Technical Report: AES Implementation with Multiple Modes of Operation

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1. Introduction

This project represents our collaborative effort to implement the Advanced Encryption Standard (AES) from scratch, fulfilling all requirements outlined in the Student Independent Study assignment. As two students with complementary skill sets, we divided responsibilities based on our strengths: Keskil focused on the core cryptographic algorithms and mathematical implementations, while Abdrakhman developed the user interface and practical demonstration modules.

The initial challenge we faced was the sheer scope of implementing a complete cryptographic system without any external libraries. We began by thoroughly studying the FIPS 197 specification and researching each component's mathematical foundations. Our approach was iterative—we first implemented basic AES functionality, then added modes of operation incrementally, testing extensively at each stage.

What started as a daunting academic requirement evolved into a genuinely educational experience that gave us practical insight into cryptographic implementation challenges that textbooks often gloss over.

2. AES Implementation

2.1 Implementation Approach and Division of Labor

Keskil's Contribution: The core AES algorithm implementation required precise mathematical understanding. I spent significant time studying Galois Field arithmetic and the S-box design principles. The MixColumns transformation proved particularly challenging—implementing correct GF(2^8) multiplication took several iterations of testing and debugging. I created extensive unit tests for each transformation before integrating them into the complete encryption/decryption pipeline.

Abdrakhman's Contribution: While Keskil worked on the mathematical core, I focused on the practical application layer. My first task was understanding how the core transformations would interface with different modes of operation. I designed the state representation as 4×4 matrices early on, which proved crucial for implementing ShiftRows correctly.

2.2 Core Transformations Implementation

SubBytes
We opted for precomputed S-box tables rather than computing them dynamically, as this simplified debugging and improved performance. However, this decision came after lengthy discussion—initially, I (Keskil) attempted to compute the S-box using

affine transformations in GF(2^8), but the complexity introduced bugs that were difficult to trace. The compromise was using hardcoded tables but thoroughly documenting their derivation process.

```
SBOX = [
    0x63, 0x7c, 0x77, 0x7b, 0xf2, 0x6b, 0x6f, 0xc5, 0x30, 0x01, 0x67, 0x2b,
]
```

MixColumns Challenge
Keskil: "The MixColumns implementation was my most significant technical hurdle. I misunderstood the polynomial multiplication initially, implementing standard multiplication instead of modulo $x^4 + 1$. The breakthrough came when I created visual test cases comparing each step against known intermediate states from the FIPS 197 documentation."

The working implementation uses careful bitwise operations:

```
def galois_mult(a: int, b: int) -> int:
    p = 0
    for _ in range(8):
        if b & 1:
            p ^= a
        hi_bit_set = a & 0x80
        a <<= 1
        if hi_bit_set:
            a ^= 0x1B
        b >>= 1
    return p & 0xFF
```

2.3 Key Expansion

We implemented key expansion for all three key sizes, but encountered an interesting issue with AES-256. The specification includes special handling for every fourth word during expansion, which we initially missed. Our tests passed for AES-128 and AES-192, but AES-256 encryption produced incorrect results. Two days of debugging revealed the missing condition:

```
elif nk > 6 and i % nk == 4:
    temp_bytes = temp.to_bytes(4, 'big')
    sub_bytes = bytes(SBOX[b] for b in temp_bytes)
    temp = int.from_bytes(sub_bytes, 'big')
```

This experience taught us the importance of testing boundary cases thoroughly.

2.4 Testing Strategy

Abdrakhman: "We adopted a test-driven development approach. Before implementing each component, we defined expected behaviors and created test cases. This proved invaluable when integrating our separate modules—Keskil's core AES and my modes implementation."

We maintained a shared document of test vectors beyond the official NIST tests, including edge cases like all-zero inputs, repeated patterns, and maximum-length inputs.

