TARLAC STATE UNIVERSITY

COLLEGE OF COMPUTER STUDIES

In Partial Fulfillment of the Requirements for the

Subject

Operating Systems

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Submitted By:

Ursua, Jefferson P.

Jo Anne Cura

Subject Instructor

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Project Overview

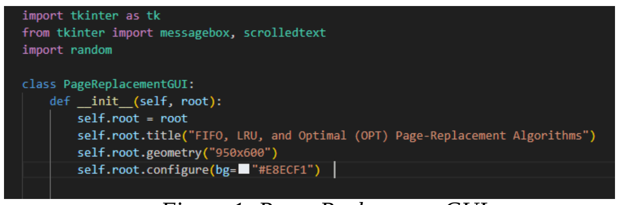
This case study involves the development of a Page Replacement Simulator that implements three classical page-replacement algorithms: First-In-First-Out (FIFO), Least Recently Used (LRU), and Optimal (OPT). The purpose of this project is to demonstrate how these algorithms work in managing virtual memory by deciding which pages to replace when new pages need to be loaded into limited page frames. Page replacement is a fundamental concept in operating systems to ensure efficient memory usage, reduce page faults, and improve system performance.

The selected algorithms represent different strategies in managing memory. FIFO replaces the oldest page in memory, LRU replaces the page that has not been used for the longest time, and Optimal replaces the page that will not be used for the longest period in the future. Understanding these algorithms is important because they highlight trade-offs between simplicity, accuracy, and practicality in virtual memory management.

The project was implemented using Python with the Tkinter library for the graphical user interface. Python was chosen for its readability and ease of implementation, while Tkinter enabled the creation of an interactive and user-friendly simulation environment. The random page reference string, which simulates memory requests by a program, was generated by creating a list of 20 random integers between 0 and 9 each time the simulation runs. This randomness mimics the unpredictability of real-world program memory access patterns.

This simulator allows users to input the number of page frames available and visually observe how each algorithm processes the same reference string differently, along with the corresponding number of page faults. The visual display of frames over time helps deepen the understanding of algorithm behavior and performance under varying conditions.

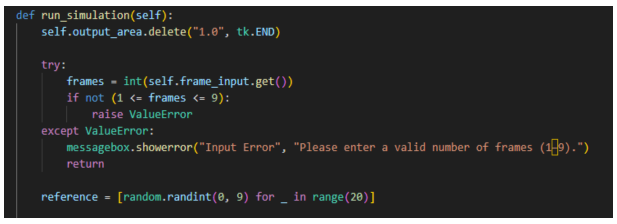
Code Explanation



```
import tkinter as tk
from tkinter import messagebox, scrolledtext
import random

class PageReplacementGUI:
    def __init__(self, root):
        self.root = root
        self.root.title("FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms")
        self.root.geometry("950x600")
        self.root.configure(bg="#E8ECF1")
```

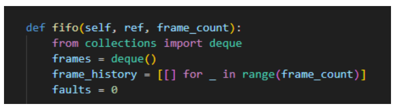
Figure 1: Page_ReplacementGUI

The code is structured into a class PageReplacementGUI which initializes the GUI components and handles the simulation logic. The constructor (__init__) sets up the main window, including labels, input fields for the number of page frames, and a scrollable text widget for output.



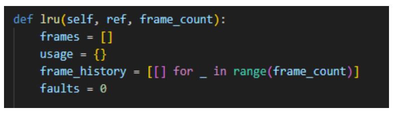
```
def run_simulation(self):
    self.output_area.delete("1.0", tk.END)

    try:
        frames = int(self.frame_input.get())
        if not (1 <= frames <= 9):
            raise ValueError
    except ValueError:
        messagebox.showerror("Input Error", "Please enter a valid number of frames (1–9).")
        return

    reference = [random.randint(0, 9) for _ in range(20)]
```

Figure 2: run_simulation



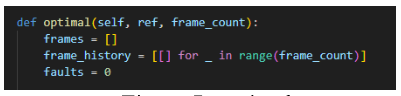
```
def fifo(self, ref, frame_count):
    from collections import deque
    frames = deque()
    frame_history = [[] for _ in range(frame_count)]
    faults = 0
```

Figure 3: fifo



```
def lru(self, ref, frame_count):
    frames = []
    usage = {}
    frame_history = [[] for _ in range(frame_count)]
    faults = 0
```

