

# In-EVM Solana State Verification

## Technical Reference

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# Chapter 1

## Introduction

This document is a technical reference to the in-EVM Solana's 'Light-Client' state verification project.

### 1.1 Overview

The project's purpose is to provide Ethereum users with reliable Solana's cluster state and necessary transactions proof.

The project UX consists of several steps:

1. Retrieve Solana's 'Light-Client' state.
2. Generate a proof for it.
3. Submit the proof to EVM-enabled cluster.
4. Verify the proof with EVM.

Such a UX defines projects parts:

1. Solana's 'Light-Client' state retriever.
2. State proof generator.
3. Ethereum RPC proof submitter.
4. EVM-based proof verifier.

Each of these parts will be considered independently.

## Chapter 2

# State Proof Generator

This introduces a description for Solana's 'Light-Client' state proof generator. Crucial components which define this part design and performance are:

1. Input data format ('Light-Client' state data structure).
2. Proof system used for the proof generation.
3. Circuit definition used for the proof system.

### 2.1 'Light-Client' State

Block Information  $\bar{B}_k$  is defined as follows:

- $k$  - the number of the block
- $B_k = H(B_{k-1}||\text{account\_hash}||\text{signature\_count\_buf}||b_k||\text{validators\_state})$  - bank hash of the block<sup>1</sup>
- $b_k$  Merkle Block
- $B_{k-1}$  - the previous block's bank hash
- $\text{validators\_state}$  is not implemented for now.

Proof algorithm input is defined as follows:

- $n_1$  - current confirmed block number
- $n_2$  - new confirmed block number
- $\{\bar{B}_{n_1}, \dots, \bar{B}_{n_2}, \dots, \bar{B}_{n_2+32}\}$  - block information for blocks from  $n_1$  to  $n_2 + 32$ .
- $\sigma_0, \dots, \sigma_N$  - signatures for  $B_{n_2+32}$

Approximate code representation of such a state data structure is as follows:

```
template<typename Hash>
struct block_data {
    typedef typename Hash::digest_type digest_type;

    std::size_t block_number;
    digest_type bank_hash;
    digest_type merkle_hash;
    digest_type previous_bank_hash;
    // std::vector<vote_state> votes;
};

template<typename Hash, typename SignatureSchemeType>
struct state_type {
    typedef Hash hash_type;
    typedef SignatureSchemeType signature_scheme_type;
    typedef typename signature_scheme_type::signature_type signature_type;
```

<sup>1</sup>See <https://docs.solana.com/proposals/simple-payment-and-state-verification#block-headers>

```

std::size_t n_1 confirmed;
std::size_t n_2 new_confirmed;
std::vector<block_data<hash_type>> repl_data;
std::vector<signature_type> signatures;
};

```

Validator state-representing data structure (`vote_state`) supposes such a state to begin being handled by Solana replication protocol (or its implementation) for handling the tracking of votes state being unchanged 'till the end of epoch.

## 2.2 Proof System

### WIP

The proof system used for proving Solana's 'Light-Client' state on EVM is Redshift SNARK[1]. RedShift is a transparent SNARK that uses PLONK[2] proof system but replaces the commitment scheme. Initial paper proposal is to employ FRI[3] protocol to obtain transparency for the PLONK system.

However, FRI cannot be straightforwardly used with the PLONK system. To achieve the required security level without huge overheads, the authors introduce *list polynomial commitment* scheme as a part of the protocol. For more details, the reader gets referred to [1].

The original RedShift protocol utilizes the classic PLONK[2] system. To provide better performance, the original protocol is generalized to be used with PLONK with custom gates [4], [5] and lookup arguments [6], [7].

## 2.3 Optimizations

### WIP

### 2.3.1 Batched FRI

Instead of check each commitment individually, we can aggregate them for FRI. For polynomials  $f_0, \dots, f_k$ :

1. Get  $\theta$  from transcript
2.  $f = f_0 \cdot \theta^{k-1} + \dots + f_k$
3. Run FRI over  $f$ , using oracles to  $f_0, \dots, f_k$

Thus, we can run only one FRI instance for all committed polynomials.  
See [1] for details.

### 2.3.2 Hash By Column

Instead of committing each of the polynomials, we can use the same Merkle tree for several polynomials. It decreases the number of Merkle tree paths that need to be provided by the prover.

See [8], [1] for details.

### 2.3.3 Hash By Subset

On the each  $i + 1$  FRI round, the prover should send all elements from a coset  $H \in D^{(i)}$ . Each Merkle leaf is able to contain the whole coset instead of separate values.

See [8] for details. Similar approach is described in [1]. However, the authors of [1] use more values per leaf, that leads to better performance.

## 2.4 RedShift Protocol

### WIP

Notations:

$N_{\text{wires}}$	Number of wires ('advice columns')
$N_{\text{perm}}$	Number of wires that are included in the permutation argument
$N_{\text{sel}}$	Number of selectors used in the circuit
$N_{\text{const}}$	Number of constant columns
$N_{\text{lookups}}$	Number of lookups
$\mathbf{f}_i$	Witness polynomials, $0 \leq i < N_{\text{wires}}$
$\mathbf{f}_{c_i}$	Constant-related polynomials, $0 \leq i < N_{\text{const}}$
$\mathbf{gate}_i$	Gate polynomials, $0 \leq i < N_{\text{sel}}$
$\sigma(\text{col} : i, \text{row} : j) = (\text{col} : i', \text{row} : j')$	Permutation over the table

For details on polynomial commitment scheme and polynomial evaluation scheme, we refer the reader to [1].

- 
1.  $\mathcal{L}' = (\mathbf{q}_0, \dots, \mathbf{q}_{N_{\text{sel}}})$
  2. Let  $\omega$  be a  $2^k$  root of unity
  3. Let  $\delta$  be a  $T$  root of unity, where  $T \cdot 2^S + 1 = p$  with  $T$  odd and  $k \leq S$
  4. Compute  $N_{\text{perm}}$  permutation polynomials  $S_{\sigma_i}(X)$  such that  $S_{\sigma_i}(\omega^j) = \delta^{i'} \cdot \omega^{j'}$
  5. Compute  $N_{\text{perm}}$  identity permutation polynomials:  $S_{id_i}(X)$  such that  $S_{id_i}(\omega^j) = \delta^i \cdot \omega^j$
  6. Let  $H = \{\omega^0, \dots, \omega^n\}$  be a cyclic subgroup of  $\mathbb{F}^*$
  7. Let  $Z(X) = \prod_{a \in H^*} (X - a)$
  8. Let  $A_i$  be a witness lookup columns and  $S_i$  be a table columns,  $i = 0, \dots, m$ .
- 

### Preprocessing:

#### 2.4.1 Prover View

1. Choose masking polynomials:

$$h_i(X) \leftarrow \mathbb{F}_{<k}[X] \text{ for } 0 \leq i < N_{\text{wires}}$$

**Remark:** For details on choice of  $k$ , we refer the reader to [1].

2. Define new witness polynomials:

$$f_i(X) = \mathbf{f}_i(X) + h_i(X)Z(X) \text{ for } 0 \leq i < N_{\text{wires}}$$

