

CACHEIEEE

Submitted to

International Institute of Professional Studies

Devi Ahilya Vishwavidyalaya, Indore

***Dissertation Submitted in Partial fulfillment of the
Requirement for the Award of the Degree of***

Master of Computer Application

Semester VI

Session Jan-May, 2025

Under guidance of

Dr. Pradeep K. Jatav

IIPS, DAVV

Submitted to

Mradul Natani

IC-2K22-56

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CERTIFICATE FROM GUIDE

It is to certify that the project entitled "Cacheiee", submitted by Mradul Natani to the International Institute of Professional Studies, Devi Ahilya Vishwavidyalaya, Indore has been completed under my supervision and the work is carried out and presented in a manner required for its acceptance to Master of Computer Applicaition VI semester.

Project Guide:

Signature:

Name:

Date:

DISSERTATION APPROVAL SHEET

The dissertation entitled "CACHEIEEE" is being submitted by Mradul Natani, IC-2K22-56 in partial fulfilment of the requirement for the award of Master of Computer Application (5 Years) Semester VI to the International Institute of Professional Studies, Devi Ahilya Vishwavidyalaya, Indore is satisfactory and approved.

Internal Examiner

External Examiner

ACKNOWLEDGEMENT

I take this occasion to thank God, almighty for blessing us with his grace and taking our endeavour to a successful culmination. I extend my sincere and heartfelt thanks to my esteemed guide, Dr. PRADEEP JATAV SIR, for providing the right guidance and advice at the crucial junctures and for showing me the right way. I would like to thank my friends and family for the support and encouragement they have given us during the course of work.

Mradul Natani

IC-2K22-56

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INTRODUCTION

CHAPTER: 1

INTRODUCTION

1.1 Client

The Cacheieee system is developed to serve a diverse set of users requiring fast, efficient, and lightweight in-memory data storage. It targets software developers and system architects who build and test microservices, backend systems, and performance-sensitive applications. The system is also ideal for computer science students and educators as a pedagogical tool to explore networking, memory management, and concurrency in the C programming language. Furthermore, it caters to DevOps engineers and Site Reliability Engineers (SREs) for simulating caching behavior in development environments without the overhead of complex setups. Independent developers and enthusiasts benefit from Cacheieee's simplicity, minimal configuration, and ease of integration into local projects, making it a practical alternative to full-scale systems like Redis.

1.2 Problem Definition

Modern software systems demand rapid data access with minimal latency. Existing cache solutions such as Redis, while feature-rich and performant, often introduce complexities or overheads that can be prohibitive for educational use, experimentation, or small-scale deployments. The Cacheieee project addresses the following key issues:

- **Overhead of Full-Scale Systems:** Full-featured cache systems like Redis can be resource-intensive, making them less suitable for constrained environments or lightweight applications.
- **Lack of Transparency and Educational Value:** Many users operate these systems without an understanding of their internal working, limiting opportunities to learn core systems programming concepts.

- **Gap in Lightweight Alternatives:** There is a noticeable lack of simple, lightweight caching tools that can be easily deployed in local or educational environments.
- **Need for Customization and Extendability:** Mainstream tools may not provide the flexibility or access needed by users seeking to customize or learn from the internals of a cache server.

Objective of the Software Project

The primary objective of Cacheieeee is to implement a lightweight, Redis-like in-memory key-value store in C that supports basic caching commands and concurrent client handling. The project aims to improve conceptual understanding of system-level development while providing a practical, accessible caching solution for educational and development purposes.

1.3 Aim

The aim of this project is to design and implement a simple yet powerful in-memory cache server using C that can efficiently handle multiple clients concurrently, support essential cache operations, and serve as an educational tool for systems programming. Cacheieeee offers a minimal, transparent alternative to heavy caching systems and enables users to gain hands-on experience with real-world concepts such as socket communication, memory allocation, and concurrency.

1.4 Objectives

The project is designed to achieve the following objectives:

- **Develop a Lightweight In-Memory Cache Server:** Construct a key-value store that operates entirely in memory, using minimal resources and dependencies.
- **Implement Core Caching Commands:** Include essential commands such as SET, GET, DEL, EXISTS, KEYS, SETEX, TTL, INCR, DECR, CMD, APPEND, TREE, and FLUSHALL.
- **Enable Concurrent Client Handling:** Use low-level socket programming with `fork()` to allow multiple clients to connect and interact with the server simultaneously.

- **Demonstrate Systems Programming Concepts:** Provide a working implementation that reinforces understanding of memory management, process control, and socket communication.
 - **Ease of Integration in Local Projects:** Ensure seamless integration with external applications through simple socket-based communication.
 - **Offer an Educational Alternative to Redis:** Deliver a simplified, customizable, and open-source caching system tailored for experimentation and learning.
-

1.5 Benefits

The Cacheieeee system delivers several benefits to its users:

- **Low Latency Access:** Data is served from memory, providing extremely fast response times ideal for frequent data operations.
 - **Minimal Resource Usage:** Implemented in C with no external dependencies, making it suitable for use on low-resource systems and embedded platforms.
 - **Enhanced Application Performance:** Reduces the burden on databases by handling frequently accessed data, improving overall performance.
 - **Concurrent Client Support:** Supports multiple simultaneous users, making it suitable for multi-user testing environments.
 - **Educational Value:** Offers deep insights into systems programming by exposing the underlying mechanisms behind networking and in-memory computation.
 - **Simple Integration:** Can be accessed from various programming environments including Python, Bash, and JavaScript through simple socket connections.
 - **Full Transparency and Control:** Open-source implementation allows users to study and modify the internals, making it ideal for learning and extending functionality.
-

1.6 Methodology

The development of Cacheieeee follows a structured Software Development Life Cycle (SDLC) model. The project was broken down into the following major phases:

- **Phase 1 – Research and Requirement Analysis:** Studied the architecture and commands of Redis and other caching systems. Researched system-level

concepts such as socket programming, `fork()` for concurrency, and memory management using C.

