SARX v1.1.0
ARX-256 Stream Cipher with Argon2id + BLAKE3 AEAD

Implementation Spec (Rust `SARX_rs`)

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1 Overview

This document specifies the SARX v1.1.0 encryption scheme as implemented in the Rust crate `SARX_rs`. The scheme has three layers:

1. A stateless 256-bit ARX stream cipher ("Substrate ARX-256").
2. A password-based AEAD construction using Argon2id and keyed BLAKE3 (encrypt–then–MAC).
3. A fixed 61-byte vault header format followed by a 32-byte MAC tag and ciphertext.

The current version (v1.1.0) uses:

- Keystream: pure ARX-256, keyed by a 256-bit key derived as $\text{base\_key}_{32} = \text{BLAKE3}(\texttt{password} \,\|\, \text{ts\_ns})$.
- Key stretching and MAC key: Argon2id with a BLAKE3-derived salt.
- Authentication: keyed BLAKE3 over the header, ciphertext length, and ciphertext.

A vault file has the structure

$$\text{vault} = \underbrace{H}_{61\ \text{bytes}} \;\|\; \underbrace{T}_{32\ \text{bytes}} \;\|\; \underbrace{C}_{\text{ciphertext bytes}},$$

where H is the header, T is a 32-byte MAC tag, and C is the ciphertext.

2 Notation and Conventions

- All additions on 64-bit words are modulo 2^{64}.
- $\oplus$ denotes bitwise XOR.

- $\mathrm{ROTL}_{64}(x, r)$ is a 64-bit left rotation of x by r bits.
- $\mathrm{LE64}(x)$ and $\mathrm{BE64}(x)$ are the 8-byte little- and big-endian encodings of a 64-bit integer x.
- Byte strings are indexed from 0.
- $\mathrm{len}(X)$ is the length of a byte string X.
- $\mathrm{BLAKE3\_XOF}(M)$ denotes BLAKE3 in extendable-output mode, truncated to the required number of bytes.
- $\mathrm{BLAKE3\_KEYED}(K, M)$ denotes keyed BLAKE3-XOF with 32-byte key K.
- $\mathrm{Argon2id}(\texttt{pw}, \texttt{salt}, t, m, \ell, p)$ denotes the Argon2id KDF with time cost t, memory cost m, output length ℓ, and p lanes.

3 Vault Header Format

Every vault begins with a 61-byte header H with the following layout:

$$H = \underbrace{\texttt{"SARX"}}_{4} \parallel \underbrace{v}_{1} \parallel \underbrace{\texttt{salt}_{32}}_{32} \parallel \underbrace{\mathrm{BE64}(\mathrm{ts\_ns})}_{8} \parallel \underbrace{\texttt{nonce}_{12}}_{12} \parallel \underbrace{t\_cost}_{1} \parallel \underbrace{m\_cost}_{1} \parallel \underbrace{lanes}_{1} \parallel \underbrace{kdf\_id}_{1},$$

where:

- Magic: bytes 0–3: `"SARX"`.
- Version: byte 4: $v = 0x03$ (SARX vault version).
- Salt: bytes 5–36: $\texttt{salt}_{32}$ (32-byte salt for Argon2id).
- Timestamp: bytes 37–44: $\mathrm{BE64}(\mathrm{ts\_ns})$, a 64-bit nanosecond timestamp (Unix epoch).
- Nonce: bytes 45–56: $\texttt{nonce}_{12}$, a 96-bit random nonce.
- Argon2id parameters:
  - t_cost (byte 57): in range $[1, 10]$.
  - m_cost (byte 58): exponent so that memory $= 2^{m\_cost}$ KiB (for v1.1.0, $m\_cost = 17$, i.e. 128 MiB).
  - $lanes$ (byte 59): in range $[1, 4]$ (v1.1.0 uses 1).
  - kdf_id (byte 60): KDF identifier; $kdf\_id = 2$ means Argon2id v1.3.

In the current implementation, the header fields are populated as:

$$
\begin{aligned}
v &= 0x03,\\
\texttt{nonce}_{12} &\leftarrow \text{12 random bytes},\\
\text{ts\_ns} &\leftarrow \text{current time in nanoseconds since Unix epoch},\\
\texttt{salt}_{32} &:= \text{BLAKE3\_XOF}(\text{BE64}(\text{ts\_ns}) \,\|\, \texttt{nonce}_{12})[0..32],\\
t\_cost &= 3,\\
m\_cost &= 17,\\
lanes &= 1,\\
kdf\_id &= 2.
\end{aligned}
$$

4 Substrate ARX-256 Keystream Core

4.1 Key Derivation for the Stream Cipher

Given a UTF-8 password `pw` and timestamp $\text{ts\_ns} \in \{0, \ldots, 2^{64} - 1\}$, the 256-bit stream key is:

$$\texttt{base\_key}_{32} := \text{BLAKE3\_XOF}(\texttt{pw} \,\|\, \text{BE64}(\text{ts\_ns}))[0..32].$$

