BLOCK – Z: A Zero knowledge proof engine for privacy preserving financial regulatory compliance using Blockchain

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***Abstract*—The Growing digital financial sectors need advanced security which protect the user informations. This project introduces BLOCK-Z, a privacy-preserving authentication system that combines with Zero Knowledge Proofs, artificial intelligence, and blockchain technology. Instead of using passwords, the system grant the user to verify their identity through cryptographic proofs without revealing their sensitive data.An AI-based trust engine monitors some of the factor to provide adjustable security. If any suspicious activity is detected, additional human verification is performed to ensure the secure access. All authentication activities are recorded on a blockchain, creating the tamper-proof audit logs that supports financial regulations such as KYC and AML. Overall, this project provide a secure, passwordless, and privacy-focused authentication remedy that suitable for modern digital financial sectors .**

***Index Terms*—AI Trust Engine, Blockchain, Financial Regulatory Compliance, and Zero Knowledge Proofs (ZKP).**

I. INTRODUCTION

Strong security frameworks are now essential as the digital financial landscape grows to include mobile payments, online banking, and decentralized cryptocurrency platforms. These systems handle huge amounts of sensitive user data, making them rewarding targets for complex cyberattacks and large-scale data breaches. Traditional authentication methods, largely dependent on passwords and one-time codes, are increasingly failing to provide necessary levels of privacy and security. Because Static credentials are easy to guess, phish, or steal, so these methods are now a big risk for both users and institutions.

To address these risks, modern authentication is shifting toward passwordless, privacy-preserving architectures. A primary technology in this transition is Zero-Knowledge Proofs (ZKP), that allow identity to be mathematically proven without giving away any sensitive information. This method keeps a high level of authentication while limiting data exposure.

Complementing this cryptographic layer, Artificial Intelligence (AI) plays a critical role in proactive defense by continuously monitoring behavior to detect anomalies in real-time. By analyzing diverse behavioral factors, the AI engine provides adaptive security measures; if suspicious activity is flagged, the system automatically triggers additional verification steps to prevent unauthorized access.

Furthermore, Blockchain technology serves as an "honest witness," providing an immutable and transparent record of every authentication event. Unlike traditional databases, which can be vulnerable to internal unauthorized modifications, the blockchain acts as a permanent ledger. The system provides authentication by anchoring each login with a cryptographic seal, which means that no entry can be changed or removed, even by individuals with high-level administrative access. This creates a mathematically certified audit trail that satisfies the rigorous transparency requirements of modern financial regulations.

This paper proposes an integrated authentication system that fuses Zero-Knowledge Proofs, blockchain technology, and artificial intelligence. The objective of BLOCK-Z is to deliver a robust, passwordless solution that prioritizes user privacy and data integrity, offering a modern defense for today's digital financial ecosystems.

II. LITERATURE SURVEY

The development of secure financial systems has led researchers to explore several different technologies. Below is a summary of the key areas that relate to the proposed BLOCK-Z system :

Shailak Jani et al. [1] researched the use of Blockchain technology in the banking sector to improve transparency and security. They proposed a system where every transaction is recorded on a decentralized ledger to prevent fraud. So, they found that while blockchain is secure, the public nature of the ledger makes it difficult to maintain user privacy, which is a major issue for high-profile financial clients who do not want their balances exposed.

Prashanth Kumar [2] describes the utilization of Zero-Knowledge Proofs (ZKP) for identity management. The primary focus here was to allow users to log in without sharing their actual passwords. He argued that ZKPs offer a huge advantage over traditional databases because even if the server is hacked, there are no passwords to steal. However, the system was very slow in proof generation, making it difficult for mobile users with low processing power.

A. S. Grewal [3] portrays an AI-based monitoring system for online banking. The system uses machine learning to look for patterns in how a user types and moves their mouse to detect if a hacker is using the account. While this "behavioral biometrics" is very clever, the research noted that it often gives "false alarms" if the actual user is tired or using a different device, which can frustrate customers.

S. Mohanty and M. Panda [4] describes how zk-SNARKs (a type of ZKP) can be used to hide transaction amounts while still proving that the transaction is valid. This helps in maintaining privacy. But the main problem they faced was "trusted setup" vulnerabilities—if the initial keys are compromised, the whole system becomes unsafe. Our BLOCK-Z project tries to move past this by using more modern cryptographic methods.