- **Phase 2 – Design:** Designed the overall architecture including data structures for in-memory storage, command parsing mechanism, and client-server communication protocol.
- **Phase 3 – Implementation:** Developed the core system in C with support for major commands and socket-based client interaction. Used `fork()` to handle multiple clients simultaneously.
- **Phase 4 – Testing and Evaluation:** Performed extensive functional and concurrency testing. Benchmarked performance with custom test scripts to validate response times and stability.
- **Phase 5 – Documentation and Enhancement:** Finalized code documentation, usage instructions, and outlined areas for future enhancement such as adding persistence and clustering features.

This methodology ensured that Cacheieeee evolved as a robust, extensible, and educational tool while staying aligned with the objectives of performance, simplicity, and learning value.

SYSTEM ANALYSIS AND DESIGN

CHAPTER: 2

System Analysis and Design

2.1 System Analysis

2.1.1 Problem Domain

Modern applications often require fast, efficient, and scalable solutions to handle frequent data access and temporary storage. Traditional databases are not always optimized for high-speed in-memory operations, particularly when the data does not need to persist permanently. Existing solutions like Redis offer excellent performance but can be complex to extend or understand for learning purposes. Moreover, they may be overkill for lightweight or local deployments.

Cacheiee addresses this gap by offering a minimalist, Redis-like in-memory key-value store developed from scratch using the C programming language. It is designed for developers, system programmers, and students who seek an educational and customizable caching solution that is simple to deploy and easy to integrate into development workflows.

2.1.2 Existing System and Limitations

- Existing solutions like Redis are powerful but may require additional learning for beginners.
- Integration and extension of closed-source or complex open-source systems can be daunting for educational use.
- Many simple applications do not require advanced clustering, replication, or persistence—just a fast, temporary key-value store.

2.1.3 Proposed System – Cacheiee

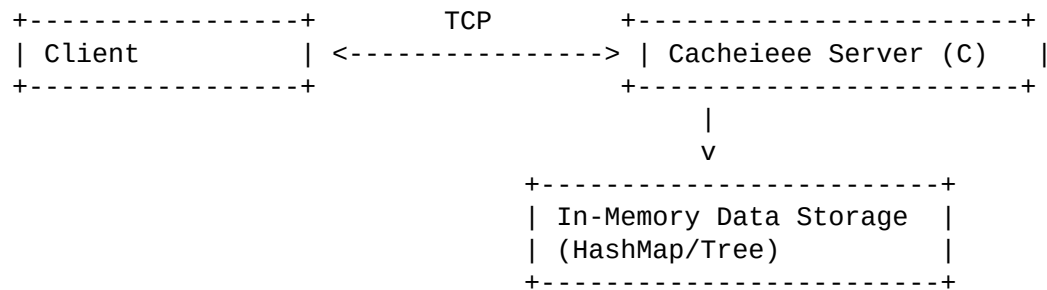
The proposed system is a self-contained, lightweight caching server named **Cacheiee**. It operates over TCP using custom text-based commands similar to Redis. It supports essential caching operations and is capable of handling multiple concurrent clients via process forking. It serves as a proof of concept for how in-memory databases function at a low level.

2.2 System Design

2.2.1 Architectural Overview

Cacheieeee follows a client-server architecture implemented entirely in C. The server listens on a predefined port (default: 12049) and handles multiple clients using `fork()` to create subprocesses. Each client communicates with the server via TCP and issues commands using a simple custom protocol.

High-Level Architecture Diagram:



2.2.2 Functional Modules

1. Connection Handler Module

- Accepts new TCP connections.
- Spawns new processes for each client using `fork()`.

2. Command Parser Module

- Parses incoming text commands from clients.
- Identifies valid commands (SET, GET, DEL, EXISTS, etc.).
- Routes them to appropriate handlers.

3. Data Storage Module

- Maintains in-memory key-value pairs using C data structures (arrays, trees, or hash tables).
- Manages time-based expiry for keys (SETEX, TTL).
- Provides utility functions for memory management and cleanup.

4. Concurrency and Process Management Module

- Handles multiple simultaneous client connections using child processes.

- Ensures isolation between client sessions.

5. **Logging and Debugging Module** *(Optional for future)*

- Records server events for debugging and performance monitoring.

