An Integrated Approach for Secure User Authentication and Verification Using Cryptographic Methods

***Abstract*—** In this paper, we propose a unified, secure authentication mechanism that combines cryptographic principles with the MERN (MongoDB, Express, React, Node.js) stack, eliminating the need for storing user passwords directly. Instead, we employ a robust cryptographic approach where user registration and login processes are validated through modular exponentiation and hash functions. Our methodology leverages the generation of large prime numbers and the application of public and private key exchanges. This process not only enhances security by eliminating the need to store passwords but also ensures that sensitive data, such as public keys and prime numbers, is securely managed.

During the registration phase, we generate random prime numbers g and p, along with a private key derived from the hashed password. Using these elements, we compute the public key y, which is stored in the MongoDB database without requiring the password. The login process involves a cryptographic challenge-response validation using random numbers and modular hashing. The user's credentials are verified by comparing both sides of a derived equation involving modular exponentiation, thus confirming the authenticity of the user without direct password access.

Our proposed solution provides significant advantages over traditional password-based authentication by reducing the risk of data breaches and enhancing user privacy. Testing across multiple user scenarios demonstrates the robustness and efficiency of our approach. This cryptographic solution offers a promising pathway for secure, scalable authentication in modern web applications, setting the stage for more resilient security frameworks in the field of web development.

Keywords— Password less authentication, MERN stack, cryptography, prime number generation, modular exponentiation, database security.

1. INTRODUCTION

The need for secure and efficient user authentication systems has become critical in modern web applications, especially with the increasing risks associated with traditional password-based systems. In this context, we propose an integrated cryptographic authentication solution on the MERN (MongoDB, Express, React, Node.js) stack that eliminates the need for storing user passwords directly. Instead, we utilize cryptographic methods, including modular exponentiation and hashing, to ensure secure user verification. This approach ensures that sensitive user information, such as passwords, is never stored in the database, minimizing the risk of data breaches and enhancing security.

The primary objective of this project is to develop a secure user authentication system where registration and login processes are validated through cryptographic protocols. During registration, a user's password is hashed, and a private key is derived from this hash. Using prime numbers g and p, the public key y is generated and stored in MongoDB, while the password itself is never saved. During login, a cryptographic challenge-response method is employed, where random numbers and modular exponentiation are used to verify the user's credentials. The system uses a mathematical equation to ensure that the user's identity is verified without exposing the password. This method ensures a higher level of security than traditional password storage techniques, which are vulnerable to breaches and attacks.

The secondary objective is to develop a robust and scalable authentication system that can be integrated into modern web applications built on the MERN stack. By utilizing cryptographic techniques, we aim to make the authentication process more secure, ensuring that even if the database is compromised, sensitive user data remains protected. Furthermore, our approach helps reduce the attack surface by eliminating the need for traditional password management systems. We demonstrate that this method is not only secure but also efficient in terms of computational resources, making it a suitable solution for real-world applications.

Through our research, we aim to contribute to the advancement of user authentication systems by incorporating cryptographic techniques, thus enhancing the overall security of web applications. This approach holds significant potential for scalable and secure applications, offering a safer alternative to conventional password-based methods. The cryptographic validation system enables secure user verification while minimizing the risk of exposing sensitive information, making it a promising solution for modern authentication requirements.

2. LITERATURE REVIEW

Passwordless authentication has gained significant attention as a solution to the vulnerabilities associated with traditional password-based systems. With increasing cyber threats, researchers have focused on developing authentication mechanisms that enhance security and user experience by eliminating the need for passwords. This literature survey reviews various approaches and methodologies in password less authentication, highlighting their advantages and challenges.

2.1 CRYPTOGRAPHIC APPROACHES

Cryptographic methods play a crucial role in password less authentication. Public Key Infrastructure (PKI) is foundational, utilizing asymmetric cryptography where users possess a private key stored locally and a public key shared with the server. This method enhances security by allowing authentication through digital signatures without exposing sensitive information (Menezes et al., 1996). Zero-knowledge proofs also offer a robust alternative, enabling one party to prove knowledge of a value without revealing the value itself, thus ensuring secure authentication (Goldwasser et al., 1985). Additionally, modular exponentiation is employed in challenge-response protocols, validating user credentials while maintaining password confidentiality (Katz & Lindell, 2014).