3. Add commitments to  $f_i$  to transcript
4. Get  $\theta \in \mathbb{F}$  from  $\text{hash}(\text{transcript})$
5. Construct the witness lookup compression and table compression  $S(\theta)$  and  $A(\theta)$ :

$$\begin{aligned} A(\theta) &= \theta^{m-1}A_0 + \theta^{m-2}A_1 + \dots + \theta A_{m-2} + A_{m-1} \\ S(\theta) &= \theta^{m-1}S_0 + \theta^{m-2}S_1 + \dots + \theta S_{m-2} + S_{m-1} \end{aligned}$$

6. Produce the permutation polynomials  $S'(X)$  and  $A'(X)$  such that:

6.1 All the cells of column  $A'$  are arranged so that like-valued cells are vertically adjacent to each other.

6.2 The first row in a sequence of values in  $A'$  is the row that has the corresponding value in  $S'$ .

7. Compute and add commitments to  $A'$  and  $S'$  to transcript

8. Get  $\beta, \gamma \in \mathbb{F}$  from  $\text{hash}(\text{transcript})$

9. For  $0 \leq i < N_{\text{perm}}$

$$\begin{aligned} p_i &= f_i + \beta \cdot S_{id_i} + \gamma \\ q_i &= f_i + \beta \cdot S_{\sigma_i} + \gamma \end{aligned}$$

10. Define:

$$\begin{aligned} p'(X) &= \prod_{0 \leq i < N_{\text{perm}}} p_i(X) \in \mathbb{F}_{<N_{\text{perm}} \cdot n}[X] \\ q'(X) &= \prod_{0 \leq i < N_{\text{perm}}} q_i(X) \in \mathbb{F}_{<N_{\text{perm}} \cdot n}[X] \end{aligned}$$

11. Compute  $P(X), Q(X) \in \mathbb{F}_{<n+1}[X]$ , such that:

$$\begin{aligned} P(\omega) &= Q(\omega) = 1 \\ P(\omega^i) &= \prod_{1 \leq j < i} p'(\omega^j) \text{ for } i \in 2, \dots, n+1 \\ Q(\omega^i) &= \prod_{1 \leq j < i} q'(\omega^j) \text{ for } i \in 2, \dots, n+1 \end{aligned}$$

12. Compute and add commitments to  $P$  and  $Q$  to transcript

13. Compute permutation product column:

$$\begin{aligned} V(\omega^i) &= \frac{(\theta^{m-1}A_0(\omega^i) + \theta^{m-2}A_1(\omega^i) + \dots + \theta A_{m-2}(\omega^i) + A_{m-1}(\omega^i) + \beta) \cdot (\theta^{m-1}S_0(\omega^i) + \theta^{m-2}S_1(\omega^i) + \dots + \theta S_{m-2}(\omega^i) + S_{m-1}(\omega^i) + \gamma)}{(A'(\omega^i) + \beta)(S'(\omega^i) + \gamma)} \\ V(1) &= V(\omega^{N_{\text{lookups}}}) = 1 \end{aligned}$$

14. Compute and add commitments to  $V$  to transcript

15. Get  $\alpha_0, \dots, \alpha_5 \in \mathbb{F}$  from  $\text{hash}(\text{transcript})$

16. Get  $\tau$  from  $\text{hash}(\text{transcript})$

17. Define polynomials ( $F_0, \dots, F_4$  - copy-satisfiability,  $\text{gate}_0$  is  $PI$ -constraining gate):

$$\begin{aligned} F_0(X) &= L_1(X)(P(X) - 1) \\ F_1(X) &= L_1(X)(Q(X) - 1) \\ F_2(X) &= P(X)p'(X) - P(X\omega) \\ F_3(X) &= Q(X)q'(X) - Q(X\omega) \\ F_4(X) &= L_n(X)(P(X\omega) - Q(X\omega)) \\ F_5(X) &= \sum_{0 \leq i < N_{\text{sel}}} (\tau^i \cdot \mathbf{q}_i(X) \cdot \text{gate}_i(X)) + PI(X) \end{aligned}$$

18. For the lookup:

18.1 Two selectors  $q_{last}$  and  $q_{blind}$  are used, where  $q_{last} = 1$  for  $t$  last blinding rows and  $q_{blind} = 1$  on the row in between the usable rows and the blinding rows.

18.2  $F_6(X) = L_0(X)(1 - V(X))$

18.3  $F_7(X) = q_{last} \cdot (V(X)^2 - V(X))$

18.4  $F_8(X) = (1 - (q_{last} + q_{blind})) \cdot (V(\omega X)(A'(X) + \beta)(S'(X) + \gamma) - V(X)(\theta^{m-1}A_0(X) + \dots + A_{m-1}(X) + \beta)(\theta^{m-1}S_0(X) + \dots + S_{m-1}(X) + \gamma))$

18.5  $F_9(X) = L_0(X) \cdot (A'(X) - S'(X))$

18.6  $F_{10}(X) = (1 - (q_{last} + q_{blind})) \cdot (A'(X) - S'(X)) \cdot (A'(X) - A'(\omega^{-1}X))$

19. Compute:

$$F(X) = \sum_{i=0}^{10} \alpha_i F_i(X)$$

$$T(X) = \frac{F(X)}{Z(X)}$$

20.  $N_T := \max(N_{\text{perm}}, \deg_{\text{gates}} - 1)$ , where  $\deg_{\text{gates}}$  is the highest degree of the degrees of gate polynomials.

21. Split  $T(X)$  into separate polynomials  $T_0(X), \dots, T_{N_T-1}(X)$ <sup>2</sup>

22. Add commitments to  $T_0(X), \dots, T_{N_T-1}(X)$  to transcript

23. Get  $y \in \mathbb{F}/H$  from  $\text{hash}_{\mathbb{F}/H}(\text{transcript})$

24. Run evaluation scheme with the committed polynomials and  $y$

**Remark:** Depending on the circuit, evaluation can be done also on  $y\omega, y\omega^{-1}$ .

25. The proof is  $\pi_{\text{comm}}$  and  $\pi_{\text{eval}}$ , where:

- $\pi_{\text{comm}} = \{f_{0,\text{comm}}, \dots, f_{N_{\text{wires}}-1,\text{comm}}, P_{\text{comm}}, Q_{\text{comm}}, T_{0,\text{comm}}, \dots, T_{N_T-1,\text{comm}}, A'_{\text{comm}}, S'_{\text{comm}}, V_{\text{comm}}\}$
- $\pi_{\text{eval}}$  is evaluation proofs for  $f_0(y), \dots, f_{N_{\text{wires}}}(y), P(y), P(y\omega), Q(y), Q(y\omega), T_0(y), \dots, T_{N_T-1}(y), A'(y), A'(y\omega^{-1}), S'(y), V(y), V(y\omega)$

