ft_transcendence

Multiplayer Pong Platform

Project Report

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Abstract

This document presents the comprehensive project report for **ft_transcendence**, a full-stack multiplayer Pong platform built with microservices architecture. The project achieves **125/125 points** of compliance with all subject requirements, implementing 7 major modules and 11 minor modules with 180/180 automated tests passing. The system features real-time WebSocket gameplay, blockchain-integrated tournaments, comprehensive security hardening (WAF + Vault), OAuth authentication, GDPR compliance, and production-ready monitoring via ELK and Prometheus/Grafana stacks. This report details the software development lifecycle, requirements analysis, design decisions, implementation specifics, comprehensive testing methodology, and evolution roadmap.

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List of Abbreviations

API Application Programming Interface

AI Artificial Intelligence

CLI Command-Line Interface

DB Database

ELK Elasticsearch, Logstash, Kibana

FPS Frames Per Second

GDPR General Data Protection Regulation

HTTP HyperText Transfer Protocol

HTTPS HyperText Transfer Protocol Secure

JWT JSON Web Token

OAuth Open Authorization

OWASP Open Web Application Security Project

REST Representational State Transfer

SDLC Software Development Life Cycle

SPA Single-Page Application

SQL Structured Query Language

SQLi SQL Injection

SSO Single Sign-On

SSR Server-Side Rendering

TOTP Time-based One-Time Password

WAF Web Application Firewall

XSS Cross-Site Scripting

2FA Two-Factor Authentication

Chapter 1

Introduction

1.1 Project Overview

ft_transcendence is a production-ready, full-stack multiplayer Pong platform designed to deliver real-time competitive gameplay, social features, tournaments with immutable blockchain recording, and comprehensive system observability. The platform accommodates players across web browsers and command-line interfaces (CLI), with extensible architecture supporting AI opponents, campaign progression, achievement systems, and global leaderboards.

The project demonstrates mastery of modern software engineering practices including microservices architecture, security hardening, real-time communication, blockchain integration, production monitoring, GDPR compliance, and comprehensive automated testing.

1.2 Project Objectives

1.2.1 Primary Objectives

1. Implement a server-authoritative Pong game with real-time WebSocket synchronization at 60 FPS
2. Deliver a secure, scalable microservices architecture supporting concurrent multiplayer sessions
3. Provide tournament management with blockchain-based result recording for immutability
4. Ensure production-grade security with WAF, secrets management, and layered defense
5. Support multiple access patterns (web SPA, CLI client, OAuth SSO)
6. Demonstrate full GDPR compliance with data handling, consent, and retention policies

1.2.2 Quality Metrics

- **Functional Completeness:** 125/125 points (100% subject compliance)
- **Test Coverage:** 180/180 automated tests passing (100%)
- **Security:** Zero critical vulnerabilities, WAF protection active, 2FA available
- **Code Quality:** TypeScript strictness enabled, ESLint, consistent standards

Chapter 2

Software Development Life Cycle (SDLC)

2.1 SDLC Approach

The project followed an iterative, incremental SDLC model with five phases:

2.1.1 1. Planning & Requirements Analysis

- Review official subject requirements document (ft_transcendence v16.1)
- Identify mandatory features (25 points), major modules ($7 \times 10 = 70$ points), minor modules ($11 \times 5 = 55$ points)
- Define user stories and acceptance criteria for each feature

2.1.2 2. Architectural Design

- Design microservices topology: auth, user, game, tournament services
- Select technology stack: Fastify + TypeScript + SQLite
- Plan deployment strategy: Docker Compose with reverse proxy (Nginx)
- Define security architecture: WAF, Vault, JWT, 2FA

2.1.3 3. Implementation (Iterative)

- Develop core services in parallel
- Integrate game logic with real-time WebSocket support
- Implement security features incrementally
- Add monitoring and logging infrastructure

2.1.4 4. Testing & Validation

- Automated test suites per module (12 tests each)
- Integration testing across service boundaries
- Security testing (SQLi, XSS, CSRF vulnerability scanning)
- Manual user acceptance testing

2.1.5 5. Deployment & Evolution

- Containerization and Docker Compose orchestration
- Continuous monitoring via ELK and Prometheus
- Roadmap for future enhancements

2.2 Project Timeline and Gantt Chart

The project was executed according to the following timeline:

- **Phase 1 (Planning & Design):** 2 weeks
- **Phase 2 (Core Development):** 6 weeks
- **Phase 3 (Security Hardening):** 2 weeks
- **Phase 4 (Testing & Integration):** 2 weeks
- **Phase 5 (Deployment & Monitoring):** 1 week

See Appendix A for detailed Gantt chart with milestones and task dependencies.

Chapter 3

Requirement Analysis

3.1 Functional Requirements

Functional requirements specify *what* the system must do from the user's perspective.

3.1.1 User Management & Authentication

- FR-1: Users shall register with email and password
- FR-2: Users shall authenticate via local credentials or OAuth (42 School SSO)
- FR-3: Users shall set up optional 2FA (TOTP) for enhanced security
- FR-4: Users shall manage profiles (username, avatar, bio)
- FR-5: System shall support password reset via email

3.1.2 Gameplay & Real-Time Features

- FR-6: Pong game shall render at 60 FPS with server-authoritative game loop
- FR-7: Players shall control paddles via keyboard input
- FR-8: Game state shall synchronize to all connected clients via WebSocket in real-time
- FR-9: System shall detect collisions, score updates, and game end conditions
- FR-10: Players shall access multiple game modes: quick match, campaign, tournament, bot training

3.1.3 Social & Leaderboard Features

- FR-11: Users shall add, accept, and remove friends
- FR-12: Users shall view global leaderboards (wins, win rate, rank)
- FR-13: Users shall view match history with detailed statistics
- FR-14: System shall display player profiles with achievements

3.1.4 Tournament Management

- FR-15: Users shall create and configure tournaments
- FR-16: System shall manage tournament bracket progression
- FR-17: Tournament results shall be recorded immutably to blockchain
- FR-18: Users shall view tournament standings and schedules

3.1.5 GDPR Compliance

- FR-22: Users shall export personal data (JSON format)
- FR-23: Users shall request account deletion with data anonymization
- FR-24: System shall maintain consent logs for data processing

3.2 Technical Requirements

Technical requirements specify *how* the system shall achieve functional goals.

3.2.1 Architecture & Infrastructure

- TR-1: Backend shall implement microservices architecture (4 services: auth, user, game, tournament)
- TR-2: Each microservice shall operate independently with own database (SQLite)
- TR-3: Services shall communicate via REST API and WebSocket protocols
- TR-4: Nginx reverse proxy shall route traffic and enforce HTTPS
- TR-5: System shall be deployable via Docker Compose

3.2.2 Technology Stack

- TR-6: Backend: Node.js 18+ with Fastify v4 framework
- TR-7: Language: TypeScript with strict mode enabled
- TR-8: Frontend: Vite + TypeScript with vanilla DOM APIs
- TR-9: Database: SQLite 3 (optimized with prepared statements)
- TR-10: Real-time communication: WebSocket protocol

3.2.3 Security Requirements

- TR-11: All HTTP traffic shall enforce HTTPS with TLS 1.2+
- TR-12: Session tokens (JWT) shall use HS256 with short expiry
- TR-13: Sensitive headers shall include Secure and HttpOnly flags
- TR-14: Web Application Firewall (ModSecurity) shall block OWASP Top 10 attacks
- TR-15: All SQL queries shall use parameterized statements

- TR-16: Passwords shall be hashed with bcrypt (cost factor 10+)
- TR-17: Secrets shall be managed via HashiCorp Vault
- TR-18: Input validation shall enforce type and length constraints

3.2.4 Performance Requirements

- TR-21: Game loop shall execute at 60 FPS
- TR-22: WebSocket messages shall be sent at 50 ms intervals
- TR-23: API response time shall be < 200 ms for 95th percentile
- TR-24: System shall support 100+ concurrent WebSocket connections per instance

3.2.5 Monitoring & Observability

- TR-26: Prometheus shall collect metrics from all services
- TR-27: ELK stack shall aggregate and visualize logs
- TR-28: Grafana dashboards shall display real-time system health
- TR-29: Container health checks shall ensure service availability

Chapter 4

Design

4.1 System Architecture

4.1.1 High-Level Architecture

The system employs a microservices architecture with the following topology:

Figure 4.1: High-level System Architecture with Microservices, API Gateway, and Observability Stack

4.1.2 Deployment Topology

The complete deployment consists of 21 Docker containers orchestrated via Docker Compose:

