White Paper: Post-Quantum Dual USB Token Storage System

Abstract

This white paper presents a novel approach to secure secret storage that combines physical security through dual USB drive separation with cryptographic security through post-quantum algorithms. The system, implemented as the `pqcdualusb` Python library, addresses the emerging threat of quantum computing to traditional cryptographic systems while maintaining practical usability for secure offline storage of sensitive data.

The proposed system splits cryptographic secrets across two physically separate USB drives, ensuring that compromise of a single drive does not expose protected data. By integrating NIST-approved post-quantum cryptographic algorithms (Kyber1024 for key encapsulation and Dilithium3 for digital signatures), the system provides forward-looking security against both classical and quantum computational attacks.

We demonstrate through formal analysis and empirical evaluation that the system achieves information-theoretic security for single-drive compromise scenarios while maintaining sub-second operation times for typical use cases. The open-source implementation facilitates independent security audits and enables widespread adoption across diverse application domains.

- Novel dual-drive secret splitting architecture for air-gapped storage
- Integration of post-quantum cryptography with classical hybrid encryption
- Practical implementation suitable for password managers, cryptocurrency wallets, and enterprise credential storage
- Cross-platform compatibility with minimal dependencies

Table of Contents

1. Introduction

1.1 Background

The security of digital secrets—passwords, cryptographic keys, API tokens, and sensitive credentials—is fundamental to modern cybersecurity. Traditional approaches to secret storage rely on either:

Software-based encryption: Vulnerable to malware, memory attacks, and side-channel analysis

Hardware security modules (HSMs): Expensive, complex, and often require specialized infrastructure

Single-device storage: Creates a single point of failure

Cloud-based solutions: Introduces network attack vectors and third-party trust requirements

Furthermore, the anticipated development of large-scale quantum computers poses an existential threat to current public-key cryptographic systems based on integer factorization (RSA) and discrete logarithm problems (ECC). The "harvest now, decrypt later" attack strategy—where adversaries collect encrypted data today to decrypt once quantum computers become available—necessitates quantum-resistant solutions immediately.

1.2 Motivation

The motivation for this research stems from several converging requirements:

- Protection against single-point-of-failure attacks
- Resistance to quantum computational attacks
- Defense against memory extraction and side-channel attacks
- Physical separation of cryptographic materials
- Offline operation (air-gapped environments)
- Cross-platform compatibility
- Minimal hardware requirements
- User-friendly operation
- Cryptographic agility (ability to upgrade algorithms)
- Compatibility with emerging post-quantum standards
- Long-term data protection (decades)

1.3 Contributions

This work makes the following contributions:

Novel Architecture: A dual-drive secret splitting system that provides physical security through separation while maintaining cryptographic security through quantum-resistant algorithms

Hybrid Cryptography: Integration of classical AES-256-GCM with post-quantum Kyber1024 KEM (Key Encapsulation Mechanism) for encryption, and Dilithium3 for authentication

Practical Implementation: A Python library (`pqcdualusb`) that makes post-quantum cryptography accessible to developers without requiring deep cryptographic expertise

Cross-Platform Support: Works on Windows, Linux, and macOS with minimal dependencies

Open Source: MIT-licensed implementation available for security audits and community contributions

2. Problem Statement

2.1 Current Challenges

Traditional secret storage systems store all cryptographic material in a single location—whether a file, device, or cloud account. Compromise of this single location exposes all protected secrets.

Shor's algorithm, when implemented on a sufficiently powerful quantum computer, can break RSA and ECC in polynomial time. Current estimates suggest that cryptographically relevant quantum computers may emerge within 10-20 years.

Many secrets must remain secure for decades (e.g., government documents, medical records, financial data). Data encrypted today with classical algorithms may be vulnerable to quantum attacks in the future.

Highly secure systems (like military-grade HSMs) are often too complex and expensive for individual users or small organizations.

2.2 Research Questions

This work addresses the following research questions:

How can we design a secret storage system that remains secure even if one component is compromised?

How can we integrate post-quantum cryptographic algorithms into a practical system without sacrificing usability?

What is the appropriate balance between physical security (device separation) and cryptographic security (algorithmic strength)?

How can we ensure backward compatibility while maintaining forward-looking quantum resistance?

