Operating System

Lecturer: Dr. Do Quoc Huy

Memory Management

Virtual Memory Paging Simulation with Page Replacement Algorithms

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1 Introduction

1.1 Motivation

Efficient memory management is essential for ensuring that a modern operating system remains both responsive and performant. Among the available techniques, paging stands out as a foundational approach: it enables non-contiguous use of physical memory, streamlines address translation, and underpins the realization of virtual memory. The effectiveness of paging, however, hinges on the chosen page replacement algorithm - particularly in environments where physical frames are limited and multiple processes contend for resources.
This project addresses the gap between theoretical descriptions and practical behavior by simulating a variety of page replacement strategies under identical workloads and measuring their performance characteristics. Its objectives include:

- **Deepen conceptual understanding**: Rather than relying solely on abstract explanations, the simulation reveals how algorithms such as FIFO, LRU... respond to realistic page-request streams.
- **Quantifying trade-offs**: Each algorithm carries its own set of advantages and disadvantages - some minimize page faults in certain scenarios, while others are simpler to implement but may perform poorly under specific access patterns. Through simulation, we can compare hit rates, fault rates, and overhead costs to determine which algorithm is "best" under different constraints.
- **Informing design choices**: Operating system architects must select replacement policies that strike an appropriate balance between implementation complexity, memory overhead, and runtime performance. Insights gleaned from this hands-on exploration clarify why particular algorithms are favored in production systems and under what circumstances an alternative might prove more advantageous.

By examining and contrasting different page replacement schemes, this work offers a nuanced perspective on how operating systems manage scarce physical memory, make eviction decisions, and ultimately influence overall system behavior and application performance.

1.2 Overview of Memory Management in Operating Systems

In any computing environment, the CPU executes instructions and processes data, but it can only operate on information present in memory. Because memory is structured in a hierarchy—registers and caches closest to the CPU for fastest access, followed by main memory (RAM), and then secondary storage (disk or SSD) with greater capacity but higher latency—the operating system must coordinate data movement across these layers to sustain efficient execution, even when the aggregate demand for memory exceeds physical capacity.

Effective memory management addresses several critical responsibilities:

- **Address Translation**: Programs issue requests using logical (or virtual) addresses, which must be translated into physical addresses before memory access. This translation must occur rapidly (to avoid performance bottlenecks) and enforce strict isolation (to prevent one process from accessing another's data).
- **Dynamic Memory Allocation**: As processes allocate, deallocate, and resize their memory footprints, the operating system must assign and reclaim memory regions on the fly, minimizing fragmentation and avoiding wasted space.
- **Memory Sharing**: When multiple processes require access to the same code libraries or shared data buffers, the operating system must map those shared pages into each process's address space without compromising process isolation.
- **Memory Protection**: Hardware-enforced protection bits and page table entries guarantee that read, write, or execute permissions are respected, so that one process cannot inadvertently - or maliciously - modify another's memory.

Traditional contiguous allocation schemes (such as fixed or dynamic partitions) struggle to accommodate modern workloads with highly variable and large memory demands. Paging addresses these limitations by dividing both physical memory and each process's virtual address space into equal-sized units - frames and pages, respectively. A page table maintained per process maps virtual pages to physical frames; when a process references a page not currently resident in RAM, a page fault is generated. The operating system then loads the required page from secondary storage into a free frame or, if no free frame exists, selects an existing page to evict according to a replacement policy.

Paging delivers several key advantages:

- **Non-Contiguous Allocation**: By allowing pages to reside in physically disparate frames, external fragmentation is greatly reduced, and memory utilization becomes more flexible.
- **Simplified Address Translation**: Hardware support such as a Translation Lookaside Buffer (TLB) accelerates the mapping from virtual to physical addresses, minimizing translation overhead.
- **Virtual Memory**: Processes behave as though they possess a large, contiguous address space - far exceeding physical RAM - since the operating system transparently pages data between RAM and secondary storage as needed.
- **Protection and Isolation**: Each page table entry can enforce read, write, and execute permissions, ensuring that processes cannot interact with pages they do not own.

Although paging streamlines memory allocation and protection, it also introduces complexity in determining which page to evict when physical frames are exhausted. An effective replacement policy must balance eviction accuracy against implementation overhead, because optimal foresight of future memory references is unattainable in practice. This trade-off shapes overall system performance, as different policies yield varying impacts on hit rates, fault rates, and runtime overhead.

1.3 Scope and Limitations

This project delivers a command-line simulation of virtual memory management via paging, focusing on how an operating system responds to memory access requests and resolves page faults through different replacement policies. Specifically, the simulation:

- Implements five established page replacement algorithms - Least Recently Used (LRU), First In First Out (FIFO), Least Frequently Used (LFU), Not Recently Used (NRU), and Second Chance - each encapsulated within a unified framework.
- Enables users to specify both the number of logical pages and the number of physical frames, then to provide a custom sequence of page-reference requests.

- Collects and reports essential performance metrics, including total page hits, total page faults, hit ratio, and fault ratio, allowing direct comparison across algorithms.

Despite its educational value, the simulation does not attempt to replicate every subtlety of a real operating system. Its primary limitations include:

- **Absence of Hardware Interaction**: This is purely a software model running in user space; it does not interface with actual CPU or memory hardware, nor does it reside in an OS kernel.
- **Simplified Memory Model**: All pages and frames are assumed to be the same fixed size. The simulation does not account for address translation overhead (e.g., TLB misses), memory protection mechanisms, or the time costs associated with disk I/O when loading pages from secondary storage.
- **Exclusion of Optimal Policy**: Algorithms that require foreknowledge of future memory references - such as Belady's Optimal - are omitted, since their practical implementation is infeasible without perfect prediction.

By narrowing the focus to these five replacement strategies and abstracting away lower-level details, the simulation remains both tractable and instructive. It offers a clear, hands-on demonstration of how different eviction policies impact overall memory performance, while acknowledging that real-world operating systems involve additional layers of complexity.

1.4 Purpose of the Project

- **Examine fundamental principles and responsibilities of memory management**, emphasizing its pivotal role in maximizing system performance, maintaining process isolation, and ensuring efficient allocation of resources.
- **Analyze established memory management methodologies**, with a primary focus on paging—addressing concerns such as fragmentation, logical-to-physical address translation, and optimizing memory access.
- **Implement and simulate five prevalent page replacement algorithms in C++** - including Least Recently Used (LRU), First In First Out (FIFO), Least Frequently Used (LFU), Not Recently Used

(NRU), and Second Chance - to demonstrate each algorithm's behavior across diverse access patterns.

- **Evaluate and compare algorithmic performance** using quantitative metrics (page hit count, page fault count, hit ratio, and fault ratio), thereby revealing the relative efficiency of each strategy under varying memory-usage scenarios.

By uniting theoretical concepts with hands-on implementation, this project delivers a comprehensive analysis of how paging and replacement techniques influence operating system memory management.

2 Main Content

2.1 Implementation of Page Replacement Strategies

This project implements five classical page-replacement strategies within a unified C++ framework. Each algorithm manages which page to evict when physical memory frames are exhausted, trading off between simplicity, performance overhead, and fault-minimization capabilities.

