**Abstract**

fundamental privacy deficit, requiring users to trust providers with their data and encryption keys. This research confronts this challenge by presenting the design, implementation, and rigorous evaluation of a client-side encryption (CSE) system that enforces a verifiable zero-knowledge architecture. The prototype, built as a web application, leverages established cryptographic primitives, including AES-256-GCM for authenticated encryption and PBKDF2 for robust, password-based key derivation. The prevailing server-side encryption model in cloud storage services creates a

A central contribution of this work is the empirical validation of the system's security claims. The architecture was subjected to a series of targeted tests informed by the OWASP Web Security Testing Guide, which confirmed its ability to protect data confidentiality and integrity against a compromised server. The findings demonstrate the feasibility of creating a highly secure CSE system using standard web technologies. However, the analysis also highlights the critical trade-off between absolute security and user-centric key management, identifying the risk of permanent data loss as a primary barrier to adoption. This work contributes a validated blueprint for private-by-design cloud applications and concludes by outlining critical directions for future research, including advanced metadata protection and the integration of post-quantum cryptography.

**1. Introduction**

The proliferation of cloud computing has revolutionized data storage, offering unprecedented convenience and accessibility. However, this shift has also introduced significant security and privacy challenges. When users entrust their data to third-party cloud providers, they relinquish direct control, creating potential vulnerabilities to data breaches, unauthorized access, and surveillance (Zissis, 2012). While server-side encryption is a common security measure, it often leaves data accessible to the cloud provider, who manages the encryption keys. This creates a single point of failure and a potential target for attackers.

To address these concerns, **client-side encryption (CSE)** has emerged as a powerful alternative. By encrypting data on the user's device *before* it is uploaded to the cloud, CSE ensures that the cloud provider only ever receives and stores ciphertext. The encryption keys remain in the user's possession, providing a much higher level of data confidentiality and control. However, the practical implementation of CSE in web applications presents its own set of challenges, particularly concerning secure key management, user authentication, and overall usability (I. P. A. G. A. P, 2023).

This research project addresses these challenges by designing, developing, and evaluating a secure cloud storage application that leverages client-side encryption and **zero-knowledge principles**. The system aims to provide a practical and user-friendly solution that guarantees data privacy by ensuring that the server has no knowledge of the user's encryption keys or the content of their files.

**1.1. Research Questions**

This project is guided by the following research questions:

1. How can a web-based, client-side encryption system be designed and implemented to ensure that a user's data is incomprehensible to the cloud server, even if the server is compromised?
2. What are the most effective cryptographic techniques for deriving, wrapping, and managing user encryption keys in a browser environment to prevent unauthorized access?
3. To what extent can a zero-knowledge authentication and data handling protocol be implemented to provide robust security while maintaining a high level of usability for the end-user?

**1.2. Key Objectives**

To answer these research questions, the project will pursue the following key objectives:

1. **Design and implement a client-side encryption protocol** using modern, robust cryptographic libraries (AES-256-GCM) to encrypt and decrypt files directly in the user's browser.
2. **Develop a secure key derivation and management system** using PBKDF2 to generate a master key from the user's password, which is then used to unwrap individual file keys, ensuring that raw keys are never stored on the server.
3. **Build a prototype web application** using Python (Flask) for the backend and JavaScript for the frontend to demonstrate the practical viability of the proposed system.
4. **Conduct a comprehensive security evaluation** of the prototype, including testing for data confidentiality, integrity, and the server's inability to access plaintext data.

**1.3. Report Structure**

This report is structured as follows: Chapter 2 provides a critical review of the relevant literature on client-side encryption, zero-knowledge proofs, and key management techniques. Chapter 3 details the design and architecture of the proposed system. Chapter 4 describes the implementation of the prototype application. Chapter 5 presents the results of the security testing and evaluation. Finally, Chapter 6 discusses the findings, outlines the limitations of the study, and suggests directions for future research.

**Chapter 2: Literature Review**

**2.1 Introduction: From Description to Critical Analysis**

This chapter presents a critical review and synthesis of the academic and technical literature relevant to the design of a secure and usable client-side encryption system. The purpose of this review is not merely to summarize existing work but to critically evaluate different approaches, identify prevailing debates, and establish the research gap that this project aims to address (Jesson, 2011) .A descriptive summary simply states what has been done, whereas a critical analysis evaluates the significance, strengths, and weaknesses of that work to build a compelling argument for new research . (Petticrew, 2008).This review is structured thematically to explore the core controversies in CSE architectures, the nuanced application of zero-knowledge principles, and the critical field of usable security, which examines the human factors that ultimately determine a security system's effectiveness.

**2.2 The Central Debate: Trust vs. Accessibility in CSE Architectures**

The foundational principle of client-side encryption is to shift the locus of trust away from the service provider to the user's own device (Abu-Salma, 2017). However, the implementation of this principle has created a central and ongoing debate in the literature surrounding the architectural trade-offs between establishing a truly trusted computing base and providing maximum accessibility for users.

This debate is most evident in the distinction between **native applications** and **browser-based web applications**. Native applications, installed directly on a user's operating system, can more readily establish a trusted environment, as the code is locally verified and less susceptible to in-transit modification. Conversely, browser-based CSE solutions, while offering superior platform independence and ease of deployment, introduce a significant controversy: the client-side code (typically JavaScript) that performs the encryption is delivered by the very server that is meant to be untrusted (Johns, 2020). This creates a critical attack vector where a malicious server could deliver compromised code to exfiltrate the user's password or keys. While solutions like "Crypto Membranes" have been proposed to isolate cryptographic operations within browser extensions (Johns, 2020), they introduce their own usability hurdles, requiring users to install and manage yet another piece of software.

This architectural dilemma is compounded by the **unresolved controversy of key management** (Edler, 2023). If a user loses their master key, their data is rendered permanently inaccessible—a catastrophic failure mode that undermines the very purpose of the storage system (Ogorzalek, 2017)The literature presents a spectrum of mitigation strategies, from simplistic user-managed backups (e.g., printing a recovery key) to complex cryptographic recovery mechanisms. However, no single solution has emerged as superior. Each approach represents a difficult trade-off between security and usability, a tension that remains a significant open problem in the field and a primary focus of this research project.

**Introduction to the Code Delivery Attack Vector**

A foundational promise of any Client-Side Encryption (CSE) architecture is that sensitive data is encrypted locally within the user's environment—typically a web browser—before being transmitted to the server. This ensures that the server operator, and any adversary who compromises the server, cannot access the user's unencrypted information. The server is relegated to the role of a "zero-knowledge" storage provider, handling only opaque, encrypted data blobs. However, the integrity of this entire security model hinges on a critical and often overlooked assumption: the integrity of the client-side code itself.

In a typical web application architecture, such as the one employed by this project's prototype, a server-side framework (e.g., Python Flask) is responsible for delivering the application's constituent parts to the user's browser. This includes the HTML structure, CSS for styling, and, most importantly, the JavaScript code that performs the cryptographic operations. The project's

app.py serves the script.js file, which contains the logic for key derivation, encryption, and decryption. This creates a fundamental dependency: the client's browser must implicitly trust the server to deliver a legitimate, non-malicious version of this JavaScript file on every visit.

This dependency is the locus of the "code delivery" or "malicious server" attack vector. If an attacker gains control of the application server, they can subvert the entire security guarantee of the CSE model without needing to break the underlying cryptography. Instead of attacking the encryption algorithms, the adversary can simply modify the script.js file before it is sent to the user. A modified script could, for instance, exfiltrate the user's password upon entry, send the derived master key to an attacker-controlled server, or transmit the plaintext of a file just before it is encrypted. To the end-user, the application would appear to function normally, yet their data would be silently compromised. Therefore, the security of a browser-based CSE system is not merely a function of its cryptographic design but is inextricably linked to the security of the code delivery channel. Acknowledging and mitigating this threat is essential for the development of a credible and robust CSE system.

**2.X.2 Mitigation via sub resource Integrity (SRI)**

One of the primary technical controls developed to address the threat of compromised content delivery is sub resource Integrity (SRI). SRI is a security feature standardized by the W3C that enables browsers to verify that the resources they fetch, such as scripts or stylesheets, are delivered without unexpected manipulation. The mechanism is implemented by adding an integrity attribute to <script> and <link> elements in the HTML document.

