

Ramulator 2.0 Summary

*Intelligent System
Laboratory*

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.

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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.

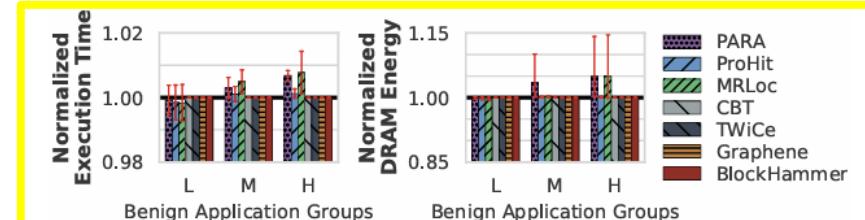


Figure 4: Execution time and DRAM energy consumption for benign single-core applications, normalized to baseline.

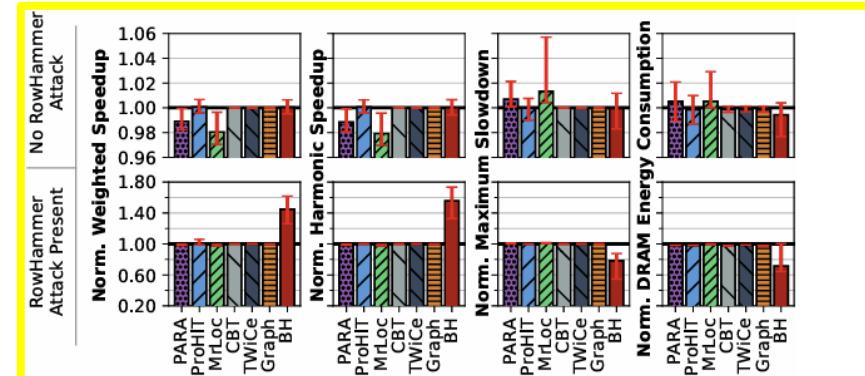
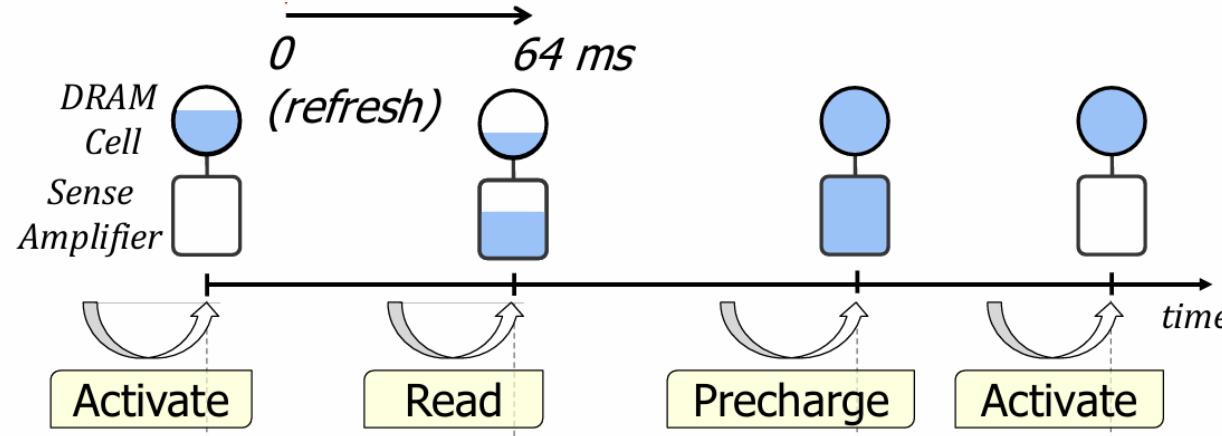


Figure 5: Performance and DRAM energy consumption for multiprogrammed workloads, normalized to baseline.

DRAM Operations & States

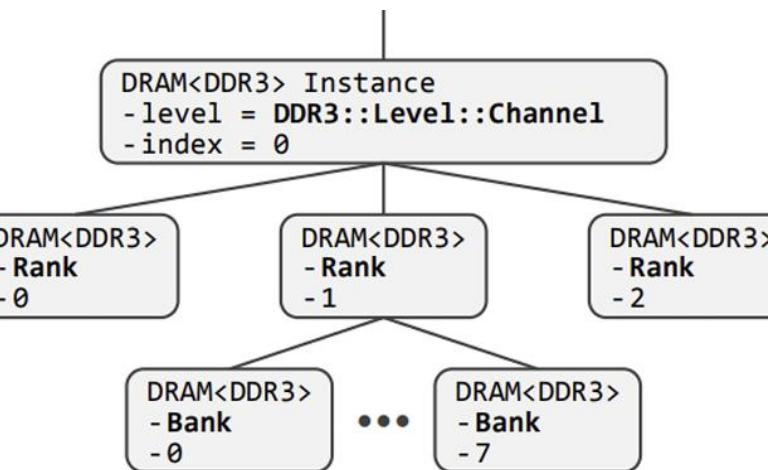
□ DRAM Operations & States



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

```
1 // DRAM.h
2 template <typename T>
3 class DRAM {
4     DRAM<T>* parent;
5     vector<DRAM<T>*>
6         children;
7     T::Level level;
8     int index;
9     // more code...
10};
```

```
1 // DDR3.h/cpp
2 class DDR3 {
3     enum class Level {
4         Channel, Rank, Bank,
5         Row, Column, MAX
6     };
7
8     // more code...
9 };
10};
```



src files <=> DRAM Operation

□ Simulation Configuration

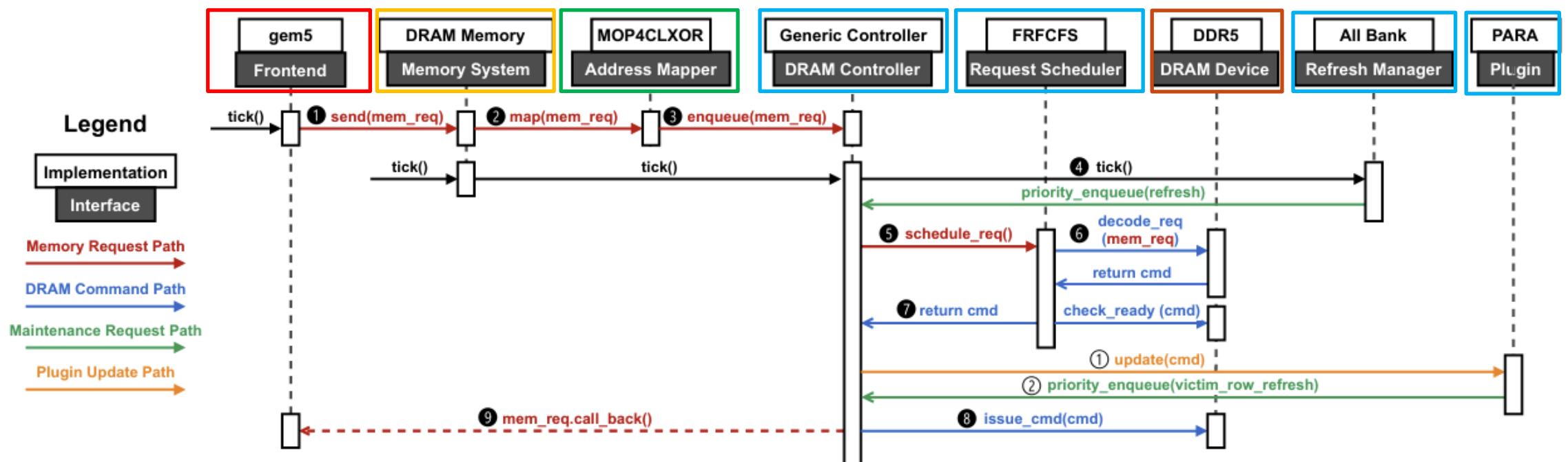
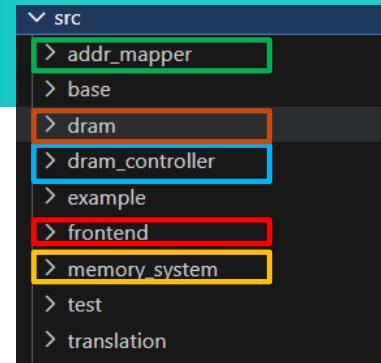


