

User Authentication System Design

Overview

The user authentication system provides secure identity verification and session management through a layered architecture. The system implements industry-standard security practices including password hashing, secure session management, and protection against common attacks like brute force and timing attacks.

The design follows a modular approach with clear separation between authentication logic, data persistence, and user interface components. This enables maintainability, testability, and future extensibility for features like multi-factor authentication or OAuth integration.

Architecture

The system uses a three-tier architecture:

1. **Presentation Layer:** User interface components for login, registration, and password reset forms
2. **Business Logic Layer:** Authentication services, session management, and security enforcement
3. **Data Access Layer:** User repository, session storage, and audit logging

```
graph TB
    UI[User Interface] --> Auth[Authentication Service]
    Auth --> Session[Session Manager]
    Auth --> User[User Service]
    Auth --> Security[Security Service]

    User --> UserRepo[User Repository]
    Session --> SessionStore[Session Storage]
    Security --> AuditLog[Audit Logger]

    UserRepo --> DB[(Database)]
    SessionStore --> Cache[(Session Cache)]
    AuditLog --> LogDB[(Log Storage)]
```

Components and Interfaces

Authentication Service

Central orchestrator for all authentication operations:

- `register(email, password): Promise<User>`
- `login(email, password): Promise<Session>`
- `logout(sessionId): Promise<void>`
- `initiatePasswordReset(email): Promise<void>`
- `resetPassword(token, newPassword): Promise<void>`

User Service

Manages user account operations:

- `createUser(userData): Promise<User>`
- `findByEmail(email): Promise<User | null>`
- `updatePassword(userId, hashedPassword): Promise<void>`
- `verifyEmail(userId): Promise<void>`

Session Manager

Handles session lifecycle and validation:

- `createSession(userId): Promise<Session>`
- `validateSession(sessionId): Promise<Session | null>`
- `extendSession(sessionId): Promise<void>`
- `invalidateSession(sessionId): Promise<void>`

Security Service

Implements security measures and validation:

- `hashPassword(password): Promise<string>`
- `verifyPassword(password, hash): Promise<boolean>`
- `generateResetToken(): string`
- `validatePasswordStrength(password): boolean`
- `checkRateLimit(identifier): Promise<boolean>`

Data Models

User Model

```
interface User {  
  id: string;  
  email: string;  
  passwordHash: string;  
  emailVerified: boolean;  
  createdAt: Date;  
  lastLoginAt: Date | null;  
  failedLoginAttempts: number;  
  lockedUntil: Date | null;  
}
```

Session Model

```
interface Session {  
  id: string;  
  userId: string;
```

```
    createdAt: Date;
    expiresAt: Date;
    lastAccessedAt: Date;
    ipAddress: string;
    userAgent: string;
}
```

Password Reset Token Model

```
interface PasswordResetToken {
    token: string;
    userId: string;
    createdAt: Date;
    expiresAt: Date;
    used: boolean;
}
```

Correctness Properties

A property is a characteristic or behavior that should hold true across all valid executions of a system—essentially, a formal statement about what the system should do. Properties serve as the bridge between human-readable specifications and machine-verifiable correctness guarantees.

Property Reflection

After analyzing all acceptance criteria, several properties can be consolidated to eliminate redundancy:

- Registration validation properties (1.3, 1.4) can be combined into input validation
- Login failure properties (2.2, 2.3) can be combined into authentication rejection
- Session management properties (6.1, 6.2) can be combined into session lifecycle
- Security logging properties (3.4, 5.5) can be combined into audit trail

Core Properties

Property 1: User registration with valid credentials

For any valid email and secure password, registration should create a new user account with properly hashed credentials

Validates: Requirements 1.1

Property 2: Duplicate email prevention

For any email address, attempting to register twice should reject the second registration attempt

Validates: Requirements 1.2

Property 3: Input validation rejection

For any invalid email format or weak password, registration should be rejected with appropriate error messages

Validates: Requirements 1.3, 1.4

Property 4: Registration email notification

For any successful registration, an email verification message should be sent to the provided email address

Validates: Requirements 1.5

Property 5: Valid login creates session

For any verified user with correct credentials, login should create a valid session and grant access