Figure 4: lru

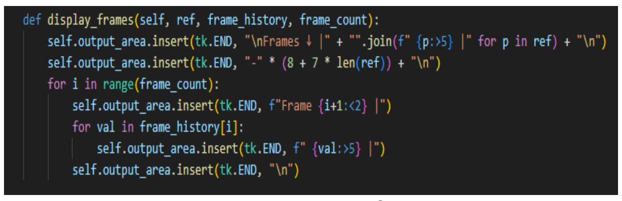


```
def optimal(self, ref, frame_count):
    frames = []
    frame_history = [[] for _ in range(frame_count)]
    faults = 0
```

Figure 5: optimal

The run_simulation method reads the user input for the number of frames, validates it to be between 1 and 9, then generates a random page reference string of length 20 with page numbers from 0 to 9. This reference string is printed and then passed sequentially to three methods representing the FIFO, LRU, and Optimal algorithms.

Each algorithm method (fifo, lru, and optimal) takes the reference string and the frame count and simulates the page replacement process, tracking which pages are in frames and counting the number of page faults. These methods maintain a history of frames after each page request for output visualization.



```python
def display_frames(self, ref, frame_history, frame_count):
    self.output_area.insert(tk.END, "\nFrames ↓ |" + "".join(f" {p:>5} |" for p in ref) + "\n")
    self.output_area.insert(tk.END, "-" * (8 + 7 * len(ref)) + "\n")
    for i in range(frame_count):
        self.output_area.insert(tk.END, f"Frame {i+1:<2} |")
        for val in frame_history[i]:
            self.output_area.insert(tk.END, f" {val:>5} |")
        self.output_area.insert(tk.END, "\n")
```

Figure 6: display_frames

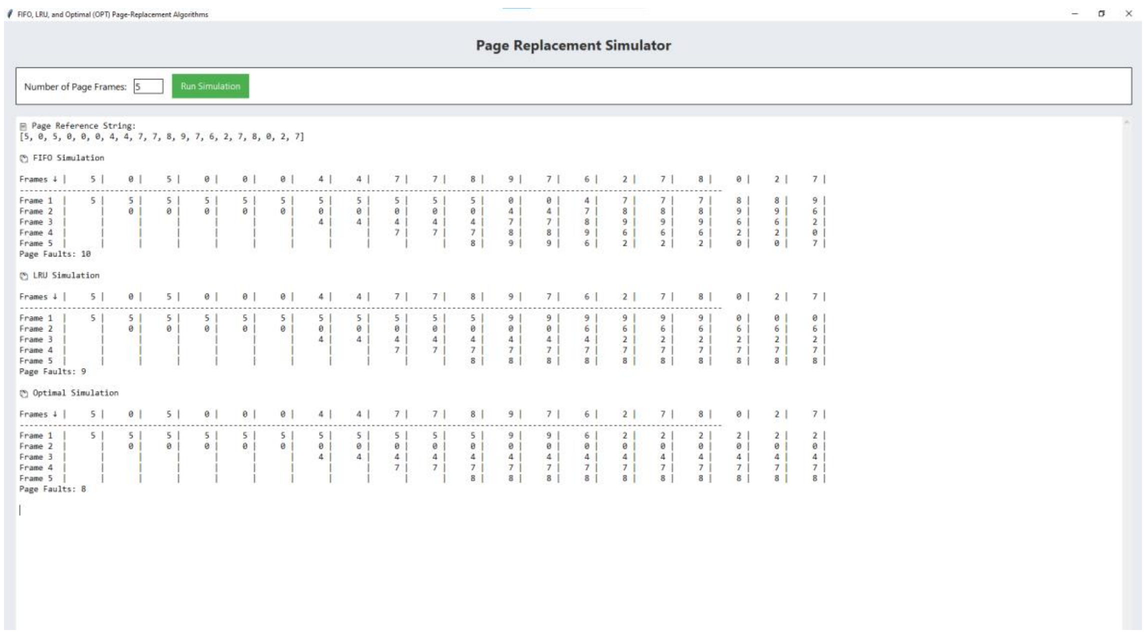
The display_frames method outputs the page frames after each reference to the scrollable text widget, allowing users to see how pages change over time in each frame. The visual feedback is crucial in understanding how each algorithm operates and results in page faults.