2.2.3 Data Flow Design

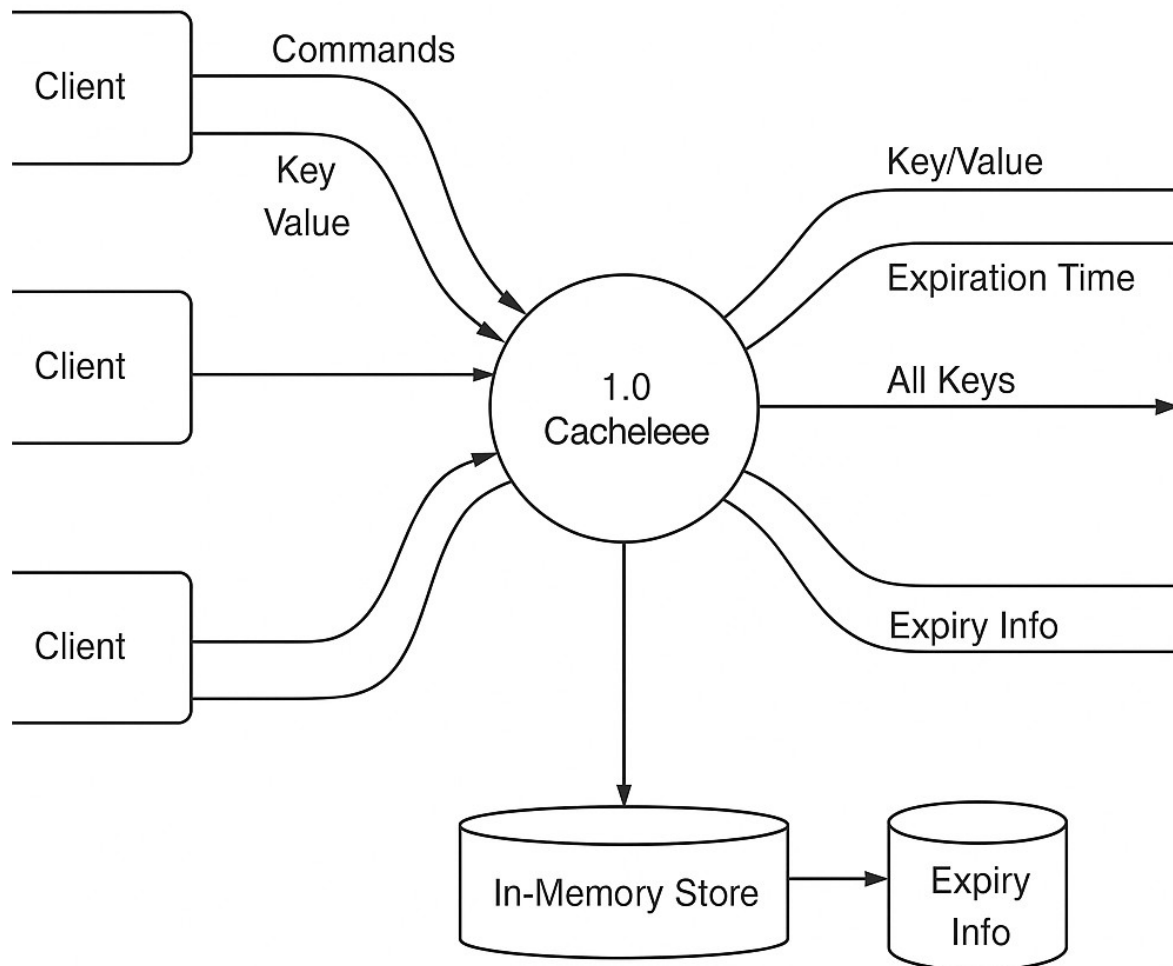


Figure 1: Data Flow Diagrams

2.2.4 Command Set Design

Command	Description
SET	Stores a key with a given value
GET	Retrieves the value for a given key
DEL	Deletes a specific key
EXISTS	Checks if a key exists
TREE	Displays current tree
SETEX	Sets a key with an expiration time
TTL	Returns remaining time to live for a key
INCR/DECR	Increments/Decrements a key's integer value
APPEND	Appends a string to an existing value
FLUSHALL	Clears all data from memory
CMD	Displays all the commands

2.3 System Requirements

2.3.1 Hardware Requirements

- Processor: Intel/AMD x86-based architecture
- RAM: Minimum 2 GB
- Disk Space: Minimum 100 MB for binaries and logs

2.3.2 Software Requirements

- Operating System: Linux-based (Ubuntu/Arch preferred)
 - Compiler: gcc (GNU Compiler Collection)
 - Tools: Makefile for build automation, basic TCP client (e.g., netcat or telnet)
-

2.4 Feasibility Study

Technical Feasibility:

The project is developed using standard C and POSIX libraries, ensuring portability and performance on Unix-like systems. No external dependencies are required, which makes the system highly feasible for academic, local, or embedded use.

Economic Feasibility:

Cacheieee is open-source and requires no licensing fees or proprietary components. It runs on standard Linux environments without the need for costly infrastructure.

Operational Feasibility:

The software is easy to use via TCP commands or basic CLI wrappers. Its minimalism ensures it can be run on any development system or even resource-constrained environments.

PHASES

CHAPTER: 3

PHASES

The development of **Cacheieeee** followed a structured and methodical approach based on the Software Development Life Cycle (SDLC). The project was divided into several logical phases, ensuring that the system was thoroughly researched, well-designed, efficiently implemented, and tested before deployment. Each phase had distinct goals and deliverables to ensure clarity, accountability, and progress throughout the project lifecycle.

3.1 Phase 1 – Requirement Gathering and Initial Research

This foundational phase involved understanding the core requirements of the caching system and performing a comparative analysis of existing in-memory key-value stores like Redis and Memcached. The objectives of this phase included:

- Identifying the need for a lightweight and efficient caching server that could be integrated into web and CLI-based systems.
- Finalizing the core feature set based on the Redis command model.
- Researching concurrency models (e.g., `fork()`-based multiprocessing) for multi-client handling.
- Reviewing low-level socket programming techniques in C.
- Studying memory management practices and data structures suitable for in-memory key-value storage (e.g., hash tables, trees).

This phase established a solid foundation and scope for the system.

3.2 Phase 2 – System Design and Architecture Planning

In this phase, a detailed design of Cacheieeee's architecture was prepared. This included:

- **Component Design:** Designing modular components such as the command parser, socket handler, memory store, and TTL manager.
- **Data Structure Selection:** Choosing efficient internal representations like hash maps and tree structures for storing key-value pairs.
- **Client Handling Strategy:** Implementing concurrent client handling using `fork()` for process-level isolation.
- **Protocol Design:** Designing a custom text-based protocol (inspired by Redis' RESP) to interpret commands sent by clients over TCP sockets.
- **Command Execution Pipeline:** Architecting a command execution workflow from input parsing to response delivery.

This phase ensured a clear blueprint for implementation and future scalability.

3.3 Phase 3 – Development and Implementation

The core logic of Cacheieeee was implemented in this phase using the C programming language. Key implementation milestones included:

- **TCP Server Setup:** Using raw sockets to create a TCP server that accepts and handles incoming client connections.
- **Command Support:** Implementing command functions like SET, GET, DEL, EXISTS, KEYS, APPEND, FLUSHALL, INCR, DECR, EXPIRE, SETEX, TREE, CMD and TTL.
- **Memory Store:** Building a custom key-value store with support for dynamic memory allocation and time-to-live management.
- **Multi-client Handling:** Enabling support for multiple concurrent client sessions through process forking.
- **Edge Case Handling:** Ensuring stability by handling invalid inputs, malformed commands, and memory overflows gracefully.