2.2 Biometric Authentication

Biometric methods have emerged as effective password less solutions, leveraging unique physical traits for user verification. Fingerprint recognition, for instance, has been successfully integrated into authentication systems, providing high security and user convenience (Jain et al., 2004). Facial recognition technologies, utilizing deep learning algorithms, demonstrate significant accuracy in user verification, further reducing reliance on passwords (Schroff et al., 2015). These biometric approaches not only enhance security but also improve user experience by simplifying the authentication process.

2.3 One-Time Passwords (OTPs) and Time-based Tokens

One-Time Passwords (OTPs) represent a dynamic alternative to static passwords, enhancing security through temporary codes sent to users via SMS or email. The Time-based One-Time Password (TOTP) algorithm generates unique codes based on the current time and a shared secret key, significantly reducing unauthorized access risks (Bellare et al., 2001). Furthermore, the FIDO (Fast Identity Online) Alliance has established standards for password less authentication using OTPs and biometric data, emphasizing user privacy and security across various platforms (FIDO Alliance, 2020).

2.4 Behavioral Biometrics

Behavioral biometrics analyze user behavior patterns, such as typing speed and mouse movement, to authenticate users. Keystroke dynamics offer a reliable security layer by analyzing unique typing patterns, providing continuous authentication (Kumar et al., 2014). Similarly, mouse movement analysis can serve as an additional authentication factor, enhancing security without the need for passwords (Bai et al., 2018). These methods not only improve security but also create a seamless user experience by eliminating traditional password requirements.

Despite advancements in passwordless authentication, several challenges persist. User acceptance remains a critical factor, as transitioning from traditional password systems requires education on the benefits of new technologies (Sasse et al., 2001). Privacy concerns surrounding biometric data usage also need to be addressed, ensuring that sensitive information is stored securely and ethically (Woodward et al., 2018). Additionally, integrating passwordless systems with legacy applications presents technical challenges that must be overcome for widespread adoption.

Passwordless authentication represents a promising solution for enhancing security in modern web applications. By leveraging cryptographic techniques, biometrics, and behavioral analysis, researchers are paving the way for more secure and user-friendly authentication mechanisms. Continued exploration of these technologies will contribute to the development of robust frameworks that meet the demands of contemporary digital environments.

3. SYSTEM ARCHITECTURE

3.1 Architecture of the System

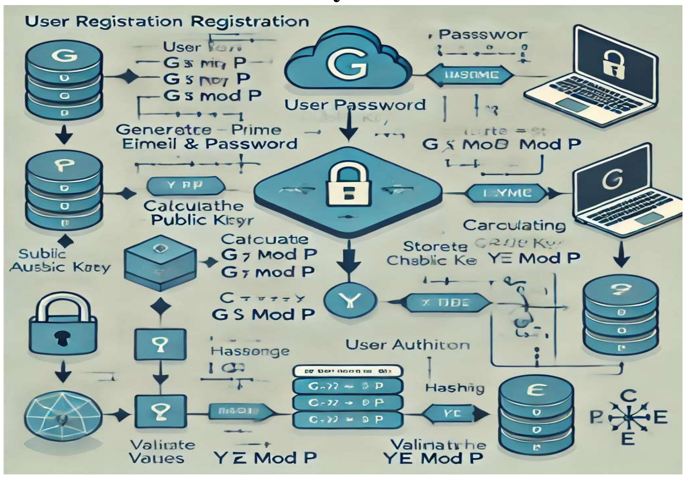


Figure-1 Architectural Diagram

The architecture of the secure authentication system is shown in **Figure 1**. The system operates with two main components: user registration and login verification. The registration process involves generating a public key for the user using their password and cryptographic methods, while the login process verifies the user based on cryptographic calculations.

3.1.1 REGISTRATION PROCESS

- **Input**: The user provides an email and a password.
- **Key Generation**: Two random prime numbers, **g** and **p**, are generated. The password is hashed and used as the private key **s**. A public key **y** is then calculated as y = g^s mod p and stored in the database.
- **Database Storage**: Only the public key **y**, along with **g** and **p**, is stored in MongoDB. The password itself is never stored.

3.1.2 LOGIN PROCESS

- **Input**: The user provides their email and password.
- **Verification**: The system retrieves **g**, **p**, and **y** from the database. A random number **r** is generated, and a challenge **c = g^r mod p** is computed. The system hashes **c** to produce **e**.
- **Validation**: The system computes a value **z = r + s * e mod p**, where **s** is the hashed password, and verifies if g^z mod p == c * y^e mod p. If the equation holds true, the user is authenticated.