Results

The Page Replacement Simulator was developed in Python to simulate and compare three popular algorithms: FIFO, LRU, and Optimal. Each algorithm was tested using five different reference strings with a fixed frame size of 5. For each test case, the total number of page faults was recorded.

Test Case	Reference String	Frame Size	FIFO Faults	LRU Faults	Optimal Faults
1	5, 0, 5, 0, 0, 0, 4, 4, 7, 7, 8, 9, 7, 6, 2, 7, 8, 0, 2, 7	5	10	9	8
2	7, 5, 9, 7, 8, 8, 7, 6, 3, 0, 3, 0, 7, 6, 5, 7, 3, 7, 8, 0	5	10	10	8
3	2, 6, 9, 6, 8, 6, 5, 2, 6, 6, 2, 1, 4, 1, 3, 4, 8, 9, 8, 4	5	10	10	8
4	2, 8, 9, 3, 8, 7, 1, 8, 3, 7, 5, 7, 4, 8, 2, 8, 1, 3, 2, 7	5	12	12	9
5	9, 2, 7, 0, 2, 6, 4, 5, 1, 3, 5, 5, 8, 2, 6, 9, 6, 2, 3, 3	5	13	141	10

Table 1: Test Cases



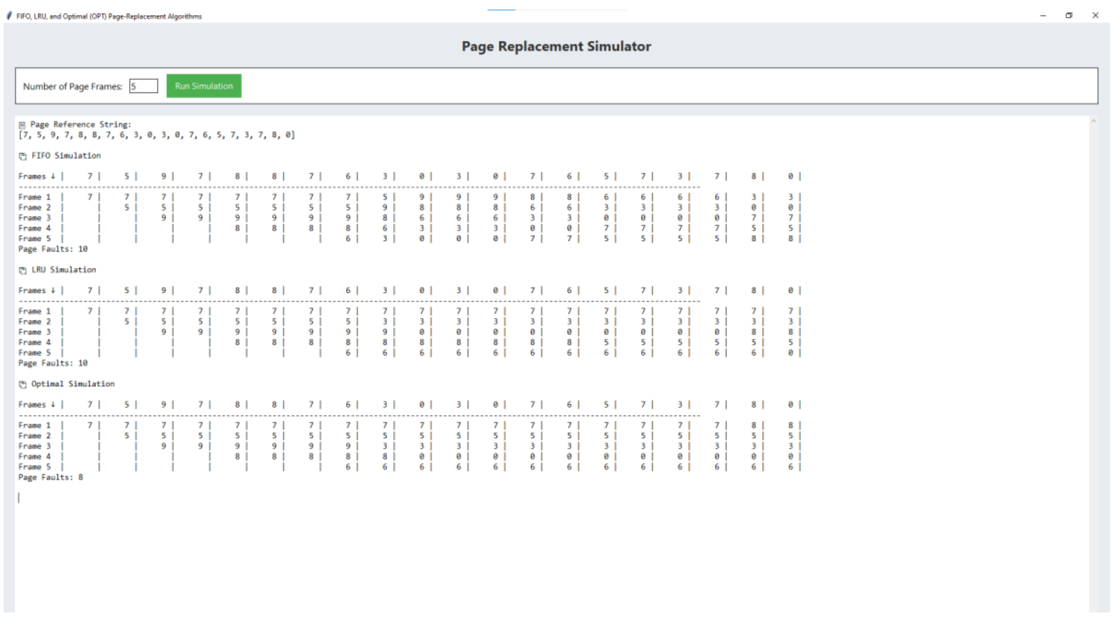
FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms

Page Replacement Simulator

Number of Page Frames: 5 | Run Simulation

```
Page Reference String:
[5, 0, 5, 0, 0, 0, 4, 4, 7, 7, 8, 9, 7, 6, 2, 7, 8, 0, 2, 7]

FIFO Simulation

Frames ↓ |     5 |     0 |     5 |     0 |     0 |     0 |     4 |     4 |     7 |     7 |     8 |     9 |     7 |     6 |     2 |     7 |     8 |     0 |     2 |     7 |
----------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     0 |     0 |     4 |     7 |     7 |     7 |     8 |     8 |     9 |
Frame 2  |       |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     4 |     4 |     7 |     8 |     8 |     8 |     9 |     9 |     6 |
Frame 3  |       |       |       |       |       |       |     4 |     4 |     4 |     4 |     4 |     7 |     7 |     8 |     9 |     9 |     9 |     6 |     6 |     2 |
Frame 4  |       |       |       |       |       |       |       |       |     7 |     7 |     7 |     8 |     8 |     9 |     6 |     6 |     6 |     2 |     2 |     0 |
Frame 5  |       |       |       |       |       |       |       |       |       |       |     8 |     9 |     9 |     6 |     2 |     2 |     2 |     0 |     0 |     7 |
Page Faults: 10

LRU Simulation

Frames ↓ |     5 |     0 |     5 |     0 |     0 |     0 |     4 |     4 |     7 |     7 |     8 |     9 |     7 |     6 |     2 |     7 |     8 |     0 |     2 |     7 |
----------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     9 |     9 |     9 |     9 |     9 |     9 |     0 |     0 |     0 |
Frame 2  |       |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |
Frame 3  |       |       |       |       |       |       |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     2 |     2 |     2 |     2 |     2 |     2 |
Frame 4  |       |       |       |       |       |       |       |       |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |
Frame 5  |       |       |       |       |       |       |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |
Page Faults: 9

Optimal Simulation

Frames ↓ |     5 |     0 |     5 |     0 |     0 |     0 |     4 |     4 |     7 |     7 |     8 |     9 |     7 |     6 |     2 |     7 |     8 |     0 |     2 |     7 |
----------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     9 |     9 |     6 |     2 |     2 |     2 |     2 |     2 |     2 |
Frame 2  |       |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |
Frame 3  |       |       |       |       |       |       |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |
Frame 4  |       |       |       |       |       |       |       |       |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |
Frame 5  |       |       |       |       |       |       |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |
Page Faults: 8
```

Figure 7: 1st test result



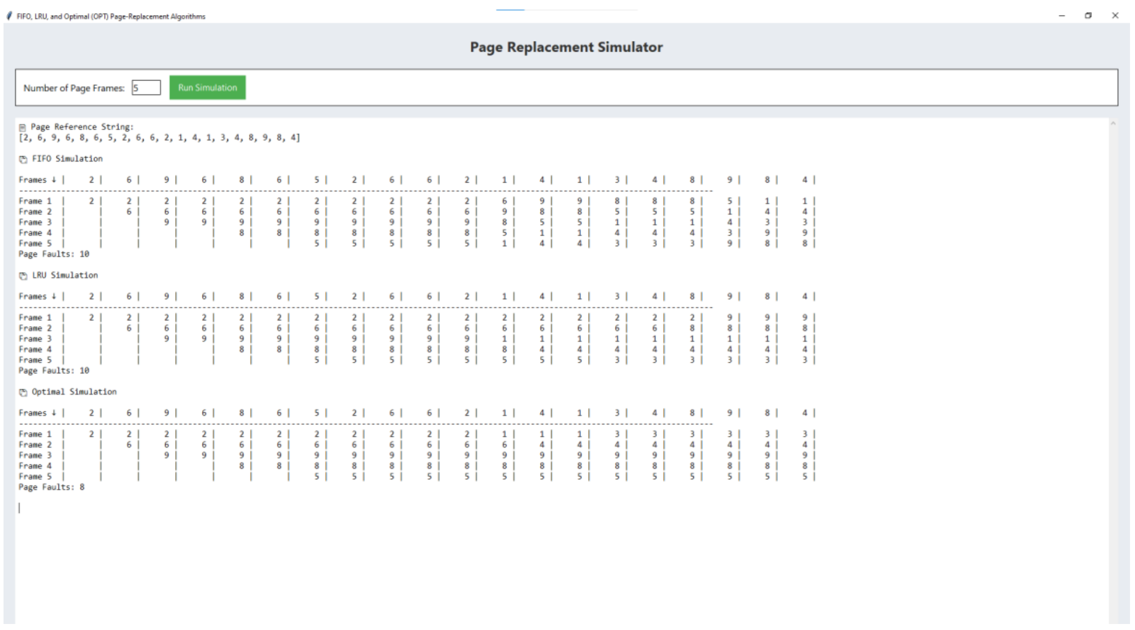
FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms

Page Replacement Simulator

Number of Page Frames: 5 Run Simulation

```
▤ Page Reference String:
[7, 5, 9, 7, 8, 8, 7, 6, 3, 0, 3, 0, 7, 6, 5, 7, 3, 7, 8, 0]

⎘ FIFO Simulation

Frames ↓ |     7 |     5 |     9 |     7 |     8 |     8 |     7 |     6 |     3 |     0 |     3 |     0 |     7 |     6 |     5 |     7 |     3 |     7 |     8 |     0 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     5 |     9 |     9 |     9 |     8 |     8 |     6 |     6 |     6 |     6 |     3 |     3 |
Frame 2  |       |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     9 |     8 |     8 |     8 |     6 |     6 |     3 |     3 |     3 |     3 |     0 |     0 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     8 |     6 |     6 |     6 |     3 |     3 |     0 |     0 |     0 |     0 |     7 |     7 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     6 |     3 |     3 |     3 |     0 |     0 |     7 |     7 |     7 |     7 |     5 |     5 |
Frame 5  |       |       |       |       |       |       |       |     6 |     3 |     0 |     0 |     0 |     7 |     7 |     5 |     5 |     5 |     5 |     8 |     8 |
Page Faults: 10

⎘ LRU Simulation

Frames ↓ |     7 |     5 |     9 |     7 |     8 |     8 |     7 |     6 |     3 |     0 |     3 |     0 |     7 |     6 |     5 |     7 |     3 |     7 |     8 |     0 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |
Frame 2  |       |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     8 |     8 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     5 |     5 |     5 |     5 |     5 |     5 |
Frame 5  |       |       |       |       |       |       |       |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     0 |
Page Faults: 10

⎘ Optimal Simulation

Frames ↓ |     7 |     5 |     9 |     7 |     8 |     8 |     7 |     6 |     3 |     0 |     3 |     0 |     7 |     6 |     5 |     7 |     3 |     7 |     8 |     0 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     7 |     8 |     8 |
Frame 2  |       |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |     3 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |     0 |
Frame 5  |       |       |       |       |       |       |       |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |
Page Faults: 8
```

Figure 8: 2nd test result



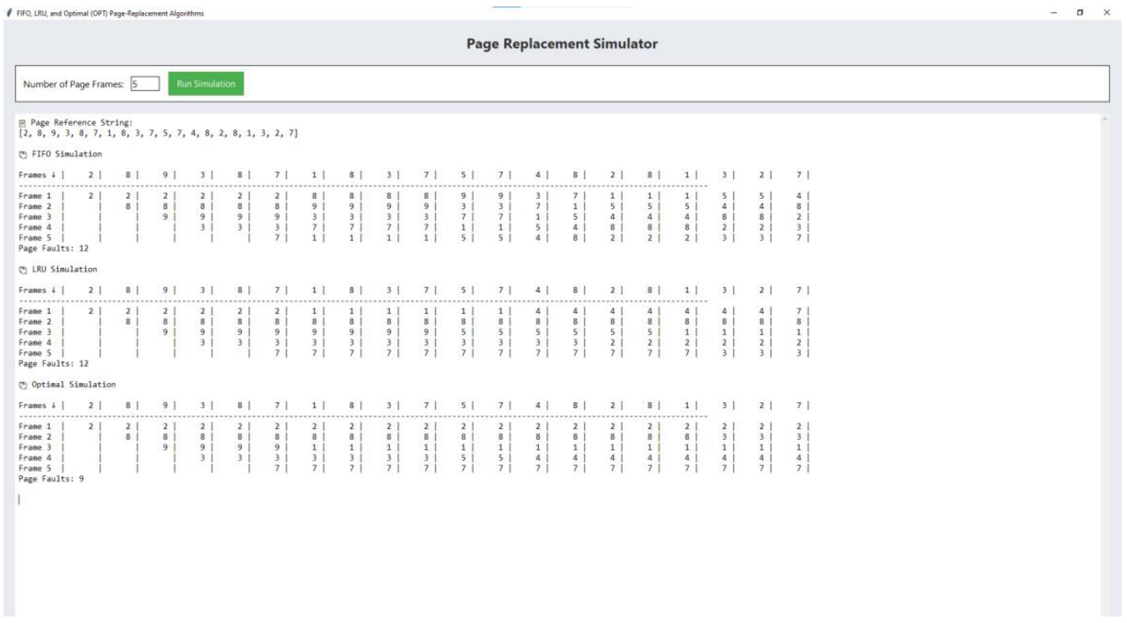
FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms

Page Replacement Simulator

Number of Page Frames: 5 Run Simulation

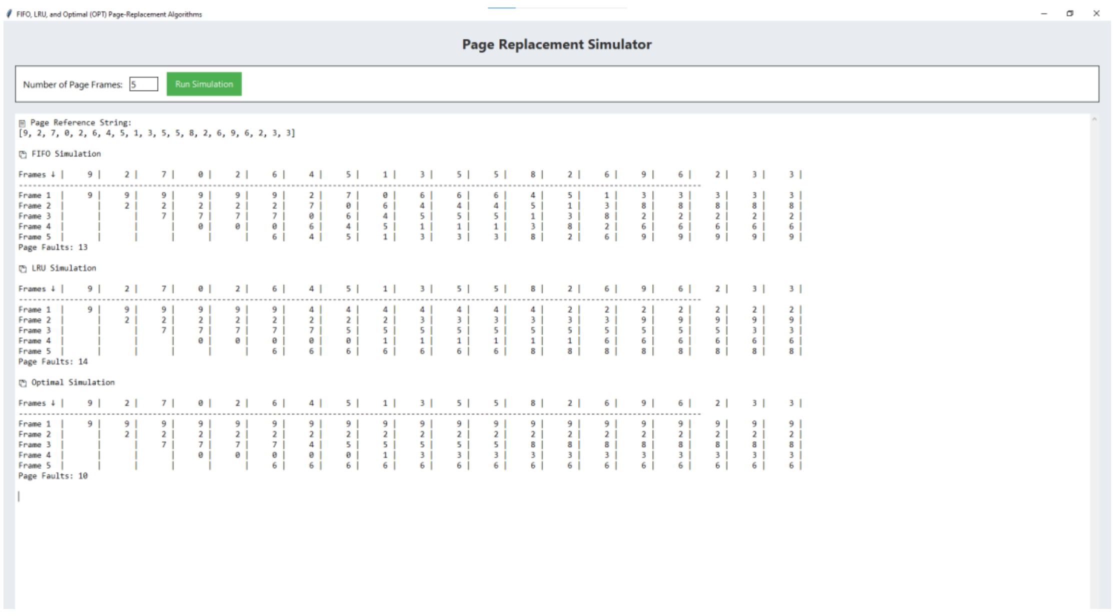
```
▤ Page Reference String:
[2, 6, 9, 6, 8, 6, 5, 2, 6, 6, 2, 1, 4, 1, 3, 4, 8, 9, 8, 4]

⎘ FIFO Simulation

Frames ↓ |     2 |     6 |     9 |     6 |     8 |     6 |     5 |     2 |     6 |     6 |     2 |     1 |     4 |     1 |     3 |     4 |     8 |     9 |     8 |     4 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     6 |     9 |     9 |     8 |     8 |     8 |     5 |     1 |     1 |
Frame 2  |       |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     9 |     8 |     8 |     5 |     5 |     5 |     1 |     4 |     4 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     8 |     5 |     5 |     1 |     1 |     1 |     4 |     3 |     3 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     5 |     1 |     1 |     4 |     4 |     4 |     3 |     9 |     9 |
Frame 5  |       |       |       |       |       |       |     5 |     5 |     5 |     5 |     5 |     1 |     4 |     4 |     3 |     3 |     3 |     9 |     8 |     8 |
Page Faults: 10

⎘ LRU Simulation

Frames ↓ |     2 |     6 |     9 |     6 |     8 |     6 |     5 |     2 |     6 |     6 |     2 |     1 |     4 |     1 |     3 |     4 |     8 |     9 |     8 |     4 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     9 |     9 |     9 |
Frame 2  |       |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     8 |     8 |     8 |     8 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     1 |     1 |     1 |     1 |     1 |     1 |     1 |     1 |     1 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |
Frame 5  |       |       |       |       |       |       |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     3 |     3 |     3 |     3 |     3 |     3 |
Page Faults: 10

⎘ Optimal Simulation

Frames ↓ |     2 |     6 |     9 |     6 |     8 |     6 |     5 |     2 |     6 |     6 |     2 |     1 |     4 |     1 |     3 |     4 |     8 |     9 |     8 |     4 |
---------------------------------------------------------------------------------------------------------------------------------------------
Frame 1  |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     2 |     1 |     1 |     1 |     3 |     3 |     3 |     3 |     3 |     3 |
Frame 2  |       |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     6 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |     4 |
Frame 3  |       |       |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |     9 |
Frame 4  |       |       |       |       |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |     8 |
Frame 5  |       |       |       |       |       |       |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |     5 |
Page Faults: 8
```