The value of the integrity attribute is a string containing at least one cryptographic hash (e.g., SHA-384) of the expected resource, prefixed by the hash algorithm and encoded in base64. For example, a script tag might look like this:

<script src="https://example.com/script.js" integrity="sha384-oqVuAfXRKap7fdgcCY5uykM6+R9GqQ8K/uxy9rx7HNQlGYl1kPzQho1wx4JwY8wN" crossorigin="anonymous"></script>

When a browser encounters an HTML element with an integrity attribute, it first fetches the resource from the specified URL. Before executing the resource, the browser calculates its own cryptographic hash of the received file's content using the same algorithm specified in the attribute. It then compares its calculated hash with the hash value provided in the integrity attribute. If the two hashes match, the browser concludes the file is authentic and executes it. If the hashes do not match, it signifies that the file's content has been altered in transit or on the server. In this case, the browser will refuse to execute the resource, triggering an error and effectively preventing the execution of the potentially malicious code.

While SRI provides a powerful defence against the modification of external script files, its effectiveness is contingent on the integrity of the document that contains the SRI attributes—the HTML file itself. In an architecture where the same server is responsible for delivering both the HTML (index.html) and the JavaScript (script.js), as is the case in this project, SRI's protection is incomplete. A sophisticated attacker who has compromised the server could simply modify both the JavaScript file and the corresponding hash value within the HTML file. The browser, upon receiving the malicious script and the matching malicious hash, would find them to be consistent and would execute the code. Therefore, while SRI is a valuable layer of defence, it is not a complete solution on its own when the primary HTML document is served from the same potentially untrusted source.

**2.X.3 Mitigation via Content Security Policy (CSP)**

A more comprehensive and powerful mechanism for mitigating code delivery attacks is the Content Security Policy (CSP). CSP is a defence-in-depth security layer, delivered as an HTTP response header (Content-Security-Policy), that provides fine-grained control over the resources a browser is allowed to load and execute for a given page. Rather than only verifying the integrity of a single resource, CSP establishes a broad policy that can significantly reduce the attack surface of a web application.

CSP operates through a series of directives, each controlling a specific type of resource or action. For a CSE application, several directives are of critical importance:

* **script-src**: This directive whitelists permissible sources for JavaScript. A strict policy could limit scripts to 'self' (the same origin) and include the base64-encoded hashes of all expected scripts. This effectively integrates the protection of SRI directly into the CSP header, providing the same integrity check while also preventing the loading of scripts from any other unauthorized location.
* **connect-src**: This directive restricts the URLs to which the client can connect via XMLHttpRequest, Fetch APIs, and WebSockets. This is a crucial control for preventing data exfiltration. Even if an attacker managed to inject malicious code that bypasses the script-src control (e.g., through a browser vulnerability), a strict connect-src policy that only whitelists the application's own API endpoint and required third-party APIs (like Google Drive) would prevent the malicious script from sending the user's password or keys to an attacker-controlled domain.
* **form-action**: This directive restricts the URLs that can be used as targets for form submissions, mitigating the risk of form hijacking to exfiltrate credentials.
* **object-src 'none'**: This directive prevents the embedding of potentially dangerous plugin content (e.g., Flash), a common vector for client-side attacks.

A well-configured CSP provides a more robust defence than SRI alone because it operates on the principle of proactive restriction rather than reactive verification. By defining a whitelist of trusted sources and behaviours, it can prevent an attack from succeeding even if a malicious script finds its way onto the page. For the CSE prototype, implementing a CSP header that restricts script sources to a specific hash and connect-src to only the necessary API endpoints would create a hardened client environment, making unauthorized data exfiltration significantly more difficult for an attacker.

**2.X.4 Synthesis and Architectural Implications**

Neither Sub resource Integrity nor Content Security Policy is a panacea for the code delivery problem in browser-based cryptography. SRI is effective but brittle, as its security relies on the integrity of the containing document. CSP is powerful but can be complex to configure correctly and may not prevent all forms of malicious code execution if there are vulnerabilities in whitelisted sources.

The current best practice, therefore, involves a layered defence-in-depth approach that combines both mechanisms. Using SRI for critical script files provides a clear, explicit integrity check, while a strict CSP provides a broader policy-based enforcement that mitigates a wider range of attacks, including data exfiltration.

For this dissertation's prototype, this analysis has profound architectural implications. It demonstrates that the security of the system is not contained solely within the cryptographic logic of script.js but is dependent on the secure operational deployment of the application. The Flask server (app.py) must be configured to serve the application with the correct and restrictive Content-Security-Policy HTTP header. This shifts the trust boundary; while the user does not need to trust the server with their data, they must trust the server's administrator to configure the web server correctly. This nuanced understanding is critical, as it reframes the prototype not as a perfectly secure, self-contained system, but as an application architecture whose security guarantees rely on a combination of strong cryptography and disciplined server-side security hygiene. This acknowledgment is essential for any credible claim of providing secure client-side encryption on the web.

**2.3 A Matter of Definition: The "Zero-Knowledge" Principle in System Design**

The term "zero-knowledge" carries a specific, formal meaning in cryptography, referring to a **Zero-Knowledge Proof (ZKP)**. A formal ZKP is an interactive protocol where a "prover" convinces a "verifier" that a statement is true without revealing any information beyond the statement's validity (Goldwasser, 1989). These protocols are powerful but are often computationally expensive and complex to implement.

However, a definitional debate arises when the term is applied more broadly in system architecture. In the context of this project and much of the literature on secure cloud systems, "zero-knowledge" refers to an **architectural property** rather than a formal proof (Yang, 2025). A "zero-knowledge system" is one where the server has zero knowledge of the user's sensitive data—specifically their plaintext files and the decryption keys (Edler, 2023). This is a crucial distinction. The system is not proving knowledge of a secret in the formal cryptographic sense; rather, it is architecturally designed to make it impossible for the server to ever gain that knowledge. This architectural paradigm is a practical application of the zero-trust security model, which mandates that no entity is trusted by default (Gilman, 2017). The critical evaluation here lies in recognizing that while the system achieves the *spirit* of zero-knowledge (server ignorance), it does not employ the formal cryptographic machinery of a ZKP, a distinction that is essential for academic clarity.

**2.4 The Adoption Paradox: Why Technically Superior Security Fails**

A security system is only effective if it is used, and used correctly. This simple fact gives rise to the **adoption paradox**: technically superior security solutions often fail to gain traction because their usability creates an insurmountable barrier for non-expert users (Whitten, 1999). The field of usable security and privacy investigates this paradox, providing a wealth of evidence that systems with poor usability are frequently bypassed, misconfigured, or abandoned, leading to catastrophic security failures (Krol, 2019).

The most prominent case study of this paradox is end-to-end encrypted email. Technologies like **PGP (Pretty Good Privacy)** have existed for decades and are cryptographically robust, yet their adoption by the general public remains negligible (Fবার্টzle, 2021). The critical failure of PGP is not in its cryptography, but in its usability. Studies consistently show that users are overwhelmed by the complexity of public key management, including the generation, distribution, and verification of keys (Ruoti, 2020). This highlights a critical flaw in a purely technocentric view of security. The literature makes a compelling case that the cognitive load placed on the user is as much a part of the system's attack surface as any software vulnerability. Therefore, any new CSE system must be evaluated not just on its cryptographic strength, but on its ability to resolve this adoption paradox by integrating security seamlessly into the user's workflow.

**2.5 Synthesis and Identification of the Research Gap**

The literature firmly establishes the need for client-side encryption and provides a rich toolkit of cryptographic primitives. However, this critical review reveals a significant disconnect between the design of cryptographically secure systems and the development of usable, adoptable products. The debates surrounding architecture and the paradox of adoption show that technical soundness alone is insufficient.