Least Recently Used (LRU)

Concept: LRU evicts the page that has not been accessed for the longest time, on the assumption that pages used recently are more likely to be used again soon.

Implementation Details:

- Each page-table entry maintains a `last_access_time` field, updated on every access.
- When a page fault occurs and no free frames remain, the simulator scans all resident pages, selects the one with the smallest `last_access_time` value (i.e., the "oldest" reference), and evicts it.
- The freed frame is then assigned to the newly requested page.

First In First Out (FIFO)

Concept: FIFO evicts pages in the order they were loaded into memory - i.e., the first page to arrive is the first to be evicted—regardless of how often or recently it has been accessed.

Implementation Details:

- A simple queue (`fifo_queue`) tracks the sequence of page numbers as they are loaded.

- On a page fault with no free frame, the page at the front of `fifo_queue` is evicted (popped from the queue and removed from memory), and its frame is recycled.
- The newly loaded page is appended to the back of `fifo_queue`.

Least Frequently Used (LFU)

Concept: LFU evicts the page with the lowest frequency of accesses, under the assumption that pages accessed seldomly are less likely to be needed again.

Implementation Details:

- A vector of pairs, `lfu_list`, tracks `<page_number, frequency_count>` for each resident page.
- Every time a page in memory is accessed, its frequency counter is incremented.
- During eviction, the page with the smallest frequency count in `lfu_list` is chosen as victim. That entry is then removed from `lfu_list`, its frame is freed, and the new page is loaded in its place with frequency initialized to 1.

Not Recently Used (NRU)

Concept: NRU classifies pages into four categories (classes 0–3) based on their *referenced* (R) and *modified* (M) bits:

$$\begin{array}{lcl} R = 0,\ M = 0 & \rightarrow & \text{Class 0 (unreferenced, unmodified)} \\ R = 0,\ M = 1 & \rightarrow & \text{Class 1 (unreferenced, modified)} \\ R = 1,\ M = 0 & \rightarrow & \text{Class 2 (referenced, unmodified)} \\ R = 1,\ M = 1 & \rightarrow & \text{Class 3 (referenced, modified)} \end{array}$$

When eviction is required, the algorithm picks a victim from the lowest-numbered nonempty class, evicting "unused and unmodified" pages first. Periodically, all R bits are reset to zero to prevent starvation of higher-class pages.

Implementation Details:

- Each `Page` object has:
  - A `referenced` flag (set to 1 upon every access).
  - A `modified` flag (randomly simulated as "write" with 40% chance on each access, to approximate dirty pages).

- Every `RESET_INTERVAL` accesses (where `RESET_INTERVAL = 10`), the code calls `reset_reference_bits()`, clearing all R bits to 0.
- On eviction, all valid pages are grouped into four vectors (`class_0`, `class_1`, `class_2`, `class_3`) based on their (R, M) values. The first nonempty vector in class order yields the eviction candidate, whose frame is then freed.

Second Chance

Concept: Second Chance is a FIFO-like algorithm that gives each page a "second chance" if its R bit is set. Pages are arranged in a circular queue. When eviction is required, the front page is inspected:

- If R = 0, evict it;
- If R = 1, clear its R bit, move it to the back of the queue, and continue scanning until a page with R = 0 is found.

This approximates LRU behavior at lower implementation complexity, because it does not require sorting by exact recency.

Implementation Details:

- A `second_chance_queue` vector holds page numbers in the order they were loaded.
- On each access, the page's `referenced` bit is set to 1.
- Every `RESET_INTERVAL` accesses, all R bits are reset to 0 via `reset_reference_bits()`.
- When a page fault occurs and no free frame remains, the code repeatedly inspects - and possibly rotates - pages in `second_chance_queue` until it finds one with R = 0, evicting that page.

2.2 Functions and Their Purposes

All page-table logic resides in the `PageTable` class (declared in `PageTable.h` and implemented in `virtual_memory_manager.cpp`). The `main()` function within `virtual_memory_manager.cpp` handles user interaction, invokes the appropriate `PageTable` methods, and computes final metrics. Below is a breakdown of every function and its role.

2.2.1 *pagetable.h*

```
class PageTable {
private:
    ll current_time;
    ll page_fault_count;
    ll access_counter = 0;

    class Page {
    public:
        ll last_access_time;
        ll frame_number;
        int is_valid, referenced, modified;

        Page() : last_access_time(0), frame_number(-1), is_valid(0), referenced(0), modified(0) {}
    };

    vector<Page> page_table;
    vector<ll> free_frame_list;
    vector<ll> fifo_queue;
    vector<pair<ll, ll>> lfu_list;
    vector<ll> second_chance_queue;

    ll replace_page(int choice);
    ll evict_page(ll victim_page_index);
    void reset_reference_bits();

public:
    PageTable(ll logical_memory_size, ll physical_memory_size);

    bool is_page_in_memory(ll page_number);
    void access_page(ll page_number, int choice);
    void load_page(ll page_number, int choice);
    void display_page_table();
    ll get_page_fault_count();
    void set_page_fault_count(int count);
};
```

- **Constructor:**

```
PageTable::PageTable(ll logical_memory_size, ll physical_memory_size) : current_time(1), page_fault_count(0) {
    for (ll i = physical_memory_size - 1; i >= 0; i--) {
        free_frame_list.push_back(i);
    }
    page_table.resize(logical_memory_size);
}
```

  – *Purpose:* Initialize internal data structures.

– *Details:*

* Set `current_time = 1`, `page_fault_count = 0`, `access_counter = 0`.
* Build `free_frame_list` containing all frame indices `0 ... physical_memory_size - 1`.
* Resize `page_table` to hold `logical_memory_size` entries, each initially invalid.

- **Resident-Check:**

```
bool PageTable::is_page_in_memory(ll page_number) {
    return page_table[page_number].is_valid;
}
```

– *Purpose:* Check if a given page is currently resident (valid) in physical memory.

– *Details:* Return `true` if `page_table[page_number].is_valid == 1`.

- **Page Access Update:**

```cpp
void PageTable::access_page(ll page_number, int choice) {
    ll frame = page_table[page_number].frame_number;

    page_table[page_number].last_access_time = current_time++;
    page_table[page_number].referenced = 1;

    // Simulate memory access type with 40% probability for write operations.
    // If the result is less than 4 (out of 10), it's a write (modified = 1); otherwise, it's a read.

    page_table[page_number].modified = (rand() % 10 < 4) ? 1 : 0;

    if (choice == 3) {
        for (auto& entry : lfu_list) {
            if (entry.first == page_number) {
                entry.second++;
                break;
            }
        }
    }

    access_counter++;

    if ((choice == 4 || choice == 5) && access_counter % RESET_INTERVAL == 0) {
        reset_reference_bits();
        cout << "[Info] Reference bits reset.\n";
    }

    display_page_table();

    cout << "Page " << page_number << " accessed in frame " << frame << ".\n\n";
}
```

– *Purpose:* Update data when a page is accessed (either on a hit or immediately after loading it).