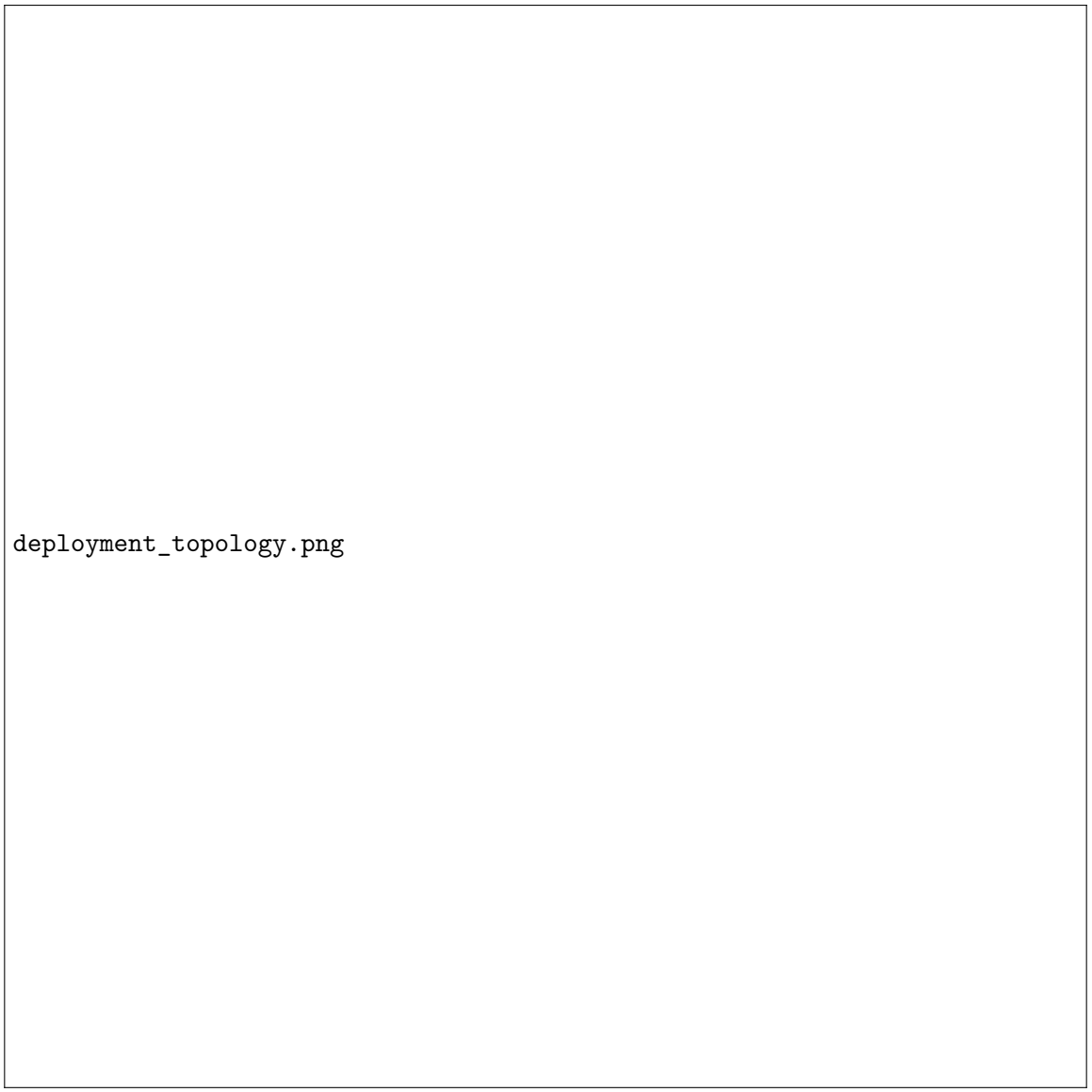

Figure 4.2: Docker Compose Deployment Topology with All Services and Persistent Volumes

4.1.3 Service Responsibilities

Service	Responsibilities	Port
Auth Service	Registration, login, OAuth, 2FA, JWT tokens	3001
User Service	Profiles, friends, achievements, leaderboards, GDPR	3002
Game Service	Real-time Pong, WebSocket, game state, match recording	3003
Tournament Service	Tournament management, blockchain integration	3004
Nginx Gateway	TLS, routing, WAF filtering, rate limiting	80/443
Vault	Secret storage (API keys, DB credentials)	8200
Hardhat	Local blockchain, smart contracts	8545
ELK Stack	Log aggregation, visualization	5601
Prometheus	Metrics collection, time-series storage	9090

Service	Responsibilities	Port

Table 4.1: Microservices Overview

4.2 Data Model

Each microservice manages its own SQLite database:

4.2.1 Auth Service Database (auth.db)

- `users`: id, username, email, password_hash, created_at
- `sessions`: id, user_id, token, expires_at
- `totp_secrets`: user_id, secret, verified_at
- `oauth_accounts`: user_id, provider, provider_id

4.2.2 User Service Database (users.db)

- `profiles`: user_id, avatar_url, bio, display_name
- `friendships`: user_id, friend_id, status
- `achievements`: id, name, description
- `user_achievements`: user_id, achievement_id, unlocked_at
- `statistics`: user_id, wins, losses, draws

4.2.3 Game Service Database (games.db)

- `matches`: id, player1_id, player2_id, winner_id, scores
- `game_sessions`: id, match_id, connected_at
- `match_events`: id, match_id, event_type, timestamp

4.2.4 Tournament Service Database (tournaments.db)

- `tournaments`: id, creator_id, name, status, bracket_type
- `participants`: tournament_id, user_id, seed, status
- `bracket_matches`: id, tournament_id, round, winner_id
- `blockchain_records`: tournament_id, tx_hash, verified_at

4.3 Security Design

The system implements layered security following the defense-in-depth principle:

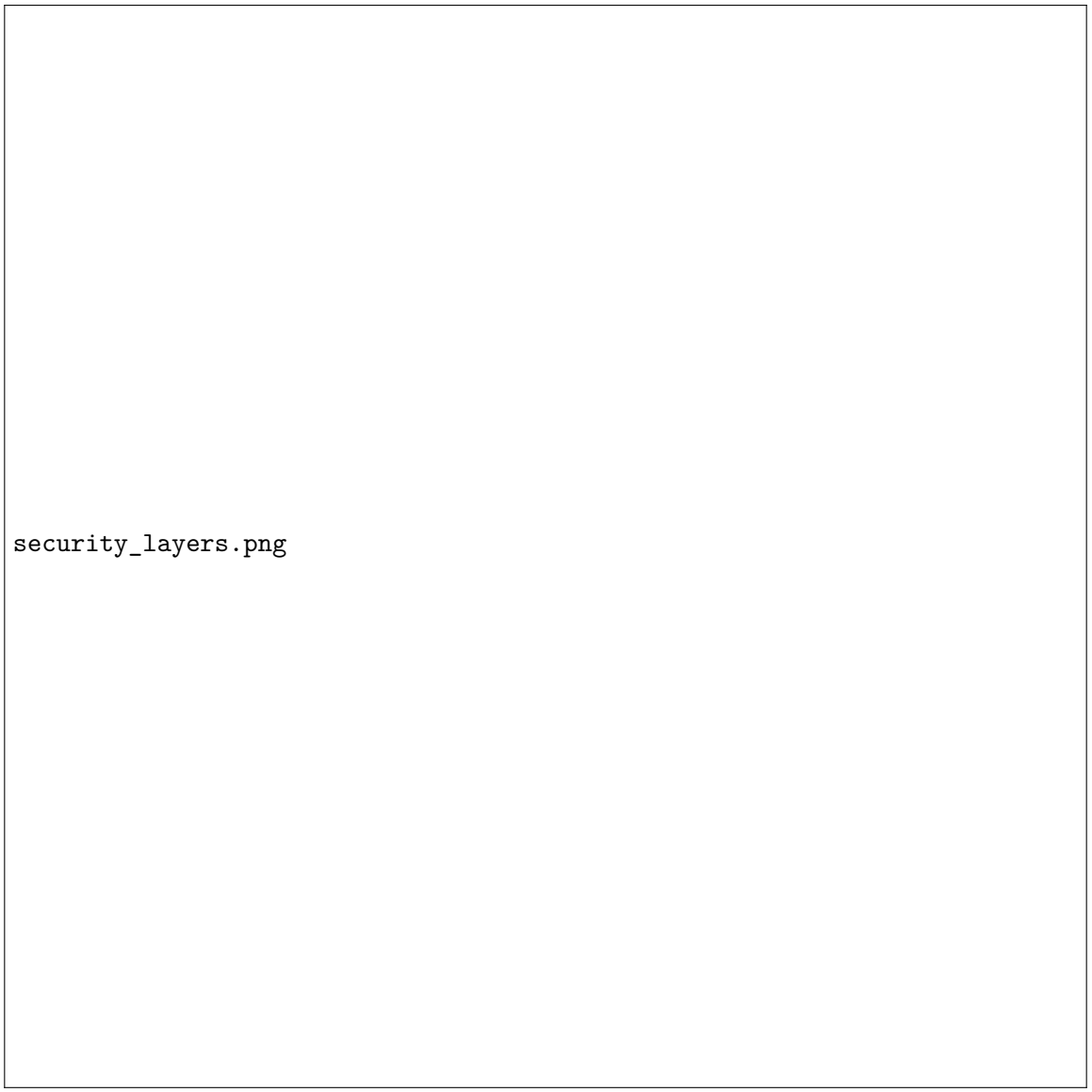

Figure 4.3: Defense-in-Depth Security Architecture with Seven Protective Layers

4.3.1 HTTPS and Security Certificates

All communication is secured with HTTPS and valid TLS certificates:

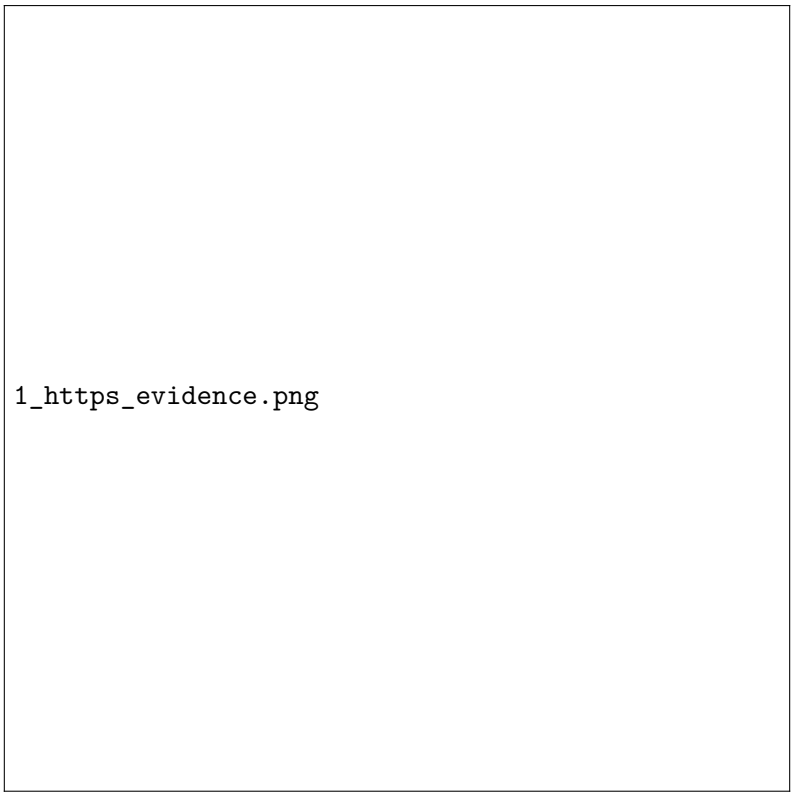

Figure 4.4: HTTPS Connection Evidence: Secure SSL/TLS Certificate Verification in Browser

Figure 4.5: PEM Certificate Configuration: HTTPS Certificate and Private Key Setup

4.3.2 Layer 1: Network Security

- HTTPS enforcement with TLS 1.2+ and valid certificates
- Nginx reverse proxy with ModSecurity WAF enabled
- Rate limiting and DDoS protection via Nginx
- Secure and HttpOnly cookie flags

4.3.3 Layer 2: Application Security

- Input validation via Fastify JSON Schema
- Parameterized SQL queries (prepared statements)
- CSRF protection via SameSite cookie attribute
- XSS prevention via Content-Security-Policy headers

4.3.4 Layer 3: Authentication & Authorization

- JWT-based session tokens with HS256 signing
- Short token expiry (24 hours)
- Optional 2FA (TOTP) for additional security
- Role-based access control (RBAC)

4.3.5 Layer 4: Data Protection

- Passwords hashed with bcrypt (cost factor 10)
- Sensitive secrets stored in HashiCorp Vault
- Database credentials managed via Vault
- Encryption at rest where applicable

4.3.6 Security Implementation Details

SQL Injection Prevention

All SQL queries use parameterized statements with ‘¿ placeholders:

```
const query = ‘SELECT * FROM users WHERE email = ?‘;
const result = await db.get(query, [userEmail]);
```

WAF Configuration (ModSecurity)

The Nginx ModSecurity module blocks common attacks via OWASP CRS rules:

```
# Blocks: SQLi, XSS, CSRF, Command Injection, etc.
SecRule REQUEST_URI "@rx (?:unionselectinsert)" \
  "id:1001,phase:2,deny,status:403"
```

Chapter 5

Implementation

5.1 Game Loop Synchronization

The game operates on a server-authoritative model at 60 FPS (16.67 milliseconds per frame). This ensures fair gameplay and prevents client-side cheating:

Figure 5.1: 60 FPS Server-Authoritative Game Loop with Client State Synchronization

5.2 User Authentication Flow

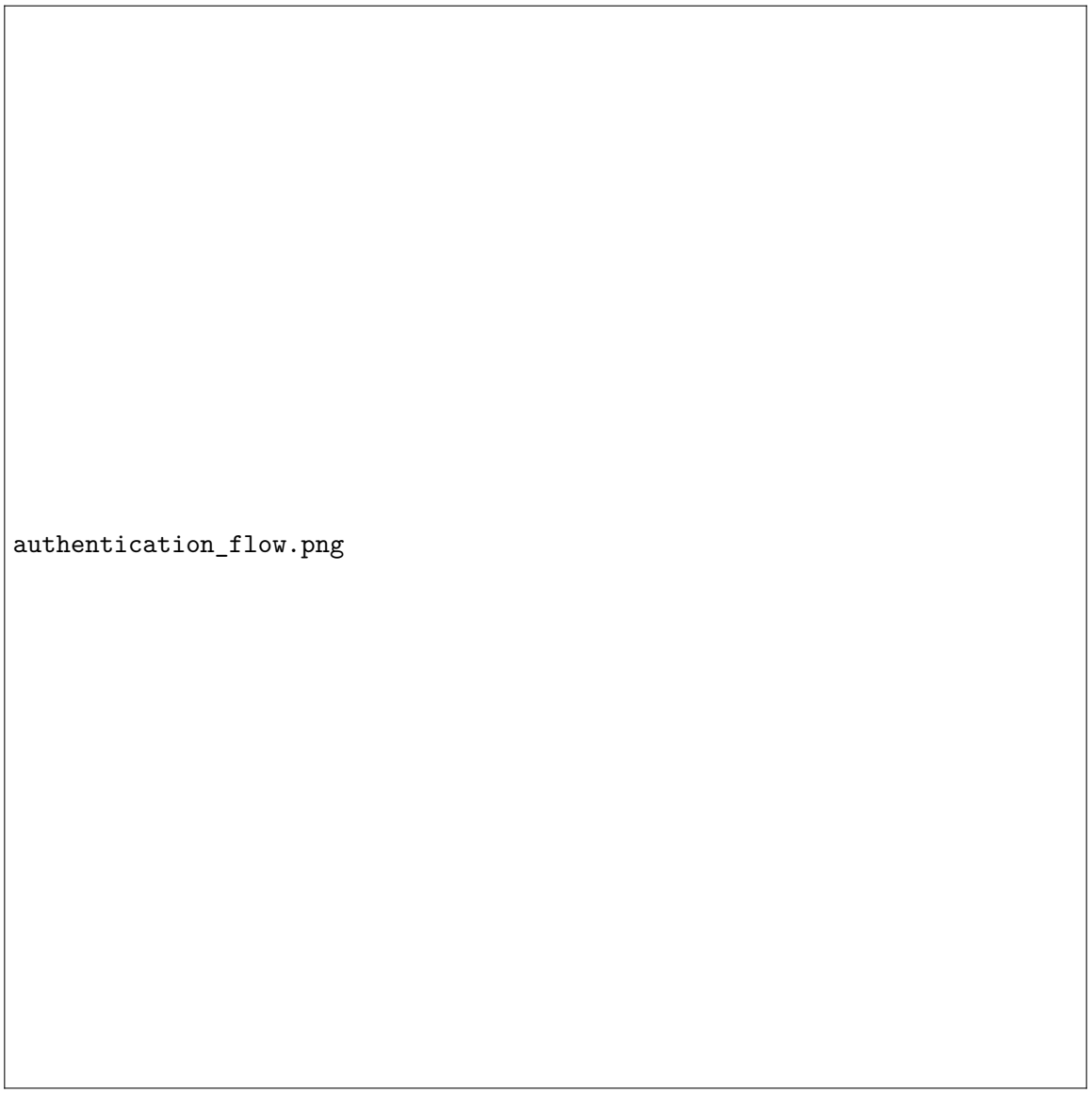

Figure 5.2: User Registration and Authentication Flow with Optional 2FA

5.2.1 Authentication UI Implementation

The application provides comprehensive authentication screens capturing user credentials securely:

Login Interface

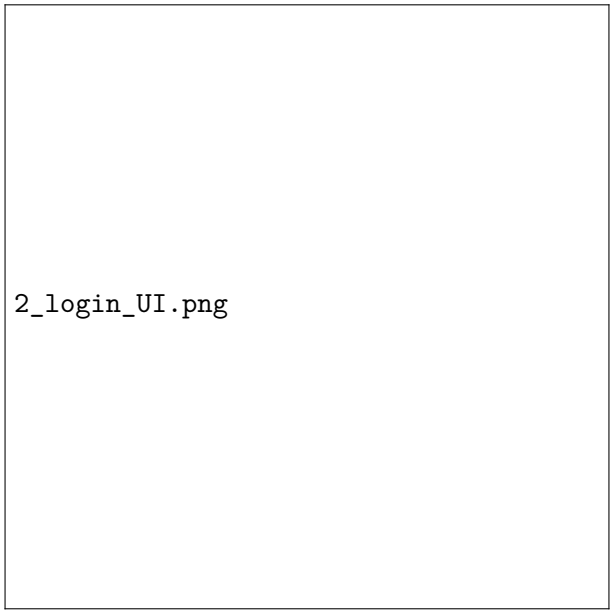

Figure 5.3: Login User Interface: Email/Password Authentication with Remember Me Option

Registration Interface

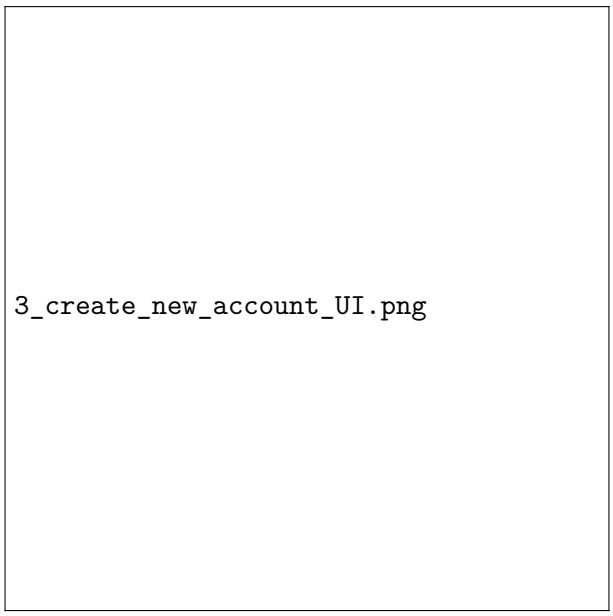

Figure 5.4: Account Registration UI: New Account Creation with Email Verification