Fig. 1: High-level software architecture of Ramulator 2.0 using an example DDR5 system configuration

src files <=> DRAM Operation

□ Simulation Configuration

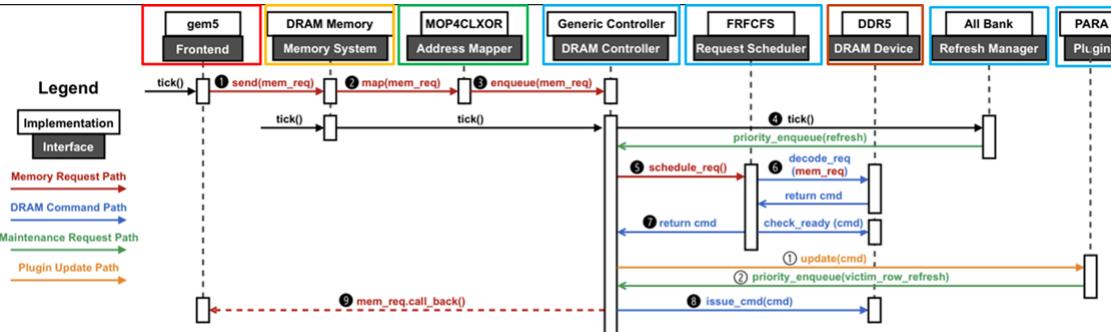
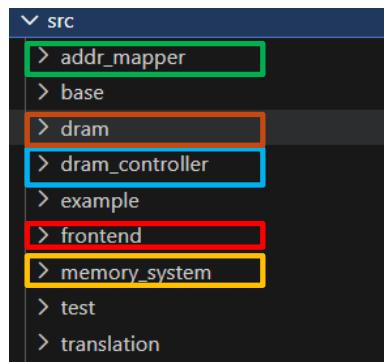


Fig. 1: High-level software architecture of Ramulator 2.0 using an example DDR5 system configuration



- 1. Requests are sent:** Front-end(trace file)에서 Memory Request를 보냄
- 2. Memory Addresses are Mapped:** Address Mapper가 Request Address를 DRAM 구조에 맞게 변환
- 3. Enqueue:** DRAM Ctrlr의 Buffer에 Request를 넣음
- 4. DRAM Ctrlr - Ticking Refresh Manager:** Ctrlr가 Refresh Manager를 호출해 high-priority maintenance request(ex. Refresh)을 추가
- 5. DRAM Ctrlr - Request Scheduling:** Request Scheduler에게 최적의 Request를 선택하라고 요청
- 6. DRAM Device가 Request 확인:** Scheduler가 DRAM Device Model을 참조해 적합한 Command를 Decode
- 7. Issue Command:** DRAM Ctrlr가 DRAM Command를 보냄
- 8. Updates the behavior and timing information:** DRAM Command Issue시 State & Timing이 Update
- 9. Notify the frontend:** Memory Request가 끝나면 callback으로 frontend에 알림

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 // Connect the frontend and the memory system together,
25 // this recursively calls the "setup" function in all instantiated components
26 // so that they can get each other's parameters (if needed) after their initialization
27 frontend->connect_memory_system(memory_system);
28 memory_system->connect_frontend(frontend);
29
30 // Get the relative clock ratio between the frontend and memory system
31 int frontend_tick = frontend->get_clock_ratio();
32 int mem_tick = memory_system->get_clock_ratio();
33
34 int tick_mult = frontend_tick * mem_tick;
35
36 for (uint64_t i = 0; i++) {
37     if (((i % tick_mult) % mem_tick) == 0) {
38         frontend->tick();
39     }
40
41     if (frontend->is_finished()) {
42         break;
43     }
44
45     if ((i % tick_mult) % frontend_tick == 0) {
46         memory_system->tick();
47     }
48
49 }
50
51 // Finalize the simulation. Recursively print all statistics from all components
52 frontend->finalize();
53 memory_system->finalize();
54
55 return 0;
56 }
```

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 실행한 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 file**에서 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
⇒ Simulation이 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

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

```
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2    impl: SimpleO3
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5  traces:
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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 nRC nRCD nRP nRAS nRC nWR nRTP nWL nCCDS nCCDL nRRDS nRRDL nWTRS nW
28    {"DDR4_1600", {1600, 4, 10, 10, 10, 28, 38, 12, 6, 9, 4, 5, -1, -1, -1, 2,
29    {"DDR4_1600K", {1600, 4, 11, 11, 11, 28, 39, 12, 6, 9, 4, 5, -1, -1, -1, 2,
30    {"DDR4_1600L", {1600, 4, 12, 12, 12, 28, 40, 12, 6, 9, 4, 5, -1, -1, -1, 2,
31    {"DDR4_1866L", {1866, 4, 12, 12, 12, 32, 44, 14, 7, 10, 4, 5, -1, -1, -1, 3,
32    {"DDR4_1866M", {1866, 4, 13, 13, 13, 32, 45, 14, 7, 10, 4, 5, -1, -1, -1, 3,
33    {"DDR4_1866N", {1866, 4, 14, 14, 14, 32, 46, 14, 7, 10, 4, 5, -1, -1, -1, 3,
34    {"DDR4_2133N", {2133, 4, 14, 14, 14, 36, 50, 16, 8, 11, 4, 6, -1, -1, -1, 3,
35    {"DDR4_2133P", {2133, 4, 15, 15, 15, 36, 51, 16, 8, 11, 4, 6, -1, -1, -1, 3,
36    {"DDR4_2133R", {2133, 4, 16, 16, 16, 36, 52, 16, 8, 11, 4, 6, -1, -1, -1, 3,
37    {"DDR4_2400P", {2400, 4, 15, 15, 15, 39, 54, 18, 9, 12, 4, 6, -1, -1, -1, 3,
38    {"DDR4_2400R", {2400, 4, 16, 16, 16, 39, 55, 18, 9, 12, 4, 6, -1, -1, -1, 3,
39    {"DDR4_2400U", {2400, 4, 17, 17, 17, 39, 56, 18, 9, 12, 4, 6, -1, -1, -1, 3,
40    {"DDR4_2400T", {2400, 4, 18, 18, 18, 39, 57, 18, 9, 12, 4, 6, -1, -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
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14    impl: GenericDRAM
15    clock_ratio: 3
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17    DRAM:
18      impl: DDR4
19      org:
20        preset: DDR4_8Gb_x8
21        channel: 1
22        rank: 2
23        timing:
24          preset: DDR4_2400R
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27      impl: Generic
28      Scheduler:
29        impl: FRFCFS
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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
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21        |         channel: 1
22        |         rank: 2
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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

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

The diagram illustrates the flow of data from a trace file to the CPU model. A red arrow points from the highlighted code in `trace.cpp` to the `SimpleO3Core::Tick()` function in `core.cpp`. A green arrow points from the `SimpleO3Core::Tick()` function back to the `example_inst.trace` file.