3.2 Security Aspects

The key strength of this approach lies in the fact that the password is never directly involved in the verification process. Instead, only the public key and a series of cryptographic calculations are used, significantly reducing the attack surface for password-based breaches.

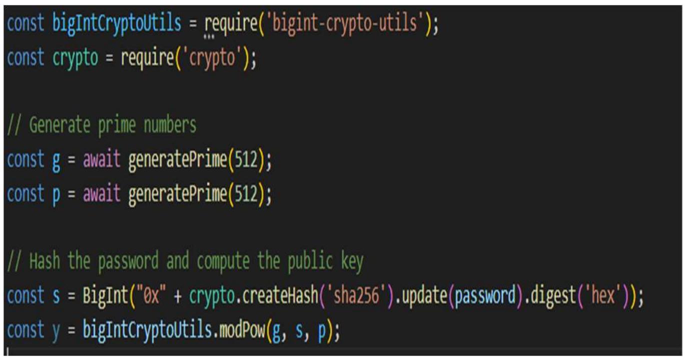
4. IMPLEMENTATION

4.1 BACKEND IMPLEMENTATION

The backend is built with Express.js, and MongoDB is used to store user data securely. The cryptographic operations are performed using Node.js's crypto module and the bigint-crypto-utils package for prime number generation and modular exponentiation.

4.1.1 KEY GENERATION

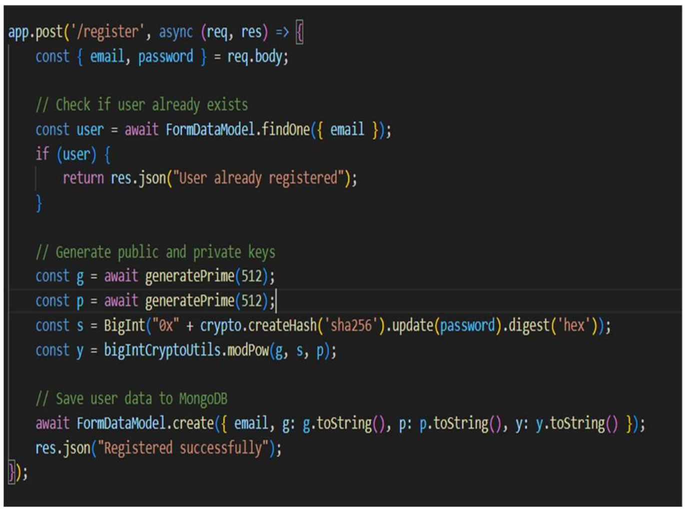
Prime numbers g and p are generated dynamically for each user. The user's password is hashed, and this hash serves as the private key s. The public key y is calculated using modular exponentiation as:



```
const bigIntCryptoUtils = require('bigint-crypto-utils');
const crypto = require('crypto');

// Generate prime numbers
const g = await generatePrime(512);
const p = await generatePrime(512);

// Hash the password and compute the public key
const s = BigInt("0x" + crypto.createHash('sha256').update(password).digest('hex'));
const y = bigIntCryptoUtils.modPow(g, s, p);
```

4.1.2 REGISTRATION ENDPOINT

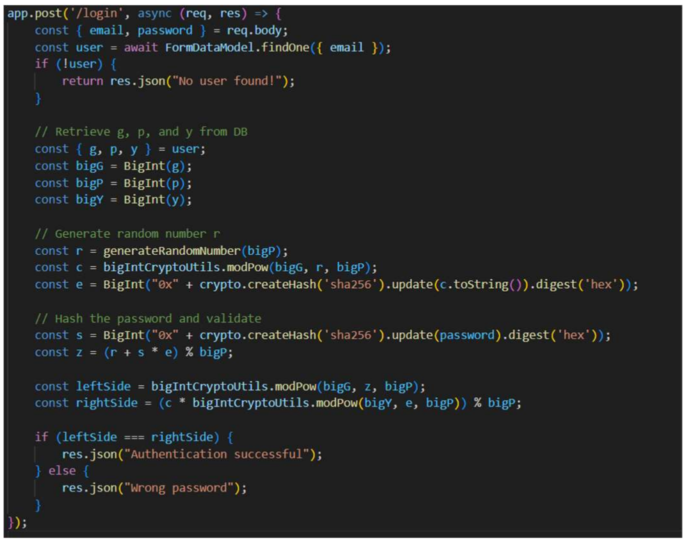
The registration endpoint saves g, p, and y in the MongoDB database:



```
app.post('/register', async (req, res) => {
    const { email, password } = req.body;

    // Check if user already exists
    const user = await FormDataModel.findOne({ email });
    if (user) {
        return res.json("User already registered");
    }

    // Generate public and private keys
    const g = await generatePrime(512);
    const p = await generatePrime(512);
    const s = BigInt("0x" + crypto.createHash('sha256').update(password).digest('hex'));
    const y = bigIntCryptoUtils.modPow(g, s, p);

    // Save user data to MongoDB
    await FormDataModel.create({ email, g: g.toString(), p: p.toString(), y: y.toString() });
    res.json("Registered successfully");
});
```