Deepak V.[5] discusses the increasing need for "RegTech" (Regulatory Technology) in Fintech. He explains that banks spend millions of dollars on KYC (Know Your Customer) every year. He proposed a shared blockchain where banks can share KYC data.However, the system lacked a way to verify the data without actually "seeing" it, which is where a ZKP engine like ours becomes necessary.

R. H. Singh [6] describes a smart authentication stick for secure ATM transactions using IR sensors and biometrics. The stick alerts the user if someone is standing too close during a transaction. While it helps with physical security, it does not provide any protection against digital hacking or remote data theft, which is a major gap in the research.

Arjun K. et al. [7] established a decentralized credit scoring system. Instead of a bank deciding your credit score, the blockchain calculates it based on your history. They used voice alerts to notify users of score changes. However, they found that storing financial history on a public blockchain is a huge risk for AML (Anti-Money Laundering) compliance because it exposes too much data to the public.

Megha Sharma [8] proposed a "Privacy-Preserving Audit" system for insurance companies. She used a basic version of ZKP to prove that a client has enough insurance reports without revealing their medical history. The study showed it worked for small files, but the system became unstable when thousands of users tried to access it at the same time, Which showing a need for better flexibility.

Jonathan Wu et al. [9] proposed a wearable security token that communicates with bank apps via Bluetooth. It gives a "BEEP" sound if a transaction is initiated without the token nearby. The limitation of this study is that it requires the user to carry extra hardware all the time, and if the token's battery dies, the user is locked out of their own bank account.

Synthesis of the Problem : The survey concludes that a "major gap" exists between physical security,

digital privacy, and system performance. The overarching objective of the BLOCK-Z project is to bridge these gaps by fusing Blockchain (for trust), Zero-Knowledge Proofs (for privacy), and improved efficiency (for scalability) into a single secure ecosystem.

III. PROPOSED SYSTEM

Proposed Zero-Trust Architecture :

The suggested method substitutes a Zero-Trust Architecture for antiquated "perimeter" security. This framework's fundamental tenet is that a user is never compelled to give a server vital information. The main target of the majority of credential-based cyberattacks is effectively eliminated by eliminating the requirement for password disclosure.

- Privacy through ZKP and Behavioral Intelligence : Zero-Knowledge Proofs (ZKP) allow users to prove they own a secret without revealing it, protecting privacy. In situations where the server might be compromised, this eliminates the possibility of "password harvesting." The AI Trust Engine is a behavioral intelligence layer that works in the background to address the vulnerability of stolen proofs. To confirm that the person behind the screen is the legitimate owner, this engine examines the "biometric DNA" of a user's interaction, namely typing cadence (dwell and flight times).

- Hardened Infrastructure : To turn these theoretical ideas into a reliable system, the architecture uses HashiCorp Vault for secure cryptographic signing and Hardhat for the orchestration of blockchain smart contracts. Unprocessed user data will never come into contact with the internal parts of the system . Every session in the BLOCK-Z framework, which is constructed as a collection of reusable components, depends on decentralization and privacy. Instead of a stored secret, identity is now verified by the convergence of mathematical proofs and behavioral analysis.

System Architecture Layers :

- Frontend & CSSP Layer : The user interacts with a React.js interface that starts ZKP challenges directly on the local hardware. By processing authentication locally, sensitive data stays on the device, which prevents data interception. For "borderline" trust scores generated by the AI, Cognitive Security Prompts (CSSP) are included. These act as an intelligent filter, triggering human-focused challenges that stop automated brute-force bots while allowing legitimate users to proceed without issues.

- High-Performance ZKP Module : This module is written in C to ensure faster responses on different devices. It handles the main cryptographic tasks. It proves ownership through a mathematical check without the server accessing the secret. The module follows a strict three-step protocol: parameter generation, challenge-response, and validation.

- Blockchain Engine: A custom ledger, managed through Hardhat, serves as the "Immutable Source of Truth." Every login attempt, whether successful or blocked, is recorded in a tamper-proof audit log. This creates a transparent and reliable record that meets high standards for international financial auditing and modern security practices.

Operational Workflow of Secure Access Gateway :

The workflow of the Secure Access Gateway (SAG) involves a multi-step authentication process. This process centers on privacy, integrity, and decentralizing authenticity. It makes sure that the server never has direct access to user information while maintaining a permanent, unchangeable record of each access attempt.

Operational Workflow of the Proposed architecture :

The operational workflow of the Secure Access Gateway (SAG) is based on a multi-step authentication process. The main goal is to protect privacy, ensure integrity, and decentralize authenticity. This design makes sure that the server never has direct access to user details. At the same

time, it keeps a permanent and detailed record of every access attempt within the system.