– *Details:*

* Record `current_time` into `page_table[page_number].last_access_time` before incrementing `current_time`.
* Set the page's `referenced` bit to 1.
* Randomly set the page's `modified` bit to 1 with 40% probability.
* If `choice == 3` (LFU), find that page in `lfu_list` and increment its frequency.
* Increment `access_counter`. If `(choice == 4 || choice ==`

5) and access_counter % RESET_INTERVAL == 0, call reset_reference_bits().

* Call display_page_table() and print "Page <page_number> accessed in frame <frame_number>."

- **Page Load (on fault):**

```
void PageTable::load_page(ll page_number, int choice) {
    ll frame;

    if (!free_frame_list.empty()) {
        frame = free_frame_list.back();
        free_frame_list.pop_back();
    } else {
        frame = replace_page(choice);
    }

    page_table[page_number].frame_number = frame;
    page_table[page_number].is_valid = 1;

    cout << "Page Fault: Loaded page " << page_number << " into frame " << frame << ".\n";

    page_fault_count++;

    switch (choice) {
        case 2:
            fifo_queue.push_back(page_number);
            break;
        case 3:
            lfu_list.push_back({ page_number, 1 });
            break;
        case 5:
            second_chance_queue.push_back(page_number);
            break;
    }
}
```

  – *Purpose:* Handle a page fault by loading the requested page into memory.

  – *Details:*

    * If free_frame_list is nonempty, pop a frame from its back; otherwise, invoke replace_page(choice) to evict a victim.

* Mark `page_table[page_number]` as valid in that frame.
* Increment `page_fault_count` and print a "Page Fault" message.
* For FIFO (`choice == 2`), append `page_number` to `fifo_queue`.
* For LFU (`choice == 3`), push `<page_number, 1>` into `lfu_list`.
* For Second Chance (`choice == 5`), append `page_number` to `second_chance_queue`.

- **Page Replacement:**

```
case 1: {
            ll earliest_time = current_time;
            ll victim_page_index = -1;
            for (ll j = 0; j < page_table.size(); j++) {
                if (page_table[j].is_valid == 1) {
                    if (page_table[j].last_access_time < earliest_time) {
                        earliest_time = page_table[j].last_access_time;
                        victim_page_index = j;
                    }
                }
            }
            frame_to_free = evict_page(victim_page_index);
            break;
        }
```

```
case 2: {
            ll victim_page_index = fifo_queue.front();
            fifo_queue.erase(fifo_queue.begin());
            frame_to_free = evict_page(victim_page_index);
            break;
        }
```

```
case 3: {
            ll least_frequent_index = 0;
            for (ll i = 1; i < lfu_list.size(); i++) {
                if (lfu_list[i].second < lfu_list[least_frequent_index].second) {
                    least_frequent_index = i;
                }
            }
            ll victim_page_index = lfu_list[least_frequent_index].first;
            lfu_list.erase(lfu_list.begin() + least_frequent_index);
            frame_to_free = evict_page(victim_page_index);
            break;
        }
```

```
case 5: {
              while (true) {
                  ll candidate_page = second_chance_queue.front();
                  second_chance_queue.erase(second_chance_queue.begin());
                  if (page_table[candidate_page].referenced == 0) {
                      frame_to_free = evict_page(candidate_page);
                      break;
                  } else {
                      page_table[candidate_page].referenced = 0;
                      second_chance_queue.push_back(candidate_page);
                  }
              }
              break;
          }
```

```
case 4: {
            vector<ll> class_0, class_1, class_2, class_3;
            for (ll i = 0; i < page_table.size(); i++) {
                if (page_table[i].is_valid) {
                    int R = page_table[i].referenced;
                    int M = page_table[i].modified;
                    if (R == 0 && M == 0)
                        class_0.push_back(i);
                    else if (R == 0 && M == 1)
                        class_1.push_back(i);
                    else if (R == 1 && M == 0)
                        class_2.push_back(i);
                    else
                        class_3.push_back(i);
                }
            }
            vector<ll>* victim_class = nullptr;
            if (!class_0.empty())
                victim_class = &class_0;
            else if (!class_1.empty())
                victim_class = &class_1;
            else if (!class_2.empty())
                victim_class = &class_2;
            else
                victim_class = &class_3;
            ll victim_page_index = (*victim_class)[0];
            frame_to_free = evict_page(victim_page_index);
            break;
        }
```

– *Purpose:* Select a resident page to evict when no free frames exist.

– *Details:* Behavior depends on `choice`:

* **LRU (1):** Scan all valid pages, find minimal `last_access_time`, evict it.
* **FIFO (2):** Pop front of `fifo_queue`, evict that page.
* **LFU (3):** Scan `lfu_list` for minimal frequency, remove that entry, evict corresponding page.
* **NRU (4):**
  · Partition valid pages into four classes based on `(referenced,modified)`.
  · Evict the first page in the lowest-numbered nonempty class.
* **Second Chance (5):**
  · Repeatedly pop from front of `second_chance_queue`:
  · If page's `referenced == 0`, evict it; else set `referenced = 0` and push it to the back.

– Return the freed frame index (via `evict_page(victim_page_index)`).

- **Evict Page:**

```
ll PageTable::evict_page(ll victim_page_index) {
    ll frame_to_free = page_table[victim_page_index].frame_number;
    page_table[victim_page_index].is_valid = 0;
    page_table[victim_page_index].frame_number = -1;
    page_table[victim_page_index].referenced = 0;
    page_table[victim_page_index].modified = 0;
    page_table[victim_page_index].last_access_time = 0;
    return frame_to_free;
}
```

– *Purpose:* Remove a specified page from physical memory, resetting its data.

– *Details:*

* Store `frame_to_free = page_table[victim_page_index].frame_number`.
* Set `is_valid = 0`, `frame_number = -1`, `referenced = 0`, `modified = 0`, `last_access_time = 0`.

* Return `frame_to_free`.

- **Reset Reference Bits:**

```
void PageTable::reset_reference_bits() {
    for (auto& page : page_table) {
        page.referenced = 0;
    }
}
```

  - *Purpose:* Clear the `referenced` bit on every page entry - used by NRU and Second Chance to avoid indefinite retention.
  - *Details:* Iterate over all pages in `page_table` and set `referenced = 0`.

- **Display Page Table:**

```
void PageTable::display_page_table() {
    cout << "\n==== PAGE TABLE ====\n";
    cout << "+--------------+---------------+-------------+-------------------+--------------+------------+\n";
    cout << "|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |\n";
    cout << "+--------------+---------------+-------------+-------------------+--------------+------------+\n";
    for (int i = 0; i < page_table.size(); i++) {
        cout << "| " << setw(13) << left << i
             << "| " << setw(15) << page_table[i].frame_number
             << "| " << setw(12) << (page_table[i].is_valid ? "YES" : "NO")
             << "| " << setw(19) << page_table[i].last_access_time
             << "| " << setw(13) << (page_table[i].referenced ? "YES" : "NO")
             << "| " << setw(11) << (page_table[i].modified ? "YES" : "NO")
             << "|\n";
        cout << "+--------------+---------------+-------------+-------------------+--------------+------------+\n";
    }

    cout << "\n==== FREE FRAME POOL ====\n";
    cout << "+----------------------+\n";
    cout << "|     Frame Index      |\n";
    cout << "+----------------------+\n";
    for (int frame : free_frame_list) {
        cout << "| " << setw(20) << left << frame << "|\n";
        cout << "+----------------------+\n";
    }
}
```

– *Purpose:* Print a human-readable snapshot of every page's status plus the list of free frames.

