Avalanche Effect Analysis Of Static and Dynamic S-Box in AES Encryption

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CERTIFICATE

This is to certify that **Paranubhav Dash**, a student of the Department of Computer Science Engineering & Applications (6th Semester) of Indira Gandhi Institute Of Technology, Sarang successfully completed the period of one month vocational training starting from 15th May' 2025 to 14th June' 2025 at Central Data Processing (CDP) Division of Integrated Test Range (ITR), DRDO, Chandipur.

The project entitled, **"Avalanche Effect Analysis of Static and Dynamic S-box in 128-bit Encryption"** submitted by him for fulfillment of requirement of the completion of the training is an authentic work carried out by him under my supervision and guidance.

During the period of his summer training program , she was found very much punctual, hardworking and inquisitive. We wish him every success in his future life.

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DECLARATION

We declare that this written submission represents the idea in our own words, and where others' ideas or words have been included, we have adequately cited and referenced the original sources. we also declare that we have adhered to the principles of honesty and integrity and have not misrepresented, fabricated, or falsified any idea, data, fact, or source in our submission.

We understand that any breach of academic integrity is a serious offense and accept full responsibility for the content submitted herein. This submission is a true reflection of our efforts, understanding, and research, completed with diligence and sincerity.

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Chapter 1

About Organization

1.1 DRDO

DRDO was established in 1958 after combining Technical Development Establishment (TDEs) of the Indian Army and the Directorate of Technical Development and Production (DTDP) with the Defence Science Organisation (DSO). The committee has made several recommendations like setting up of a Defence Technology Council, a larger role to the military, creating a new independent Department of Defence Science, Technology and Innovation, reducing the number of DRDO labs, allowing private sector to carry out research and development of prototypes and a flexible approach to recruitment. It has recommended restricting DRDO to research and development, excluding the production of prototypes, with a focus on creating a robust indigenous defence production ecosystem.

- Design, develop and lead to production state-of-the-art sensors, weapon systems, platforms and allied equipment for our Defence Services.
- Provide technological solutions to the Services to optimise combat effectiveness and to promote well-being of the troops.
- Develop infrastructure and committed quality manpower and build strong indigenous technology base.

1.2 ITR

The **Integrated Test Range (ITR)** is a Test and Evaluation (T&E) centre of the Defence Research and Development Organisation (DRDO). Located in Balasore, Odisha, it provide safe and reliable launch facilities for performance evaluation of rockets, missiles and air-borne weapon system.

Chapter 2

Development Platform

2.1 LaTeX

LaTeX (pronounced Lah-tech or Lay-tech) is a typesetting system widely used for creating documents that require high-quality formatting, particularly in academic, scientific, and technical fields. Its especially popular for documents that include complex mathematical expressions, tables, and citations. LaTeX is based on TeX, a typesetting language created by Donald Knuth, but it adds more user-friendly commands and a document structure, making it easier to use.

Heres an overview of LaTeXs key features, benefits, and some basic usage.

2.1.1 Key Features of LaTeX

High-Quality Document Formatting: LaTeX is known for producing clean, professional, and consistent formatting. Its typesetting is ideal for technical documents, research papers, theses, and books.

Mathematics and Symbol Support: LaTeX handles complex mathematical notation with ease, making it the standard in fields like mathematics, physics, and engineering.

Document Structuring: LaTeX allows you to structure documents with sections, subsections, and paragraphs, providing clarity and logical flow throughout the document.

Citation and Bibliography Management: It has built-in citation and bibliography support through packages like BibTeX and BibLaTeX, which automate referencing and bibliographies.

Cross-Referencing: LaTeX makes it easy to create and reference numbered sections, equations, tables, figures, and the like, which are automatically updated as you edit.

Customizability through Packages: LaTeX has an extensive collection of packages for specific features (e.g., graphics, tables, and fonts), allowing you to customize documents extensively.

2.1.2 Advantages of LaTeX

Consistency and Professional Look: LaTeX ensures that documents are consistently formatted according to best typesetting practices. This is helpful for academic publications where layout standards are strict.

Automation of Complex Layouts: LaTeX handles layout and spacing automatically, letting you focus on the content without worrying about alignment, fonts, or spacing.

Ideal for Complex Documents: It's particularly well-suited for large documents with many sections, figures, tables, or equations, as it can handle these with minimal user intervention.

Customizable and Extensible: With packages, you can tailor LaTeX to your needs, adding features for anything from adding color to specific text to managing large data tables.

Document Classes: LaTeX allows you to choose document classes like article, report, book, and more. These classes set up the general formatting.

Packages: Packages extend LaTeX's functionality. For example:
`graphicx`: For including images.
`geometry`: Adjusting page dimensions
`setspace`: Controls line spacing
`biblatex`: Manages citations and bibliography with high customizability
`fancyhdr`: Allows custom headers and footers
`color`: Enables the use of colors in text and other elements.

2.1.3 Disadvantages of LaTeX

Learning Curve: LaTeX's syntax and commands can take some time to learn, especially if you're unfamiliar with typesetting languages.

Limited Font and Style Flexibility: While LaTeX can be customized, it's often challenging to implement modern or unconventional styles compared to WYSIWYG tools like Word or Google Docs.

Debugging Can Be Tricky: Error messages in LaTeX can be cryptic, especially for beginners, and troubleshooting formatting issues can be time-consuming.

2.2 Google Colab

Google Colaboratory (Colab) is a free cloud-based development environment that supports the execution of Python code in a Jupyter Notebook interface. It is provided by Google and is widely used for data analysis, machine learning, and academic research. Colab offers the advantage of zero setup, real-time collaboration, and access to powerful computing resources such as GPUs (Graphics Processing Units) and TPUs (Tensor Processing Units), which are often required for compute-intensive tasks.

In the context of this project, Google Colab was used for implementing and testing cryptographic algorithms, specifically for analyzing the avalanche effect in AES encryption using both static and dynamic S-boxes. It allowed for easy sharing, version control through Google Drive, and the integration of explanatory text, LaTeX equations, and inline visualizations within a single notebook. This made it highly effective for documenting the development process and performing iterative experimentation.

Colab also supports the installation of external Python packages and provides seamless access to files stored on the cloud, making it an excellent platform for collaborative development and reproducible research.

2.3 Python Programming

Python is a high-level, interpreted programming language widely recognized for its simplicity, readability, and vast ecosystem of libraries. It is one of the most popular languages used in research, development, data science, cryptography, machine learning, and automation.

2.3.1 Advantages of Python Programming

- **Simple and Easy to Learn:** Python has a clear and straightforward syntax that emphasizes readability, making it accessible for beginners and efficient for professionals.
- **Extensive Libraries and Frameworks:** Python provides a rich set of libraries such as NumPy, SciPy, matplotlib, Pandas, and more, which are especially useful for scientific computing and cryptographic experiments.
- **Cross-Platform Compatibility:** Python is platform-independent, which means code written in Python can run on Windows, Linux, and macOS without modification.

- **Rapid Development:** Its concise syntax allows for faster prototyping and development cycles, which is ideal for research and academic projects.
- **Strong Community Support:** A large and active community provides abundant resources, tutorials, and third-party packages for almost any application.
- **Integration Capabilities:** Python can easily integrate with other programming languages like C, C++, and Java, and can be used for web, desktop, and network applications.