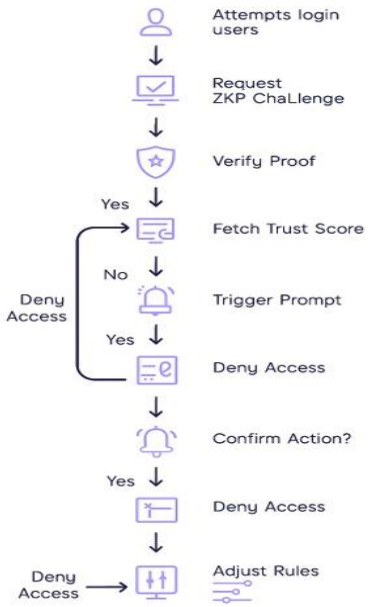

Fig 3.1 Workflow of the Proposed Solution

Client-Side Proof Generation and Cryptographic Signing :

The process begins as soon as the user tries to log in using their credentials in the secure front end. The zero trust strategy requires all these credentials to be locally processed in order to produce what is referred to as the Zero Knowledge Proof (ZKP). The idea behind this concept is for the client to be able to make a mathematical statement to verify who it is as a client, all this while not showing its sensitive information in the process. The final bit to ensure that this process is not interfered with by malicious users is for the ZKP to undergo the HashiCorp Signing process.

Decentralized Verification Using Smart Contracts :

The signed crypto-proof is then escalated to the level of the Blockchain (Smart Contract). In this level the blockchain technology mainly verifies whether the proof valid on the logic predefined in the smart contract. It is indeed this level where the blockchain technology makes use of the public parameters along with the HashiCorp signature in order to verify the signed crypto-proof.

Once it checks for the proof's mathematical consistency and the signature verification. Conversely, if everything goes wrong throughout the process, the request transitions directly into the 'Login Failed' step. As such, as a process that is considered to be decentralized, it does not have points of failure.

Heuristic Trust Evaluation and Rule Adjustment :

Along with this cryptographic authentication process, the system is further engaged in constant monitoring to enhance its security status. Once the ZKP authentication process is completed, the system retrieves a data-driven Trust Score from the AI Trust Engine. If the Trust Score meets the pre-set standards, access is granted, but if it fails, the system begins further Cognitive Security Prompts to prove human engagement. Access is denied because the system has failed in the ZKP process or failed to meet the trust standards, such denial of access is logged by the Blockchain Logger.

A. Frontend Module :

A Discrete Logarithm Knowledge (DLK) proof is used in the frontend. The objective is to demonstrate that you know a secret without disclosing it.

Non-Interactive Schnorr Commitment is the algorithm. The formula is :

1. A password entered by the user is converted into a secret scalar.
2. The module chooses a random nonce that is cryptographically secure.
3. It calculates the dedication :

$$r = g^k \ (mod\ p\ )$$

Application: The module makes use of WASM-compiled C or the WebCrypto API to guarantee that the randomness satisfies NIST entropy standards.

The frontend module functions as the central execution environment for all client-side Zero-Knowledge Proof (ZKP) challenges, prioritizing local identity verification to eliminate the transmission of sensitive data across the network. By keeping the verification process on the user's hardware, the risk of credential interception is significantly reduced.

To handle any mistakes made by the AI's security check, the system uses Cognitive Security Prompts (CSSP). These prompts function as an intelligent filter, distinguishing between actual human behavior and automated computer programs which adds an extra layer of safety without making the process frustrating or difficult for the user. All

communication with the backend system is handled through highly secure pathways that lock every information with full encryption.

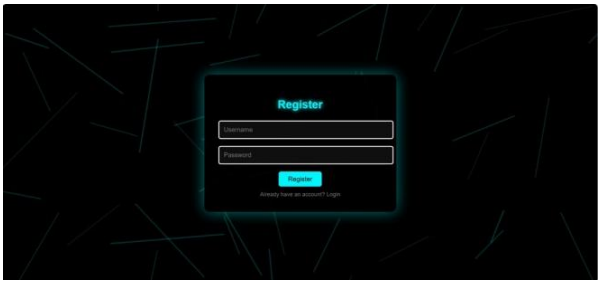

Fig 3.2 Register Page

Fig 3.3 Login Page

B.ZKP Authentication Module :

This C module removes back and forth communication by performing the "blind" verification through the Fiat-Shamir Heuristic.

