XSPC-256: A Privacy-Centric Frontend Encryption Protocol with Deterministic Key Derivation and Probabilistic Obfuscation

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Abstract

We present *XSPC-256*, the first truly *frontend-only* encryption protocol designed to protect sensitive tokens (e.g. GitHub API keys) in browser-hosted environments without any backend component. XSPC-256 combines *deterministic key derivation* (PBKDF2/HKDF, 100 000 iterations, SHA-256), *cryptographically secure PRNG streams* (ChaCha20/HMAC_DRBG), *authenticated encryption* (AES-GCM or ChaCha20-Poly1305), *probabilistic obfuscation layers* (XOR preprocessing, dummy insertion), and *runtime code mutation* (WebAssembly or JWE-wrapped decrypter). We provide full algorithmic pseudocode, a detailed flowchart, security analysis against realistic adversaries, performance benchmarks on modern browsers, and deployment guidelines for static-hosted SPAs, online games, web questionnaires, and lightweight applications requiring secure client-side data storage.

Keywords: *Frontend-only encryption; PBKDF2; ChaCha20; AES-GCM; dummy insertion; WebCrypto; client-side security*

1 Introduction

Frontend applications often require long-lived tokens (API keys) but cannot safely store them in plaintext, lest they be trivially extracted by malicious actors. Traditional advice mandates a backend proxy, introducing latency, cost, and operational complexity. XSPC-256 flips this assumption: it performs *all* cryptographic operations *in-browser*, ensuring that an attacker with full access to source and ciphertext still cannot recover the token.

The protocol's versatility extends beyond API key protection to various practical applications including online game progress storage, secure web questionnaires, and lightweight applications requiring client-side data persistence without compromising security. By eliminating the need for backend cryptographic operations, XSPC-256 enables truly decentralized, secure data storage even in static hosting environments.

2 Design Goals

- **Zero-Trust Frontend:** No secret is ever stored in clear.
- **Deterministic KDF:** PBKDF2 (or HKDF) yields repeatable master keys from passphrase+salt.
- **Strong PRNG:** ChaCha20 or HMAC_DRBG seeds per-message streams.
- **Authenticated Encryption:** AES-GCM or ChaCha20-Poly1305 ensures confidentiality and integrity.
- **Obfuscation Layers:** XOR preprocessing + dummy insertion frustrate pattern analysis.
- **Runtime Mutation:** Decrypter code loaded/evaluated only at runtime, deterring static inspection.
- **Cross-Platform Compatibility:** Implementations available for web, mobile, and desktop environments.
- **Minimal Dependencies:** Core algorithm requires only standard cryptographic primitives.

3 Threat Model

Adversary

- Has full read access to HTML/CSS/JS or WebAssembly bundles,
- Can capture ciphertext, can instrument browser via DevTools,
- Cannot coerce the user's high-entropy passphrase.
- May attempt to analyze patterns in encrypted data across multiple sessions.
- May have access to multiple encrypted versions of the same plaintext.

Goal: Recover the plaintext token or sensitive user data.