trace.cpp (Left)

```
src > frontend > impl > processor > simpleO3 > trace.cpp > ...
std::string line;
while (std::getline(trace_file, line)) {
    std::vector<std::string> tokens;
    tokenize(tokens, line, " ");
    int num_tokens = tokens.size();
    if (num_tokens != 2 & num_tokens != 3) {
        throw ConfigurationError("Trace {} format invalid!", file_path_str);
    }
    int bubble_count = std::stoi(tokens[0]);
    Addr_t load_addr = std::stoll(tokens[1]);
    bool has_store = num_tokens == 2 ? false : true;
    if (has_store) {
        Addr_t store_addr = std::stoll(tokens[2]);
        m_trace.push_back({bubble_count, load_addr, store_addr});
    } else {
        m_trace.push_back({bubble_count, load_addr, -1});
    }
}
trace_file.close();
m_trace_length = m_trace.size();
```

각 줄이 하나의 Instruction처럼 CPU 모델에 들어감

`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	

core.cpp (Right)

```
src > frontend > impl > processor > simpleO3 > core.cpp > tick()
void SimpleO3Core::Tick() {
    m_clk++;
    s_insts_retired += m_window.retire();
    if (!reached_expected_num_insts) {
        if (s_insts_retired >= m_num_expected_insts) {
            reached_expected_num_insts = true;
            s_cycles_recorded = m_clk;
        }
    }
    // First, issue the non-memory instructions
    int num_inserted_insts = 0;
    while (m_num_bubbles > 0) {
        if (num_inserted_insts == m_window.m_ipc) {
            return;
        }
        if (m_window.is_full()) {
            return;
        }
        m_window.insert(true, -1);
        num_inserted_insts++;
        m_num_bubbles--;
    }
    // Second, try to send the load to the LLC
    if (m_load_addr != -1) {
        if (num_inserted_insts == m_window.m_ipc) {
            return;
        }
        if (m_window.is_full()) {
            return;
        }
        auto inst = m_trace.get_next_inst();
        m_num_bubbles = inst.bubble_count;
        m_load_addr = inst.load_addr;
        m_writeback_addr = inst.store_addr;
    }
    Request load_request(m_load_addr, Request::Type::Read, m_id, m_callback);
    if (!m_translation->translate(load_request)) {
        return;
    }
    if (m_llc->send(load_request)) {
        m_window.insert(false, load_request.addr);
        m_load_addr = -1;
        if (m_writeback_addr != -1) {
            // If there is still writeback, return without getting the next trace line
            // The write back will be issued in the next cycle
            // TODO: Should we allow both load and writeback to issue at the same cycle?
            return;
        }
    } else {
        return;
    }
    // Third, try to send the writeback to the LLC
    if (m_writeback_addr != -1) {
        Request writeback_request(m_writeback_addr, Request::Type::Write, m_id, m_callback);
        if (!m_translation->translate(writeback_request)) {
            return;
        }
        if (!m_llc->send(writeback_request)) {
            return;
        }
    }
}
```

- Trace file을 arg로 받아, Frontend (ex: simpleO3.cpp)에서 처리되어 메모리 접근 request를 생성
- simpleO3 CPU model 기준: trace의 token[0]: bubble / token[1]: load address / token[2]: store address

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
```

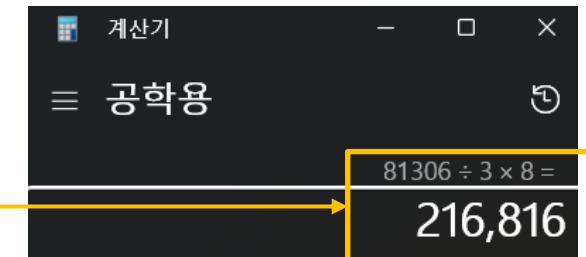
Other requests: read/write를 제외한 open-row와 같은 request 등을 의미

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
- abcd

trace file result

□ power는 어떻게 측정하느냐면

- yaml file에 아래 drampower_enable 옵션을 넣음
- dram.h -> DDR4.cpp 의 power함수 enable됨

```
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      drampower_enable: true  
26      # power_debug: true  # option: debug log  
27    voltage:  
28      preset: Default  # option: voltage preset  
29    current:  
30      preset: Default  # option: current preset  
31
```

```
DRAM:  
impl: DDR4  
active_cycles_rank1: 9361  
pre_background_energy_rank1: 3850.965247500003  
total_background_energy_rank0: 4424.017184999997  
idle_cycles_rank1: 68489  
total_cmd_energy: 3203.034273599993  
total_cmd_energy_rank0: 1601.876992799997  
total_energy_rank0: 6025.894177799989  
act_background_energy_rank0: 572.1522975000003  
pre_background_energy_rank0: 3851.864887499999  
active_cycles_rank0: 9345  
act_background_energy_rank1: 573.1319055000002  
total_energy: 12051.1486116  
idle_cycles_rank0: 68505  
total_energy_rank1: 6025.254433800007  
total_background_energy_rank1: 4424.097153000006  
total_background_energy: 8848.114337999994  
total_cmd_energy_rank1: 1601.157280799996  
AddrMapper:  
impl: RoBaRaCoCh
```

trace file result

□ power는 어떻게 측정하느냐면

- power_debug option enable 시
- 오른쪽과 같은 power log 확인 가능

```
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          drampower_enable: true  
26          # power_debug: true # option: debug log  
27  ✓  voltage:  
28          preset: Default # option: voltage preset  
29  ✓  current:  
30          preset: Default # option: current preset  
31
```

```
● root@947e591ed45c:/workspace# ./ramulator2 -f ./example_config_power_en.yaml  
[Power] Rank0 -----ACT----- @ 19  
[Power] Rank0 Rank is idle. idle_cycles: 19 active_start_cycle: 19 @ 19  
[Power] Rank0 Incrementing ACT counter. @ 19  
[Power] Rank1 -----ACT----- @ 20  
[Power] Rank1 Rank is idle. idle_cycles: 20 active_start_cycle: 20 @ 20  
[Power] Rank1 Bank2 Incrementing ACT counter. @ 20  
[Power] Rank0 -----ACT----- @ 23  
[Power] Rank0 Bank3 Incrementing ACT counter. @ 23  
[Power] Rank1 -----ACT----- @ 24  
[Power] Rank1 Bank3 Incrementing ACT counter. @ 24  
[Power] Rank0 Bank0 Incrementing RD counter. @ 35  
[Power] Rank0 Bank3 Incrementing RD counter. @ 39  
[Power] Rank0 Bank0 Incrementing RD counter. @ 43  
[Power] Rank1 Bank2 Incrementing RD counter. @ 49  
[Power] Rank1 Bank3 Incrementing RD counter. @ 53  
[Power] Rank0 Bank0 Incrementing RD counter. @ 59  
[Power] Rank0 -----PREA----- @ 9364  
[Power] Rank0 Incrementing PRE counter. @ 9364  
[Power] Rank0 Rank is not idle. active_cycles: 9345 idle_start_cycle: 9364 @ 9364  
[Power] Rank0 -----REFab----- @ 9380  
[Power] Rank0 Refresh starts. idle_cycles: 35 @ 9380  
[Power] Rank1 -----PREA----- @ 9381  
[Power] Rank1 Incrementing PRE counter. @ 9381  
[Power] Rank1 Rank is not idle. active_cycles: 9361 idle_start_cycle: 9381 @ 9381  
[Power] Rank1 -----REFab----- @ 9397  
[Power] Rank1 Refresh starts. idle_cycles: 36 @ 9397  
[Power] Rank0 -----REFab_end----- @ 9812  
[Power] Rank0 Refresh ends. idle_start_cycle: 9812 @ 9812  
[Power] Rank1 -----REFab_end----- @ 9829  
[Power] Rank1 Refresh ends. idle_start_cycle: 9829 @ 9829  
[Power] Rank0 -----REFab----- @ 18728  
[Power] Rank0 Refresh starts. idle_cycles: 8951 @ 18728  
[Power] Rank1 -----REFab----- @ 18729  
[Power] Rank1 Refresh starts. idle_cycles: 8936 @ 18729  
[Power] Rank0 -----REFab_end----- @ 19160  
[Power] Rank0 Refresh ends. idle_start_cycle: 19160 @ 19160  
[Power] Rank1 -----REFab_end----- @ 19161  
[Power] Rank1 Refresh ends. idle_start_cycle: 19161 @ 19161  
[Power] Rank0 -----REFab----- @ 28092
```

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

src/frontend folder

□ simpleO3 Core Operations

- class SimpleO3 – init()

