# **Project Title:** Comparison of Encryption Algorithms and Password Hashing Techniques for Large-Scale Data

## Overview:

In this project, I evaluated the performance of several encryption algorithms and password hashing techniques across varying data sizes, focusing on their runtime for encryption, decryption, and password verification. With growing data sizes, especially in fields like cloud storage, secure communication, and large-scale computing, efficient encryption and password hashing are critical for security and performance.

The objective of this project is to compare different algorithms and understand how their encryption and decryption times scale with the data size, culminating with a 100GB dataset. The study includes both symmetric and asymmetric encryption algorithms along with commonly used password hashing algorithms.

## Real-World Application of the Problem:

In the digital age, where data breaches and cyberattacks are on the rise, encryption and password hashing techniques play a pivotal role in ensuring data security. Companies need to protect data at rest (in storage) and data in transit (during communication), especially when handling large amounts of sensitive information. This project mimics such real-world use cases, where various encryption algorithms are applied to datasets of increasing sizes, and password hashing is evaluated for secure storage of credentials.

Some real-world applications include:

- Cloud Storage Encryption: Encryption of large files stored in cloud environments to ensure data confidentiality.
- Secure Communication: Ensuring safe transmission of data across networks (e.g., messaging apps, email encryption).
- Database Security: Protecting sensitive data in databases, including customer data, financial records, and healthcare information.
- Password Management Systems: Securely hashing passwords for safe storage and verifying passwords during user authentication.

Encryption and decryption speed plays a critical role in ensuring the efficiency, scalability, and performance of various real-world systems. Here are several areas where the speed of these operations has a significant impact:

1. **Data Transfer and Communication**: Fast encryption/decryption is essential for minimizing latency in real-time communications, such as messaging, video conferencing, and VoIP.

2. **Cloud Storage and Backup**: Encryption speed affects how quickly large files can be uploaded to or downloaded from cloud storage systems, ensuring rapid backups and disaster recovery.
3. **Large File Transfers**: In services like streaming or file-sharing, the ability to encrypt and decrypt large files efficiently ensures smooth data transfers.
4. **Database Encryption**: For real-time applications or secure databases, the speed of encryption and decryption directly impacts system performance and query response times.
5. **Mobile and Embedded Devices**: Encryption algorithms must be fast and efficient, especially on devices with limited computational resources, such as smartphones and IoT devices.
6. **High-Volume Systems**: Large-scale systems, such as banking platforms and stock exchanges, require fast encryption to handle millions of transactions without bottlenecks.
7. **Secure Boot and Software Updates**: Encryption speeds are important for ensuring quick boot times and secure firmware updates in devices.
8. **Legal Compliance**: Encryption is often mandated by regulatory requirements (GDPR, HIPAA) to protect sensitive data. Speed is important to ensure compliance without performance trade-offs.
9. **Authentication Systems**: Password hashing speeds influence the user experience during login and authentication processes, ensuring that systems remain responsive.

In each of these areas, balancing encryption speed with security is essential. Slow encryption can lead to poor user experiences, system inefficiencies, and scalability challenges, while overly fast algorithms may compromise security.

## Results:

The results of the study show the performance of the following encryption algorithms:

- AES-GCM (Advanced Encryption Standard - Galois/Counter Mode)
- AES-CBC (Advanced Encryption Standard - Cipher Block Chaining)
- ChaCha20 (a fast stream cipher)
- Blowfish (a block cipher designed for speed)
- Triple DES (3DES) (Triple Data Encryption Standard)
- RSA+AES (Hybrid encryption, where RSA encrypts an AES key, and AES is used to encrypt data)

I measured both the encryption and decryption times for each algorithm at the following data sizes: 1KB, 1MB, 10MB, 100MB, 1GB, 10GB, and 100GB.

Key insights include:

- AES-GCM and ChaCha20 demonstrate efficient encryption for larger datasets, even as data sizes approach 1GB.