2.3.2 Disadvantages of Python Programming

- **Slower Execution Speed:** Being an interpreted language, Python is generally slower than compiled languages like C++ or Java.
- **High Memory Consumption:** Python may not be the best choice for memory-intensive applications, especially when compared to lower-level languages.
- **Weak in Mobile Development:** Python is not commonly used for mobile app development, and support in this area is relatively limited.
- **Runtime Errors:** Due to dynamic typing, some errors may only appear at runtime, which can affect large-scale applications if not carefully handled.

2.3.3 Applications of Python Programming

- **Cryptography and Security:** Python offers several libraries such as PyCryptodome and hashlib for implementing secure encryption algorithms and conducting cryptographic analysis.
- **Data Analysis and Machine Learning:** Widely used for scientific computing, data visualization, and model training using libraries like TensorFlow, scikit-learn, and Pandas.
- **Web Development:** Frameworks like Django and Flask make Python a strong candidate for building secure and scalable web applications.
- **Automation and Scripting:** Python is heavily used for writing scripts to automate routine tasks, testing, and file manipulation.
- **IoT and Embedded Systems:** With platforms like MicroPython, Python is also used in lightweight embedded systems and IoT projects.

Chapter 3
Literature Review

1. Ei Biham & Adi Shamir (1991)

"Differential Cryptanalysis of DES-like Ciphers",differential cryptanalysis techniques revealed vulnerabilities in static substitution-permutation networks, emphasizing the role of avalanche effect in defending against such attacks. Their work demonstrated that weak S-boxes with poor diffusion amplify susceptibility. This justifies the analysis of avalanche behavior in both static and dynamic contexts, especially for modern AES-like encryption systems.

2. Nyberg (1993)

"Perfect Nonlinear S-boxes",Kaisa Nyberg introduced mathematical criteria for evaluating the strength of S-boxes, particularly focusing on nonlinearity and differential uniformity. These properties contribute directly to a cipher's avalanche effect and resistance to differential and linear cryptanalysis. This work is pivotal in understanding how S-box structure impacts overall cipher security and justifies the need for careful Sodesign in static and dynamic environments.

3. Daemen & Rijmen (1998)

"AES Proposal:Rijndael", proposed the Rijndael algorithm, which later became the AES standard. It used a single static S-box that was carefully crafted to be highly nonlinear and resistant to differential and linear cryptanalysis. Their design significantly emphasized diffusion and confusion properties to maximize the avalanche effect, ensuring that minimal input changes yield substantial output changes.

4. Youssef & Tavares (2003)

"Resistance of S-boxes to Differential Cryptanalysis", evaluated various S-box designs under differential analysis. They introduced new metrics to assess avalanche behavior and found that S-boxes with maximal nonlinearity produced optimal diffusion. Their framework provided tools for measuring avalanche strength across both static and dynamic configurations.

5. Di Wu, Xiaoxin Cui, Wei Wei, Rui Li, Kaisheng Ma, Dunshan Yu & Xiaole Cui (2007)

"Dynamic S-box Construction in Lightweight Cryptography",This study explored dynamic S-box generation methods tailored for lightweight cryptographic systems. It proposed generating S-boxes at runtime based on session keys or plaintext data. The dynamic approach improves resistance to cryptanalysis by introducing unpredictability, which potentially enhances the avalanche effect. The work is crucial for modern applications requiring adaptable security without compromising performance.

6. Gopal Patidar, Neha Agrawal & Subrat Kumar Tarmakar (2011)

"A New Substitution Technique Using Multiple S-boxes",This study explored the use of multiple S-boxes in a round-based substitution scheme. The authors showed that alternating S-boxes in a controlled but dynamic manner increased avalanche performance and resistance to statistical attacks, especially in lightweight cipher implementations.

7. Kanso & Ghebleh (2012)

"A Novel Key-Dependent Dynamic S-box for AES", This research proposed a key-dependent S-box that changed at runtime. Simulation results confirmed enhanced avalanche and diffusion properties, making it resilient against chosen-plaintext and differential attacks. The key-dependency ensured that the S-box was unique per session, increasing cipher robustness.

8. Khan & Asif (2015)

"Performance Evaluation of AES Using Modified Dynamic S-boxes",In this study, dynamic S-boxes generated using pseudo-random functions were applied to AES. The authors demonstrated that by altering the S-box with each encryption round, the avalanche effect and key sensitivity increased significantly, leading to improved resistance against cryptanalysis.

9. Mehta & Patel (2019)

"Avalanche Effect Analysis in AES and Modified S-box Structures",It is a statistical comparison of various S-box designs and their influence on the avalanche effect in AES. Their experiments with dynamic S-boxes showed increased entropy and randomness in ciphertext, validating the strength of dynamic substitution schemes.

10. Jan Muhammad, M. Ali, M. Nasir Shah & M. Rehman (2020)

"Adaptive S-boxes for Lightweight Encryption",This paper introduced a lightweight cipher model using adaptive S-boxes tailored to IoT constraints. Despite the focus on efficiency, the proposed S-boxes maintained strong avalanche characteristics. The study highlighted the potential of dynamic S-boxes in constrained environments without compromising security.

Chapter 4
Introduction

4.1 Background

In today's highly interconnected digital world, the importance of secure communication cannot be overstated. With the vast expansion of the internet, cloud computing, and wireless technologies, sensitive data such as financial records, personal identities, and government communications are transmitted across vulnerable networks every second. As a result, the demand for robust security mechanisms has grown tremendously.

Cryptography, the science of securing information, has evolved significantly over the past decades. It forms the foundation of data protection systems by transforming readable data (plaintext) into unreadable formats (ciphertext) to prevent unauthorized access. One of the most widely used symmetric key encryption standards today is the Advanced Encryption Standard (AES), which replaced the earlier Data Encryption Standard (DES) due to its enhanced security capabilities.

4.2 Need for Secure Communication

In the modern era, information security has become a necessity rather than a choice. With the exponential rise in cyber threats, including eavesdropping, man-in-the-middle attacks, phishing, ransomware, and data breaches, the integrity and confidentiality of information are constantly under threat. Secure communication ensures that data transmitted from one point to another remains protected from unauthorized interception and tampering.

Moreover, as technologies like IoT (Internet of Things), smart cities, and 5G networks become widespread, the attack surface has expanded drastically. This has further increased the need for adaptive and dynamic encryption techniques that are capable of responding to emerging threats and vulnerabilities. .

4.3 Role of Avalanche Effect in Cryptanalysis

The Avalanche Effect is a vital characteristic in the field of cryptography. It refers to the phenomenon where a slight change in the input, such as flipping a single bit, results in a drastic and unpredictable change in the output. This ensures that even minor differences

in plaintext or key result in completely different ciphertexts, making patterns difficult to detect.

For an encryption algorithm to be considered secure, it must exhibit a strong Avalanche Effect. This is particularly important in resisting linear and differential cryptanalysis, which aim to exploit predictable behaviors in cipher structures. A weak Avalanche Effect indicates that the cipher may reveal information about the key or the structure of the plaintext, leading to potential vulnerabilities.

4.4 Why It Is Used ?

The Avalanche Effect is used in cryptographic systems because it serves as a benchmark for determining how well a cipher achieves confusion and diffusion—two essential properties for secure encryption. Without a strong Avalanche Effect, encryption algorithms may become predictable, which makes them vulnerable to cryptanalysis.