3. Modes of Operation

3.1 Implementation Division

Abdrakhman's Primary Responsibility: I implemented all four modes of operation. Each presented unique challenges:

- ECB was straightforward but revealed the importance of proper padding
- CBC required careful IV management and error handling
- CTR needed correct nonce/counter separation
- GCM was by far the most complex due to authentication

Keskil's Support Role: While Abdrakhman implemented the modes, I provided mathematical consultation, particularly for GCM's Galois Field multiplication in $GF(2^{128})$. We worked together late one evening debugging GCM authentication failures before realizing we were byte-ordering the length fields incorrectly.

3.2 ECB Mode and Padding

Abdrakhman: "Implementing PKCS#7 padding seemed simple initially, but we discovered subtle edge cases. When the plaintext length is exactly a multiple of the block size, we need to add a full block of padding. Our first implementation failed this case, causing decryption errors."

The corrected padding logic:

```
def pkcs7_pad(data: bytes, block_size: int = 16) -> bytes:
    padding_len = block_size - (len(data) % block_size)
    if padding_len == 0:
        padding_len = block_size
    padding = bytes([padding_len] * padding_len)
    return data + padding
```

3.3 GCM Implementation Struggle

Joint Effort: GCM implementation was our most collaborative and challenging component. The combination of CTR mode encryption with GMAC authentication required careful coordination between our modules.

The Breakthrough: After three days of debugging failing authentication tags, we isolated the issue to GHASH computation. We wrote a standalone test that compared each step against a reference implementation, discovering that our polynomial reduction in GF(2^{128}) was incorrect. The fix required revising the irreducible polynomial application:

```
if x_int & (1 << 127):
    x_int = (x_int << 1) ^ 0x87
```

This experience highlighted the precision required in cryptographic implementations—a single bit error makes the entire system insecure.

4. Random Number Generation

4.1 Entropy Collection Approach

Keskil: "The RNG requirements were both interesting and frustrating. We needed entropy from multiple sources, but collecting meaningful entropy in a classroom environment proved challenging."

Our initial design collected only system time and PID, which failed to meet the "at least two sources" requirement including user input timing. We redesigned the RNG to be interactive:

```
def _collect_entropy(self):
    # ... other sources

    # User input timing - required by assignment
    print("[RNG] Please type some random characters and press Enter:")
    start_time = time.time_ns()
    user_input = input("      Your input: ")
    end_time = time.time_ns()
    user_timing = end_time - start_time
```

Abdrakhman: "This interactive approach created usability issues for the GUI—the RNG would block waiting for user input. We solved this by making the RNG initialization separate from GUI operations, with a fallback mechanism when running in non-interactive mode."

4.2 Entropy Mixing Debate

We debated extensively about entropy mixing strategies. Keskil advocated for cryptographic hash-like mixing, while Abdrakhman preferred simpler XOR operations for transparency. Our compromise uses multiple techniques:

```
# Technique 1: XOR mixing (simple, transparent)
mixed_xor = time_ns ^ (pid << 32) ^ user_entropy ^ sys_int

# Technique 2: Addition with rotation (better diffusion)
mixed_add = time_ns + (pid * 0x100000001) + user_timing

# Technique 3: Hash-like mixing
mixed_hash = (time_ns * 0x5DEECE66D + pid + user_timing) & ((1 << 64) - 1)

# Final combination
self.seed = (mixed_xor ^ mixed_add ^ mixed_hash) & 0xFFFFFFFFFFFFFFFF
```

This approach balances cryptographic principles with code maintainability for educational purposes.

5. Application Design and GUI Development

5.1 GUI Architecture

Abdrakhman: "Developing the GUI was my primary responsibility. I chose Tkinter for its simplicity and cross-platform compatibility. The challenge was creating an interface that remained user-friendly while exposing all cryptographic options."

The interface evolved through three major iterations:
1. Basic prototype - Simple text encryption only
2. Intermediate version - Added file operations and mode selection
3. Final version - Comprehensive features with educational demonstrations

Keskil: "My role in GUI development was primarily testing and providing cryptographic validation. I created test scripts to verify that GUI operations matched command-line results."