This review identifies a specific **gap in the existing body of work**: while many papers discuss CSE theoretically or describe bespoke systems, there is a lack of research that presents a complete, end-to-end case study of designing, implementing, and—most importantly—rigorously evaluating a CSE system for a major, mainstream cloud platform like Google Drive. Existing work often fails to provide a detailed, literature-informed justification for its specific cryptographic choices (e.g., the selection of a key derivation function) against current industry standards from organizations like OWASP. Furthermore, few studies combine a formal security verification, grounded in the identified debates, with a critical analysis of the system's usability and potential to overcome the adoption paradox.

**This project aims to fill that gap.** It will provide a holistic account of a CSE prototype, from a theoretical design that directly confronts the trust-vs-accessibility debate, through to empirical security testing and a reflective usability analysis that addresses the lessons learned from the failures of past technologies.

**Chapter 3: System Design and Methodology**

**3.1 Introduction and Design Philosophy**

This chapter details the architectural design and technical methodology employed to build the prototype secure storage application. The design is underpinned by a core philosophy derived directly from the research objectives and the critical analysis of the literature in Chapter 2. This philosophy is defined by three guiding principles:

1. **Zero-Knowledge Architecture:** The system is architected such that the server remains completely ignorant of the contents of user files and the cryptographic keys used to protect them. This principle is the cornerstone of the system's security guarantee.
2. **Client-Centric Trust:** All sensitive cryptographic operations, particularly encryption, decryption, and key derivation, are performed exclusively on the client-side (the user's browser). The server is treated as an untrusted entity responsible only for storing and retrieving opaque blocks of data.
3. **Pragmatic Usability:** While maintaining robust security, the design prioritizes simplicity and adherence to familiar web conventions to mitigate the "adoption paradox" identified in the literature (Whitten, 1999). The goal is to make strong encryption accessible without imposing an excessive cognitive burden on the user.

This chapter will first outline the high-level system architecture and justify the choice of technologies. It will then provide a detailed, step-by-step explanation of the cryptographic protocols that form the core of the system, illustrated with sequence diagrams. Finally, it will define the system's threat model and security guarantees.

**3.2 System Architecture**

The application is implemented using a classic two-tier client-server architecture, which is well-suited for web applications. This model provides a clear separation of concerns between the user interface and the data storage logic.

* **The Client (Frontend):** This is a web interface built with HTML, CSS, and vanilla JavaScript that runs entirely within the user's web browser. It is responsible for all user interactions, but most critically, it is the exclusive domain for all cryptographic operations. It communicates with the backend via a RESTful API.
* **The Server (Backend):** This is a Python application built using the Flask micro-framework. Its sole responsibilities are to handle user authentication (registration and login), manage user accounts, and act as a simple storage gateway. It receives pre-encrypted data from the client and stores it, without any ability to inspect or modify its contents. A SQLite database is used for storing user metadata and the encrypted file information.

This architecture, illustrated in Figure 3.1, ensures that the server's role is minimized to that of a simple, "dumb" storage provider, directly aligning with the zero-knowledge design philosophy.

**Figure 3.1: High-Level System Architecture**

**3.3 Technology Stack Justification**

The selection of technologies was guided by the principles of simplicity, security, and rapid prototyping.

* **Frontend (Vanilla JavaScript & Web Crypto API):**
  + **Justification:** Instead of a complex framework like React or Angular, vanilla JavaScript was chosen to keep the client-side codebase minimal and transparent. This is a critical security consideration; a smaller, simpler codebase is easier to audit and has a smaller attack surface. The core cryptographic functions are implemented using the **Web Crypto API**, a W3C standard built directly into modern browsers. This API provides a secure, low-level interface to the browser's underlying cryptographic modules and is the recommended best practice for performing cryptography in a web context (W3C., (2017).).
* **Backend (Python, Flask, SQLite):**
  + **Justification:** **Python** was selected for its readability and extensive library support. **Flask** is a lightweight "micro-framework" that provides the essential tools for building a REST API without imposing a rigid structure or including unnecessary components. This minimalism is ideal for a prototype where the backend's logic is intentionally simple. **SQLite** was chosen as the database engine because it is serverless, self-contained, and requires no complex configuration, making it perfectly suited for a single-server prototype. The database schema (see init\_db.py) consists of a users table for account information and a wrapped\_keys table to store the metadata associated with each encrypted file.

**3.4 The Cryptographic Core: A Zero-Knowledge Protocol**

The security of the entire system rests on a carefully designed set of cryptographic protocols that ensure the server never has access to sensitive information. This protocol is broken down into three key phases: user registration, file encryption, and file decryption.

### Section 3.4.1

The choice of **PBKDF2** was made after careful consideration of modern alternatives, most notably **Argon2**, the winner of the Password Hashing Competition. While Argon2 is often recommended for new systems due to its superior resistance to custom hardware attacks,

**PBKDF2** was selected for this project for a critical, practical reason: its native and standardized implementation within the **Web Crypto API**.

This project's client-side components rely exclusively on this W3C standard to ensure a minimal and transparent codebase, which is a core security consideration . Opting for

**PBKDF2** allows the prototype to perform all key derivations using the browser's built-in, vetted cryptographic modules without introducing external JavaScript libraries for Argon2, which would increase the system's complexity and potential attack surface. Given that

**PBKDF2** remains a robust, industry-standard recommendation by organizations like OWASP and is configured with a high iteration count (100,000) in this implementation, it provides a more than sufficient security baseline to validate the architectural goals of this prototype.

**3.4.2 User Registration and Master Key Derivation**

A user's password is the single root of trust for all their cryptographic keys. To transform this low-entropy secret into a high-entropy cryptographic key, a robust key derivation function is required.

* **Process:** When a user registers, their chosen password is not sent to the server. Instead, the client-side JavaScript uses the **Password-Based Key Derivation Function 2 (PBKDF2)** to derive a 256-bit **Master Key**.
* **Justification:** Using a simple hash function like SHA-256 on a password is insufficient and insecure. PBKDF2 is the industry-standard recommendation by organizations like the **Open Web Application Security Project (OWASP)** because it incorporates two crucial security features:
  1. **A Salt:** A unique, random salt is generated for each user. This salt is stored on the server and prevents attackers from using pre-computed "rainbow tables" to crack multiple passwords simultaneously.
  2. **An Iteration Count:** The function is computationally intensive by design, running the core hashing algorithm (HMAC-SHA-256) thousands of times (e.g., 100,000+ iterations). This makes brute-force attacks against a single password prohibitively slow and expensive.
* **Zero-Knowledge Principle:** The derived **Master Key** exists *only* in the browser's memory for the duration of the user's session. It is never transmitted to the server, and the server has no way to compute it, as it only stores the password hash (for login verification) and the salt.

The sequence of this process is illustrated in Figure 3.2.

**Figure 3.2: User Registration and Master Key Derivation Sequence**

**3.4.3 File Encryption and Key Wrapping**

To avoid reusing the Master Key for direct file encryption (a poor cryptographic practice), a hierarchical key structure is used. Each file is encrypted with its own unique key.

* **Process:**
  1. When a user chooses a file to upload, the client-side JavaScript generates a new, cryptographically random 256-bit **File Key**.
  2. The file's content is encrypted using this **File Key** with the **AES-256-GCM** algorithm. AES-GCM is an **Authenticated Encryption with Associated Data (AEAD)** cipher, meaning it provides both **confidentiality** (the data is unreadable) and **integrity/authenticity** (the data cannot be undetectably tampered with).
  3. The **File Key** itself is then encrypted—a process known as **key wrapping**—using the user's **Master Key** (also with AES-GCM).
  4. The client then sends the encrypted file content, the wrapped File Key, and the necessary metadata (IVs, salt) to the server for storage.
* **Justification:** This per-file key approach is highly flexible and aligns with the cryptographic principle of key separation. **AES-GCM** is chosen as it is a modern, highly secure, and efficient authenticated cipher recommended by the U.S. National Institute of Standards and Technology (Dworkin, 2007).

The sequence for encrypting and uploading a file is shown in Figure 3.3.

**Figure 3.3: File Encryption and Upload Sequence**

**3.4.4 File Decryption and Key Unwrapping**

The decryption process is the exact reverse of encryption, again ensuring all sensitive operations occur on the client.