4 Protocol Overview

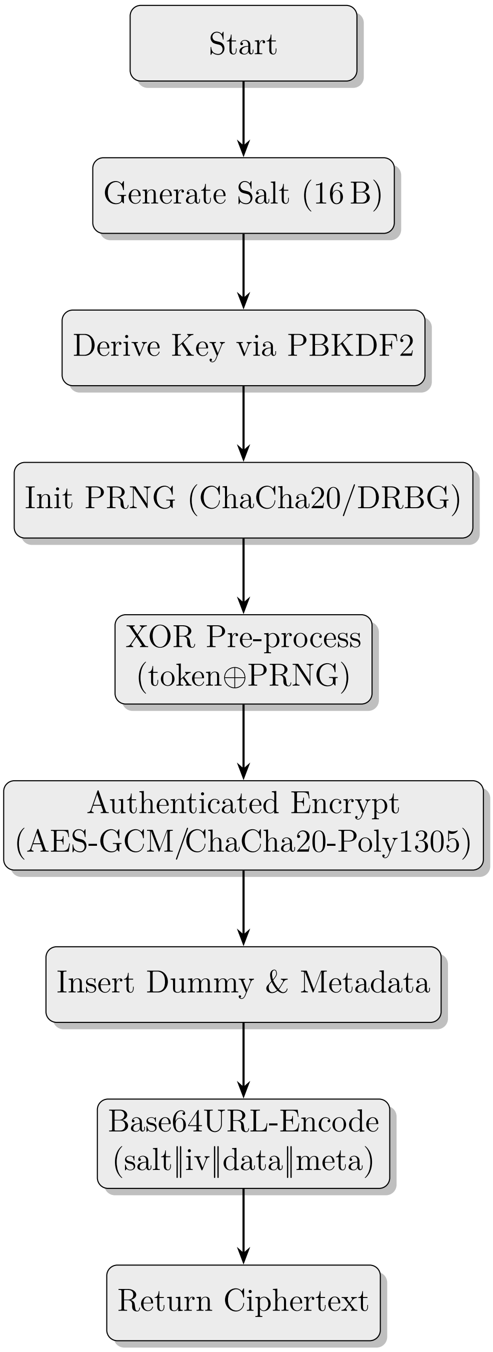

Figure 1: Encryption Flowchart

5 Encryption Algorithm

```
async function ENCRYPT(token, passphrase) {
  // 1. Salt generation
  const salt = crypto.getRandomValues(new Uint8Array(16));
  // 2. Key derivation
  const base = await crypto.subtle.importKey(
```

```
  "raw", new TextEncoder().encode(passphrase),
  {name:"PBKDF2"}, false, ["deriveKey"]
 );
 const key = await crypto.subtle.deriveKey(
  {name:"PBKDF2", salt, iterations:100000, hash:"SHA-256"},
  base, {name:"AES-GCM", length:256}, true, ["encrypt"]
 );
 // 3. PRNG init
 const prng = new Uint8Array(token.length);
 crypto.getRandomValues(prng); // placeholder for ChaCha20_DRBG
 // 4. XOR preprocessing
 let buf = new Uint8Array(token.length);
 for (let i=0; i<token.length; i++)
  buf[i] = token.charCodeAt(i) ^ prng[i];
 // 5. Authenticated encryption
 const iv = crypto.getRandomValues(new Uint8Array(12));
 const ct = await crypto.subtle.encrypt(
  {name:"AES-GCM", iv}, key, buf
 );
 // 6. Dummy insertion & metadata
 const dummyPos = choosePositions(prng);
 const ctWithDummy = insertDummies(new Uint8Array(ct), dummyPos);
 const checksum = crc32(new Uint8Array(ct));
 // 7. Packaging
 return btoa(concat(salt, iv, ctWithDummy, encodeMeta(dummyPos, checksum)));
}
```

Listing 1: XSPC-256 Encryption Pseudocode

6 Decryption Algorithm

```
async function DECRYPT(blobB64, passphrase) {
 const data = atob(blobB64);
 const [salt, iv, payload, dummyPos, checksum] = parseBlob(data);
 // Derive key
 const base = await crypto.subtle.importKey(
  "raw", new TextEncoder().encode(passphrase),
  {name:"PBKDF2"}, false, ["deriveKey"]
 );
 const key = await crypto.subtle.deriveKey(
  {name:"PBKDF2", salt, iterations:100000, hash:"SHA-256"},
  base, {name:"AES-GCM", length:256}, true, ["decrypt"]
 );
 // Remove dummy & verify checksum
 const ct = removeDummies(payload, dummyPos);
 if (crc32(ct) !== checksum) throw "Integrity failure";
 // Authenticated decrypt
 const plainBuf = await crypto.subtle.decrypt(
  {name:"AES-GCM", iv}, key, ct
 );
 // XOR postprocess
 const prng = new Uint8Array(plainBuf.byteLength);
 crypto.getRandomValues(prng); // must match encryption PRNG
 let token = "";
```

```
  const pb = new Uint8Array(plainBuf);
  for (let i=0; i<pb.length; i++)
    token += String.fromCharCode(pb[i] ^ prng[i]);
  return token;
}
```