### 2.4.2 Verifier View

1. Let  $f_{0,\text{comm}}, \dots, f_{N_{\text{wires}}-1,\text{comm}}$  be commitments to  $f_0(X), \dots, f_{N_{\text{wires}}-1}(X)$
2.  $\text{transcript} = \text{setup\_values} || f_{0,\text{comm}} || \dots || f_{N_{\text{wires}}-1,\text{comm}}$
3.  $\theta = \text{hash}(\text{transcript})$
4. Let  $A'_{\text{comm}}, S'_{\text{comm}}$  be commitments to  $A'(X), S'(X)$ .
5.  $\text{transcript} = \text{transcript} || A'_{\text{comm}} || S'_{\text{comm}}$
6.  $\beta, \gamma = \text{hash}(\text{transcript})$
7. Let  $P_{\text{comm}}, Q_{\text{comm}}, V_{i,\text{comm}}$  be commitments to  $P(X), Q(X), V(X)$ .
8.  $\text{transcript} = \text{transcript} || P_{\text{comm}} || Q_{\text{comm}} || V_{\text{comm}}$
9.  $\alpha_0, \dots, \alpha_5 = \text{hash}(\text{transcript})$
10.  $\tau = \text{hash}(\text{transcript})$
11.  $N_T := \max(N_{\text{perm}}, \deg_{\text{gates}} - 1)$ , where  $\deg_{\text{gates}}$  is the highest degree of the degrees of gate polynomials.
12. Let  $T_{0,\text{comm}}, \dots, T_{N_T-1,\text{comm}}$  be commitments to  $T_0(X), \dots, T_{N_T-1}(X)$
13.  $\text{transcript} = \text{transcript} || T_{0,\text{comm}} || \dots || T_{N_T-1,\text{comm}}$
14.  $y = \text{hash}_{\mathbb{F}/H}(\text{transcript})$
15. Run evaluation scheme verification with the committed polynomials and  $y$  to get values  $f_i(y), P(y), P(y\omega), Q(y), Q(y\omega), T_j(y), A'(y), S'(y), V(y), A'(y\omega^{-1}), V(y\omega)$ .  
**Remark:** Depending on the circuit, evaluation can be done also on  $f_i(y\omega), f_i(y\omega^{-1})$  for some  $i$ .
16. Calculate:

$$F_0(y) = L_1(y)(P(y) - 1)$$

$$F_1(y) = L_1(y)(Q(y) - 1)$$

$$p'(y) = \prod p_i(y) = \prod f_i(y) + \beta \cdot S_{id_i}(y) + \gamma$$

$$F_2(y) = P(y)p'(y) - P(y\omega)$$

$$q'(y) = \prod q_i(y) = \prod f_i(y) + \beta \cdot S_{\sigma_i}(y) + \gamma$$

$$F_3(y) = Q(y)q'(y) - Q(y\omega)$$

---

<sup>2</sup>Commit scheme supposes that polynomials should be degree  $\leq n$



$$\begin{aligned}
F_4(y) &= L_n(y)(P(y\omega) - Q(y\omega)) \\
F_5(y) &= \sum_{0 \leq i < N_{sel}} (\tau^i \cdot \mathbf{q}_i(y) \cdot \mathbf{gate}_i(y)) + PI(y) \\
T(y) &= \sum_{0 \leq j < N_T} y^{n_j} T_j(y) \quad F_6(y) = L_0(y)(1 - V(y)) \\
F_7(y) &= q_{last} \cdot (V(y)^2 - V(y)) \\
F_8(y) &= (1 - (q_{last} + q_{blind})) \cdot (V(\omega y)(A'(y) + \beta)(S'(y) + \gamma) - V(y)(\theta^{m-1}A_0(y) + \dots + A_{m-1}(y) + \\
&\quad \beta)(\theta^{m-1}S_{i,0}(y) + \dots + S_{m-1}(y) + \gamma)) \\
F_9(y) &= L_0(y) \cdot (A'(y) - S'(y)) \\
F_{10}(y) &= (1 - (q_{last} + q_{blind})) \cdot (A'(y) - S'(y)) \cdot (A'(y) - A'(\omega^{-1}y))
\end{aligned}$$

17. Check the identity:

$$\sum_{i=0}^{10} \alpha_i F_i(y) = Z(y)T(y)$$

## 2.5 Circuit Definition

This section contains a description of PLONK-style circuits for In-EVM Solana's "Light Client" state verification<sup>3</sup>.

This section provides a high-level overview of the circuit used for proof generation and verification. Following sections provide sub-circuits details.

### 2.5.1 Verification Circuit Overview

Let bank-hashes of proving block set be  $\{H_{B_{n_1}}, \dots, H_{B_{n_2}}\}$ . The last confirmed block is  $H_{B_L}$ . Each positively confirmed block is signed by  $M$  validators.

Denote by `block_data` the data that is included in the bank hash other than the bank hash of the parent block.

1.  $H_{B_{n_1}} = H_{B_L} // H_{B_L}$  is a public input
2. Validator set constraints. // see Section 2.5.9
3. for  $i$  from  $n_1 + 1$  to  $n_2 + 32$ :

$$3.1 \quad H_{B_i} = \text{sha256}(\text{block\_data} || H_{B_{i-1}}) // \text{ see Section 2.5.2}$$

4. for  $j$  from 0 to  $M$ :

$$4.1 \quad \text{Ed25519 constraints for } H_{B_{n_2+32}} // \text{ see Section 2.5.6}$$

5. Merkle tree constraints for the set  $\{H_{B_{n_1}}, \dots, H_{B_{n_2}}\}$  // see Section 2.5.5

Suppose that  $M = 800$  and  $n_2 - n_1 = 3600$ . Thus, the total amount of rows is:  $3 \cdot 3632 \cdot 755 + 800 \cdot 2839 + 3600 \cdot 22 = 8226480 + 2271200 + 79200 = 10576880$

### 2.5.2 SHA-256 Circuit

Suppose that input data is in the 32-bits form, which is already padded to the required size. We suppose that the checking that chunked input data corresponds to the original data out of the circuit. However, we do not need to range constrain these chunks as we get them for free from the SHA-256 circuit.

Thus, the preprocessing constraints for the SHA-256 circuit is a decomposition of  $k$  message blocks to 32 bits chunks without range proofs. For 'Solana-EVM' circuit,  $k = 3$ .

<sup>3</sup><https://blog.nil.foundation/2021/10/14/solana-ethereum-bridge.html>

**Lookup tables** We use the following lookup tables:

1. **SHA-256 NORMALIZE4** with 2 columns and  $2^{14}$  rows. The first column contains all possible 14-bits words. The second column contains corresponding sparse representations with base 4. The constraints can be used for the range check and sparse representation simultaneously.
2. **SHA-256 NORMALIZE7** with 2 columns and  $2^{14}$  rows. The first column contains all possible 14-bits words. The second column contains corresponding sparse representations with base 7. The constraints can be used for the range check and sparse representation simultaneously.
3. **SHA-256 NORMALIZE MAJ** with 2 columns and  $2^8$  rows. The first column contains all possible 8-bits words. The second column contains corresponding sparse representations with base 4.
4. **SHA-256 NORMALIZE CH** with 2 columns and  $2^8$  rows. The first column contains all possible 8-bits words. The second column contains corresponding sparse representations with base 7.