* **Process:**
  1. The user selects a file to download. The client requests the encrypted file data and its associated wrapped File Key from the server.
  2. The user is prompted for their password. The client re-derives the **Master Key** using the password and the user's stored salt (fetched from the server).
  3. The client uses the derived **Master Key** to decrypt (unwrap) the wrapped File Key.
  4. With the plaintext **File Key** now available, the client decrypts the file content using AES-GCM.
  5. The plaintext file is then presented to the user for download, having never been exposed on the server.

The decryption and download sequence is illustrated in Figure 3.4.

**Figure 3.4: File Decryption and Download Sequence**

**3.5 Security Methodology and Threat Model**

To formalize the security evaluation, the system is designed to operate under a specific threat model.

* **Threat Model:** The system is designed to protect against a **"honest-but-curious" or compromised server provider**. This threat model assumes:
  + The attacker has **full read/write access** to the server's file system and database. They can view, copy, or delete all stored data at will.
  + The attacker can act as a **passive network eavesdropper**, monitoring all traffic between the client and the server.
  + The attacker is **not** able to compromise the client device itself (e.g., via malware or a keylogger) or deliver malicious JavaScript to the client (a limitation discussed below).
* **Security Guarantees:**
  + **Confidentiality:** An attacker with full server access cannot determine the content of any stored user file.
  + **Integrity:** An attacker cannot tamper with or corrupt a user's encrypted file without the client detecting the modification during the decryption process (a feature of AES-GCM).
  + **Key Secrecy:** An attacker cannot recover a user's Master Key or any individual File Key from the data stored on the server.
* **Acknowledged Limitations:**
  + **Client-Side Compromise:** The model does not protect against an attacker who has compromised the user's computer (e.g., with a keylogger or other malware).
  + **Malicious Code Delivery:** As identified in the literature (Johns, 2020), the most significant threat to a browser-based CSE system is the server itself delivering malicious JavaScript. While this prototype assumes a trusted codebase is delivered, a production system would require additional mitigation like Sub resource Integrity (SRI) or a Content Security Policy (CSP).

**3.5 Security Methodology and Threat Model (Expanded Version)**

To formalize the security evaluation, the system is designed and analysed under a specific threat model using the **STRIDE framework**. Developed by Microsoft, STRIDE is a model of threats used to identify and categorize potential security vulnerabilities. The framework provides a structured approach to ensure all likely threats are considered. The threat model assumes an

**"honest-but-curious" or compromised server provider** , where an attacker has full read/write access to the server's file system and database but cannot directly compromise the client device itself.

The system's design choices are evaluated against each of the six STRIDE categories:

* **Spoofing:** This threat involves an unauthorized entity illicitly accessing the system by posing as a legitimate user. The prototype mitigates this at the authentication level. The server authenticates users by comparing the hash of a submitted password against the stored hash using Werkzeug's check\_password\_hash function. Since the server never stores or handles the plaintext password, it cannot be spoofed by a compromised database administrator without knowing the user's actual password. Each user also has a unique salt, preventing an attacker from using a single stolen hash to impersonate users on other systems.
* **Tampering:** This threat involves the unauthorized modification of data. The system's design provides strong, cryptographically enforced protection against this. The use of

**AES-256-GCM** for file encryption is the primary mitigation. As an Authenticated Encryption with Associated Data (AEAD) cipher, GCM mode produces an authentication tag alongside the ciphertext. As empirically verified in security test

**SVT-02**, any modification to the ciphertext at rest—even altering a single byte—will cause the authentication tag verification to fail during decryption on the client side. This ensures that tampered data is immediately detected and rejected, guaranteeing data integrity.

* **Repudiation:** This threat involves a user denying they performed an action when they did. The current prototype has limited specific mitigations for repudiation, as it does not implement comprehensive audit logs. However, the cryptographic binding of a file to a user's Master Key provides a degree of non-repudiation for data creation. Since only the user who knows the correct password can derive the Master Key needed to create a valid wrapped file key, it is cryptographically infeasible for a user to deny having created a specific encrypted file linked to their account.
* **Information Disclosure:** This is the primary threat the system is designed to prevent. The zero-knowledge architecture ensures that the server and any attacker with access to it can never view the plaintext content of user files. All encryption and decryption happen exclusively on the client-side, a principle validated in test

**SVT-01**. However, the system acknowledges a degree of

**metadata leakage**. While filenames are encrypted, an attacker with server access can still observe file sizes, creation timestamps, and access patterns. This residual information could be used to infer user activity, representing a known limitation of this architectural approach.

* **Denial of Service (DoS):** This threat involves preventing legitimate users from accessing the service. An attacker with server access could easily mount a DoS attack by deleting user data from the database or shutting down the server. The prototype's architecture does not provide a defence against this, as this threat falls outside its core goal of protecting data confidentiality and integrity. Production-grade systems would mitigate this through operational security measures like redundant infrastructure, backups, and network-level DoS protection.
* **Elevation of Privilege:** This threat involves a user gaining capabilities they are not entitled to. In this system, the primary risk would be one user accessing another user's data. The hierarchical key wrapping model provides strong protection against this. As validated in test

**SVT-05**, the key unwrapping operation will only succeed if performed with the correct Master Key. Therefore,

User A cannot decrypt a file belonging to User B, because User A's Master Key cannot correctly unwrap User B's file key. This cryptographically enforces the separation between user accounts.

**3.6 Security of Third-Party Integration: Google Drive**

Integrating with a third-party service like Google Drive introduces new security considerations, primarily centred around authorization and token management. The prototype uses the **OAuth 2.0** protocol to gain access to the user's Drive, following modern security best practices.

The security of this integration relies on several key principles:

1. **Authorization via OAuth 2.0:** Instead of handling the user's Google credentials directly, the application uses the standard OAuth 2.0 authorization code flow. The user authenticates directly with Google, which then provides the application with a short-lived **access token**. This token grants the application specific, limited permissions to the user's account without ever exposing their password.
2. **Principle of Least Privilege (Scope Minimization):** The application requests the most restrictive permission scope necessary for its function. The SCOPES variable in app.py is set to [' <https://www.googleapis.com/auth/drive.file>’ ]. This scope is critical because it **only grants access to files created by the application itself**. It does not grant permission to read, modify, or even see other files in the user's Google Drive, thus drastically limiting the potential impact of a compromised application server.
3. **Secure Token Management:** The OAuth 2.0 flow provides both an access token (which expires quickly) and a **refresh token** (which is long-lived). The application server is responsible for securely storing these tokens in the users table. The access token is used to make API calls, and when it expires, the refresh token is used to request a new access token from Google without requiring the user to log in again. Secure storage of these tokens on the server is paramount. In a production system, this would require encryption-at-rest for the database column containing these tokens.

**3.7 Comparative Analysis of Cryptographic Primitives**

The selection of cryptographic primitives is a critical design decision with long-term security implications. While the prototype implements PBKDF2 and AES-GCM, a thorough analysis requires comparing these choices against their leading alternatives. This section provides a literature-informed justification by evaluating the trade-offs between different key derivation functions and authenticated encryption ciphers, demonstrating an awareness of the broader cryptographic landscape.

**3.7.1 Key Derivation Functions: PBKDF2 vs. scrypt vs. Argon2**

The primary defence against an offline brute-force attack on user passwords is a slow, resource-intensive key derivation function. The goal is to make cracking a single password so computationally expensive that it is infeasible for an attacker, even one with access to the entire user database. The leading candidates are PBKDF2, scrypt, and Argon2.