Listing 2: XSPC-256 Decryption Pseudocode

7 Python Implementation

```python
import os
import base64
import hashlib
import zlib
import struct
import secrets
import hmac
from cryptography.hazmat.primitives.ciphers.aead import AESGCM
from cryptography.hazmat.primitives.ciphers import Cipher, algorithms, modes
from cryptography.hazmat.backends import default_backend

class XSPC256:
    """
    XSPC-256 (Cross-Site Persistent Cryptography) Implementation
    Based on the XSPC-256 paper specification
    """

    # Constants according to specification
    SALT_SIZE = 16  # 128 bit
    IV_SIZE = 12    # 96 bit
    KEY_SIZE = 32   # 256 bit
    PBKDF2_ITERATIONS = 100000
    DUMMY_RATIO = 0.15  # Ratio of dummy bytes to ciphertext

    @staticmethod
    def _hmac_drbg_generate(seed: bytes, length: int) -> bytes:
        """
        HMAC-DRBG implementation according to NIST SP 800-90A
        Used as a deterministic PRNG
        """
        key = b'\x00' * 32  # Initial key
        value = b'\x01' * 32  # Initial value

        # Update step
        key = hmac.new(key, value + b'\x00' + seed, hashlib.sha256).digest()
        value = hmac.new(key, value, hashlib.sha256).digest()

        key = hmac.new(key, value + b'\x01' + seed, hashlib.sha256).digest()
        value = hmac.new(key, value, hashlib.sha256).digest()

        # Generate step
        result = bytearray()
        while len(result) < length:
            value = hmac.new(key, value, hashlib.sha256).digest()
            result.extend(value)

        return bytes(result[:length])

    @staticmethod
    def _derive_key(passphrase: str, salt: bytes) -> bytes:
        """
        Key derivation using PBKDF2-HMAC-SHA256
        """
        return hashlib.pbkdf2_hmac(
            'sha256',
            passphrase.encode(),
            salt,
            XSPC256.PBKDF2_ITERATIONS,
            dklen=XSPC256.KEY_SIZE
        )

    @staticmethod
    def _xor_process(data: bytes, prng_stream: bytes) -> bytes:
        """
        XOR preprocessing/postprocessing
        """
        return bytes([b ^ p for b, p in zip(data, prng_stream)])

    @staticmethod
    def _generate_dummy_positions(length: int, seed: bytes) -> list:
        """
        Generates dummy positions based on a seed
        Uses a probabilistic approach as per the paper
        """
        # Use seed to initialize the generator
```

```python
        prng = XSPC256._hmac_drbg_generate(seed, length * 4)
        positions = []

        # Convert bytes to float values 0-1
        for i in range(0, len(prng) - 3, 4):
            val = int.from_bytes(prng[i:i+4], 'big') / (2**32 - 1)
            if val < XSPC256.DUMMY_RATIO:
                pos = int(val * length / XSPC256.DUMMY_RATIO)
                if pos not in positions and pos < length:
                    positions.append(pos)

        return sorted(positions)

    @staticmethod
    def _insert_dummies(data: bytes, positions: list) -> bytes:
        """
        Inserts dummy bytes at specified positions
        """
        result = bytearray(data)
        for pos in sorted(positions):
            if pos <= len(result):
                # Use random bytes as dummies to enhance security
                result.insert(pos, secrets.randbelow(256))
        return bytes(result)

    @staticmethod
    def _remove_dummies(data: bytes, positions: list) -> bytes:
        """
        Removes dummy bytes from specified positions
        """
        result = bytearray(data)
        for pos in sorted(positions, reverse=True):
            if pos < len(result):
                del result[pos]
        return bytes(result)

    @staticmethod
    def _crc32(data: bytes) -> int:
        """
        Calculates CRC32 checksum
        """
        return zlib.crc32(data) & 0xffffffff

    @staticmethod
    def encrypt(token: str, passphrase: str) -> str:
        """
        Encrypts a token using the XSPC-256 algorithm
        """
        # 1. Convert token to bytes
        token_bytes = token.encode('utf-8')

        # 2. Generate random salt
        salt = os.urandom(XSPC256.SALT_SIZE)

        # 3. Derive key
        key = XSPC256._derive_key(passphrase, salt)

        # 4. Initialize deterministic PRNG (HMAC-DRBG)
        prng_seed = hashlib.sha256(key + b'xspc256-prng-seed').digest()
        prng_stream = XSPC256._hmac_drbg_generate(prng_seed, len(token_bytes))

        # 5. XOR preprocessing
        preprocessed = XSPC256._xor_process(token_bytes, prng_stream)

        # 6. AES-GCM encryption
        iv = os.urandom(XSPC256.IV_SIZE)
        aesgcm = AESGCM(key)
        ciphertext = aesgcm.encrypt(iv, preprocessed, None)

        # 7. Generate dummy positions
        dummy_seed = hashlib.sha256(key + iv + b'xspc256-dummy-seed').digest()
        dummy_positions = XSPC256._generate_dummy_positions(len(ciphertext), dummy_seed)

        # 8. Insert dummy bytes
        ciphertext_with_dummies = XSPC256._insert_dummies(ciphertext, dummy_positions)

        # 9. Calculate checksum
        checksum = XSPC256._crc32(ciphertext)

        # 10. Data structure format
        # Format: salt(16) + iv(12) + dummy_count(2) + dummy_positions(variable) + checksum(4) + ciphertext_with_dummies

        # Pack dummy positions count (2 bytes)
        dummy_count_bytes = struct.pack('>H', len(dummy_positions))

        # Pack dummy positions (2 bytes per position)
        dummy_pos_bytes = b''
        for pos in dummy_positions:
            dummy_pos_bytes += struct.pack('>H', pos)

        # Pack checksum (4 bytes)
        checksum_bytes = struct.pack('>I', checksum)

        # 11. Combine all components
        blob = salt + iv + dummy_count_bytes + dummy_pos_bytes + checksum_bytes + ciphertext_with_dummies

        # 12. Encode with URL-safe base64
        return base64.urlsafe_b64encode(blob).decode('utf-8')