– *Details:*

∗ Output a table header with columns:

```
+--------------+---------------+------------+------------------+-------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+------------+------------------+-------------+------------+
```

∗ For each page index i:

· Show i, `frame_number` (or "-1" if invalid), "YES/NO" for `is_valid`, numeric `last_access_time`, and "YES/NO" for `referenced` and `modified`.

∗ After each row, print a separator line.

∗ Then print a "Free Frame Pool" table listing all indices in `free_frame_list`.

- **Get/Set Page Fault Count:**

```cpp
void PageTable::set_page_fault_count(int count) {
    page_fault_count = count;
}


ll PageTable::get_page_fault_count() {
    return page_fault_count;
}
```

– *Purpose:* Accessor and mutator for `page_fault_count`.

– *Details:* `get_page_fault_count()` returns the final fault total; `set_page_fault_count()` resets the counter to a provided value.

2.2.2 virtual_memory_manager.cpp

- **Read Memory Sizes:**

```
cout << "Enter the number of pages in logical memory space: ";
cin >> logical_memory_size;

if (!is_valid_size(logical_memory_size)) {
    cerr << "Error: Invalid number of logical pages.\n";
    return 1;
}

cout << "Enter the number of frames in physical memory space: ";
cin >> physical_memory_size;

if (!is_valid_size(physical_memory_size)) {
    cerr << "Error: Invalid number of physical frames.\n";
    return 1;
}
```

  - *Purpose:* Let the user specify how many virtual pages and how many physical frames to simulate. Negative or zero values are rejected.

- **Main Menu Loop:**

```
while (true) {
    cout << "\nSelect a page replacement algorithm:\n";
    cout << "1. Least Recently Used (LRU)\n";
    cout << "2. First In First Out (FIFO)\n";
    cout << "3. Least Frequently Used (LFU)\n";
    cout << "4. Not Recently Used (NRU)\n";
    cout << "5. Second Chance\n";
    cout << "6. Exit\n";
    cout << "Your choice: ";
    cin >> choice;

    if (choice == 6) {
        cout << "Goodbye!\n";
        break;
    }

    if (choice < 1 || choice > 6) {
        cerr << "Invalid choice. Please select a number between 1 and 6.\n";
        continue;
    }
```

  - *Purpose:* Repeatedly present choices 1-5 for the five replacement policies (6 to exit). Input is validated to ensure an integer in $[1, 6]$.

- **Simulation Setup:**

```
PageTable page_table(logical_memory_size, physical_memory_size);
page_table.set_page_fault_count(0);

ll page_hit_count = 0;

cout << "Enter the number of page accesses: ";
cin >> reference_count;

ll page_references[reference_count];
```

– *Purpose:*

* Create a fresh `PageTable` object for each run.
* Reset the page-fault counter to zero.
* Initialize `page_hit_count`.
* Read how many page references will be simulated.

- **Reading and Simulating Page References:**

```
for (ll i = 0; i < reference_count; i++) {
    cout << "\n[Input] Enter page number #" << i + 1 << ": ";
    cin >> page_references[i];
    page_number = page_references[i];
    cout << "Accessing page " << page_number << "...\n\n";
    if (page_number < 0 || page_number > logical_memory_size - 1) {
        cerr << "Invalid page number. Please enter a number between 0 and " << logical_memory_size - 1 << ".\n";
        i--;
        continue;
    }
    if (page_table.is_page_in_memory(page_number)) {
        page_hit_count++;
        page_table.access_page(page_number, choice);
    } else {
        page_table.load_page(page_number, choice);
        page_table.access_page(page_number, choice);
    }
}
```

– *Purpose:*

* Prompt the user for each page reference in the specified sequence.
* Validate that `page_number` is within $[0, \mathit{logical\_memory\_size} - 1]$. If invalid, repeat the iteration.
* On a *hit* (`is_page_in_memory(...)` returns `true`): increment `page_hit_count` and call `access_page(...)` to update data.
* On a *fault*: call `load_page(...)` to allocate or evict a page, then call `access_page(...)` to set the initial `referenced`, `modified`, `last_time_access` fields.

- **Final Metrics Calculation and Display:**

```
int page_fault_count = page_table.get_page_fault_count();
double hit_ratio = static_cast<double>(page_hit_count) / reference_count;
double fault_ratio = static_cast<double>(page_fault_count) / reference_count;


cout << "\n=== Simulation Result ===\n";
cout << "Total page accesses: " << reference_count << "\n";
cout << "Total page hits: " << page_hit_count << "\n";
cout << "Total page faults: " << page_fault_count << "\n";
cout << fixed << setprecision(2);
cout << "Hit ratio: " << hit_ratio * 100 << "%\n";
cout << "Fault ratio: " << fault_ratio * 100 << "%\n";
```

  - *Purpose:*
    - Retrieve the final page-fault count.
    - Compute `hit_ratio` and `fault_ratio`.
    - Print a concise summary showing total accesses, hits, faults, and percentages with two-digit precision.

2.3 Execution Flow

1. **User provides:**
   - Number of logical pages (N_p).
   - Number of physical frames (N_f).
   - Choice of replacement algorithm (1–5).
   - Number of page references (R).
   - Sequence of R page numbers (each in $[0,\ N_p - 1]$).
2. **Constructs** a `PageTable`(N_p, N_f).
3. **For each referenced page** p**:**
   - If p is already valid (resident in memory):
     - Increment the hit counter.
     - Call `PageTable::access_page`(p, *choice*) to update `referenced`, `modified`, and `last_access_time`.
   - Otherwise (page fault):

- Call `PageTable::load_page(`p, *choice*`)` to allocate a free frame or evict a victim via `replace_page(choice)`.
- Inside `load_page`, if no free frame exists, `replace_page(choice)` eventually calls `evict_page(victim)`.
- Call `PageTable::access_page(`p, *choice*`)` to set initial `referenced`, `modified`, and `last_access_time` fields.

4. **During simulation:**
   - Every 10 accesses, `reset_reference_bits()` is invoked to clear all pages' `referenced` bits.
5. **After R references,** `virtual_memory_manager.cpp` queries `page_fault_count` and computes final ratios for output.