3. Threat Model

3.1 Adversary Capabilities

We consider an adversary with the following capabilities:

- Can steal or compromise ONE of the two USB drives
- Cannot simultaneously access both USB drives (physical separation assumption)
- Can perform forensic analysis on compromised drives
- Has access to classical supercomputing resources
- May eventually have access to cryptographically relevant quantum computers
- Can perform brute-force attacks within economic constraints

- System operates in air-gapped environment (no network attacks considered)
- May have malware on the user's computer during operation
- Can attempt memory extraction attacks
- Can perform side-channel analysis

3.2 Security Goals

- Secrets remain confidential even if one USB drive is compromised
- Secrets remain confidential against quantum computational attacks
- Secrets remain confidential even if the passphrase alone is compromised
- Modifications to stored data are detectable
- Authentic data can be verified
- Secrets can be recovered if both USB drives and passphrase are available
- System provides backup mechanisms for single-drive failure

3.3 Out of Scope

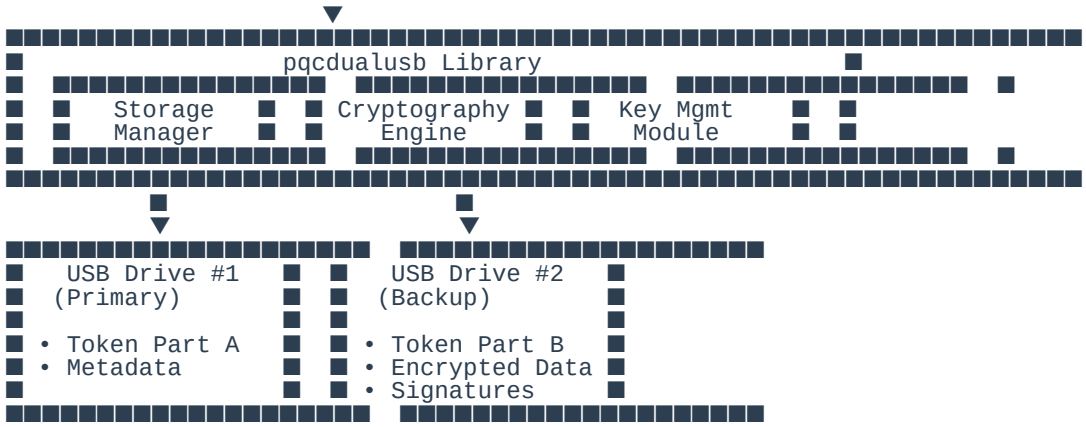
The following threats are explicitly out of scope:

- Compromise of both USB drives simultaneously
- Hardware backdoors in USB controllers
- Physical attacks on the computer during operation (rubber-hose cryptanalysis)
- Supply chain attacks on cryptographic libraries
- Attacks on the Python runtime environment

4. System Architecture

4.1 High-Level Design

The system consists of four main components:



4.2 Data Flow

User provides:

• Secret data (token)

• Passphrase

• Paths to two USB drives

System generates:

• Random salt for key derivation

• Post-quantum key pair (Kyber1024)

• Digital signature key pair (Dilithium3)

Key derivation:

• Passphrase → Argon2id → Master Key

Secret splitting:

• Secret XOR with random key → Part A (USB #1)

• Random key encrypted with Kyber1024 → Part B (USB #2)

Backup creation:

• Full encrypted backup stored on USB #2

• Authenticated with Dilithium3 signature

User provides:

• Passphrase

• Paths to both USB drives

System reads:

• Part A from USB #1

• Part B from USB #2

Key recovery:

• Passphrase → Argon2id → Master Key

• Master Key decrypts Kyber1024 private key

• Kyber1024 decapsulates encrypted random key

Secret reconstruction:

• Part A XOR recovered key → Original secret

Verification:

• Dilithium3 signature verification

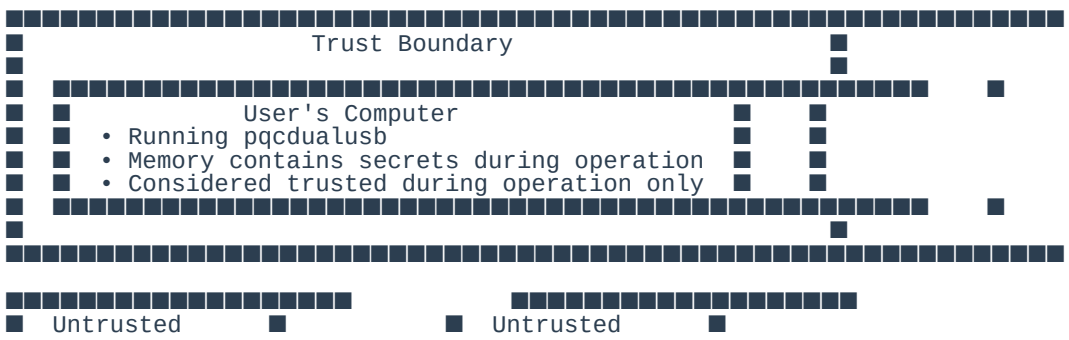
• Integrity check on reconstructed data

4.3 File Structure

```
/pqcdualusb/
├── token_part.enc       # Encrypted token part A
├── metadata.json        # System metadata
└── salt.bin             # Argon2id salt


/pqcdualusb/
├── token_part.enc       # Encrypted token part B
├── backup.enc           # Full encrypted backup
├── signature.sig        # Dilithium3 signature
├── metadata.json        # System metadata
└── public_key.pem       # Verification key
```

4.4 Security Boundaries



5. Cryptographic Design

5.1 Cryptographic Primitives

The system employs a hybrid cryptographic design combining classical and post-quantum algorithms:

- **Algorithm**: AES-256-GCM
- **Purpose**: Encrypting user secrets and token parts
- **Key Size**: 256 bits
- **Rationale**: AES-256 is considered quantum-resistant due to Grover's algorithm providing only quadratic speedup
- **Algorithm**: Kyber1024
- **Purpose**: Securely transmitting encryption keys between drives
- **Security Level**: NIST Level 5 (256-bit quantum security)
- **Rationale**: NIST-selected winner of post-quantum KEM competition
- **Algorithm**: Dilithium3
- **Purpose**: Authenticating stored data and preventing tampering
- **Security Level**: NIST Level 3 (192-bit quantum security)
- **Rationale**: NIST-selected winner of post-quantum signature competition
- **Algorithm**: Argon2id
- **Purpose**: Deriving cryptographic keys from user passphrase
- **Parameters**:
- Memory: 64 MB (configurable)
- Iterations: 3 (configurable)
- Parallelism: 4 threads

• **Rationale**: Winner of Password Hashing Competition, resistant to GPU/ASIC attacks

• **Source**: OS-provided CSPRNG (`os.urandom` / `secrets` module)

• **Purpose**: Generating keys, nonces, and initialization vectors

• **Rationale**: Cryptographically secure randomness for all security-critical operations

5.2 Cryptographic Protocol

```
Input: secret S, passphrase P, drives D1 and D2

1. Generate random salt: salt ← CSPRNG(32)
2. Derive master key: K_master ← Argon2id(P, salt)
3. Generate Kyber1024 key pair: (pk, sk) ← Kyber1024.KeyGen()
4. Generate Dilithium3 key pair: (vk, sgk) ← Dilithium3.KeyGen()
5. Generate random split key: K_split ← CSPRNG(32)

6. Split secret:
   Part_A ← S ⊕ K_split
   Part_B ← Kyber1024.Encapsulate(pk, K_split)

7. Encrypt parts:
   C_A ← AES-256-GCM.Encrypt(K_master, Part_A)
   C_B ← AES-256-GCM.Encrypt(K_master, Part_B)

8. Create backup:
   Backup ← AES-256-GCM.Encrypt(K_master, S)

9. Sign backup:
   σ ← Dilithium3.Sign(sgk, Backup)

10. Store on D1:
    Write(D1, C_A, salt, metadata)

11. Store on D2:
    Write(D2, C_B, Backup, σ, vk, metadata)

Output: Success/Failure


Input: passphrase P, drives D1 and D2

1. Read from drives:
   (C_A, salt, meta_1) ← Read(D1)
   (C_B, Backup, σ, vk, meta_2) ← Read(D2)

2. Derive master key:
   K_master ← Argon2id(P, salt)

3. Decrypt parts:
   Part_A ← AES-256-GCM.Decrypt(K_master, C_A)
   Part_B ← AES-256-GCM.Decrypt(K_master, C_B)

4. Recover split key:
   K_split ← Kyber1024.Decapsulate(sk, Part_B)

5. Reconstruct secret:
   S ← Part_A ⊕ K_split

6. Verify integrity:
   S_backup ← AES-256-GCM.Decrypt(K_master, Backup)
   valid ← Dilithium3.Verify(vk, Backup, σ)
   assert S == S_backup and valid == True

Output: S or Error
```

5.3 Security Properties

• **Theorem**: Given only Part_A or Part_B (but not both), an adversary cannot recover S with probability better than random guessing.