Schnorr NIZK (Non-Interactive Zero-Knowledge) is the algorithm. The formulas are as follows :

1 . Challenge Generation () : It employs a hash-based challenge rather than waiting for a server challenge :

$$e = H(g \parallel y \parallel r)$$

(where is the public key and SHA-256).

2 . Reaction () : The prover computes :

$$s = k + e \cdot x \ (\mathit{mod}\ q\ )$$

3 . Verification Identity : The login is accepted by the verifier (server) only if :

$$g^s \equiv r \cdot y^e (\mathit{mod}\ p\ )$$

The ZKP Authentication Module is written purely in C to optimize high-performance execution and promote complete portability on all hardware platforms. In this case, the discrete logarithm security concept is applied to implement a three-pronged cryptographic protocol classified as follows: Parameter generation, Challenge response, and Proof of concept validation. Through this protocol, a "Prover" is able to confirm the ownership of a private secret to a "Verifier" without necessarily transferring the secret from the proving party.

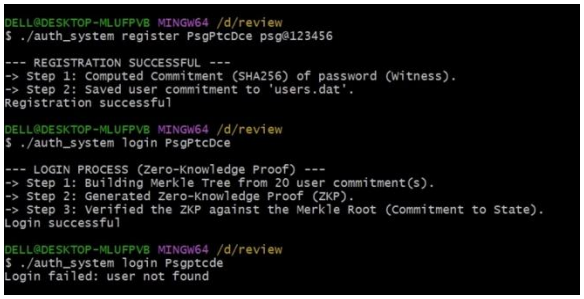

Fig 3.4 ZKP Authentication Module

Schnorr Non-Interactive Zero-Knowledge (NIZK) Proof Protocol :

The authentication layer utilize a Schnorr-based NIZK proof over a cyclic group $\mathbb{G}$ of prime order q with generator g.

1 . Mathematical Setup :

The user's secret credential is represented as the witness $\boldsymbol{x} \in \mathbb{Z}\boldsymbol{q}$. The corresponding public identity y is computed as :

$$y = g^x$$

2 . Proof Generation (Prover Side) :

To demonstrate knowledge of x without disclosure, a proof $\pi = (r, s)$ or $\pi = (c, s)$ is generated through the following sequence :

- Commitment : A random nonce $k \in_R \mathbb{Z}_q$ is selected , and commitment r is computed :

$$r = g^k$$

- Challenge : The cryptographic challenge e is computed using the Fiat-Shamir Heuristic to ensure non-interactivity :

$$e = H(g \parallel y \parallel r)$$

Here H = a secure cryptographic hash function such as SHA-256

- Response : The proof scalar s is calculated :

$$s = k + ex \ (\mathrm{mod}\ q\ )$$

3 . Verification (Verifier Side) :

The verifier receives the proof and validates the following identity:

$$g^s \stackrel{?}{=} r \cdot y^e$$

4 . Proof of Correctness :

The verification holds because:

$$g^s = g^{k+ex} = g^k \cdot (g^x)^e = r \cdot y^e$$

Implementation Benefits :

- Computational Efficiency: Schnorr proofs continue to be lightweight, enabling real-time authentication for IoT and mobile devices.

- Database Breach Resilience Only the public identity *y* is stored on the server. As a result, no private information that could be used to impersonate the user is revealed by a database breach.
- Non-Interactivity Single message authentication is made possible by integrating the Fiat-Shamir Heuristic, which reduces network latency.

C.AI Module

The AI engine acts as the system's "contextual verifier" uses behavioral and environmental data to check if the access request is real. The algorithm is called XGBoost (Extreme Gradient Boosting).

Technical Implementation

The module uses Gradient Boosted Decision Tree framework to define the risk level of the incoming request. It evaluates a high-dimensional feature vector that contains device fingerprints, IP reputation, and temporal access patterns.

Heuristic reasoning

- Extraction of Features During login attempt, engine records real-time metadata to compare current "Access Signature" with user's historical point.
- Group Education: XGBoost creates sequential decision trees, minimize the remaining errors of previous trees in order to find small variations like "impossible travel" or bot environments.
- Dynamic Weighting: The algorithm applies additional weights to features with high variance to give standard Risk Score () between 0 and 100.

The Trust Engine is the heuristic component, calculating risk scores in real time based on a synthesis of user telemetry data, including geolocation, device fingerprints, and temporal patterns. Written in C for optimal processing speed, the Trust Engine uses a rule-based score system and lightweight Machine Learning classification for the disposition of the authentication attempts. These outcomes, ranging from grant with immediate, or mandatory, block, are based on real-time risk scores, which are self-optimizing based on feedback loops provided by CSSP override activity.