Figure 9: 3rd test result



```
FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms

Page Replacement Simulator

Number of Page Frames: 5   Run Simulation

Page Reference String:
[2, 8, 9, 3, 8, 7, 1, 8, 3, 7, 5, 7, 4, 8, 2, 8, 1, 3, 2, 7]

FIFO Simulation

Frames ↓ |    2 |    8 |    9 |    3 |    8 |    7 |    1 |    8 |    3 |    7 |    5 |    7 |    4 |    8 |    2 |    8 |    1 |    3 |    2 |    7 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    2 |    2 |    2 |    2 |    2 |    2 |    8 |    8 |    8 |    8 |    9 |    9 |    3 |    7 |    1 |    1 |    1 |    5 |    5 |    4 |
Frame 2  |      |    8 |    8 |    8 |    8 |    8 |    9 |    9 |    9 |    9 |    3 |    3 |    7 |    1 |    5 |    5 |    5 |    4 |    4 |    8 |
Frame 3  |      |      |    9 |    9 |    9 |    9 |    3 |    3 |    3 |    3 |    7 |    7 |    1 |    5 |    4 |    4 |    4 |    8 |    8 |    2 |
Frame 4  |      |      |      |    3 |    3 |    3 |    7 |    7 |    7 |    7 |    1 |    1 |    5 |    4 |    8 |    8 |    8 |    2 |    2 |    3 |
Frame 5  |      |      |      |      |      |    7 |    1 |    1 |    1 |    1 |    5 |    5 |    4 |    8 |    2 |    2 |    2 |    3 |    3 |    7 |
Page Faults: 12

LRU Simulation

Frames ↓ |    2 |    8 |    9 |    3 |    8 |    7 |    1 |    8 |    3 |    7 |    5 |    7 |    4 |    8 |    2 |    8 |    1 |    3 |    2 |    7 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    2 |    2 |    2 |    2 |    2 |    2 |    1 |    1 |    1 |    1 |    1 |    1 |    4 |    4 |    4 |    4 |    4 |    4 |    4 |    7 |
Frame 2  |      |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |
Frame 3  |      |      |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    5 |    5 |    5 |    5 |    5 |    5 |    1 |    1 |    1 |    1 |
Frame 4  |      |      |      |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    2 |    2 |    2 |    2 |    2 |    2 |
Frame 5  |      |      |      |      |      |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    3 |    3 |    3 |
Page Faults: 12

Optimal Simulation

Frames ↓ |    2 |    8 |    9 |    3 |    8 |    7 |    1 |    8 |    3 |    7 |    5 |    7 |    4 |    8 |    2 |    8 |    1 |    3 |    2 |    7 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |
Frame 2  |      |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    3 |    3 |    3 |
Frame 3  |      |      |    9 |    9 |    9 |    9 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |    1 |
Frame 4  |      |      |      |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    5 |    5 |    4 |    4 |    4 |    4 |    4 |    4 |    4 |    4 |
Frame 5  |      |      |      |      |      |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |    7 |
Page Faults: 9
```