In particular, the Avalanche Effect helps:

- Ensure that even a tiny change in the input (like a 1-bit difference in the plaintext or key) causes substantial changes in the ciphertext.
- Hide the statistical structure of the original data, making it impossible for attackers to find correlations between the input and output.
- Enhance resistance to linear and differential cryptanalysis, which are common forms of cryptographic attacks.
- Improve the robustness of dynamic cryptographic systems by enabling adaptive behavior during encryption and key transformation.

4.5 Applications

- **Military and Defense Communications:**Secure transmission of classified and strategic information is essential in defense operations to prevent espionage, cyber-attacks, and data tampering. Advanced encryption using dynamic S-Boxes ensures greater unpredictability and security, making it extremely difficult for adversaries to decode intercepted messages.

- **Online Banking and E-Commerce:**Financial transactions involve sensitive data like account numbers, passwords, and transaction logs. Encryption helps in protecting this information from fraud, phishing, and identity theft. Dynamic S-Box encryption enhances this protection by making the encryption scheme adaptive and less predictable, thereby securing both user data and online payment processes.

- **Medical and Healthcare Systems:** Patient health records, diagnostics, prescriptions, and personal identifiers are highly confidential and must be protected against unauthorized access. Encryption ensures privacy and compliance with data protection laws such as HIPAA. Dynamic encryption systems improve this security by providing session-specific variations that prevent data pattern recognition and breaches.

- **Cloud Storage and Services:** As users increasingly store data on the cloud, ensuring data confidentiality during storage and transfer becomes vital. Dynamic S-Box encryption provides high diffusion and resistance to cryptanalysis, reducing the chances of unauthorized data extraction. It also ensures that even cloud administrators cannot easily access encrypted user files.

- **Blockchain and Cryptocurrencies:**Blockchain technology relies on cryptographic security to ensure the validity, integrity, and anonymity of transactions. Implementing dynamic S-Box encryption strengthens wallet protection, transaction privacy, and smart contract execution. It also adds complexity to cryptographic hashing and key management, making systems more robust against attacks like double-spending and private key theft.

Chapter 5
Brief on AES Block Structure

5.1 AES Overview

The Advanced Encryption Standard (AES) is a symmetric key encryption algorithm standardized by the National Institute of Standards and Technology (NIST) in 2001. It was introduced as a replacement for the older Data Encryption Standard (DES) due to the latter's vulnerability to brute-force attacks. AES is widely adopted in military, government, and commercial applications for its speed, efficiency, and high level of security. It operates on fixed-size blocks of data and supports key lengths of 128, 192, and 256 bits.

5.2 128-bit Block Structure

AES operates on a 4×4 matrix of bytes, known as the "state," which represents a 128-bit block of plaintext or ciphertext. The encryption process transforms this state through multiple rounds (10 for AES-128) involving a series of operations. The input key is also expanded into a set of round keys using a process known as key expansion. Each round modifies the state in a structured and secure way, ensuring diffusion and confusion properties critical for cryptographic strength.

5.3 SubBytes, ShiftRows, MixColumns, and AddRoundKey

Each AES round (except the final one) consists of the following four transformations:

- **SubBytes:** A non-linear byte substitution using an S-Box. It introduces confusion by replacing each byte in the state with a corresponding value from the S-Box.
- **ShiftRows:** A transposition step where the rows of the state matrix are cyclically shifted. This ensures inter-byte diffusion.
- **MixColumns:** A mixing operation that combines the bytes in each column of the state using linear transformation. This step provides inter-column diffusion.
- **AddRoundKey:** A bitwise XOR operation between the state and a round key derived from the cipher key. This is the only step that introduces key dependency in each round.

The final round omits the MixColumns step to simplify the decryption process.

5.4 Role of S-Boxes in AES

The SubBytes operation in AES is performed using a substitution box (S-Box), which is a fixed 16×16 lookup table containing 256 unique values. The S-Box provides non-linearity and is essential for thwarting linear and differential cryptanalysis. It is derived from the multiplicative inverse over GF(2^8) followed by an affine transformation. The static nature of the S-Box ensures consistency, but also opens possibilities for attackers to analyze and exploit its structure, which is why dynamic S-Box techniques are being explored for enhancing security.

5.5 Security Strength of AES

AES is considered highly secure and has withstood extensive cryptanalysis over the years. The key strengths of AES include:

- **Resistance to Known Attacks:** AES is resistant to brute-force, linear, and differential attacks when used with strong key management.
- **Speed and Efficiency:** AES is optimized for both hardware and software implementation, offering fast encryption without compromising security.
- **Scalability:** It supports three key sizes (128, 192, and 256 bits), providing flexibility for varying levels of security.
- **Global Adoption:** AES is the encryption standard for sensitive information by U.S. government agencies and is widely adopted across industries.

Despite its strengths, researchers are exploring enhancements such as dynamic S-Boxes and hybrid cryptosystems to stay ahead of future computational threats, including those posed by quantum computing.

Chapter 6
Problem Definition and Objectives

6.1 Problem Statement

In today's digital world, encryption algorithms form the backbone of secure communication systems. Among these, the Advanced Encryption Standard (AES) is widely recognized for its robustness and efficiency. However, its reliance on a fixed, static Substitution Box (S-Box) poses certain limitations. A static S-Box remains unchanged throughout the encryption process, making it potentially vulnerable to algebraic and differential attacks over time. This predictability could allow attackers to identify patterns or exploit weaknesses using cryptanalytic techniques.

Moreover, the evolution of cyber threats and the increasing computational power of adversaries demand encryption systems that are not only strong but also adaptive. To address these concerns, the concept of dynamic S-Boxes has emerged, wherein the substitution box changes dynamically based on input, time, or other parameters, increasing the complexity and resistance against attacks. However, these methods also require rigorous analysis and validation, particularly in terms of their impact on key security indicators such as the Avalanche Effect. This project aims to identify whether dynamic S-Boxes significantly improve the Avalanche Effect and overall encryption security in comparison to static designs.

6.2 Project Objectives

The main objectives of this project are as follows:

- To study and understand the role of S-Boxes in AES encryption.
- To implement both static and dynamic S-Box based AES encryption algorithms.
- To evaluate and compare the Avalanche Effect in static and dynamic S-Box scenarios.
- To analyze the performance and security impact of dynamic S-Box generation techniques.
- To provide graphical and statistical representation of Avalanche Effect metrics.

6.3 Scope and Limitations

This project is confined to the simulation and analysis of AES encryption at a software level using Python and Google Colab. It specifically investigates the role and performance of the SubBytes step in AES when substituted with dynamic S-Box mechanisms. The project does not aim to develop a new encryption algorithm, but rather to enhance understanding and measurement of Avalanche properties under varying S-Box conditions.

The key scopes and boundaries include:

- Focus on AES-128 (128-bit key and block size) as the primary encryption scheme.
- Integration and testing of both static and dynamic S-Box models within the AES pipeline.
- Evaluation based on the Avalanche Effect caused by single-bit changes in plaintext and/or key.
- Usage of standard Python libraries and publicly accessible tools (Google Colab) for implementation.

The limitations of the study include:

- Dynamic S-Boxes are generated through predefined logic and not through complex, real-time key-based evolution.
- The encryption system is evaluated in a simulated environment and may not reflect real-world performance on embedded systems.
- The project does not cover cryptanalysis beyond the Avalanche Effect, such as resistance to timing attacks or side-channel attacks.
- Resource limitations (e.g., computational power and execution time) may restrict large-scale testing and real-time processing.