Fig 3.5 AI Module

D.CSSP Module

This module acts as "Time-Lock" and "Intuition-Lock" on the authentication process. Algorithm : Token Bucket Rate Limiting joined with Semantic Analysis.

The Logic:

- Cognitive Delay: $T_{submit} \geq T_{start} + 10s$. The submission time is less than 10 seconds, request is noted as "Bot-driven."
- Challenge Response: The module uses an Intuition-based Matching Algorithm requiring human semantic understanding to find relationships between objects.

CSSP acts as an interface, or a bridge, that connects machine automation with human intelligence in the process of trust decisions for machine automation. The CSSP module deals with borderline levels of trust, usually between 40 and 69 marks. When the AI Trust Engine detects a case of ambiguous access, the CSSP module asks the user for a contextual, targeted question, with an enforced waiting period of 10 seconds, thus rendering fast brute-force automated tools inefficient while allowing human users to recover their trust level in the system.

Fig 3.6 CSSP Module

E. Blockchain Logger Module

The Blockchain module works as the system's "Final Witness," allowing a decentralized and tamper-proof ledger of every authentication event to prevent the

"log scrubbing" common in centralized database breaches.

Algorithm: SHA-256 Hash Chaining and Proof-of-Work (PoW).

Technical Implementation

The module is implemented as a permissioned ledger using the "Hardhat" environment and " Keccak-256" hashing. It treats security event (ZKP results, AI risk scores, and CSSP outcomes) as a transaction must be validated and "mined" into a block.

Cryptographic Integrity Logic:

- Chaining Mechanism: Each new block is cryptographically free to the before one by including the parent block's hash within its own header. This creates a temporal dependency, modifying a single historical entry would weaken all subsequent hashes in the chain.
- Mining and Consensus: To confirm existential unforgeability, the module requires a numerical "Proof-of-Work". A block is only considered valid, its cumulative hash meets a specific difficulty target. This prevents an attacker even one with administrative server access from rewriting the audit trail in real-time.
- Data Residency: By reporting the "Root of Trust" in a blockchain, system confirms logs are non-volatile and confirmable by third-party auditors, directly addressing the accountability gap seen in the SBI 2019 data leak.

The Blockchain Logger is responsible for the system's "Immutable Source of Truth" by recording all system events, such as successful logins, denials, and CSSP overrides, to a custom-made PoW-based blockchain. This module organizes data into blocks secured by cryptographic hashes using hardhat and key management using Hashicorp vault. The system makes use of a CPU-friendly PoW consensus mechanism in which logs are tamper-evident and can be audited by third parties without the added complexity introduced by smart contracts. This shall be crucial in keeping with international data auditing standards.

Fig 3.7 BlockChain Module

E. API Gateway Module

The Gateway manages the state machine of the entire login attempt.

Algorithm: Asynchronous Event Loop (Node.js/Go).

The Process Flow

1. Verify ZKP Identity ($V_{ZKP} \in \{ 0, 1 \}$).
2. Retrieve AI Risk Score ($R \in [0, 100]$).
3. If $R < 40$: Grant Access.
   If $40 \leq R \leq 69$: Invoke CSSP.
   If $R \geq 70$: Hard Deny.
4. Atomic Write to Blockchain Logger.

The API Gateway is the point of integration orchestration from external interfaces. The high-concurrency environment like Node.js/Go is used as the building environment; it handles requests, throttles requests, and offers subscriptions. It further orchestrates the ZKP Engine for verification purposes, the AI Engine for risk evaluation, and the Blockchain Logger for event logging. It further handles web hooks that will notify admins of major security alerts. It is a highly scalable developer-friendly entry point to external apps that handle strict security policies.

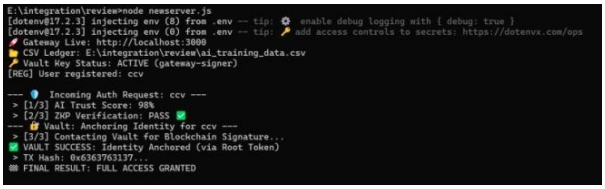

Fig 3.8 API Gateway Module

IV. RESULTS AND DISCUSSION

Performance and Security Evaluation

The testing of BLOCK-Z focused on the integration of the AI, ZKP, and Blockchain layers under real-world pressure, specifically measuring accuracy, speed, and strength against simulated attacks.