3 Demonstration and Comparative Evaluation of Page Replacement Algorithms

3.1 Demonstration

- Number of logical pages: $N_p = 8$.
- Number of physical frames: $N_f = 3$.
- Number of page references: $R = 10$.
- Sequence of R page numbers: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3

3.1.1 *Least Recently Used (LRU)*

```
Page Fault: Loaded page 7 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
| 2                   |
+---------------------+
| 1                   |
+---------------------+
Page 7 accessed in frame 0.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+---------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number |  Valid Bit |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+------------+--------------------+--------------+------------+
| 0            | 1             | YES        | 2                  | YES          | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 1            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 2            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 3            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 4            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 5            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 6            | -1            | NO         | 0                  | NO           | NO         |
+--------------+---------------+------------+--------------------+--------------+------------+
| 7            | 0             | YES        | 1                  | YES          | YES        |
+--------------+---------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 1 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 1 accessed in frame 2.
```

```
Page Fault: Loaded page 2 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 4                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 2 accessed in frame 0.
```

```
==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 1.
```

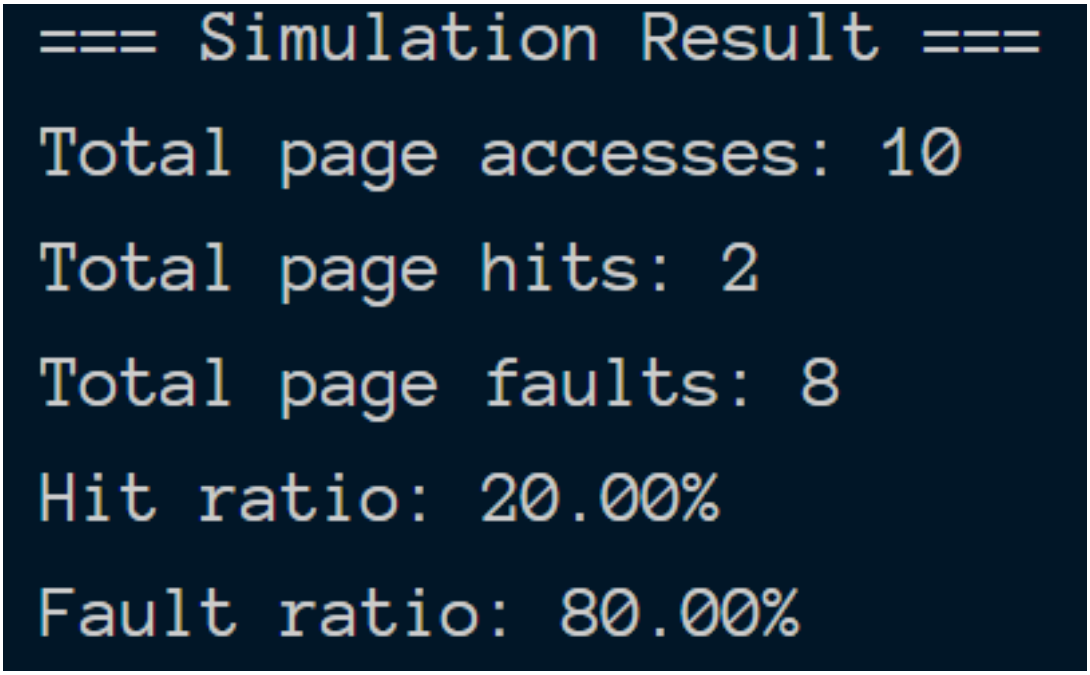
```
Page Fault: Loaded page 3 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | 2              | YES         | 6                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 3 accessed in frame 2.
```

```
==== PAGE TABLE ====
+--------------+---------------+------------+-------------------+--------------+------------+
|  Page Index  |  Frame Number |  Valid Bit |  Last Access Time |  Referenced  |  Modified  |
+--------------+---------------+------------+-------------------+--------------+------------+
| 0            | 1             | YES        | 7                 | YES          | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 1            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 2            | 0             | YES        | 4                 | YES          | YES        |
+--------------+---------------+------------+-------------------+--------------+------------+
| 3            | 2             | YES        | 6                 | YES          | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 4            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 5            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 6            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 7            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 4 into frame 0.

==== PAGE TABLE ====
+--------------+---------------+------------+-------------------+--------------+------------+
|  Page Index  |  Frame Number |  Valid Bit |  Last Access Time |  Referenced  |  Modified  |
+--------------+---------------+------------+-------------------+--------------+------------+
| 0            | 1             | YES        | 7                 | YES          | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 1            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 2            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 3            | 2             | YES        | 6                 | YES          | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 4            | 0             | YES        | 8                 | YES          | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 5            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 6            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+
| 7            | -1            | NO         | 0                 | NO           | NO         |
+--------------+---------------+------------+-------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 4 accessed in frame 0.
```

```
Page Fault: Loaded page 2 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 7                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 2              | YES         | 9                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | 0              | YES         | 8                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 2.
```

```
Page Fault: Loaded page 3 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 2              | YES         | 9                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | 1              | YES         | 10                 | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | 0              | YES         | 8                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 3 accessed in frame 1.
```



3.1.2 First In First Out (FIFO)

```
Page Fault: Loaded page 7 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
| 1                  |
+--------------------+
Page 7 accessed in frame 0.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 1 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 1 accessed in frame 2.
```

```
Page Fault: Loaded page 2 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 4                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 0.
```

```
==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 5                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 4                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 1.
```

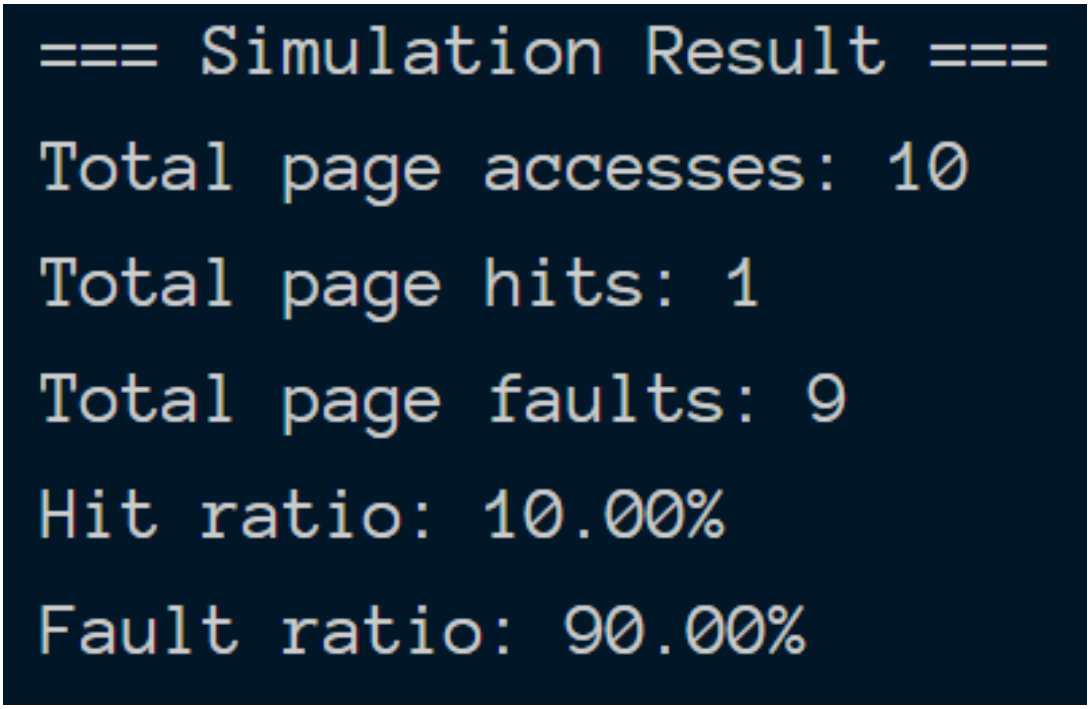
```
Page Fault: Loaded page 3 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 4                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | 1              | YES         | 6                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 3 accessed in frame 1.
```

```
Page Fault: Loaded page 0 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 2              | YES        | 7                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | 0              | YES        | 4                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | 1              | YES        | 6                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 2.
```

```
Page Fault: Loaded page 4 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 2              | YES        | 7                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | 1              | YES        | 6                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | 0              | YES        | 8                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 4 accessed in frame 0.
```

```
Page Fault: Loaded page 2 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 2              | YES         | 7                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 1              | YES         | 9                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | 0              | YES         | 8                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 2 accessed in frame 1.
```

```
Page Fault: Loaded page 3 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 1              | YES         | 9                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | 2              | YES         | 10                 | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | 0              | YES         | 8                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 3 accessed in frame 2.
```