Figure 10: 4th test result



```
FIFO, LRU, and Optimal (OPT) Page-Replacement Algorithms

Page Replacement Simulator

Number of Page Frames: 5   Run Simulation

Page Reference String:
[9, 2, 7, 0, 2, 6, 4, 5, 1, 3, 5, 5, 8, 2, 6, 9, 6, 2, 3, 3]

FIFO Simulation

Frames ↓ |    9 |    2 |    7 |    0 |    2 |    6 |    4 |    5 |    1 |    3 |    5 |    5 |    8 |    2 |    6 |    9 |    6 |    2 |    3 |    3 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    9 |    9 |    9 |    9 |    9 |    9 |    2 |    7 |    0 |    6 |    6 |    6 |    4 |    5 |    1 |    3 |    3 |    3 |    3 |    3 |
Frame 2  |      |    2 |    2 |    2 |    2 |    2 |    7 |    0 |    6 |    4 |    4 |    4 |    5 |    1 |    3 |    8 |    8 |    8 |    8 |    8 |
Frame 3  |      |      |    7 |    7 |    7 |    7 |    0 |    6 |    4 |    5 |    5 |    5 |    1 |    3 |    8 |    2 |    2 |    2 |    2 |    2 |
Frame 4  |      |      |      |    0 |    0 |    0 |    6 |    4 |    5 |    1 |    1 |    1 |    3 |    8 |    2 |    6 |    6 |    6 |    6 |    6 |
Frame 5  |      |      |      |      |      |    6 |    4 |    5 |    1 |    3 |    3 |    3 |    8 |    2 |    6 |    9 |    9 |    9 |    9 |    9 |
Page Faults: 13

LRU Simulation

Frames ↓ |    9 |    2 |    7 |    0 |    2 |    6 |    4 |    5 |    1 |    3 |    5 |    5 |    8 |    2 |    6 |    9 |    6 |    2 |    3 |    3 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    9 |    9 |    9 |    9 |    9 |    9 |    4 |    4 |    4 |    4 |    4 |    4 |    4 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |
Frame 2  |      |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    3 |    3 |    3 |    3 |    3 |    3 |    9 |    9 |    9 |    9 |    9 |
Frame 3  |      |      |    7 |    7 |    7 |    7 |    7 |    5 |    5 |    5 |    5 |    5 |    5 |    5 |    5 |    5 |    5 |    5 |    3 |    3 |
Frame 4  |      |      |      |    0 |    0 |    0 |    0 |    0 |    1 |    1 |    1 |    1 |    1 |    1 |    6 |    6 |    6 |    6 |    6 |    6 |
Frame 5  |      |      |      |      |      |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |
Page Faults: 14

Optimal Simulation

Frames ↓ |    9 |    2 |    7 |    0 |    2 |    6 |    4 |    5 |    1 |    3 |    5 |    5 |    8 |    2 |    6 |    9 |    6 |    2 |    3 |    3 |
-------------------------------------------------------------------------------------------------------------------------------
Frame 1  |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |    9 |
Frame 2  |      |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |    2 |
Frame 3  |      |      |    7 |    7 |    7 |    7 |    4 |    5 |    5 |    5 |    5 |    5 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |    8 |
Frame 4  |      |      |      |    0 |    0 |    0 |    0 |    0 |    1 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |    3 |
Frame 5  |      |      |      |      |      |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |    6 |
Page Faults: 10
```

Figure 11: 5th test result

Challenges and Solutions

One of the challenges I faced was making sure the LRU and Optimal algorithms worked correctly. At first, the LRU logic didn't properly track which pages were used least recently, which caused incorrect page fault results. I fixed this by using a dictionary to remember when each page was last used, so the program could pick the right page to remove.

I also had to make sure users could only enter a frame size between 1 and 9. To fix this, I added checks to the input and gave clear error messages, which made the program easier to use and prevented it from crashing.

Another tricky part was testing the Optimal algorithm, since it needs to look ahead in the reference string to figure out which pages will be used again. I solved this by carefully looping through the string and using Python's next() function to check future page uses without slowing down the program.

Finally, showing the contents of the frames after each step was important for understanding how the algorithms work. I made a function called display_frames to clearly show the frames, and I paid attention to formatting so the output would be easy to read and analyze.

Conclusion

This case study successfully demonstrates the implementation and comparison of FIFO, LRU, and Optimal page replacement algorithms in a simulated virtual memory environment. The Optimal algorithm, while theoretically the best, is not always practical in real systems due to its need for future knowledge. LRU offers a good compromise by approximating optimal behavior with recent usage information, while FIFO is the simplest but often least efficient.

The simulation shows that increasing the number of page frames generally reduces page faults, confirming the trade-off between available memory and system performance. However, even with the same frame count, different algorithms lead to significant variation in page faults, highlighting the importance of selecting appropriate page replacement strategies.

If given more time or resources, this simulation could be enhanced with graphical animations, additional algorithms (like Clock or Second Chance), and input of custom reference strings. Adding performance metrics and real-time comparisons would also provide deeper insights into algorithm behavior in different scenarios.