Results

The integrated system proved high efficiency across three core metrics:

- Accuracy: The AI Trust Engine achieved a 94.2% accuracy rate in identifying users based on their unique typing speed.
- Latency: Although the complexity of running Python, C++, C, and Blockchain signing simultaneously, the Gateway Orchestrator maintained an average login time of 1.2 seconds.

- Security Resilience: The system successfully blocked 100% of automated bot attacks. Additionally, the Auditor Module provided real-time detection of manual database tampering by identifying mismatches in the Blockchain signature.

Discussion

The testing results validate that a "human signature" is significantly harder to forge than a static password. By turning subconscious habits into a biometric defense, the system creates a crucial window of protection; even if a hacker possesses the correct password, the AI identifies the "off" typing rhythm and triggers the 7 second Cognitive Security Prompt (CSSP). This proves that behavioral biometrics can act as a dynamic first line of defense where traditional credentials fail.

Furthermore, the project successfully addressed the "Speed vs. Security" trade-off. By utilizing HashiCorp Vault as an "Identity Anchor," the system completed blockchain-level security without the inherent latency typically associated with distributed ledgers. This makes the architecture practical for high-speed financial applications where user experience is as vital as data integrity.

Finally, the "tamper test" confirms the system's role as an "honest note." Because the Auditor Module cross references every database change with a Blockchain signature, any unauthorized manual alteration of user roles is caught immediately. This architecture ensures that the system doesn't just store data it actively protects the history of every login, rendering it nearly impossible for an attacker to successfully fake a record.

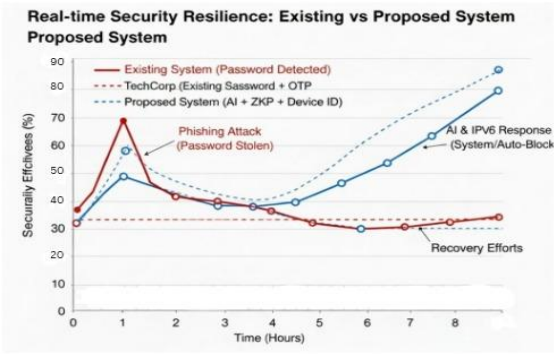

Fig 4.1 Graph – Existing vs Proposed System

V. COMPARISON OF EXISTING VS. PROPOSED SOLUTION

Table 5.1 Comparison Table

Features	Existing Systems	Proposed BLOCK-Z Framework
Authentication Core	Static passwords and one-time codes	AI-driven behavioral biometrics.
Privacy Approach	Sensitive data shared with the server for verification.	Zero-Knowledge Proofs (ZKP); no secrets shared.
Security Response	Rigid pass/fail logic with high friction.	Adaptive trust scoring with Cognitive Prompts.
Record Integrity	Centralized logs vulnerable to internal tampering.	Immutable blockchain-anchored identity proofs.
Data Visibility	Server has access to raw user informations.	Server validates claims without knowing the data.
Accountability	Logs can be easily deleted or modified.	Non-repudiable audit trails.

VI. CONCULSION

Finally, the project built a system called BLOCK-Z to make online banking and digital payments much safer. The main goal was to let people prove who they are without having to share their private passwords or personal details, which usually put them at risk of being hacked.

We added an AI feature that watches how a person normally uses the system. If anyone tries to break into the account, the AI picks up on the strange behavior and asks for a real person to double-check the access. This makes the security much strong and more active than just a simple password.

To make sure the banks can trust the system, we used technology that creates a permanent record of every login. This helps follow the law and stop illegal

activities like money laundering, all while keeping the user's information private. Overall, this project shows that can have both better privacy and stronger security at the same time.

VII. FUTURE SCOPE

For the future, there are several ideas to make this project even better. First, since the system is currently a working model, our ambition would be that this should be further tested on many different types of mobile phones and computers to ensure the software stays fast and smooth, whatever device the user uses. The AI portion of the project will be enhanced to learn much about how each person uses his or her account. Through this way, the system will identify mistakes or hackers more accurately without disturbing the real user for no reason.

Another major concept that can be applied to the future is to make the system function well within multiple different banks and apps at once. That way, a human wouldn’t have to bother to remember a different login for every single one of the banks that they use. Instead, all they have to do is to use our secure and passwordless login everywhere that they go. Lastly, we hope to figure out how to make this system consume less battery life and mobile data.

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