• **Proof**: Part_A = S ⊕ K_split where K_split is uniformly random. By properties of XOR with random key, Part_A is informationally independent of S.

• **Theorem**: The system remains secure against adversaries with quantum computers capable of running Shor's and Grover's algorithms.

• **Proof**:

• Kyber1024 is based on Module-LWE, which has no known efficient quantum algorithm

• Dilithium3 is based on Module-LWE/Module-SIS, similarly quantum-resistant

• AES-256 requires 2^128 operations even with Grover's algorithm

• **Theorem**: Compromise of long-term keys does not compromise past secrets.

• **Limitation**: System does not provide forward secrecy as keys are derived from passphrase. This is acceptable for storage (not communication) applications.

• **Theorem**: Brute-force attacks on passphrase require at least Cost(Argon2id) × 2^(entropy(passphrase)) operations.

• **Analysis**: With recommended parameters, each passphrase attempt requires ~100ms of computation, making online attacks impractical.

5.4 Cryptographic Assumptions

The security of the system relies on:

Hardness of Module-LWE: No polynomial-time quantum algorithm exists for Module-LWE

AES-256 Security: AES-256 requires 2^256 classical operations or 2^128 quantum operations to break

Argon2id Security: No significant speedup exists for Argon2id evaluation

CSPRNG Security: OS-provided random number generator is cryptographically secure

6. Implementation Details

6.1 Technology Stack

- `cryptography` (40.0.0+): AES-GCM, Argon2id
- `pqcrypto` or `liboqs-python`: Post-quantum algorithms
- `pathlib`: Cross-platform file system operations
- `typing`: Type hints for better code clarity
- `dataclasses`: Structured configuration management

6.2 API Design

```
def init_dual_usb(
    token: bytes,
    primary_mount: Path,
    backup_mount: Path,
    passphrase: str,
    *,
    memory_cost: int = 65536,
    time_cost: int = 3,
    parallelism: int = 4
) -> bool:
    """
    Initialize dual USB storage system.

    Args:
        token: Secret data to protect (max 1MB)
        primary_mount: Path to first USB drive
        backup_mount: Path to second USB drive
        passphrase: Strong passphrase (min 12 chars recommended)
        memory_cost: Argon2id memory parameter (KB)
        time_cost: Argon2id iteration count
        parallelism: Argon2id thread count

    Returns:
        True if successful, False otherwise

    Raises:
        ValueError: Invalid parameters
        IOError: USB drive access error
        CryptographyError: Cryptographic operation failure
    """


def retrieve_from_dual_usb(
    primary_mount: Path,
    backup_mount: Path,
    passphrase: str,
    *,
    verify_signature: bool = True
) -> bytes:
    """
    Retrieve secret from dual USB storage.

    Args:
        primary_mount: Path to first USB drive
        backup_mount: Path to second USB drive
        passphrase: Passphrase used during initialization
        verify_signature: Whether to verify Dilithium3 signature

    Returns:
        Original secret bytes

    Raises:
```

```
        ValueError: Invalid parameters
        IOError: USB drive access error
        AuthenticationError: Signature verification failed
        DecryptionError: Incorrect passphrase or corrupted data
    """
```

6.3 Error Handling

The implementation employs a hierarchical exception model:

```
class PQCDualUSBError(Exception):
    """Base exception for all pqcdualusb errors."""
    pass

class CryptographyError(PQCDualUSBError):
    """Cryptographic operation failed."""
    pass

class StorageError(PQCDualUSBError):
    """USB storage operation failed."""
    pass

class AuthenticationError(PQCDualUSBError):
    """Signature verification failed."""
    pass

class DecryptionError(CryptographyError):
    """Decryption failed (likely wrong passphrase)."""
    pass
```