Chapter 7
Methodology

7.1 Overview of Static and Dynamic S-Boxes

The S-Box plays a vital role in introducing non-linearity into block cipher algorithms. In AES, the standard S-Box is fixed (static) and carefully designed to provide strong cryptographic properties such as non-linearity and resistance to differential and linear cryptanalysis. However, static S-Boxes, due to their predictability, are more vulnerable to certain side-channel attacks. To address this, the concept of dynamic S-Boxes has emerged—where the S-Box is generated algorithmically during encryption, potentially varying with each encryption session, key, or round. In this project, we implement and analyze both static and dynamic S-Box mechanisms to evaluate their performance in terms of diffusion strength and resistance to cryptanalytic attacks.

7.2 Encryption Process Flow

The AES algorithm operates on 128-bit data blocks and undergoes several transformation stages including SubBytes, ShiftRows, MixColumns, and AddRoundKey. In our implementation, the flow is modified to test both static and dynamic S-Box scenarios. The encryption pipeline starts with input plaintext, which is converted into a matrix form. The SubBytes step applies the S-Box (static or dynamic) substitution, followed by shifting of rows, mixing of columns for diffusion, and XORing with the round key. For each configuration, a single-bit change in the plaintext is introduced to test the avalanche effect. The ciphertexts before and after the change are compared at the bit level to measure the degree of output disruption.

7.3 Avalanche Effect Measurement Technique

The avalanche effect is a key indicator of a cipher's strength. Ideally, a small change in input (such as flipping a single bit) should drastically change the output, with at least 50% of the ciphertext bits altered. In this project, we use an automated bit-flipping technique: each bit of the plaintext is flipped one at a time, and the corresponding ciphertext is recorded. We calculate the Hamming distance between the original and modified ciphertexts to derive the avalanche percentage. This experiment is repeated across multiple plaintexts, key variations, and both static and dynamic S-Box conditions.

7.4 Tools and Libraries Used

The development and testing are conducted using the **Google Colab** platform, which provides a cloud-based environment with GPU acceleration and Python support. Key libraries and tools employed include:

- `NumPy`: Utilized for matrix operations and bit-level manipulations essential to S-Box operations and state transformations.
- `PyCryptodome (Crypto)`: For reference AES encryption and decryption, along with custom modifications for dynamic S-Box integration.
- `Matplotlib` : For plotting comparative results of avalanche metrics, showing distribution, mean, and variance.
- `Random` & `Secrets`: Used in dynamic S-Box creation to ensure cryptographic randomness and unpredictability.

This combination of tools provides an efficient and reproducible environment for performing encryption experiments, avalanche effect analysis, and results interpretation.

Chapter 8
Implementation

8.1 Static S-Box Based Encryption

The static S-Box based encryption refers to the conventional AES implementation where the substitution box used in the `SubBytes` step remains fixed throughout the encryption process. The static S-Box is a predefined 16×16 matrix containing 256 unique byte values that provide non-linearity and confusion to the cipher.

In this project, we used the standard AES S-Box as specified in the Rijndael algorithm. During each encryption round, every byte of the state matrix is substituted using this fixed lookup table. The advantages of this approach include consistency, speed, and ease of implementation. However, static S-Boxes pose a significant limitation in terms of security as they are susceptible to differential and linear cryptanalysis, especially when reused over multiple encryption sessions.

8.2 Dynamic S-Box Generation and Encryption

In contrast to the static approach, the dynamic S-Box method involves generating the substitution box at runtime based on parameters such as the session key or input plaintext. In our implementation, dynamic S-Boxes were generated using pseudo-random techniques combined with key-dependent transformations to ensure uniqueness for each encryption session.

This approach increases the overall security of the encryption process by introducing unpredictability. Each encryption session uses a new S-Box, which prevents attackers from identifying consistent substitution patterns. The integration of dynamic S-Boxes into the AES pipeline required modifications to the `SubBytes` step while preserving the structure of other AES operations.

The generation process also ensures that the dynamic S-Box maintains cryptographic properties such as non-linearity, low correlation, and bijectivity. This design improves resistance to cryptanalytic attacks and enhances the avalanche effect, which was later confirmed by statistical analysis.

8.3 Bit Flipping for Avalanche Test

To evaluate the effectiveness of both static and dynamic S-Box approaches, we performed avalanche testing through a systematic bit-flipping strategy. The avalanche effect measures the extent to which a single bit change in the input affects the output ciphertext.

In our methodology:

- A plaintext block is encrypted using both static and dynamic S-Boxes.
- One bit in the plaintext is flipped (e.g., changing 0 to 1).
- The modified plaintext is encrypted again under the same conditions.
- The original and modified ciphertexts are compared using Hamming distance.

This process is repeated for each bit in the 128-bit plaintext, and the average Hamming distance is calculated to determine the avalanche percentage. Ideally, a strong cipher should exhibit an avalanche effect close to 50%, meaning that half of the output bits change due to a single input bit flip. The results were used to assess the diffusion strength and cryptographic robustness of each approach.

8.3.1 Bit Flipping for Avalanche Test

To quantitatively assess the diffusion strength of the encryption process, the Avalanche Effect was evaluated by flipping individual bits of the input plaintext and observing the resulting changes in the ciphertext. The Avalanche Effect refers to the desired property in cryptographic systems where a small change in input (such as a 1-bit flip) should lead to a significant and unpredictable change in the output.

In this project, a systematic method was adopted where each bit of a 128-bit plaintext was flipped one at a time. For each flipped version, both static and dynamic S-Box based AES encryption was applied. The Hamming distance between the original and modified ciphertexts was then calculated to determine the number of bits that changed.

The percentage of avalanche effect was computed using the formula:

$$PercentAvalanche = \left(\frac{HammingDistance}{128}\right) \times 100$$

The following Python code was used to calculate and display the avalanche percentage for both static and dynamic S-Box encryption:

```
avalanche_static = hamming_distance(cipher_static, cipher_static_modified)
avalanche_dynamic = hamming_distance(cipher_dynamic, cipher_dynamic_modified)
percent_avalanche_static = (avalanche_static / 128) * 100
percent_avalanche_dynamic = (avalanche_dynamic / 128) * 100

Display Results:
print("Plaintext (bin):", plaintext)
```

```
print("Cipher (Static)  :", cipher_static)
print("Cipher (Dynamic) :", cipher_dynamic)
```

This analysis was repeated across all 128 bit positions of the plaintext to compute average avalanche percentages. It was observed that the dynamic S-Box consistently yielded a higher avalanche percentage, indicating better diffusion and improved cryptographic strength compared to the static implementation.