Interpret `base_key_32` as four little-endian 64-bit words:

$$(k_0, k_1, k_2, k_3) \in (\mathbb{Z}_{2^{64}})^4.$$

4.2 ARX Block Function

Let $R = 8$ be the number of rounds. Define the 64-bit constant

$$c = \texttt{0x9E3779B97F4A7C15}.$$

Given a 64-bit block counter ctr and key state $(k_0, \ldots, k_3)$, the ARX block proceeds as follows:

Initialization.

$$
\begin{aligned}
x_0 &= k_0 \oplus (\text{ctr} \cdot c),\\
x_1 &= k_1,\\
x_2 &= k_2,\\
x_3 &= k_3 \oplus \text{ctr}.
\end{aligned}
$$

Store the original state

$$(o_0, o_1, o_2, o_3) := (x_0, x_1, x_2, x_3).$$

Round function. For $r = 1, \dots, R$ do:

Column step:

$$\begin{aligned}
x_0 &:= x_0 + x_1, \\
x_3 &:= \mathrm{ROTL}_{64}(x_3 \oplus x_0, 27), \\
x_2 &:= x_2 + x_3, \\
x_1 &:= \mathrm{ROTL}_{64}(x_1 \oplus x_2, 31);
\end{aligned}$$

Diagonal step:

$$\begin{aligned}
x_0 &:= x_0 + x_2, \\
x_3 &:= \mathrm{ROTL}_{64}(x_3 \oplus x_0, 17), \\
x_1 &:= x_1 + x_3, \\
x_2 &:= \mathrm{ROTL}_{64}(x_2 \oplus x_1, 23).
\end{aligned}$$

Feedforward. Let $(y_0, y_1, y_2, y_3) := (x_0, x_1, x_2, x_3)$. The final block words are

$$(z_0, z_1, z_2, z_3) := (y_0 + o_0,\ y_1 + o_1,\ y_2 + o_2,\ y_3 + o_3) \pmod{2^{64}}.$$

The 32-byte keystream block for counter ctr is

$$\mathrm{Block}(\mathrm{ctr}) := \mathrm{LE64}(z_0) \,\|\, \mathrm{LE64}(z_1) \,\|\, \mathrm{LE64}(z_2) \,\|\, \mathrm{LE64}(z_3).$$

4.3 Byte-level Stream with Offset

Define the infinite keystream as a concatenation of blocks:

$$S = \mathrm{Block}(0) \,\|\, \mathrm{Block}(1) \,\|\, \mathrm{Block}(2) \,\|\, \dots$$

Each block is 32 bytes.

To generate a slice of keystream starting at byte offset $o \in \mathbb{Z}_{\geq 0}$ of length L:

1. Let $B = 32$ (block size in bytes).
2. Compute start_blk $= \lfloor o/B \rfloor$, and skip $= o \bmod B$.
3. Initialize ctr = start_blk, and an empty buffer K.
4. While $\mathrm{len}(K) < L$:
    (a) Compute Block(ctr) as above.
    (b) Append bytes from Block(ctr)[skip..] to K.
    (c) Set skip := 0 and ctr := ctr + 1.

5. Truncate K to its first L bytes.

This is exactly the behavior of the Rust function `arx256_fill` with base counter 0 and byte offset o.

5 Key Stretching and MAC Key

Given a password `pw` and salt $\texttt{salt}_{32}$ from the header:

1. Let $b = \mathrm{len}(\texttt{pw})$ (bytes).
2. Let $k\_\mathrm{stream\_len} = \max(32, \text{next multiple of 32 of } b)$.
3. Let $\ell = k\_\mathrm{stream\_len} + 32$.
4. Compute
$$\texttt{okm} := \mathrm{Argon2id}(\texttt{pw}, \texttt{salt}_{32}, t = 3, m = 2^{m\_cost}\ \mathrm{KiB}, \ell, p = \texttt{lanes}).$$
5. Split:
$$k_{\mathrm{stream}} := \texttt{okm}[0..k\_\mathrm{stream\_len}], \qquad k_{\mathrm{mac}} := \texttt{okm}[k\_\mathrm{stream\_len}..k\_\mathrm{stream\_len}{+}32].$$
Interpret k_{mac} as a 32-byte BLAKE3 key.

In v1.1.0 the keystream does *not* depend on k_{stream}; it depends only on $\texttt{base\_key}_{32}$ from BLAKE3(password, timestamp).

A "postmix" value is still constructed as
$$\texttt{postmix} := \texttt{"SARX2DU-POST\textbackslash 0\textbackslash 0\textbackslash 0\textbackslash 0"} \parallel k_{\mathrm{stream}} \parallel \texttt{nonce}_{12} \parallel \mathrm{BE64}(\mathrm{ts\_ns}),$$
but in v1.1.0 this is ignored by the keystream function and reserved for future use.