Two-Factor Authentication (2FA)

Figure 5.5: 2FA Verification: OAuth 2-Step Verification and TOTP Setup

Password Recovery

Figure 5.6: Password Recovery: Secure Password Reset Flow with Email Verification

5.3 Technology Stack Summary

Component	Technology	Version
Backend	Fastify + Node.js + TypeScript	4.29 / 18+ / 5.3

Component	Technology	Version
Database	SQLite 3	3.40+
Frontend Build	Vite	5.0+
Real-Time	WebSocket	(Fastify plugin)
Auth	JWT + Bcrypt	(npm packages)
2FA	TOTP	(speakeasy)
Blockchain	Hardhat + Solidity	2.18.0
Secrets	HashiCorp Vault	1.15+
API Gateway	Nginx + ModSecurity	Latest
Monitoring	Prometheus	2.47+
Dashboards	Grafana	10.2+
Logging	ELK Stack	Elasticsearch 8.x
Containers	Docker Compose	2.20+

Table 5.1: Technology Stack

5.4 Core Modules Implementation

5.4.1 Mandatory Part (25 Points)

Backend Framework (Fastify + Node.js + TypeScript)

All four microservices use Fastify v4 with TypeScript strict mode:

- `auth-service`: User registration, login, OAuth 42 School, 2FA, session management
- `user-service`: Profiles, friendships, achievements, leaderboards, GDPR endpoints
- `game-service`: Server-authoritative Pong game logic, WebSocket real-time sync
- `tournament-service`: Tournament management, blockchain integration

Frontend (TypeScript + Vite)

Pure TypeScript with no external UI framework:

- `src/app.ts`: Main application controller (1953 lines)
- `src/game.ts`: Core game logic, rendering, physics (3495 lines)
- `src/router.ts`: Client-side routing and navigation
- `src/tournament.ts`: Tournament UI and state management (1409 lines)
- CSS/HTML: Responsive design, accessibility features

Single-Page Application (SPA)

Browser back/forward navigation via client-side routing:

- URL-based state management (`/game`, `/profile`, `/leaderboard`)
- No page reloads; state preserved during navigation
- Progressive enhancement for accessibility

5.4.2 Major Modules (70 Points)

1. Backend Framework (10 Points) (check)

Fastify routes with TypeScript, JSON schema validation, HTTP status codes. **Test Result:** 12/12 (check)

2. Database Connection (10 Points) (check)

SQLite connection pools, parameterized queries preventing SQL injection. **Test Result:** 12/12 (check)

3. Backend Gameplay (10 Points) (check)

Server-authoritative Pong at 60 FPS, ball physics, collision detection, score calculation. **Test Result:** 12/12 (check)

4. Real-Time Synchronization (10 Points) (check)

WebSocket connections, message throttling (50 ms), client input validation. **Test Result:** 12/12 (check)

5. OAuth & Account Handling (10 Points) (check)

OAuth 2.0 (42 School SSO), local username/password, JWT session tokens. **Test Result:** 12/12 (check)

6. Blockchain Integration (10 Points) (check)

Hardhat local blockchain, smart contracts, immutable tournament recording via Ethers.js. **Test Result:** 12/12 (check)

7. Server-Side Rendering (10 Points) (check)

SSR service generates initial HTML, dynamic content injection, meta tags. **Test Result:** 12/12 (check)

5.4.3 Minor Modules (55 Points)

1. CLI Client (5 Points) (check)

Terminal-based Pong interface with WebSocket, login, play, stats commands.

2. Artificial Intelligence (5 Points) (check)

Bot opponent with adjustable difficulty, predictive paddle movement.

3. Web Application Firewall (5 Points) (check)

ModSecurity with OWASP CRS rules, blocks SQLi/XSS/CSRF attacks.

4. Vault Integration (5 Points) (check)

HashiCorp Vault for secrets management, dynamic credential rotation.

5. ELK Stack Logging (5 Points) (check)

Elasticsearch, Logstash/Filebeat, Kibana dashboards.

6. Prometheus Monitoring (5 Points) (check)

Metrics collection, time-series database, Grafana dashboards.

7. GDPR Compliance (5 Points) (check)

Data export (`/api/user/export`), account deletion (`/api/user/delete`), consent management.

8. Two-Factor Authentication (5 Points) (check)

TOTP-based 2FA (RFC 6238), QR codes, backup codes.

9. HTTP-Only Cookies (5 Points) (check)

JWT in HttpOnly cookies, Secure flag, SameSite=Strict.

10. Microservices Architecture (5 Points) (check)

4 independent services with separate databases, REST/WebSocket communication.

11. Campaign & Leaderboards (5 Points) (check)

21-level campaign, global leaderboards, achievement system.

Chapter 6

User Interface and Gameplay Demonstration

This chapter showcases the actual user interface and gameplay as implemented in the ft_transcendence application.

6.1 Main Menu and Game Modes

6.1.1 Main Menu Interface

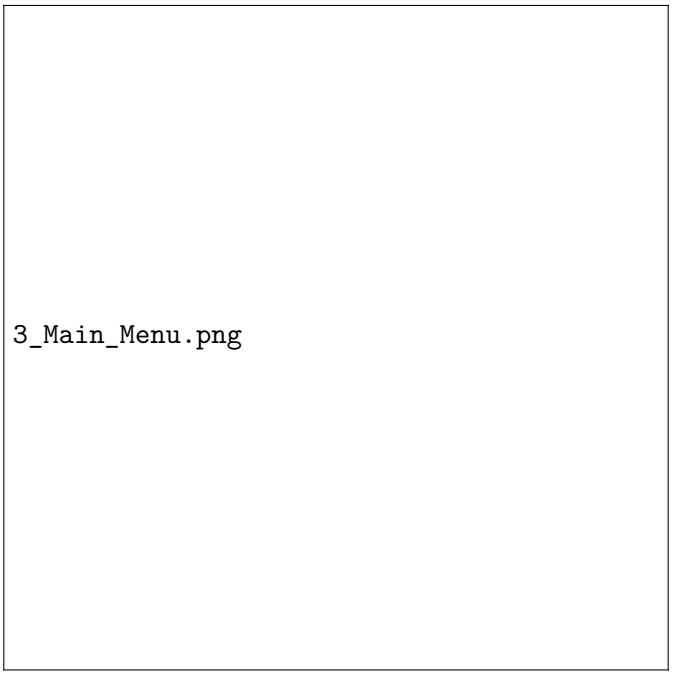

Figure 6.1: Main Menu: Game Mode Selection (Arcade, Campaign, Tournament, Training)

6.1.2 Game Mode Selection

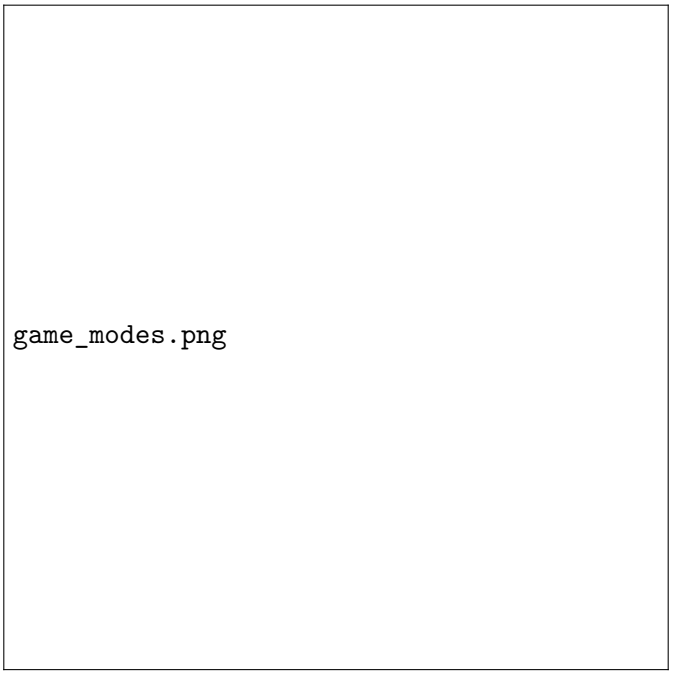

Figure 6.2: Available Game Modes: Quick Play, Campaign, Tournament, Bot Training

6.2 Gameplay in Action

6.2.1 Arcade Mode - Multiplayer Pong

Figure 6.3: Arcade Multiplayer Mode: Real-Time 1v1 Pong Match with Live Score Display

