary

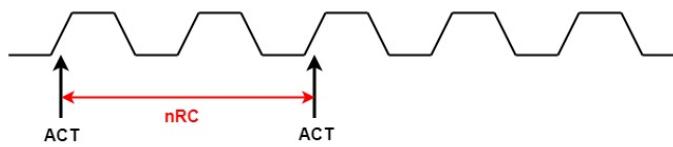
□ DRAM Timings – Bank Group level



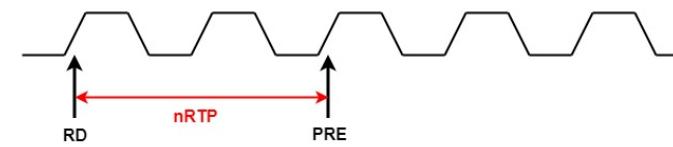
DDR4 Summary

□ DRAM Timings – Bank level

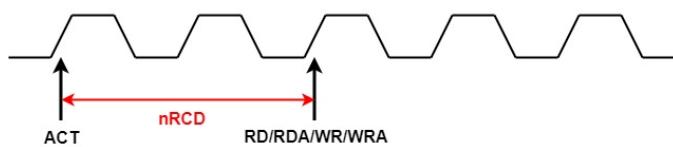
Level: Bank



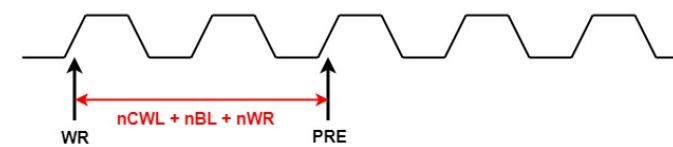
Level: Bank



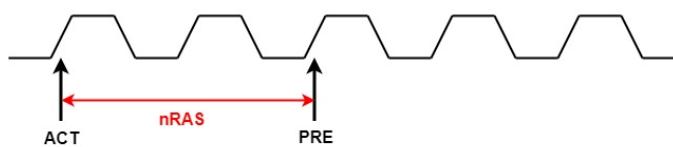
Level: Bank



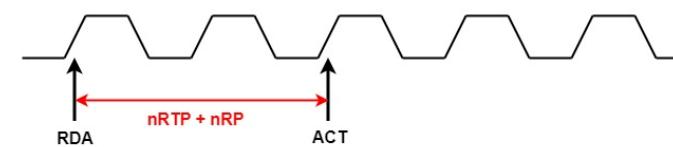
Level: Bank



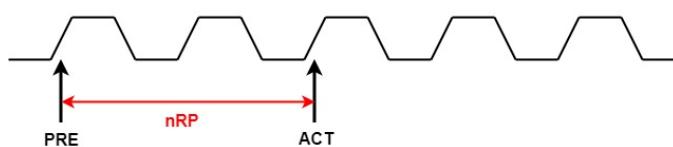
Level: Bank



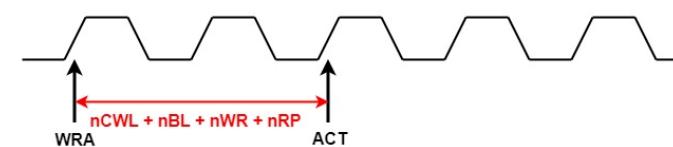
Level: Bank



Level: Bank



Level: Bank



DDR4 Summary

□ How Ramulator Models DDR4 Timings

DDR4.cpp

```
26 v inline static const std::map<std::string, std::vector<int>> timing_presets = {  
27     //   name      rate  nBL  nCL  nRCD  nRP   nRAS  nRC   nWR  nRTP  nCWL  nCCDS  nCCDL  nRRDS  nRRDL  nWTRS  nWTRL  nFAW   nRFC  nREFI  nCS,  tCK_ps  
28     {"DDR4_1600J", {1600,  4, 10, 10, 10, 28, 38, 12, 6, 9, 4, 5, -1, -1, 2, 6, -1, -1, -1, 2, 1250}},  
29     {"DDR4_1600K", {1600,  4, 11, 11, 11, 28, 39, 12, 6, 9, 4, 5, -1, -1, 2, 6, -1, -1, -1, 2, 1250}},  
30     {"DDR4_1600L", {1600,  4, 12, 12, 12, 28, 40, 12, 6, 9, 4, 5, -1, -1, 2, 6, -1, -1, -1, 2, 1250}},  
31     {"DDR4_1866L", {1866,  4, 12, 12, 12, 32, 44, 14, 7, 10, 4, 5, -1, -1, 3, 7, -1, -1, -1, 2, 1071}},  
32     {"DDR4_1866M", {1866,  4, 13, 13, 13, 32, 45, 14, 7, 10, 4, 5, -1, -1, 3, 7, -1, -1, -1, 2, 1071}},  
33     {"DDR4_1866N", {1866,  4, 14, 14, 14, 32, 46, 14, 7, 10, 4, 5, -1, -1, 3, 7, -1, -1, -1, 2, 1071}},  
34     {"DDR4_2133N", {2133,  4, 14, 14, 14, 36, 50, 16, 8, 11, 4, 6, -1, -1, 3, 8, -1, -1, -1, 2, 937}},  
35     {"DDR4_2133P", {2133,  4, 15, 15, 15, 36, 51, 16, 8, 11, 4, 6, -1, -1, 3, 8, -1, -1, -1, 2, 937}},  
36     {"DDR4_2133R", {2133,  4, 16, 16, 16, 36, 52, 16, 8, 11, 4, 6, -1, -1, 3, 8, -1, -1, -1, 2, 937}},  
37     {"DDR4_2400P", {2400,  4, 15, 15, 15, 39, 54, 18, 9, 12, 4, 6, -1, -1, 3, 9, -1, -1, -1, 2, 833}},  
38     {"DDR4_2400R", {2400,  4, 16, 16, 16, 39, 55, 18, 9, 12, 4, 6, -1, -1, 3, 9, -1, -1, -1, 2, 833}},  
39     {"DDR4_2400U", {2400,  4, 17, 17, 17, 39, 56, 18, 9, 12, 4, 6, -1, -1, 3, 9, -1, -1, -1, 2, 833}},  
40     {"DDR4_2400T", {2400,  4, 18, 18, 18, 39, 57, 18, 9, 12, 4, 6, -1, -1, 3, 9, -1, -1, -1, 2, 833}},  
41     {"DDR4_2666T", {2666,  4, 17, 17, 17, 43, 60, 20, 10, 14, 4, 7, -1, -1, 4, 10, -1, -1, -1, 2, 750}},  
42     {"DDR4_2666U", {2666,  4, 18, 18, 18, 43, 61, 20, 10, 14, 4, 7, -1, -1, 4, 10, -1, -1, -1, 2, 750}},  
43     {"DDR4_2666V", {2666,  4, 19, 19, 19, 43, 62, 20, 10, 14, 4, 7, -1, -1, 4, 10, -1, -1, -1, 2, 750}},  
44     {"DDR4_2666W", {2666,  4, 20, 20, 20, 43, 63, 20, 10, 14, 4, 7, -1, -1, 4, 10, -1, -1, -1, 2, 750}},  
45     {"DDR4_2933V", {2933,  4, 19, 19, 19, 47, 66, 22, 11, 16, 4, 8, -1, -1, 4, 11, -1, -1, -1, 2, 682}},  
46     {"DDR4_2933W", {2933,  4, 20, 20, 20, 47, 67, 22, 11, 16, 4, 8, -1, -1, 4, 11, -1, -1, -1, 2, 682}},  
47     {"DDR4_2933Y", {2933,  4, 21, 21, 21, 47, 68, 22, 11, 16, 4, 8, -1, -1, 4, 11, -1, -1, -1, 2, 682}},  
48     {"DDR4_2933AA", {2933,  4, 22, 22, 22, 47, 69, 22, 11, 16, 4, 8, -1, -1, 4, 11, -1, -1, -1, 2, 682}},  
49     {"DDR4_3200W", {3200,  4, 20, 20, 20, 52, 72, 24, 12, 16, 4, 8, -1, -1, 4, 12, -1, -1, -1, 2, 625}},  
50     {"DDR4_3200AA", {3200,  4, 22, 22, 22, 52, 74, 24, 12, 16, 4, 8, -1, -1, 4, 12, -1, -1, -1, 2, 625}},  
51     {"DDR4_3200AC", {3200,  4, 24, 24, 24, 52, 76, 24, 12, 16, 4, 8, -1, -1, 4, 12, -1, -1, -1, 2, 625}}},  
52 }
```

DDR4 Summary

□ DRAM Commands

- DRAM은 아래 Truth Table에 기반하여 ACT_n, RAS_n, CAS_n 및 WE_n 입력의 조합을 Command로 해석

Function	Shortcode	CS_n	ACT_n	RAS_n/A16	CAS_n/A15	WE_n/A14	A10/AP
Refresh	REF	L	H	L	L	H	H or L
Single Bank Precharge	PRE	L	H	L	H	L	L
Bank Activate	ACT	L	L	Row Address			
Write	WR	L	H	H	L	L	L
Write with Auto-Precharge	WRA	L	H	H	L	L	H
Read	RD	L	H	H	L	H	L
Read with Auto-Precharge	RDA	L	H	H	L	H	H

Basic DRAM Commands

Partial Command Truth-Table

How to measure off-chip power?

□ Analysis based on the paper below

BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

- Section 6. Hardware Complexity Analysis

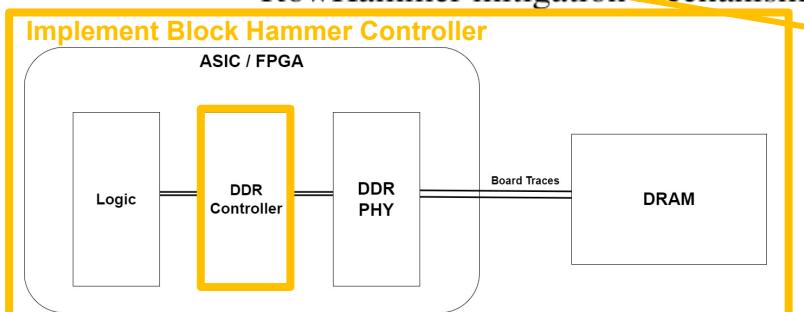
- In case of **on-chip** analysis

6. Hardware Complexity Analysis

We evaluate BlockHammer's (1) chip area, static power, and access energy consumption using CACTI [99] and (2) circuit latency using Synopsys DC [143]. We demonstrate that BlockHammer's physical costs are competitive with state-of-the-art RowHammer mitigation mechanisms.

6.2. Latency Analysis

We implement BlockHammer in Verilog HDL and synthesize our design using Synopsys DC [143] with a 65 nm process technology to evaluate the latency impact on memory accesses. According to our RTL model, which we open source [124], BlockHammer responds to an “*Is this ACT RowHammer-safe?*” query (1 in Figure 2) in only 0.97 ns. This latency can be hidden because it is one-to-two orders of magnitude smaller than the row access latency (e.g., 45–50 ns) that DRAM standards (e.g., DDRx, LPDDRx, GDDRx) enforce [36, 53, 55].



Mitigation Mechanism	$N_{RH}=32K^*$						$N_{RH}=1K$					
	SRAM KB	CAM KB	Area mm ²	% CPU	Access Energy (pJ)	Static Power (mW)	SRAM KB	CAM KB	Area mm ²	% CPU	Access Energy (pJ)	Static Power (mW)
BlockHammer	51.48	1.73	0.14	0.06	20.30	22.27	441.33	55.58	1.57	0.64	99.64	220.99
Dual counting Bloom filters	48.00	-	0.11	0.04	18.11	19.81	384.00	-	0.74	0.30	86.29	158.46
H3 hash functions	-	-	< 0.01	< 0.01	-	-	-	-	< 0.01	< 0.01	-	-
Row activation history buffer	1.73	1.73	0.03	0.01	1.83	2.05	55.58	55.58	0.83	0.34	12.99	62.12
AttackThrottler counters	1.75	-	< 0.01	< 0.01	0.36	0.41	1.75	-	< 0.01	< 0.01	0.36	0.41
PARA [73]	-	-	< 0.01	-	-	-	-	-	< 0.01	-	-	-
ProHIT [137]*	-	0.22	< 0.01	< 0.01	3.67	0.14	-	-	-	-	-	-
MrLoc [161]*	-	0.47	< 0.01	< 0.01	4.44	0.21	-	-	-	-	-	-
CBT [132]	16.00	8.50	0.20	0.08	9.13	35.55	512.00	272.00	3.95	1.60	127.93	535.50
TWice [84]	23.10	14.02	0.15	0.06	7.99	21.28	738.32	448.27	5.17	2.10	124.79	631.98
Graphene [113]	-	5.22	0.04	0.02	40.67	3.11	-	166.03	1.14	0.46	917.55	93.96

* ProHIT [137] and MrLoc [161] do not provide a concrete discussion on how to adjust their empirically-determined parameters for different N_{RH} values. Therefore, we (1) report their values for a fixed design point that each paper provides for $N_{RH}=2K$ and (2) mark values we cannot estimate using ×.

Table 4: Per-rank area, access energy, and static power of BlockHammer vs. state-of-the-art RowHammer mitigation mechanisms.

How to measure off-chip power?

□ Analysis based on the paper below

BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

- Section 6. Hardware Complexity Analysis

- In case of off-chip analysis

7. Experimental Methodology

We evaluate BlockHammer's effect on a typical DDR4-based memory subsystem's performance and energy consumption as compared to six prior RowHammer mitigation mechanisms [73, 84, 113, 132, 137, 161]. We use Ramulator [77, 125] for performance evaluation and DRAMPower [18] to estimate DRAM energy consumption. We open-source our infrastructure, which implements both BlockHammer and six state-of-the-art RowHammer mitigation mechanisms [124]. Table 5 shows our system configuration.

Processor	3.2 GHz, {1,8} core, 4-wide issue, 128-entry instr. window
Last-Level Cache	64-byte cache line, 8-way set-associative, 16 MB
Memory Controller	64-entry each read and write request queues; Scheduling policy: FR-FCFS [122, 164]; Address mapping: MOP [60]
Main Memory	DDR4, 1 channel, 1 rank, 4 bank groups, 4 banks/bank group, 64K rows/bank

Table 5: Simulated system configuration.

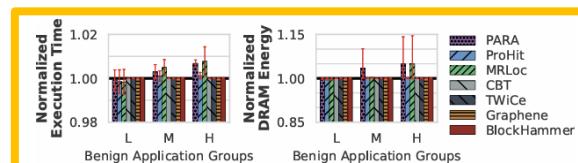


Figure 4: Execution time and DRAM energy consumption for benign single-core applications, normalized to baseline.

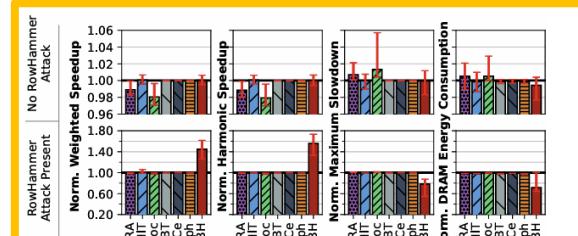
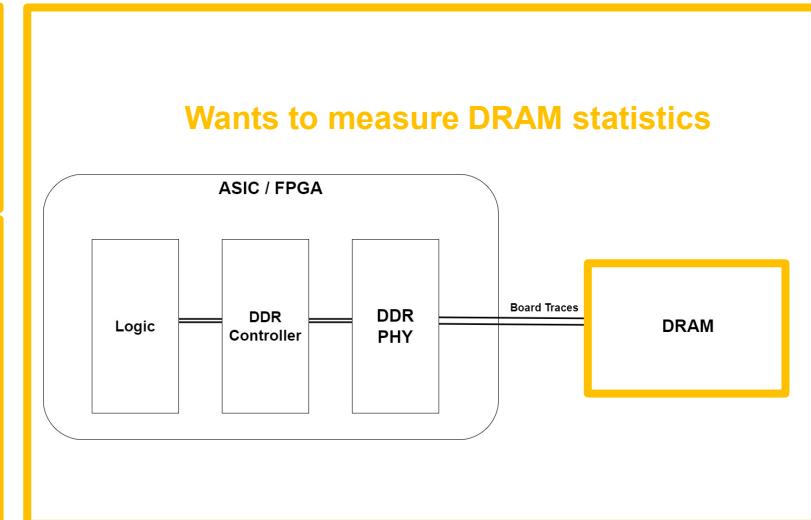


Figure 5: Performance and DRAM energy consumption for multiprogrammed workloads, normalized to baseline.

Wants to measure DRAM statistics



src files <=> DRAM Operation

□ Simulation Configuration

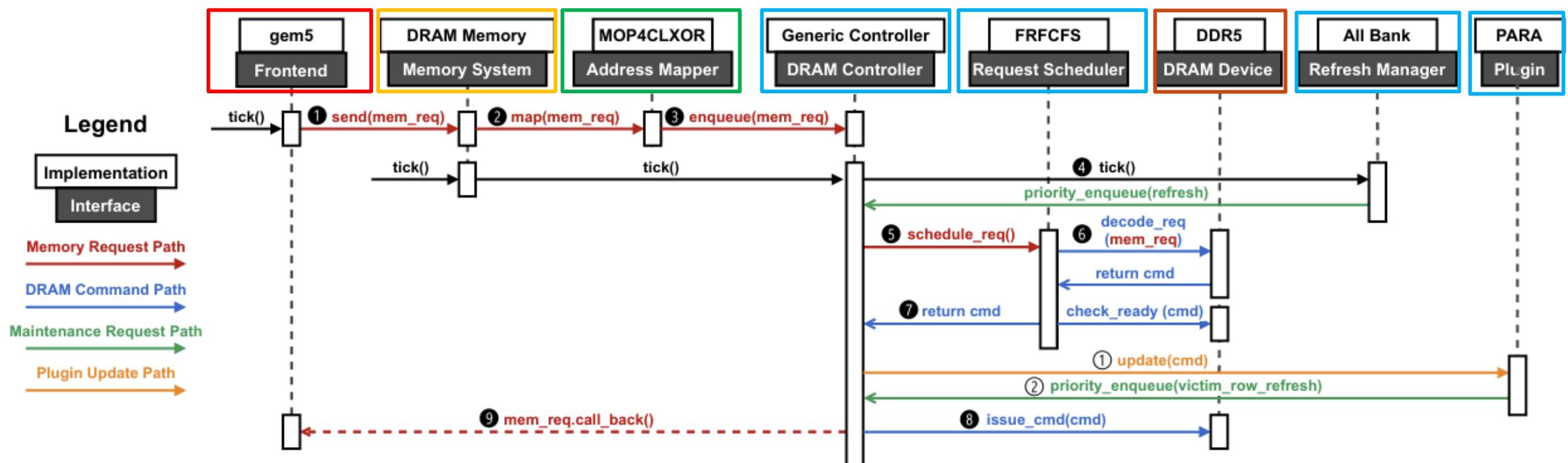
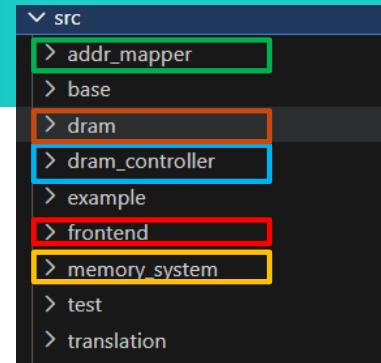


Fig. 1: High-level software architecture of Ramulator 2.0 using an example DDR5 system configuration

main function

□ main.cpp

```
13 ~ int main(int argc, char* argv[]) {  
14     // Parse command line arguments  
15     argparse::ArgumentParser program("Ramulator", "2.0");  
16     program.add_argument("-c", "-config").metavar("\\"dumped YAML configuration\\")  
17         .help("String dump of the yaml configuration.");  
18     program.add_argument("-f", "-config_file").metavar("path-to-configuration-file")  
19         .help("Path to a YAML configuration file.");  
20     program.add_argument("-p", "--param").metavar("KEY=VALUE")  
21         .append()  
22         .help("specify parameter to override in the configuration file. Repeat this option to change multiple parameters.");  
23       
24     :  
25     :  
26     :  
27     :  
28     :  
29     :  
30     :  
31     :  
32     :  
33     :  
34     :  
35     :  
36     :  
37     :  
38     :  
39     :  
40     :  
41     :  
42     :  
43     :  
44     :  
45     :  
46     :  
47     :  
48     :  
49     :  
50     :  
51     :  
52     :  
53     :  
54     :  
55     :  
56     :  
57     :  
58     :  
59     :  
60     :  
61     :  
62     :  
63     :  
64     :  
65     :  
66     :  
67     :  
68     :  
69     :  
70     :  
71     :  
72     :  
73     :  
74     :  
75     :  
76     :  
77     :  
78     :  
79     :  
80     :  
81     :  
82     :  
83     :  
84     :  
85     :  
86     :  
87     :  
88     // Connect the frontend and the memory system together,  
89     // this recursively calls the "setup" function in all instantiated components  
90     // so that they can get each other's parameters (if needed) after their initialization  
91     frontend->connect_memory_system(memory_system);  
92     memory_system->connect_frontend(frontend);  
93       
94     // Get the relative clock ratio between the frontend and memory system  
95     int frontend_tick = frontend->get_clock_ratio();  
96     int mem_tick = memory_system->get_clock_ratio();  
97       
98     int tick_mult = frontend_tick * mem_tick;  
99       
100    for (uint64_t i = 0; i++;)  
101        if (((i % tick_mult) % mem_tick) == 0) {  
102            frontend->tick();  
103        }  
104          
105        if (frontend->is_finished()) {  
106            break;  
107        }  
108          
109        if ((i % tick_mult) % frontend_tick == 0) {  
110            memory_system->tick();  
111        }  
112    }  
113      
114    // Finalize the simulation. Recursively print all statistics from all components  
115    frontend->finalize();  
116    memory_system->finalize();  
117      
118    return 0;  
119 }
```

main.cpp

1. Argument 받는 부분

- Options

1. -c: command line dump
2. -f: YAML document
3. -p: overriding parameters in a YAML document