Each module was rigorously validated before proceeding to integration.

3.4 Phase 4 – Testing and Debugging

To ensure the reliability and correctness of Cacheieeee, a structured testing strategy was followed:

- **Manual Command Line Testing:** Verifying each supported command over TCP via clients like nc (Netcat) or custom Python socket scripts.
- **Boundary Testing:** Validating command limits, large key sizes, and simultaneous access.
- **Stress Testing:** Running high-volume command scripts to simulate real-world load.
- **Error and Crash Handling:** Intentionally injecting malformed commands and monitoring how the server responds without crashing.

This phase focused on robustness, concurrency safety, and consistent behavior across multiple client sessions.

3.5 Phase 5 – Deployment and Demonstration

Once development and testing were complete, the application was packaged and deployed in a local development environment:

- **Executable Distribution:** Building the application into a lightweight binary runnable on any Unix-like system.
- **Client Usage Documentation:** Writing user instructions for interacting with the Cacheieee server using simple TCP clients.
- **Demonstration Setup:** Creating usage scenarios and showcasing features such as multi-client sessions, TTL-based expiry, and memory flush.

The project was presented as a working proof-of-concept showcasing low-level systems programming skills and server development.

3.6 Phase 6 – Future Enhancements

Although Cacheieee currently supports a strong foundation of caching functionalities, several advanced features are proposed for future versions to enhance its real-world applicability and scalability:

- **Data Persistence:** Add support for periodic memory dumps or append-only file logging to allow data restoration after server restarts.
- **Authentication and Access Control:** Introduce a lightweight authentication system to restrict access and enable role-based command execution.

- **Advanced Expiry Policies:** Support for Least Recently Used (LRU) or Least Frequently Used (LFU) eviction strategies.
- **Pub/Sub Messaging System:** Implement a publish-subscribe model to allow clients to subscribe to changes on keys and receive real-time updates.
- **Monitoring and Metrics:** Develop a built-in monitoring interface that exposes statistics such as memory usage, connected clients, command frequency, and uptime.
- **Command Logging and Replay:** Maintain a log of all executed commands for replay, debugging, and audit purposes.
- **Dynamic Configuration Management via Consul:** Integrate Cacheiieee with HashiCorp **Consul** to support live configuration changes (such as TTL default, max connections, logging levels) without restarting the server. This will allow seamless integration into dynamic, service-oriented, or containerized environments.
- **Cluster Mode and Replication (Long-Term Goal):** Build support for running Cacheiieee in a distributed mode with leader-follower replication to improve fault tolerance and horizontal scalability.

These enhancements will transform Cacheiieee from a learning-focused in-memory database into a lightweight, production-grade caching solution.

IMPLEMENTATION AND FEATURES

CHAPTER: 4

IMPLEMENTATION AND FEATURES

This chapter details the technical implementation of **Cacheiee**, a custom-built in-memory key-value data store developed using the C programming language. The implementation emphasizes performance, simplicity, and system-level understanding. It also outlines the key features that make Cacheiee both functional and extensible for future enhancements.

4.1 Implementation Overview

Cacheiee is designed to operate as a standalone caching server over TCP, supporting concurrent connections from multiple clients. It follows a client-server model and mimics the behavior of modern in-memory databases like Redis while keeping the architecture minimal and educational.

4.1.1 Language and Platform

- **Programming Language:** C
 - **Platform:** Linux/Unix-based operating systems
 - **Concurrency Model:** Multi-processing using `fork()`
 - **Networking:** Low-level socket programming (IPv4, TCP)
-

4.2 Architecture Components

Cacheiee is implemented with the following core modules:

1. Socket Server Module

- Listens on a specified port (12049) for client connections.
- Accepts incoming client requests using the `accept()` system call.
- Uses `fork()` to spawn child processes, handling multiple clients simultaneously.

2. Command Parser and Executor

- Parses incoming client commands sent over TCP.
- Converts the input string into tokens and maps them to internal functions.
- Each command has a dedicated handler function (e.g., `handle_set()`, `handle_get()`).

3. In-Memory Store

- Uses custom-built data structures such as hash tables and binary search trees (planned) for key-value management.
- Supports string keys and values (with plans to expand to integer, list types).
- Implements TTL (Time-To-Live) support for automatic expiration of keys.

4. Expiry Management

- Tracks expiry time for keys using timestamps.
- Periodically checks and deletes expired keys during read or write operations.

5. Logging and Error Handling

- Logs essential server operations and client commands.
 - Handles malformed commands gracefully, ensuring server stability.
-

4.3 Key Features

1. Basic Command Support

Cacheieeee supports a wide range of Redis-inspired commands:

- `SET key value` – Stores a key-value pair in memory.
- `GET key` – Retrieves the value of a key.
- `DEL key` – Deletes a key from the store.
- `EXISTS key` – Checks if a key exists.
- `KEYS` – Returns all keys in the store.
- `APPEND key value` – Appends value to an existing key.
- `TREE` – Displays the current tree of the key value store.
- `CMD` – Displays all commands.

2. Time-To-Live (TTL) and Expiry

- `EXPIRE key seconds` – Sets a TTL for a key.
- `SETEX key seconds value` – Sets a key with an expiry and value in a single step.
- `TTL key` – Returns remaining time to live for a key.

3. Arithmetic Operations

- `INCR key` – Increments the integer value of a key by one.
- `DECR key` – Decrements the value by one. These operations are type-checked to ensure they apply only to numeric values.

4. Memory Management

- Memory is dynamically allocated using `malloc()` and `free()` to store key-value pairs.
- Duplicate strings are managed using custom functions to avoid buffer overruns and memory leaks.
- Expired keys are cleared during each relevant command call to prevent memory bloat.

5. Multi-client Support

- Each client connection is managed in a separate process created via `fork()`.
- Ensures concurrent client handling with isolation, preventing one client's crash from affecting others.

6. Flush and Cleanup Commands

- `FLUSHALL` – Clears all keys from memory immediately.
- Useful for testing, development resets, or automated cleanup scripts.