3.1.3 *Least Frequently Used (LFU)*

```
Page Fault: Loaded page 7 into frame 0.

==== PAGE TABLE ====
+--------------+---------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 0            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 1            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 2            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 3            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 4            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 5            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 6            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+-------------+
| 7            | 0             | YES         | 1                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
| 2                   |
+---------------------+
| 1                   |
+---------------------+
Page 7 accessed in frame 0.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 1 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 1 accessed in frame 2.
```

```
Page Fault: Loaded page 2 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 0.
```

```
==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 1.
```

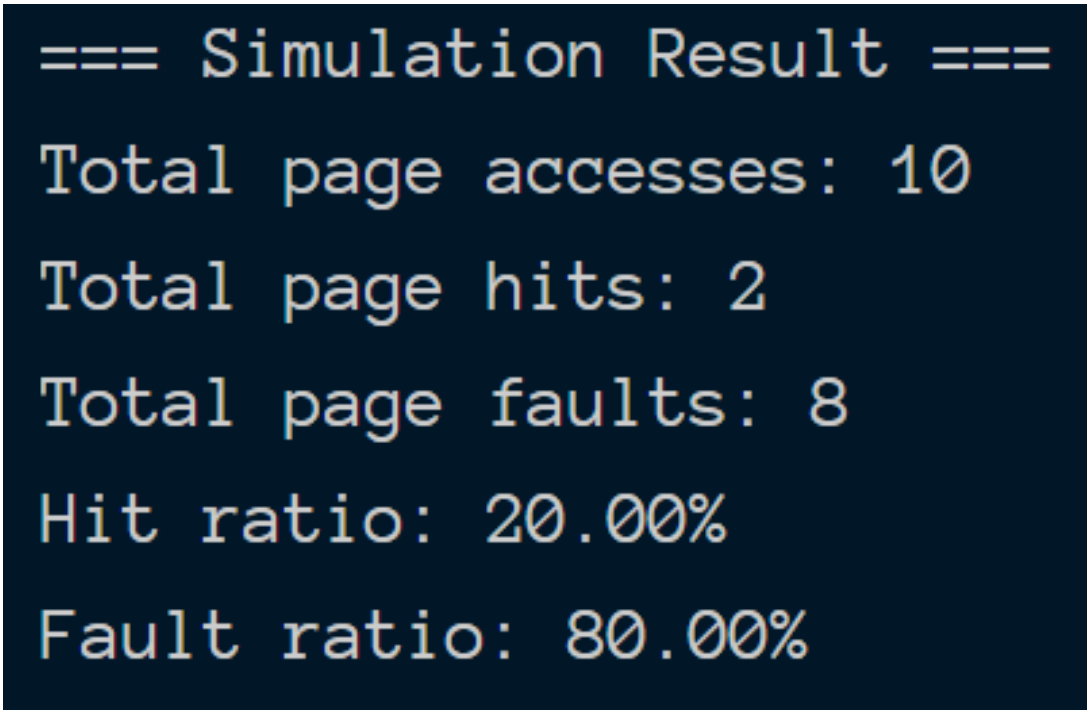
```
Page Fault: Loaded page 3 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | 2              | YES         | 6                  | YES          | YES        |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 3 accessed in frame 2.
```

```
==== PAGE TABLE ====
+--------------+---------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 0            | 1             | YES         | 7                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 1            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 2            | 0             | YES         | 4                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 3            | 2             | YES         | 6                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 4            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 5            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 6            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 7            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 4 into frame 0.

==== PAGE TABLE ====
+--------------+---------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 0            | 1             | YES         | 7                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 1            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 2            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 3            | 2             | YES         | 6                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 4            | 0             | YES         | 8                  | YES          | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 5            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 6            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 7            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 4 accessed in frame 0.
```

```
Page Fault: Loaded page 2 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 7                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 2              | YES         | 9                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | 0              | YES         | 8                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 2.
```

```
Page Fault: Loaded page 3 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 7                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 2              | YES         | 9                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 0              | YES         | 10                 | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 3 accessed in frame 0.
```



3.1.4 Not Recently Used (NRU)

```
Page Fault: Loaded page 7 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
| 2                   |
+---------------------+
| 1                   |
+---------------------+
Page 7 accessed in frame 0.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+------------+--------------------+--------------+------------+
| 0            | 1              | YES        | 2                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 1            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 2            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 3            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 4            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 5            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 6            | -1             | NO         | 0                  | NO           | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+
| 7            | 0              | YES        | 1                  | YES          | NO         |
+--------------+----------------+------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 1 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | 1              | YES         | 2                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 1 accessed in frame 2.
```

```
Page Fault: Loaded page 2 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 1              | YES         | 4                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | 0              | YES         | 1                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 2 accessed in frame 1.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 0 accessed in frame 1.
```