* **PBKDF2:** As implemented in this project , PBKDF2's strength comes from its configurable iteration count, which enforces a time-based work factor. Its primary advantages are its long history, widespread industry adoption, and inclusion in official standards like NIST SP 800-132. Its native implementation in the Web Crypto API makes it the default choice for browser-based cryptography without external dependencies. However, its main drawback is that its computational demand is purely time-based. This makes it susceptible to significant optimisation through specialised, parallelised hardware like Graphics Processing Units (GPUs) and Application-Specific Integrated Circuits (ASICs), which can perform orders of magnitude more calculations per second than a standard CPU.
* **scrypt:** Introduced by Colin Percival in 2009, scrypt was designed specifically to counter the threat of hardware-based attacks. Its key innovation is **memory hardness**. In addition to a configurable time cost, scrypt requires a significant amount of RAM to compute. While a legitimate user's computer can easily allocate the necessary memory for a single login, an attacker attempting to check millions of passwords in parallel would need an infeasible amount of RAM, making large-scale attacks prohibitively expensive. This memory-hard property provides a stronger defence against GPU and ASIC-based cracking than PBKDF2.
* **Argon2:** As the winner of the 2015 Password Hashing Competition, Argon2 is the current state-of-the-art recommendation by most cryptographers for new systems. It improves upon scrypt by offering memory hardness, time hardness, and resistance to timing attacks. It comes in two main variants: **Argon2d** (maximises resistance to GPU cracking by having data-dependent memory access) and **Argon2i** (optimised to resist side-channel attacks by having data-independent memory access). The hybrid **Argon2id** is now the recommended standard for most web applications as it provides a robust, balanced defence against both types of attacks.

**Synthesis and Justification:** While Argon2id is technically superior for new systems, the decision to use PBKDF2 in this prototype remains a justified and pragmatic choice. The project's core security principle was to minimise the client-side attack surface by exclusively using the native Web Crypto API. As Argon2 is not yet part of that standard, implementing it would require introducing a third-party JavaScript library, which would violate this principle and introduce an external dependency that would need to be vetted. Therefore, using the browser's native, FIPS-compliant PBKDF2 implementation with a high iteration count (100,000) was the correct architectural decision for this specific project's goals.

**3.7.2 Authenticated Ciphers: AES-GCM vs. ChaCha20-Poly1305**

For encrypting the file contents, an authenticated encryption cipher is essential to provide both confidentiality and integrity. The two leading standards are AES-GCM and ChaCha20-Poly1305.

* **AES-GCM:** Implemented in the prototype , AES-GCM is the industry standard, endorsed by NIST. Its primary advantage is exceptional performance on modern hardware. Most modern CPUs (from Intel and AMD) include the

**AES-NI instruction set**, which provides hardware acceleration for AES operations. This makes encryption and decryption extremely fast and also hardens the implementation against side-channel timing attacks. Its status as a NIST standard makes it a widely trusted and vetted choice.

* **ChaCha20-Poly1305:** Standardised by the IETF in RFC 8439, ChaCha20-Poly1305 has emerged as the leading alternative to AES-GCM, adopted by companies like Google and Cloudflare for TLS. It is an ARX cipher (based on Add-Rotate-XOR operations). Its main advantage is that it offers excellent performance and security on platforms that **lack** dedicated AES hardware, such as low-power mobile devices or older embedded systems. Because it was designed from the ground up for efficient software implementation, it is not susceptible to the cache-timing attacks that can affect software-only AES implementations.

**Synthesis and Justification:** For a web application targeting modern desktop and high-end mobile browsers, AES-GCM is an excellent and well-justified choice, as hardware acceleration is nearly ubiquitous. The Web Crypto API provides a secure, standardised interface to this hardware, ensuring both high performance and robust security. However, it is important to acknowledge that were the application being designed for a different context, such as a lightweight mobile app or for low-power IoT devices, ChaCha20-Poly1305 would present a compelling, and often superior, alternative due to its high-performance software implementation.

**Chapter 4: Implementation**

**4.1 Introduction**

This chapter details the practical implementation of the secure storage system, translating the architectural design and cryptographic protocols outlined in Chapter 3 into a functional software prototype. The primary objective is to provide tangible evidence of the system's construction and to demonstrate how the core principles of zero-knowledge and client-side trust were realized in code.

The implementation is divided into two main components: the server-side backend, developed using the Python Flask framework, and the client-side frontend, built with standard HTML, CSS, and JavaScript. This chapter will present key code excerpts from both components, explaining their function and explicitly linking them back to the design specifications.

**4.2 Backend Implementation: The Untrusted Server**

The backend was developed using Python and the Flask micro-framework, with its role strictly limited to user management and the storage of opaque, encrypted data blobs, in accordance with the zero-knowledge design principle.

**4.2.1 Database and API Setup**

The foundation of the backend is the app.py script, which initializes the Flask application and defines the API endpoints. A SQLite database, created by the init\_db.py script, serves as the data store. The database schema is critical, as it is designed to hold user credentials and file metadata without ever storing plaintext keys or content. The wrapped keys table, for instance, stores the encrypted file key (wrapped key) and associated cryptographic metadata (IVs, salt), but the actual file content is stored as an opaque BLOB.

**4.2.2 User Authentication Endpoints**

The server handles user registration and login. Crucially, at no point does the server handle the user's raw password. During registration, the server receives a pre-hashed password from the client and stores it. During login, it uses this stored hash for verification.

The /api/register endpoint in app.py demonstrates this principle in action.

# Excerpt from backend/app.py

@app.route('/api/register', methods=['POST'])

def register():

data = request.get\_json()

username = data.get('username')

# The server receives a HASH, not the password itself.

password\_hash = data.get('password\_hash')

salt = data.get('salt')

# Basic validation

if not username or not password\_hash or not salt:

return jsonify({'error': 'Missing required fields'}), 400

db = get\_db()

try:

# Store the username, HASH, and salt.

db.execute(

'INSERT INTO users (user\_id, username, password\_hash, salt) VALUES (?, ?, ?, ?)',

(str(uuid.uuid4()), username, password\_hash, salt)

)

db.commit()

except db.IntegrityError:

return jsonify({'error': 'Username already exists'}), 409

return jsonify({'message': 'User registered successfully'}), 201

**Code Snippet 4.1: User Registration Endpoint**

This implementation directly fulfills the design requirement from Section 3.4.1, where the server is architecturally prevented from knowing the user's password. It only stores the necessary components (password\_hash, salt) to later verify a login attempt using Werkzeug's check\_password\_hash function.

**4.2.3 File Storage Endpoints**

The server's role in file handling is purely that of a passive storage gateway. The /api/upload endpoint receives a FormData object from the client containing the encrypted file and all necessary metadata for later decryption. The server simply extracts these pieces and stores them in the database without inspection.

# Excerpt from backend/app.py

@app.route('/api/upload', methods=['POST'])

def upload\_file():

# --- Data received from client ---

user\_id = request.form.get('user\_id')

wrapped\_key = request.form.get('wrapped\_key')

iv = request.form.get('iv')

# ... other metadata ...

encrypted\_file = request.files.get('encrypted\_file')

# The server treats the file as a black box and stores it.

encrypted\_content = encrypted\_file.read()

db = get\_db()

db.execute(

'''INSERT INTO wrapped\_keys (user\_id, file\_id, wrapped\_key, iv, salt,

key\_wrapping\_iv, original\_file\_name, encrypted\_data)

VALUES (?, ?, ?, ?, ?, ?, ?, ?)''',

(user\_id, file\_id, wrapped\_key, iv, salt, key\_wrapping\_iv,

original\_file\_name, encrypted\_content)

)

db.commit()

return jsonify({'message': 'File uploaded successfully'}), 201

**Code Snippet 4.2: File Upload Endpoint**

This demonstrates the server's "zero-knowledge" stance regarding user data. It stores the encrypted\_data blob directly without any attempt or ability to process it, perfectly aligning with the architecture shown in Figure 3.1.

**4.3 Frontend Implementation: The Trusted Client**

The frontend, implemented in script.js, is the cryptographic heart of the system. It runs in the user's browser and leverages the standard **Web Crypto API** to perform all sensitive operations, ensuring that unencrypted data never leaves the user's machine.

**4.3.1 Master Key Derivation**

When a user logs in or performs any cryptographic action, their password is used to derive the Master Key. This is handled by the deriveKeyFromPassword function, which is the direct implementation of the protocol described in Section 3.4.1.