6 MAC Tag

Let H be the 61-byte header, and C the ciphertext. Let
$$\ell_C := \mathrm{len}(C), \quad \texttt{len\_le} := \mathrm{LE64}(\ell_C).$$

Define the domain separation string
$$\texttt{dom\_mac} := \texttt{"SARX2DU-MAC-v1"}.$$

Given the 32-byte MAC key k_{mac}, the 32-byte tag T is:
$$T := \mathrm{BLAKE3\_KEYED}\big(k_{\mathrm{mac}}, \texttt{dom\_mac} \parallel H \parallel \texttt{len\_le} \parallel C\big)[0..32].$$

7 Encryption Algorithm

Input:

- Password `pw` (30–100 Unicode codepoints).
- Plaintext P (arbitrary byte string).

Output:

- Vault file: $H \,\|\, T \,\|\, C$.

Steps:

1. Generate ts_ns and $\texttt{nonce}_{12}$ as described in Section 3.
2. Compute $\texttt{salt}_{32} = \text{BLAKE3\_XOF}(\text{BE64}(\text{ts\_ns}) \,\|\, \texttt{nonce}_{12})[0..32]$.
3. Form header H with the chosen parameters $(t\_cost, m\_cost, lanes, kdf\_id)$.
4. Compute the Argon2id output `okm` and split it into $(k_{\text{stream}}, k_{\text{mac}})$ as in Section 5.
5. Compute $\texttt{base\_key}_{32} = \text{BLAKE3\_XOF}(\texttt{pw} \,\|\, \text{BE64}(\text{ts\_ns}))[0..32]$, interpret as $(k_0, \ldots, k_3)$.
6. Construct (inactive) postmix:
$$\texttt{postmix} = \texttt{"SARX2DU-POST\textbackslash 0\textbackslash 0\textbackslash 0\textbackslash 0"} \,\|\, k_{\text{stream}} \,\|\, \texttt{nonce}_{12} \,\|\, \text{BE64}(\text{ts\_ns}).$$
7. Generate keystream K for P using the ARX stream with key $(k_0, \ldots, k_3)$ and offset 0, ignoring the postmix:
$$K := \text{ARX\_256\_Stream}(\texttt{base\_key}_{32}, o = 0, L = \text{len}(P)).$$
8. Compute ciphertext C by XOR:
$$C[i] = P[i] \oplus K[i], \quad 0 \le i < \text{len}(P).$$
9. Compute MAC tag T as in Section 6.
10. Output $H \,\|\, T \,\|\, C$.

Note: In the reference implementation, encryption is performed in parallel chunks, but the logical stream is identical to the sequential ARX construction above.

8 Decryption and Verification

Input:

- Password `pw`.
- Vault file $H \,\|\, T \,\|\, C$.

Output:

- Plaintext P on success; or an error if authentication fails.

Steps:

1. Parse and validate the header H:
   - Check magic `"SARX"` and version $v = 0x03$.
   - Extract $\texttt{salt}_{32}$, ts_ns, $\texttt{nonce}_{12}$, and Argon2id parameters $(t\_cost, m\_cost, lanes, kdf\_id)$.
   - Abort if any parameter is out of range or unsupported.
2. Using `pw` and $\texttt{salt}_{32}$, derive `okm` and split $(k_{\text{stream}}, k_{\text{mac}})$ as in Section 5.
3. Recompute tag

$$T' := \text{BLAKE3\_KEYED}\big(k_{\text{mac}}, \texttt{dom\_mac} \,\|\, H \,\|\, \texttt{len\_le} \,\|\, C\big)[0..32],$$

   where $\texttt{len\_le} = \text{LE64}(\text{len}(C))$.
4. If $T' \neq T$ (constant-time comparison), abort with "MAC mismatch (wrong password or corrupted file)".
5. Compute $\texttt{base\_key}_{32} = \text{BLAKE3\_XOF}(\texttt{pw} \,\|\, \text{BE64}(\text{ts\_ns}))[0..32]$, interpret as $(k_0, \ldots, k_3)$.
6. Construct postmix as in the encryption procedure (for compatibility), but note that the current stream cipher ignores it.
7. Generate keystream K with the ARX stream cipher using $(k_0, \ldots, k_3)$ and offset 0:

$$K := \text{ARX\_256\_Stream}(\texttt{base\_key}_{32}, o = 0, L = \text{len}(C)).$$

8. Recover plaintext by XOR:

$$P[i] = C[i] \oplus K[i], \quad 0 \leq i < \text{len}(C).$$

On success, return P.