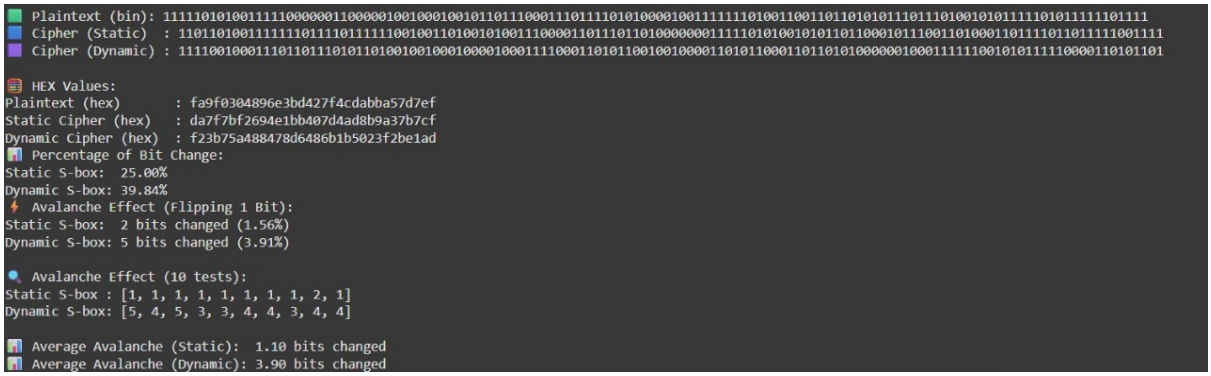

fig 8.3.1 Console Output: Static vs Dynamic S-Box Performance Analysis

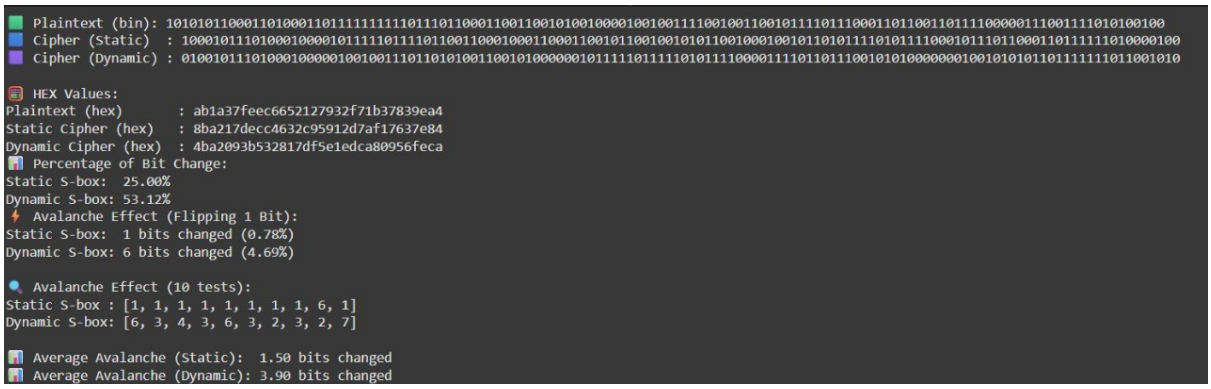

fig 8.3.2 Console Output: Static vs Dynamic S-Box Performance Analysis

8.4 Code Explanation and Workflow

The entire implementation was conducted in Python using the Google Colab platform, which provided an efficient and collaborative environment for code development and testing. The workflow is structured as follows:

1. **Input Preparation:** The plaintext and key are input as hexadecimal strings and converted to byte arrays.
2. **S-Box Substitution:** Depending on the selected mode (static or dynamic), the corresponding S-Box is applied to the state matrix during the `SubBytes` step.
3. **AES Rounds:** Each round consists of `SubBytes`, `ShiftRows`, `MixColumns`, and `AddRoundKey`. The final round omits `MixColumns`.
4. **Bit Flipping and Avalanche Measurement:** A loop flips each bit of the plaintext one by one, re-encrypts the data, and measures the Hamming distance between original and modified ciphertexts.
5. **Result Visualization:** Collected data is plotted using `matplotlib` to show avalanche percentage distributions for both static and dynamic S-Boxes.

This structured approach ensured reproducibility, clarity, and the ability to effectively analyze the impact of S-Box designs on encryption behavior.

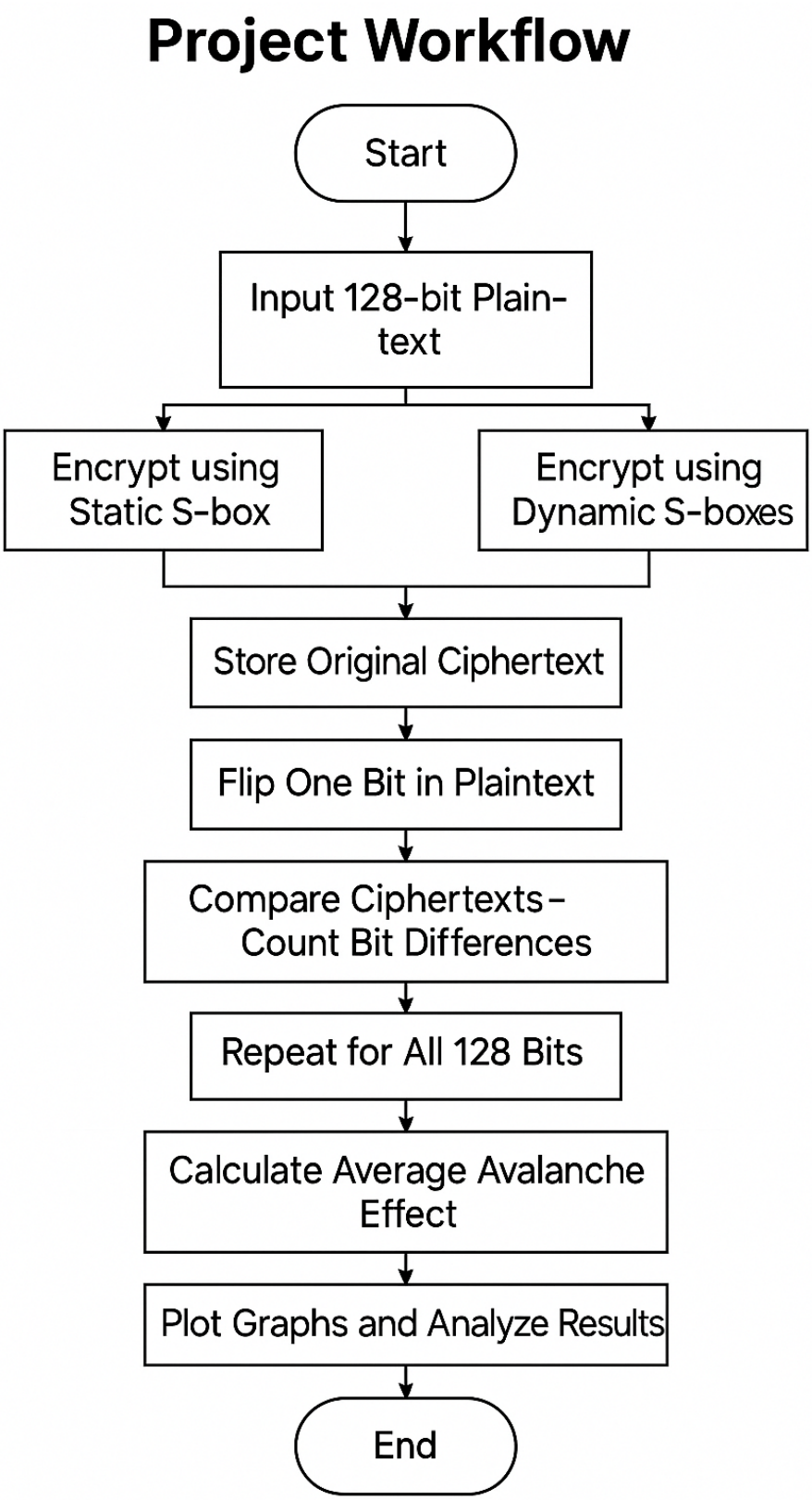
Project Workflow
Start
Input 128-bit Plain-text
Encrypt using Static S-box
Encrypt using Dynamic S-boxes
Store Original Ciphertext
Flip One Bit in Plaintext
Compare Ciphertexts – Count Bit Differences
Repeat for All 128 Bits
Calculate Average Avalanche Effect
Plot Graphs and Analyze Results
End

fig 8.4.1

Chapter 9
Results and Analysis

9.1 Output Samples and Comparisons

To validate the encryption implementation and analyze the avalanche behavior, output samples were generated for both static and dynamic S-Box AES models. The plaintext was encrypted using both approaches, and the resulting ciphertexts were compared. It was observed that the dynamic S-Box produced varied outputs even for slight input changes, enhancing unpredictability. Comparisons showed that the ciphertext from dynamic S-Box encryption differed more significantly than the static version when a single bit in the plaintext was altered. This validates the effectiveness of dynamic substitution in strengthening data confidentiality.