2. Long for loop를 통한 tick() 기반 simul

1. frontend(core)가 발행한 예상 instructions들을 모두 처리시 is_finished()가 true가 됨

yaml file

□ example_config.yaml

```
1  Frontend:
2    impl: SimpleO3
3    clock_ratio: 8
4    num_expected_insts: 500000
5  traces:
6    - example_inst.trace
7
8  Translation:
9    impl: RandomTranslation
10   max_addr: 2147483648
11
13 MemorySystem:
14   impl: GenericDRAM
15   clock_ratio: 3
16
17 DRAM:
18   impl: DDR4
19   org:
20     preset: DDR4_8Gb_x8
21     channel: 1
22     rank: 2
23   timing:
24     preset: DDR4_2400R
25
26 Controller:
27   impl: Generic
28   Scheduler:
29     impl: FRFCFS
30   RefreshManager:
31     impl: AllBank
32   RowPolicy:
33     impl: ClosedRowPolicy
34     cap: 4
35   plugins:
36
37 AddrMapper:
38   impl: RoBaRaCoCh
```

1. Frontend Interface(IFrontEnd) 부분

- trace file에서 Instruction 읽고, Memory Request 생성
- impl: SimpleO3
 - ⇒ Simple Out-of-Order (O3) CPU
- clock ratio: 8
 - ⇒ global CLK 대비 Frontend CLK 속도
- num expected insts: 500000
 - ⇒ Simulation0| 해당 instruction 수에 도달 시 종료
- traces
 - ⇒ Instruction trace file(include memory access Inst)
- impl: RandomTranslation
 - ⇒ Physical Memory ↔ Virtual Memory 변환
 - ⇒ System의 Page Table 등을 간단히 Modeling
- max addr: 2147483648
 - ⇒ Translation 시 address overflow 방지

yaml file

□ example_config.yaml

```
1  Frontend:  
2    impl: SimpleOS  
3    clock_ratio: 8  
4    num_expected_insts: 500000  
5  traces:  
6    - example_inst.trace  
7  
8  Translation:  
9    impl: RandomTranslation  
10   max_addr: 2147483648  
11  
13  MemorySystem:  
14    impl: GenericDRAM  
15    clock_ratio: 3  
16  
17  DRAM:  
18    impl: DDR4  
19    org:  
20      preset: DDR4_8Gb_x8  
21      channel: 1  
22      rank: 2  
23    timing:  
24      preset: DDR4_2400R  
25  
26  Controller:  
27    impl: Generic  
28    Scheduler:  
29      impl: FRFCFS  
30    RefreshManager:  
31      impl: AllBank  
32    RowPolicy:  
33      impl: ClosedRowPolicy  
34      cap: 4  
35    plugins:  
36  
37  AddrMapper:  
38    impl: RoBaRaCoCh
```

2. MemorySystem Interface 부분

- Frontend의 Request를 받아 DRAM Ctrlr을 통해 처리
- Latency, en/dequeue, Timing Constraints 처리
- impl: GenericDRAM
 - ⇒ 기본 DRAM 기반 System, Ctrlr와 DRAM을 통합
- clock ratio: 3
 - ⇒ global CLK 대비 MemorySystem CLK 속도
 - ⇒ 현재: DRAM이 CPU보다 느린 System (= 3:8)

yaml file

example_config.yaml

```
1  Frontend:          13  MemorySystem:
2    impl: SimpleO3   14    impl: GenericDRAM
3    clock_ratio: 8   15    clock_ratio: 3
4    num_expected_insts: 500000
5  traces:
6    - example_inst.trace
7
8  Translation:
9    impl: RandomTranslation
10   max_addr: 2147483648
11
12
13  MemorySystem:
14    impl: GenericDRAM
15    clock_ratio: 3
16
17  DRAM:
18    impl: DDR4
19    org:
20      preset: DDR4_8Gb_x8
21      channel: 1
22      rank: 2
23      timing:
24        preset: DDR4_2400R
25
26  Controller:
27    impl: Generic
28  Scheduler:
29    impl: FRFCFS
30  RefreshManager:
31    impl: AllBank
32  RowPolicy:
33    impl: ClosedRowPolicy
34    cap: 4
35  plugins:
36
37  AddrMapper:
38    impl: RoBaRaCoCh
```

```
26  inline static const std::map<std::string, std::vector<int>> timing_presets = {
27    // name      rate nBL nRCd nRP nRas nRc nWr nRtp nCld nCds nCdl nRdls nWrts nW
28    {"DDR4_1600"}, {1600, 4, 10, 10, 10, 28, 38, 12, 6, 9, 4, 5, -1, -1, 2,
29    {"DDR4_1600K"}, {1600, 4, 11, 11, 11, 28, 39, 12, 6, 9, 4, 5, -1, -1, 2,
30    {"DDR4_1600L"}, {1600, 4, 12, 12, 12, 28, 40, 12, 6, 9, 4, 5, -1, -1, 2,
31    {"DDR4_1866L"}, {1866, 4, 12, 12, 12, 32, 44, 14, 7, 10, 4, 5, -1, -1, 3,
32    {"DDR4_1866M"}, {1866, 4, 13, 13, 13, 32, 45, 14, 7, 10, 4, 5, -1, -1, 3,
33    {"DDR4_1866N"}, {1866, 4, 14, 14, 14, 32, 46, 14, 7, 10, 4, 5, -1, -1, 3,
34    {"DDR4_2133N"}, {2133, 4, 14, 14, 14, 36, 50, 16, 8, 11, 4, 6, -1, -1, 3,
35    {"DDR4_2133P"}, {2133, 4, 15, 15, 15, 36, 51, 16, 8, 11, 4, 6, -1, -1, 3,
36    {"DDR4_2133R"}, {2133, 4, 16, 16, 16, 36, 52, 16, 8, 11, 4, 6, -1, -1, 3,
37    {"DDR4_2400P"}, {2400, 4, 15, 15, 15, 39, 54, 18, 9, 12, 4, 6, -1, -1, 3,
38    {"DDR4_2400R"}, {2400, 4, 16, 16, 16, 39, 55, 18, 9, 12, 4, 6, -1, -1, 3,
39    {"DDR4_2400U"}, {2400, 4, 17, 17, 17, 39, 56, 18, 9, 12, 4, 6, -1, -1, 3,
40    {"DDR4_2400T"}, {2400, 4, 18, 18, 18, 39, 57, 18, 9, 12, 4, 6, -1, -1, 3,
```

2. MemorySystem Interface 부분

- DRAM Section

- impl: DDR4

⇒ tick() 시 Timing Check / Command Issue 실행.

- org: DDR4 8Gb x8

⇒ 현재 DRAM preset - 8Gb 용량, x8bit data bus

⇒ Channel/Rank 설정 시 기본 Preset 설정을 Override 함

- timing: DDR4 2400R

⇒ Timing preset - nRCD등의 Timing Constraint 정의

⇒ 이를 이용해 tick() 시 Latency 계산

```
class DDR4 : public IDRAM, public Implementation {
  RAMULATOR_REGISTER_IMPLEMENTATION(IDRAM, DDR4, "DDR4", "DDR4 Device Model")
public:
  inline static const std::map<std::string, Organization> org_presets = {
    // name      density DQ Ch Ra Bg Ba Ro Co
    {"DDR4_2Gb_x4", {2<<10, 4, {1, 1, 4, 4, 1<<15, 1<<10}}},
    {"DDR4_2Gb_x8", {2<<10, 8, {1, 1, 4, 4, 1<<14, 1<<10}}},
    {"DDR4_2Gb_x16", {2<<10, 16, {1, 1, 2, 4, 1<<14, 1<<10}}},
    {"DDR4_4Gb_x4", {4<<10, 4, {1, 1, 4, 4, 1<<16, 1<<10}}},
    {"DDR4_4Gb_x8", {4<<10, 8, {1, 1, 4, 4, 1<<15, 1<<10}}},
    {"DDR4_4Gb_x16", {4<<10, 16, {1, 1, 2, 4, 1<<15, 1<<10}}},
    {"DDR4_8Gb_x4", {8<<10, 4, {1, 1, 4, 4, 1<<17, 1<<10}}},
    {"DDR4_8Gb_x8", {8<<10, 8, {1, 1, 4, 4, 1<<16, 1<<10}}},
    {"DDR4_8Gb_x16", {8<<10, 16, {1, 1, 2, 4, 1<<16, 1<<10}}},
    {"DDR4_16Gb_x4", {16<<10, 4, {1, 1, 4, 4, 1<<18, 1<<10}}},
    {"DDR4_16Gb_x8", {16<<10, 8, {1, 1, 4, 4, 1<<17, 1<<10}}},
    {"DDR4_16Gb_x16", {16<<10, 16, {1, 1, 2, 4, 1<<17, 1<<10}}},
  };
}
```

```
class DDR4 : public IDRAM, public Implementation {
  void tick() override {
    void init() override {
      RAMULATOR_DECLARE_SPECS();
      set_organization();
      set_timing_vals();
      set_actions();
      set_preqs();
      set_rowhits();
      set_rowopens();
      set_powers();
      create_nodes();
    };
  };
}
```

yaml file

□ example_config.yaml

```
1  Frontend:
2    impl: SimpleOS
3    clock_ratio: 8
4    num_expected_insts: 500000
5  traces:
6    - example_inst.trace
7
8  Translation:
9    impl: RandomTranslation
10   max_addr: 2147483648
11
13  MemorySystem:
14    impl: GenericDRAM
15    clock_ratio: 3
16
17    DRAM:
18      impl: DDR4
19      org:
20        preset: DDR4_8Gb_x8
21        channel: 1
22        rank: 2
23        timing:
24          preset: DDR4_2400R
25
26    Controller:
27      impl: Generic
28      Scheduler:
29        impl: FRFCFS
30      RefreshManager:
31        impl: AllBank
32      RowPolicy:
33        impl: ClosedRowPolicy
34        cap: 4
35      plugins:
36
37    AddrMapper:
38      impl: RoBaRaCoCh
```

2. MemorySystem Interface 부분

- **Controller Section**
- *impl: Generic*
 - ⇒ Generic - 기본 Ctrlr
 - ⇒ Request Queue/Scheduling 등 관리
- *Scheduler - impl: FRFCFS*
 - ⇒ FRFCFS - First-Ready First-Come-First-Serve
 - ⇒ 준비된 Request를 Queue에서 꺼내 우선 처리
- *RefreshManager - impl: AllBank*
 - ⇒ AllBank - 모든 Bank simultaneous Refresh
- *RowPolicy - impl: ClosedRowPolicy*
 - ⇒ ClosedRowPolicy - 사용 후 Row 즉시 닫음(Precharge)
 - ⇒ cap:4 - 열려있는 Row 최대 수 제한
- *plugins*
 - ⇒ 현재 Ramulator에서는 Row Hammering 완화 기법을 plugin으로 제공해줌

yaml file

□ example_config.yaml

```
1  ✓ Frontend:
2    |   impl: SimpleOS
3    |   clock_ratio: 8
4    |   num_expected_insts: 500000
5  ✓ traces:
6    |   - example_inst.trace
7
8  ✓ Translation:
9    |   impl: RandomTranslation
10   |   max_addr: 2147483648
11
13  MemorySystem:
14    |   impl: GenericDRAM
15    |   clock_ratio: 3
16
17  DRAM:
18    |   impl: DDR4
19    |   org:
20      |     preset: DDR4_8Gb_x8
21      |     channel: 1
22      |     rank: 2
23      |     timing:
24      |       preset: DDR4_2400R
25
26  Controller:
27    |   impl: Generic
28    |   Scheduler:
29      |     impl: FRFCFS
30    |   RefreshManager:
31      |     impl: AllBank
32    |   RowPolicy:
33      |     impl: ClosedRowPolicy
34      |     cap: 4
35    |   plugins:
36
37  AddrMapper:
38    |   impl: RoBaRaCoCh
```

2. MemorySystem Interface 부분

- AddrMapper Section

- impl: RoBaRaCoCh

⇒ Row-Bank-Rank-Column-Channel Mapping Scheme

⇒ Requested Address 변환(Physical → DRAM Vector)

[Physical → DRAM Vector Example]

⇒ Physical Address: 0x12345678

⇒ DRAM Vector:

[Channel:0, Rank:1, Bank:2, Row:128, Column:512]

trace file

□ example_inst.trace & trace.cpp & core.cpp

- simpleO3 CPU model 기준

- Ramulator는 “Memory” Simulator

- Memory 명령어만 취급하기에, 3가지로만 Instruction을 분리한다.

- 1. Not Memory Operation

- 2. Load

- 3. Store

- 따라서, simpleO3 기반 trace파일:

- 1st column은 Not Memory Operation Cycle 수 (or ticks 수)

- 2nd column은 load operation address

- 3rd column은 store operation address

example_inst.trace		
1	3	20734016
2	1	20846400
3	6	20734208
4	1	20846400
5	8	20841280
6	0	20734144
7	2	20918976
8	1	20846400
9		20734016

- 각 line은 load(& store)동작을 나타낸다.

- 1st line : 3cycle동안 stall → load

- 5th line : 8cycle동안 stall → load → store

trace file result

□ ./ramulator2 -f ./example_config.yaml

```
root@947e591ed45c:/workspace# ./ramulator2 -f ./example_config.yaml
Frontend:
  impl: simple03
  memory_access_cycles_recorded_core_0: 61
  cycles_recorded_core_0: 216815
  llc_mshr_unavailable: 0
  llc_read_misses: 37
  llc_read_access: 133336
  llc_write_misses: 8
  llc_write_access: 33334
  llc_eviction: 0
  num_expected_insts: 500000
Translation:
  impl: RandomTranslation

MemorySystem:
  impl: GenericDRAM
  total_num_other_requests: 0
  total_num_write_requests: 0
  total_num_read_requests: 6
  memory_system_cycles: 81306
DRAM:
  impl: DDR4
AddrMapper:
  impl: RoBaRaCoCh

Controller:
  impl: Generic
  id: Channel 0
  avg_read_latency_0: 46.5
  read_queue_len_avg_0: 0.00232455181
  write_queue_len_0: 0
  queue_len_0: 245
  num_other_reqs_0: 0
  num_write_reqs_0: 0
  read_latency_0: 279
  priority_queue_len_avg_0: 0.000688756059
  row_hits_0: 2
  priority_queue_len_0: 56
  row_misses_0: 4
  row_conflicts_0: 0
  read_row_misses_0: 4
  queue_len_avg_0: 0.00301330769
  read_row_conflicts_core_0: 0
  read_row_hits_0: 2
  write_queue_len_avg_0: 0
  read_row_conflicts_0: 0
  write_row_misses_0: 0
  write_row_conflicts_0: 0
  read_queue_len_0: 189
  write_row_hits_0: 0
  read_row_hits_core_0: 2
  read_row_misses_core_0: 4
  num_read_reqs_0: 6
Scheduler:
  impl: FRFCFS
RefreshManager:
  impl: AllBank

RowPolicy:
  impl: ClosedRowPolicy
  num_close_reqs: 0
```

- 기본 yaml file setting을 이용.
=> trace file의 Inst 실행결과가 분석됨
- 1. Frontend:
CPU ↔ Memory<Cache> 접근 분석
- 2. MemorySystem<DRAM> 관점 분석
 - Request 수
 - Cycle 수
 - Latency
 - Queue 길이
 - Row Hit / Miss

trace file result analysis

□ ./ramulator2 -f ./example_config.yaml

- 분석 시 사용한 trace file은 오른쪽의 example_inst이다.
- 예상 simulation 결과는 다음과 같아야 한다 → 이를 실제 Results와 비교한다.
- 8번의 load (address: 0x20846400가 3번 나온다)
- 2번의 write (1st Inst의 address, 5th Inst의 address에 Write [이미 load된 address 접근 → cache hit])
 - DRAM 관점
 - 이를 통해서 6번의 DRAM Read Access를 요구하는 것을 예측 가능
 - 나머지 중복 load들은 cache line에 hit되어 DRAM Access X
 - Write의 경우 이미 Load된 address에 write하므로 cache이용 : 0번의 DRAM Write Access
 - SRAM(cache) 관점
 - 적은 memory 주소만 반복 접근 하므로 cache eviction X (이전에 load된 addr들은 다 hit 됨)
 - Initial Read Misses: 6번 / Initial Write Misses: 0번

≡ example_inst.trace		
1	3	20734016
2	1	20846400
3	6	20734208
4	1	20846400
5	8	20841280 20841280
6	0	20734144
7	2	20918976 20734016
8	1	20846400
9		

trace file result analysis

□ ./ramulator2 -f ./example_config.yaml

```
root@947e591ed45c:/workspace# ./ramulator2 -f ./example_config.yaml
Frontend:
  impl: SimpleO3
  memory_access_cycles_recorded_core_0: 61
  cycles_recorded_core_0: 216815
  llc_mshr_unavailable: 0
  llc_read_misses: 37
  llc_read_accesses: 133336
  llc_write_misses: 8
  llc_write_accesses: 33334
  llc_eviction: 0
  num_expected_insts: 500000
  Translation:
    impl: RandomTranslation

Controller:
  impl: Generic
  id: channel 0
  avg read latency 0: 46.5
  read queue len avg 0: 0.00232455181
  write queue len 0: 0
  queue_len_0: 245
  num_other_reqs_0: 0
  num_write_reqs_0: 0
  read latency 0: 279
  priority_queue_len_avg_0: 0.000688756059
  row_hits_0: 2
  priority_queue_len_0: 56
  row_misses_0: 4
  row_conflicts_0: 0
  read_row_misses_0: 0
  queue_len_avg_0: 0.00301330769
  read_row_conflicts_core_0: 0
  read_row_hits_0: 2
  write_queue_len_avg_0: 0
  read_row_conflicts_0: 0
  write_row_misses_0: 0
  write_row_conflicts_0: 0
  read_queue_len_0: 189
  write_row_hits_0: 0
  read_row_hits_core_0: 2
  read_row_misses_core_0: 4
  num_read_reqs_0: 6
  Scheduler:
    impl: FRFCFS
  RefreshManager:
    impl: AllBank

RowPolicy:
  impl: ClosedRowPolicy
  num_close_reqs: 0

52 const SimpleO3Core::Trace::Inst& SimpleO3Core::Trace::get_next_inst(
53   const Inst& inst = m_trace[m_curr_trace_idx];
54   m_curr_trace_idx = (m_curr_trace_idx + 1) % m_trace_length;
55   return inst;
56 }
```

짧은 trace지만 반복 실행 되기에 많은 access 발생

1. Frontend

- Last Level Cache(LLC) 분석
 - Core 0의 Memory(Cache 포함) 접근 Cycles
 - LLC의 Read Request Cache Miss 수
 - LLC의 Read Access 수
 - Miss Status Handling Register(MSHR) unavailable cnt
→ MSHR가 가득 차서 Request 거부된 횟수
 - LLC의 Write Request Cache Miss 수
 - LLC의 Write Access 수
 - LLC의 Eviction 수
→ Cache Line 교체된 수 (DRAM Write 유발)

이전의 예상치와 다르게 LLC의 miss수가 훨씬 많음

- dependency check, reorder buffer 등 때문일 수 있음
- LLC operation 코드 분석이 필요 → OoO CPU의 특성 때문임
- bool SimpleO3LLC::send(Request req)

trace file result analysis

□ ./ramulator2 -f ./example_config.yaml

```
root@947e591ed45c:/workspace# ./ramulator2 -f ./example_config.yaml
Frontend:
  impl: Simple03
  memory_access cycles recorded core_0: 61
  cycles recorded core_0: 216815
  l1c_mshrs unavailable: 0
  l1c_read_misses: 37
  l1c_read_accesses: 13336
  l1c_write_misses: 8
  l1c_write_accesses: 3334
  l1c_eviction: 0
  num_expected_insts: 500000
Translation:
  impl: RandomTranslation

MemorySystem:
  impl: GenericDRAM
  total_num_other_requests: 0
  total_num_write_requests: 0
  total_num_read_requests: 6
  memory_system_cycles: 81306
  DRAM:
    impl: DDR4
    AddrMapper:
      impl: RoBaRaCoCh

Controller:
  impl: Generic
  id: channel 0
  avg_read_latency_0: 46.5
  read_queue_len_avg_0: 0.00232455181
  write_queue_len_0: 0
  queue_len_0: 245
  num_other_reqs_0: 0
  num_write_reqs_0: 0
  read_latency_0: 279
  priority_queue_len_avg_0: 0.000688756059
  row_hits_0: 2
  priority_queue_len_0: 56
  row_misses_0: 4
  row_conflicts_0: 0
  read_row_misses_0: 0
  queue_len_avg_0: 0.00301330769
  read_row_conflicts_core_0: 0
  read_row_hits_0: 2
  write_queue_len_avg_0: 0
  read_row_conflicts_0: 0
  write_row_misses_0: 0
  write_row_conflicts_0: 0
  read_queue_len_0: 189
  write_row_hits_0: 0
  read_row_hits_0: 0
  read_row_hits_core_0: 2
  read_row_misses_core_0: 4
  num_read_reqs_0: 6
  Scheduler:
    impl: FRFCFS
    RefreshManager:
      impl: AllBank

RowPolicy:
  impl: ClosedRowPolicy
  num_close_reqs: 0

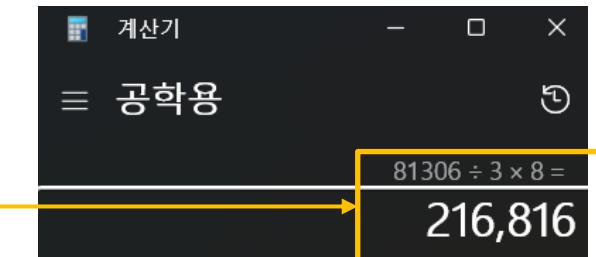
108  inline static const execp::ImplDef m_requests = {
109  | "read", "write", "all-bank-refresh", "open-row", "close-row"
110  };
111
112  inline static const ImplLUT m_request_translations = LUT(
113  | m_requests, m_commands, {
114  | | {"read", "RD"}, {"write", "WR"}, {"all-bank-refresh", "REFab"}, 
115  | | {"open-row", "ACT"}, {"close-row", "PRE"}
116  | );
117
```