```
28 void init() override {
29     m_clock_ratio = param<uint>("clock_ratio").required();
30
31     // Core params
32     std::vector<std::vector<std::string>> trace_list = param<std::vector<std::string>>("traces").desc("A list of traces.").required();
33     m_num_cores = trace_list.size();
34
35     int ipc = param<int>("ipc").desc("IPC of the SimpleO3 core.").default_val(4);
36     int depth = param<int>("inst_window_depth").desc("Instruction window size of the SimpleO3 core.").default_val(128);
37
38     // LLC params
39     int llc_latency = param<int>("llc_latency").desc("Aggregated latency of the LLC.").default_val(47);
40     int llc_linesize_bytes = param<int>("llc_linesize").desc("LLC cache line size in bytes.").default_val(64);
41     int llc_associativity = param<int>("llc_associativity").desc("LLC set associativity.").default_val(8);
42     int llc_capacity_per_core = parse_capacity_str(param<std::string>("llc_capacity_per_core")).desc("LLC capacity per core.").default_val("2MB");
43     int llc_num_mshr_per_core = param<int>("llc_num_mshr_per_core").desc("Number of LLC MSHR entries per core.").default_val(16);
44
45     // Simulation parameters
46     m_num_expected_insts = param<int>("num_expected_insts").desc("Number of instructions that the frontend should execute.").required();
47
48     // Create address translation module
49     m_translation = create_child_iface<ITranslation>();
50
51     // Create the LLC
52     m_llc = new SimpleO3LLC(llc_latency, llc_capacity_per_core * m_num_cores, llc_linesize_bytes, llc_associativity, llc_num_mshr_per_core * m_num_cores);
53     // m_llc->deserialize(serialization_filename);
54     // m_llc->serialize(serialization_filename);
55
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[id], m_translation, m_llc);
59         core->m_callback = [this](Request& req){return this->receive(req);};
60         m_cores.push_back(core);
61     }
62
63     m_logger = Logging::create_logger("SimpleO3");
64
65     // Register the stats
66     register_stat(m_num_expected_insts).name("num_expected_insts");
67     register_stat(m_llc->s_llc_eviction).name("llc_eviction");
68     register_stat(m_llc->s_llc_read_access).name("llc_read_access");
69     register_stat(m_llc->s_llc_write_access).name("llc_write_access");
70     register_stat(m_llc->s_llc_read_misses).name("llc_read_misses");
71     register_stat(m_llc->s_llc_write_misses).name("llc_write_misses");
72     register_stat(m_llc->s_llc_mshr_unavailable).name("llc_mshr_unavailable");
73
74     for (int core_id = 0; core_id < m_cores.size(); core_id++) {
75         // register_stat(m_cores[core_id]->s_insts_retired).name("cycles_retired_core_{}", core_id);
76         register_stat(m_cores[core_id]->s_cycles_recorded).name("cycles_recorded_core_{}", core_id);
77         register_stat(m_cores[core_id]->s_mem_access_cycles).name("memory_access_cycles_recorded_core_{}", core_id);
78     }
79 }
80 }
```

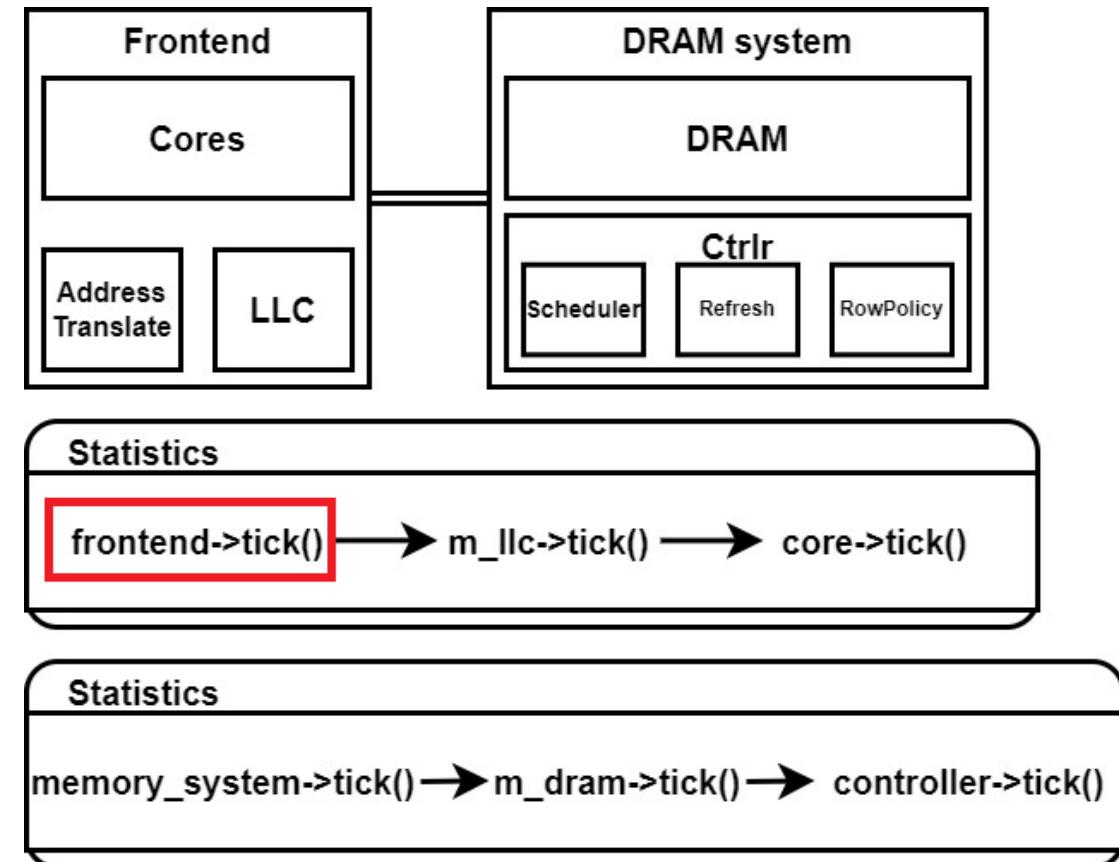
1. Core Parameters를 yaml file에서 가져옴 → clock_ratio / traces (ipc, depth 하드 코딩)
2. LLC Parameters (latency, cache line size, 몇 assosiative cache인지, MSHR 수, cache size) 하드 코딩
3. Address Translation / LLC / Cores(trace file의 수만큼 생성 됨) Instance 생성
4. LLC의 동작 통계 변수들은 registration class에 등록

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 }
```