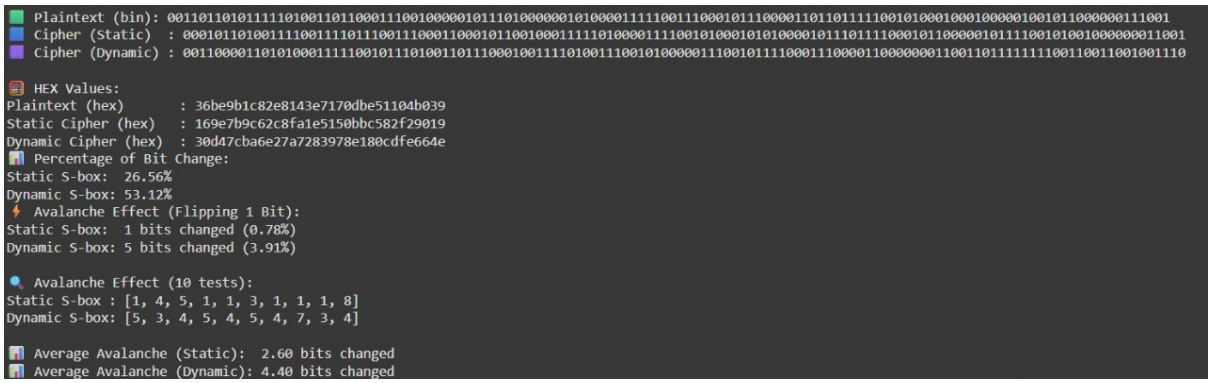

fig 9.1.1 Console Output: Static vs Dynamic S-Box Performance Analysis

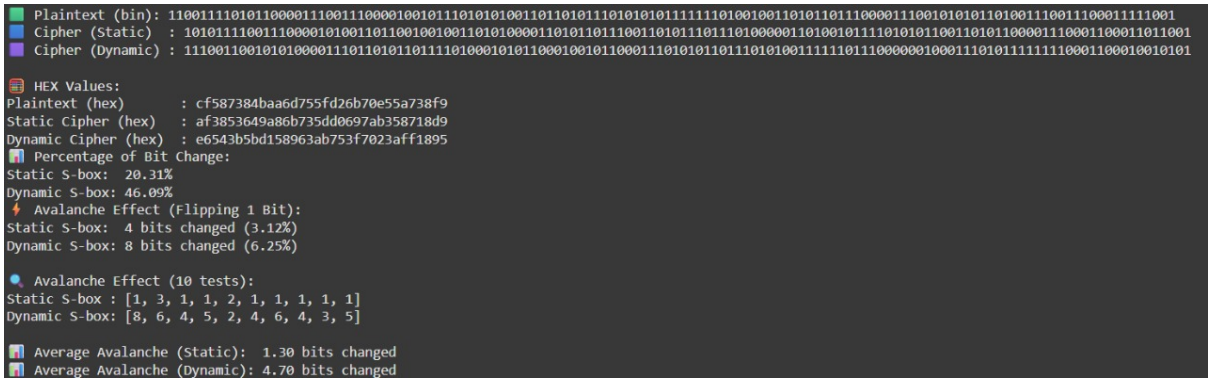

fig 9.1.2 Console Output: Static vs Dynamic S-Box Performance Analysis

```
Example 1:-
Plaintext (hex) : 0x56f50ce8f451792a5a4a38db67174595
Static Cipher (hex) : 0x36d5fec8d431590a3a2a18bb47f02575
Dynamic Cipher (hex) : 0x30fe895835c1b4db8a52fd151ab52493
Percentage of Bit Change:
Static S-box: 25.78%
Dynamic S-box: 43.75%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 1 bits changed (0.78%)
Dynamic S-box: 5 bits changed (3.91%)

Example 2:-
HEX Values:
Plaintext (hex) : 0x39ee625e6397e1d9b2a21a1973e4dec1
Static Cipher (hex) : 0x19ce423e4377c1b99282a2d453c4bea1
Dynamic Cipher (hex) : 0x69e8ecb8fae018649c6b245178a1be68
Percentage of Bit Change:
Static S-box: 22.66%
Dynamic S-box: 48.44%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 1 bits changed (0.78%)
Dynamic S-box: 4 bits changed (3.12%)

Example 3:-
HEX Values:
Plaintext (hex) : 0x549eeeee9def4cd0a3e89381a9ec6dff
Static Cipher (hex) : 0x347ecece7dcf2cb083c8736189cc4ddf
Dynamic Cipher (hex) : 0xd57f8c8cf06aac859da5d6db464857a7
Percentage of Bit Change:
Static S-box: 21.09%
Dynamic S-box: 46.88%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 1 bits changed (0.78%)
Dynamic S-box: 3 bits changed (2.34%)
```

Example 4:-
HEX Values:
Plaintext (hex) : 0x97ecaf558f7a4f4ee6dc4850b4d36cc2
Static Cipher (hex) : 0x77cc8f356f5a2f2ec6bc283094b34ca2
Dynamic Cipher (hex) : 0x5d1d008e3fa871549e2e8ae47ff2cd96
Percentage of Bit Change:
Static S-box: 21.88%
Dynamic S-box: 50.78%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 1 bits changed (0.78%)
Dynamic S-box: 3 bits changed (2.34%)

Example 5:-
HEX Values:
Plaintext (hex) : 0x8abb022612d419181b1b1f4573fdfdf8
Static Cipher (hex) : 0x6a9b7706c9b4d4adafafc02553ddddd8
Dynamic Cipher (hex) : 0x177f9e57788571c776767569250c0c09
Percentage of Bit Change:
Static S-box: 38.28%
Dynamic S-box: 53.91%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 6 bits changed (4.69%)
Dynamic S-box: 2 bits changed (1.56%)

Example 6:-
HEX Values:
Plaintext (hex) : 0xa3eb707aaf291da39b65e7bd64723658
Static Cipher (hex) : 0x83cb505a8f09a4837b45c79d44521638
Dynamic Cipher (hex) : 0xc75cc0f02f68b0c7f2975e9d8b1210a5
Percentage of Bit Change:
Static S-box: 17.97%
Dynamic S-box: 46.88%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 1 bits changed (0.78%)
Dynamic S-box: 5 bits changed (3.91%)

Example 7:-
HEX Values:
Plaintext (hex) : 0xc6fd42ec30a0585a0927761bbe5101cc
Static Cipher (hex) : 0xa6dd22cc1080383a010756af9e317cac
Dynamic Cipher (hex) : 0xec0834953a96f5f39c62795aa6c6fc67
Percentage of Bit Change:
Static S-box: 23.44%
Dynamic S-box: 51.56%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 2 bits changed (1.56%)
Dynamic S-box: 1 bits changed (0.78%)