Other requests: read/write를 제외한 open-row와 같은 request 등을 의미

2. MemorySystem Interface

• DRAM 분석

- Read/Write 외 other requests 수 이전의 예상치와 일치
- write requests 수 → 현재 0 (cache eviction 없었기에)
- read requests 수 → 현재 6 (initial cache line load)
- Memory system cycles
→ Memory CLK과 Proc CLK이 다르기에 (= 3:8)



DRAM CLK : Processor CLK = 3:8

trace file result analysis

□ ./ramulator2 -f ./example_config.yaml

```
root@947e591ed45c:/workspace# ./ramulator2 -f ./example_config.yaml
Frontend:
  impl: Simple03
  memory_access_cycles_recorded_core_0: 61
  cycles_recorded_core_0: 216815
  l1c_mshrs_unavailable: 0
  l1c_read_misses: 37
  l1c_read_accesses: 133336
  l1c_write_misses: 8
  l1c_write_accesses: 33334
  l1c_eviction: 0
  num_expected_insts: 500000
Translation:
  impl: RandomTranslation

MemorySystem:
  impl: GenericDRAM
  total_num_other_requests: 0
  total_num_write_requests: 0
  total_num_read_requests: 6
  memory_system_cycles: 81306
  DRAM:
    impl: DDR4
  AddrMapper:
    impl: RoBaRaCoch

Controller:
  impl: Generic
  id: channel 0
  avg_read_latency_0: 46.5
  read_queue_len_avg_0: 0.00232455181
  write_queue_len_0: 0
  queue_len_0: 245
  num_other_reqs_0: 0
  num_write_reqs_0: 0
  read_latency_0: 279
  priority_queue_len_avg_0: 0.000688756059
  row_hits_0: 2
  priority_queue_len_0: 56
  row_misses_0: 4
  row_conflicts_0: 0
  read_row_misses_0: 0
  queue_len_avg_0: 0.00301330769
  read_row_conflicts_core_0: 0
  read_row_hits_0: 2
  write_queue_len_avg_0: 0
  read_row_conflicts_0: 0
  write_row_misses_0: 0
  write_row_conflicts_0: 0
  read_queue_len_0: 189
  write_row_hits_0: 0
  read_row_hits_core_0: 2
  read_row_misses_core_0: 4
  num_read_reqs_0: 6
  Scheduler:
    impl: FRFCFS
  RefreshManager:
    impl: Allbank

RowPolicy:
  impl: ClosedRowPolicy
  num_close_reqs: 0
```

2. MemorySystem Interface

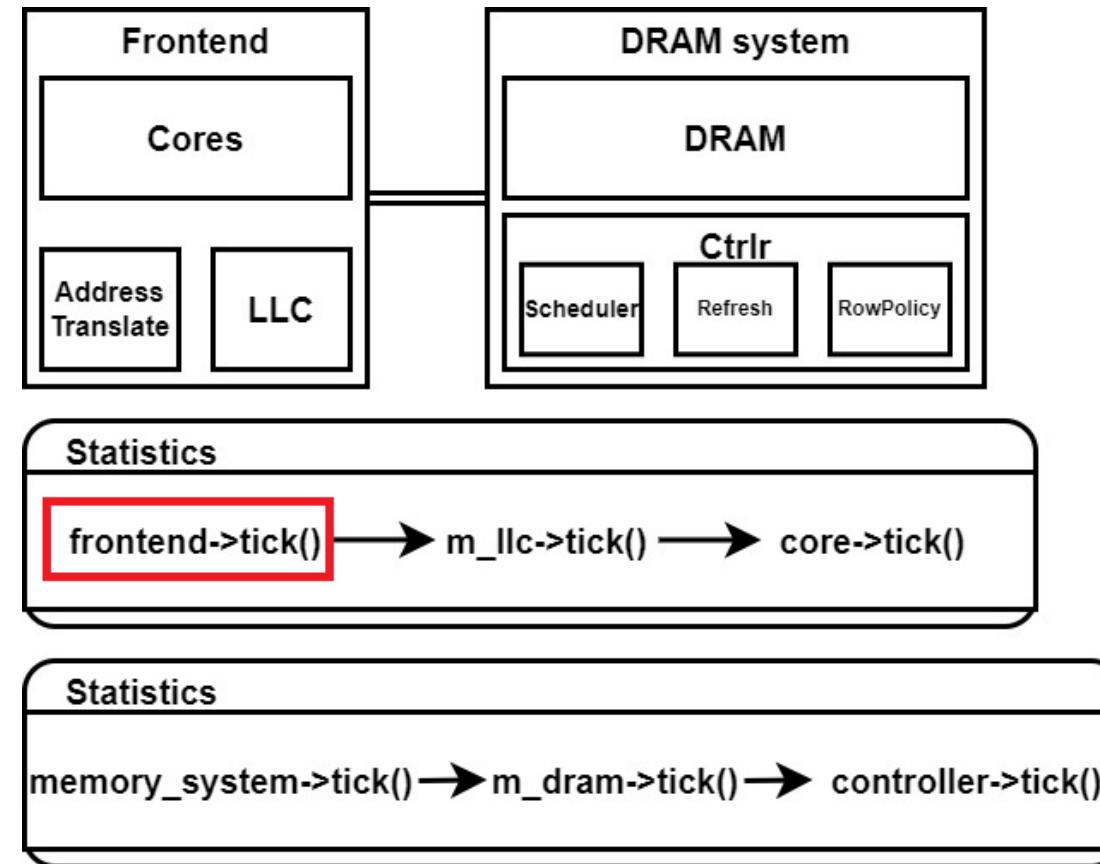
- DRAM Controller 분석

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → frontend->tick()

```
81 void tick() override {  
82     m_clk++;  
83  
84     if(m_clk % 10000000 == 0) {  
85         m_logger->info("Processor Heartbeat {} cycles.", m_clk);  
86     }  
87  
88     m_llc->tick();  
89     for (auto core : m_cores) {  
90         core->tick();  
91     }  
92 }
```



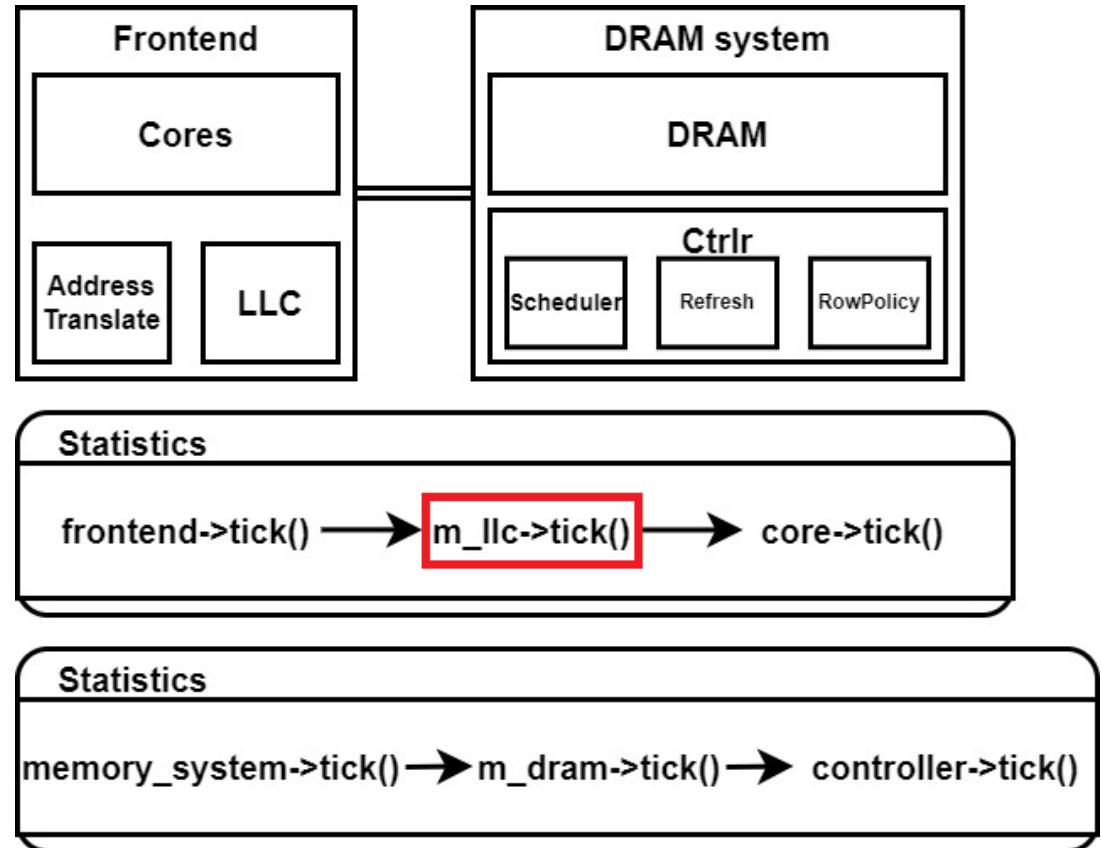
- `m_clk` (processor clk) 증가
- 아래의 순서로 frontend 동작
- Last Level Cache tick() → Core tick()

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → **m_llc->tick()**

```
20 void SimpleO3LLC::tick() {
21     m_clk++;
22
23     // Send miss requests to the memory system when LLC latency is met
24     // TODO: Optimization by assuming in-order issue?
25     auto it = m_miss_list.begin();
26     while (it != m_miss_list.end()) {
27         if (m_clk >= it->first) {
28             if (!m_memory_system->send(it->second)) {
29                 it++;
30             }
31             else {
32                 it = m_miss_list.erase(it);
33             }
34         } else {
35             it++;
36         }
37     }
38
39     // call hit request callback when LLC latency is met
40     it = m_hit_list.begin();
41     while (it != m_hit_list.end()) {
42         if (m_clk >= it->first) {
43             std::vector<Request> _req_v{it->second};
44             m_receive_requests[it->second.addr] = _req_v;
45
46             it->second.callback(it->second);
47             it = m_hit_list.erase(it);
48         }
49         else {
50             it++;
51         }
52     }
53 }
54
55 void SimpleO3LLC::evict_line(CacheSet_t& set, CacheSet_t::iterator victim_it) {
56     DEBUG_LOG(DSIMPLEO3LLC, m_logger, "Evicting {}.", victim_it->addr);
57     s_llc_eviction++;
58
59     // Generate writeback request if victim line is dirty
60     if (victim_it->dirty) {
61         Request writeback_req(victim_it->addr, Request::Type::Write);
62         m_miss_list.push_back(std::make_pair(m_clk + m_latency, writeback_req));
63     }
64
65     DEBUG_LOG(DSIMPLEO3LLC, m_logger, "Writeback Request will be issued at Clk({}.)", m_clk + m_latency);
66
67     set.erase(victim_it);
68 }
```



- Miss List에서 자연 끝난 Missed Request을 MemorySystem으로 전달
- LLC latency(m_latency) Simulation & Send missed req to DRAM
- 현재: LLC latency modeling 값 → m_latency = 47

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → m_llc->tick()

```
20 void SimpleO3LLC::tick() {
21     m_clk++;
22
23     // Send miss requests to the memory system when LLC latency is met
24     // TODO: Optimization by assuming in-order issue?
25     auto it = m_miss_list.begin();
26     while (it != m_miss_list.end()) {
27         if (*it >= it->first) {
28             if (!m_memory_system->send(it->second)) {
29                 it++;
30             }
31         } else {
32             it = m_miss_list.erase(it);
33         }
34     } else {
35         it++;
36     }
37 }
38
39 // call hit request callback when LLC latency is met
40 it = m_hit_list.begin();
41 while (it != m_hit_list.end()) {
42     if (*it >= it->first) {
43         std::vector<Request> _req_v{it->second};
44         m_receive_requests[it->second.addr] = _req_v;
45
46         it->second.callback(it->second);
47         it = m_hit_list.erase(it);
48     }
49     else {
50         it++;
51     }
52 }
```

```
64     if (auto line_it = check_set_hit(set, req.addr); line_it != set.end()) {
65         // Hit in the set
66         DEBUG_LOG(OSIMPLEO3LLC, m_logger,
67             "[Clk={} Request Source: {}, Type: {}, Addr: {}, Index: {}, Tag: {} Hit, will finish at Clk={}",
68             m_clk, req.source_id, req.type_id, req.addr, get_index(req.addr), get_tag(req.addr), m_clk + m_latency
69         );
70
71         // Update the LRU status
72         set.push_back({req.addr, get_tag(req.addr), line_it->dirty || (req.type_id == Request::Type::Write), true});
73         set.erase(line_it);
74
75         // Add to the hit list to callback when finished
76         m_hit_list.push_back(std::make_pair(m_clk + m_latency, req));
77         return true;
78     } else {
79 }
```

```
void receive(Request& req) {
    m_llc->receive(req);

    // TODO: LLC latency for the core to receive the request?
    for (auto r : m_llc->m_receive_requests[req.addr]) {
        r.arrive = req.arrive;
        r.depart = req.depart;
        m_cores[r.source_id]->receive(r);
    }
    m_llc->m_receive_requests[req.addr].clear();
}
```

```
56     // Create the cores
57     for (int id = 0; id < m_num_cores; id++) {
58         SimpleO3Core* core = new SimpleO3Core(id, ipc, depth, m_num_expected_insts, trace_list
59         core->m_callback = [this](Request& req){return this->receive(req);};
60         m_cores.push_back(core);
61     }
62 }
```

- Hit List에서 자연 끝난 Request들을 m_receive_requests배열에 저장
 - 여러 Core가 같은 주소를 가지는 Requests를 기다리고 있을 때, 완료되면 모든 Core에게 통지할 수 있도록 Mapping 하는 것
 - ex. m_receive_requests[0x1000] = [Request(addr=0x1000, source_id=0)]
- callback이 호출됨 (이 callback은 SimpleO3::receive를 가리킴)

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → m_llc->tick() → callback

```
56 // Create the cores
57 for (int id = 0; id < m_num_cores; id++) {
58     SimpleO3Core* core = new SimpleO3Core(id, ipc, depth, m_num_expected_insts, trace_list
59     core->m_callback = [this](Request& req){return this->receive(req);};
60     m_cores.push_back(core);
61 }
```

```
void receive(Request& req) {
    m_llc->receive(req); } → cache 내 MSLR 처리

// TODO: LLC latency for the core to receive the request?
for (auto r : m_llc->m_receive_requests[req.addr]) {
    r.arrive = req.arrive;
    r.depart = req.depart;
    m_cores[r.source_id]->receive(r);
}
m_llc->m_receive_requests[req.addr].clear();
```

```
184 void SimpleO3Core::receive(Request& req) {
185     m_window.set_ready(req.addr);
186
187     if (req.arrive != -1 && req.depart > m_last_mem_cycle) {
188         if (!reached_expected_num_insts) {
189             s_mem_access_cycles += (req.depart - std::max(m_last_mem_cycle, req.arrive));
190             m_last_mem_cycle = req.depart;
191         }
192     }
193 }
```

```
90 void SimpleO3Core::InstWindow::set_ready(Addr_t addr) {
91     if (m_load == 0) return;
92
93     int index = m_tail_idx;
94     for (int i = 0; i < m_load; i++) {
95         if (m_addr_list[index] == addr) {
96             m_ready_list[index] = true;
97         }
98         index++;
99         if (index == m_depth) {
100             index = 0;
101         }
102     }
103 }
```

- ROB에 쌓인 이미 완료된 Instruction은 이제 sequential하게 기존 Instruction 순서에 맞게 commit됨

Cycle 1: Instruction Issue → Cycle 2: Load 요청

Load addr=0x1000 → Request 생성 → LLC로 전송

Cycle 3-49: LLC latency (latency=47)

LLC: Hit 시 m_hit_list에 저장 후 latency 대기

Cycle 50: LLC Hit → callback

1. m_receive_requests[0x1000] = [Request(src=0)]
2. it->second.callback(it->second)
3. SimpleO3::receive() 실행
4. m_cores[0]->receive() 호출
5. m_window.set_ready(0x1000) 호출
6. ROB의 m_ready_list[idx] = true ← ready 표시

다음 core->tick() 시

1. m_window.retrieve()에서 0 Instruction 확인
2. ready_list[idx] == true이므로 Instruction Commit 가능
3. s_insts_retired++ (Commit된 Instructions 증가)
이때, 현재 IPC = 4 이므로, 1cycle에 최대 4개 처리
but 중간에 ready 아닌 것이 있으면 그 뒤는 모두 대기

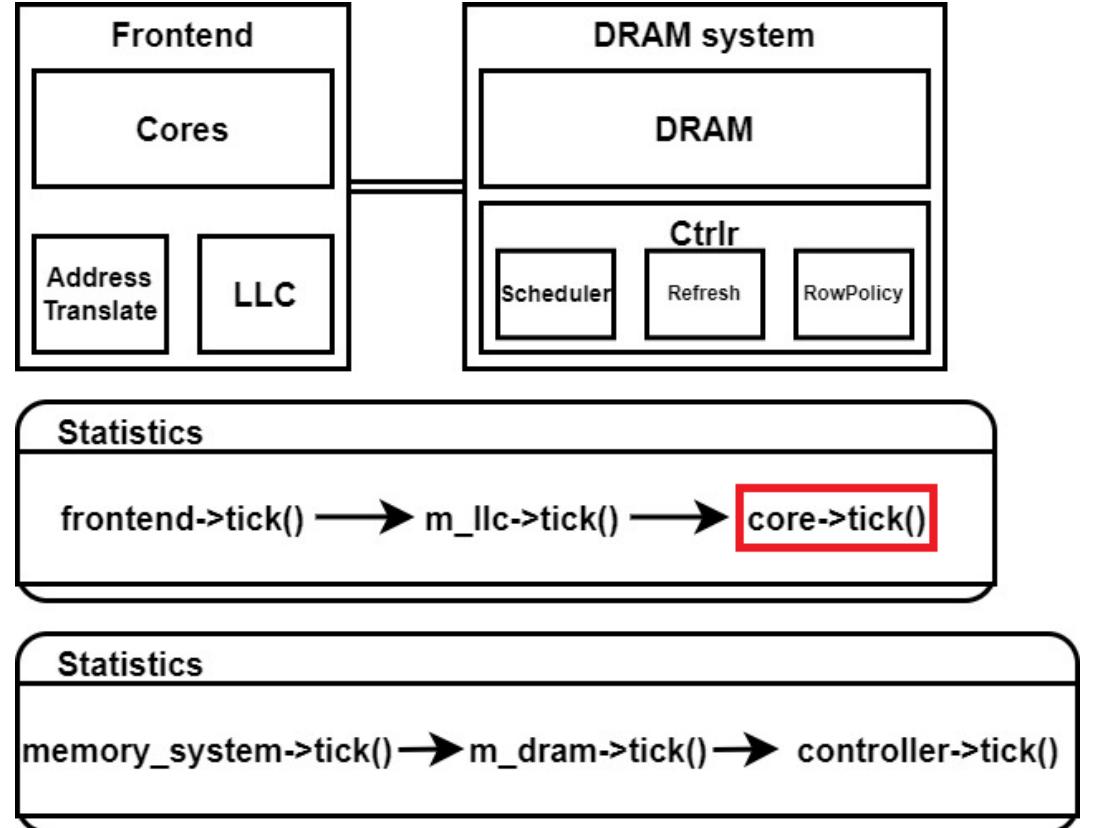
src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick()

```
148 void SimpleO3Core::tick() {  
149     m_clk++;  
150  
151     // 목표 명령어 개수 도달 시 시간 기록  
152     s_insts_retired += m_window.retire();  
153     if (!reached_expected_num_insts) {  
154         if (s_insts_retired >= m_num_expected_insts) {  
155             reached_expected_num_insts = true;  
156             s_cycles_recorded = m_clk;  
157         }  
158     }  
159 }
```

```
96 int SimpleO3Core::InstWindow::retire() {  
97     if (m_load == 0) return 0;           // ROB 비어있으면 0 반환  
98  
99     int num_retired = 0;  
100    while (m_load > 0 && num_retired < m_ipc) {  
101        if (!m_ready_list.at(m_tail_idx))  
102            break;  
103  
104        m_tail_idx = (m_tail_idx + 1) % m_depth; // tail 이동  
105        m_load--;                         // ROB 사용량 감소  
106        num_retired++;                   // commit한 명령어 개수 증가  
107    }  
108    return num_retired;                // 이 cycle에 commit된 명령어 수 반환  
109 }
```



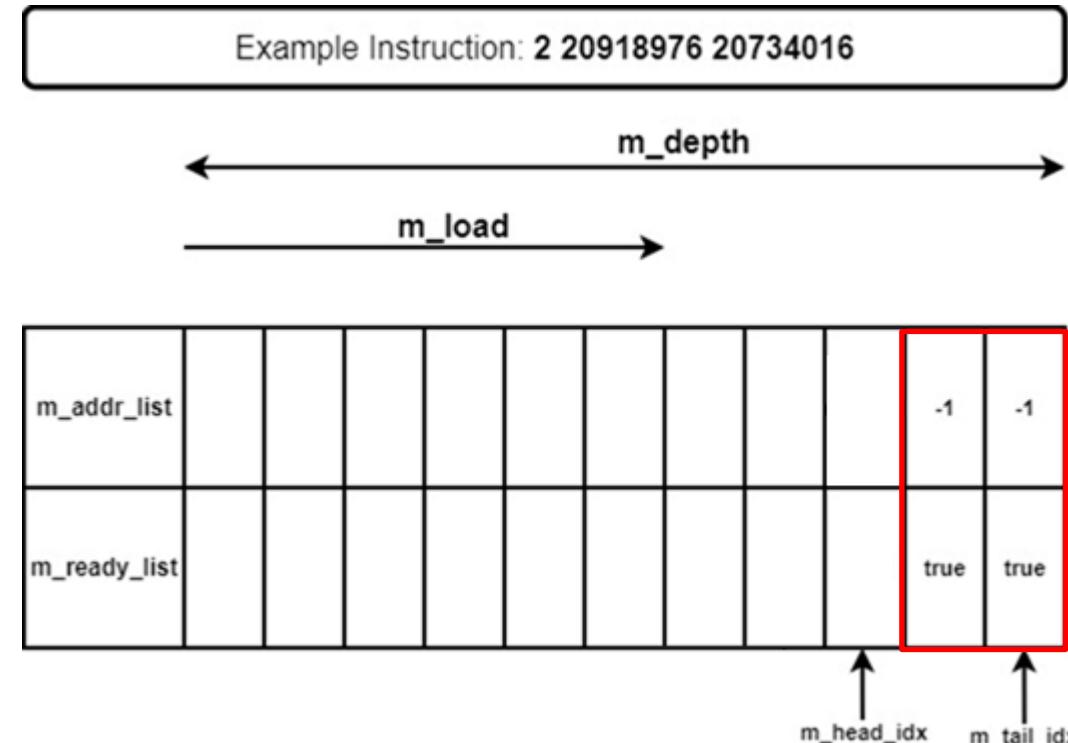
- ROB에서 명령어가 실행될 준비가 되면 ready flag를 **true**로 바꿈
- 이 경우 instruction이 실행되기 위한 **data가 존재한다는 뜻**
- 따라서, **ready = true**이면 해당 Inst를 commit 시킴 → Inst 처리됨