Validates: Requirements 2.1

Property 6: Invalid authentication rejection

For any invalid credentials or unverified email, login attempts should be rejected with appropriate error messages

Validates: Requirements 2.2, 2.3

Property 7: Login timestamp recording

For any successful login, the system should update the user's last login timestamp

Validates: Requirements 2.4

Property 8: Account locking after failed attempts

For any user account, multiple consecutive failed login attempts should result in temporary account locking

Validates: Requirements 2.5

Property 9: Session invalidation on logout

For any active session, logout should invalidate the session and remove authentication tokens

Validates: Requirements 3.1

Property 10: Access denial after logout

For any logged-out user, attempts to access protected resources should be denied and prompt re-authentication

Validates: Requirements 3.3

Property 11: Password reset token generation

For any registered email address, password reset requests should generate secure tokens and send reset emails

Validates: Requirements 4.1

Property 12: Silent handling of unregistered emails

For any unregistered email address, password reset requests should complete without revealing account existence

Validates: Requirements 4.2

Property 13: Password reset completion

For any valid reset token and new password, the reset process should update the password and invalidate the token

Validates: Requirements 4.4

Property 14: Reset token single-use enforcement

For any expired or previously used reset token, subsequent usage attempts should be rejected

Validates: Requirements 4.5

Property 15: Password hashing security

For any password, storage should use cryptographically secure hashing with salt, never storing plaintext

Validates: Requirements 5.1

Property 16: Reset token randomness

For any generated reset token, it should be cryptographically random with sufficient entropy for security

Validates: Requirements 5.3

Property 17: Rate limiting enforcement

For any sensitive operation, rapid successive requests should trigger rate limiting to prevent abuse

Validates: Requirements 5.4

Property 18: Session lifecycle management

For any active session, user activity should extend expiration, while inactivity should lead to expiration and access denial

Validates: Requirements 6.1, 6.2

Property 19: New device notification

For any login from a previously unseen device or location, the system should optionally send security notification emails

Validates: Requirements 6.5

Property 20: Security audit logging

For any authentication event (login, logout, password reset), the system should create audit log entries with timestamps

Validates: Requirements 3.4, 5.5

Error Handling

The system implements comprehensive error handling across all components:

Authentication Errors

- Invalid credentials: Generic "authentication failed" message to prevent user enumeration
- Account locked: Clear message with lockout duration and unlock instructions
- Unverified email: Specific message with resend verification option
- Rate limiting: Clear message indicating temporary restriction

Validation Errors

- Email format: Specific validation message with format requirements
- Password strength: Detailed requirements (length, complexity, etc.)
- Missing fields: Field-specific error messages

System Errors

- Database connectivity: Graceful degradation with retry mechanisms
- Email service failures: Queue for retry with fallback notifications
- Session storage issues: Automatic cleanup and re-authentication prompts

Security Errors

- Suspicious activity: Automatic session invalidation with security notifications
- Token tampering: Silent rejection with security logging
- Brute force attempts: Progressive delays and account protection

Testing Strategy

The authentication system requires comprehensive testing using both unit tests and property-based testing to ensure security and correctness.

Unit Testing Approach

Unit tests will verify specific scenarios and edge cases:

- Specific email format validation cases
- Password strength requirement boundaries
- Session timeout edge cases
- Error message accuracy and consistency
- Integration between authentication components

Property-Based Testing Approach

Property-based tests will verify universal behaviors across all inputs using **fast-check** library for JavaScript/TypeScript:

- Each property test will run a minimum of 100 iterations
- Tests will use smart generators that create realistic but varied test data
- Each property-based test will include a comment explicitly referencing the design document property
- Format: ****Feature: user-authentication, Property {number}: {property_text}****

Test Data Generation

- Email generators: Valid formats, invalid formats, edge cases
- Password generators: Strong passwords, weak passwords, boundary cases
- User generators: Various account states (verified, unverified, locked)
- Session generators: Active, expired, and edge-case sessions
- Token generators: Valid, expired, and malformed reset tokens

Security Testing

- Timing attack resistance verification
- Rate limiting effectiveness validation
- Password hash strength verification
- Session security validation
- Audit log completeness verification

The dual testing approach ensures both concrete correctness (unit tests) and universal properties (property-based tests), providing comprehensive coverage for this security-critical system.