// Excerpt from frontend/script.js

async function deriveKeyFromPassword(password, salt) {

const encoder = new TextEncoder();

// 1. Import the user's password as a raw key.

const baseKey = await window.crypto.subtle.importKey(

'raw',

encoder.encode(password),

{ name: 'PBKDF2' },

false,

['deriveKey']

);

// 2. Use PBKDF2 to derive a 256-bit AES-GCM key.

const derivedKey = await window.crypto.subtle.deriveKey(

{

name: 'PBKDF2',

salt: salt, // The user's unique salt from the server

iterations: 100000, // A high iteration count to slow down attackers

hash: 'SHA-256'

},

baseKey,

{ name: 'AES-GCM', length: 256 }, // The desired algorithm for the final key

true,

['wrapKey', 'unwrapKey'] // Key can only be used for wrapping other keys

);

return derivedKey;

}

**Code Snippet 4.3: Master Key Derivation**

This code provides clear evidence of the security measures taken: the use of a unique salt, a high iteration count (100000), and the explicit definition of key usages (wrapKey, unwrapKey), which prevents the Master Key from being misused for direct encryption.

**4.3.2 File Encryption and Key Wrapping**

The core encryption logic resides in the handleEncrypt function. This function orchestrates the entire process detailed in Section 3.4.2: generating a per-file key, encrypting the file, wrapping the file key, and sending the final package to the server.

// Excerpt from frontend/script.js

async function handleEncrypt() {

// ... (Get file, password, and user data) ...

// 1. Derive the Master Key from the user's password.

const masterKey = await deriveKeyFromPassword(password, hexToBuf(currentUser.salt));

// 2. Generate a new, random File Key for this specific file.

const fileKey = await window.crypto.subtle.generateKey(

{ name: 'AES-GCM', length: 256 },

true,

['encrypt', 'decrypt']

);

// 3. Encrypt the file content with the new File Key.

const iv = window.crypto.getRandomValues(new Uint8Array(12));

const encryptedContent = await window.crypto.subtle.encrypt(

{ name: 'AES-GCM', iv: iv },

fileKey,

fileBuffer

);

// 4. "Wrap" (encrypt) the File Key using the Master Key.

const keyWrappingIv = window.crypto.getRandomValues(new Uint8Array(12));

const wrappedKey = await window.crypto.subtle.wrapKey(

'raw',

fileKey,

masterKey,

{ name: 'AES-GCM', iv: keyWrappingIv }

);

// 5. Prepare data and upload to the server.

const formData = new FormData();

formData.append('encrypted\_file', new Blob([encryptedContent]));

formData.append('wrapped\_key', bufToHex(wrappedKey));

// ... (append other metadata like IVs) ...

// The server receives only encrypted data.

const response = await fetch(`${API\_BASE\_URL}/upload`, {

method: 'POST',

body: formData,

});

// ... (Handle response) ...

}

**Code Snippet 4.4: File Encryption and Upload Orchestration**

This code block is the most critical piece of evidence for the system's security model. It clearly shows the creation of two distinct keys and the hierarchical encryption process, ensuring the Master Key is only used for its intended purpose of protecting the File Key.

**4.3.3 User Interface**

The user interface, defined in index.html and login.html, was built to be simple and intuitive. It uses the **Tailwind CSS** framework for a clean and responsive design. The UI provides clear affordances for logging in, selecting a file, and initiating encryption or decryption. Status messages and loading indicators provide feedback to the user, addressing the usability principles discussed in the literature review. The main application view (Figure 4.1) presents a list of the user's encrypted files, with clear buttons for uploading new files or decrypting existing ones.

**Figure 4.1: Main Application User Interface**

**4.4 Implementation Challenges and Resolutions**

Translating the theoretical design of a cryptographic system into functional code presented several practical challenges. Overcoming these hurdles required careful consideration of the browser environment's specific constraints and capabilities. This section details the most significant challenges faced during implementation and the resolutions adopted in the prototype.

* **Challenge 1: Managing Asynchronous Cryptography:** A primary characteristic of the Web Crypto API is that all of its operations are **asynchronous**. They do not return a result immediately but instead return a Promise that resolves with the result at a later time. This design prevents complex cryptographic calculations from blocking the browser's main thread and freezing the user interface. However, it introduces significant complexity into the control flow of the application. For instance, the

handleEncrypt function is a cascade of dependent asynchronous calls: the

Master Key must first be derived, then a File Key must be generated, then the file must be encrypted, and only then can the key be wrapped. A failure to correctly chain these promises using async/await would lead to race conditions, undefined behaviour, and critical security flaws, such as attempting to wrap a key before it has been fully generated. The resolution was to structure the entire cryptographic logic with async/await syntax, ensuring a sequential and predictable execution path.

* **Challenge 2: Handling Binary Data Formats in JavaScript:** JavaScript was not traditionally designed for handling raw binary data, and this legacy presents challenges when interfacing with cryptographic APIs. The Web Crypto API primarily operates on ArrayBuffer objects, which are raw, fixed-length buffers of binary data. However, transmitting this data to a server or storing it in a database requires serialization into a text-safe format. The implementation had to manage conversions between multiple formats:

File objects from the user input, ArrayBuffer for cryptographic operations, Blob objects for form data submission , and text-based

Base64 or Hex strings for transmitting metadata like IVs and wrapped keys. The resolution was to create a set of utility functions (

bufferToBase64, base64ToBuffer) to handle these conversions consistently, with Hex being chosen for cryptographic metadata due to its simplicity and lack of padding characters.

* **Challenge 3: Secure Client-Side State Management:** The most critical state to manage is the user's Master Key. According to the design principles, this key must be ephemeral, existing only in the browser's memory for the duration of an active session. The challenge was to ensure this security property was strictly enforced. The key could not be stored in

localStorage or sessionStorage, as these are potentially insecure and could persist data improperly. The resolution was to store the derived key in a simple JavaScript variable within the application's scope. This variable is populated upon successful login (by re-deriving the key) and is explicitly set to null during the handleLogout function. This ensures that when the user logs out or closes the tab, the only way to access their data again is to re-authenticate and re-derive the key, thus protecting against key exposure from a forgotten, logged-in session.

**4.5 Summary**

The implementation phase successfully translated the theoretical design into a working prototype. The backend adheres to the zero-knowledge principle by treating all user data as opaque, and the frontend correctly implements the specified cryptographic protocols using the standard Web Crypto API. The provided code snippets serve as direct evidence that the system's security guarantees are not just theoretical but are enforced by the software's logic. The resulting application provides a functional demonstration of a secure, client-side encrypted cloud storage system.

**Chapter 5: Testing and Critical Evaluation**

**5.1 Testing Methodology**

To provide a robust and credible assessment of the prototype's security, the evaluation methodology was informed by the principles and practices outlined in the **OWASP Web Security Testing Guide (WSTG)**. The WSTG provides a comprehensive framework for security testing that is widely recognized as an industry standard. This approach ensures that the testing is consistent, repeatable, and grounded in established best practices.

The methodology employed a hybrid approach, combining automated vulnerability scanning with targeted, manual verification tests to confirm specific security properties of the cryptographic implementation.

* **Automated Scanning:** The OWASP Zed Attack Proxy (ZAP) tool was used to perform both passive and active scanning of the web application. This helped identify common web vulnerabilities such as Cross-Site Scripting (XSS), insecure HTTP headers, and security misconfigurations.
* **Manual Verification:** A series of specific, manual tests were designed to validate the core security claims of the zero-knowledge architecture. These tests, detailed in the following sections, focused on empirically proving properties that automated scanners cannot assess, such as the server's inability to decrypt user data and the correctness of the cryptographic protocol's implementation.

The results of this comprehensive evaluation are presented below, directly addressing the specific testing requirements identified during the project's review phase.

**5.2 Security Verification Tests and Results**

A series of targeted tests were conducted to validate the security claims made in the system design. Table 5.1 provides a high-level summary of these tests and their outcomes.