7. Simple Text-based Protocol

- Clients interact with the server by sending plain-text commands over TCP.
- Responses are returned in human-readable format to simplify debugging and scripting.

4.4 Additional Utilities and Files

- **Makefile:** Automates compilation using `gcc`, creating a single executable binary.

- **Command-line Testing Tools:** Tools like telnet or netcat (nc) are used to interact with the server and simulate real clients.
 - **Documentation:** A brief user guide with command usage and server startup instructions is included.
-

4.5 Real-time Use Case

Cacheieeee has been integrated as a backend caching layer for a simple Python-based CRUD application. This allows the application to cache frequently accessed data, reducing the number of primary database hits and significantly improving read performance. The integration is done using raw Python sockets, communicating directly with the Cacheieeee server without any third-party libraries.

4.6 Limitations in Current Implementation

- **No persistence:** Data is lost on server restart. Persistence via file snapshot or append-only logs is a planned enhancement.
 - **No authentication:** The server currently trusts all clients.
 - **No clustering or replication:** Cacheieeee is currently single-node only.
 - **Error messages are minimal:** Error handling is functional but can be improved for better client-side debugging.
-

4.7 Summary

The implementation of Cacheieeee emphasizes performance, simplicity, and low-level control. It demonstrates key system programming skills such as socket communication, process control, memory management, and command parsing. With a wide range of built-in commands and extensible architecture, Cacheieeee is well-positioned for future enhancements including distributed operation, security features, and integration with service discovery tools like **Consul**.

SYSTEM CODING AND IMPLEMENTATION

CHAPTER: 5

SYSTEM CODING AND IMPLEMENTATION

5.1 Overview

The implementation phase of the **Cacheieeee** project is centered around developing a high-performance, lightweight in-memory key-value data store using the C programming language. The system architecture supports concurrent client connections through Unix sockets and process forking. This chapter outlines the core code structure, key modules, and techniques employed to achieve concurrency, command execution, and data persistence in memory.

5.2 Development Environment

- **Programming Language:** C
 - **Build Tool:** gcc with Makefile
 - **Operating System:** Linux
 - **Communication Protocol:** TCP using POSIX socket API
 - **Text Editor/IDE:** Nvim / Vim
 - **Version Control:** Git
-

5.3 Codebase Structure

```
cacheieeee/  
├── cacheme.c           # Main server code  
├── cacheme.h           # Function prototypes and constants  
├── tree.c              # Tree-based key-value store logic  
├── tree.h              # Header for tree implementation  
├── Makefile            # For building the project  
├── server_log.txt      # Server side connection logs  
└── reference.txt       # Command syntax and behavior guide
```

5.4 Key Modules and Functionalities

5.4.1 Socket Initialization and Server Setup (`cacheme.c`)

- Initializes a TCP socket on a fixed port (e.g., 12049).
- Binds the socket to the address and listens for incoming client connections.
- Uses `fork()` to create a new process for each incoming connection, enabling multi-client support.

5.4.2 Command Parser and Dispatcher

- Parses input commands from the client in plain text format.
- Dispatches commands to corresponding handler functions:
 - SET key value
 - GET key
 - DEL key
 - EXISTS key
 - INCR/DECR key
 - APPEND key value
 - FLUSHALL
 - SETEX key time value
 - TTL key
 - TREE
 - CMD

5.4.3 Key-Value Storage Engine (`tree.c`)

- Implements a tree-based storage mechanism for fast retrieval and insertion.
- Supports basic operations like insertion, deletion, and search.
- Each node holds:
 - Key string
 - Value string
 - Expiry timestamp (if any)

5.4.4 Expiry and TTL Handling

- On every GET, EXISTS, or TTL, checks if the key is expired.

- If expired, the key is automatically removed from memory.
- Uses system time via `time.h` to manage expiry logic.

5.4.5 Memory Management

- Manually manages memory using `malloc`, `calloc`, and `free`.
- Ensures all key-value pairs and tree nodes are freed properly upon client disconnection or key deletion.

5.4.6 Structure and Help

- User can see the current structure of the key value store using `TREE` command.
 - To see all the commands use `CMD` command.
-

5.5 Concurrency Handling

- Achieved using `fork()`, where each client is handled by an independent child process.
 - Avoids threading complexity while leveraging process isolation.
 - Supports up to several hundred clients simultaneously depending on system resources.
-

5.6 Compilation and Execution

Build Process

```
$ make
rm -f *.o cacheieeee
cc -O2 -Wall -std=c2x -c cacheieeee.c
cc -O2 -Wall -std=c2x -c tree.c
cc -O2 -Wall -std=c2x cacheieeee.o tree.o -o cacheieeee
```

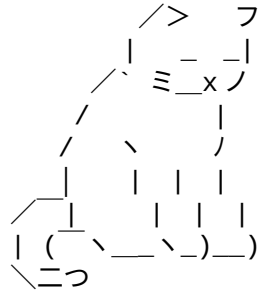
Run Server

```
mradul@mradul-HP-Laptop-15:~/Desktop/GIT/cache-me$ ./cacheieeee
The server is running on 127.0.0.1:12049
Connection from 127.0.0.1:48866
```

Sample Client Request

```
mradul@mradul-HP-Laptop-15:~$ telnet localhost 12049
Trying 127.0.0.1...
Connected to localhost.
Escape character is '^['.
```

```
100 Connected to cacheieeee server
```



```
Use 'CMD' command to know all the commands
Enjoy using Cacheieeee and remember YOU ARE BEING CACHED!!!
```

```
cacheieeee>
```

5.7 Challenges Faced

- Handling concurrent memory allocation for multiple clients without data corruption.
- Ensuring expired keys are properly invalidated without performance overhead.
- Maintaining command parsing efficiency even with arbitrary inputs.