□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick()

```
160 // First, issue the non-memory instructions
161 int num_inserted_insts = 0;
162 while (m_num_bubbles > 0) {
163     if (num_inserted_insts == m_window.m_ipc) { // IPC 제한 도달
164         return;
165     }
166     if (m_window.is_full()) { // ROB 가득 참
167         return;
168     };
169     m_window.insert(true, -1); // ready=true (메모리 operation 아니기에)
170     num_inserted_insts++;
171     m_num_bubbles--;
172 }
```

```
80 // ROB에 새로운 명령어를 삽입
81 void SimpleO3Core::InstWindow::insert(bool ready, Addr_t addr) {
82     m_ready_list.at(m_head_idx) = ready;
83     m_addr_list.at(m_head_idx) = addr;
84
85     m_head_idx = (m_head_idx + 1) % m_depth;
86     m_load++;
87 }
```



- ROB에 Non-Memory Operation을 최대 IPC이하의 개수만큼 채워 넣음
- 위 Example Inst. (= 2 20918976 20734016)의 경우 Non-Memory Op가 2개이기에 위 그림의 빨간 박스 부분이 완성됨

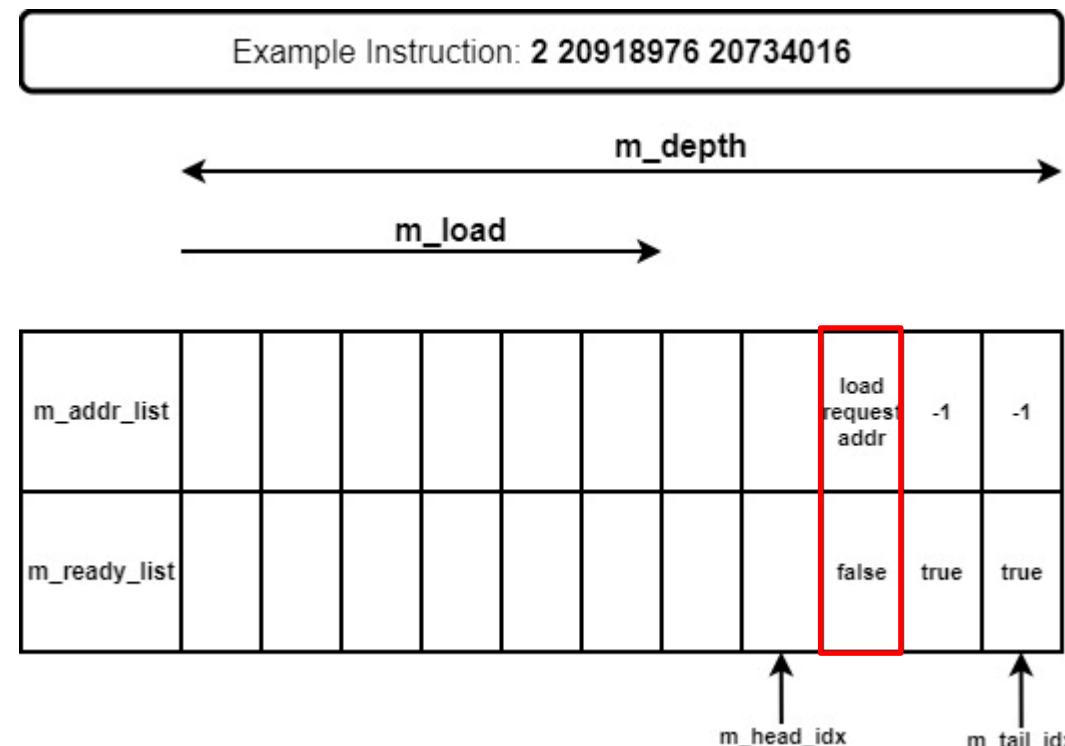
src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick()

```
174 // Second, try to send the load to the LLC
175 if (m_load_addr != -1) {
176     if (num_inserted_insts == m_window.m_ipc) { // IPC 제한
177         return;
178     }
179     if (m_window.is_full()) { // ROB 가득 참
180         return;
181     }
182
183     // Load 요청 생성 (가상 주소)
184     Request load_request(m_load_addr, Request::Type::Read, m_id, m_callback);
185
186     // 주소 변환 (가상 → 물리)
187     if (!m_translation->translate(load_request)) {
188         return; // 변환 실패
189     }
190
191     // LLC로 요청 발송
192     if (m_llc->send(load_request)) {
193         m_window.insert(false, load_request.addr); // ready=false (메모리 대기)
194         m_load_addr = -1; // 처리 완료
195         if (m_writeback_addr != -1) { // Store 있으면 다음 사이클에 발행
196             // If there is still writeback, return without getting the next trace line
197             // The write back will be issued in the next cycle
198             // TODO: Should we allow both load and writeback to issue at the same cycle?
199             return;
200         }
201     } else {
202         return;
203     }
204 }
```

ROB = InstWindow



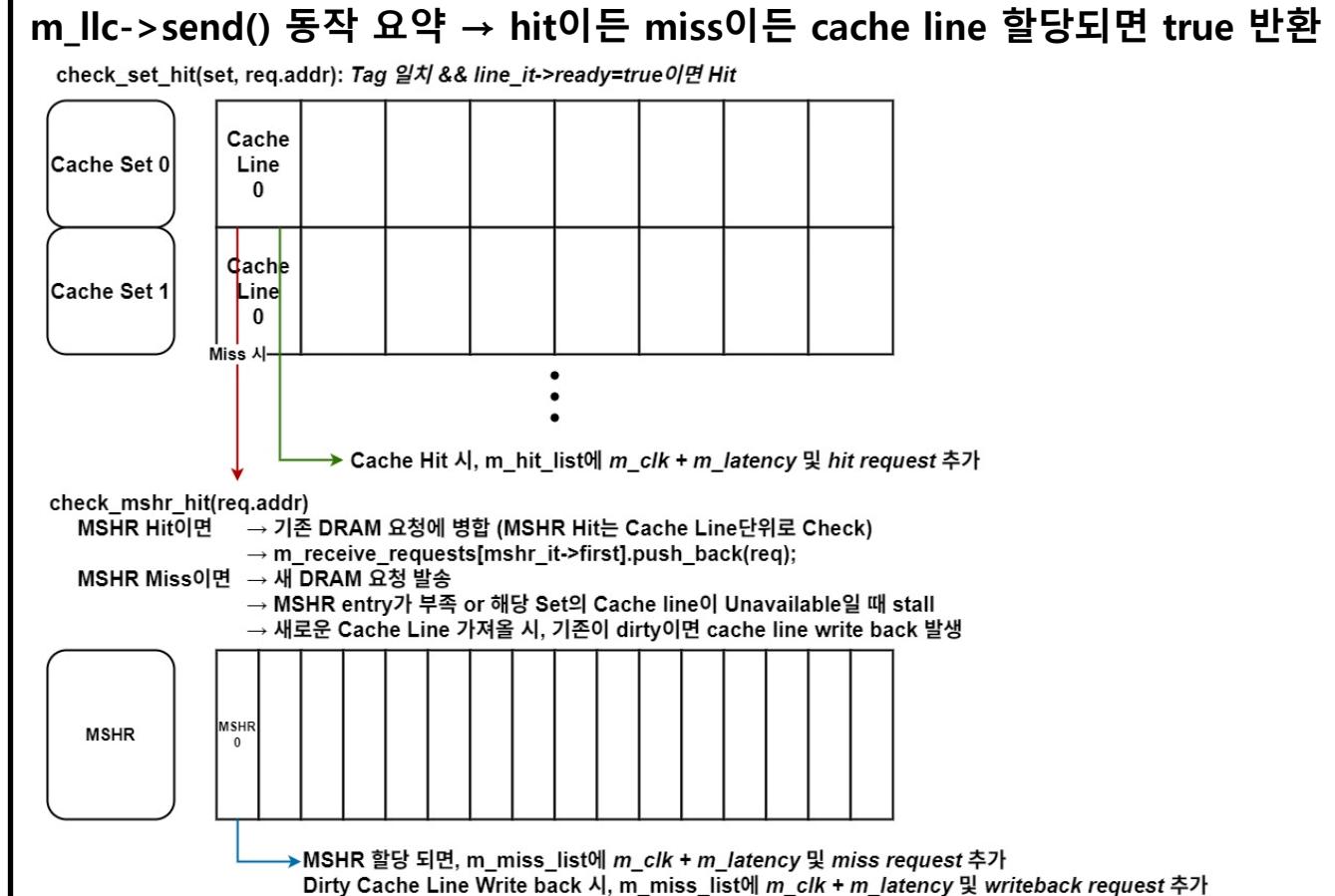
- Load Request가 존재하면, Load 요청의 주소를 translate
- 그 후, LLC로 Request를 보냄

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick() → m_llc->send(load_request)

```
174 // Second, try to send the load to the LLC
175 if (m_load_addr != -1) {
176     if (num_inserted_insts == m_window.m_ipc) { // IPC 제한
177         return;
178     }
179     if (m_window.is_full()) { // ROB 가득 참
180         return;
181     };
182
183     // Load 요청 생성 (가상 주소)
184     Request load_request(m_load_addr, Request::Type::Read, m_id, m_callback);
185
186     // 주소 변환 (가상 → 물리)
187     if (!m_translation->translate(load_request)) {
188         return; // 변환 실패
189     };
190
191     // LLC로 요청 발송
192     if (m_llc->send(load_request)) {
193         m_window.insert(false, load_request.addr); // ready=false (메모리 대기)
194         m_load_addr = -1; // 처리 완료
195         if (m_writeback_addr != -1) { // Store 있으면 다음 사이클에 실행
196             // If there is still writeback, return without getting the next trace line
197             // The write back will be issued in the next cycle
198             // TODO: Should we allow both load and writeback to issue at the same cycle?
199             return;
200         }
201     } else {
202         return;
203     }
204 }
```



src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick()

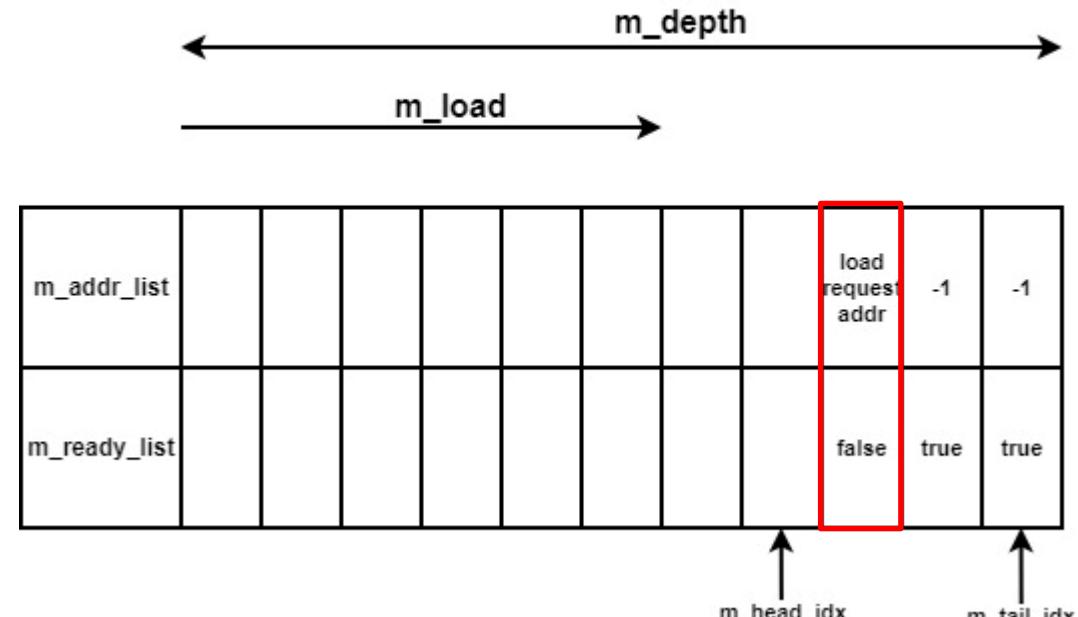
```
174 // Second, try to send the load to the LLC
175 if (m_load_addr != -1) {
176     if (num_inserted_insts == m_window.m_ipc) { // IPC 제한
177         return;
178     }
179     if (m_window.is_full()) { // ROB 가득 참
180         return;
181     }
182
183     // Load 요청 생성 (가상 주소)
184     Request load_request(m_load_addr, Request::Type::Read, m_id, m_callback);
185
186     // 주소 변환 (가상 → 물리)
187     if (!m_translation->translate(load_request)) {
188         return; // 변환 실패
189     }
190
191     // LLC로 요청 발송
192     if (m_llc->send(load_request)) {
193         m_window.insert(false, load_request.addr); // ready=false (메모리 대기)
194         m_load_addr = -1; // 처리 완료
195         if (m_writeback_addr != -1) { // Store 있으면 다음 사이클에 발행
196             // If there is still writeback, return without getting the next trace line
197             // The write back will be issued in the next cycle
198             // TODO: Should we allow both load and writeback to issue at the same cycle?
199             return;
200         }
201     } else {
202         return;
203     }
204 }
```

80 // ROB에 새로운 명령어를 삽입

```
81 void SimpleO3Core::InstWindow::insert(bool ready, Addr_t addr) {
82     m_ready_list.at(m_head_idx) = ready;
83     m_addr_list.at(m_head_idx) = addr;
84
85     m_head_idx = (m_head_idx + 1) % m_depth;
86     m_load++;
87 }
```

ROB = InstWindow

Example Instruction: 2 20918976 20734016



- LLC에 Request를 send하였으므로, 해당 Load Request를 Instruction Window에 넣음
- Write Request가 존재 시, 이는 다음 tick()=cycle에 처리
- Write Request가 존재 시, return됨

src/frontend folder

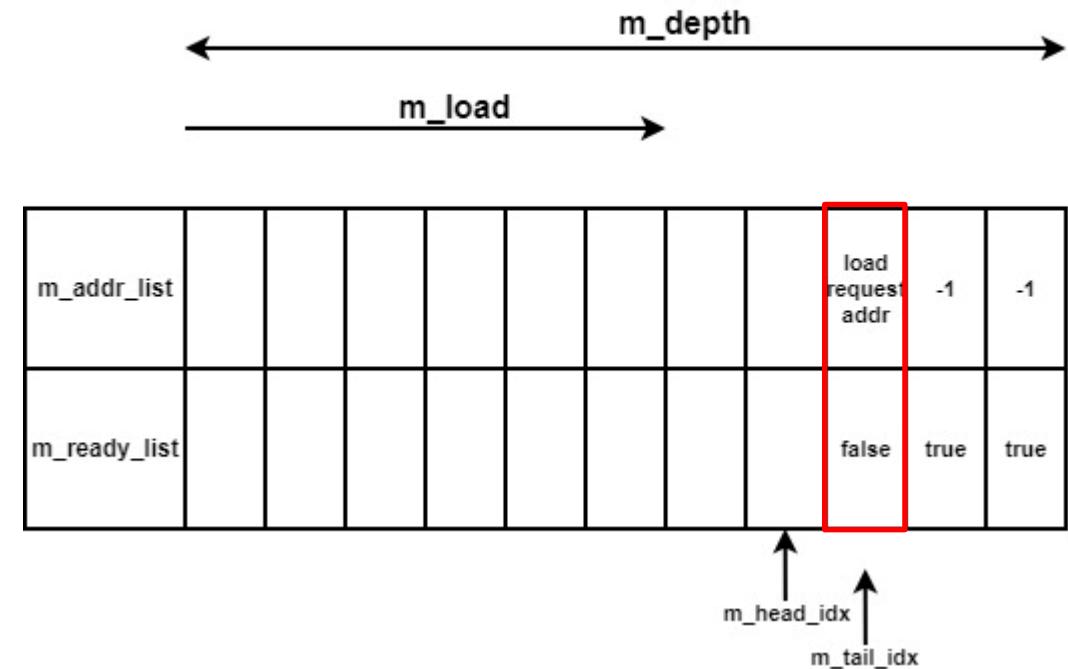
□ simpleO3 Core Operations

- class SimpleO3 – tick() → core->tick()

```
206 // Third, try to send the writeback to the LLC
207 // Store(Writeback) 요청 발행
208 if (m_writeback_addr != -1) {
209     Request writeback_request(m_writeback_addr, Request::Type::Write, m_id, m_callback);
210     if (!m_translation->translate(writeback_request)) {
211         return;
212     };
213     if (!m_llc->send(writeback_request)) {
214         return;
215     }
216 }
217
218 // 다음 명령어 미리 로드
219 auto inst = m_trace.get_next_inst();
220 m_num_bubbles = inst.bubble_count;
221 m_load_addr = inst.load_addr;
222 m_writeback_addr = inst.store_addr;
223 }
```

ROB = InstWindow

Example Instruction: 2 20918976 20734016



- Write Request가 존재 시, return되었기에, trace의 다음 Instruction load가 되지 않고, 진행되고 있던 Inst 처리
- core->tick()에서 1. issue the non-memory instructions / 2. try to send the load to the LLC 건너뛰고 Write 처리
- Write Request도 Read와 마찬가지로, LLC의 send()함수를 실행시킨다.
- 그 후, 다음 Instruction의 정보를 core.h에 update한다.
- 또한, Write Request는 CPU가 issue후 신경 안 써도 되니, ROB에 저장하지 않는다.

src/memory_system folder

□ cache to memory_system

- class SimpleO3 – tick() → m_llc->tick() → m_memory_system – send()

```
37 void SimpleO3LLC::tick() {  
38     m_clk++;  
  
39     // Send miss requests to the memory system when LLC latency is met  
40     // TODO: optimization by assuming in-order issue?  
41     auto it = m_miss_list.begin();  
42     while (it != m_miss_list.end()) {  
43         if (m_clk >= it->first) {  
44             if (!m_memory_system->send(it->second)) { // 지역 완료되었는가?  
45                 it++;  
46             }  
47             else {  
48                 it = m_miss_list.erase(it); // 발송 성공 → 제거  
49             }  
50         }  
51     }  
52     else {  
53         it++;  
54     }  
}
```

```
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
  
    bool send(Request req) override {  
        // separate physical address to dram vector, [channel, rank, bank, ...]  
        m_addr_mapper->apply(req);  
        int channel_id = req.addr_vec[0];  
        // 채널 ID 추출  
        bool is_success = m_controllers[channel_id]->send(req); // 해당 채널 컨트롤러로 요청 전송  
  
        // update statistics  
        if (is_success) {  
            switch (req.type_id) {  
                case Request::Type::Read: {  
                    s_num_read_requests++;  
                    break;  
                }  
                case Request::Type::Write: {  
                    s_num_write_requests++;  
                    break;  
                }  
                default: {  
                    s_num_other_requests++;  
                    break;  
                }  
            }  
        }  
        return is_success;  
    };
```

- Frontend에서 LLC miss가 발생 시, 해당 request들을 m_miss_list에 queuing하고,
- cache latency가 끝나면, m_miss_list의 request들을 memory_system으로 send
- memory_system은 physical address → dram vector 후 알맞은 channel의 ctrlr으로 send

src/memory_system folder

□ cache to memory_system

- `m_memory_system - send()` → `m_controllers[channel_id] - send()`

```
50 |     bool send(Request req) override {
51 |         // separate physical address to dram vector, [channel, rank, bank, ...]
52 |         m_addr_mapper->apply(req);
53 |         int channel_id = req.addr_vec[0];
54 |         bool is_success = m_controllers[channel_id]->send(req); // 채널 ID 추출
55 |
56 |         // update statistics
57 |         if (is_success) {
58 |             switch (req.type_id) {
59 |                 case Request::Type::Read: {
60 |                     s_num_read_reqs++;
61 |                     break;
62 |                 }
63 |                 case Request::Type::Write: {
64 |                     s_num_write_reqs++;
65 |                     break;
66 |                 }
67 |                 default: {
68 |                     s_num_other_requests++;
69 |                     break;
70 |                 }
71 |             }
72 |         }
73 |
74 |         return is_success;
75 |     }
```