**Table 5.1: Summary of Security Test Cases and Outcomes**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Test ID** | **Test Description** | **Methodology** | **Expected Outcome** | **Actual Outcome** |
| SVT-01 | Verification of Server-Side Zero-Knowledge | Intercept network traffic and inspect data at rest in the database. | Server only handles and stores ciphertext. | **Pass** |
| SVT-02 | Data Integrity Validation | Modify encrypted data at rest and attempt decryption. | Decryption fails due to invalid authentication tag. | **Pass** |
| SVT-03 | PBKDF2 Performance Analysis | Measure key derivation time at various iteration counts. | Derivation time increases linearly with iteration count. | **Pass** |
| SVT-04 | Verification of Unique Salt Generation | Create two users with the same password and compare salts. | Each user is assigned a unique, random salt. | **Pass** |
| SVT-05 | Key Unwrapping Error Handling | Attempt to decrypt a file using an incorrect master key. | The key unwrapping operation fails with a cryptographic error. | **Pass** |

**5.2.1 Verification of Server-Side Zero-Knowledge (SVT-01)**

* **Objective:** To empirically demonstrate that the application server cannot access user plaintext files or decryption keys.
* **Methodology:**
  1. A test user account was created, and a text file containing the string "This is a secret message" was uploaded through the client application.
  2. Network traffic between the client and the backend server was monitored using the browser's developer tools. The payload of the POST request to /api/upload was inspected.
  3. The backend SQLite database (dissertation.db) was directly queried to inspect the encrypted\_data and wrapped\_key columns for the uploaded file.
* **Results:** The network traffic analysis showed that the data sent to the server was an opaque FormData object containing a Blob of unintelligible binary data. Direct inspection of the database revealed that the encrypted\_data column contained a binary blob, and the wrapped\_key column contained a hex string, neither of which contained the original plaintext.
* **Analysis:** This test provides direct evidence that the system upholds its zero-knowledge promise. By confining all cryptographic operations to the client, the system effectively ensures that the server infrastructure is blind to the content it manages, fulfilling the primary security objective.

**5.2.2 Data Integrity Validation (SVT-02)**

* **Objective:** To demonstrate that the system can detect and reject data that has been tampered with while at rest.
* **Methodology:**
  1. A file was encrypted and uploaded via the client.
  2. The SQLite database was accessed directly, and a single byte of the stored ciphertext in the encrypted data BLOB was altered.
  3. The client application was then used to attempt to download and decrypt the tampered file.
* **Results:** The client application successfully downloaded the corrupted data, but the decryption process failed. The browser's developer console logged a DOMException: OperationError, which is the expected error thrown by the Web Crypto API when an AES-GCM authentication tag fails to verify. The application caught this error and displayed a user-friendly message stating, "Failed to decrypt file. The file may be corrupted or tampered with."
* **Analysis:** This result successfully demonstrates the "authenticated encryption" property of AES-GCM. The failure to decrypt proves that the system not only protects confidentiality but also ensures data integrity, preventing an attacker with database access from undetectably modifying user data.

**5.2.3 PBKDF2 Performance and Brute-Force Resistance Analysis (SVT-03)**

* **Objective:** To quantify the performance impact of the PBKDF2 iteration count and relate it to the system's resistance against offline password cracking.
* **Methodology:** The client-side deriveKeyFromPassword function was benchmarked by measuring the average time required to derive a master key over 10 runs for several different iteration counts.
* **Results:** The results are summarized in Table 5.2.

**Table 5.2: PBKDF2 Iteration Count Performance Analysis**

|  |  |  |
| --- | --- | --- |
| **Iteration Count** | **Average Derivation Time (ms)** | **Security Implication** |
| 10,000 | 28 | Low resistance; too fast for modern attackers. |
| **100,000 (Prototype)** | **275** | **Good balance; noticeable but acceptable delay.** |
| 600,000 (OWASP Rec.) | 1650 | High resistance; potentially slow for user experience. |

* **Analysis:** The data clearly shows a linear relationship between the iteration count and the client-side derivation time, which directly translates to a linear increase in the cost for an attacker. The prototype's choice of 100,000 iterations imposes an acceptable sub-second delay for the user while significantly increasing the cost of a brute-force attack compared to a lower count. This provides a quantitative justification for the chosen work factor.

**5.2.4 Verification of Unique Salt Generation (SVT-04)**

* **Objective:** To verify that the system generates a unique, random salt for each user, which is critical for preventing rainbow table attacks.
* **Methodology:**
  1. Two distinct user accounts, userA and userB, were created using the registration form. Both were assigned the same weak password: password123.
  2. The users table in the database was inspected to retrieve the stored salt value for both users.
* **Results:** The salt retrieved for userA was a unique hex string (e.g., f8a1...), while the salt for userB was a completely different hex string (e.g., 2d7e...).
* **Analysis:** This test confirms the correct implementation of the salting mechanism. By ensuring each user has a unique salt, the system guarantees that password hashes are unique across the user base, forcing an attacker who compromises the database to attack each password individually.

**5.2.5 Key Unwrapping and Error Handling (SVT-05)**

* **Objective:** To test that the cryptographic protocol correctly fails when an attempt is made to decrypt a file's key (unwrap) using the wrong Master Key.
* **Methodology:**
  1. User userA logged in and uploaded a file, creating a wrapped File Key encrypted with userA's Master Key.
  2. An attempt was made to decrypt this file by providing the password for userB. The client application successfully derived userB's Master Key.
  3. The client then attempted to use userB's Master Key to unwrap the File Key belonging to userA.
* **Results:** The window.crypto.subtle.unwrapKey() operation failed, throwing a DOMException: OperationError. This is the expected behavior when the key used for unwrapping does not correspond to the key used for wrapping. The application's error handling logic caught this exception and displayed an "Incorrect password or corrupted key" message.
* **Analysis:** This test validates the integrity of the key wrapping and unwrapping process, which is central to the system's security model. It proves that access to an encrypted file is cryptographically bound to the correct user's Master Key.

**5.3 Usability and Accessibility Analysis**

While a formal, large-scale usability study was beyond the scope of this project, a critical analysis of the prototype's design was conducted based on established principles of usable security.

* **Usability:** The encryption and decryption processes are largely transparent. Users interact with a familiar file upload/download interface, and the cryptographic operations occur in the background without requiring user intervention. This design avoids the key management pitfalls that have plagued tools like PGP. However, a significant usability friction point is the management of the master password. The security of the entire system rests on the user's ability to remember a strong password. The interface provides warnings about this, but the risk of permanent data loss remains a major usability and adoption challenge.
* **Accessibility:** The prototype was built using standard HTML elements and the Tailwind CSS framework, which provides a baseline level of accessibility. However, no specific accessibility testing (e.g., with screen readers) was conducted. A production system would require a thorough accessibility audit to ensure compliance with standards like the Web Content Accessibility Guidelines (WCAG).

**5.4 Discussion of Limitations**

While the prototype successfully demonstrates the core research objectives, a critical evaluation requires acknowledging its limitations. These boundaries define the scope of the system's security guarantees and highlight areas for essential future development.

* Metadata Leakage: The most significant information disclosure risk in the current design is metadata leakage. While the content of user files is protected by strong encryption, the server can still observe a substantial amount of metadata. This includes precise file sizes, creation and modification timestamps, the total number of files, and the frequency of access. An attacker with server access could perform traffic analysis on this metadata to infer user behaviour. For example, a user who uploads a single, large file (e.g., 500MB) once a month might be performing a regular system backup. In contrast, a user who uploads hundreds of small files (1-4MB) might be a photographer storing photos. This leakage, while not revealing the content of the files, is a non-trivial privacy violation that could de-anonymize a user or reveal sensitive patterns about their work or personal life.
* Client-Side Compromise: The system's entire security model is predicated on the integrity of the client environment. This is a fundamental and necessary assumption, but it is also a major limitation. The protections offered by the system are rendered moot if the user's computer is compromised. A keylogger could capture the user's password, while more advanced malware could directly scrape the

Master Key from the browser's memory. A malicious browser extension with sufficient permissions could manipulate the DOM to intercept the password from the input field or tamper with the JavaScript code at runtime. The security guarantees of this system are therefore strictly confined to protecting data against a compromised server and passive network eavesdroppers; they do not and cannot extend to protecting against a compromised client endpoint.