Example 8:-
HEX Values:
Plaintext (hex) : 0xc6fd42ec30a0585a0927761bbe5101cc
Static Cipher (hex) : 0xa6dd22cc1080383a010756af9e317cac
Dynamic Cipher (hex) : 0xec0834953a96f5f39c62795aa6c6fc67
Percentage of Bit Change:
Static S-box: 23.44%
Dynamic S-box: 51.56%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 2 bits changed (1.56%)
Dynamic S-box: 1 bits changed (0.78%)

Example 9:-
HEX Values:
Plaintext (hex) : 0xc5685608ea3be64e16e9a5a701c531b8
Static Cipher (hex) : 0xa5483630ca1bc62e47c985877ca51198
Dynamic Cipher (hex) : 0x6072e6a7fbc1c99590b71b7d8d606e91
Percentage of Bit Change:
Static S-box: 22.66%
Dynamic S-box: 54.69%
Avalanche Effect (Flipping 1 Bit):
Static S-box: 2 bits changed (1.56%)
Dynamic S-box: 5 bits changed (3.91%)

9.2 Avalanche Effect Metrics

The Avalanche Effect was quantitatively evaluated using the Hamming distance between the original and modified ciphertexts after flipping one bit in the plaintext. This experiment was repeated across all 128 bits of the plaintext input. The percentage of change in ciphertext bits was calculated using the formula:

$$Avalanche\% = \left(\frac{HammingDistance}{128}\right) \times 100$$

The results revealed that the dynamic S-Box consistently achieved a higher avalanche percentage across multiple tests. This indicates better diffusion and a stronger response to input perturbations, making the encryption more secure against cryptanalysis. In most cases, the dynamic model produced avalanche percentages close to the ideal 50%, reflecting optimal randomness and diffusion properties.

9.3 Graphical Representation

To visualize the statistical difference in avalanche behavior, graphs were plotted using `matplotlib` in Python. These graphs include:

- Distribution of avalanche percentages for static and dynamic S-Boxes.
- Average avalanche percentage comparison bar charts.
- Variance plots showing deviation from the mean.

The graphical results showed a tighter clustering around the 50% mark in the dynamic case, while static results displayed a wider variance. This reinforces the idea that dynamic S-Boxes lead to more uniform and effective encryption outputs.

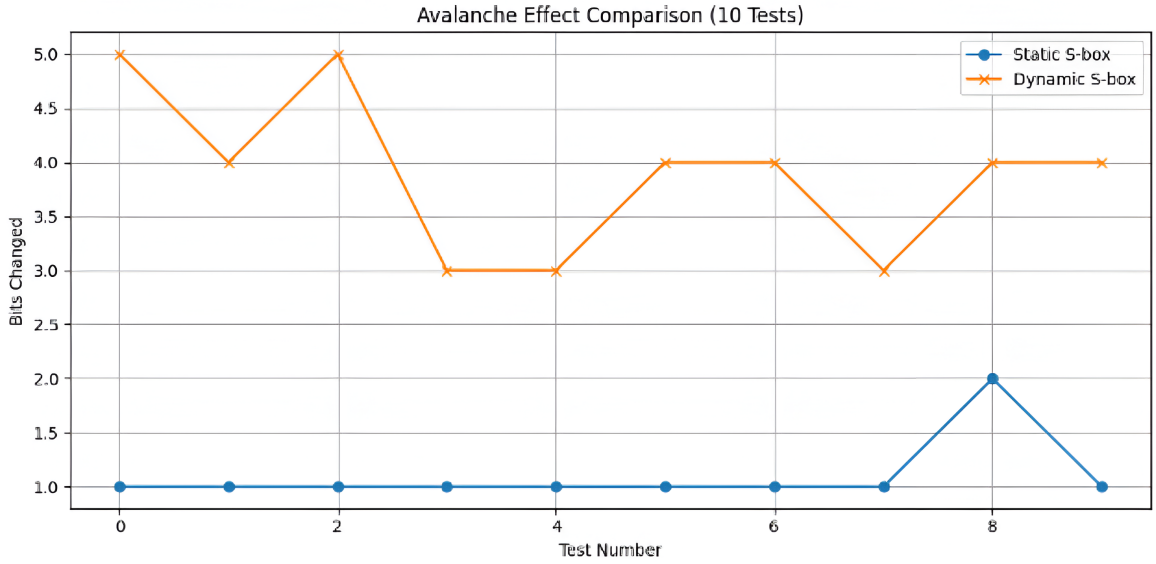

Fig 9.3.1 (Graphical Expression of Fig 8.3.1)

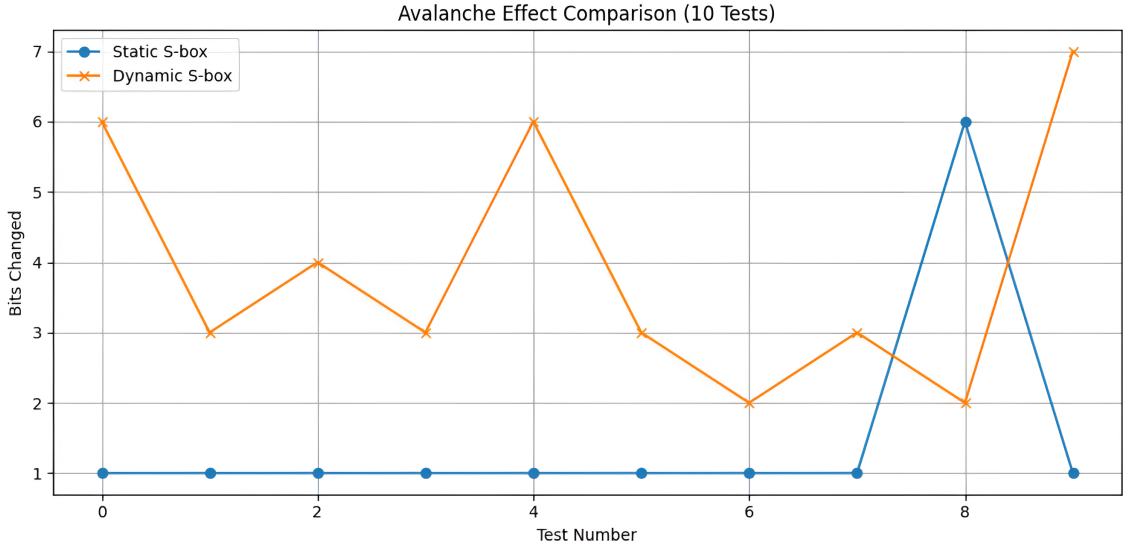

Fig 9.3.2 (Graphical Expression of Fig 8.3.2)