- AES-CBC shows relatively slower performance due to its block mode padding, especially for larger datasets.
- Triple DES and Blowfish, while secure, tend to perform slower than modern ciphers like AES and ChaCha20 as data sizes increase.
- RSA+AES (hybrid encryption) shows high efficiency for encrypting large data, leveraging the speed of AES and the security of RSA for key exchange.

Additionally, I evaluated the following password hashing algorithms for secure credential storage:

- Argon2
- bcrypt
- PBKDF2
- scrypt

Results from the hashing algorithms highlight the performance in terms of password hashing and verification times, where Argon2 and bcrypt offer balanced security and speed for password hashing and verification.

## Components:

The project consists of the following components:

1. Encryption Algorithms: AES-GCM, AES-CBC, ChaCha20, Blowfish, Triple DES, and Hybrid RSA+AES.
    - Functions to perform encryption and decryption.
    - Benchmarking code to measure encryption and decryption times for each algorithm across different data sizes.
    - Graphs to visually compare encryption and decryption times for each algorithm.
2. Password Hashing Techniques: Argon2, bcrypt, PBKDF2, scrypt, SHA-256, and SHA-3-256.
    - Functions to hash passwords and verify hashed passwords.
    - Benchmarking code to measure hashing and verification times.
    - Graphs to compare hashing and verification times for each technique.
3. Data Sizes: Data sizes ranging from 1KB to 1GB are used to test how each algorithm scales.
4. Plotting and Visualization:
    - Individual graphs showing encryption and decryption times for each algorithm at different data sizes.
    - Two final comparison graphs highlighting encryption and decryption times for all algorithms at the 1GB data size.

## Deliverables:

1. Python Script:
    - A fully functional Python script that benchmarks both encryption algorithms and password hashing techniques.
    - Includes functions for encryption, decryption, password hashing, and verification.
2. Visualization:
    - Graphs that show how each encryption algorithm performs for different data sizes.
    - Two final comparison graphs showing how encryption and decryption times vary for all algorithms at the 1GB data size.
3. Report:
    - A comprehensive project report (this document), including the project title, overview, real-world application, results, components, and deliverables.

**Literature Review:**

**Introduction**

Encryption and password hashing are fundamental components of modern cybersecurity. As digital data grows exponentially—driven by applications such as cloud storage, real-time communication, and large-scale databases—the efficiency of encryption and hashing algorithms becomes a critical concern. The speed of encryption and decryption, particularly for large datasets, influences the usability and performance of systems ranging from cloud computing environments to mobile devices and Internet of Things (IoT) ecosystems. This literature review explores recent research on encryption and password hashing techniques, focusing on their efficiency, scalability, and performance in handling large data volumes.

**Symmetric Encryption Algorithms**

Symmetric encryption algorithms like Advanced Encryption Standard (AES) and ChaCha20 are widely used due to their speed and efficiency, particularly for large datasets. AES is commonly used in modes such as Galois/Counter Mode (GCM) and Cipher Block Chaining (CBC). Research by Daemen and Rijmen [1], the inventors of AES, highlights the algorithm's robustness and adaptability in real-world applications. However, AES's performance is highly dependent on the mode of operation. AES-GCM, for instance, offers both encryption and integrity verification, making it faster and more suitable for environments like cloud storage where data integrity is crucial [2].

ChaCha20, developed by Bernstein [3], is noted for its efficiency on platforms that lack hardware acceleration for AES. Studies have shown that ChaCha20 outperforms AES in certain environments, particularly in mobile and low-power devices, due to its simplicity and ability to handle large data sizes without significant performance degradation [3].

Blowfish and Triple DES (3DES) are legacy encryption algorithms that, while still used in some systems, are considered less efficient for modern large-scale applications. Schneier [4] introduced Blowfish as a fast alternative to existing encryption methods, but as data sizes increase, its performance lags behind more contemporary ciphers like AES [4]. Similarly, 3DES, despite offering enhanced security through triple encryption, suffers from high computational overhead, particularly when handling large volumes of data [5].