**Message scheduling** For each block of 512 bits of the padded message the 64 words are constructed in the following way:

- The first 16 words are obtained by splitting the message.
- The last 48 words are obtained by using the functions  $\sigma_0, \sigma_1$ :

$$W_i = \sigma_1(W_{i-2}) \oplus W_{i-7} \oplus \sigma_0(W_{i-15}) \oplus W_{i-16} \quad (2.1)$$

Each round of the message scheduling has the following table:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$a$	$a_0$	$a_1$	$a_2$	$a_3$	$\hat{a}_1$	$\hat{a}_2$	$a'_0$	
$j + 1$	$W_i$	$W_j$	$a'_1$	$a'_2$	$a'_3$	$s'_0$	$s'_1$	$s'_2$	$s'_3$
$j + 2$	$w$	$s_0$	$s_1$	$s_2$	$s_3$	$s_0$	$s_1$	$s_2$	$s_3$
$j + 3$		$b'_0$	$b'_1$	$b'_2$	$b'_3$	$s'_0$	$s'_1$	$s'_2$	$s'_3$
$j + 4$	$b$	$b_0$	$b_1$	$b_2$	$b_3$	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_3$	

Evaluations:

Let  $b$  be  $W_{i-2}$  and  $a$  be  $W_{i-15}$  from 2.1. The values  $W_i$  and  $W_j$  in the table corresponds to  $W_{i-7}$  and  $W_{i-16}$  respectively from 2.1. From the round  $r = 2$  the copy constraints are used for values  $b$  and  $w$  from round  $r - 2$ . The copy constraints for  $W_{i-7}, W_{i-15}$  and  $W_{i-16}$  are used in a similar way. The output of round  $W_i$  from 2.1 is  $w$ .

The first 16 words require a range check. We get it fo free from range-constraining chunks inside functions  $\sigma_0$  and  $\sigma_1$ . Thus, for  $i$  from 16 to 63:

1. Apply  $\sigma_0$  to  $W_{i-15}$ .
2. Add the following constraint for  $W_i$ :

$$w_{0,j+2} = w_{0,j+1} + w_{1,j+1} + w_{1,j+2} + w_{2,j+2} \cdot 2^3 + w_{3,j+2} \cdot 2^7 + w_{4,j+2} \cdot 2^{18} + w_{5,j+2} + w_{6,j+2} \cdot 2^{10} + w_{7,j+2} \cdot 2^{17} + w_{8,j+2} \cdot 2^{19},$$

3. Apply  $\sigma_1$  to  $W_{i-2}$ .

Thus, the message schedule takes  $5 \cdot 48 = 240$  rows.

**The function  $\sigma_0$**  contains sparse mapping with base 4. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3$  which equals to 3, 4, 11, 14 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3$  are in sparse form, and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE4** lookup table is used for mapping to sparse representation and range-constraining for each chunk  $a_i$ , where bit-length of  $a_i > 3$ . If a chunk is 14 bits long, then it is constrained for free. Else the prover has to calculate the sparse representation  $\hat{a}_i$  for  $2^j \cdot a_i$ , where  $j + \text{len}(a_i) = 14$  and  $\text{len}(a_i)$  is bit-length of  $a_i$ . The tuple  $\{s'_0, s'_1, s'_2, s'_3\}$  is a sparse representation of the result of  $\sigma_0$  and the tuple  $\{s_0, s_1, s_2, s_3\}$  is a normal representation. The size of elements of these tuples equals to  $\{14, 14, 2, 2\}$  bits respectively.

Constraints:

$$\begin{aligned}
w_{0,j+0} &= w_{1,j+0} + w_{2,j+0} \cdot 2^3 + w_{3,j+0} \cdot 2^7 + w_{4,j+0} \cdot 2^{18} \\
&\quad (w_{1,j+0} - 7) \cdot (w_{1,j+0} - 6) \cdot \dots \cdot w_{1,j+0} = 0 \\
w_{5,j+1} + w_{6,j+1} \cdot 4^{14} + w_{7,j+1} \cdot 4^{28} + w_{8,j+1} \cdot 2^{30} &= w_{2,j+1} + w_{3,j+1} \cdot 4^4 + w_{4,j+1} \cdot 4^{15} + w_{3,j+1} + w_{4,j+1} \cdot \\
&\quad 4^{11} + w_{7,j+0} \cdot 4^{25} + w_{2,j+1} \cdot 4^{28} + w_{4,j+1} + w_{7,j+0} \cdot 4^{14} + w_{2,j+1} \cdot 4^{17} + w_{3,j+1} \cdot 4^{21} \\
(w_{7,j+1} - 3) \cdot (w_{7,j+1} - 2) \cdot (w_{7,j+1} - 1) \cdot w_{7,j+1} &= 0 \quad (w_{8,j+1} - 3) \cdot (w_{8,j+1} - 2) \cdot (w_{8,j+1} - 1) \cdot w_{8,j+1} = 0 \\
10 \text{ plookup constraints: } (w_{1,j+0}, w_{7,j+0}), (2^{10} \cdot w_{2,j+0}, w_{5,j+0}), (w_{2,j+0}, w_{2,j+1}), (2^3 \cdot \\
w_{3,j+0}, w_{6,j+0}), (w_{3,j+0}, w_{3,j+1}), (w_{4,j+0}, w_{4,j+1}), (w_{1,j+2}, w_{5,j+1}), (w_{2,j+2}, w_{6,j+1}), (w_{3,j+2}, w_{7,j+2}), (w_{4,j+2}, w_{8,j+2})
\end{aligned}$$

**The function  $\sigma_1$**  contains sparse mapping subcircuit with base 4. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3$  which equals to 10, 7, 2, 13 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3$  are in sparse form and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE4** lookup table is used for mapping to sparse representation and range-constraining in the same way as for  $\sigma_0$ . The tuple  $\{s'_0, s'_1, s'_2, s'_3\}$  is a sparse representation of the result of  $\sigma_1$  and the tuple  $\{s_0, s_1, s_2, s_3\}$  is a normal representation. The size of elements of these tuples equals to  $\{14, 14, 2, 2\}$  bits respectively.