- 각 request의 final command를 지정
 - Request가 끝났는지 판단하기 위해 사용
- Requests의 통계 update

```
m_controllers[channel_id] - send() 처음 부분
115 |     bool send(Request& req) override {
116 |         // Request type별 최종 커맨드 결정
117 |         req.final_command = m_dram->m_request_translations(req.type_id);
118 |
119 |         switch (req.type_id) {
120 |             case Request::Type::Read: {
121 |                 s_num_read_reqs++;
122 |                 break;
123 |             }
124 |             case Request::Type::Write: {
125 |                 s_num_write_reqs++;
126 |                 break;
127 |             }
128 |             default: {
129 |                 s_num_other_requests++;
130 |                 break;
131 |             }
132 |         }
133 |
134 |         inline static const ImplUT m_request_translations = LUT (
135 |             m_requests, m_commands,
136 |             {"read", "RD"}, {"write", "WR"}, {"all-bank-refresh", "REFab"},
137 |             {"open-row", "ACT"}, {"close-row", "PRE"}
138 |         );
139 |
140 |
141 |
142 |
143 |
144 |
145 |
146 |
147 |         // Else, enqueue them to corresponding buffer based on request type id
148 |         bool is_success = false;
149 |         req.arrive = m_clk; // 도착 시간 기록
150 |         if (req.type_id == Request::Type::Read) {
151 |             is_success = m_read_buffer.enqueue(req);
152 |         } else if (req.type_id == Request::Type::Write) {
153 |             is_success = m_write_buffer.enqueue(req);
154 |         } else {
155 |             throw std::runtime_error("Invalid request type!");
156 |         }
157 |         if (!is_success) {
158 |             // We could not enqueue the request
159 |             req.arrive = -1;
160 |             return false;
161 |         }
162 |
163 |         return true;
164 |     }
```

src/memory_system folder

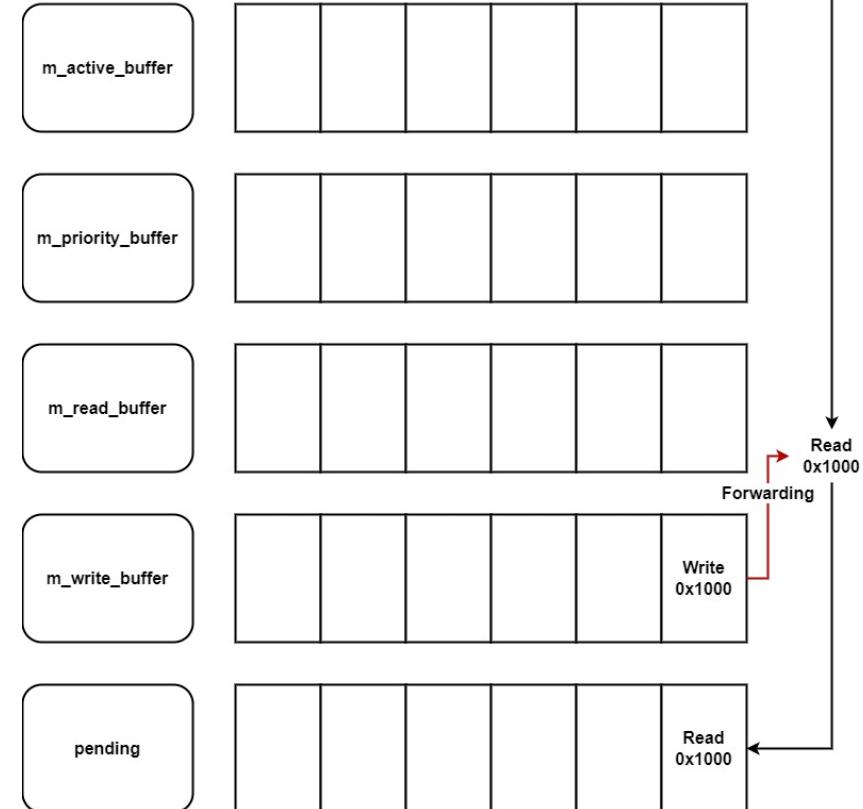
□ cache to memory_system

- `m_memory_system - send() → m_controllers[channel_id] - send()`

`m_controllers[channel_id] - send()` continued ...

```
134     // Forward existing write requests to incoming read requests
135     if (req.type_id == Request::Type::Read) {
136         auto compare_addr = [req](const Request& wreq) {
137             return wreq.addr == req.addr;
138         };
139         if (std::find_if(m_write_buffer.begin(), m_write_buffer.end(), compare_addr) != m_write_buffer.end()) {
140             // The request will depart at the next cycle
141             req.depart = m_clk + 1;
142             pending.push_back(req); // DRAM 접근 없이 반환 -> 다음 사이클에 데이터 전달
143             return true;
144         }
145     }
```

```
generic_dram_controller.cpp -> send(Request& req)
Clk | 동작
100 | Write(0x1000, X)           → m_write_buffer 삽입
101 | Write 스케줄 대기...      → write mode가 아니라고 가정
102 | Write 스케줄 대기...      → write mode가 아니라고 가정
103 | Read(0x1000)              → m_write_buffer에서 같은 주소 발견
|   → depart = 104 설정
|   → pending queue 삽입
104 | serve_completed_reads() → callback 호출
|   → 을바른 data 반환
|   → latency: 1 cycle
```



- **Read Request**가 들어왔을 시,
- 기존 **write buffer**에 **Read Request**와 같은 주소를 가지는 **Req** 존재 시,
- **Data Forwarding** 진행
- **Read** 요청이 원하는 **Data**를 **forwarding**을 통해 얻었음.
- 0| **Read Request**를 **Pending Queue**에 넣음

src/memory_system folder

□ cache to memory_system

- `m_memory_system - send() → m_controllers[channel_id] - send()`

`m_controllers[channel_id] - send()` continued ...

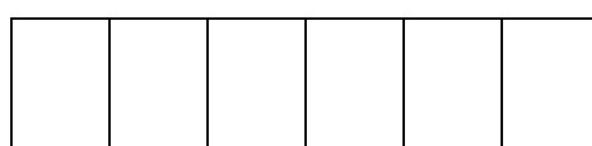
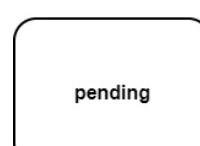
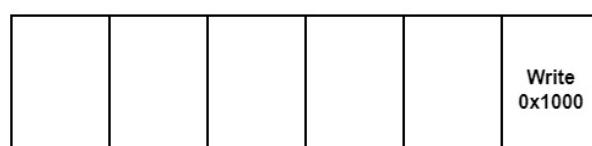
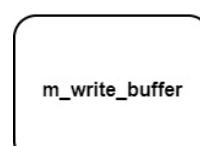
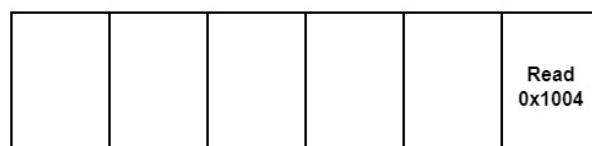
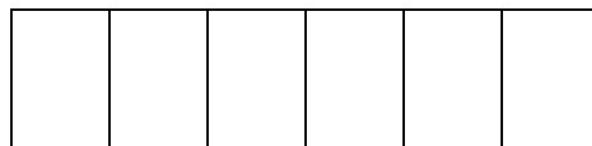
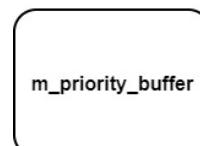
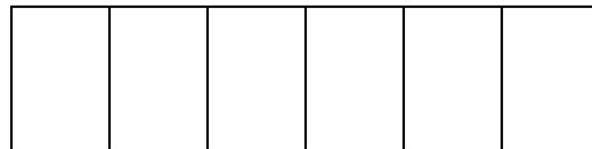
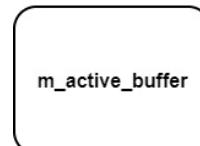
```
147     // Else, enqueue them to corresponding buffer based on request type id
148     bool is_success = false;
149     req.arrive = m_clk;                                // 도착 시간 기록
150     if (req.type_id == Request::Type::Read) {
151         is_success = m_read_buffer.enqueue(req);
152     } else if (req.type_id == Request::Type::Write) {
153         is_success = m_write_buffer.enqueue(req);
154     } else {
155         throw std::runtime_error("Invalid request type!");
156     }
157     if (!is_success) {
158         // We could not enqueue the request
159         req.arrive = -1;
160         return false;
161     }
```

- Data Forwarding 진행할 수 있는 조건 X 시,
- Request Type에 맞춰서 해당하는 buffer에 넣음

generic_dram_controller.cpp -> send(Request& req)

Clk | 동작
100 | Write(0x1000, X)
101 | Write 스케줄 대기...
102 | Write 스케줄 대기...
103 | Read(0x1004, Y)

→ `m_write_buffer` 삽입
→ write mode가 아니라고 가정
→ write mode가 아니라고 가정
→ `m_write_buffer`에서 같은 주소 발견 X



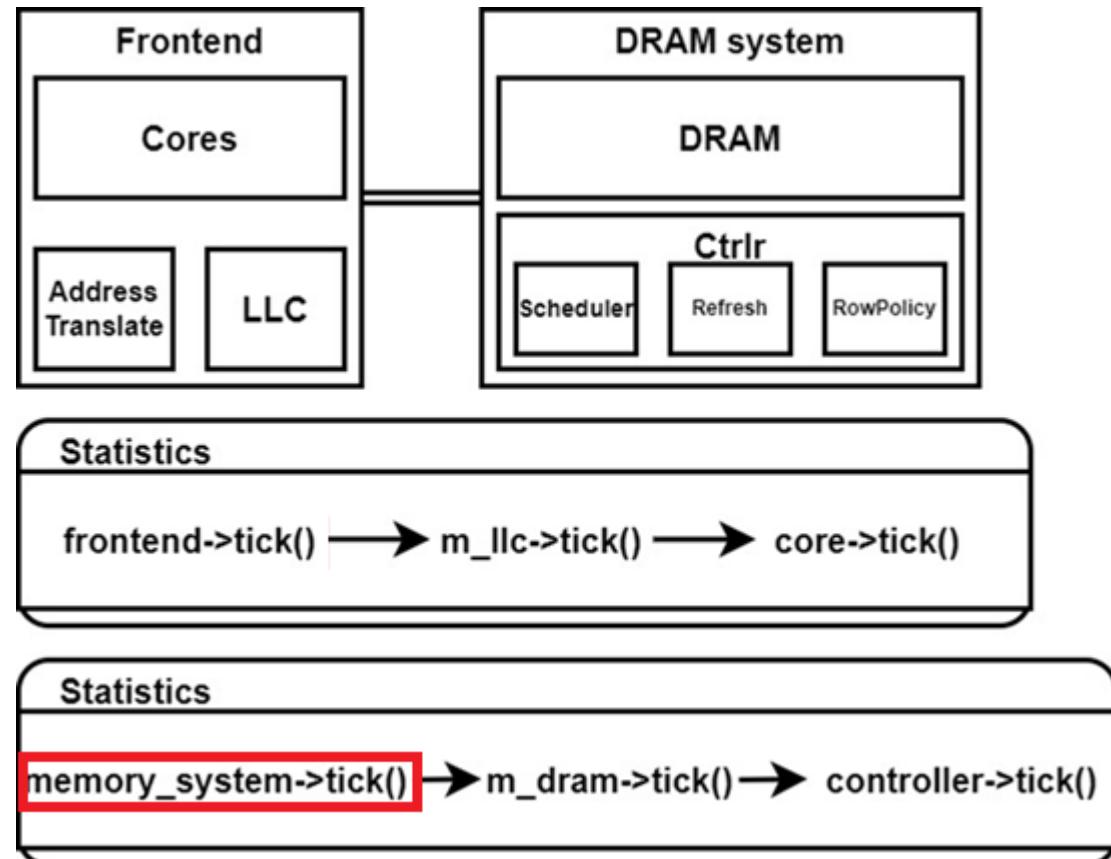
src/memory_system folder

□ memory_system

- `m_memory_system - tick()`

```
77    void tick() override {  
78        m_clk++;  
79        m_dram->tick();      // DRAM 내부 상태 업데이트 (리프레시, 데이터 전송 등)  
80        for (auto controller : m_controllers) {  
81            controller->tick(); // 요청 스케줄링, 커맨드 발행, 완료 처리  
82        }  
83    };
```

- `m_clk (memory clk)` 증가
- 아래의 순서로 Memory System 동작
- Dram tick() → Controller tick()



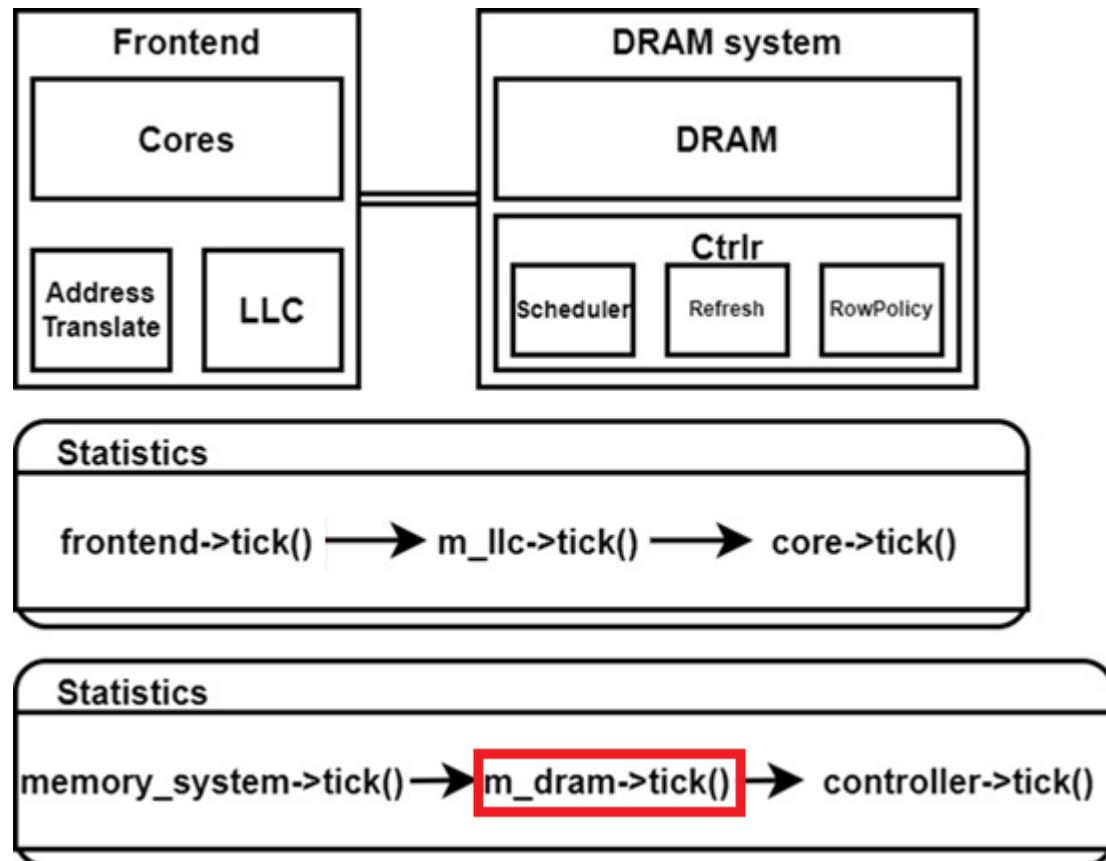
src/memory_system folder

□ memory_system

- `m_memory_system - tick() → m_dram - tick()`

```
183 void tick() override {
184     m_clk++;
185
186     // Check if there is any future action at this cycle
187     for (int i = m_future_actions.size() - 1; i >= 0; i--) {
188         auto& future_action = m_future_actions[i];
189         if (future_action.clk == m_clk) {
190             handle_future_action(future_action.cmd, future_action.addr_vec);
191             m_future_actions.erase(m_future_actions.begin() + i);
192         }
193     }
194 }
```

232 void handle_future_action(int command, const AddrVec_t& addr_vec) {
233 int channel_id = addr_vec[m_levels["channel"]];
234 switch (command) {
235 case m_commands("REFab"):
236 m_channels[channel_id]->update_powers(m_commands("REFab_end"), addr_vec, m_clk);
237 m_channels[channel_id]->update_states(m_commands("REFab_end"), addr_vec, m_clk);
238 break;
239 default:
240 // Other commands do not require future actions
241 break;
242 }
243 }



- **future_action** 배열은 Dram Controller에서 DRAM으로 *REFab command*을 issue 시 push_back됨
- `m_dram->tick()` 시에는 이 **future_action** 배열을 확인하고,
- **timing constraints**를 만족하는 `clk` 때, `REFab_end`를 issue.
- `REFab`가 issue되고, 해당 Rank가 Refreshing되는 동안 해당 Rank는 다른 command issue 불가

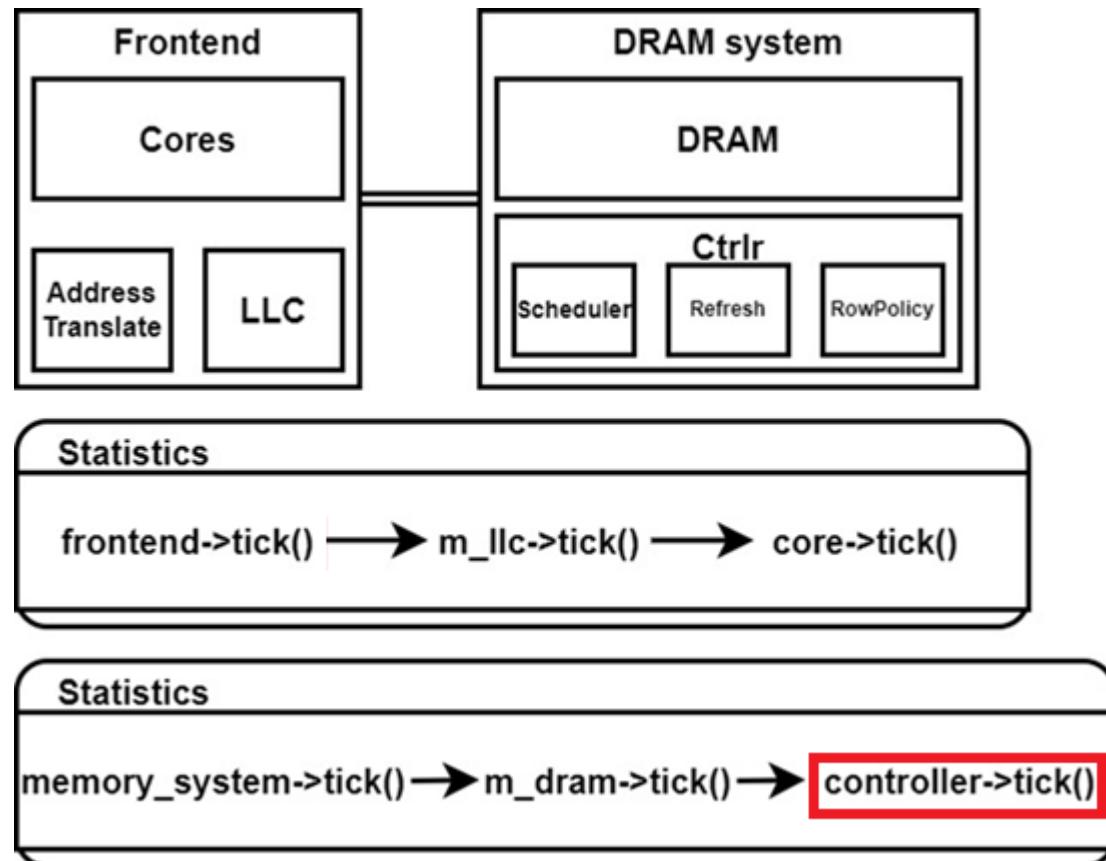
src/memory_system folder

□ memory_system

- m_memory_system – tick()

```
77    void tick() override {  
78        m_clk++;  
79        m_dram->tick();           // DRAM 내부 상태 업데이트 (리프레시, 데이터 전송 등)  
80        for (auto controller : m_controllers) {  
81            controller->tick();   // 요청 스케줄링, 커맨드 발행, 완료 처리  
82        }  
83    };
```

- m_clk (memory clk) 증가
- 아래의 순서로 Memory System 동작
- Dram tick() → Controller tick()
- Controller는 서로 다른 channel마다 존재



src/memory_system folder

□ memory_system

- **m_memory_system – tick() → m_controllers[channel_id] – tick()**

```
174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size() + m_priority_buffer.size() + pending.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads(); // Yellow box highlights this line
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve. - 스케줄링 (어떤 요청을 실행할지 결정)
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200
201     // 4. Finally, issue the commands to serve the request
202     if (request_found) {
203         // If we find a real request to serve
204         if (req_it->is_stat_updated == false) {
205             update_request_stats(req_it); // 히트/미스 통계
206         }
207
208         m_dram->issue_command(req_it->command, req_it->addr_vec);
209
210         // If we are issuing the last command, set depart clock cycle and move the request to the pending queue
211         if (req_it->command == req_it->final_command) {
212             if (req_it->type_id == Request::Type::Read) {
213                 req_it->depart = m_clk + m_dram->m_read_latency;
214                 pending.push_back(*req_it);
215             } else if (req_it->type_id == Request::Type::Write) {
216                 // TODO: Add code to update statistics
217             }
218             buffer->remove(req_it);
219         } else {
220             void serve_completed_reads() {
221                 if (pending.size()) {
222                     if (m_dram->is_dram_accessing) {
223                         pending.pop_front();
224                     } else {
225                         pending.push_back(*req_it);
226                     }
227                 }
228             }
229         }
230     }
231 }
```

1. 먼저 pending queue[0]에서 depart시간 constraint를 만족 시킨 read request를 완료 처리 함

src/memory_system folder

□ memory_system

- **m_memory_system – tick() → m_controllers[channel_id] – tick()**

```
174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size() + m_priority_buffer.size() + pending.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads();
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve.- 스케줄링 (어떤 요청을 발행할지 결정)
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200 }
```

```
201 // 4. Finally, issue the commands to serve the request
202 if (request_found) {
203     // If we find a real request to serve
204     if (req_it->is_stat_updated == false) {
205         update_request_stats(req_it); // 히트/미스 통계
206     }
207
208     m_dram->issue_command(req_it->command, req_it->addr_vec);
209
210     // If we are issuing the last command, set depart clock cycle and move the request to the pending queue
211     if (req_it->command == req_it->final_command) {
212         if (req_it->type_id == Request::Type::Read) {
213             req_it->depart = m_clk + m_dram->m_read_latency;
214             pending.push_back(*req_it);
215         } else if (req_it->type_id == Request::Type::Write) {
216             // TODO: Add code to update statistics
217         }
218         buffer->remove(req_it);
219     } else {
220         if (m_dram->m_command_meta(req_it->command).is_opening) {
221             if (m_active < 40) {
222                 void tick() {
223                     if (m_clk == m_next_refresh_cycle) {
224                         m_next_refresh_cycle += m_nrefi;
225                         for (int r = 0; r < m_num_ranks; r++) {
226                             std::vector<int> addr_vec(m_dram_org_levels, -1);
227                             addr_vec[0] = m_ctrl->m_channel_id;
228                             addr_vec[1] = r;
229                             Request req(addr_vec, m_ref_req_id);
230
231                             bool is_success = m_ctrl->priority_send(req);
232                             if (!is_success) {
233                                 throw std::runtime_error("Failed to send refresh!");
234                             }
235                         }
236                     }
237                 }
238             }
239         }
240     }
241 }
```