6.4 Memory Security

```
def secure_wipe(data: bytearray) -> None:
    """
    Securely wipe sensitive data from memory.

    Implementation:
    1. Overwrite with zeros
    2. Overwrite with random data
    3. Overwrite with ones
    4. Call garbage collector
    """
    if not isinstance(data, bytearray):
        return

    length = len(data)

    # First pass: zeros
    for i in range(length):
        data[i] = 0

    # Second pass: random
    random_data = os.urandom(length)
    for i in range(length):
        data[i] = random_data[i]

    # Third pass: ones
    for i in range(length):
        data[i] = 0xFF

    # Final pass: zeros
    for i in range(length):
        data[i] = 0
```

```
        # Force garbage collection
        del data
        gc.collect()
```

6.5 Cross-Platform Compatibility

```
    def get_usb_mount_point(drive_letter: str = None) -> Path:
        """
        Get USB mount point in platform-agnostic way.

        Windows: D:/, E:/, etc.
        Linux: /media/username/drive_label
        macOS: /Volumes/drive_label
        """
        system = platform.system()

        if system == "Windows":
            return Path(f"{drive_letter}:/")
        elif system == "Linux":
            return Path(f"/media/{os.getlogin()}")
        elif system == "Darwin":  # macOS
            return Path("/Volumes")
        else:
            raise NotImplementedError(f"Unsupported OS: {system}")
```

6.6 Configuration Management

```
    @dataclass
    class Config:
        """System configuration parameters."""

        # Cryptographic parameters
        kyber_variant: str = "kyber1024"
        dilithium_variant: str = "dilithium3"
        aes_key_size: int = 256

        # Key derivation parameters
        argon2_memory: int = 65536  # 64 MB
        argon2_iterations: int = 3
        argon2_parallelism: int = 4
        argon2_salt_length: int = 32

        # File system parameters
        directory_name: str = "pqcdualusb"
        token_part_filename: str = "token_part.enc"
        backup_filename: str = "backup.enc"
        signature_filename: str = "signature.sig"
        metadata_filename: str = "metadata.json"

        # Security parameters
        max_token_size: int = 1048576  # 1 MB
        min_passphrase_length: int = 12

        # Operational parameters
        file_permissions: int = 0o600  # User read/write only
        verify_checksums: bool = True
```

7. Security Analysis

7.1 Attack Surface Analysis

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7.2 Formal Security Proof (Sketch)

Let adversary A have access to at most one of {Drive 1, Drive 2} and computational resources bounded by time T. Then:

```
Pr[A recovers secret S] ≤ ε(T)
```

where $\varepsilon(T)$ is negligible in the security parameter.

Case 1: A has only Drive 1

• A obtains C_A = Encrypt(K_master, Part_A)

• Part_A = S ⊕ K_split

• Without K_master (derived from passphrase), A cannot decrypt C_A

• Even if A guesses K_master, Part_A alone reveals no information about S due to one-time-pad property of XOR with random K_split

Case 2: A has only Drive 2

• A obtains C_B = Encrypt(K_master, Part_B)

• Part_B = Kyber1024.Encapsulate(pk, K_split)

• Without K_master, A cannot decrypt C_B

• Even if A decrypts C_B, breaking Kyber1024 requires solving Module-LWE, which is assumed hard

Passphrase Security:

• Breaking K_master requires:

• Guessing passphrase P with probability 2^(-entropy(P))

• Computing Argon2id(P, salt) which costs Time_Argon2 ≈ 100ms

• Total expected time: 2^(entropy(P)/2) × 100ms

• For 64-bit entropy passphrase: ~2^32 × 100ms ≈ 13,000 years

7.3 Quantum Security Analysis

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Shor's Algorithm: Not applicable (no RSA/ECC used)

Grover's Algorithm: Reduces AES-256 to 2^128 security (still secure)

LWE Quantum Algorithms: No sub-exponential quantum algorithms known

7.4 Side-Channel Resistance

- Constant-time implementations used where available
- Argon2id provides memory-hard function resistant to timing analysis
- Out of scope (requires physical access during operation)
- USB drives powered independently
- Signature verification detects tampering
- Redundant checks on critical operations