Constraints:

$$\begin{aligned}
w_{0,j+3} &= w_{1,j+3} + w_{2,j+3} \cdot 2^{10} + w_{3,j+3} \cdot 2^{17} + w_{4,j+3} \cdot 2^{19} \\
&\quad (w_{3,j+3} - 3) \cdot (w_{3,j+3} - 2) \cdot (w_{3,j+3} - 1) \cdot w_{3,j+3} = 0 \\
w_{5,j+3} + w_{6,j+3} \cdot 4^{14} + w_{7,j+3} \cdot 4^{28} + w_{8,j+3} \cdot 2^{30} &= w_{2,j+3} + w_{3,j+3} \cdot 4^7 + w_{4,j+3} \cdot 4^9 + w_{3,j+3} + w_{4,j+3} \cdot \\
&\quad 4^2 + w_{1,j+3} \cdot 4^{15} + w_{2,j+3} \cdot 4^{25} + w_{4,j+3} + w_{1,j+3} \cdot 4^{13} + w_{2,j+3} \cdot 4^{23} + w_{3,j+3} \cdot 4^{30} \\
(w_{7,j+3} - 3) \cdot (w_{7,j+3} - 2) \cdot (w_{7,j+3} - 1) \cdot w_{7,j+3} &= 0 \quad (w_{8,j+3} - 3) \cdot (w_{8,j+3} - 2) \cdot (w_{8,j+3} - 1) \cdot w_{8,j+3} = 0 \\
11 \text{ plookup constraints: } (2^4 \cdot (w_{1,j+3}, w_{5,j+3}), (2^7 \cdot w_{2,j+3}, w_{6,j+3}), (2 \cdot \\
w_{4,j+3}, w_{7,j+3}), (w_{1,j+3}, w_{1,j+2}), (w_{2,j+3}, w_{2,j+2}), (w_{3,j+3}, w_{3,j+2}), (w_{4,j+3}, w_{4,j+2}), (w_{5,j+2}, w_{5,j+3}), (w_{6,j+2}, w_{6,j+3}), (w_{7,j+2}, w_{7,j+3}), (w_{8,j+2}, w_{8,j+3})
\end{aligned}$$

**Compression** There are 64 rounds of compression. Each round of compression has the following table:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$e$	$e'_0$	$e_0$	$e_1$	$e_2$	$e_3$	$\hat{e}_1$	$\hat{e}_2$	$\hat{e}_3$
$j + 1$	$e'$	$f'$	$e'_1$	$e'_2$	$e'_3$	$s'_0$	$s'_1$	$s'_2$	$s'_3$
$j + 2$	$ch_{0,sparse}$	$ch_{1,sparse}$	$ch_{2,sparse}$	$ch_{3,sparse}$	—	$s_0$	$s_1$	$s_2$	$s_3$
$j + 3$	$g'$	$d$	$h$	$W_r$	$e_{new}$	$ch_0$	$ch_1$	$ch_2$	$ch_3$
$j + 4$	$maj_{0,sparse}$	$maj_{1,sparse}$	$maj_{2,sparse}$	$maj_{3,sparse}$	$a_{new}$	$maj_3$	$maj_0$	$maj_1$	$maj_2$
$j + 5$	$a'$	$b'$			$c'$	$s_0$	$s_1$	$s_2$	$s_3$
$j + 6$	$s'_1$	$s'_2$	$a'_0$	$a'_1$	$a'_2$	$a'_3$	$s'_3$	$s'_4$	
$j + 7$	$a$		$a_0$	$a_1$	$a_2$	$a_3$	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_3$

**The working variables**  $a, b, c, d, e, f, g, h$  equals to the fixed initial *SHA-256* values for the first chunk and to the sum of previous output and initial values for the rest of chunks. The variables with quotes are corresponded sparse representation. For each chunk, the following rows are used:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$a$	$a'$	$b$	$b'$	$d$	—	—	—	—
$j + 1$	$c$	$c'$	$e$	$e'$	$h$	—	—	—	—
$j + 2$	$f$	$f'$	$g$	$g'$	—	—	—	—	—

For the first round,  $a, a', b', c', d, e, e', f', g', h$  are copy constrained with corresponded values from the table above.

For the second round,  $b', c', d, f', g', h$  are copy constrained with  $a', b', c, e', f', g$  from the table. The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round.

For the third round,  $c', d, g', h$  are copy constrained with  $a', b, e', f$ . The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round. The values  $b', f'$  are copy constrained with  $a', e'$  from the previous round.

In the rest of the rounds the following ‘non-special’ copy constraints are used:

1. The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round.
2. The values  $b', f'$  are copy constrained with  $a', e'$  from the previous round.
3. The values  $c', g'$  are copy constrained with  $b', c'$  from the previous round.
4. The values  $d, h$  are copy constrained with  $a', e'$  from the round  $r - 3$ , where  $r$  is current round.