2. Refresh는 next_refresh_cycle에 도달할 때마다,
모든 Rank에 Refresh 요청 발행
이때, priority queue에 REFab cmd를 넣음

src/memory_system folder

□ memory_system

- `m_memory_system - tick() → m_controllers[channel_id] - tick()`

```
174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size() + m_priority_buffer.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads();
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve.- 스케줄링 (어떤 요청을 발행할지 결정)
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200 }
```

```
356     bool schedule_request(ReqBuffer::iterator& req_it, ReqBuffer*& req_buffer) {
357         bool request_found = false;
358         // 2.1 First, check the act buffer to serve requests that are already activating (avoid useless ACTs)
359         if (req_it == m_scheduler->get_best_request(m_active_buffer); req_it != m_active_buffer.end()) {
360             if (m_dram->check_ready(req_it->command, req_it->addr_vec)) {
361                 request_found = true;
362                 req_buffer = &m_active_buffer;
363             }
364         }
365
366         // 2.2 If no requests can be scheduled from the act buffer, check the rest of the buffers
367         if (!request_found) {
368             // 2.2.1 We first check the priority buffer to prioritize e.g., maintenance requests
369             if (m_priority_buffer.size() != 0) {
370                 req_buffer = &m_priority_buffer;
371                 req_it = m_priority_buffer.begin();
372                 req_it->command = m_dram->get_preq_command(req_it->final_command, req_it->addr_vec);
373
374                 request_found = m_dram->check_ready(req_it->command, req_it->addr_vec);
375                 if (!request_found & m_priority_buffer.size() != 0) {
376                     return false;
377                 }
378             }
379
380             // 2.2.2 If no request to be scheduled in the priority buffer, check the read and write buffers.
381             if (!request_found) {
382                 // Query the write policy to decide which buffer to serve
383                 set_write_mode();
384                 auto& buffer = m_is_write_mode ? m_write_buffer : m_read_buffer;
385                 if (req_it == m_scheduler->get_best_request(buffer); req_it != buffer.end()) {
386                     request_found = m_dram->check_ready(req_it->command, req_it->addr_vec);
387                     req_buffer = &buffer;
388                 }
389             }
390         }
391
392         // 2.3 If we find a request to schedule, we need to check if it will close an opened row in the active buffer.
393         if (request_found) {
394             if (m_dram->meta(req_it->command).is_closing) {
395                 auto& rowgroup = req_it->addr_vec;
396                 for (auto _it = m_active_buffer.begin(); _it != m_active_buffer.end(); _it++) {
397                     auto& _it_rowgroup = _it->addr_vec;
398                     bool is_matching = true;
399                     for (int i = 0; i < m_bank_addr_idx + 1; i++) {
400                         if (_it_rowgroup[i] != rowgroup[i] && _it_rowgroup[i] != -1 && rowgroup[i] != -1) {
401                             is_matching = false;
402                             break;
403                         }
404                     }
405                     if (is_matching) {
406                         request_found = false;
407                         break;
408                     }
409                 }
410             }
411         }
412     }
413
414     return request_found;
415 }
```

3. Request들을 Scheduling하여 적절한 Request Buffer를 buffer에 넣고, iteration pointer도 반환

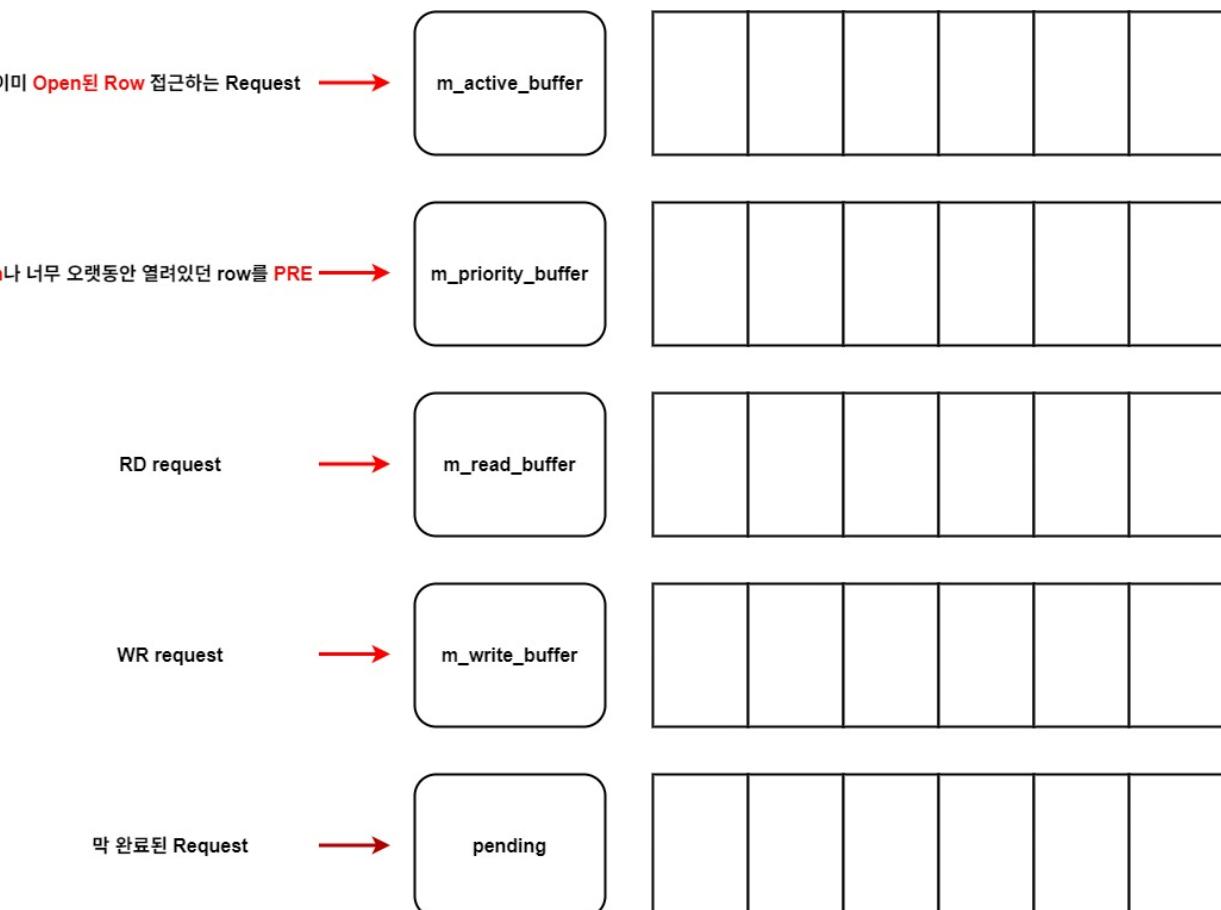
src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick() → **schedule_request(req_it, buffer)**

schedule_request()의 Buffers Review

- DRAM Controller에 존재하는 Buffer들



src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick() → schedule_request(req_it, buffer)

schedule_request()

- 3.1. 우선 순위가 가장 높은 **active buffer**를 먼저 확인 (scheduling 기법 – FRFCFS)
- 3.2. 우선 순위가 다음으로 높은 **priority buffer**를 확인 (scheduling 기법 – FRFCFS)
 - priority 요청은 순서를 깨지 않고 직렬로 처리해야 하는 유지보수성 traffic 이라고 함
 - 즉, 3.1과 3.3의 경우 get_best_request() 함수를 통해 buffer를 순회하며 적절한 req를 찾음
 - 하지만, 3.2의 경우 **priority buffer**의 첫번째 req만 확인하고, timing, preq가 안 맞으면 넘어감
- 3.3. 다음으로, write mode인지에 따라 **read or write buffer**를 확인 (scheduling 기법 – FRFCFS)
- 3.4. **active buffer**에 있는 대기중인 ACT command 중 지금 발행하려는 req와 같은 bank를 가지는 command가 있으면, request를 취소 함(같은 Bank에는 동시에 한 row만 열려 있음)

src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick() → schedule_request(req_it, buffer) → get_best_request()

3. schedule_request(req_it, buffer) ③/④/

1. schedule_request() 호출

2. Scheduler가 buffer에서 best request 선택

3. get_preq_command() 호출 ← Prerequisite 확인 (재귀적으로)

- └ Channel 레벨 preq 확인 (등록 없으면 pass)
- └ Rank 레벨 preq 확인 (REFab: RequireAllBanksClosed)
- └ BankGroup 레벨 preq 확인 (등록 없으면 pass)
- └ Bank 레벨 preq 확인 (RD/WR: RequireRowOpen)
 - └ Bank 상태가 "Refreshing"이면 ACT 반환 (실행 불가)

4. check_ready(command, addr_vec) 호출 ← Timing Constraints 확인(재귀)

- └ Channel 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ Rank 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ BankGroup 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ Bank 레벨: m_cmd_ready_clk[command] >= clk 확인
 - └ 모든 레벨 통과 → true 반환

5. request_found = true이면 issue_command() 호출

- └ update_timing() 호출 → future timing constraints 업데이트

```
41 ✓ ReqBuffer::iterator get_best_request(ReqBuffer& buffer) override {  
42 ✓     if (buffer.size() == 0) {  
43 ✓         return buffer.end();  
44 ✓     }  
45 ✓  
46 ✓     for (auto& req : buffer) {  
47 ✓         req.command = m_dram->get_preq_command(req.final_command, req.addr_vec);  
48 ✓     }  
49 ✓  
50 ✓     auto candidate = buffer.begin();  
51 ✓     for (auto next = std::next(buffer.begin(), 1); next != buffer.end(); next++) {  
52 ✓         candidate = compare(candidate, next);  
53 ✓     }  
54 ✓     return candidate;  
55 ✓ }  
56 ✓
```

```
22 ✓ ReqBuffer::iterator compare(ReqBuffer::iterator req1, ReqBuffer::iterator req2) override {  
23 ✓     bool ready1 = m_dram->check_ready(req1->command, req1->addr_vec);  
24 ✓     bool ready2 = m_dram->check_ready(req2->command, req2->addr_vec);  
25 ✓  
26 ✓     if (ready1 ^ ready2) {  
27 ✓         if (ready1) {  
28 ✓             return req1;  
29 ✓         } else {  
30 ✓             return req2;  
31 ✓         }  
32 ✓     }  
33 ✓  
34 ✓     // Fallback to FCFS  
35 ✓     if (req1->arrive <= req2->arrive) {  
36 ✓         return req1;  
37 ✓     } else {  
38 ✓         return req2;  
39 ✓     }  
40 ✓ }
```

compare()

- Ready가 아니면 Ready인 것
- 둘 다 Ready이면 FCFS

src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick() → schedule_request(req_it, buffer) → get_best_request() → get_preq_command()

3. schedule_request(req_it, buffer) 0/x/

1. schedule_request() 호출

2. Scheduler가 buffer에서 best request 선택

3. get_preq_command() 호출 ← Prerequisite 확인 (재귀적으로)

- └ Channel 레벨 preq 확인 (등록 없으면 pass)
- └ Rank 레벨 preq 확인 (REFab: RequireAllBanksClosed)
- └ BankGroup 레벨 preq 확인 (등록 없으면 pass)
- └ Bank 레벨 preq 확인 (RD/WR: RequireRowOpen)
 - └ Bank 상태가 "Refreshing"이면 ACT 반환 (실행 불가)

4. check_ready(command, addr_vec) 호출 ← Timing Constraints 확인(재귀)

- └ Channel 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ Rank 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ BankGroup 레벨: m_cmd_ready_clk[command] >= clk 확인
- └ Bank 레벨: m_cmd_ready_clk[command] >= clk 확인
 - └ 모든 레벨 통과 → true 반환

5. request_found = true이면 issue_command() 호출

- └ update_timing() 호출 → future timing constraints 업데이트

```
190  int get_preq_command(int command, const AddrVec_t& addr_vec, Clk_t m_clk) {  
191      int child_id = addr_vec[m_level + 1];  
192      if (m_spec->m_preqs[m_level][command]) {  
193          int preq_cmd = m_spec->m_preqs[m_level][command](static_cast<NodeType*>(this), command, addr_vec, m_clk);  
194          if (preq_cmd != -1) {  
195              // stop recursion: there is a prerequisite at this level  
196              return preq_cmd;  
197          }  
198      }  
199      if (!m_child_nodes.size()) {  
200          // stop recursion: there were no prerequisites at any level  
201          return command;  
202      }  
203      // recursively get preq command at my child  
204      return m_child_nodes[child_id]->get_preq_command(command, addr_vec, m_clk);  
205  };  
206  
```

재귀

```
511  void set_preqs() {  
512      m_preqs.resize(m_levels.size(), std::vector<PreqFunc_t<Node>>(m_commands.size()));  
513      // Rank Actions  
514      m_preqs[m_levels["rank"]][m_commands["REFab"]] = Lambdas::Preq::Rank::RequireAllBanksClosed<DDR4>;  
515      // Bank actions  
516      m_preqs[m_levels["bank"]][m_commands["RD"]] = Lambdas::Preq::Bank::RequireRowOpen<DDR4>;  
517      m_preqs[m_levels["bank"]][m_commands["WR"]] = Lambdas::Preq::Bank::RequireRowOpen<DDR4>;  
518      m_preqs[m_levels["bank"]][m_commands["ACT"]] = Lambdas::Preq::Bank::RequireRowOpen<DDR4>;  
519      m_preqs[m_levels["bank"]][m_commands["PRE"]] = Lambdas::Preq::Bank::RequireBankClosed<DDR4>;  
520  };  
521  
```

src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick() → schedule_request(req_it, buffer) → check_ready()

3. schedule_request(req_it, buffer) 0/x/

1. schedule_request() 호출

2. Scheduler가 buffer에서 best request 선택

3. get_preq_command() 호출 ← Prerequisite 확인 (재귀적으로)

└─ Channel 레벨 preq 확인 (등록 없으면 pass)

└─ Rank 레벨 preq 확인 (REFab: RequireAllBanksClosed)

└─ BankGroup 레벨 preq 확인 (등록 없으면 pass)

└─ Bank 레벨 preq 확인 (RD/WR: RequireRowOpen)

 └─ Bank 상태가 "Refreshing"이면 ACT 반환 (실행 불가)

4. check_ready(command, addr_vec) 호출 ← Timing Constraints 확인(재귀)

└─ Channel 레벨: m_cmd_ready_clk[command] >= clk 확인

└─ Rank 레벨: m_cmd_ready_clk[command] >= clk 확인

└─ BankGroup 레벨: m_cmd_ready_clk[command] >= clk 확인

└─ Bank 레벨: m_cmd_ready_clk[command] >= clk 확인

 └─ 모든 레벨 통과 → true 반환

5. request_found = true이면 issue_command() 호출

 └─ update_timing() 호출 → future timing constraints 업데이트

```
250     bool check_ready(int command, const AddrVec_t& addr_vec) override {
251         int channel_id = addr_vec[m_levels["channel"]];
252         return m_channels[channel_id]->check_ready(command, addr_vec, m_clk);
253     };
209     bool check_ready(int command, const AddrVec_t& addr_vec, Clk_t clk) {
210         if (m_cmd_ready_clk[command] != -1 && clk < m_cmd_ready_clk[command]) {
211             // stop recursion: the check failed at this level
212             return false;
213         }
214
215         int child_id = addr_vec[m_level+1];
216         if (m_level == m_spec->m_command_scopes[command] || !m_child_nodes.size()) {
217             // stop recursion: the check passed at all levels
218             return true;
219         }
220
221         if (child_id == -1) {
222             // if it is a same bank command, recurse all children in rank level
223             bool ready = true;
224             for (auto child : m_child_nodes) {
225                 ready = ready && child->check_ready(command, addr_vec, clk);
226             }
227             return ready;
228         } else {
229             // recursively check my child
230             return m_child_nodes[child_id]->check_ready(command, addr_vec, clk);
231         }
232     };

```

재귀

src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick()

3. schedule_request(req_it, buffer) ③/④

1. schedule_request() 호출

2. Scheduler가 buffer에서 best request 선택

3. get_preq_command() 호출 ← Prerequisite 확인 (재귀적으로)

- Channel 레벨 preq 확인 (등록 없으면 pass)
- Rank 레벨 preq 확인 (REFab: RequireAllBanksClosed)
- BankGroup 레벨 preq 확인 (등록 없으면 pass)
- Bank 레벨 preq 확인 (RD/WR: RequireRowOpen)
 - Bank 상태가 "Refreshing"이면 ACT 반환 (실행 불가)

4. check_ready(command, addr_vec) 호출 ← Timing Constraints 확인(재귀)

- Channel 레벨: m_cmd_ready_clk[command] >= clk 확인
- Rank 레벨: m_cmd_ready_clk[command] >= clk 확인
- BankGroup 레벨: m_cmd_ready_clk[command] >= clk 확인
- Bank 레벨: m_cmd_ready_clk[command] >= clk 확인
 - 모든 레벨 통과 → true 반환

5. schedule_request의 return값: request_found = true이면 issue_command() 호출

- update_timing() 호출 → future timing constraints 업데이트

```
201 // 4. Finally, issue the commands to serve the request
202 if (request_found) {
203     // If we find a real request to serve
204     if (req_it->is_stat_updated == false) {
205         update_request_stats(req_it); // 히트/미스 통계
206     }
207     m_dram->issue_command(req_it->command, req_it->addr_vec)
208 }
```

```
210 void issue_command(int command, const AddrVec_t& addr_vec) override {
211     int channel_id = addr_vec[m_levels["channel"]];
212     m_channels[channel_id]->update_timing(command, addr_vec, m_clk);
213     m_channels[channel_id]->update_powers(command, addr_vec, m_clk);
214     m_channels[channel_id]->update_states(command, addr_vec, m_clk);
215
216     // Check if the command requires future action
217     check_future_action(command, addr_vec);
218 }
```

src/memory_system folder

□ memory_system

- **m_memory_system – tick() → m_controllers[channel_id] – tick()**

```
174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads();
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve. - 스케줄링 (어떤 요청?
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200 }
```

```
void update(bool request_found, ReqBuffer::iterator& req_it) override {
    if (!request_found)
        return;

    if (m_dram->m_command_meta(req_it->command).is_closing ||
        m_dram->m_command_meta(req_it->command).is_refreshing) // PRE or REF
    {
        // All Bank Closes (PREF, REFab, PRE) - 서로 다른 명령어에 의해 case가 나뉨
        if (req_it->addr_vec[m_bankgroup_level] == -1 && req_it->addr_vec[m_bank_level] == -1) { // all bank closes
            // 모든 Bank의 카운터를 0으로 리셋
            for (int b = 0; b < m_num_banks; b++) {
                for (int bg = 0; bg < m_num_bankgroups; bg++) {
                    int rank_id = req_it->addr_vec[m_rank_level];
                    int flat_bank_id = b + bg * m_num_banks + rank_id * m_num_banks * m_num_bankgroups;
                    m_col_accesses[flat_bank_id] = 0;
                }
            }
        }
        else if (req_it->addr_vec[m_bankgroup_level] == -1) { // same bank closes
            // 동일한 Bank 번호를 가진 모든 BankGroup의 카운터 리셋
            for (int bg = 0; bg < m_num_bankgroups; bg++) {
                int bank_id = req_it->addr_vec[m_bank_level];
                int rank_id = req_it->addr_vec[m_rank_level];
                int flat_bank_id = bank_id + bg * m_num_banks + rank_id * m_num_banks * m_num_bankgroups;
                m_col_accesses[flat_bank_id] = 0;
            }
        }
        else { // single bank closes (PRE, VRR, RDA, WRA) - Read + Auto-Prefetch / Write + Auto-Prefetch
            // 단일 Bank만 닫음
            int flat_bank_id = req_it->addr_vec[m_bank_level] +
                req_it->addr_vec[m_bankgroup_level] * m_num_banks +
                req_it->addr_vec[m_rank_level] * m_num_banks * m_num_bankgroups;

            m_col_accesses[flat_bank_id] = 0;
        }
    }
    else if (m_dram->m_command_meta(req_it->command).is_accessing) // RD or WR - Accessing 명령 (RD, WR)
    {
        int flat_bank_id = req_it->addr_vec[m_bank_level] +
            req_it->addr_vec[m_bankgroup_level] * m_num_banks +
            req_it->addr_vec[m_rank_level] * m_num_banks * m_num_bankgroups;

        m_col_accesses[flat_bank_id]++;
        // 카운터 증가
        if (m_col_accesses[flat_bank_id] >= m_cap) {
            // Cap 초과 → 강제로 PRE 요청 발행
            Request req(req_it->addr_vec, m_PRE_req_id);
            m_ctrl->priority_send(req);
            m_col_accesses[flat_bank_id] = 0;
            s_num_close_reqs++;
        }
    }
}
```

basic_rowpolicies.cpp → update()

```
220     if (m_active_buffer.enqueue(req_it))
221         buffer->remove(req_it);
222     }
223     }
224     }
225     }
226     }
227     }
228     }
229 }
```

4. Row Policy를 적용 (update) → 특정 column이 너무 오랫동안 open되어 있으면 PRE(close명령)을 priority queue에 넣음

5. Plugin을 적용 (update)

src/memory_system folder

□ memory_system

- m_memory_system – tick() → m_controllers[channel_id] – tick()

```

174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size() + m_priority_buffer.size() + pending.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads();
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve..- 스케줄링 (어떤 요청을 발행할지 결정)
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200
201
202
203
204
205
206
207
208
209
210
211
212
213
214
215
216
217
218
219
220
221
222
223
224
225
226
227
228
229