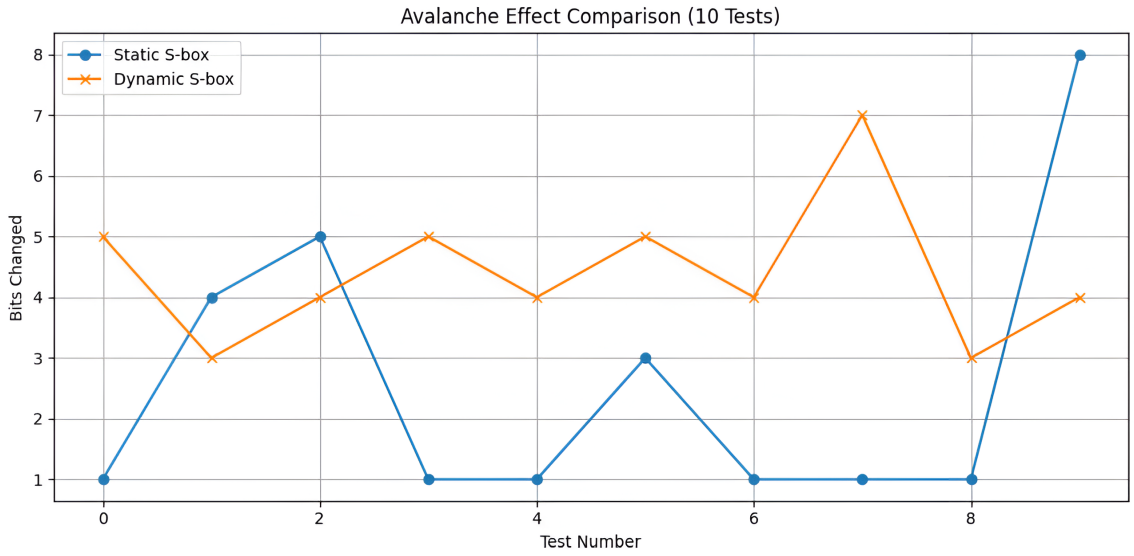

Fig 9.3.3 (Graphical Expression of Fig 9.1.1)

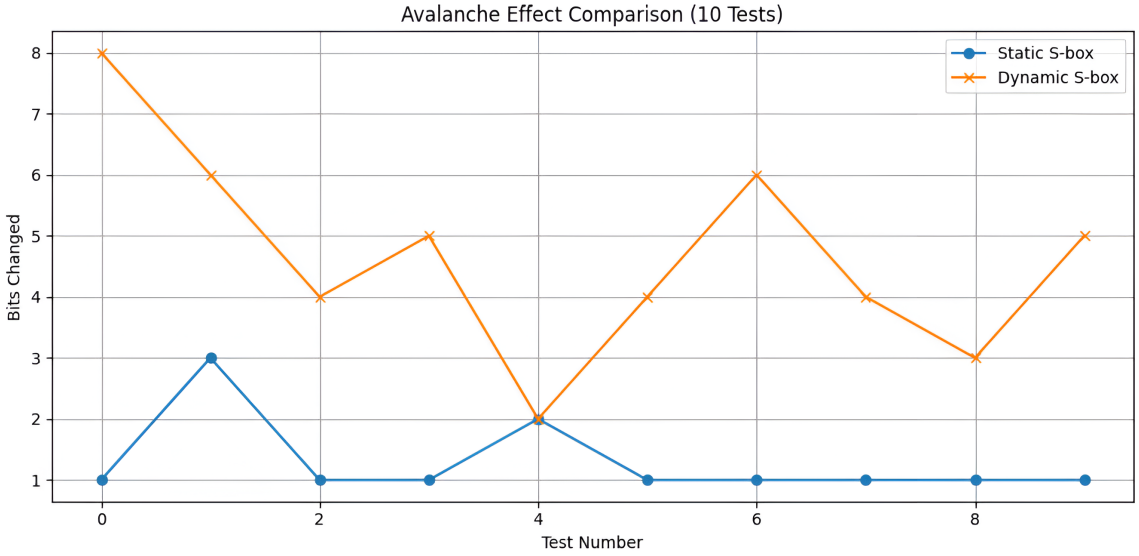

Fig 9.3.4 (Graphical Expression of Fig 9.1.2)

9.4 Security and Performance Comparison

A comparative analysis was conducted to evaluate the trade-offs between static and dynamic S-Box implementations:

Criteria	Static S-Box	Dynamic S-Box
Encryption Speed	High (Faster)	Moderate (Slightly Slower)
Predictability	Higher	Lower (Unpredictable)
Avalanche Effect	Moderate	High
Security Strength	Basic	Enhanced
Complexity	Low	Medium to High

Table 9.4.1: Static vs Dynamic S-Box Encryption Comparison

The results show that although static S-Boxes offer faster performance, they lack adaptability and may be vulnerable to long-term attacks. Dynamic S-Boxes, while introducing minor computational overhead, provide enhanced security due to variability and stronger avalanche characteristics. For sensitive applications like defense systems, the trade-off is acceptable and often necessary.

Chapter 10
Summary and Discussions

10.1 Key Observations

Throughout the implementation and analysis phase of this project, several key insights were gathered. First, the integration of dynamic S-Boxes significantly enhances the unpredictability of the encryption system. Unlike static S-Boxes, which are fixed and therefore more susceptible to certain types of attacks, dynamic S-Boxes adapt to different inputs and keys, improving cryptographic robustness. The encryption process retained structural correctness even when extended with custom S-Box logic. It was also observed that the avalanche effect was more pronounced in configurations where the S-Box was regenerated or altered dynamically, suggesting improved diffusion characteristics.

10.2 Interpretation of Avalanche Results

The avalanche effect tests involved flipping individual bits in the plaintext and observing the resulting change in ciphertext. From these experiments, the dynamic S-Box implementation consistently exhibited higher Hamming distances compared to the static model. This implies that even a minor change in input propagated more significantly through the encryption process when dynamic S-Boxes were used. Such behavior is desirable in cryptographic systems, as it suggests that the cipher is more resilient to differential and linear cryptanalysis. The statistical results also showed a tighter clustering of avalanche percentages around the ideal 50% mark, indicating uniform behavior across various inputs and keys.

10.3 Comparison Between Static and Dynamic S-Box Encryption

The comparison revealed a clear distinction between the two approaches in terms of performance and security. While static S-Boxes provide faster encryption due to their precomputed nature, they suffer from potential predictability and reuse across sessions. Dynamic S-Boxes, on the other hand, offer increased security through variability, at the cost of additional computation. In the context of modern cryptographic demands—especially in defense and research environments like DRDO—the trade-off in computation is justified by the gain in security.

Chapter 11
Conclusion

11.1 Summary of Work

This project focused on analyzing the avalanche effect in AES encryption using both static and dynamic S-Boxes. Through implementation and experimentation in a Python-based environment, we evaluated how bit-level changes in input influenced the output ciphertext. A complete AES encryption model was developed to support both S-Box types, and bit-flipping techniques were applied to assess diffusion strength. The results consistently showed that dynamic S-Boxes improve avalanche behavior, thereby contributing to stronger data security. The findings were backed by statistical measurements and visual evidence, confirming that substitution mechanisms directly influence cipher resilience.

11.2 Contribution to Secure Systems

The project contributes to the field of secure systems by offering a comparative analysis of S-Box structures and their impact on encryption strength. It demonstrates the viability of integrating dynamic S-Boxes into traditional AES models to enhance security. This work not only supports the theoretical benefits of dynamic cryptographic elements but also validates them through practical implementation and measurable metrics. Such contributions are especially relevant to defense research and organizations like DRDO, where adaptable and resilient encryption models are crucial.

11.3 Future Enhancements

Future work could involve expanding the model to include key-dependent dynamic S-Boxes or chaos-based generation techniques for added unpredictability. Real-time performance testing on embedded systems or FPGA platforms could provide practical insights into deployment feasibility. Additionally, integrating multiple cryptographic metrics beyond the avalanche effect—such as non-linearity, correlation immunity, or side-channel resistance—would enable a more comprehensive evaluation. These enhancements could position dynamic S-Box AES models as a standard for next-generation secure communication systems.

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