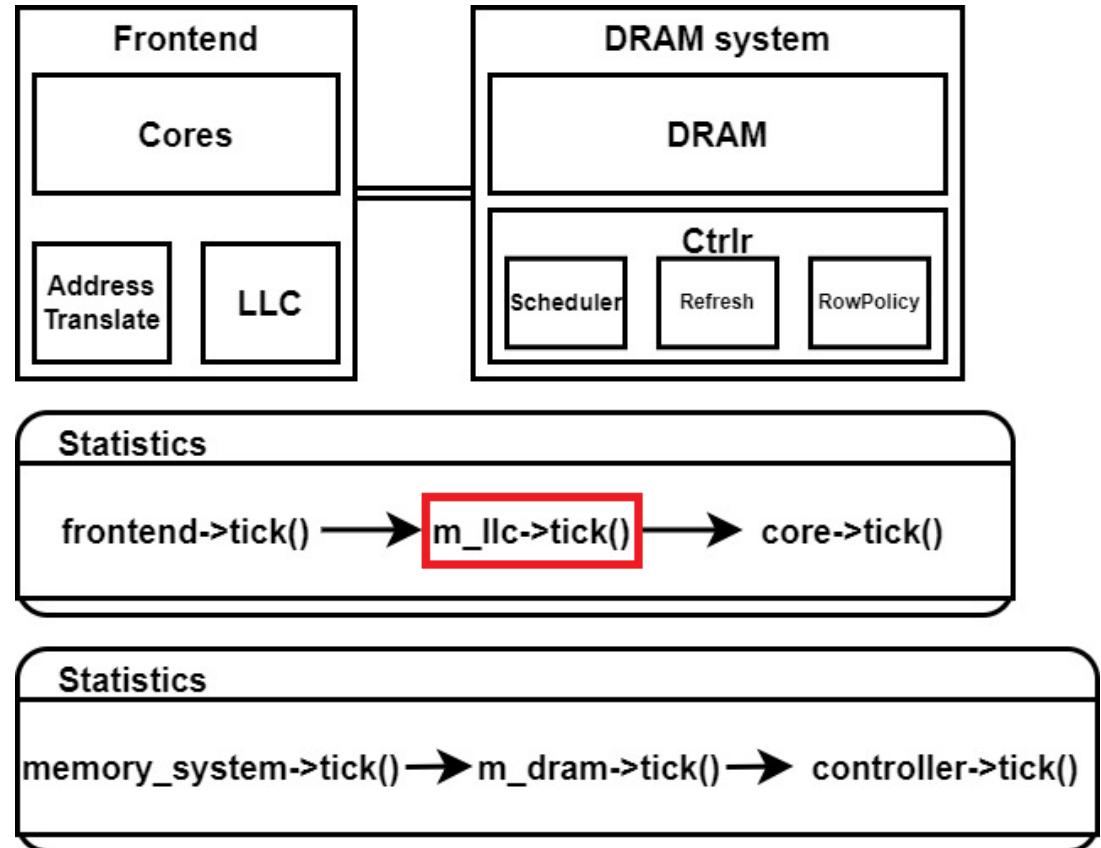
- **m_clk (global clk)** 증가
- 아래의 순서로 frontend 동작
- Last Level Cache tick() → Core tick()

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                 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     }
53 }
```

```
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
80     }
```

```
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)

□ 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 }

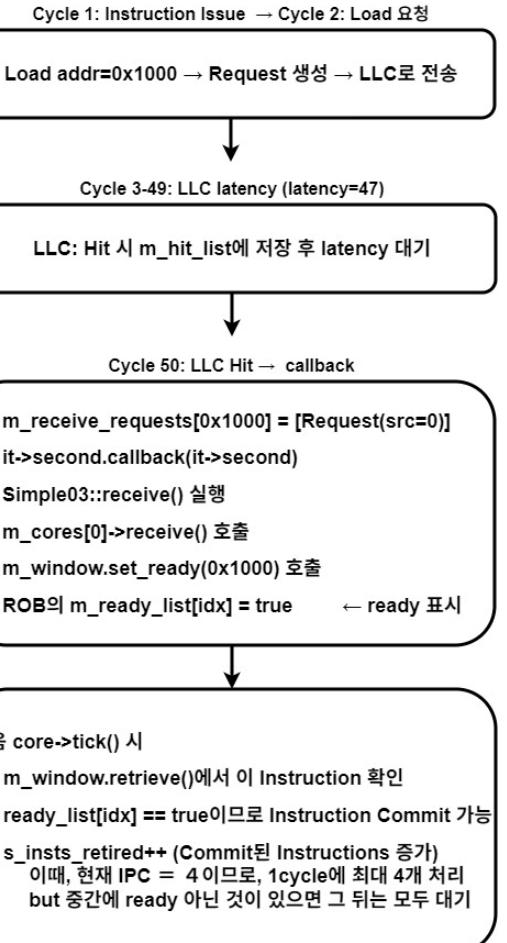
void receive(Request& req) {
    m_llc->receive(req); → cache 내 MSLR 처리
    // TODO: LLC latency for the core to receive the request?
    for (auto r : m_llc->m_receive_requests[req.addr]) {
        r.arrive = req.arrive;
        r.depart = req.depart;
        m_cores[r.source_id]->receive(r);
    }
    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}

```

- Out of order Processor는 Instruction의 Dependency를 고려하여 Instruction Re-Ordering진행
- ROB에 쌓인 이미 완료된 Instruction은 이제 sequential하게 기존 Instruction 순서에 맞게 commit됨
- 항상 Processor는 User입장에서 Sequential하게 보여야 함 - The MicroArchitecture of SuperScalar Processors(1995)



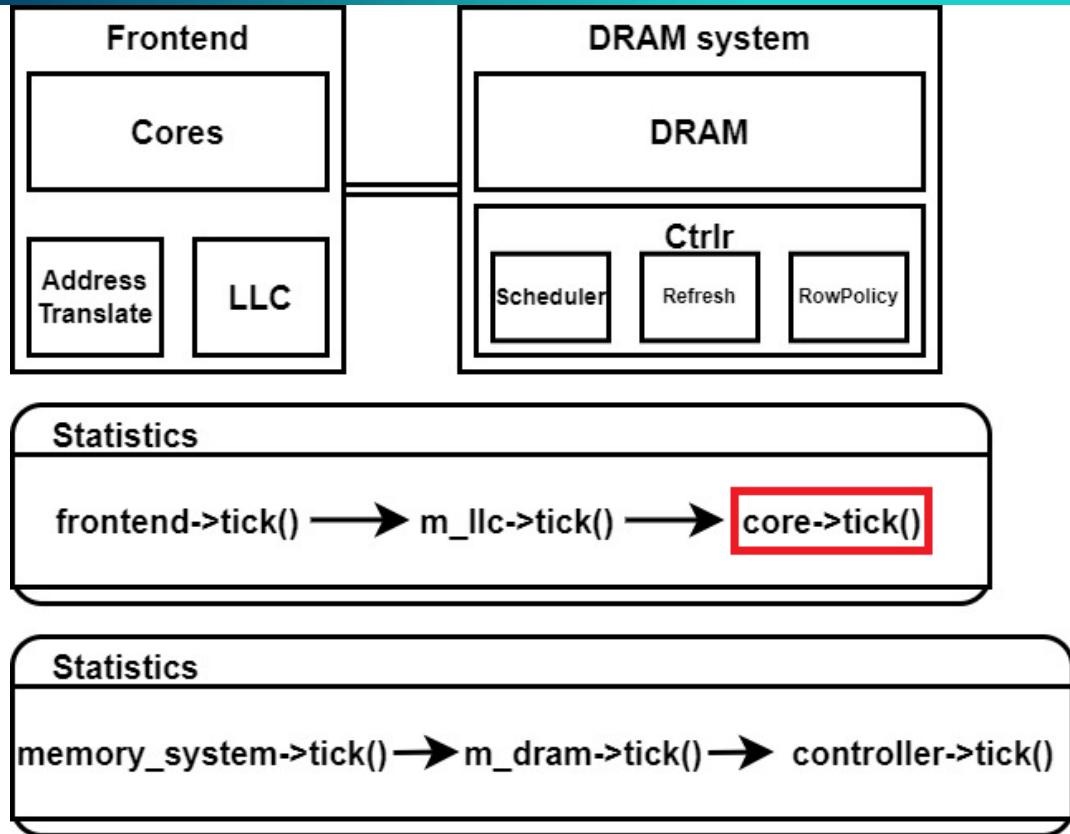
src/frontend folder

□ 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) { // IPC 제한 내에서  
101        if (!m_ready_list.at(m_tail_idx))      // tail이 준비 안 됐으면  
102            break;                            // 즉시 중단 (In-Order Retirement!)  
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 }
```