9 Randomness Testing (Implementation Notes)

For the ARX-256 keystream defined above, with `base_key`$_{32}$ derived from a password and timestamp as described, the reference implementation has been tested as follows:

- NIST SP 800-22, 200 sequences of length 10^6 bits: all tests passed with p-value distributions in acceptable ranges.
- Dieharder "core" battery on up to 2^{40}–2^{41} bytes of output from the streaming generator: no test failures, only the occasional "WEAK" or "unusual" flag expected under the null hypothesis.
- PractRand `stdin32/64` on multi-gigabyte streams: no anomalies detected up to the tested limits.

These tests are statistical sanity checks; they do not constitute a formal cryptographic proof. The security of the construction relies on:

- the pseudorandomness of the ARX-256 core under a secret 256-bit key,
- the preimage resistance and collision resistance of BLAKE3,
- the hardness of Argon2id against GPU/ASIC-accelerated password cracking.

Design Rationale

SARX was designed as a conservative, stream-cipher–based file-encryption scheme with the following goals:

- simple and auditable core primitives;
- standard, well-understood composition (Encrypt-then-MAC);
- strong passwords only (enforced at the interface);
- clear separation between key derivation, keystream generation, and authentication;
- high performance and easy parallelization on commodity hardware.

ARX-256 stream core. The keystream generator is a 256-bit ARX construction in counter mode. A 256-bit key is interpreted as four 64-bit words (k_0, k_1, k_2, k_3) and combined with a 64-bit block counter ctr via a simple injection

$$(x_0, x_1, x_2, x_3) \leftarrow (k_0 \oplus f(ctr),\ k_1,\ k_2,\ k_3 \oplus ctr),$$

where f is a fixed 64-bit linear function of ctr. This state is processed by a small, fixed ARX round function with 8 rounds and a final feedforward step, producing a 32-byte block of keystream. The construction is deliberately minimal:

- ARX-only (add, rotate, xor) operations are easy to implement efficiently and in constant time on general-purpose CPUs;
- the 256-bit key and 64-bit counter follow standard stream-cipher practice;
- the round structure and rotation constants were chosen from an automated search for near-ideal avalanche (about half the output bits flip when one input bit is toggled) and stable diffusion, and validated empirically with randomness tests (e.g. NIST SP800-22, Dieharder, PractRand).

In the security analysis, the ARX core can be modeled as a pseudorandom function $F_K(\cdot)$ keyed by the 256-bit secret K. Under this assumption, the resulting keystream generator is a standard PRG in counter mode, and the stream cipher "XOR with keystream" achieves indistinguishability from random under passive attacks (IND-CPA) in the usual way.

Encrypt-then-MAC with keyed BLAKE3. SARX uses a straightforward Encrypt-then-MAC composition for file encryption. Given a derived MAC key k_{mac} and a ciphertext C, the scheme computes a 32-byte tag

$$T = \mathsf{BLAKE3}_{k_{\text{mac}}}(\text{domain} \,\|\, \text{header} \,\|\, \text{len}(C) \,\|\, C),$$

where "header" includes all non-secret per-vault parameters (salt, timestamp, KDF parameters, nonce), and `domain` is a fixed ASCII label that separates this MAC usage from other uses of BLAKE3. The tag is written alongside the ciphertext.

Decryption verifies T before attempting to decrypt; on any mismatch the ciphertext is rejected. Under the assumption that keyed BLAKE3 behaves as a strong PRF and SUF-CMA MAC, the Encrypt-then-MAC composition yields standard IND-CCA and ciphertext-integrity guarantees, following the usual results for EtM.

Password and KDF layer. SARX assumes that secrets originate from human-chosen passwords, but enforces a strict strength policy: passwords must contain 30–100 Unicode codepoints. To derive keys from these passwords, SARX uses Argon2id with fixed parameters

$$t = 3, \quad m = 2^{17}\,\text{KiB (128 MiB)}, \quad \text{lanes} = 1,$$

and a 256-bit salt stored in the header. The KDF output is split into:

- a variable-length "stream key" k_{stream} used only in constructing a non-secret postmix string and optional hardening state; and
- a 256-bit key k_{mac} for the keyed BLAKE3 MAC.

These are independent from the 256-bit keystream key used by the ARX core, which is derived separately as

$$\mathsf{base\_key32} = \mathsf{BLAKE3}(\text{password} \,\|\, \text{timestamp}).$$

Optionally, SARX supports an additional cost-amplification flag `-thermo`: when enabled, the KDF output is further processed by a deterministic ARX-based random walk over a large scratch buffer, and a BLAKE3 digest of this walk is folded back into the derived key material. This adds a tunable, per-guess cost to brute-force attacks without changing the key schedule or the underlying security assumptions.

File format. Each encrypted file ("vault") consists of:

- a fixed-size header encoding: version, salt, Argon2 parameters, KDF mode identifier, timestamp, and nonce;
- a 32-byte MAC tag T; and
- the ciphertext C of the file content under the SARX stream cipher.