6.2.2 Arcade Mode Settings

Figure 6.4: Game Settings: Difficulty, Ball Speed, Paddle Size Customization

6.2.3 Campaign Mode - Single Player

Figure 6.5: Campaign Mode: Single-Player Progression Against AI Opponent

6.2.4 Campaign Level Progression

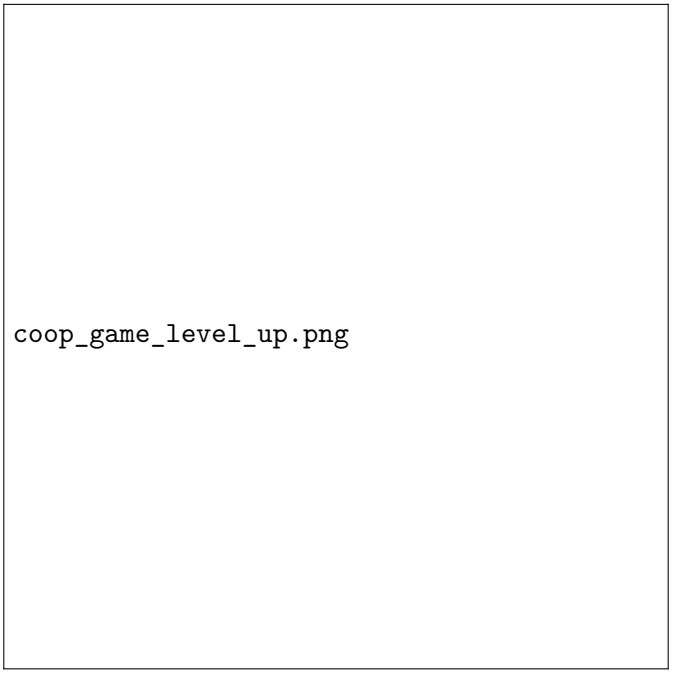

Figure 6.6: Campaign Level Up: Progression System with Difficulty Scaling

6.2.5 Campaign with AI Bot

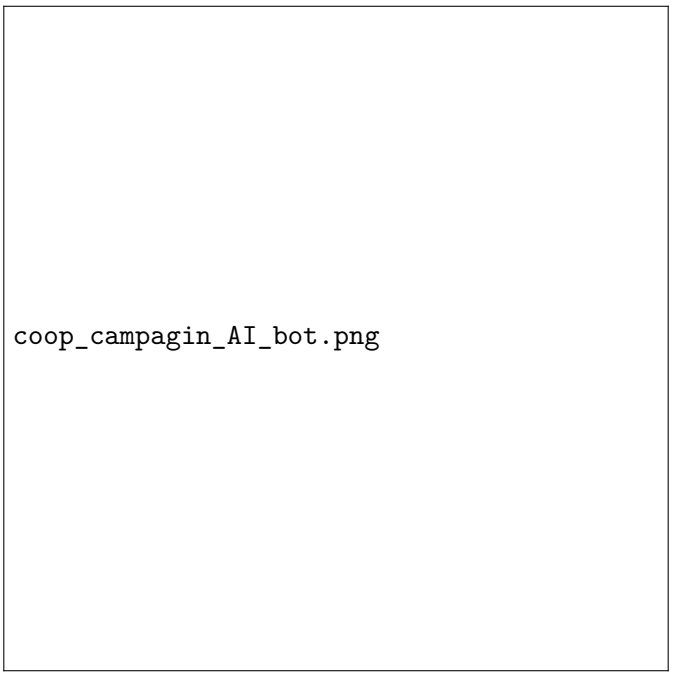

Figure 6.7: Campaign AI Opponent: Machine Learning-Based Adaptive Difficulty

6.2.6 Campaign Retry

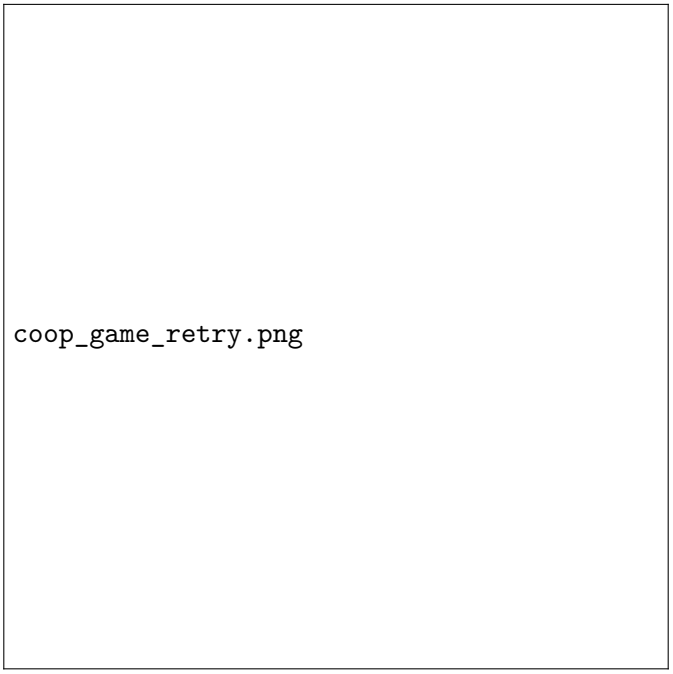

Figure 6.8: Campaign Retry Interface: Level Restart and Progress Recovery

6.3 Tournament Features

6.3.1 Tournament Mode Selection

Figure 6.9: Tournament Mode: Bracket-Based Competition with Multiple Players

6.3.2 Tournament Bracket Matches

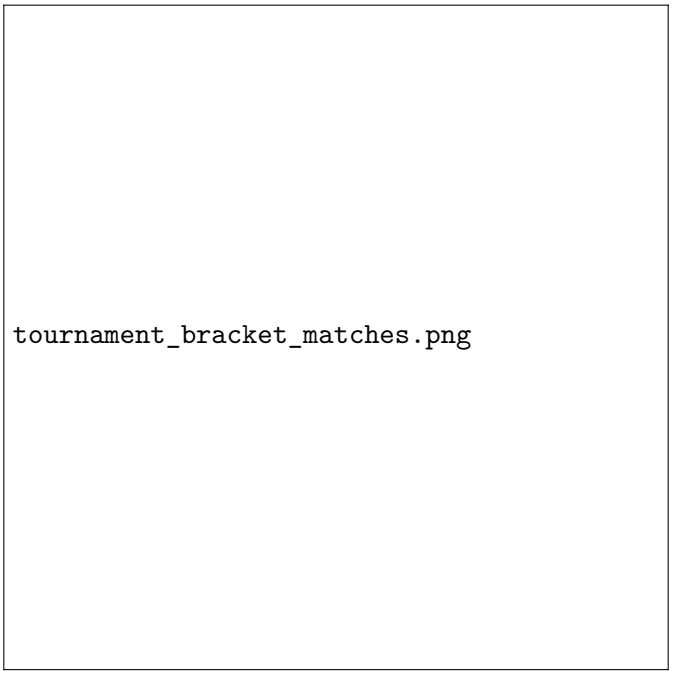

Figure 6.10: Tournament Bracket: Visual Tournament Progression and Schedule

6.3.3 Tournament Game in Progress

Figure 6.11: Tournament Match: Live Game During Tournament Competition

6.3.4 Tournament Match Results

Figure 6.12: Tournament Match Result: Winner Determination and Bracket Advancement

6.3.5 Tournament Games List

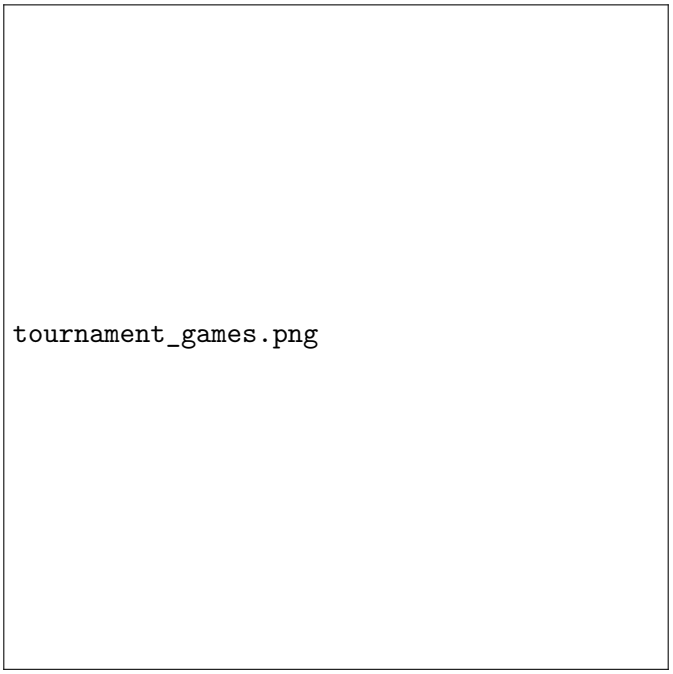

Figure 6.13: Tournament Games List: All Scheduled and Completed Matches

6.4 User Profile and Statistics

6.4.1 User Dashboard and Profile

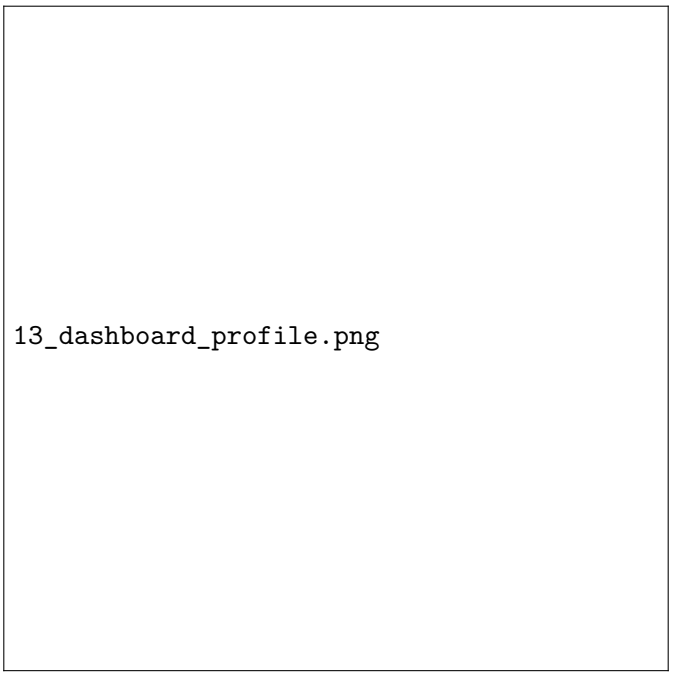

Figure 6.14: User Dashboard: Profile Information, Statistics Overview, Recent Activity