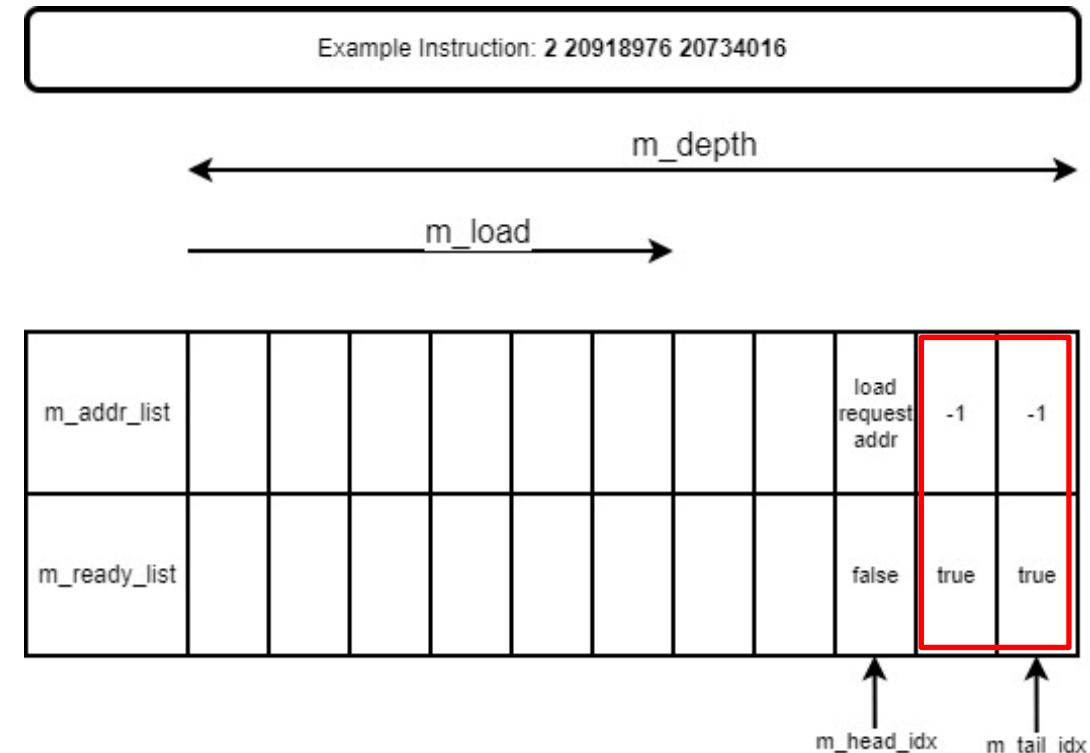
- ROB에서 명령어가 실행될 준비가 되면 ready flag를 **true**로 바꿈
- 이 경우 instruction이 실행되기 위한 data가 존재한다는 뜻
- 따라서, **ready = true**이면 해당 Inst를 commit 시킴 → Inst 처리됨

□ 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 부분**이 완성됨

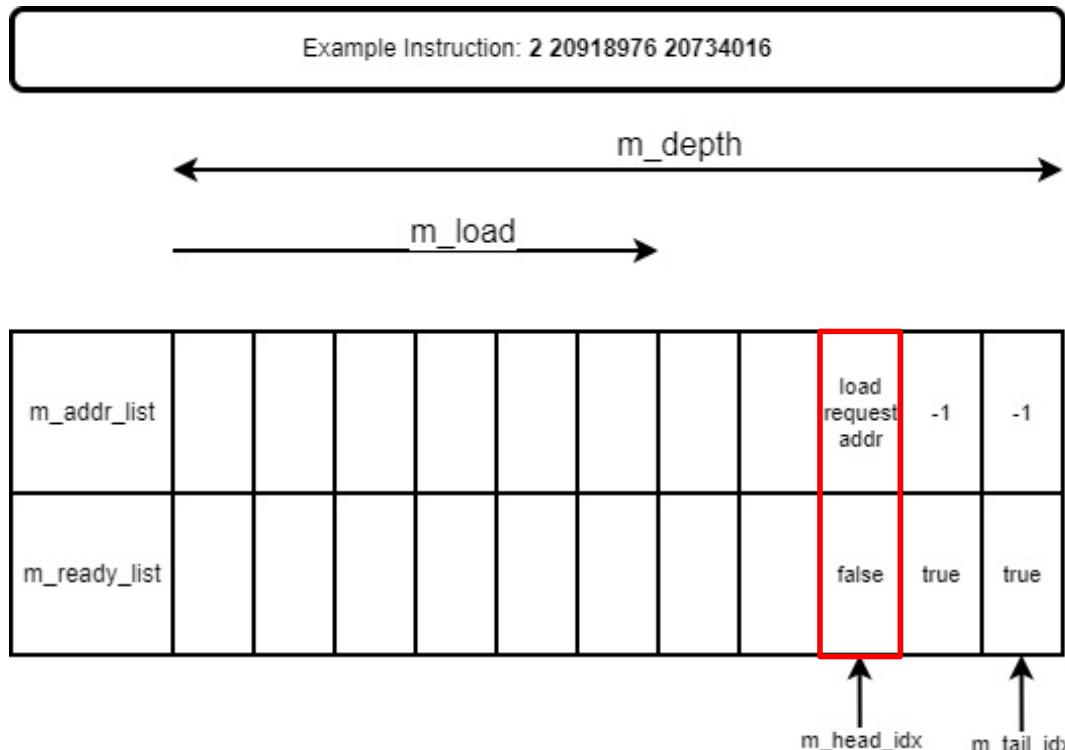
src/frontend folder

□ 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



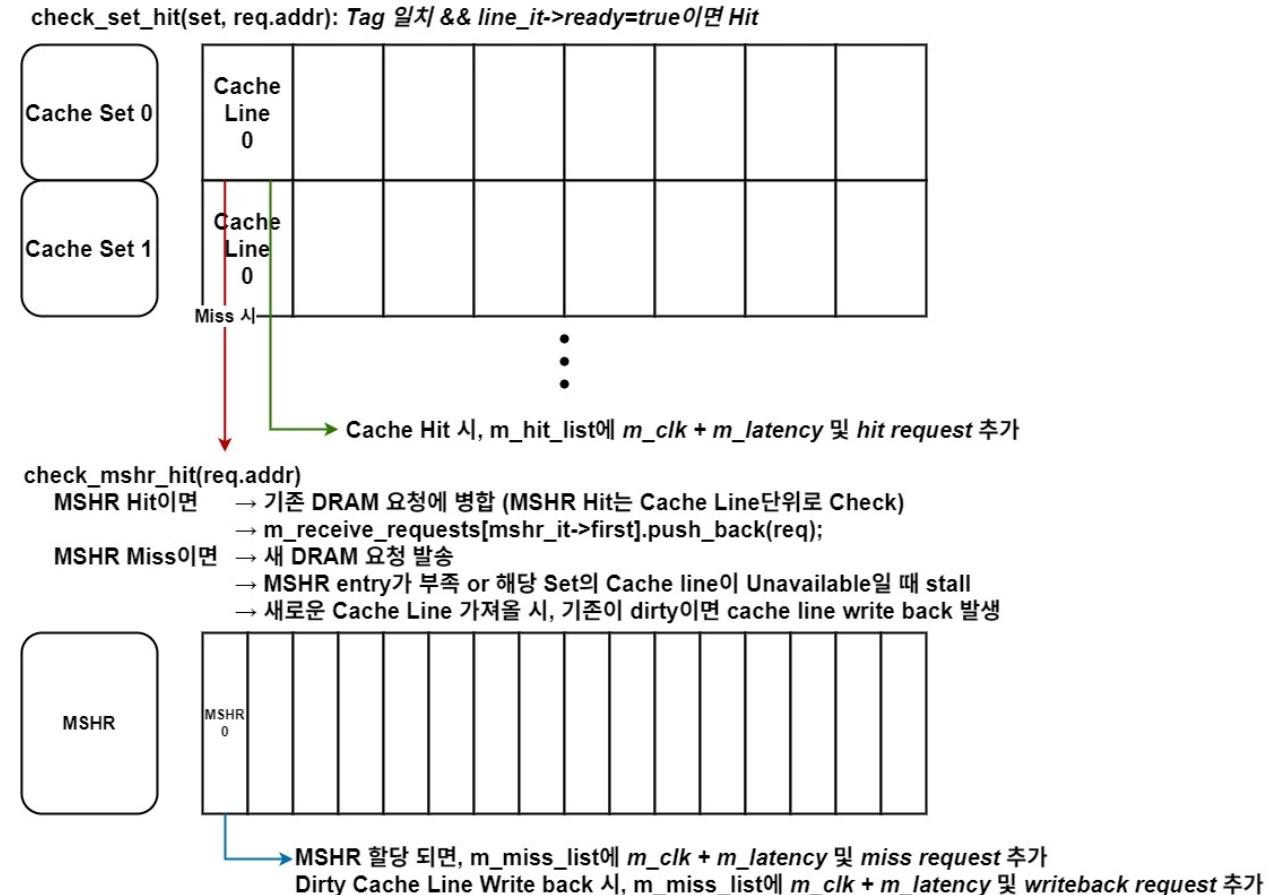
- Load Request가 존재하면, Load 요청의 주소를 translate
- 그 후, LLC로 Request를 보냄