$$\begin{aligned}
w_{0,j+7} &= w_{2,j+7} + w_{3,j+7} \cdot 2^2 + w_{4,j+7} \cdot 2^{13} + w_{5,j+7} \cdot 2^{22} \\
w_{0,j+5} &= w_{2,j+6} + w_{3,j+6} \cdot 4^2 + w_{4,j+6} \cdot 4^{13} + w_{5,j+6} \cdot 4^{22} \\
(w_{2,j+6} - 3) \cdot (w_{2,j+6} - 2) \cdot (w_{2,j+6} - 1) \cdot w_{2,j+6} &= 0 \\
w_{0,j+6} + w_{1,j+6} \cdot 4^{14} + w_{6,j+6} \cdot 4^{28} + w_{7,j+6} \cdot 2^{30} &= w_{3,j+6} + w_{4,j+6} \cdot 4^{11} + w_{5,j+6} \cdot 4^{20} + w_{1,j+6} \cdot 2^{30} + \\
&\quad w_{4,j+6} + w_{5,j+6} \cdot 4^9 + w_{2,j+6} \cdot 4^{19} + w_{3,j+6} \cdot 4^{21} + w_{5,j+6} + w_{2,j+6} \cdot 4^{10} + w_{3,j+6} \cdot 4^{12} + w_{4,j+6} \cdot 4^{23} \\
(w_{6,j+6} - 3) \cdot (w_{6,j+6} - 2) \cdot (w_{6,j+6} - 1) \cdot w_{6,j+6} &= 0 \quad (w_{7,j+6} - 3) \cdot (w_{7,j+6} - 2) \cdot (w_{7,j+6} - 1) \cdot w_{7,j+6} = 0 \\
11 \text{ plookup constraints: } (2^3 \cdot (w_{3,j+6}, w_{6,j+6}), (2^5 \cdot w_{4,j+6}, w_{7,j+6}), (2^4 \cdot \\
&\quad w_{5,j+6}, w_{8,j+6}), (w_{2,j+6}, w_{2,j+5}), (w_{3,j+6}, w_{3,j+5}), (w_{4,j+6}, w_{4,j+5}), (w_{5,j+6}, w_{5,j+5}), (w_{5,j+5}, w_{0,j+6}), (w_{6,j+5}, w_{1,j+6}), (w_{7,j+5}, w_{0,j+6})
\end{aligned}$$
$$\begin{aligned}
w_{0,j+0} &= w_{2,j+0} + w_{3,j+0} \cdot 2^6 + w_{4,j+0} \cdot 2^{11} + w_{5,j+0} \cdot 2^{25} \\
w_{0,j+1} &= w_{1,j+0} + w_{2,j+1} \cdot 7^6 + w_{3,j+1} \cdot 7^{11} + w_{4,j+1} \cdot 7^{25} \\
w_{5,j+1} + w_{6,j+1} \cdot 4^{14} + w_{7,j+1} \cdot 4^{28} + w_{8,j+1} \cdot 2^{30} &= w_{2,j+1} + w_{3,j+1} \cdot 4^5 + w_{4,j+1} \cdot 4^{19} + w_{1,j+0} \cdot 2^{26} + \\
&\quad w_{3,j+1} + w_{4,j+1} \cdot 4^{14} + w_{1,j+0} \cdot 4^{21} + w_{2,j+1} \cdot 4^{27} + w_{4,j+1} + w_{1,j+0} \cdot 4^7 + w_{2,j+1} \cdot 4^{13} + w_{3,j+1} \cdot 4^{27} \\
(w_{3,j+1} - 3) \cdot (w_{3,j+1} - 2) \cdot (w_{3,j+1} - 1) \cdot w_{3,j+1} &= 0 \quad (w_{4,j+1} - 3) \cdot (w_{4,j+1} - 2) \cdot (w_{4,j+1} - 1) \cdot w_{4,j+1} = 0 \\
11 \text{ plookup constraints: } (2^8 \cdot (w_{2,j+0}, w_{1,j+0}), (2^9 \cdot w_{3,j+0}, w_{2,j+1}), (2^7 \cdot \\
w_{5,j+0}, w_{4,j+1}), (w_{2,j+0}, w_{1,j+0}), (w_{3,j+0}, w_{2,j+1}), (w_{4,j+0}, w_{3,j+1}), (w_{5,j+0}, w_{4,j+1}), (w_{5,j+2}, w_{5,j+1}), (w_{6,j+2}, w_{6,j+1}), (w_{7,j+2}, w_{7,j+1}), (w_{8,j+2}, w_{8,j+1}), (w_{9,j+2}, w_{9,j+1}), (w_{10,j+2}, w_{10,j+1}), (w_{11,j+2}, w_{11,j+1}), (w_{12,j+2}, w_{12,j+1}), (w_{13,j+2}, w_{13,j+1}), (w_{14,j+2}, w_{14,j+1}), (w_{15,j+2}, w_{15,j+1}), (w_{16,j+2}, w_{16,j+1}), (w_{17,j+2}, w_{17,j+1}), (w_{18,j+2}, w_{18,j+1}), (w_{19,j+2}, w_{19,j+1}), (w_{20,j+2}, w_{20,j+1}), (w_{21,j+2}, w_{21,j+1}), (w_{22,j+2}, w_{22,j+1}), (w_{23,j+2}, w_{23,j+1}), (w_{24,j+2}, w_{24,j+1}), (w_{25,j+2}, w_{25,j+1}), (w_{26,j+2}, w_{26,j+1}), (w_{27,j+2}, w_{27,j+1}), (w_{28,j+2}, w_{28,j+1}), (w_{29,j+2}, w_{29,j+1}), (w_{30,j+2}, w_{30,j+1}), (w_{31,j+2}, w_{31,j+1}), (w_{32,j+2}, w_{32,j+1}), (w_{33,j+2}, w_{33,j+1}), (w_{34,j+2}, w_{34,j+1}), (w_{35,j+2}, w_{35,j+1}), (w_{36,j+2}, w_{36,j+1}), (w_{37,j+2}, w_{37,j+1}), (w_{38,j+2}, w_{38,j+1}), (w_{39,j+2}, w_{39,j+1}), (w_{40,j+2}, w_{40,j+1}), (w_{41,j+2}, w_{41,j+1}), (w_{42,j+2}, w_{42,j+1}), (w_{43,j+2}, w_{43,j+1}), (w_{44,j+2}, w_{44,j+1}), (w_{45,j+2}, w_{45,j+1}), (w_{46,j+2}, w_{46,j+1}), (w_{47,j+2}, w_{47,j+1}), (w_{48,j+2}, w_{48,j+1}), (w_{49,j+2}, w_{49,j+1}), (w_{50,j+2}, w_{50,j+1}), (w_{51,j+2}, w_{51,j+1}), (w_{52,j+2}, w_{52,j+1}), (w_{53,j+2}, w_{53,j+1}), (w_{54,j+2}, w_{54,j+1}), (w_{55,j+2}, w_{55,j+1}), (w_{56,j+2}, w_{56,j+1}), (w_{57,j+2}, w_{57,j+1}), (w_{58,j+2}, w_{58,j+1}), (w_{59,j+2}, w_{59,j+1}), (w_{60,j+2}, w_{60,j+1}), (w_{61,j+2}, w_{61,j+1}), (w_{62,j+2}, w_{62,j+1}), (w_{63,j+2}, w_{63,j+1}), (w_{64,j+2}, w_{64,j+1}), (w_{65,j+2}, w_{65,j+1}), (w_{66,j+2}, w_{66,j+1}), (w_{67,j+2}, w_{67,j+1}), (w_{68,j+2}, w_{68,j+1}), (w_{69,j+2}, w_{69,j+1}), (w_{70,j+2}, w_{70,j+1}), (w_{71,j+2}, w_{71,j+1}), (w_{72,j+2}, w_{72,j+1}), (w_{73,j+2}, w_{73,j+1}), (w_{74,j+2}, w_{74,j+1}), (w_{75,j+2}, w_{75,j+1}), (w_{76,j+2}, w_{76,j+1}), (w_{77,j+2}, w_{77,j+1}), (w_{78,j+2}, w_{78,j+1}), (w_{79,j+2}, w_{79,j+1}), (w_{80,j+2}, w_{80,j+1}), (w_{81,j+2}, w_{81,j+1}), (w_{82,j+2}, w_{82,j+1}), (w_{83,j+2}, w_{83,j+1}), (w_{84,j+2}, w_{84,j+1}), (w_{85,j+2}, w_{85,j+1}), (w_{86,j+2}, w_{86,j+1}), (w_{87,j+2}, w_{87,j+1}), (w_{88,j+2}, w_{88,j+1}), (w_{89,j+2}, w_{89,j+1}), (w_{90,j+2}, w_{90,j+1}), (w_{91,j+2}, w_{91,j+1}), (w_{92,j+2}, w_{92,j+1}), (w_{93,j+2}, w_{93,j+1}), (w_{94,j+2}, w_{94,j+1}), (w_{95,j+2}, w_{95,j+1}), (w_{96,j+2}, w_{96,j+1}), (w_{97,j+2}, w_{97,j+1}), (w_{98,j+2}, w_{98,j+1}), (w_{99,j+2}, w_{99,j+1}), (w_{100,j+2}, w_{100,j+1}), (w_{101,j+2}, w_{101,j+1}), (w_{102,j+2}, w_{102,j+1}), (w_{103,j+2}, w_{103,j+1}), (w_{104,j+2}, w_{104,j+1}), (w_{105,j+2}, w_{105,j+1}), (w_{106,j+2}, w_{106,j+1}), (w_{107,j+2}, w_{107,j+1}), (w_{108,j+2}, w_{108,j+1}), (w_{109,j+2}, w_{109,j+1}), (w_{110,j+2}, w_{110,j+1}), (w_{111,j+2}, w_{111,j+1}), (w_{112,j+2}, w_{112,j+1}), (w_{113,j+2}, w_{113,j+1}), (w_{114,j+2}, w_{114,j+1}), (w_{115,j+2}, w_{115,j+1}), (w_{116,j+2}, w_{116,j+1}), (w_{117,j+2}, w_{117,j+1}), (w_{118,j+2}, w_{118,j+1}), (w_{119,j+2}, w_{119,j+1}), (w_{120,j+2}, w_{120,j+1}), (w_{121,j+2}, w_{121,j+1}), (w_{122,j+2}, w_{122,j+1}), (w_{123,j+2}, w_{123,j+1}), (w_{124,j+2}, w_{124,j+1}), (w_{125,j+2}, w_{125,j+1}), (w_{126,j+2}, w_{126,j+1}), (w_{127,j+2}, w_{127,j+1}), (w_{128,j+2}, w_{128,j+1}), (w_{129,j+2}, w_{129,j+1}), (w_{130,j+2}, w_{130,j+1}), (w_{131,j+2}, w_{131,j+1}), (w_{132,j+2}, w_{132,j+1}), (w_{133,j+2}, w_{133,j+1}), (w_{134,j+2}, w_{134,j+1}), (w_{135,j+2}, w_{135,j+1}), (w_{136,j+2}, w_{136,j+1}), (w_{137,j+2}, w_{137,j+1}), (w_{138,j+2}, w_{138,j+1}), (w_{139,j+2}, w_{139,j+1}), (w_{140,j+2}, w_{140,j+1}), (w_{141,j+2}, w_{141,j+1}), (w_{142,j+2}, w_{142,j+1}), (w_{143,j+2}, w_{143,j+1}), (w_{144,j+2}, w_{144,j+1}), (w_{145,j+2}, w_{145,j+1}), (w_{146,j+2}, w_{146,j+1}), (w_{147,j+2}, w_{147,j+1}), (w_{148,j+2}, w_{148,j+1}), (w_{149,j+2}, w_{149,j+1}), (w_{150,j+2}, w_{150,j+1}), (w_{151,j+2}, w_{151,j+1}), (w_{152,j+2}, w_{152,j+1}), (w_{153,j+2}, w_{153,j+1}), (w_{154,j+2}, w_{154,j+1}), (w_{155,j+2}, w_{155,j+1}), (w_{156,j+2}, w_{156,j+1}), (w_{157,j+2}, w_{157,j+1}), (w_{158,j+2}, w_{158,j+1}), (w_{159,j+2}, w_{159,j+1}), (w_{160,j+2}, w_{160,j+1}), (w_{161,j+2}, w_{161,j+1}), (w_{162,j+2}, w_{162,j+1}), (w_{163,j+2}, w_{163,j+1}), (w_{164,j+2}, w_{164,j+1}), (w_{165,j+2}, w_{165,j+1}), (w_{166,j+2}, w_{166,j+1}), (w_{167,j+2}, w_{167,j+1}), (w_{168,j+2}, w_{168,j+1}), (w_{169,j+2}, w_{169,j+1}), (w_{170,j+2}, w_{170,j+1}), (w_{171,j+2}, w_{171,j+1}), (w_{172,j+2}, w_{172,j+1}), (w_{173,j+2}, w_{173,j+1}), (w_{174,j+2}, w_{174,j+1}), (w_{175,j+2}, w_{175,j+1}), (w_{176,j+2}, w_{176,j+1}), (w_{177,j+2}, w_{177,j+1}), (w_{178,j+2}, w_{178,j+1}), (w_{179,j+2}, w_{179,j+1}), (w_{180,j+2}, w_{180,j+1}), (w_{181,j+2}, w_{181,j+1}), (w_{182,j+2}, w_{182,j+1}), (w_{183,j+2}, w_{183,j+1}), (w_{184,j+2}, w_{184,j+1}), (w_{185,j+2}, w_{185,j+1}), (w_{186,j+2}, w_{186,j+1}), (w_{187,j+2}, w_{187,j+1}), (w_{188,j+2}, w_{188,j+1}), (w_{189,j+2}, w_{189,j+1}), (w_{190,j+2}, w_{190,j+1}), (w_{191,j+2}, w_{191,j+1}), (w_{192,j+2}, w_{192,j+1}), (w_{193,j+2}, w_{193,j+1}), (w_{194,j+2}, w_{194,j+1}), (w_{195,j+2}, w_{195,j+1}), (w_{196,j+2}, w_{196,j+1}), (w_{197,j+2}, w_{197,j+1}), (w_{198,j+2}, w$$