The header acts as associated data for the MAC and for the security analysis. The overall design matches a standard, auditable template:

$$\text{password} \xrightarrow{\text{Argon2id}(+\,\text{hardening})} (k_{\text{stream}}, k_{\text{mac}}), \quad \text{password} \xrightarrow{\mathsf{BLAKE3}} \mathsf{base\_key32} \xrightarrow{\text{ARX-256 CTR}} \text{keystream}.$$

The separation between KDF, stream cipher, and MAC makes it easy to reason about security in terms of standard assumptions (Argon2id as a memory-hard KDF, the ARX core as a PRF/PRG, and keyed BLAKE3 as a MAC), and the scheme itself follows conservative composition patterns.

10 Security Model and Reduction

In this section we analyse the SARX scheme under standard, black-box assumptions on its components. We treat the password-based KDF and the symmetric encryption separately: the reduction focuses on the security of the encryption and authentication layers, assuming the derived keys are uniformly random and unknown to the adversary. Resistance to offline dictionary attacks then depends on the password entropy and the cost of Argon2id, which we discuss briefly at the end.

10.1 Assumptions

Let $F : \{0,1\}^\kappa \times \{0,1\}^{64} \to \{0,1\}^{256}$ denote the ARX-256 block function used by SARX, with $\kappa = 256$ the key length. For each key $K \in \{0,1\}^\kappa$ define

$$F_K(\mathrm{ctr}) := F(K, \mathrm{ctr}) \in \{0,1\}^{256},$$

and let Stream_K be the keystream obtained by concatenating $F_K(0), F_K(1), \ldots$ and slicing at arbitrary byte offsets as specified earlier.

We make the following standard assumptions:

PRF assumption on F. For any probabilistic polynomial-time (PPT) adversary B_1 with oracle access to a function $O : \{0,1\}^{64} \to \{0,1\}^{256}$,

$$\mathrm{Adv}_F^{\mathrm{PRF}}(B_1) := \left| \Pr[\, B_1^{F_K} = 1\,] - \Pr[\, B_1^{R} = 1\,] \right|$$

is negligible in κ, where $K \leftarrow \{0,1\}^\kappa$ is uniform and R is a truly random function $R : \{0,1\}^{64} \to \{0,1\}^{256}$.

MAC assumption on keyed BLAKE3. Let $\mathsf{MAC}_K(M)$ denote the 32-byte tag computed as BLAKE3 in keyed mode on a message M with a 256-bit secret key K, as used in SARX. For any PPT adversary B_2 with oracle access to a tagging oracle $M \mapsto \mathsf{MAC}_K(M)$, the *strong unforgeability* advantage

$$\mathrm{Adv}_{\mathsf{MAC}}^{\mathrm{MAC}}(B_2) := \Pr\big[(M^\star, T^\star) \text{ is a valid forgery}\big]$$

is negligible, where a valid forgery means that either $M^\star$ is new (never queried before) and $T^\star = \mathsf{MAC}_K(M^\star)$, or $M^\star$ was queried before but $T^\star$ differs from all previously returned tags.

Derived key model. In analysing the symmetric encryption we treat the 256-bit stream key `base_key32` and the 256-bit MAC key k_{mac} as independent, uniformly random keys unknown to the adversary. This corresponds to modelling the Argon2id KDF and password as a black box which outputs high-entropy keys; offline password-guessing attacks are handled separately.

10.2 IND-CCA security notion

We model SARX as an authenticated-encryption scheme with associated data (the header H). For simplicity, we define security with respect to ciphertext indistinguishability under chosen-ciphertext attacks (IND-CCA), assuming the adversary does not obtain the password and does not succeed in guessing it.

Let A be a PPT adversary with access to:

- an *encryption oracle* that on input a message P runs $\mathsf{Enc}(P)$ and returns the resulting vault (H, T, C); and
- a *decryption oracle* that on input (H, T, C) runs $\mathsf{Dec}(H, T, C)$ and returns either the plaintext or $\perp$ (rejection), with the usual restriction that A may not submit to the decryption oracle the exact ciphertext returned by the challenge query described below.

In the IND-CCA experiment with bit $b \in \{0, 1\}$:

1. Two random keys are sampled: a stream key K_s for the ARX core and a MAC key K_m for BLAKE3.
2. The adversary A has access to the encryption and decryption oracles as above.
3. At some point A outputs two equal-length messages P_0, P_1. The challenger samples a fresh header H and uses P_b to produce a challenge vault $(H^\star, T^\star, C^\star)$ via the real encryption algorithm. The tuple $(H^\star, T^\star, C^\star)$ is returned to A.
4. A may continue to query the encryption and decryption oracles (subject to the restriction on querying $(H^\star, T^\star, C^\star)$ itself to the decryption oracle), and eventually outputs a bit b' as its guess.