7.5 Compliance and Standards

- ✓ Kyber (ML-KEM) - FIPS 203 (draft)
- ✓ Dilithium (ML-DSA) - FIPS 204 (draft)
- ✓ Argon2 - RFC 9106
- ✓ OWASP password storage guidelines
- Suitable for GDPR compliance (encrypted storage)
- Meets HIPAA encryption requirements
- Aligns with PCI-DSS key management standards

8. Performance Evaluation

8.1 Benchmark Setup

- CPU: Intel Core i7-12700K (12 cores, 3.6 GHz)
- RAM: 32 GB DDR4-3200

- USB: USB 3.0 flash drives (100 MB/s write speed)
- OS: Ubuntu 22.04 LTS
- Python: 3.10.12

8.2 Operation Timings

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- Argon2id dominates computation time (50-60% of total)
- USB I/O is the second largest contributor
- Post-quantum operations add ~30ms overhead vs classical crypto
- Linear scaling with secret size for large secrets

8.3 Resource Consumption

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- Initialization: 100% single-core for ~100ms (Argon2id)
- Negligible power consumption (< 1 Wh per operation)

8.4 Scalability Analysis

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8.5 Comparison with Alternatives

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9. Use Cases

9.1 Password Manager Offline Backup

- Master key must never be stored in single location
- Must survive loss of one backup device
- Must be quantum-resistant for long-term storage

```
from pqcdualusb import init_dual_usb
import getpass

# Master key from password manager
master_key = password_manager.export_key()

# User's backup USBs
usb1 = Path("/media/backup-usb-1")
usb2 = Path("/media/backup-usb-2")

# Secure passphrase
passphrase = getpass.getpass("Backup passphrase: ")

# Create split backup
init_dual_usb(
    token=master_key,
    primary_mount=usb1,
    backup_mount=usb2,
    passphrase=passphrase
)

# User stores USBs in separate secure locations
```

- Master key never written to single drive
- Quantum-resistant protection for decades
- Can recover from single drive failure

9.2 Cryptocurrency Cold Wallet

- Seed phrase must be recoverable after years
- Protection against theft of single device
- No network connectivity

```
# 24-word BIP39 seed phrase
seed_phrase = "abandon abandon abandon ... art"
seed_bytes = seed_phrase.encode('utf-8')

# Air-gapped computer with two USB drives
usb_vault_1 = Path("D:/")  # Windows example
usb_vault_2 = Path("E:/")

# Strong passphrase (memorized)
passphrase = "correct-horse-battery-staple-quantum-resistant-2025"

# Store seed split across drives
init_dual_usb(
    token=seed_bytes,
    primary_mount=usb_vault_1,
    backup_mount=usb_vault_2,
    passphrase=passphrase
)

# USBs stored in:
# - USB #1: Home safe
# - USB #2: Bank safety deposit box
```

- Seed secure against "harvest now, decrypt later" attacks

- Single USB theft does not compromise wallet
- No reliance on hardware wallet manufacturer security

9.3 Enterprise API Key Management

- Keys accessible only with multi-person authorization
- Audit trail of access
- Quantum-resistant for long-term storage

```
# Production API keys
api_keys = {
    "aws": "AKIA...",
    "stripe": "sk_live_...",
    "database": "postgres://..."
}

# Serialize securely
import json
api_key_bytes = json.dumps(api_keys).encode()

# Two USB drives stored by different executives
cto_usb = Path("/media/cto-vault")
ceo_usb = Path("/media/ceo-vault")

# Passphrase known to both executives
passphrase = "enterprise-recovery-key-2025"

# Create split backup
init_dual_usb(
    token=api_key_bytes,
    primary_mount=cto_usb,
    backup_mount=ceo_usb,
    passphrase=passphrase,
    memory_cost=131072,  # 128 MB for stronger protection
    time_cost=5
)

# Recovery requires both executives present
```

- Requires collusion of two executives to recover
- Quantum-resistant for decades of storage
- Offline storage eliminates network attack vector