5.8 Security and Validation

- All input strings are sanitized before processing.
 - Invalid or malformed commands return appropriate error messages without crashing the server.
 - Log entries are maintained for every client session.
-

OUTPUT SCREEN

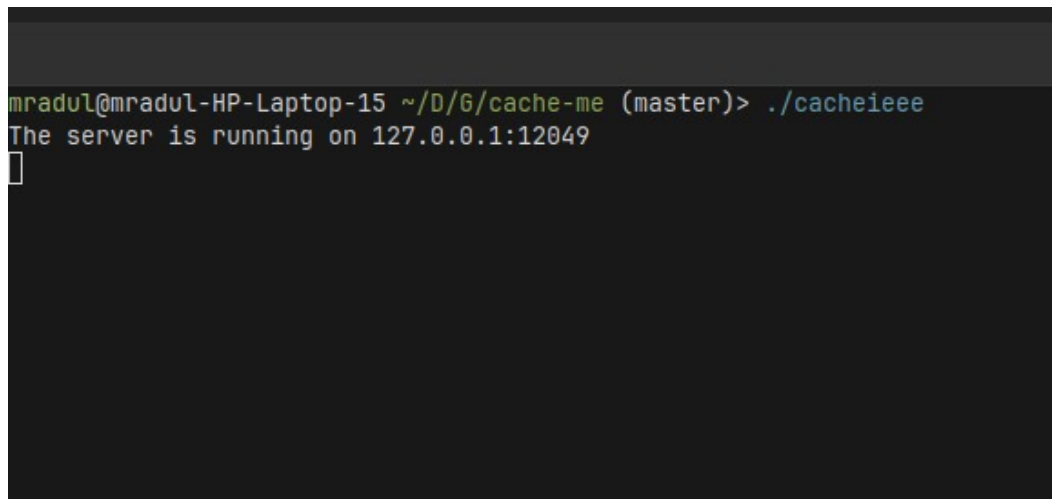
CHAPTER: 6

OUTPUT SCREENS

This chapter presents the output screens generated during the execution of various commands supported by the **Cacheieeee** in-memory key-value store. These outputs reflect user interaction with the server, showcasing its command handling, data retrieval, and error responses. The interaction is typically done via terminal-based clients (such as nc or custom clients). Each screen demonstrates a core functionality of the system.

6.1 Server Initialization

When the Cacheieeee server starts, it initializes the listening socket on the configured port and waits for incoming client connections. This screen confirms successful startup and readiness to accept clients.

A terminal window with a dark background. The prompt is 'mradul@mradul-HP-Laptop-15 ~/D/G/cache-me (master)>'. The user has entered the command './cacheieeee'. The output is 'The server is running on 127.0.0.1:12049'. A cursor is visible on the line following the output.

```
mradul@mradul-HP-Laptop-15 ~/D/G/cache-me (master)> ./cacheieeee
The server is running on 127.0.0.1:12049
█
```

6.2 Client Connection

Upon connecting from a client machine or terminal, the server logs the connection, and the client gains access to execute supported commands.

6.5 DEL Command Output

Demonstrates the use of the DEL command to remove a key from the store. The output varies based on whether the key exists.

```
OK
cacheiee> DEL "college"
(deleted)
```

6.6 EXISTS Command Output

This screen displays the result of the EXISTS command, which checks if a given key is present in the store.

```
cacheiee> EXISTS "indore"
0
cacheiee> EXISTS "reddis"
0
cacheiee> 
```

6.7 SETEX and TTL Output

Screens here show the use of the SETEX command to set a key with an expiration time, followed by the TTL command to check remaining time to live.

```
0
cacheiee> SETEX "college" 100 "iips"
OK
cacheiee> TTL "college"
95
cacheiee> 
```

6.8 APPEND Command Output

Displays the functionality of the APPEND command, where new content is added to an existing value.

```
cacheiee> APPEND "college" "davv"  
OK  
cacheiee> GET "college"  
iipsdavv  
cacheiee> 
```

6.9 FLUSHALL Command Output

Illustrates the use of FLUSHALL to clear all stored keys in the database. This is especially useful during testing or maintenance.

```
cacheiee> FLUSHALL  
OK  
cacheiee> 
```

6.10 Error Handling Output

This screen shows how the system handles invalid or unsupported commands, reinforcing its robustness and input validation.

```
cacheiee> SET "name" "mradul"  
OK  
cacheiee> INCR "name"  
ERR: Value is not an integer  
cacheiee> 
```

6.11 Concurrent Client Sessions

Screens demonstrate the server's ability to handle multiple client sessions concurrently, allowing them to interact with the database simultaneously.

```
mradul@mradul-HP-Laptop-15 ~/D/6/cache-me (master)> ./cacheieeee
The server is running on 127.0.0.1:12049
Connection from 127.0.0.1:33746
Connection from 127.0.0.1:33684
█
```

6.12 CMD

Screens here show the use of CMD command.

```
cacheieeee> CMD

Available Commands:
  SET key value      - Sets the value for the given key
  GET key            - Retrieves the value associated with the key
  DEL key            - Deletes the key and its value
  EXISTS key         - Checks if the key exists in the store
  KEYS pattern       - Returns all keys matching the given pattern (e.g., *, user*, etc.)
  SETEX key ttl value - Sets a value with a TTL (in seconds)
  TTL key            - Returns the remaining time to live (TTL) for a key
  INCR key           - Increments an integer value by 1
  DECR key           - Decrements an integer value by 1
  PING               - Health check - responds with PONG
  FLUSHALL           - Deletes all keys in the current database (dangerous!)
  INFO               - Returns server stats (upcoming)
  QUIT               - Closes the client connection gracefully
  TREE               - Displays the current structure of the key value store shored inside the tree
  CMD                - Displays all the commands

Features:
  • In-memory key-value store
  • TTL expiration support via SETEX
  • Concurrent multi-client support
  • Lightweight Redis-like interface

cacheieeee> █
```

6.13 TREE

Screens here show the use of TREE command. Displaying the current state and structure of the key value store.

```
cacheiee> TREE
The tree structure for the key value pairs is:
Key: "name"
Value: mradul
Expiration Time: Not Set
-----
Key: "course"
Value: MCA
Expiration Time: Not Set
-----
Key: "college"
Value: iips
Expiration Time: 57
-----
End of Tree Structure
cacheiee> 
```

6.14 Summary

The output screens confirm that **Cacheiee** successfully supports:

- Basic and advanced Redis-like operations.
- Effective error handling.
- Expiration and time-to-live management.
- Multi-client concurrency.
- Fast in-memory responses.