```

6. Statistics를 update함

7. Scheduling이 완료된 Request를 issue하고

8.1. 해당 Request의 current command가 last command이면, pending buffer에 넣음

8.2. 해당 Request의 current command가 last command가 아니고, row를 open하면, active buffer에 넣음

```

256     void update_request_stats(ReqBuffer::iterator& req) {
257     {
258         req->is_stat_updated = true;
259
260         if (req->type_id == Request::Type::Read) {
261             if (is_row_hit(req)) {
262                 s_read_row_hits++;
263                 s_row_hits++;
264                 if (req->source_id != -1)
265                     s_read_row_hits_per_core[req->source_id]++;
266             } else if (is_row_open(req)) {
267                 s_read_row_conflicts++;
268                 s_row_conflicts++;
269                 if (req->source_id != -1)
270                     s_read_row_conflicts_per_core[req->source_id]++;
271             } else {
272                 s_read_row_misses++;
273                 s_row_misses++;
274                 if (req->source_id != -1)
275                     s_read_row_misses_per_core[req->source_id]++;
276             }
277         }
278     }

```

// 4. Finally, issue the commands to serve the request

```

if (request_found) {
    // If we find a real request to serve
    if (req_it->is_stat_updated == false) {
        update_request_stats(req_it); // 히트/미스 통계
    }
    m_dram->issue_command(req_it->command, req_it->addr_vec);
}

```

// If we are issuing the last command, set depart clock cycle and move the request to the pending queue

```

if (req_it->command == req_it->final_command) {
    if (req_it->type_id == Request::Type::Read) {
        req_it->depart = m_clk + m_dram->m_read_latency;
        pending.push_back(*req_it);
    } else if (req_it->type_id == Request::Type::Write) {
        // TODO: Add code to update statistics
    }
    buffer->remove(req_it);
} else {
    if (m_dram->m_command_meta(req_it->command).is_opening) {
        if (m_active_buffer.enqueue(*req_it)) {
            buffer->remove(req_it);
        }
    }
}

```

```

93     inline static const ImplLUT m_command_meta = LUT<DRAMCommandMeta>(
94         m_commands, {
95             { "ACT", { true, false, false, false } },
96             { "PRE", { false, true, false, false } },
97             { "PRAE", { false, true, false, false } },
98             { "RD", { false, false, true, false } },
99             { "WR", { false, false, true, false } },
100            { "RDA", { false, true, true, false } },
101            { "WRA", { false, true, true, false } },
102            { "REFab", { false, false, false, true } },
103            { "REFab_end", { false, true, false, false } },
104        }
105    );

```

src/memory_system folder

memory_system

- **m_memory_system - tick()** → **m_controllers[channel_id] - tick()**

```
174 void tick() override {
175     m_clk++;
176
177     // Update statistics
178     s_queue_len += m_read_buffer.size() + m_write_buffer.size() + m_priority_buffer.size() + pending.size();
179     s_read_queue_len += m_read_buffer.size() + pending.size();
180     s_write_queue_len += m_write_buffer.size();
181     s_priority_queue_len += m_priority_buffer.size();
182
183     // 1. Serve completed reads - 완료된 읽기 요청 처리
184     serve_completed_reads();
185
186     m_refresh->tick(); // 리프레시 관리
187
188     // 2. Try to find a request to serve.- 스케줄링 (어떤 요청을 발행할지 결정)
189     ReqBuffer::iterator req_it;
190     ReqBuffer* buffer = nullptr;
191     bool request_found = schedule_request(req_it, buffer);
192
193     // 2.1 Take row policy action
194     m_rowpolicy->update(request_found, req_it);
195
196     // 3. Update all plugins
197     for (auto plugin : m_plugins) {
198         plugin->update(request_found, req_it);
199     }
200
201     // 4. Finally, issue the commands to serve the request
202     if (request_found) {
203         // If we find a real request to serve
204         if (req_it->is_stat_updated == false) {
205             update_request_stats(req_it); // 히트/미스 통계
206         }
207
208         m_dram->issue_command(req_it->command, req_it->addr_vec);
209
210         void issue_command(int command, const AddrVec_t& addr_vec) override {
211             int channel_id = addr_vec[m_levels["channel"]];
212             m_channels[channel_id]->update_timing(command, addr_vec, m_clk);
213             m_channels[channel_id]->update_powers(command, addr_vec, m_clk);
214             m_channels[channel_id]->update_states(command, addr_vec, m_clk);
215
216             // Check if the command requires future action
217             check_future_action(command, addr_vec);
218         };
219
220         // If we are issuing the last command, set depart clock cycle and move the request to the pending queue
221         if (req_it->command == req_it->final_command) {
222             if (req_it->type_id == Request::Type::Read) {
223                 req_it->depart = m_clk + m_dram->m_read_latency;
224                 pending.push_back(*req_it);
225             } else if (req_it->type_id == Request::Type::Write) {
226                 // TODO: Add code to update statistics
227             }
228             buffer->remove(req_it);
229         } else {
230             if (m_dram->m_command_meta(req_it->command).is_opening) {
231                 if (m_active_buffer.enqueue(*req_it)) {
232                     buffer->remove(req_it);
233                 }
234             }
235         }
236     }
237
238     inline static const ImplUT m_command_scopes = LUT (
239         m_commands, m_levels,
240         {"ACT", "row"},
```

- issue command 동작

- 해당 명령어를 기준으로 command scope별 timing constraints를 갱신
 - 해당 명령어를 기준으로 재귀적으로 command scope별 power counter 갱신
 - 해당 명령어를 기준으로 재귀적으로 command scope별 state 갱신

src/memory_system folder

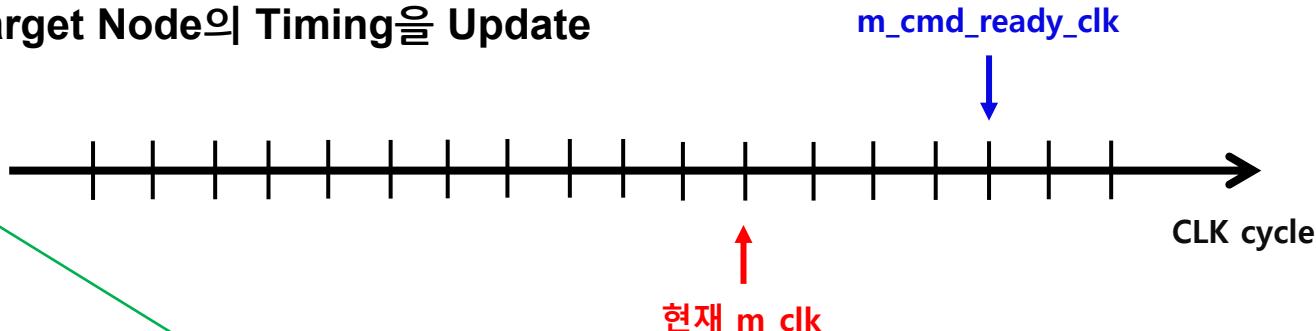
□ DRAM Issue Command

- m_memory_system - tick() → m_controllers[channel_id] - tick() → m_dram->issue_command(req_it->command, req_it->addr_vec)

```
210 void issue_command(int command, const AddrVec_t& addr_vec) override {
211     int channel_id = addr_vec[m_levels["channel"]];
212     m_channels[channel_id]->update_timing(command, addr_vec, m_clk);
213     m_channels[channel_id]->update_powers(command, addr_vec, m_clk);
214     m_channels[channel_id]->update_states(command, addr_vec, m_clk);
215
216     // Check
217     check_fu();
218 }
219
220 void update_timing(int command, const AddrVec_t& addr_vec, Clk_t clk) {
221
222     /* Update Sibling Node Timing */
223     if (m_node_id != addr_vec[m_level] && addr_vec[m_level] != -1) {
224         for (const auto& t : m_spec->m_timing_cons[m_level][command]) {
225             if (!t.sibling) {
226                 continue;
227             }
228
229             // update earliest schedulable time of every command
230             Clk_t future = clk + t.val;
231             m_cmd_ready_clk[t.cmd] = std::max(m_cmd_ready_clk[t.cmd], future);
232         }
233         // stop recursion
234         return;
235     }
236
237     /* Update Target Node Timing */
238     // update history
239     if (m_cmd_history[command].size()) {
240         m_cmd_history[command].pop_back();
241         m_cmd_history[command].push_front(clk);
242     }
243
244     for (const auto& t : m_spec->m_timing_cons[m_level][command]) {
245         if (t.sibling) {
246             continue;
247         }
248
249         // Get the oldest history
250         Clk_t past = m_cmd_history[command][t.window-1];
251         if (past < 0) {
252             // not enough history
253             continue;
254         }
255
256         // update earliest schedulable time of every command
257         Clk_t future = past + t.val;
258         m_cmd_ready_clk[t.cmd] = std::max(m_cmd_ready_clk[t.cmd], future);
259     }
260
261     if (!m_child_nodes.size()) {
262         // stop recursion: updated all levels
263         return;
264     }
265
266     // recursively update all of my children
267     for (auto child : m_child_nodes) {
268         child->update_timing(command, addr_vec, clk);
269     }
270 }
```

• update_timing()

- 1. Sibling Node를 Update (Sibling Node ex. 각 Rank에 존재하는 BankGroup)
- 2. 현재 Target Node의 Timing을 Update



NOTE

- 현재 Target Node를 Update 시,
- 마지막에서 Target Node의 Children들을 순회하며,
- 재귀적으로 update_timing()함수를 호출
- Sibling Node들에서도 update_timing()함수가 호출된다.

src/memory_system folder

□ DRAM Issue Command

- m_memory_system – tick() → m_controllers[channel_id] – tick() → m_dram->issue_command(req_it->command, req_it->addr_vec)

```
210 void issue_command(int command, const AddrVec_t& addr_vec) override {
211     int channel_id = addr_vec[m_levels["channel"]];
212     m_channels[channel_id]->update_timing(command, addr_vec, m_clk);
213     m_channels[channel_id]->update_powers(command, addr_vec, m_clk);
214     m_channels[channel_id]->update_states(command, addr_vec, m_clk);
215
216     void update_powers(int command, const AddrVec_t& addr_vec, Clk_t clk) {
217         if (!m_spec->m_drampower_enable)
218             return;
219
220         int child_id = addr_vec[m_level+1];
221         if (m_spec->m_powers[m_level][command]) {
222             // update the power model at this level
223             m_spec->m_powers[m_level][command](static_cast<NodeType*>(this), command, addr_vec, clk);
224         }
225         if (m_level == m_spec->m_command_scopes[command] || !m_child_nodes.size()) {
226             // stop recursion: updated all levels
227             return;
228         }
229         // recursively update child nodes
230         if (child_id == -1){
231             for (auto child : m_child_nodes) {
232                 child->update_powers(command, addr_vec, clk);
233             }
234         } else {
235             m_child_nodes[child_id]->update_powers(command, addr_vec, clk);
236         }
237     };
238
239     template <class T>
240     void ACT(typename T::Node* node, int cmd, const AddrVec_t& addr_vec, Clk_t clk) {
241         Rank::debug<T>(node, "-----ACT-----", clk);
242         auto& cur_power_stats = node->m_spec->m_power_stats[Rank::get_flat_rank_id<T>(node)];
243         bool is_rank_idle = get_open_bank_count<T>(node) == 0 && get_refreshing_bank_count<T>(node);
244
245         if (is_rank_idle) {
246             cur_power_stats.idle_cycles += clk - cur_power_stats.idle_start_cycle;
247             cur_power_stats.active_start_cycle = clk;
248             std::string msg = "Rank is idle. idle cycles: " + std::to_string(cur_power_stats.idle_rank::debug<T>(node, msg, clk));
249             cur_power_stats.cur_power_state = PowerStats::PowerState::ACTIVE;
250         }
251
252     }
253
254     template <class T>
255     void PRE(typename T::Node* node, int cmd, const AddrVec_t& addr_vec, Clk_t clk) {
256         Rank::debug<T>(node, "-----PRE-----", clk);
257         auto& cur_power_stats = node->m_spec->m_power_stats[Rank::get_flat_rank_id<T>(node)];
258         bool is_rank_going_idle = get_open_bank_count<T>(node) == 1 && get_refreshing_bank_count<T>(node);
259
260         if (is_rank_going_idle) {
261             cur_power_stats.active_cycles += clk - cur_power_stats.active_start_cycle;
262             cur_power_stats.idle_start_cycle = clk;
263             std::string msg = "Rank is going idle. active cycles: " + std::to_string(cur_power_stats.idle_rank::debug<T>(node, msg, clk));
264         }
265     }
266 }
```

- update_powers()

- 현재 Target Node의 Power를 Update

- Children의 경우 Children의 id == -1이면 모든 Childs의 Power를 Update
 - Children의 id != -1이면 Target Child만 Power를 Update
 - Update: cmd_counters[]를 increment시킴으로써, 나중에 Power계산에 사용

[Example]

PREA(Precharge All) Command의 경우

- Scope = “Rank” → addr_vec = [0, 1, -1, -1, -1, -1]

1. Channel Node

→ child_id = addr_vec[1] = 1

2. Rank 1 Node

→ child_id = addr_vec[2] = -1

→ 모든 BankGroup(0~3)에 재구

3. 각 BankGroup Node

→ child_id = addr_vec[3] = -1

→ 모든 Bank(0~3)에 재구

src/memory_system folder

□ DRAM Issue Command

- m_memory_system – tick() → m_controllers[channel_id] – tick() → m_dram->issue_command(req_it->command, req_it->addr_vec)

```
210 void issue_command(int command, const AddrVec_t& addr_vec) override {
211     int channel_id = addr_vec[m_levels["channel"]];
212     m_channels[channel_id]->update_timing(command, addr_vec, m_clk);
213     m_channels[channel_id]->update_powers(command, addr_vec, m_clk);
214     m_channels[channel_id]->update_states(command, addr_vec, m_clk);
215
216     // Check if the command requires future action
217     check_future_action(command, addr_vec);
218
219 void update_states(int command, const AddrVec_t& addr_vec, CLK_t clk) {
220     int child_id = addr_vec[m_level+1];
221     if (m_spec->m_actions[m_level][command]) {
222         // update the state machine at this level
223         m_spec->m_actions[m_level][command](static_cast<NodeType*>(this), command, child_id, clk);
224     }
225     if (m_level == m_spec->m_command_scopes[command] || !m_child_nodes.size()) {
226         // stop recursion: update
227         return;
228     }
229     // recursively update children
230     if (child_id == -1) {
231         for (auto child : m_child_nodes) {
232             child->update_states();
233         }
234     } else {
235         m_child_nodes[child_id];
236     }
237 }
238
239 template <class T>
240 void ACT(typename T::Node* node, int cmd, int target_id, CLK_t clk) {
241     node->m_state = T::m_states["Opened"];
242     node->m_row_state[target_id] = T::m_states["Opened"];
243 }
244
245 template <class T>
246 void PRE(typename T::Node* node, int cmd, int target_id, CLK_t clk) {
247     node->m_state = T::m_states["Closed"];
248     node->m_row_state.clear();
249 }
250
251 template <class T>
252 void VRR(typename T::Node* node, int cmd, int target_id, CLK_t clk) {
253     node->m_state = T::m_states["Refreshing"];
254 }
255
256 template <class T>
257 void VRR_end(typename T::Node* node, int cmd, int target_id, CLK_t clk) {
258     node->m_state = T::m_states["Closed"];
259 }
260
261 }
262 // namespace Bank
263
264 namespace BankGroup {
265     template <class T>
266     void PRESb(typename T::Node* node, int cmd, int target_id, CLK_t clk) {
267         if (cmd == ACT) {
268             node->m_state = T::m_states["Opened"];
269             node->m_row_state[target_id] = T::m_states["Opened"];
270         }
271     }
272 }
```

- update_states()

- 현재 Target Node의 States를 Update
 - Children의 경우 Children의 id == -1이면 모든 Childs의 State를 Update
 - Children의 id != -1이면 Target Child만 State를 Update
 - Update: node->m_state를 변경함.
 - node->m_state는 get_preq_command()에서 pre-requirement을 확인하는데 사용됨

ACT (ch0/rk1/bg2/bk3/row1234) → addr_vec: [0,1,2,3,1234,57]

1. Channel(level0,id0)
 - No Action, scope=row 미도달
 - child_id=1로 rank1으로만 내려감
2. Rank(level1,id1)
 - No Action, scope = row 미도달
 - child_id=2로 bg2으로만 내려감
3. BankGroup(level2,id2)
 - No Action, scope = row 미도달
 - child_id=3로 bk3으로만 내려감.
4. Bank(level3,id3): Bank::ACT 실행
 - state=Opened, row_state[1234]=Opened
 - scope=row지만 row Node가 없어서 bank에서 Action 후 종료

yaml/trace file for direct Read/Write Request

- example_config_dram.yaml & example_dram.trace & readwrite_trace.cpp

```
! example_config_dram.yaml
1 Frontend:
2   impl: ReadWriteTrace
3   path: example_dram.trace # trace 파일 경로 (상대/절대)
4   clock_ratio: 1
5
6 Translation:
7   impl: RandomTranslation
8   max_addr: 2147483648
9
10
11 MemorySystem:
12   impl: GenericDRAM
13   clock_ratio: 1
14
15 DRAM:
16   impl: DDR4
17   org:
18     preset: DDR4_8Gb_x8
```

```
! example_dram.trace
1 R 0,0,0,0,0
2 W 0,0,0,0,128
3 R 0,0,0,1,0
4 W 0,0,0,1,256
5 R 0,0,1,0,0
6 W 0,0,1,0,512
7 R 0,0,0,1024,0
8 W 0,0,0,1024,0
9
```

```
39 void tick() override {
40   const Trace& t = m_trace[m_curr_trace_idx];
41   m_memory_system->send({t.addr_vec, t.is_write ? Request::Type::Write : Request::Type::Read});
42   // m_curr_trace_idx = (m_curr_trace_idx + 1) % m_trace_length;
43   m_curr_trace_idx++; // revised by MinsungKim yonsei ISL lab - 2026.01.09.
44 }
```

- Trace file을 arg로 받아, Frontend (ex: readwrite_trace.cpp)에서 처리되어 메모리 접근 request를 생성
- Read-Write Trace: This frontend expects a trace file containing read (R) or store (W) requests with a DRAM address vector (i.e., which channel, rank, bank, row, column). Each line in the trace has the following format: R/W <comma-separated addr vector>:

yaml/trace file for direct Read/Write Request

□ Simulation Result

```
Frontend:  
  impl: ReadWriteTrace  
  
MemorySystem:  
  impl: GenericDRAM  
  total_num_other_requests: 0  
  total_num_write_requests: 4  
  total_num_read_requests: 4  
  memory_system_cycles: 7  
DRAM:  
  impl: DDR4  
AddrMapper:  
  impl: RoBaRaCoch  
  
Controller:  
  impl: Generic  
  id: channel 0  
  avg_read_latency_0: 4.5  
  read_queue_len_avg_0: 0.571428597  
  write_queue_len_0: 12  
  queue_len_0: 16  
  num_other_reqs_0: 0  
  num_write_reqs_0: 4  
  read_latency_0: 18  
  priority_queue_len_avg_0: 0  
  row_hits_0: 0  
  priority_queue_len_0: 0  
  row_misses_0: 1  
  row_conflicts_0: 0  
  read_row_misses_0: 1  
  queue_len_avg_0: 2.28571439  
  read_row_conflicts_core_0: 0  
  read_row_hits_0: 0  
  write_queue_len_avg_0: 1.71428573  
  read_row_conflicts_0: 0  
  write_row_misses_0: 0  
  write_row_conflicts_0: 0  
  read_queue_len_0: 4  
  write_row_hits_0: 0  
  read_row_hits_core_0: 0  
  read_row_misses_core_0: 0  
  num_read_reqs_0: 4  
Scheduler:  
  impl: FRFCFS  
RefreshManager:  
  impl: AllBank  
  
RowPolicy:  
  impl: ClosedRowPolicy  
  num_close_reqs: 0
```

결과가 나오긴하는데 말이 안되는 수치를 가짐

Currently, Ramulator 2 implements the following three frontends:

- **Memory Trace Frontend:** This frontend reads an input trace file that contains *main memory requests* of an application. It *sequentially* sends these requests to the memory system. **This mode does not model any system in sufficient detail to perform timing simulations.** Because of that, the Memory Trace Frontend is better suited for testing/debugging the functionality of newly added features. In the main tasks of this assignment, we will *not* use this frontend. Still, feel free to use this mode to test and debug your newly implemented features. Currently, Ramulator 2 implements the following two memory trace frontends:

- **Ramulator2.0은 Read/Write Request의 functionality만 검증**
- **Cycle Accurate하지 않음**

yaml/trace file for direct Read/Write Request

□ Simulation Result of Ramulator1.0

The screenshot shows a code editor interface with two main panes. The left pane displays the contents of a 'dram.trace' file, which contains memory access logs:

Index	Address	Type
1	0x12345680	R
2	0x4cbd56c0	W
3	0x35d46f00	R
4	0x696fed40	W
5	0x7876af80	R
6		

The right pane displays the contents of a 'DDR3.stats' file, which contains performance metrics:

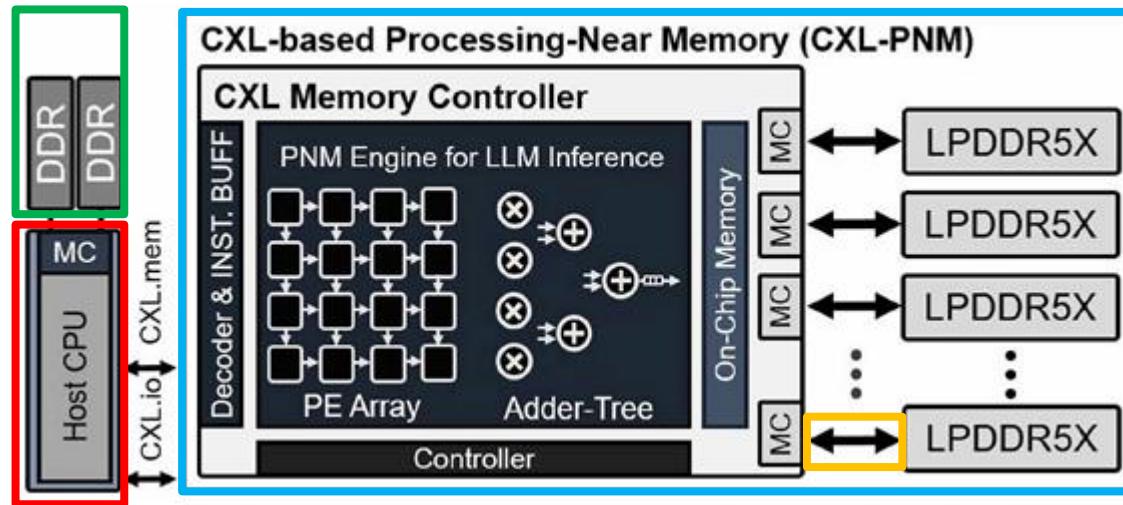
Index	Metric	Value
1	ramulator.active_cycles_0	57
2	ramulator.busy_cycles_0	57
3	ramulator.serving_requests_0	148
4	ramulator.average_serving_requests_0	2.551724
5	ramulator.active_cycles_0_0	57
6	ramulator.busy_cycles_0_0	57
7	ramulator.serving_requests_0_0	148
8	ramulator.average_serving_requests_0_0	2.551724
9	ramulator.active_cycles_0_0_0	0
10	ramulator.busy_cycles_0_0_0	0
11	ramulator.serving_requests_0_0_0	0
12	ramulator.average_serving_requests_0_0_0	0.000000
13	ramulator.active_cycles_0_0_1	0
14	ramulator.busy_cycles_0_0_1	0
15	ramulator.serving_requests_0_0_1	0
16	ramulator.average_serving_requests_0_0_1	0.000000
17	ramulator.active_cycles_0_0_2	49
18	ramulator.busy_cycles_0_0_2	49
19	ramulator.serving_requests_0_0_2	49
20	ramulator.average_serving_requests_0_0_2	0.844828
21	ramulator.active_cycles_0_0_3	43
22	ramulator.busy_cycles_0_0_3	43
23	ramulator.serving_requests_0_0_3	43
24	ramulator.average_serving_requests_0_0_3	0.741379

Ramulator1.0은 납득할 수준의 결과가 나옴

Ramulator2.0의 전체 시스템을 끝까지 리뷰 후 Ramulator1.0의 DRAM subsystem만 simulation한 결과를 바탕으로 다시 분석 예정

How about PIM?