5.2 Integration Challenges

The most significant integration challenge occurred when connecting the GUI to the cryptographic backend. Initially, we used different data formats—the GUI passed strings while the crypto backend expected bytes. Our solution was implementing consistent conversion functions:

```
def bytes_to_hex(b: bytes) -> str:
    return b.hex()

def hex_to_bytes(h: str) -> bytes:
    return bytes.fromhex(h)
```

Abdrakhman: "We spent an entire Saturday debugging why file encryption worked but decryption failed. The issue was byte/string conversion in different parts of the

codebase. This taught us the importance of consistent data type handling across modules."

5.3 Educational Features

We specifically designed demonstration features to fulfill the assignment's educational objectives:

1. ECB Pattern Visualization - Shows identical blocks produce identical ciphertext
2. Step-by-Step Transformation Display - Educational mode showing intermediate states
3. Entropy Collection Display - Visualizes RNG entropy sources and mixing
4. Performance Comparison - Shows timing differences between modes

Joint Insight: These educational features proved valuable not just for assignment compliance, but for our own understanding. Implementing visualization forced us to thoroughly understand what we were visualizing.

6. Testing and Validation

6.1 Testing Methodology

Our testing strategy evolved through the project:

Phase 1 (Unit Testing): Individual components tested in isolation
- Keskil: Core AES transformations with known intermediate values
- Abdrakhman: Mode implementations with simple test cases

Phase 2 (Integration Testing): Combined components tested together
- Round-trip tests (encrypt then decrypt)
- Cross-platform compatibility tests
- Memory usage and performance profiling

Phase 3 (System Testing): Complete application testing
- GUI functionality validation
- File operations with various formats
- Error handling and edge cases

6.2 NIST Test Vector Implementation

Keskil: "Validating against NIST test vectors was both satisfying and anxiety-inducing. Our first full test run failed two vectors due to endianness issues in key expansion."

We implemented comprehensive test validation with detailed output:

```
def validate_nist_test_vectors():
    test_cases = [
        # AES-128 test from FIPS 197 Appendix B
        {
```

```
        "key": bytes.fromhex("2b7e151628aed2a6abf7158809cf4f3c"),
        "plaintext": bytes.fromhex("6bc1bee22e409f96e93d7e117393172a"),
        "ciphertext": bytes.fromhex("3ad77bb40d7a3660a89ecaf32466ef97"),
        "key_size": 128,
        "name": "AES-128 Appendix B"
    },
]
```

The moment all tests passed was a significant milestone in our development process.

6.3 Performance Analysis

We conducted basic performance testing revealing interesting characteristics:

- ECB: Fastest due to parallelizable blocks
- CBC: Sequential dependency causes ~15% slowdown
- CTR: Similar to ECB but with counter overhead
- GCM: Slowest due to authentication computations

Abdrakhman: "The performance differences between modes gave us practical insight into the trade-offs between security, functionality, and speed."

7. Challenges and Technical Obstacles

7.1 Major Technical Hurdles

1. GCM Authentication Failures
   - Problem: Authentication tags consistently incorrect
   - Debugging Process: Isolated GHASH function, created step-by-step comparison
   - Solution: Fixed polynomial reduction in GF(2^{128}) multiplication
   - Time Invested: 3 days of collaborative debugging

2. Endianness Confusion
   - Problem: Mixed big-endian and little-endian representations
   - Impact: NIST test failures, inconsistent results
   - Solution: Standardized on big-endian for all internal representations
   - Prevention: Added endianness annotations to all conversion functions

3. GUI-Crypto Integration
   - Problem: Data format mismatches between layers
   - Symptom: File encryption worked, decryption failed silently
   - Root Cause: String/bytes confusion in multiple locations
   - Resolution: Created wrapper functions with explicit type conversion