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 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 }
```



src/frontend folder

simpleO3 Core Operations

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

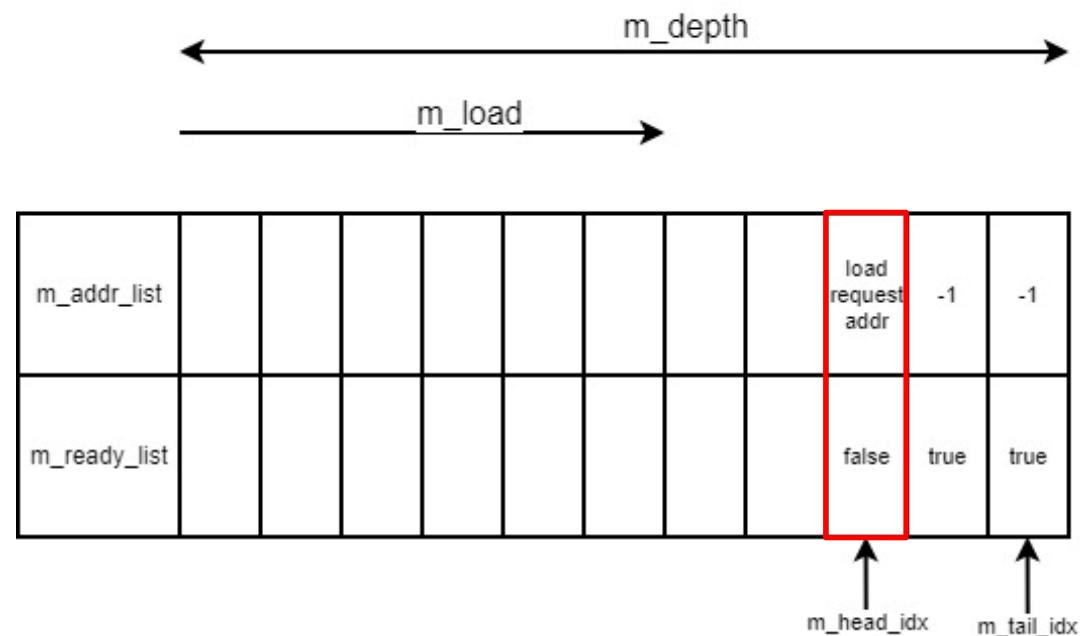
```
174 // Second, try to send the load to the LLC
175 if (m_load_addr != -1) {
176     if (num_inserted_insts == m_window.m_ipc) { // IPC 제한
177         return;
178     }
179     if (m_window.is_full()) { // ROB 가득 참
180         return;
181     };
182
183     // Load 요청 생성 (가상 주소)
184     Request load_request(m_load_addr, 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

src/memory_system folder

❑ memory_system

- abcd

src/memory_system folder

❑ memory_system

- abcd

src/addr_mapper folder

□ addr_mapper

- abcd

src/addr_mapper folder

□ addr_mapper

- abcd

src/translation folder

□ translation

- abcd

src/translation folder

□ translation

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src/translation folder

□ translation

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src/dram folder

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src/dram_controller folder

□ DRAM Controller Operations

- class GenericDRAMController – init()

(src\dram_controller\impl\ generic_dram_controller.cpp)

```
54     void init() override {
55         m_wr_low_watermark = param<float>("wr_low_watermark").desc("Threshold for switching back to read mode.").default_val(0.2f)
56         m_wr_high_watermark = param<float>("wr_high_watermark").desc("Threshold for switching to write mode.").default_val(0.8f);
57
58         m_scheduler = create_child_ifce<IScheduler>();
59         m_refresh = create_child_ifce<IRefreshManager>();
60         m_rowpolicy = create_child_ifce<IRowPolicy>();
61
62         if (m_config["plugins"]) {
63             YAML::Node plugin_configs = m_config["plugins"];
64             for (YAML::iterator it = plugin_configs.begin(); it != plugin_configs.end(); ++it) {
65                 m_plugins.push_back(create_child_ifce<IControllerPlugin>(*it));
66             }
67         }
68     }
```

- 1.1. YAML file을 통해 write buffer priority threshold를 초기화.
→ Scheduler가 사용할 buffer를 결정
- 1.2. Scheduler, Refresh Manager, Row Policy를 생성.
- 1.3. Plugin을 load하여 Controller를 확장

```
// 2.2.1 If no request to be scheduled in the priority buffer, check the read and write buffers.
if (!request_found) {
    // Query the write policy to decide which buffer to serve
    set_write_mode();
    auto& buffer = m_is_write_mode ? m_write_buffer : m_read_buffer;
    if (req_it = m_scheduler->get_best_request(buffer); req_it != buffer.end()) {
        request_found = m_dram->check_ready(req_it->command, req_it->addr_vec);
        req_buffer = &buffer;
    }
}
```