**Asymmetric Encryption and Hybrid Models**

RSA, one of the most widely used asymmetric encryption algorithms, is typically too slow for encrypting large datasets directly. However, combining RSA with symmetric encryption in a hybrid encryption model—where RSA encrypts a symmetric AES key and AES handles the data—offers a balance between security and performance. Hybrid encryption is commonly used in SSL/TLS protocols to secure web traffic, as documented by Dierks and Rescorla [6]. In such hybrid schemes, the bulk of the data encryption is handled by faster symmetric algorithms like AES, while RSA secures the key exchange, making it feasible to handle large-scale encryption tasks.

**Password Hashing Techniques**

Password hashing is critical for securing stored credentials. Techniques such as Argon2, bcrypt, and PBKDF2 are designed to slow down attackers attempting to crack passwords through brute-force attacks. Argon2, the winner of the Password Hashing Competition (PHC) in 2015, is highly regarded for its ability to be configured to use both CPU and memory resources, making it resistant to hardware attacks like those executed on GPUs [7]. Research by Biryukov *et al.* [8] shows that Argon2 outperforms bcrypt and PBKDF2 in terms of both security and flexibility.

bcrypt, introduced by Provos and Mazières [9], is another commonly used password hashing algorithm that includes a salting mechanism to defend against rainbow table attacks. However, studies have shown that bcrypt may be vulnerable to certain attacks due to its reliance on Blowfish, which can be slower than more modern ciphers under specific conditions [4], [9].

PBKDF2 (Password-Based Key Derivation Function 2), recommended by the National Institute of Standards and Technology (NIST), is widely used for securing passwords and generating encryption keys [10]. However, it is considered less secure than Argon2 due to its vulnerability to hardware acceleration attacks. scrypt, designed to be memory-intensive, improves on PBKDF2 by resisting parallelization attacks, but research by Percival [11] suggests that scrypt's adoption is limited due to its relatively slower speed compared to bcrypt and Argon2 in common implementations.

**Encryption Speed and Real-World Applications**

In practical implementations, the speed of encryption and decryption becomes paramount, especially in high-throughput systems like cloud storage, streaming platforms, and secure communication channels. Fast encryption allows for seamless uploads, downloads, and real-time data access. According to Dworkin [2], AES-GCM is favored in real-world applications due to its ability to combine encryption with authentication, making it highly efficient for both securing data and ensuring integrity.

In the cloud computing domain, encryption efficiency is critical for achieving performance scaling as data volumes increase. Studies by Ali *et al.* [12] highlight how ChaCha20 and AES-GCM provide superior performance compared to older algorithms like Blowfish and 3DES in cloud environments. Similarly, for mobile and IoT devices, where computational resources are limited, ChaCha20 has been shown to outperform AES on platforms lacking hardware support for AES instructions, making it ideal for low-latency, resource-constrained environments [3].

## Challenges in Large-Scale Encryption

While encryption algorithms like AES and ChaCha20 are optimized for speed, real-world systems face challenges in maintaining both security and performance as data scales. Large-scale systems, such as database encryption and file storage systems, require algorithms that can encrypt and decrypt large datasets without introducing bottlenecks. Research suggests that even highly optimized algorithms like AES can suffer from performance degradation when dealing with big data if not properly implemented or accelerated [13]. Batch encryption approaches, discussed by Alomari *et al.* [13], suggest that parallelization of encryption tasks can significantly improve performance for large datasets.

## Conclusion

The literature reviewed suggests that encryption and password hashing algorithms play a vital role in ensuring the security of modern systems, but the choice of algorithm depends largely on the use case and data size. Symmetric algorithms like AES-GCM and ChaCha20 offer a combination of speed and security suitable for large-scale systems, while older algorithms like Blowfish and 3DES are less efficient for handling big data. For password hashing, Argon2 and bcrypt stand out as secure and efficient choices, particularly for preventing brute-force attacks. As the digital landscape continues to evolve, balancing encryption speed and security will remain a critical area of research, especially for high-volume systems and resource-constrained environments like mobile and IoT devices.

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