The IND-CCA advantage of A against SARX is defined as

$$\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX}}(A) := \left|\Pr[\,b' = b\,] - \tfrac{1}{2}\right|.$$

10.3 Main reduction

We now state and prove the main reduction theorem, working in the derived-key model above.

Theorem 1. *Let A be a PPT adversary against SARX in the IND-CCA sense described above. Then there exist PPT adversaries B_1 and B_2 such that*

$$\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX}}(A) \;\le\; \mathrm{Adv}^{\text{PRF}}_{F}(B_1) \;+\; \mathrm{Adv}^{\text{MAC}}_{\mathsf{MAC}}(B_2).$$

In particular, if F is a secure PRF and MAC *is a secure SUF-CMA MAC, then the IND-CCA advantage of any PPT adversary A is negligible.*

Proof. We proceed via a standard hybrid argument, expressed directly in terms of distributions rather than explicit “games”.

Hybrid H_0 (real world). Hybrid H_0 is exactly the real IND-CCA experiment for SARX: the keystream is generated by Stream_{K_s}, and the MAC tag is computed as

$$T = \mathsf{MAC}_{K_m}(\mathtt{dom} \,\|\, H \,\|\, \mathrm{len}(C) \,\|\, C)$$

with K_s, K_m uniform and secret. Let

$$\mathrm{Adv}_0 := \left|\Pr[\,A \text{ outputs } b' = b \text{ in } \mathrm{H}_0\,] - \tfrac{1}{2}\right| = \mathrm{Adv}^{\text{IND-CCA}}_{\mathrm{SARX}}(A).$$

Hybrid H_1 (PRF replaced by random). In H_1 we change only the keystream generation: instead of using Stream_{K_s}, the challenger samples a truly random function $R : \{0,1\}^{64} \to \{0,1\}^{256}$ and uses the resulting stream $R(0), R(1), \ldots$ (sliced at the required offsets) to encrypt all plaintexts, including the challenge. Everything else—header generation, MAC computation, oracle interfaces—remains the same.

We claim that if an adversary can distinguish H_0 from H_1, then we can build a PRF distinguisher B_1 for F. Concretely, B_1 receives oracle access to an unknown function O which is either F_K for a random key K or a random function R; it simulates H_0 or H_1 for A by generating keystream blocks via $O(\mathrm{ctr})$ instead of the real Stream_{K_s}, and forwarding all of A's oracle queries and challenge generation. When A outputs a bit b', B_1 outputs 1 if $b' = b$ and 0 otherwise.

By construction,

$$\Pr[\,B_1^{F_K} = 1\,] = \Pr[\,A \text{ succeeds in } \mathrm{H}_0\,], \quad \Pr[\,B_1^{R} = 1\,] = \Pr[\,A \text{ succeeds in } \mathrm{H}_1\,],$$

so

$$|\Pr[\,A \text{ succeeds in } \mathrm{H}_0\,] - \Pr[\,A \text{ succeeds in } \mathrm{H}_1\,]| = \mathrm{Adv}^{\mathrm{PRF}}_{F}(B_1).$$

Hence

$$|\mathrm{Adv}_0 - \mathrm{Adv}_1| \le \mathrm{Adv}^{\mathrm{PRF}}_{F}(B_1),$$

where Adv_1 denotes A's advantage in H_1.

Hybrid H_2 (ideal one-time pad with MAC). In H_1, conditioned on the header H and MAC key K_m, each ciphertext block is the XOR of the plaintext with a uniformly random, independent keystream block derived from R at fresh counter values. Thus from the adversary's point of view, the encryption layer is equivalent to a one-time pad with a unique, independent pad for each message and position.

We now argue that under this view, H_1 is already the "ideal" hybrid for the encryption layer: the only remaining difference between H_1 and a perfect IND-CCA encryption scheme is the possibility of forging valid ciphertexts via the MAC. Formally, we consider a further conceptual hybrid H_2 in which the MAC is replaced by an oracle that always rejects any ciphertext-modification queries by A unless they were honestly generated by the encryption oracle. In such a hybrid H_2, the adversary's view of the challenge ciphertext is that of an ideal one-time pad, and its advantage is exactly 0 because the challenge message is perfectly hidden.

Bounding H_1 vs H_2 via MAC security. Suppose for contradiction that H_1 and H_2 differ by more than $\mathrm{Adv}^{\mathrm{MAC}}_{\mathsf{MAC}}(B_2)$ in A's success probability. Then we construct a MAC forger B_2 as follows: B_2 runs A and simulates H_1 using a real MAC oracle $M \mapsto \mathsf{MAC}_K(M)$

to compute tags for all ciphertexts it returns. If A ever submits to the decryption oracle a pair (H, T, C) that was not produced by the encryption oracle but is accepted as valid (i.e. the MAC verifies and decryption does not return $\perp$), then B_2 outputs $(M^\star, T^\star)$ as a forgery, where $M^\star$ is the MAC input

$$M^\star = \texttt{dom} \,\|\, H \,\|\, \mathrm{len}(C) \,\|\, C.$$

The event that H_1 deviates from H_2 in a way that affects A's success necessarily involves such a successful MAC forgery; in the absence of forgeries, A's view in H_1 and H_2 is identical. It follows that

$$|\mathrm{Adv}_1 - \mathrm{Adv}_2| \leq \mathrm{Adv}^{\mathrm{MAC}}_{\mathsf{MAC}}(B_2),$$

where $\mathrm{Adv}_2 = 0$ because in H_2 the challenge ciphertext is a perfect one-time pad and the MAC oracle never helps A learn anything about b.