4.2 LOGIN ENDPOINT

In the login process, the system generates a random value **r**, computes the challenge **c**, and hashes it to produce **e**. The system then checks the validation:



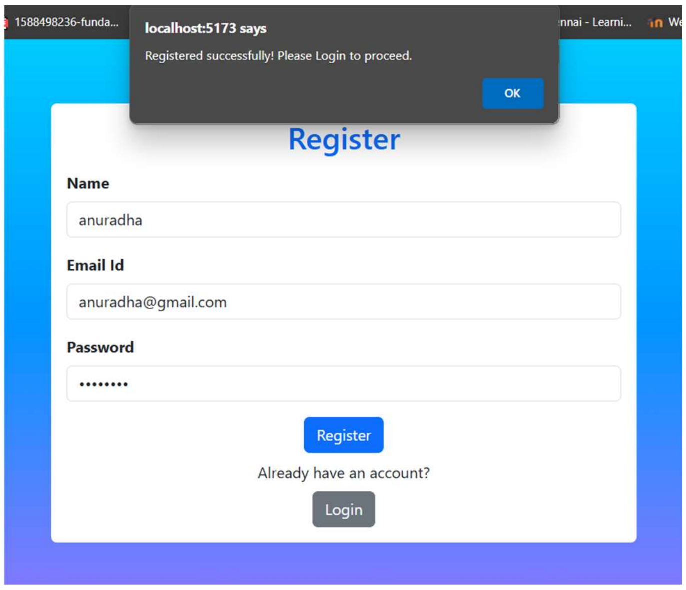
```
app.post('/login', async (req, res) => {
    const { email, password } = req.body;
    const user = await FormDataModel.findOne({ email });
    if (!user) {
        return res.json("No user found!");
    }

    // Retrieve g, p, and y from DB
    const { g, p, y } = user;
    const bigG = BigInt(g);
    const bigP = BigInt(p);
    const bigY = BigInt(y);

    // Generate random number r
    const r = generateRandomNumber(bigP);
    const c = bigIntCryptoUtils.modPow(bigG, r, bigP);
    const e = BigInt("0x" + crypto.createHash('sha256').update(c.toString()).digest('hex'));

    // Hash the password and validate
    const s = BigInt("0x" + crypto.createHash('sha256').update(password).digest('hex'));
    const z = (r + s * e) % bigP;

    const leftSide = bigIntCryptoUtils.modPow(bigG, z, bigP);
    const rightSide = (c * bigIntCryptoUtils.modPow(bigY, e, bigP)) % bigP;

    if (leftSide === rightSide) {
        res.json("Authentication successful");
    } else {
        res.json("Wrong password");
    }
});
```

5. RESULTS

To showcase the results we did a webpage which shows the outputs for secure authentication without storing password

5.1 REGISTRATION PROCESS RESULTS

During the registration phase, the system successfully generates the public key without storing the user's password. The system hashes the user's password using SHA-256 and computes the public key y through modular exponentiation. The public key, along with the prime numbers g and p, is securely stored in MongoDB, while the password remains confidential.


localhost:5173 says

Registered successfully! Please Login to proceed.

Figure 1

5.2 MONGODB STORAGE

The MongoDB database securely stores the public key y and cryptographic parameters g and p, ensuring no sensitive information like the password is stored in plaintext.