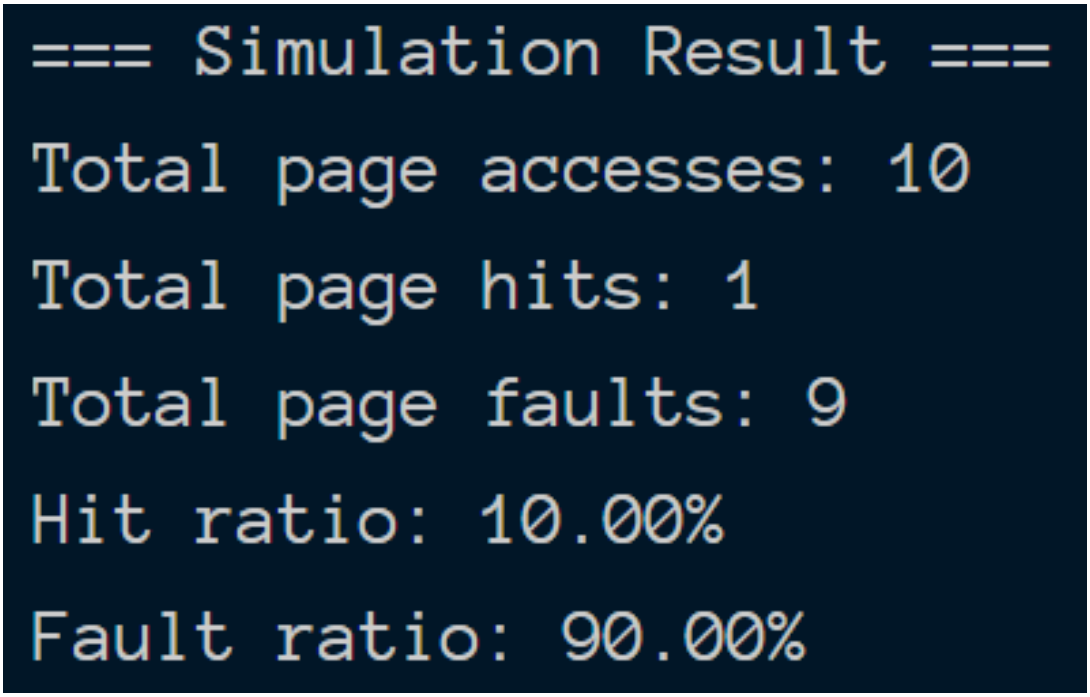
```
Page Fault: Loaded page 3 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 1              | YES         | 6                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 3 accessed in frame 1.
```

```
Page Fault: Loaded page 0 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 0              | YES         | 7                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 1              | YES         | 6                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 0 accessed in frame 0.
```

```
Page Fault: Loaded page 4 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 1              | YES         | 6                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | 0              | YES         | 8                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 4 accessed in frame 0.
```

```
Page Fault: Loaded page 2 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 9                  | YES          | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | 1              | YES         | 6                  | YES          | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 0.
```

```
[Info] Reference bits reset.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+-------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified   |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 0            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 1            | 2              | YES         | 3                  | NO           | YES         |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 2            | 0              | YES         | 9                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 3            | 1              | YES         | 10                 | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 4            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 5            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 6            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+
| 7            | -1             | NO          | 0                  | NO           | NO          |
+--------------+----------------+-------------+--------------------+--------------+-------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 3 accessed in frame 1.
```



3.1.5 Second Chance

```
Page Fault: Loaded page 7 into frame 0.

==== PAGE TABLE ====
+--------------+---------------+------------+--------------------+-------------+------------+
|  Page Index  |  Frame Number |  Valid Bit |  Last Access Time  |  Referenced |  Modified  |
+--------------+---------------+------------+--------------------+-------------+------------+
| 0            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 1            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 2            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 3            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 4            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 5            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 6            | -1            | NO         | 0                  | NO          | NO         |
+--------------+---------------+------------+--------------------+-------------+------------+
| 7            | 0             | YES        | 1                  | YES         | YES        |
+--------------+---------------+------------+--------------------+-------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
| 1                  |
+--------------------+
Page 7 accessed in frame 0.
```

```
Page Fault: Loaded page 0 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
| 2                  |
+--------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 1 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | 0              | YES         | 1                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 1 accessed in frame 2.
```

```
Page Fault: Loaded page 2 into frame 0.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 2                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+--------------------+
|     Frame Index    |
+--------------------+
Page 2 accessed in frame 0.
```

```
==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | 2              | YES         | 3                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 0 accessed in frame 1.
```

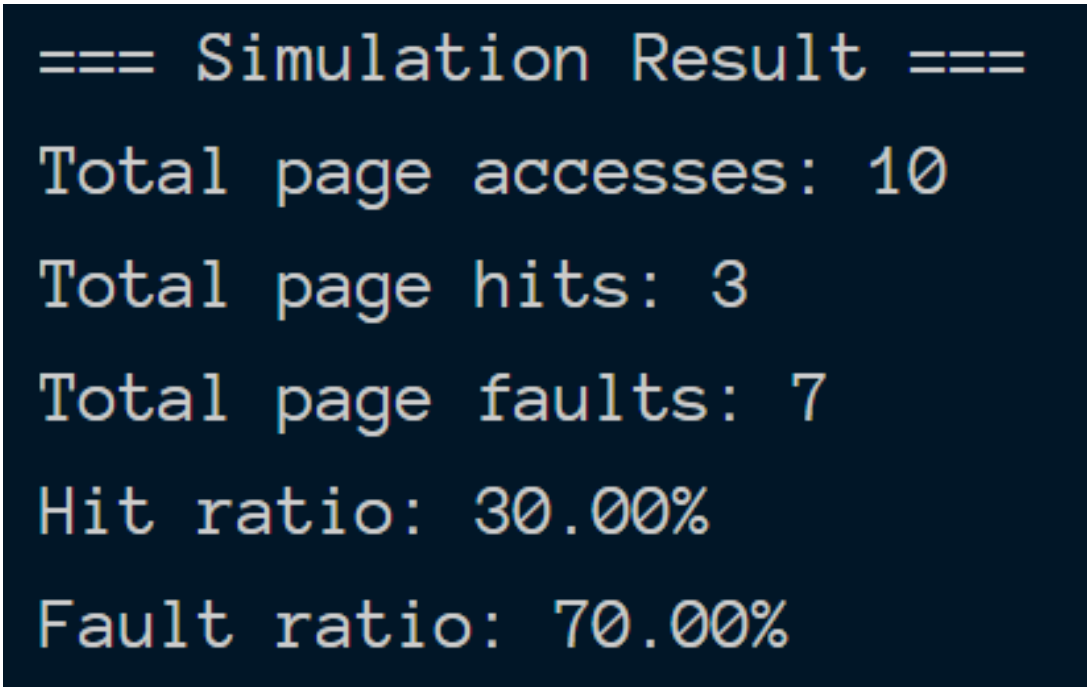
```
Page Fault: Loaded page 3 into frame 2.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | 1              | YES         | 5                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 0              | YES         | 4                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 2              | YES         | 6                  | YES          | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 3 accessed in frame 2.
```

```
==== PAGE TABLE ====
+--------------+---------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 0            | 1             | YES         | 7                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 1            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 2            | 0             | YES         | 4                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 3            | 2             | YES         | 6                  | YES          | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 4            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 5            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 6            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 7            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 0 accessed in frame 1.
```

```
Page Fault: Loaded page 4 into frame 0.

==== PAGE TABLE ====
+--------------+---------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 0            | 1             | YES         | 7                  | NO           | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 1            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 2            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 3            | 2             | YES         | 6                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 4            | 0             | YES         | 8                  | YES          | YES        |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 5            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 6            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+
| 7            | -1            | NO          | 0                  | NO           | NO         |
+--------------+---------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 4 accessed in frame 0.
```

```
Page Fault: Loaded page 2 into frame 1.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 1              | YES         | 9                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 2              | YES         | 6                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | 0              | YES         | 8                  | YES          | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 2 accessed in frame 1.
```

```
[Info] Reference bits reset.

==== PAGE TABLE ====
+--------------+----------------+-------------+--------------------+--------------+------------+
|  Page Index  |  Frame Number  |  Valid Bit  |  Last Access Time  |  Referenced  |  Modified  |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 0            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 1            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 2            | 1              | YES         | 9                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 3            | 2              | YES         | 10                 | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 4            | 0              | YES         | 8                  | NO           | YES        |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 5            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 6            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+
| 7            | -1             | NO          | 0                  | NO           | NO         |
+--------------+----------------+-------------+--------------------+--------------+------------+

==== FREE FRAME POOL ====
+---------------------+
|     Frame Index     |
+---------------------+
Page 3 accessed in frame 2.
```