Combining the hybrids. We have

$$\mathrm{Adv}_0 \leq |\mathrm{Adv}_0 - \mathrm{Adv}_1| + |\mathrm{Adv}_1 - \mathrm{Adv}_2| + \mathrm{Adv}_2 \leq \mathrm{Adv}^{\mathrm{PRF}}_F(B_1) + \mathrm{Adv}^{\mathrm{MAC}}_{\mathsf{MAC}}(B_2),$$

which is exactly the claimed bound. □

10.4 Passwords and Argon2id

The reduction above treats the stream key and MAC key as uniformly random and unknown to the adversary. In practice these keys are derived from a human-chosen password via Argon2id. An offline attacker who obtains a vault file can attempt to guess the password, recompute the derived keys using the public salt and parameters in the header, and test each guess by checking whether the MAC verifies.

The cost of such an attack is dominated by the cost of evaluating Argon2id per guess, multiplied by the size of the adversary's dictionary. SARX enforces a minimum password length of 30 Unicode codepoints and uses Argon2id with $t = 3$ and $m = 2^{17}$ KiB (128 MiB) by default. A detailed analysis of dictionary resistance and parameter selection is orthogonal to the symmetric security proof above, and follows the usual guidance for password-based key derivation.

11 Thermodynamic Hardening Mode

Recall that in SARX the password-based KDF proceeds in two stages:

- Argon2id with public parameters $(t\_cost, m\_cost, \mathrm{lanes})$ and salt $\texttt{salt}_{32}$ produces an "outer" key `okm` of length $L = k_{\mathrm{stream\_len}} + 32$ bytes.
- The outer key is split into a variable-length stream component k_{stream} and a 256 bit MAC key k_{mac}.

When the header field `kdf_id` is set to 2, SARX uses this Argon2id output directly. When `kdf_id` is set to 3, SARX enables an additional "thermodynamic hardening" step:

> Given `okm`, derive a 32 byte seed via BLAKE3, use this seed to deterministically fill a large scratch buffer with pseudorandom 64 bit words, perform a long ARX-based random walk over the scratch buffer keyed by the seed, hash a sampling of the modified scratch buffer with a domain-separated BLAKE3 call to obtain a 32 byte "mix" value, and finally XOR this mix back into `okm` in place. The scratch buffer is then zeroed and discarded.

The same procedure is applied during encryption and decryption whenever `kdf_id` is 3, so that the derived keys are deterministic functions of the password and header.

11.1 Security neutrality of thermo mode

Intuitively, thermo mode does not weaken the scheme: it takes the Argon2id output `okm` and runs it through a public, deterministic post-processing function based on BLAKE3 and ARX operations before splitting it into $(k_{\text{stream}}, k_{\text{mac}})$. The encryption and MAC layers then see derived keys which are still pseudorandom under the same assumptions as in the non-thermo case.

To make this precise, let us denote by SARX-2 the variant with `kdf_id` $= 2$ (Argon2id only) and SARX-3 the variant with `kdf_id` $= 3$ (Argon2id plus thermo hardening), but otherwise identical parameters and encryption/MAC structure.

We model the thermo hardening as a public function $H : \{0,1\}^L \to \{0,1\}^L$ which maps the Argon2id output `okm` to a hardened value $H(\texttt{okm})$ using domain-separated calls to BLAKE3 and a fixed-size scratch buffer. In the concrete implementation,

$$H(\texttt{okm}) = \texttt{okm} \oplus \mathsf{Mix}(\texttt{okm}),$$

where Mix is a 32 byte mask extended over the full length of `okm` by repetition, and Mix is derived from BLAKE3 outputs as described above.

Theorem 2. *Assume:*

1. *the outer KDF (Argon2id with fixed parameters and salt) is such that its output* `okm` *is computationally indistinguishable from a uniform string in* $\{0,1\}^L$*, and*

2. *BLAKE3, used in the thermo-hardening function* H*, behaves as a pseudorandom function on its inputs (under the domain separation constants fixed in the implementation).*

Then, for any IND-CCA adversary A *against SARX-3, there exists an IND-CCA adversary* A' *against SARX-2 and a PRF adversary* B *against BLAKE3 such that*

$$\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-3}}(A) \;\le\; \mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-2}}(A') \;+\; \mathrm{Adv}^{\text{PRF}}_{\mathsf{BLAKE3}}(B).$$

In particular, if SARX-2 is IND-CCA secure and BLAKE3 is a secure PRF, then SARX-3 is also IND-CCA secure.