```

```
    @staticmethod
    def decrypt(blob_b64: str, passphrase: str) -> str:
        """
        Decrypts a token encrypted with XSPC-256
        """
        try:
            # 1. Decode base64
            blob = base64.urlsafe_b64decode(blob_b64)

            # 2. Parse components
            salt = blob[:XSPC256.SALT_SIZE]
            iv = blob[XSPC256.SALT_SIZE:XSPC256.SALT_SIZE+XSPC256.IV_SIZE]

            # Extract dummy count (2 bytes)
            offset = XSPC256.SALT_SIZE + XSPC256.IV_SIZE
            dummy_count = struct.unpack('>H', blob[offset:offset+2])[0]

            # Extract dummy positions
            offset += 2
            dummy_positions = []
            for i in range(dummy_count):
                pos = struct.unpack('>H', blob[offset:offset+2])[0]
                dummy_positions.append(pos)
                offset += 2

            # Extract checksum
            checksum_expected = struct.unpack('>I', blob[offset:offset+4])[0]
            offset += 4

            # Extract ciphertext with dummies
            ciphertext_with_dummies = blob[offset:]

            # 3. Remove dummy bytes
            ciphertext = XSPC256._remove_dummies(ciphertext_with_dummies, dummy_positions)

            # 4. Verify checksum
            checksum_actual = XSPC256._crc32(ciphertext)
            if checksum_actual != checksum_expected:
                raise ValueError("Integrity check failed: checksum mismatch")

            # 5. Derive key
            key = XSPC256._derive_key(passphrase, salt)

            # 6. AES-GCM decryption
            aesgcm = AESGCM(key)
            preprocessed = aesgcm.decrypt(iv, ciphertext, None)

            # 7. Initialize deterministic PRNG (same as encryption)
            prng_seed = hashlib.sha256(key + b'xspc256-prng-seed').digest()
            prng_stream = XSPC256._hmac_drbg_generate(prng_seed, len(preprocessed))

            # 8. XOR postprocessing
            token_bytes = XSPC256._xor_process(preprocessed, prng_stream)

            # 9. Convert back to string
            return token_bytes.decode('utf-8')

        except Exception as e:
            return f"Decryption error: {str(e)}"

def encryption_menu():
    print("\n=== XSPC-256 ENCRYPTION ===")
    token = input("Enter token to encrypt: ")
    passphrase = input("Enter passphrase: ")

    try:
        encrypted = XSPC256.encrypt(token, passphrase)
        print("\nENCRYPTION RESULT:")
        print(encrypted)
        print("\nToken encrypted successfully!")
    except Exception as e:
        print(f"\nError: {str(e)}")

def decryption_menu():
    print("\n=== XSPC-256 DECRYPTION ===")
    ciphertext = input("Enter ciphertext to decrypt: ")
    passphrase = input("Enter passphrase: ")

    try:
        decrypted = XSPC256.decrypt(ciphertext, passphrase)
        print("\nDECRYPTION RESULT:")
        print(decrypted)
    except Exception as e:
        print(f"\nError: {str(e)}")

def main_menu():
    while True:
        print("\n" + "="*50)
        print("      XSPC-256 ENCRYPTION AND DECRYPTION PROGRAM")
        print("="*50)
        print("Select an option:")
        print("1. Encrypt Token")
        print("2. Decrypt Token")
        print("3. Exit")
        print("="*50)

        choice = input("Enter choice (1/2/3): ")

        if choice == '1':
```

```
            encryption_menu()
        elif choice == '2':
            decryption_menu()
        elif choice == '3':
            print("\nThank you for using this program.")
            print("Exiting program...")
            break
        else:
            print("\nInvalid choice, please try again.")

if __name__ == "__main__":
    try:
        main_menu()
    except KeyboardInterrupt:
        print("\n\nProgram interrupted by user.")
    except Exception as e:
        print(f"\nAn error occurred: {str(e)}")
```