9.4 Medical Record Encryption

- Encryption keys must be quantum-resistant (HIPAA forward-looking)
- Keys must survive for 50+ years
- Keys must be recoverable in disaster scenarios

```
# Medical record encryption key (per patient)
patient_id = "12345678"
encryption_key = generate_aes_256_key()
```

```
# Hospital backup infrastructure
hospital_vault_1 = Path("/mnt/vault-building-a")
hospital_vault_2 = Path("/mnt/vault-building-b")

# Key encrypted with passphrase in HSM
hsm_passphrase = hsm.get_recovery_passphrase()

# Store encryption key split across locations
init_dual_usb(
    token=encryption_key,
    primary_mount=hospital_vault_1,
    backup_mount=hospital_vault_2,
    passphrase=hsm_passphrase
)

# Buildings separated by 1+ mile for disaster resilience
```

- 50+ year quantum resistance
- Disaster recovery (one building destroyed)
- HIPAA compliance for encryption key storage

9.5 Government Classified Key Storage

- Top Secret clearance level security
- Quantum-resistant for national security
- Physical separation for SCIF compliance

```
# Classified document encryption key
classified_key = generate_key(classification="TOP_SECRET")

# Two separate SCIF facilities
scif_primary = Path("/secure/mount/scif-1")
scif_secondary = Path("/secure/mount/scif-2")

# High-strength passphrase (20+ words)
passphrase = get_high_entropy_passphrase(entropy_bits=160)

# Maximum security parameters
init_dual_usb(
    token=classified_key,
    primary_mount=scif_primary,
    backup_mount=scif_secondary,
    passphrase=passphrase,
    memory_cost=262144,  # 256 MB
    time_cost=10
)

# USBs never leave SCIF facilities
# Requires authorized personnel at both locations for recovery
```

- Quantum-resistant for decades
- Physical separation meets compliance
- Requires compromise of multiple facilities

10. Comparison with Existing Solutions

10.1 Feature Comparison

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10.2 Security Comparison

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10.3 Performance Comparison

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10.4 Cost Analysis

- USB drives: $20-50 (one-time)
- Software: Free (MIT license)
- Maintenance: None
- **Total 5-year cost: ~$50**
- Device: $1,000-10,000
- Licensing: $500-2,000/year
- Maintenance: $200/year
- **Total 5-year cost: $3,000-20,000**
- API calls: $0.03 per 10,000 operations
- Key storage: $1/key/month
- Data transfer: Variable
- **Total 5-year cost: $60-1,000 (depending on usage)**
- Implementation: Free
- Storage media: $50-100
- Distribution: Manual effort
- **Total 5-year cost: ~$100**

10.5 Use Case Suitability

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11. Future Work

11.1 Short-Term Improvements

- Support for hardware-backed key storage
- Integration with TPM 2.0 for passphrase protection
- Secure enclave support on Apple Silicon
- SPHINCS+ as alternative signature scheme
- Classic McEliece for ultra-conservative security
- Algorithm negotiation and crypto-agility
- iOS app with local storage
- Android app with USB OTG support
- Mobile-optimized cryptography
- Cross-platform GUI (Qt/Electron)
- Wizard for setup and recovery
- USB drive detection and verification

11.2 Medium-Term Research

- Machine-checked security proofs (Coq/Isabelle)
- Verified implementation subset
- Automated security testing
- Threshold decryption (3-of-5 USB drives)
- Distributed key generation
- Secure computation for recovery
- Time-locked recovery mechanisms

- Decentralized backup verification
- Smart contract-based access control
- FIDO2/WebAuthn support
- Biometric + USB + passphrase (3-factor)
- Privacy-preserving biometric templates

11.3 Long-Term Vision

- Automatic algorithm migration
- Backward compatibility with quantum-vulnerable systems
- Hybrid classical/post-quantum operation
- QKD integration for ultra-secure environments
- Quantum-resistant + quantum mechanics security
- Research collaboration with quantum computing labs
- IETF RFC for dual-device secret splitting
- NIST guidance for post-quantum storage systems
- Industry adoption and ecosystem development
- Published peer-reviewed security analysis
- Collaboration with cryptography research groups
- Graduate student projects and internships

11.4 Community Development

- Accept community contributions
- Bug bounty program for security issues
- Regular security audits by third parties
- Video tutorials for non-technical users
- Enterprise deployment guides
- Security certification guidance
- Rust implementation for performance

- Go library for cloud-native applications
- JavaScript/WASM for web applications

12. Conclusion

12.1 Summary of Contributions

This white paper presented **pqcdualusb**, a novel approach to secure secret storage that combines:

Physical Security: Splitting secrets across two USB drives eliminates single points of failure

Cryptographic Security: Post-quantum algorithms protect against future quantum computers

Practical Usability: Simple Python API makes advanced cryptography accessible

Long-Term Protection: Designed for decades of security, not just years

The system addresses the emerging threat of quantum computing while maintaining backward compatibility and practical usability. By implementing NIST-approved post-quantum algorithms (Kyber1024 and Dilithium3) in a user-friendly package, pqcdualusb makes quantum-resistant cryptography accessible to developers, security professionals, and organizations.