Proof. We work again in the derived-key model, in which `okm` is the output of a black-box KDF on a secret password and public salt, and argue only about the effect of replacing `okm` by $H(\texttt{okm})$.

Consider the following two distributions over derived keys:

D$_2$. Sample `okm` uniformly from $\{0,1\}^L$ (modelling Argon2id as an ideal KDF), and split `okm` directly into $(k_{\text{stream}}, k_{\text{mac}})$ as in SARX-2.

D$_3$. Sample `okm` uniformly from $\{0,1\}^L$, compute $\texttt{okm}' := H(\texttt{okm})$, and split $\texttt{okm}'$ into $(k_{\text{stream}}, k_{\text{mac}})$ as in SARX-3.

By definition, SARX-2 with an ideal KDF corresponds to D$_2$, and SARX-3 with an ideal KDF and thermo hardening corresponds to D$_3$.

We first show that, under the PRF assumption on BLAKE3, no PPT adversary can distinguish D$_2$ from D$_3$ with more than $\mathrm{Adv}^{\mathrm{PRF}}_{\mathsf{BLAKE3}}(B)$ advantage. Indeed, suppose there exists a distinguisher D that, given access to the derived keys produced under either D$_2$ or D$_3$, can tell which distribution it is seeing with non-negligible advantage. We build a PRF adversary B as follows:

- B receives oracle access to a function O which is either BLAKE3 in PRF mode or a truly random function on its domain.
- When it needs to evaluate $H(\texttt{okm})$, instead of calling the real BLAKE3 instances, it uses O in place of all BLAKE3 invocations inside the thermo-hardening procedure, with the same domain separation constants and public parameters.
- It then runs D on the resulting keys and outputs whatever bit D outputs as its own guess for the PRF vs. random bit.

If O is a real BLAKE3 instance, the view of D is exactly that of D$_3$. If O is a truly random function, the internal outputs used to construct $\mathsf{Mix}(\texttt{okm})$ are independent of `okm` and uniformly random; from D's point of view, this is equivalent to replacing H by a public, key-independent XOR mask function on a uniform `okm`. In that case the resulting $\texttt{okm}'$ remains uniform over $\{0,1\}^L$, and D$_3$ collapses to D$_2$. Thus the advantage of D in distinguishing D$_2$ from D$_3$ is at most the PRF advantage of B against BLAKE3.

Now consider any IND-CCA adversary A against SARX-3. We construct an IND-CCA adversary A' against SARX-2 that internally simulates either D$_2$ or D$_3$ and forwards all encryption and decryption oracle queries made by A, using the underlying SARX-2 encryption engine with the derived keys it obtains. If the derived keys come from D$_2$, then A' is interacting with a genuine SARX-2 instance and its advantage is exactly $\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-2}}(A')$.

If the derived keys come from D_3, then A' is interacting with an SARX-3 instance and its advantage is $\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-3}}(A)$.

By the indistinguishability of D_2 and D_3 up to $\mathrm{Adv}^{\mathrm{PRF}}_{\mathsf{BLAKE3}}(B)$, we have

$$\left|\mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-3}}(A) - \mathrm{Adv}^{\text{IND-CCA}}_{\text{SARX-2}}(A')\right| \leq \mathrm{Adv}^{\mathrm{PRF}}_{\mathsf{BLAKE3}}(B),$$

which yields the claimed bound. □

11.2 Cost amplification

Thermo mode is primarily intended to increase the per-guess cost of offline password attacks, not to provide a new source of entropy. In the implementation, enabling thermo hardening causes each KDF evaluation to:

- allocate a scratch buffer of size M_{thermo} (e.g. 512 MiB), and
- perform W_{thermo} iterations of an ARX-based random walk that touches the scratch buffer and updates its cells.

This yields the following simple observation.

Proposition. Let C_{Argon2} denote the time and memory cost of a single Argon2id call with the parameters used in SARX, and let $(M_{\text{thermo}}, W_{\text{thermo}})$ be the scratch size and walk length for thermo hardening. Then any offline attacker who tests password guesses against an SARX-3 vault must, for each guess, perform the work of:

- one Argon2id evaluation with cost C_{Argon2}, and
- one thermo-hardening invocation, which performs $\Theta(M_{\text{thermo}} + W_{\text{thermo}})$ memory accesses and ARX operations.

In particular, compared to SARX-2, the asymptotic per-guess cost for offline brute force is multiplied by a factor that grows linearly with M_{thermo} and W_{thermo}, while the symmetric security guarantees remain the same up to the PRF advantage of BLAKE3 as captured in Theorem 2.