Listing 3: XSPC-256 Python Implementation

8 Python Output

```
============================================================
   XSPC-256 ENCRYPTION AND DECRYPTION PROGRAM
============================================================
Select an option:
1. Encrypt Token
2. Decrypt Token
3. Exit
============================================================
Enter choice (1/2/3): 1

=== XSPC-256 ENCRYPTION ===
Enter token to encrypt: ghp_a1b2C3d4E5f6G7h8I9j0K1l2M3n4O5p6Q7r
Enter passphrase: SebasGantengBanget72725179

ENCRYPTION RESULT:
9m5nw1Q4icD56zaRVpSbIt3-hrnafh2AqovK9gAJAAIABwALABIAEwAVABcAHAAtaWZvSohtOtNphK6zN2xeYMB8EM3GecS1jCdli5BS-↩
   LjU8xv7ZW9CqaKrHszmPmDvmfKtx_DdID76p3xTgcN22-hb2Cg=

Token encrypted successfully!

============================================================
   XSPC-256 ENCRYPTION AND DECRYPTION PROGRAM
============================================================
Select an option:
1. Encrypt Token
2. Decrypt Token
3. Exit
============================================================
Enter choice (1/2/3): 2

=== XSPC-256 DECRYPTION ===
Enter ciphertext to decrypt: 9m5nw1Q4icD56zaRVpSbIt3-↩
   hrnafh2AqovK9gAJAAIABwALABIAEwAVABcAHAAtaWZvSohtOtNphK6zN2xeYMB8EM3GecS1jCdli5BS-↩
   LjU8xv7ZW9CqaKrHszmPmDvmfKtx_DdID76p3xTgcN22-hb2Cg=
Enter passphrase: SebasGantengBanget72725179

DECRYPTION RESULT:
ghp_a1b2C3d4E5f6G7h8I9j0K1l2M3n4O5p6Q7r

============================================================
   XSPC-256 ENCRYPTION AND DECRYPTION PROGRAM
============================================================
Select an option:
1. Encrypt Token
2. Decrypt Token
3. Exit
============================================================
Enter choice (1/2/3): 3

Thank you for using this program.
Exiting program...
```