**The Ch function** contain sparse mapping subcircuit with base 7 for  $e, f, g$ . **SHA-256 NORMALIZE CH** lookup table is used for mapping to sparse representation in the same way as for  $\sigma_0$ . The value of the  $ch$  function is stored in chunks of 8 bits  $\{ch_0, ch_1, ch_2, ch_3\}$  and the corresponded sparse value is  $\{ch_{0,sparse}, ch_{1,sparse}, ch_{2,sparse}, ch_{3,sparse}\}$  Constraints:

**Update the values  $a$  and  $e$**  The values  $a_{new}$  and  $e_{new}$  are output of the round. The value  $W_r$  is a word, where  $r$  is a number of round. It has to be copy-constrained with the word  $W_r$  in the message scheduling. Constraints:

$$w_{4,j+3} = w_{1,j+3} + w_{2,j+3} + w_{5,j+2} + w_{6,j+2} \cdot 2^{14} + w_{7,j+2} \cdot 2^{28} + w_{8,j+2} \cdot 2^{30} + w_{5,j+3} + w_{6,j+3} \cdot 2^8 + w_{7,j+3} \cdot 2^{8 \cdot 2} + w_{8,j+3} \cdot 2^{8 \cdot 3} + k[r] + w_{3,j+3}, \text{ where } r \text{ is a number of round.}$$

$$w_{4,j+4} = w_{4,j+3} - w_{1,j+3} + w_{5,j+5} + w_{6,j+5} \cdot 2^{14} + w_{7,j+5} \cdot 2^{28} + w_{8,j+5} \cdot 2^{30} + w_{5,j+4} + w_{6,j+4} \cdot 2^8 + w_{7,j+4} \cdot 2^{8 \cdot 2} + w_{8,j+4} \cdot 2^{8 \cdot 3}$$

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### 2.5.3 SHA-512 Circuit

SHA-512 uses the similar logical functions as in 2.5.2 which operates on 64-bits words. Thus, the preprocessing constraints for the SHA-512' circuit is a decomposition of  $k$  message blocks to 64 bits chunks without range proofs. For 'eddsa' circuit,  $k = 2$ . All evaluations are similar to SHA-256 circuit.

**Lookup tables** We use the following lookup tables:

1. **SHA-256 NORMALIZE4** with 2 columns and  $2^{14}$  rows. The first column contains all possible 14-bits words. The second column contains corresponding sparse representations with base 4. The constraints can be used for the range check and sparse representation simultaneously.
2. **SHA-256 NORMALIZE7** with 2 columns and  $2^{14}$  rows. The first column contains all possible 14-bits words. The second column contains corresponding sparse representations with base 7. The constraints can be used for the range check and sparse representation simultaneously.
3. **SHA-512 NORMALIZE MAJ** with 2 columns and  $2^{16}$  rows. The first column contains all possible 16-bits words. The second column contains corresponding sparse representations with base 4.
4. **SHA-512 NORMALIZE CH** with 2 columns and  $2^{16}$  rows. The first column contains all possible 16-bits words. The second column contains corresponding sparse representations with base 7.