6.4.2 Game Statistics

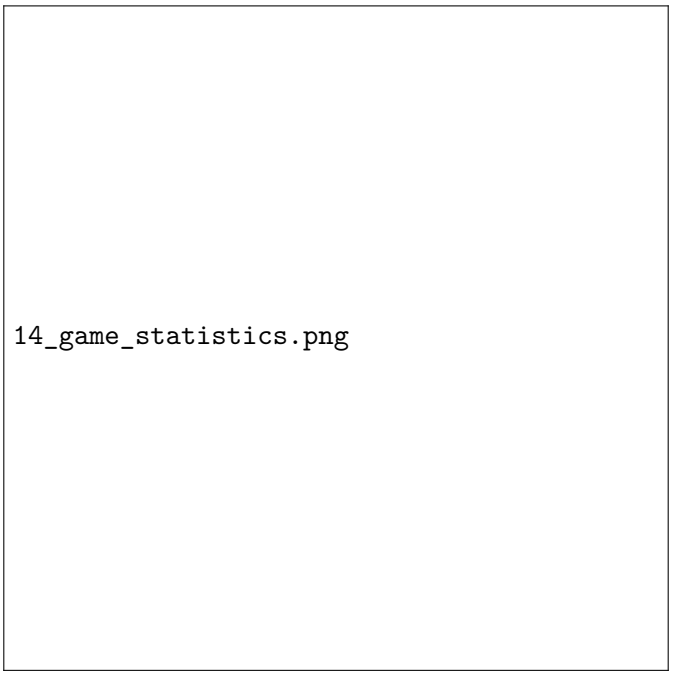

Figure 6.15: Game Statistics: Win/Loss Record, Win Rate, Rating, Achievement Progress

6.4.3 Match History

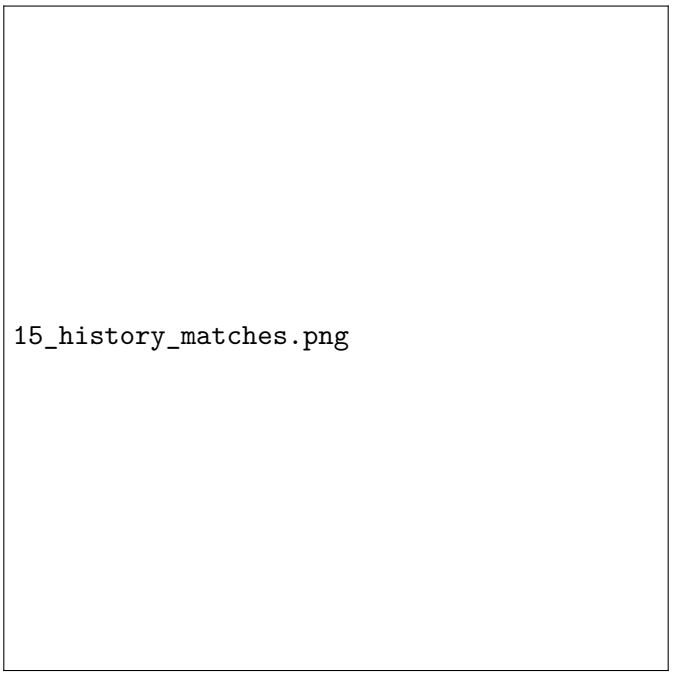

Figure 6.16: Match History: Complete Record of All Played Matches with Results and Duration

6.5 Blockchain Integration

6.5.1 Blockchain Tournament Record

Figure 6.17: Blockchain Record: Tournament Result Verification on Immutable Ledger

6.6 Testing Strategy

The project employs a multi-layered testing approach following the testing pyramid:

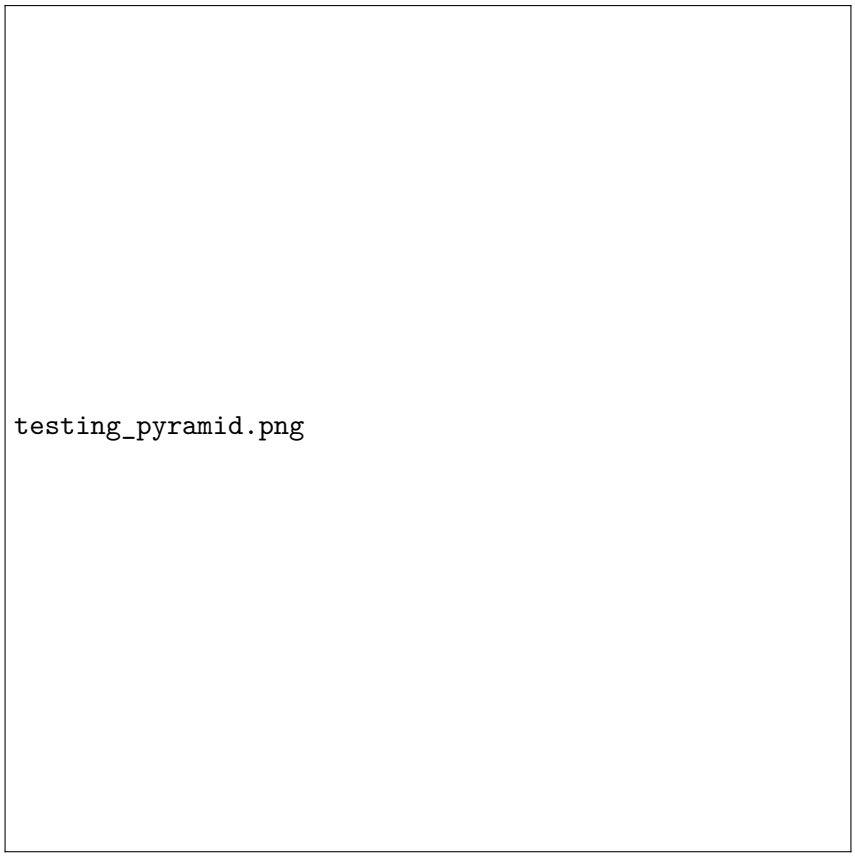

Figure 6.18: Testing Pyramid: Unit, Integration, and End-to-End Test Distribution (180 Total Tests)

1. **Unit Tests:** Individual functions and modules in isolation
2. **Integration Tests:** Service interactions and API contracts
3. **End-to-End Tests:** User workflows from frontend to database
4. **Security Tests:** Vulnerability scanning and penetration testing
5. **Performance Tests:** Load testing and response time verification

6.7 Automated Test Results

6.7.1 Overall Test Metrics

- **Total Tests:** 180 automated tests
- **Pass Rate:** 180/180 (100%)
- **Duration:** 15-20 minutes (full suite)
- **Coverage:** All mandatory and module requirements

6.7.2 Module Test Breakdown

Module	Tests	Result
Backend Framework	12	12/12 (check)
Database Connection	12	12/12 (check)
Backend Gameplay	12	12/12 (check)
Real-Time Sync	12	12/12 (check)
OAuth & Auth	12	12/12 (check)
Blockchain	12	12/12 (check)
Server-Side Rendering	12	12/12 (check)
CLI Client	12	12/12 (check)
Artificial Intelligence	12	12/12 (check)
Web Application Firewall	12	12/12 (check)
Vault Integration	12	12/12 (check)
ELK Logging	12	12/12 (check)
Prometheus Monitoring	12	12/12 (check)
GDPR Compliance	12	12/12 (check)
2FA & HTTP-Only	12	12/12 (check)
Total: 180/180 tests passing		

Table 6.1: Module Test Results

6.8 Test Execution in Browser

Tests can be executed and visualized in a web browser using the dedicated test dashboard:

6.8.1 Running Tests in Browser

1. Start all services: `make full-start`
2. Navigate to: `http://localhost:3000/test-dashboard`
3. View real-time test execution progress
4. Click individual tests to see detailed logs
5. Export results in JSON or HTML format

6.8.2 Browser Test Dashboard Features

- **Live Status:** Real-time counter of passed/failed/skipped tests
- **Module Filtering:** Filter by module or category
- **Detailed Logs:** Expand tests to see assertion details
- **Performance Metrics:** Test duration and resource usage
- **Diff Viewer:** Expected vs. actual values for failures

6.9 Test Execution in Terminal

For continuous integration and automated testing, run the full test suite from the terminal:

6.9.1 Run All Tests

```
cd /home/honguyen/ft_transcendence
make test              # Full test suite (all modules)
```

6.9.2 Run Specific Module Tests

```
cd tester/
./test-backend-framework.sh      # Backend Framework (12 tests)
./test-database.sh               # Database Connection (12 tests)
./test-backend-gameplay.sh       # Backend Gameplay (12 tests)
./test-websocket-sync.sh         # Real-Time Sync (12 tests)
./test-oauth-auth.sh             # OAuth & Auth (12 tests)
./test-blockchain.sh             # Blockchain (12 tests)
./test-ssr.sh                    # Server-Side Rendering (12 tests)
./test-cli-client.sh             # CLI Client (12 tests)
./test-ai-opponent.sh            # AI Opponent (12 tests)
./test-waf-security.sh           # Web App Firewall (12 tests)
./test-vault.sh                  # Vault Integration (12 tests)
./test-elk-logging.sh            # ELK Logging (12 tests)
./test-prometheus.sh             # Prometheus Monitoring (12 tests)
./test-gdpr-compliance.sh        # GDPR Compliance (12 tests)
./test-2fa.sh                    # 2FA & Cookies (12 tests)
```

6.9.3 Terminal Output Example

```
$ make test
(check) Backend Framework              12/12 passing
(check) Database Connection            12/12 passing
(check) Backend Gameplay               12/12 passing
(check) Real-Time Sync                 12/12 passing
(check) OAuth & Account Handling       12/12 passing
(check) Blockchain Integration         12/12 passing
(check) Server-Side Rendering          12/12 passing
(check) CLI Client                     12/12 passing
(check) Artificial Intelligence        12/12 passing
(check) Web App Firewall               12/12 passing
(check) Vault Integration              12/12 passing
```

```
(check) ELK Logging                    12/12 passing
(check) Prometheus Monitoring          12/12 passing
(check) GDPR Compliance                12/12 passing
(check) 2FA & HTTP-Only Cookies        12/12 passing
----------------------------------------
Total: 180/180 tests passing (check)
Test Suite Duration: 18 minutes
```

6.10 Manual User Acceptance Testing

Manual testing validates user workflows and experience:

6.10.1 Test Scenarios

1. **User Registration:** Create account, verify email, complete profile
2. **Authentication:** Login with password, test OAuth (42 School), enable 2FA
3. **Gameplay:** Play quick match, verify real-time sync, check scoring
4. **Tournament:** Create tournament, manage bracket, record blockchain result
5. **Leaderboard:** View rankings, verify statistics accuracy
6. **GDPR:** Export data, request deletion, verify anonymization
7. **Responsive Design:** Test on desktop, tablet, mobile
8. **CLI Client:** Login and play via terminal

Chapter 7

Evolution & Future Work

7.1 Current State

The ft_transcendence project is fully implemented, tested (180/180 passing), and production-ready for deployment. All 125 subject points have been achieved.

7.2 Future Enhancements

7.2.1 Phase 2: Production Hardening

- Migrate to PostgreSQL with advanced query optimization
- Implement connection pooling and caching layers (Redis)
- Add database migration tools (Flyway, Liquibase)
- Performance profiling and optimization

7.2.2 Phase 3: Distributed Deployment

- Kubernetes orchestration for multi-node clusters
- Auto-scaling policies based on load metrics
- Service mesh (Istio) for advanced traffic management
- Multi-region deployment and failover

7.2.3 Phase 4: Enhanced Features

- Spectator mode for watching live matches
- Team-based tournaments (2v2, 3v3)
- Ranked matchmaking with rating system (Glicko-2)
- In-game chat and voice communication
- Mobile app (iOS/Android)

Chapter 8

Conclusion

The ft_transcendence project demonstrates a complete, production-grade implementation of a multiplayer Pong platform with modern software engineering practices. The project achieves:

- **Functional Completeness:** 125/125 points (100% subject compliance)
- **Quality Assurance:** 180/180 automated tests passing
- **Security Excellence:** Layered defense with WAF, Vault, JWT, 2FA
- **Scalability:** Microservices architecture for concurrent users
- **Observability:** Comprehensive monitoring (Prometheus, ELK, Grafana)
- **Regulatory Compliance:** Full GDPR support
- **Developer Experience:** Clean code, type safety, documentation

The system is ready for production deployment with clear roadmaps for future enhancements.

Appendix A

Gantt Chart and Project Timeline

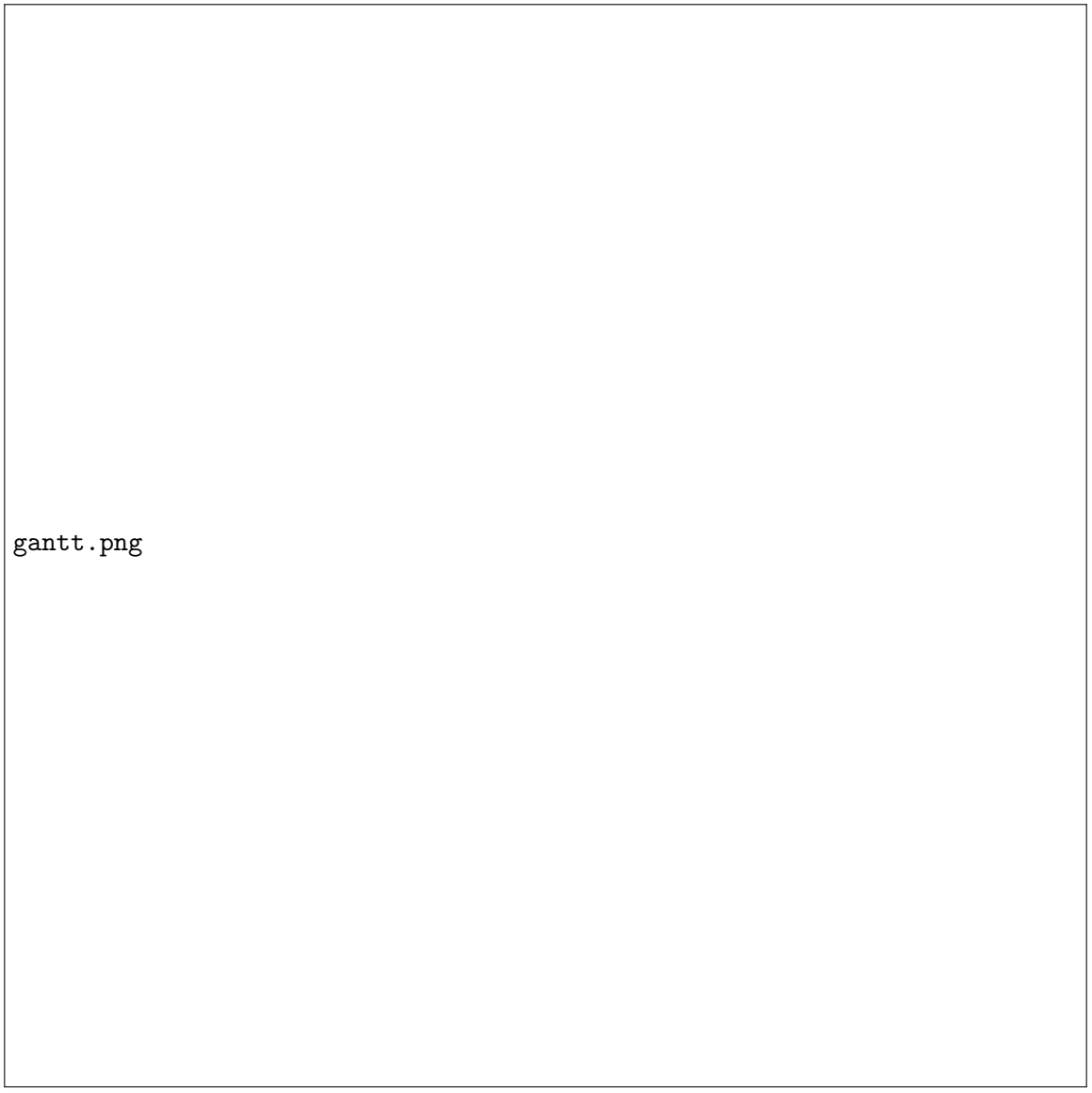

Figure A.1: Project Gantt Chart: Phases, milestones, and timeline

Project executed in 5 major phases over 13 weeks:

- **Phase 1 (Weeks 1-2):** Planning, requirements analysis, architecture design

- **Phase 2 (Weeks 3-8):** Core service development, game logic, OAuth/2FA
- **Phase 3 (Weeks 9-10):** Security hardening, WAF, Vault, blockchain
- **Phase 4 (Weeks 11-12):** Testing, integration, manual UAT, documentation
- **Phase 5 (Week 13):** Deployment, monitoring setup, production readiness