□ CXL-PNM



Maybe LPDDR5X PHY interface???

→ 근데 이 interface를 그대로 사용하면, 어디서 PNM의 이점이 존재하는 것인지?

→ 기존 폰 노이만 구조보다는 거리가 짧아져서 Power가 줄겠지만, 큰 차이가 없을 것 같은데?

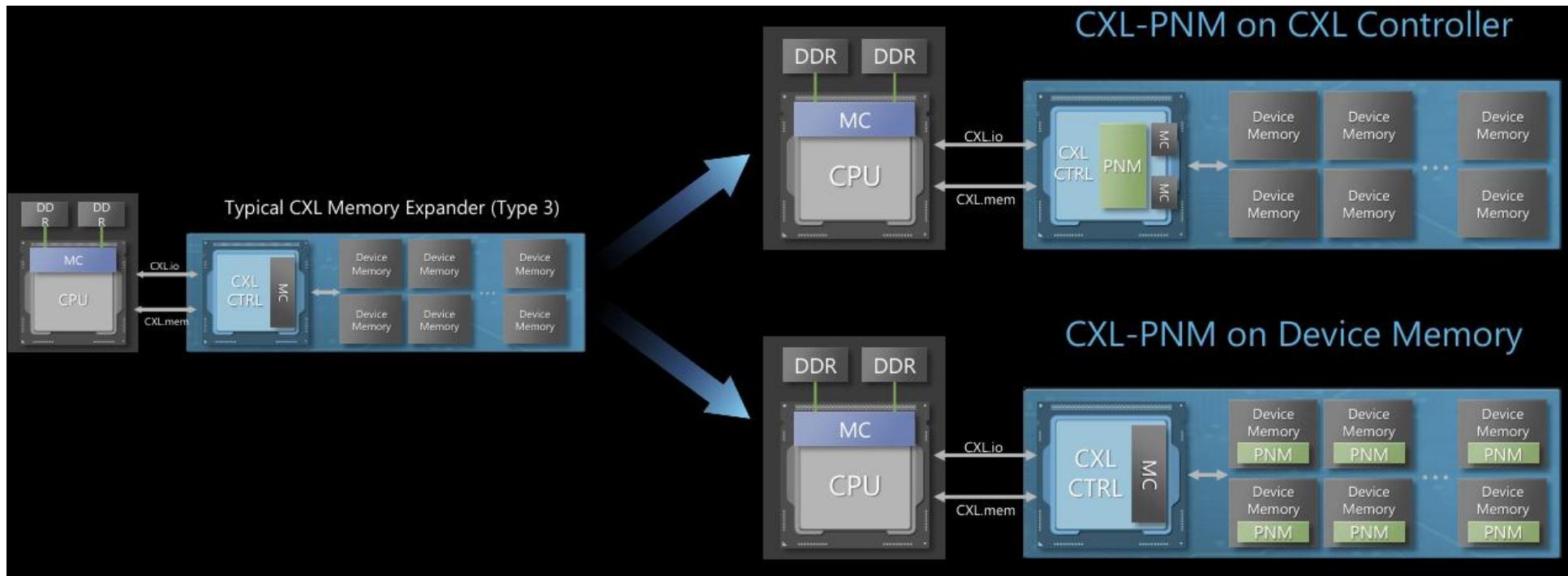
Main Memory \leftrightarrow CPU \leftrightarrow PNM
CXL

- PNM:
 - PE Array
 - On-Chip Memory (SRAM & Registers)
 - Instruction Buffer & Logic Controller
 - MC: Memory Controller
 - DDR

How about PIM?

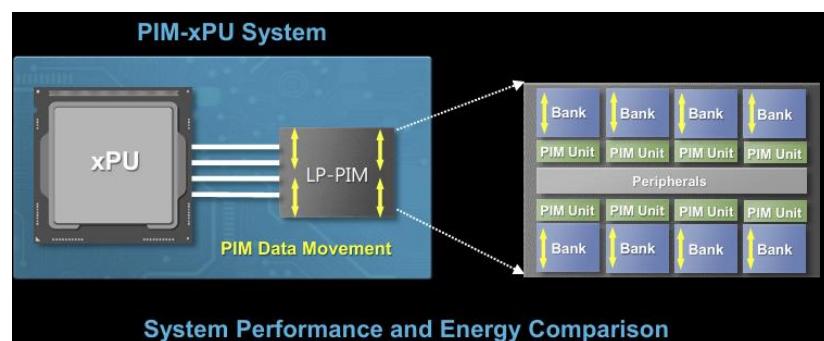
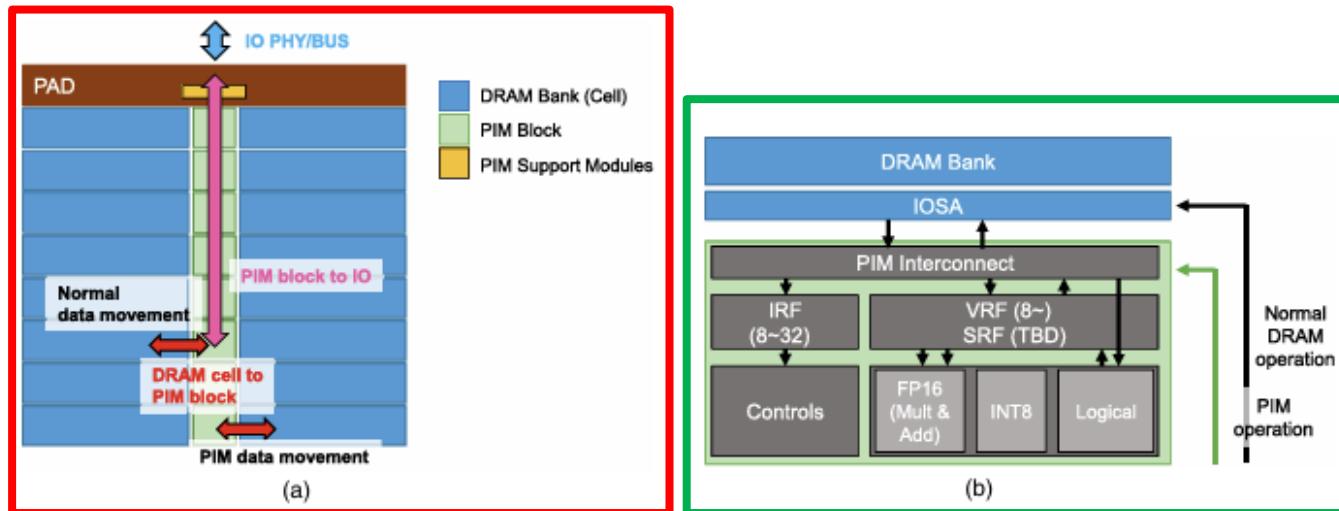
❑ CXL-PNM

- 2 Types of CXL-PNM



How about PIM?

□ LPDDR-PIM



Hotchips 2023에서 Bank 2개당 PU 1개를 Bank 1개당 PU 1개로 두면 Performance 증가한다고 함.
이는 연산 Inst. 1번 당 인접한 2개의 Bank 중 1개의 Bank만 Read함을 암시?

만약, 연산 Inst. 1번당 인접한 2개의 Bank를 모두 읽는 Inst를 만들고,
NPU에서와 같이 Locality (Reuse)를 적용하면 더 효율적이지 않을까?

C/G/NPU ↔ PIM

- LPDDR-PIM:
 - Register Files (Inst, Vector, Scalar)
 - Supporting Operations
 - ✓ FP16 mult
 - ✓ FP32 acc
 - ✓ INT8 arithmetic
 - ✓ and/or... Logical operations
- Memory Inst와 PIM Inst를 분리
 - JEDEC Inst. 호환 Memory 가능
 - ex. RD/WR/ACT/PRE 호환
- 기본적으로 Bank 2개당 PU 1개

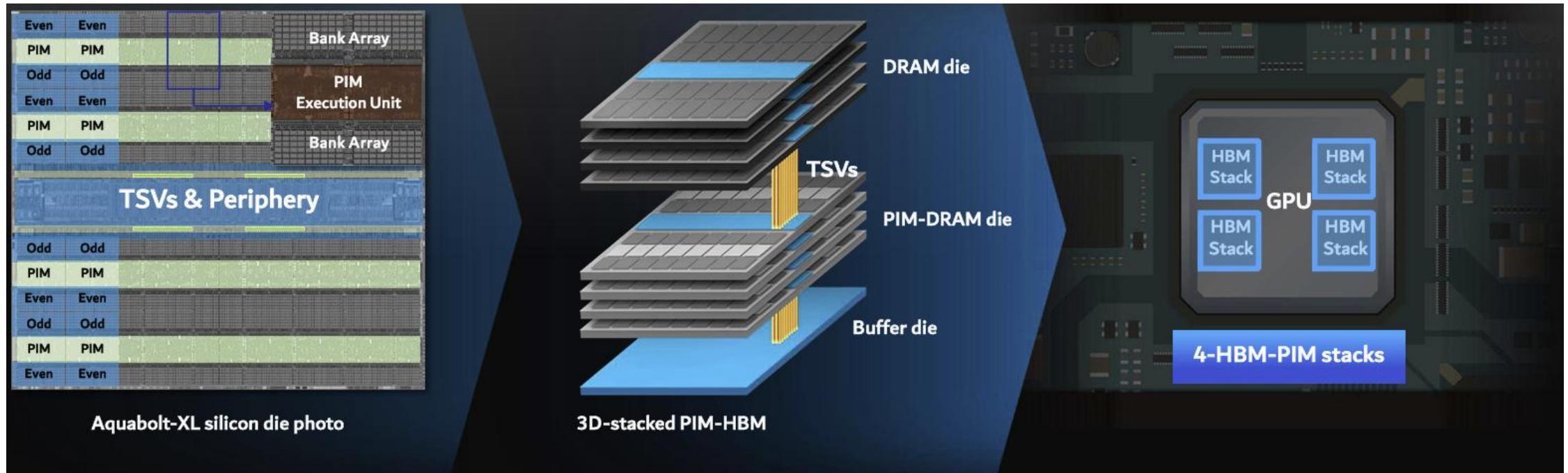
While we have demonstrated the performance and energy characteristics using one PIM block for every two banks, it is also possible to deploy one PIM block for each bank. In such a scenario, there is the potential to double the internal memory bandwidth, which means that the PIM can achieve twice the processing power than before. In further experiments, we observed 4.5×



Reference: The_Breakthrough_Memory_Solutions_for_Improved_Performance_on_LLM_Inference
Reference: Aquabolt-XL_PIM

How about PIM?

□ HBM-PIM

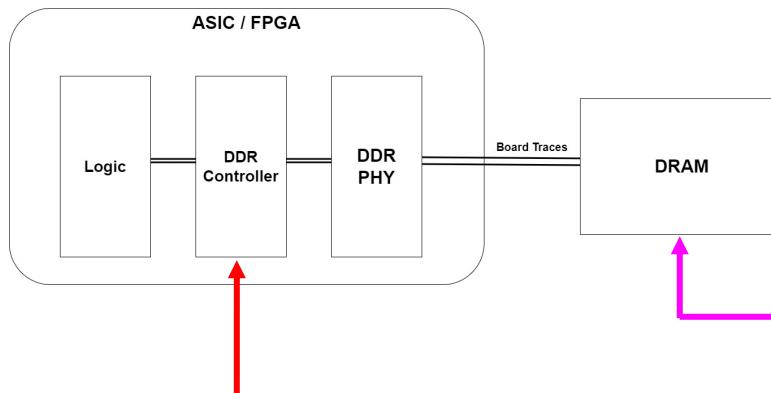
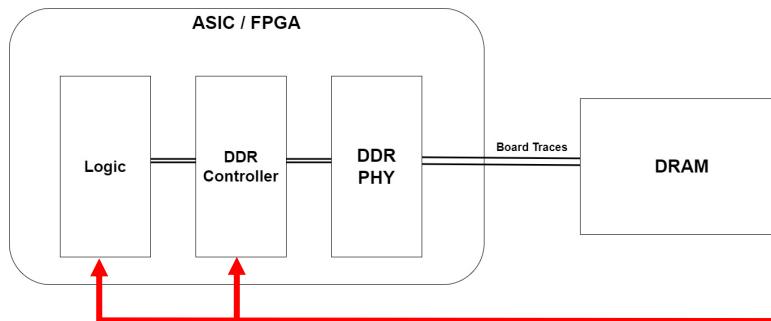


GPU ↔ HBM-PIM

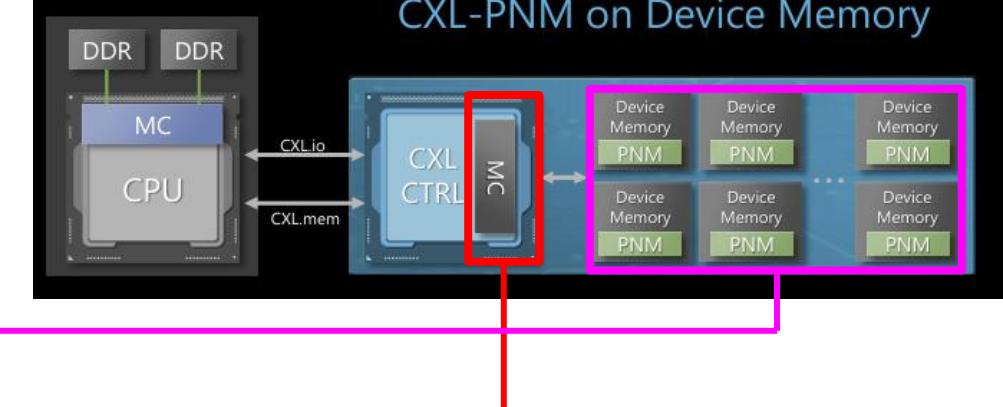
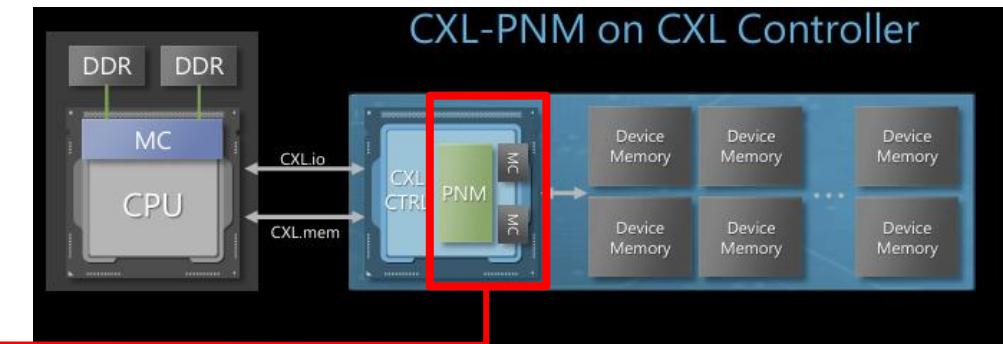
How about PIM?

□ What Should Be Modeled?

Original Ramulator2.0 Models Below



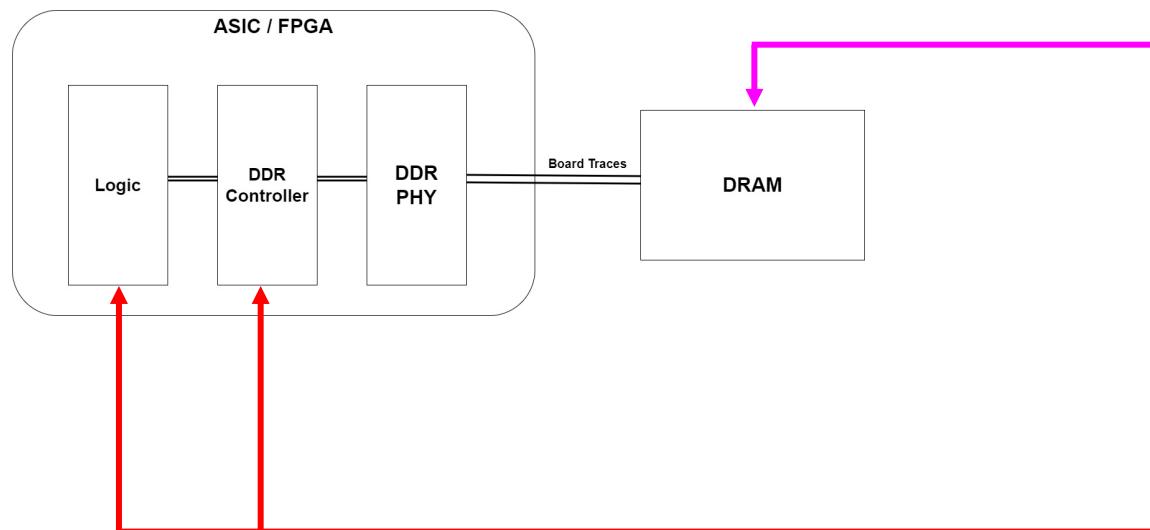
CXL-PIM



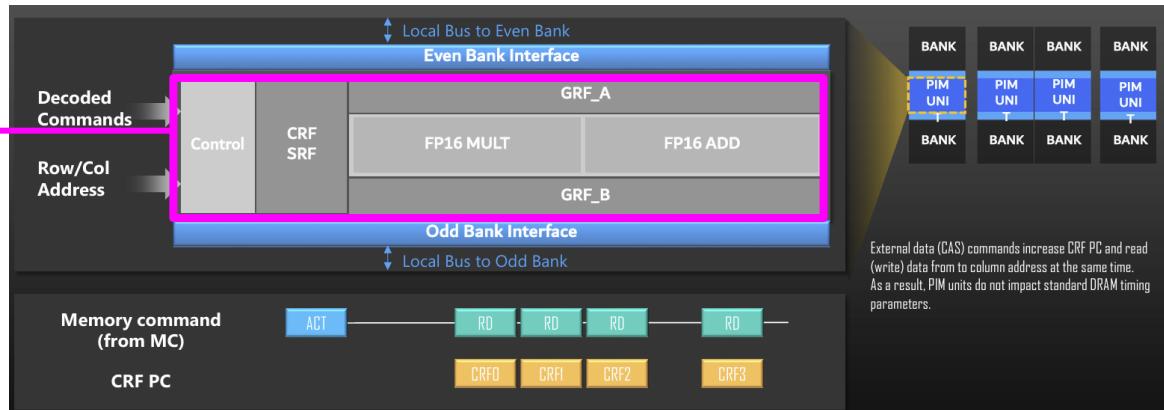
How about PIM?

□ What Should Be Modeled?

Original Ramulator2.0 Models Below



LPDDR-PIM or HBM-PIM



PIM Instruction-Set Architecture

- Supports RISC-style 32-bit instructions.
- Three Instruction types (Total 9 instructions)
 - 3 Control flow: NOP, JUMP, EXIT
 - 2 Data transfer: MOV, FILL
 - 4 Arithmetic: ADD, MUL, MAC, MAD
- JUMP instruction:
 - Zero-cycle static branch: supports only a preprogrammed numbers of iterations
- Operand type: Vector Register(GRF_A, GRF_B), Scalar Register(SRF), and Bank Row Buffer
 - DRAM commands decide where to retrieve data from DRAM for PIM arithmetic operations

Type	Operation	Operand (SRC0)	Operand (SRC1)	Result (DST)	# of combinations
Arithmetic	ADD	GRF, BANK, SRF	GRF, BANK, SRF	GRF	40
	MUL	GRF, BANK	GRF, BANK, SRF	GRF	32
	MAC	GRF, BANK	GRF, BANK, SRF	GRF_B	16
	MAD	GRF, BANK	GRF, BANK, SRF	GRF	28
Data Transfer	MOVE	GRF, BANK	GRF, SRF	GRF, SRF	24
	FILL	GRF, BANK	GRF, BANK	GRF, BANK	12
Control Flow	NOP				1
	JUMP				1
	EXIT				1