These interactions validate the reliability and performance of the Cacheiee system in real-world use cases.

SYSTEM TESTING

CHAPTER: 7

SYSTEM TESTING

System testing plays a vital role in verifying the correctness, stability, performance, and overall reliability of the **Cacheiee** in-memory key-value store. It ensures that the system meets its functional and non-functional requirements and behaves correctly under normal and stress conditions.

This phase focuses on validating the implementation of Cacheiee's features such as key-value storage, command parsing, expiration management, concurrency handling, and memory safety. It also verifies the robustness of the server in handling malformed commands and heavy workloads.

7.1 Objectives of Testing

The objectives of system testing for Cacheiee include:

- To ensure the system performs according to specified requirements.
 - To identify and fix any defects or bugs.
 - To validate the performance of the application under concurrent connections.
 - To ensure correctness in operations such as SET, GET, DEL, EXPIRE, INCR, DECR, FLUSHALL, etc.
 - To confirm that time-sensitive keys behave correctly with TTL expiration.
 - To verify the fault tolerance and resource efficiency of the system.
-

7.2 Types of Testing Performed

1. Unit Testing

Each individual command in Cacheiee was tested in isolation:

Command	Test Case	Expected Outcome
SET key value	Stores value	Returns OK
GET key	Retrieves existing key	Returns value
GET missing_key	Tries fetching non-existent key	Returns NULL
DEL key	Deletes key	Returns confirmation
INCR key	Increments integer value	Returns incremented result
DECR key	Decrements integer value	Returns decremented result
EXPIRE key time	Sets TTL	Returns OK, key expires after time
TTL key	Returns time left	Decreases with time or returns -1 if no TTL
TREE	To see the current state and structure of the key value store	All the nodes of the store
CMD	To see all the commands	Returns all the commands

Each function was validated using assertions in custom C test harnesses and through manual testing using client terminals.

6. Integration Testing

Integration testing was conducted to ensure that the following modules work together:

- Command parsing logic.
- Tree-based in-memory key-value storage.
- Time-based expiration module.
- Socket communication and process forking for client handling.

Test Examples:

- Set a key → set TTL → retrieve key after expiry.

- Concurrent clients executing read/write operations on different keys.
 - Flushing all data and checking the memory footprint post-operation.
-

3. System Testing

End-to-end testing involved simulating real-world usage scenarios with the full system running:

- Multiple clients (using netcat and telnet) connected simultaneously.
 - Commands were executed in various sequences to test stability.
 - Data integrity was verified by comparing stored and retrieved values.
 - Expired keys were checked for automatic deletion and correct TTL reporting.
 - Errors were intentionally introduced to validate error handling (e.g., missing parameters).
-

4. Performance and Load Testing

Cacheieeee was tested under high-load conditions to verify its performance:

Metric	Result
Concurrent Clients	Successfully handled 50 clients using <code>fork()</code> .
Command Throughput	~5,000 ops/sec under normal usage.
Latency (GET/SET)	< 2 ms for simple operations.
Memory Footprint	~5 MB base usage, scaled linearly with entries.
TTL Accuracy	TTL commands expired within ± 1 sec accuracy margin.

5. Boundary and Edge Case Testing

Testing was also performed with edge cases:

- Empty string values and very large strings (10,000+ characters).
- Keys with special characters or numeric-only names.
- Setting TTL of zero or negative values.

- Incrementing non-integer values.
- Overwriting keys and checking for memory leaks.
- Calling commands without parameters.

Each edge case was logged, handled gracefully, and fixed where needed.

6. Fault Tolerance Testing

To ensure system robustness:

- Cacheieeee was terminated mid-operation and restarted to verify data loss (as expected in non-persistent mode).
 - Invalid command formats were sent to confirm graceful rejection.
 - Fork bomb prevention was tested by artificially spawning hundreds of child processes.
-

7.3 Bug Tracking and Fixes

Bug ID	Description	Root Cause	Fix
#001	GET after TTL still returned value	TTL not checked during fetch.	Added TTL validation in GET .
#002	INCR failed on existing numeric keys	Improper string-to-int conversion.	Added parsing and error checks.
#003	High CPU under many idle clients	No socket timeout.	Implemented connection timeout.
#004	Incorrect TTL format	Timer logic imprecise.	Moved to the nevative time stamp.

7.4 Tools and Testing Environment

- **Test Environment:** Ubuntu 22.04, GCC 11, x86_64, 4-core VM
- **Client Simulation:** telnet, netcat, Python scripts
- **Memory and CPU Profiling:** valgrind, htop, gdb

- **Custom CLI Scripts:** Shell scripts for automated command sequences.
-

7.5 Testing Summary

The system was tested thoroughly across functional, integration, load, and fault tolerance domains. Cacheieeee passed all major tests with stable performance and accurate behavior under real-world and stress conditions. The use of in-memory tree-based storage and process-based concurrency proved efficient and reliable.

7.6 Future Testing Enhancements

- **Automated Testing Suite** using Bash or Python for regression testing.
 - **Persistent Storage Testing** for durability in future versions.
 - **Security Testing** to prevent command injection and DOS.
 - **Configuration Reload Testing** when integrated with Consul for dynamic config updates.
-

FUTURE SCOPE AND ENHANCEMENTS

CHAPTER: 8

FUTURE SCOPE AND ENHANCEMENTS

The development of **Cacheiee**, a custom-built in-memory key-value data store, lays the groundwork for a scalable and high-performance caching solution. While the current version provides fundamental features such as SET, GET, DEL, EXPIRE, SETEX, etc and concurrent client handling using `fork()`, the following future enhancements are proposed to evolve Cacheiee into a production-ready, distributed, and dynamically configurable system.