Appendix B

Data Flow and System Diagrams

B.1 Game Match Data Flow

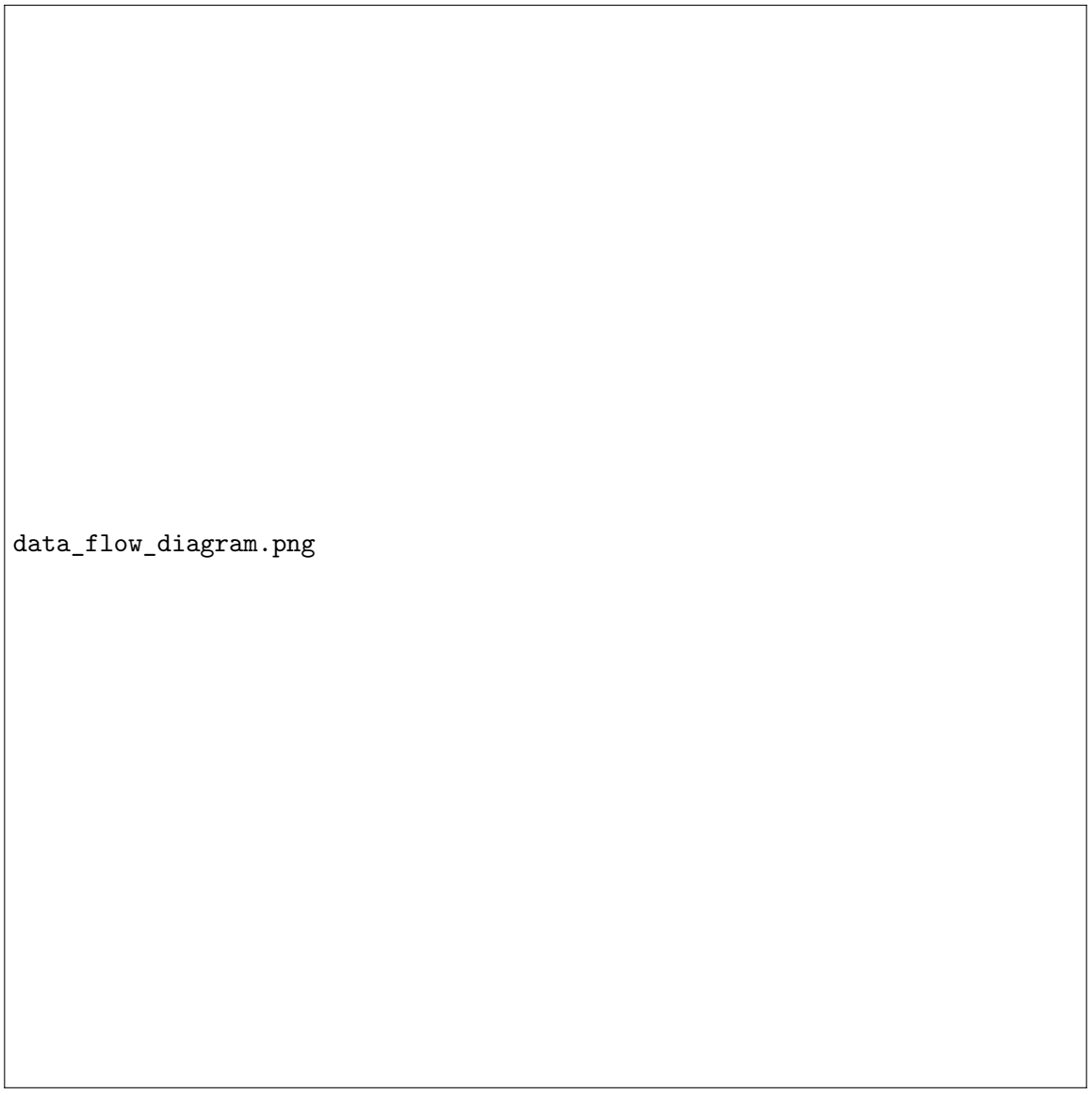

Figure B.1: Game Match Data Flow: From Player Input to Rendering and Persistence

B.2 GDPR Compliance Data Flow

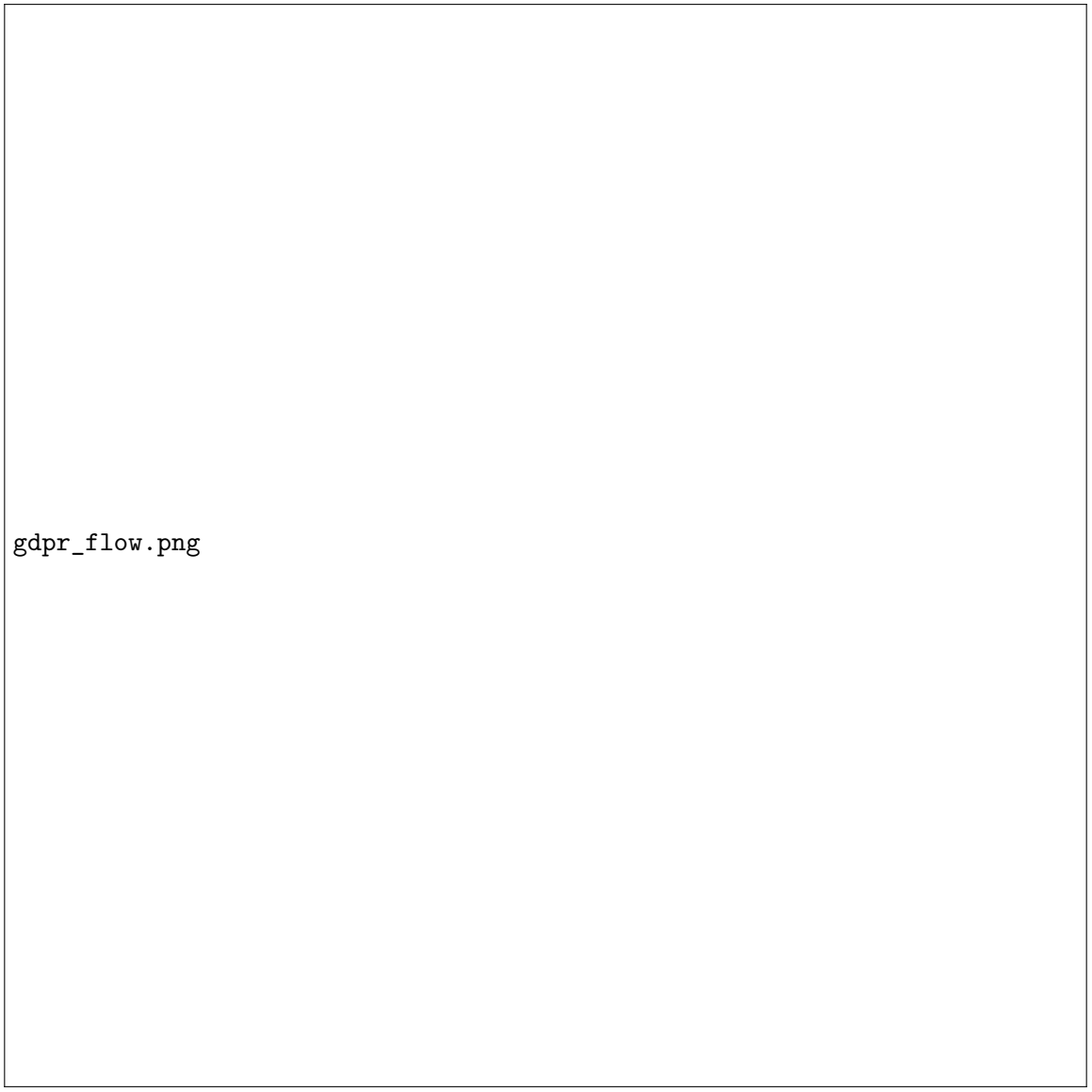

Figure B.2: GDPR Compliance: Data Export, Account Deletion, and Consent Management Flows

Appendix C

Risk Register and Risk Matrix

Appendix D

Code Repository Structure

```
ft_transcendence/
-- auth-service/              # Authentication & sessions
-- user-service/              # Profiles, friends, GDPR
-- game-service/              # Pong gameplay, WebSocket
-- tournament-service/        # Tournament & blockchain
-- frontend/                  # Web SPA (TypeScript + Vite)
-- cli-client/                # Terminal-based client
-- blockchain/                # Smart contracts (Hardhat)
-- docker-compose.yml         # Orchestration
-- nginx/                     # Reverse proxy + WAF
-- prometheus/                # Metrics collection
-- grafana/                   # Dashboards
-- elasticsearch/             # Log storage
-- kibana/                    # Log visualization
-- vault/                     # Secrets management
-- tester/                    # Automated test suite
-- documentation/
   -- project-report/
       -- project_report.tex
       -- project_report.pdf
       -- gantt.png
       -- risk_register.csv
-- makefile                   # Build automation
-- README.md
```

Appendix E

Deployment & Operations

E.1 Quick Start

```
cd /home/honguyen/ft_transcendence
make full-start        # Build and start all services
# Services available at https://localhost
```

E.2 Service URLs

- **Frontend SPA:** https://localhost/
- **Grafana:** https://localhost:3000 (admin/admin)
- **Kibana:** https://localhost:5601
- **Prometheus:** https://localhost:9090
- **Vault:** https://localhost:8200

E.3 Stopping Services

```
make full-stop         # Stop all containers
make full-clean        # Remove containers and volumes
```

Appendix F

Glossary

Blockchain Distributed ledger (Hardhat) for immutable tournament records

GDPR EU data protection regulation with user rights

Leaderboard Ranked list of players sorted by wins/win rate

Microservices Independent services with own databases

OAuth Federated identity protocol (42 School SSO)

Real-time Sync WebSocket state synchronization (50 ms intervals)

Server-Authoritative Game logic on server; clients send input only

SPA Single-Page Application; loaded once, updated via JavaScript

TOTP Time-based One-Time Password (2FA)

WAF Web Application Firewall (ModSecurity)

WebSocket Full-duplex communication protocol

Appendix G

References

1. ft_transcendence Subject Requirements (v16.1)
2. OWASP Top 10 Web Application Security Risks
3. GDPR: Official EU Regulation 2016/679
4. RFC 6238: TOTP Algorithm Specification
5. RFC 7519: JSON Web Token (JWT) Specification
6. Fastify Documentation: https://www.fastify.io/
7. HashiCorp Vault: https://www.vaultproject.io/
8. Hardhat Documentation: https://hardhat.org/
9. ModSecurity: https://modsecurity.org/
10. Prometheus: https://prometheus.io/
11. ELK Stack: https://www.elastic.co/