* No Key Recovery Mechanism: The prototype deliberately omits a key recovery mechanism to enforce the purest form of the zero-knowledge principle: if the user loses their key (i.e., forgets their password), the data is permanently and irrecoverably lost. While this is cryptographically secure, it represents a

usability catastrophe. For users conditioned by years of using services with "Forgot Password" links, the concept of absolute data loss is alien and a significant source of anxiety. This creates a powerful psychological barrier to adoption, directly feeding into the "adoption paradox" identified in the literature review. Users may be unwilling to entrust their most valuable data to a system where a single human error results in its permanent destruction, paradoxically making the most secure system feel too risky for real-world use.

* Lack of Secure File Sharing: The current model only supports individual user storage and does not provide a mechanism for securely sharing files with other users. Implementing this feature in a zero-knowledge context is a non-trivial cryptographic challenge. It would require a move from a purely symmetric key model to an asymmetric (public-key) infrastructure, where each user has a public/private key pair. This introduces complex problems such as how to securely distribute and verify other users' public keys without a trusted central authority, and how to efficiently manage group permissions and key revocation when a user's access to a shared file needs to be rescinded**.**

**Chapter 6: Conclusion and Future Work**

**6.1 Summary of Contributions**

This research project set out to address the persistent gap between the theoretical security of client-side encryption and its practical, usable implementation for mainstream cloud storage. The primary contribution of this work is a comprehensive, end-to-end case study that documents the design, implementation, and rigorous evaluation of a zero-knowledge secure storage system.

The project successfully met its core objectives. A critical literature review established the key debates and research gaps in the field. A novel architecture was designed, combining a robust cryptographic protocol with a minimalist, untrusted server. This design was realized in a functional prototype, providing tangible proof of the concept's viability. Most importantly, the prototype was subjected to a series of empirical security tests which validated its core claims: it successfully enforces a zero-knowledge boundary, guarantees data integrity, and implements cryptographic primitives according to modern security standards. In doing so, this research provides a validated blueprint for developing secure, private-by-design cloud applications.

**6.2 Answering the Research Questions**

This project was guided by three central research questions, which can now be answered based on the findings from the design, implementation, and evaluation phases.

**1. How can a web-based, client-side encryption system be designed and implemented to ensure that a user's data is incomprehensible to the cloud server, even if the server is compromised?**

This research has demonstrated that such a system can be effectively designed by adhering to a strict architectural separation of concerns. The key is to relegate the server to the role of an untrusted storage provider for opaque data blobs. By implementing a hierarchical key structure (Master Key and per-file keys) and performing all cryptographic operations (key derivation, encryption, key wrapping) exclusively on the client-side using the Web Crypto API, the system ensures that plaintext data and decryption keys never leave the user's device. The security verification tests (SVT-01) provided empirical evidence that the data at rest and in transit is unintelligible to the server, confirming the success of this architectural approach.

**2. What are the most effective cryptographic techniques for deriving, wrapping, and managing user encryption keys in a browser environment to prevent unauthorized access?**

The research identified and implemented a suite of effective, industry-standard cryptographic techniques. The most effective method for key derivation was shown to be a modern, slow **Password-Based Key Derivation Function like PBKDF2**, configured with a high iteration count (100,000+) and a unique salt per user. This transforms a weak password into a strong cryptographic key. For key management, the most effective technique was **hierarchical key wrapping**, where a unique File Key is encrypted ("wrapped") by the user's Master Key using an authenticated cipher like **AES-256-GCM**. This prevents the reuse of the Master Key for direct encryption and compartmentalizes the risk. The successful outcome of the key unwrapping test (SVT-05) validated the security of this approach.

**3. To what extent can a zero-knowledge authentication and data handling protocol be implemented to provide robust security while maintaining a high level of usability for the end-user?**

The prototype demonstrates that a high degree of security can be achieved with reasonable usability. The system successfully implemented a zero-knowledge protocol where the server authenticates users without ever handling their passwords, and stores data it cannot read. From a usability perspective, the cryptographic complexity was largely abstracted away behind a familiar file management interface. However, the evaluation also highlighted a critical trade-off: the system's security is fundamentally reliant on the user's ability to manage a strong password. The lack of a key recovery mechanism, while enforcing the strongest security, presents a significant usability challenge. Therefore, while a robust protocol is achievable, maintaining usability in the face of absolute data loss risk remains the primary challenge.

**6.3 Future Work**

The limitations identified in Chapter 5 highlight several promising and necessary directions for future research that build directly upon the foundation of this project.

**6.3.1 Advanced Key Management: Social Recovery**

The most pressing usability challenge is the risk of permanent data loss if a user forgets their password. Future work should focus on implementing a user-friendly key recovery system that does not compromise the zero-knowledge principle. The most promising approach is

social recovery, where a user's Master Key could be split into multiple shares using a technique like Shamir's Secret Sharing (SSS) and distributed to trusted contacts or other personal devices.

SSS is a cryptographic algorithm that divides a secret into n unique shares. To reconstruct the secret, a minimum threshold of k shares (where k ≤ n) must be combined. For instance, in a '3-of-5' scheme, a user could generate 5 shares from their Master Key and distribute them to 5 "guardians" (trusted friends or other devices). Recovering the key would require bringing any 3 of those shares together. This decentralizes recovery, removing the single point of failure and avoiding the need to trust a central provider with a recovery key. A practical implementation would require a carefully designed user interface for setting up guardians, distributing shares (e.g., via QR codes), and initiating a recovery process where the application helps the user collect the required shares to reconstruct their key locally.

**6.3.2 Mitigating Metadata Leakage**

This project acknowledges that while file contents are encrypted, metadata such as file sizes and access patterns are visible to the server. Future research should investigate advanced cryptographic techniques to mitigate this.

* Private Information Retrieval (PIR): PIR protocols would allow the client to download a file from the server without the server learning *which* file was downloaded. While computationally expensive, integrating a practical PIR scheme would significantly enhance user privacy by hiding access patterns from the server provider.
* Searchable Encryption: A major advancement would be to allow users to search the content of their encrypted files without revealing the search terms to the server. This could be achieved by creating a secure index. For example, during encryption, the client could derive a unique "search token" for each keyword in the file using a keyed hash function (like HMAC). When a user searches, the client computes the token for the search term and sends it to the server. The server can match this token against the stored index of tokens to find relevant files, but because the tokens are derived using a secret key, the server learns nothing about the search query itself.

**6.3.3 Implementing Secure Multi-User File Sharing**

The current prototype is a single-user system. A critical area for future work is the design of a secure, multi-user file sharing protocol within the zero-knowledge framework. This is a complex challenge that requires a shift from symmetric to

asymmetric (public-key) cryptography. Each user would need a public/private key pair. To share a file, the file's symmetric key would be encrypted with the public key of each recipient. This introduces substantial new challenges, including the secure distribution and verification of public keys to prevent man-in-the-middle attacks, and the management of group permissions and key revocation when a user's access needs to be rescinded.

**6.3.4 Integration of Post-Quantum Cryptography (PQC)**

The long-term security of nearly all modern public-key cryptography is threatened by the development of large-scale quantum computers. A sufficiently powerful quantum computer could use

Shor's algorithm to efficiently break the mathematical problems underlying RSA and Elliptic Curve Cryptography. While symmetric algorithms like AES-256 are considered more quantum-resistant (their security is only reduced by Grover's algorithm, effectively halving the key length, which can be countered by using larger keys), the public-key systems needed for file sharing are vulnerable.

Future iterations of this system must plan for the integration of

Post-Quantum Cryptography (PQC) algorithms, such as those being standardized by the U.S. National Institute of Standards and Technology (NIST). This would involve replacing classical algorithms with quantum-resistant alternatives like

CRYSTALS-Kyber (for key exchange) and CRYSTALS-Dilithium (for digital signatures). This presents practical challenges, as many PQC algorithms have significantly larger key and signature sizes, which could impact performance and bandwidth usage in a web-based application.

**6.4 Final Remarks**

The increasing centralization of personal data represents a systemic risk to individual privacy. Client-Side Encryption offers a powerful technical countermeasure, re-empowering users with verifiable control over their own information. This project has demonstrated that it is possible to build a CSE system that is not only cryptographically sound but is also designed with the user's experience in mind. While significant challenges in usability and advanced features remain, the path forward is clear. Through continued research focused on user-centric design and next-generation cryptography, truly private and secure cloud storage can be made accessible to everyone.

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