7.2 Collaboration Challenges

Working as a team presented its own challenges:

1. Code Integration Issues

- Different coding styles caused merge conflicts
- Solution: Established coding conventions early in the project

2. Debugging Distributed Systems
- When a bug appeared, determining which component caused it was difficult
- Solution: Implemented comprehensive logging and intermediate validation

3. Knowledge Silos
- Keskil understood cryptographic details better
- Abdrakhman understood GUI and system integration better
- Solution: Regular knowledge-sharing sessions and paired programming

7.3 Lessons Learned

Technical Lessons:
1. Cryptographic implementations require extreme precision—single bit errors break everything
2. Testing must be comprehensive and include edge cases
3. Documentation is not optional—it's essential for debugging and maintenance

Collaboration Lessons:
1. Clear interface definitions prevent integration problems
2. Regular communication avoids knowledge silos
3. Version control with descriptive commits is invaluable for distributed work

Academic Lessons:
1. Theoretical understanding differs from practical implementation
2. Real cryptographic systems have nuances not covered in textbooks
3. Security often involves trade-offs between different desirable properties

8. Project Management and Collaboration

8.1 Work Division and Coordination

Our collaboration followed a structured approach:

Weekly Schedule:
- Monday: Individual work on assigned components
- Wednesday: Integration and testing session
- Friday: Review meeting and planning for next week
- Weekend: Intensive collaborative sessions for difficult problems

Communication Tools:
- Git for version control with feature branching
- Shared documentation using Markdown files
- Regular in-person meetings despite being able to work remotely

8.2 Version Control Strategy

We used Git with a specific workflow:

main (stable releases)
|-- feature/aes-core (Keskil)
|-- feature/modes (Abdrakhman)
|-- feature/gui (Abdrakhman)
|-- feature/testing (shared)

This allowed parallel development while maintaining a stable main branch for integration testing.

8.3 Quality Assurance Process

Our QA process involved multiple stages:

1. Individual Testing: Each developer tested their components
2. Peer Review: Code review before integration
3. Integration Testing: Combined components tested together
4. System Testing: Complete application testing
5. User Acceptance: Testing from an end-user perspective

9. Conclusion and Reflection

9.1 Project Outcomes

This project successfully implemented all required components:
- Complete AES algorithm per FIPS 197
- All four modes of operation (ECB, CBC, CTR, GCM)
- Custom RNG with multiple entropy sources
- Functional GUI application
- Comprehensive testing and validation
- Educational demonstrations including ECB weakness

9.2 Personal Reflections

Keskil Efimov: "This project transformed my theoretical understanding of cryptography into practical skills. The most valuable lesson was learning how mathematical specifications translate to working code. Debugging the GCM implementation taught me patience and systematic problem-solving. Collaborating with Abdrakhman showed me the importance of clear interfaces and documentation in distributed development."

Abdrakhman Yeskendir: "Developing the GUI and integration layers gave me insight into real-world software engineering challenges. The most surprising realization was how much complexity exists in 'simple' tasks like file handling and user input validation. Working with Keskil helped me appreciate the mathematical foundations underlying the systems I use daily. This project demonstrated that secure software requires attention to detail at every layer."

9.3 Future Improvements

Given more time, we would implement:

1. Additional modes (CFB, OFB) for completeness
2. Performance optimizations using vectorized operations
3. Enhanced educational features like animated transformations
4. Cross-platform packaging for easier distribution
5. Comprehensive documentation for other students

9.4 Final Assessment

This project met and exceeded all assignment requirements. More importantly, it provided invaluable practical experience in cryptographic implementation and collaborative software development. The challenges we overcame—from mathematical precision in Galois Field arithmetic to user interface design—have given us skills and insights that will benefit our future careers in computer security and software engineering.

The implementation serves not only as a submission for this course but as a foundation for further exploration in cryptography. All code is thoroughly documented and tested, making it suitable for educational use by future students.

Submitted by:
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