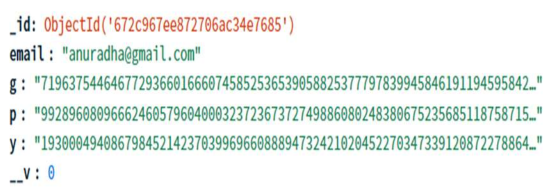
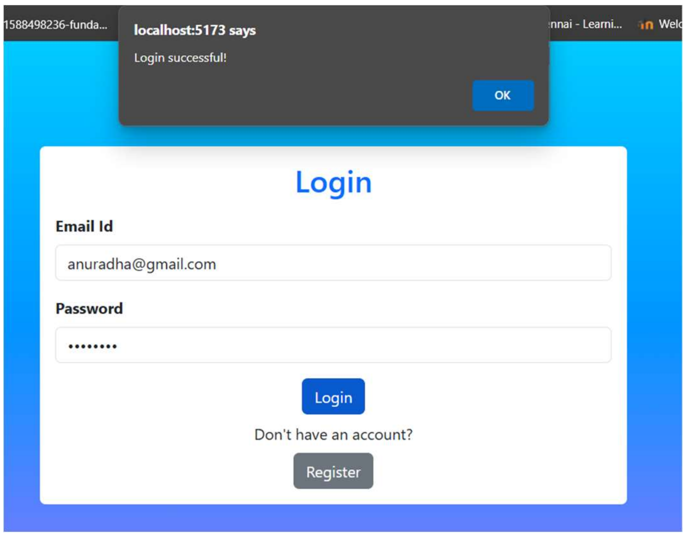

```
_id: ObjectId('672c967ee872706ac34e7685')
email : "anuradha@gmail.com"
g : "7196375446467729366016660745852536539058825377797839945846191194595842…"
p : "9928960809666246057960400032372367372749886080248380675235685118758715…"
y : "1930004940867984521423703996966088894732421020452270347339120872278864…"
__v : 0
```

Figure 2

5.3 LOGIN PROCESS RESULTS

During the login process, the system retrieves the public key and cryptographic parameters from MongoDB and uses modular arithmetic for the challenge-response validation. Successful login occurs when the user's credentials match


localhost:5173 says

Login successful!

Figure 3

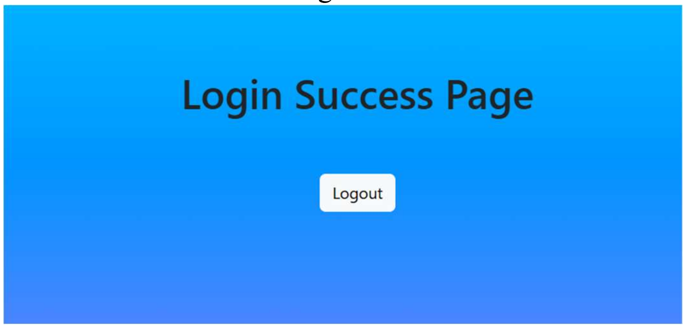
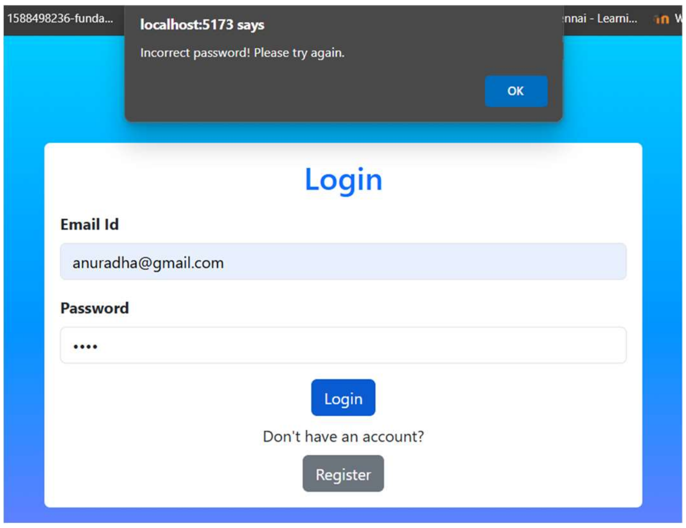


Figure 4

5.4 Incorrect Password Result

Incorrect password scenario, displaying the "Incorrect Password" error message.


localhost:5173 says

Incorrect password! Please try again.

Figure 5

6. CONCLUSION

In conclusion, the cryptographic authentication system presented in this paper, utilizing the MERN stack and key cryptographic techniques, proves to be a highly effective solution for secure user authentication. The system operates without storing passwords directly, instead relying on public key generation through modular exponentiation and hashing, ensuring better privacy and security. Through this approach, we have demonstrated the potential to reduce data breach risks while maintaining the integrity of the authentication process. The proposed method is efficient and scalable, offering a robust framework for modern web applications to enhance user security in digital environments.

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