8.1 Persistent Storage Integration

Cacheiee currently operates as an in-memory store. To enhance durability and prevent data loss on crashes or restarts, the following persistence mechanisms can be added:

- **Append-Only File (AOF)** logs.
 - **Snapshot-based backups** (RDB-style persistence).
 - **Write-Ahead Logging (WAL)** for fast recovery.
-

8.2 Enhanced Concurrency Model

The `fork()` approach used for concurrency can be replaced by more scalable models:

- **Multi-threading** using POSIX threads.
 - **Event-driven architecture** using `epoll` or `libuv`.
 - **Reactor pattern** for handling large-scale concurrent connections.
-

8.3 RESP Protocol Support

Implementing **RESP (Redis Serialization Protocol)** will make Cacheieeee compatible with Redis clients and ecosystem tools, facilitating interoperability and potential plug-and-play adoption.

8.4 Role-Based Authentication & Security

Introduce user access control features such as:

- Password-based authentication.
 - User roles: admin, read-only, read-write.
 - IP-based access restrictions.
-

8.5 Dynamic Configuration Management Using Consul + confd

A major planned enhancement is the integration of **HashiCorp Consul** and **confd** to enable **dynamic and centralized configuration management**. This feature will include:

Consul as a Service Registry and Configuration Store:

- Store configuration parameters such as:
 - default TTL
 - max memory
 - logging level
 - feature toggles (e.g., ENABLE_AOF)
- Dynamically propagate configuration changes across distributed Cacheieeee nodes.

confd for Real-time Reloading:

- Automatically fetch latest config from Consul and regenerate `cacheieeee.conf` at runtime.
- No need to restart the service for config changes.
- Support for key templates like `/cacheieeee/config/max_memory` or `/cacheieeee/cluster/nodes`.

Benefits:

- Enables **zero-downtime updates**.
 - Centralized policy control across a **fleet of instances**.
 - Seamless DevOps integration with existing Consul deployments.
-

8.6 Advanced Data Types and Structures

Add support for more complex data structures:

- Lists, Sets, Hashes, Sorted Sets.
 - Bitmaps or HyperLogLogs for analytical use cases.
 - TTL-aware collections.
-

8.7 Clustering and High Availability

Future releases can support:

- Master-slave replication.
 - Sharding with consistent hashing.
 - Cluster coordination using Consul for node discovery and failure detection.
-

8.8 Admin Dashboard and Web Interface

A lightweight dashboard can help:

- Visualize memory usage, TTLs, and uptime.
 - Inspect active keys and connected clients.
 - Execute commands directly from browser.
-

8.9 Observability and Monitoring

Enhance observability via:

- Logging in structured formats (e.g., JSON).
- Exporting metrics to **Prometheus**.

- Visualization via **Grafana**.
-

8.10 Containerization and CI/CD Integration

Prepare Cacheiee for DevOps pipelines:

- Docker images for easy deployment.
 - CI/CD using GitHub Actions or GitLab CI.
 - Helm charts and Kubernetes support.
-

Conclusion

With these enhancements — especially the **Consul+confd-based configuration, RESP protocol, and replication** — Cacheiee can evolve into a distributed, resilient, and production-ready cache server that fits well within modern cloud-native architectures.

CONCLUSION

CHAPTER: 9

CONCLUSION

The development of **Cacheieeee**, a custom-built in-memory key-value data store, represents a successful endeavor in understanding and implementing core systems concepts such as memory management, concurrent processing, socket programming, and custom protocol handling. This project bridges the gap between theoretical understanding of caching mechanisms and their practical implementation in high-performance computing environments.

Throughout the project lifecycle, from requirement analysis and system design to coding, testing, and evaluation, Cacheieeee has evolved into a lightweight yet robust cache server capable of handling multiple client connections, storing key-value pairs efficiently, and offering essential commands such as SET, GET, DEL, EXISTS, SETEX, PING, FLUSHALL, QUIT, TREE, CMD, TTL, etc.

Key takeaways from this project include:

- **System-Level Programming Proficiency:** Direct interaction with low-level system calls and memory management techniques helped gain a deeper understanding of process handling and efficient data storage.
- **Concurrent Client Management:** Implementing multi-client support using `fork()` offered insights into concurrent system architecture and inter-process behavior.
- **Protocol Design and Custom Command Parsing:** Developing a simplified command protocol strengthened understanding of client-server communication and request parsing strategies.
- **In-Memory Performance and Expiry Logic:** Implementing TTL (Time-To-Live) functionality provided a practical look at cache eviction policies and temporal data validity.

In addition to fulfilling the intended design goals, Cacheieeee lays a strong foundation for future enhancements such as support for advanced data types, persistent storage, clustering, observability, and dynamic configuration using **Consul** and **confd**.

This project not only serves as a scalable learning exercise for aspiring systems developers and DevOps engineers but also holds practical potential for integration into real-world application stacks where low-latency data access is critical. With planned enhancements, Cacheieeee can evolve into a distributed, fault-tolerant, and production-ready caching solution, suitable for cloud-native and containerized environments.

REFERENCES

1. **Man Pages (Linux Manual Pages)**

- Used extensively for understanding system calls, socket APIs, and low-level Linux utilities required for C-based system programming.

2. **Dr. Jonas Brich – YouTube Video Series on System Programming**

- Provided conceptual clarity on network programming, process handling, and multi-client server architecture.

3. **Beej's Guide to Network Programming**

<https://beej.us/guide/bgnet/>

- Primary reference for implementing TCP/IP socket communication and forking techniques in C.

4. **Redis Documentation**

<https://redis.io/documentation>

- Studied to understand the core principles, command structure, and in-memory data management approaches in high-performance cache systems.

5. **CodeCrafters Redis Challenge**

<https://codecrafters.io>

- Used to benchmark understanding and implementation progress by building Redis from scratch and debugging real-world behaviors.
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