src/dram_controller folder

□ DRAM Controller Operations

- class GenericDRAMController – setup()

```
70 void setup(IFrontEnd* frontend, IMemorySystem* memory_system) override {
71     m_dram = memory_system->get_ifce<IDRAMY>();
72     m_bank_addr_idx = m_dram->m_levels("bank");
73     m_priority_buffer.max_size = 512*3 + 32;
74
75     m_num_cores = frontend->get_num_cores();
76
77     s_read_row_hits_per_core.resize(m_num_cores, 0);
78     s_read_row_misses_per_core.resize(m_num_cores, 0);
79     s_read_row_conflicts_per_core.resize(m_num_cores, 0);
80
81     register_stat(s_row_hits).name("row_hits_{}", m_channel_id);
82     register_stat(s_row_misses).name("row_misses_{}", m_channel_id);
83     register_stat(s_row_conflicts).name("row_conflicts_{}", m_channel_id);
84     register_stat(s_read_row_hits).name("read_row_hits_{}", m_channel_id);
85     register_stat(s_read_row_misses).name("read_row_misses_{}", m_channel_id);
86     register_stat(s_read_row_conflicts).name("read_row_conflicts_{}", m_channel_id);
87     register_stat(s_write_row_hits).name("write_row_hits_{}", m_channel_id);
88     register_stat(s_write_row_misses).name("write_row_misses_{}", m_channel_id);
89     register_stat(s_write_row_conflicts).name("write_row_conflicts_{}", m_channel_id);
90
91     for (size_t core_id = 0; core_id < m_num_cores; core_id++) {
92         register_stat(s_read_row_hits_per_core[core_id]).name("read_row_hits_core_{}", core_id);
93         register_stat(s_read_row_misses_per_core[core_id]).name("read_row_misses_core_{}", core_id);
94         register_stat(s_read_row_conflicts_per_core[core_id]).name("read_row_conflicts_core_{}", core_id);
95     }
96
97     register_stat(s_num_read_reqs).name("num_read_reqs_{}", m_channel_id);
98     register_stat(s_num_write_reqs).name("num_write_reqs_{}", m_channel_id);
99     register_stat(s_num_other_reqs).name("num_other_reqs_{}", m_channel_id);
100    register_stat(s_queue_len).name("queue_len_{}", m_channel_id);
101    register_stat(s_read_queue_len).name("read_queue_len_{}", m_channel_id);
102    register_stat(s_write_queue_len).name("write_queue_len_{}", m_channel_id);
103    register_stat(s_priority_queue_len).name("priority_queue_len_{}", m_channel_id);
104    register_stat(s_queue_len_avg).name("queue_len_avg_{}", m_channel_id);
105    register_stat(s_read_queue_len_avg).name("read_queue_len_avg_{}", m_channel_id);
106    register_stat(s_write_queue_len_avg).name("write_queue_len_avg_{}", m_channel_id);
107    register_stat(s_priority_queue_len_avg).name("priority_queue_len_avg_{}", m_channel_id);
108
109    register_stat(s_read_latency).name("read_latency_{}", m_channel_id);
110    register_stat(s_avg_read_latency).name("avg_read_latency_{}", m_channel_id);
111}
```

2.1. DRAM Interface 연결 - (ex. dram.h → DDR4)

2.2. Bank level의 index를 조회

- DRAM Address Vector → ex. addr_vec[0] = channel, [1] = rank, [2] = bankgroup, [3] = bank, [4] = row, [5] = column
- 이 경우, Bank level index = 3
- 아래는 Row Hit 판별을 위해 Bank level index가 어떻게 사용되는지를 나타냄
- m_bank_addr_idx = 3 → bank = addr_vec[3] = 2 → Row Hit Check: open_rows[bank=2]의 row=1024 check → hit?

2.3. priority buffer Size를 하드 코딩

src/dram_controller folder

□ DRAM Controller Operations

- class GenericDRAMController – setup()

```
70 void setup(IFrontEnd* frontend, IMemorySystem* memory_system) override {
71     m_dram = memory_system->get_ifce<IDRAMP>();
72     m_bank_addr_idx = m_dram->m_levels("bank");
73     m_priority_buffer.max_size = 512*3 + 32;
74
75     m_num_cores = frontend->get_num_cores();
76
77     s_read_row_hits_per_core.resize(m_num_cores, 0);
78     s_read_row_misses_per_core.resize(m_num_cores, 0);
79     s_read_row_conflicts_per_core.resize(m_num_cores, 0);
80
81     register_stat(s_row_hits).name("row_hits_{}", m_channel_id);
82     register_stat(s_row_misses).name("row_misses_{}", m_channel_id);
83     register_stat(s_row_conflicts).name("row_conflicts_{}", m_channel_id);
84     register_stat(s_read_row_hits).name("read_row_hits_{}", m_channel_id);
85     register_stat(s_read_row_misses).name("read_row_misses_{}", m_channel_id);
86     register_stat(s_read_row_conflicts).name("read_row_conflicts_{}", m_channel_id);
87     register_stat(s_write_row_hits).name("write_row_hits_{}", m_channel_id);
88     register_stat(s_write_row_misses).name("write_row_misses_{}", m_channel_id);
89     register_stat(s_write_row_conflicts).name("write_row_conflicts_{}", m_channel_id);
90
91     for (size_t core_id = 0; core_id < m_num_cores; core_id++) {
92         register_stat(s_read_row_hits_per_core[core_id]).name("read_row_hits_core_{}", core_id);
93         register_stat(s_read_row_misses_per_core[core_id]).name("read_row_misses_core_{}", core_id);
94         register_stat(s_read_row_conflicts_per_core[core_id]).name("read_row_conflicts_core_{}", core_id);
95     }
96
97     register_stat(s_num_read_reqs).name("num_read_reqs_{}", m_channel_id);
98     register_stat(s_num_write_reqs).name("num_write_reqs_{}", m_channel_id);
99     register_stat(s_num_other_reqs).name("num_other_reqs_{}", m_channel_id);
100    register_stat(s_queue_len).name("queue_len_{}", m_channel_id);
101    register_stat(s_read_queue_len).name("read_queue_len_{}", m_channel_id);
102    register_stat(s_write_queue_len).name("write_queue_len_{}", m_channel_id);
103    register_stat(s_priority_queue_len).name("priority_queue_len_{}", m_channel_id);
104    register_stat(s_queue_len_avg).name("queue_len_avg_{}", m_channel_id);
105    register_stat(s_read_queue_len_avg).name("read_queue_len_avg_{}", m_channel_id);
106    register_stat(s_write_queue_len_avg).name("write_queue_len_avg_{}", m_channel_id);
107    register_stat(s_priority_queue_len_avg).name("priority_queue_len_avg_{}", m_channel_id);
108
109    register_stat(s_read_latency).name("read_latency_{}", m_channel_id);
110    register_stat(s_avg_read_latency).name("avg_read_latency_{}", m_channel_id);
111}
```

2.4. Frontend에서 core 수를 조회하여 m_num_cores에 저장

2.5. Read Row Hit Per Core, ... , Read Row Conflict Per Core 등의 배열 초기화 → multi core 지원을 위해 초기화

→ 위 배열들은 통계를 수집하고 출력 용도로만 사용됨

2.6. 다양한 통계 variable를 register하여 DRAM controller의 동작을 분석 → 통계를 수집하고 출력

src/dram_controller folder

□ DRAM Controller Operations

- class GenericDRAMController – send()

```
113  bool send(Request& req) override {
114    req.final_command = m_dram->m_request_translations(req.type_id);
115
116    switch (req.type_id) {
117      case Request::Type::Read: {
118        s_num_read_reqs++;
119        break;
120      }
121      case Request::Type::Write: {
122        s_num_write_reqs++;
123        break;
124      }
125      default: {
126        s_num_other_reqs++;
127        break;
128      }
129    }
130
131    // Forward existing write requests to incoming read requests
132    if (req.type_id == Request::Type::Read) {
133      auto compare_addr = [req](const Request& wreq) {
134        return wreq.addr == req.addr;
135      };
136      if (std::find_if(m_write_buffer.begin(), m_write_buffer.end(), compare_addr) != m_write_buffer.end()) {
137        // The request will depart at the next cycle
138        req.depart = m_clk + 1;
139        pending.push_back(req);
140        return true;
141      }
142    }
143
144    // Else, enqueue them to corresponding buffer based on request type id
145    bool is_success = false;
146    req.arrive = m_clk;
147    if (req.type_id == Request::Type::Read) {
148      is_success = m_read_buffer.enqueue(req);
149    } else if (req.type_id == Request::Type::Write) {
150      is_success = m_write_buffer.enqueue(req);
151    } else {
152      throw std::runtime_error("Invalid request type!");
153    }
154    if (!is_success) {
155      // We could not enqueue the request
156      req.arrive = -1;
157      return false;
158    }
159
160    return true;
161 }
```

src/dram_controller folder

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src/base folder

base

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