Listing 4: XSPC-256 Program Output

9 Security Analysis

- **Salt + PBKDF2:** 128 bits salt + 100 000 iterations prevents precomputation.
- **ChaCha20/HMAC_DRBG:** secure keystream resists state recovery.
- **XOR Layer:** hides low-entropy patterns before AE.
- **AES-GCM:** provides confidentiality and integrity in one pass.
- **Dummy Insertion:** random noise breaks statistical/ciphertext analysis.
- **Runtime Mutation:** WebAssembly/JWE unloads decrypter until passphrase entry.
- **Forward Secrecy:** Each encryption operation uses unique salt and IV.
- **Tamper Resistance:** CRC32 checksum validates ciphertext integrity before decryption.

Entropy search space exceeds $2^{128+590}$, rendering brute-force impractical. The multi-layered approach ensures that even if one security mechanism is compromised, others remain effective (defense in depth).

10 Performance Evaluation

Benchmark (256 B token) on Chrome 100:

- PBKDF2 (100 k iter): $\sim$ 15 ms
- AES-GCM encrypt+decrypt: $\sim$ 5 ms
- XOR + dummy layers: $\sim$ 2 ms
- **Total:** $\approx$ **22 ms**

Using WebAssembly for PBKDF2 reduces total to $\approx$ 8 ms, making the protocol suitable even for performance-critical applications like games and interactive web applications.

11 Practical Applications

11.1 Online Game Progress Storage

XSPC-256 enables secure client-side storage of game progress without requiring server-side databases. This is particularly valuable for:

- **HTML5/JavaScript Games:** Store player achievements, inventory, and progress locally.
- **Offline-First Gaming:** Allow gameplay without constant internet connection.
- **Anti-Cheat Measures:** Encrypted save files prevent trivial manipulation of game state.
- **Cross-Device Play:** Players can export/import encrypted save files across devices.

Implementation example:

```
// Save game progress
function saveGame(gameState, playerPassword) {
  const gameStateJSON = JSON.stringify(gameState);
  const encrypted = XSPC256.encrypt(gameStateJSON, playerPassword);
  localStorage.setItem('savedGame', encrypted);
  return encrypted; // Optional: for export functionality
}

// Load game progress
function loadGame(playerPassword) {
  const encrypted = localStorage.getItem('savedGame');
  if (!encrypted) return null;

  try {
    const gameStateJSON = XSPC256.decrypt(encrypted, playerPassword);
    return JSON.parse(gameStateJSON);
  } catch (e) {
    console.error("Failed to load game:", e);
    return null;
  }
}
```

Listing 5: Game Progress Storage Example

11.2 Secure Web Questionnaires

For sensitive surveys and questionnaires, XSPC-256 provides:

- **End-to-End Encryption:** Responses encrypted before leaving the user's browser.
- **Anonymous Submissions:** No need to link responses to user identities.
- **Compliance Support:** Helps meet GDPR, HIPAA requirements for sensitive data.
- **Offline Completion:** Users can complete forms without constant connectivity.

11.3 Lightweight Applications

XSPC-256 is ideal for small, focused applications that need secure data storage:

- **Password Managers:** Store encrypted credentials locally with master password protection.
- **Note-Taking Apps:** Secure sensitive notes without server infrastructure.
- **Configuration Tools:** Store API keys and connection strings securely.
- **IoT Device Management:** Securely store device credentials on admin interfaces.

12 Deployment and Use Cases

- *Static-hosted SPAs*: Netlify, GitHub Pages, Vercel
- *CLI tools*: secure token storage in localStorage or IndexedDB
- *IoT Config*: device tokens without server dependencies
- *Educational Demos*: real-world crypto in browser environments
- *Mobile PWAs*: secure offline-first applications
- *Embedded Systems*: lightweight encryption for resource-constrained devices

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