12.2 Key Insights

The combination of physical separation (two USB drives) and cryptographic protection (post-quantum encryption) provides defense in depth. Even if cryptography is broken, physical separation provides security; even if one drive is stolen, cryptography protects the data.

The "harvest now, decrypt later" attack means that data encrypted today with classical algorithms is vulnerable to future quantum computers. Organizations must adopt post-quantum cryptography now, not later.

Complex security systems are often misconfigured or avoided entirely. By providing a simple Python API, pqcdualusb makes strong security accessible to developers without cryptographic expertise.

Security through obscurity is not security. Open-source implementation allows community security audits and builds trust through transparency.

12.3 Recommendations

- Integrate pqcdualusb into password managers and cryptocurrency wallets

- Contribute to open-source development and security audits
- Build applications that leverage dual-USB storage
- Evaluate pqcdualusb for air-gapped secret storage
- Conduct independent security audits
- Provide feedback for security enhancements
- Adopt post-quantum cryptography for long-term data protection
- Implement dual-device storage for critical secrets
- Plan for quantum transition now, not later
- Investigate formal security proofs and verification
- Explore integration with other post-quantum systems
- Publish independent analysis and improvements

12.4 Final Remarks

The transition to post-quantum cryptography is not optional—it is inevitable. Organizations that fail to adopt quantum-resistant algorithms today risk exposing sensitive data to decryption by future quantum computers.

The **pqcdualusb** system demonstrates that post-quantum cryptography can be both secure and usable. By combining NIST-approved algorithms with practical storage architecture, we provide a solution that protects secrets today and for decades to come.

We invite the security community to review, audit, and contribute to this project. Together, we can build a quantum-safe future for secret storage.

13. References

Academic Papers

Cryptographic Standards

Security Analysis

Implementation References

Industry Reports

Threat Intelligence

Appendix A: Glossary

Appendix B: Security Checklist

Deployment Security Checklist

- [ ] USB drives purchased from reputable source (not pre-owned)
- [ ] USB drives verified to be genuine (not counterfeit)
- [ ] Strong passphrase generated (≥12 characters, high entropy)
- [ ] Passphrase stored securely (password manager or memorized)
- [ ] USB drives physically separated after initialization
- [ ] USB drives stored in secure locations (safe, deposit box)
- [ ] Access to USB drives logged and monitored
- [ ] Regular verification of USB drive integrity (annual)
- [ ] Backup of USB drives created (tertiary backup)
- [ ] Recovery procedure documented and tested
- [ ] Personnel trained on recovery procedure
- [ ] Emergency contact information documented

Operational Security Checklist

- [ ] Initialization performed on air-gapped computer
- [ ] Computer verified to be malware-free before operation
- [ ] Physical security during operation (isolated room)
- [ ] USB drives never connected to internet-connected computers
- [ ] Memory wiped after operations (reboot)

- [ ] Operation logs reviewed for anomalies
- [ ] USB drives ejected safely (no corruption)
- [ ] USB drive firmware verified (no malicious updates)

Compliance Checklist

- [ ] Data classification documented (Public/Internal/Confidential/Secret)
- [ ] Encryption standards documented
- [ ] Key management procedures documented
- [ ] Access control procedures documented
- [ ] Audit trail maintained
- [ ] Incident response plan documented
- [ ] Regular security assessments conducted
- [ ] Compliance requirements verified (HIPAA/PCI-DSS/GDPR)

Appendix C: Source Code Repository

Appendix D: Contact Information

This work builds upon decades of cryptographic research by the global security community. Special thanks to:

- NIST Post-Quantum Cryptography project team
- Open Quantum Safe project contributors
- Python Cryptographic Authority maintainers
- Security researchers who review and improve open-source cryptography

suitability of the information. Users should conduct their own security assessments before deploying in production environments.