3.2 Performance Observations and Comparative Analysis

After running the simulator on an identical reference string and fixed number of physical frames, the following hit ratios were observed for each page replacement algorithm:

- **Least Recently Used (LRU):** 20%
- **First In First Out (FIFO):** 10%
- **Least Frequently Used (LFU):** 20%
- **Not Recently Used (NRU):** 10%
- **Second Chance:** 30%

These results illustrate how different replacement policies respond to the same access pattern. Below is a detailed comparison and discussion of the trade-offs inherent in each technique.

Hit-Ratio Comparison

- **Second Chance (30%)** Second Chance achieved the highest hit ratio (30%). By giving each page a "second chance" if its referenced bit was set, it effectively approximated LRU behavior without maintaining a full timestamp for every page. In this particular access sequence, frequently referenced pages were able to remain resident longer, explaining the superior hit rate.

- **LRU and LFU (20% each)** Both LRU and LFU yielded a 20% hit ratio.
  - *LRU*: By evicting the page that had gone longest without use, LRU captures temporal locality. In this scenario, however, the working set occasionally shifted rapidly enough that LRU still suffered two-thirds of the time.
  - *LFU*: By evicting pages with the lowest access frequency, LFU also benefits from repeatedly used pages. However, LFU can be misled if a page was "popular" earlier but not needed later. In this run, ties in frequency forced arbitrary evictions that matched LRU's fault count.
- **FIFO and NRU (10% each)** Both FIFO and NRU produced the lowest hit ratios (10%).
  - *FIFO*: Evicting strictly by arrival order ignores all recent or frequent access information. In workloads with looping or repeated references, FIFO can evict a page right before it is needed again, leading to Belady's anomaly. That behavior is evident here: FIFO discarded "hot" pages prematurely.
  - *NRU*: Although NRU classifies pages by "referenced" and "modified" bits, it resets all reference bits periodically. In this short trace, NRU often categorized many pages as "recently used" (R = 1) or "dirty" (M = 1), forcing evictions from higher-priority classes. As a result, it performed no better than FIFO on hit ratio.

Trade-Offs and Overhead

1. **Complexity vs. Hit Ratio**
   - *LRU* requires updating a timestamp on every access and scanning all valid pages on every eviction to find the minimum timestamp. In a large page table, that scanning cost can become expensive.
   - *LFU* similarly increments a frequency counter on each access and searches through the `lfu_list` to find the smallest count, which may also be $O(n)$ in the number of resident pages.
   - *Second Chance* maintains a simple queue plus a single reference bit per page. On a page fault, it may rotate through several pages

to find one with R = 0 but does not require a full table scan. This yields lower per-eviction overhead than pure LRU, while still approximating its behavior - hence its superior hit ratio in this experiment.

- *FIFO* has minimal overhead (just a queue), but its naïve eviction order leads to poor hit rates.
- *NRU* periodically resets all R bits (every 10 accesses), which adds an $O(n)$ cost at each interval. Its class-based eviction can avoid writing "dirty" pages back to disk more often, but in a short trace that benefit is not realized, and its hit rate suffers.

2. **Memory Overhead**

- *LRU* and *LFU* require extra storage - timestamps or counters—per page.
- *NRU* and *Second Chance* need only a single reference bit (plus a modified bit, which is inherent in most hardware page-table entries).
- *FIFO* requires no per-page metadata beyond the valid bit and frame number.

3. **Sensitivity to Access Patterns**

- *LRU* excels when the workload exhibits strong temporal locality - that is, once a page is accessed, it is likely to be accessed again soon.
- *LFU* excels when the workload has a stable set of "hot" pages that are accessed repeatedly. However, it can be misled by pages that were once hot but are no longer needed.
- *Second Chance* offers a practical compromise: it retains the most recently used pages while incurring low overhead, making it robust across a variety of patterns.
- *FIFO* performs poorly whenever there is a working-set overlap that causes Belady's anomaly. It can never "learn" which pages are frequently used.
- *NRU* strikes a balance by distinguishing "dirty" versus "clean" pages and keeping track of recent use only until the next reset.

If the interval is chosen poorly or the trace is short, it may not provide significant benefit over FIFO.

Summary of Insights

- *Second Chance* emerged as the best performer on this sample trace, achieving a 30% hit ratio while requiring only one reference bit per page and a simple circular queue.
- *LRU* and *LFU* both achieved moderate results (20%). Their higher bookkeeping overhead - timestamps or frequency counters - did not translate into enough reduction in page faults for this particular sequence. In larger or more localized workloads, LRU often outperforms FIFO and NRU.
- *FIFO* and *NRU* delivered the weakest hit ratios (10%) here. FIFO's naive eviction policy made it vulnerable to typical "looping" patterns, while NRU's periodic resets failed to discriminate effectively in a short reference string.

Overall, this comparative evaluation demonstrates that while algorithms like LRU and LFU are theoretically optimal under certain assumptions, practical approximations such as Second Chance often strike the best balance between low overhead and high hit ratio in realistic, resource-constrained environments.

4 Task & Role Breakdown

Team Member	Tasks
Vu Hoang Minh	• Develop LRU page replacement algorithm • Collect and summarize LRU test results. • Contribute to the report writing & slide preparation
Pham Duc Cuong	• Develop LFU page replacement algorithm • Collect and summarize LFU test results. • Contribute to the report writing & slide preparation
Trinh Hong Anh	• Develop Second Chance page replacement algorithm • Collect and summarize Second Chance test results. • Contribute to the report writing & slide preparation
Cao Truong Xuan	• Develop FIFO & NRU page replacement algorithm • Collect and summarize FIFO & NRU test results. • Contribute to the report writing & slide preparation

5 Reference

https://www.geeksforgeeks.org/program-for-least-recently-used-lru-page-replacement-algorithm/

https://www.geeksforgeeks.org/page-replacement-algorithms-in-operating-systems/

https://www.geeksforgeeks.org/least-frequently-used-lfu-cache-implementation/

https://www.geeksforgeeks.org/not-recently-used-nru-page-replacement-algorithm/

https://www.geeksforgeeks.org/second-chance-or-clock-page-replacement-policy/

https://www.geeksforgeeks.org/page-replacement-algorithms-in-operating-systems/

https://www.geeksforgeeks.org/memory-management-in-operating-system/

https://www.geeksforgeeks.org/paging-in-operating-system/