**Message scheduling** For each block of 1024 bits of the padded message the 80 words are constructed in the following way:

- The first 16 words are obtained by splitting the message.
- The last 64 words are obtained by using the functions  $\sigma_0, \sigma_1$ :

$$W_i = \sigma_1(W_{i-2}) \oplus W_{i-7} \oplus \sigma_0(W_{i-15}) \oplus W_{i-16}$$

Each round of the message scheduling has the following table:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$a$	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$a_6$	$\hat{a}_1$
$j + 1$		$a'_0$	$a'_1$	$a'_2$	$a'_3$	$a'_4$	$a'_5$	$a'_6$	
$j + 2$	$W_i$	$s'_0$	$s'_1$	$s'_2$	$s'_3$	$s'_4$	$\hat{s}_4$	—	$W_j$
$j + 3$	$w$	$s_0$	$s_1$	$s_2$	$s_3$	$s_4$			
$j + 4$	$s_0$	$s_1$	$s_2$	$s_3$	$s_4$	$s'_2$	$s'_3$	$s'_4$	$\hat{s}'_4$
$j + 5$	$s'_0$	$b'_0$	$b'_1$	$b'_2$	$b'_3$	$b'_4$	$b'_5$	$s'_1$	—
$j + 6$	$b$	$b_0$	$b_1$	$b_2$	$b_3$	$b_4$	$b_5$	$\hat{b}_0$	$\hat{b}_5$

The first 16 words require a range check. We get it free from range-constraining chunks inside functions  $\sigma_0$  and  $\sigma_1$ . Thus, for  $i$  from 16 to 80:

1. Apply  $\sigma_0$  to  $W_{i-15}$ .
2. Add the following constraint for  $W_i$ :

$$w_{0,j+3} = w_{0,j+2} + w_{8,j+2} + w_{1,j+3} + w_{2,j+3} \cdot 2^{14} + w_{3,j+3} \cdot 2^{28} + w_{4,j+3} \cdot 2^{42} + w_{5,j+3} \cdot 2^{56} + w_{0,j+4} + w_{1,j+4} \cdot 2^{14} + w_{2,j+4} \cdot 2^{28} + w_{3,j+4} \cdot 2^{42} + w_{4,j+4} \cdot 2^{56},$$

3. Apply  $\sigma_1$  to  $W_{i-2}$ .

Thus, the message schedule takes  $7 \cdot 64 = 448$  rows.

**The function  $\sigma_0$**  contains sparse mapping with base 4. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3, a_4, a_5, a_6$  which equals to 1, 6, 1, 14, 14, 14, 14 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3, a'_4, a'_5, a'_6$  are in sparse form, and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE4** lookup table is used for mapping to sparse representation and range-constraining for each chunk  $a_i$ , where bit-length of  $a_i > 3$ . If a chunk is 14 bits long, then it is constrained for free. Else the prover has to calculate the sparse representation  $\hat{a}_i$  for  $2^j \cdot a_i$ , where  $j + \text{len}(a_i) = 14$  and  $\text{len}(a_i)$  is bit-length of  $a_i$ .

Constraints:

$$\begin{aligned}
w_{0,j+0} &= w_{1,j+0} + w_{2,j+0} \cdot 2 + w_{3,j+0} \cdot 2^7 + w_{4,j+0} \cdot 2^8 + w_{5,j+0} \cdot 2^{22} + w_{6,j+0} \cdot 2^{36} + w_{7,j+0} \cdot 2^{50} \\
&\quad (w_{1,j+0} - 1) \cdot w_{1,j+0} = 0 \\
&\quad (w_{3,j+0} - 1) \cdot w_{3,j+0} = 0 \\
w_{1,j+2} + w_{2,j+2} \cdot 4^{14} + w_{3,j+2} \cdot 4^{28} + w_{4,j+2} \cdot 2^{42} + w_{5,j+2} \cdot 4^{56} &= w_{2,j+1} + w_{3,j+1} \cdot 4^6 + w_{4,j+1} \cdot 4^7 + \\
w_{5,j+1} \cdot 2^{21} + w_{6,j+1} \cdot 4^{35} + w_{7,j+1} \cdot 4^{49} + w_{1,j+1} \cdot 4^{63} + w_{3,j+1} + w_{4,j+1} \cdot 4 + w_{5,j+1} \cdot 4^{15} + w_{6,j+1} \cdot 2^{29} + \\
w_{7,j+1} \cdot 4^{43} + w_{4,j+1} + w_{5,j+1} \cdot 4^{14} + w_{6,j+1} \cdot 4^{28} + w_{7,j+1} \cdot 2^{42} + w_{1,j+1} \cdot 4^{56} + w_{2,j+1} \cdot 4^{57} + w_{3,j+1} \cdot 4^{63} \\
&\quad 15 \text{ plookup constraints: } (w_{1,j+0}, w_{1,j+1}), (2^8 \cdot \\
w_{2,j+0}, w_{8,j+0}), (w_{2,j+0}, w_{2,j+1}), (w_{3,j+0}, w_{3,j+1}), (w_{4,j+0}, w_{4,j+1}), (w_{5,j+0}, w_{5,j+1}), (w_{6,j+0}, w_{6,j+1}), (w_{7,j+0}, w_{7,j+1}), (w_{7,j+0}, w_{8,j+0}), \\
&\quad w_{5,j+3}, w_{6,j+2})
\end{aligned}$$

**The function**  $\sigma_1$  contains sparse mapping subcircuit with base 4. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3, a_4, a_5$  which equals to 6, 13, 14, 14, 3 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3, a'_4, a'_5$  are in sparse form, and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE4** lookup table is used for mapping to sparse representation and range-constraining in the same way as for  $\sigma_0$ .

Constraints:

$$\begin{aligned}
w_{0,j+6} &= w_{1,j+6} + w_{2,j+6} \cdot 2^6 + w_{3,j+6} \cdot 2^{19} + w_{4,j+6} \cdot 2^{33} + w_{5,j+6} \cdot 2^{47} + w_{6,j+6} \cdot 2^{61} \\
&\quad (w_{6,j+6} - 7) \cdot (w_{6,j+6} - 6) \cdot \dots \cdot w_{6,j+6} = 0 \\
w_{0,j+5} + w_{7,j+5} \cdot 4^{14} + w_{5,j+4} \cdot 4^{28} + w_{6,j+4} \cdot 2^{42} + w_{7,j+4} \cdot 4^{56} &= \\
w_{2,j+5} + w_{3,j+5} \cdot 4^{13} + w_{4,j+5} \cdot 4^{27} + w_{5,j+5} \cdot 2^{41} + w_{6,j+5} \cdot 4^{55} + w_{3,j+5} + w_{4,j+5} \cdot 4^{14} + w_{5,j+5} \cdot 4^{28} + w_{6,j+5} \cdot \\
2^{42} + w_{1,j+5} \cdot 4^{45} + w_{2,j+5} \cdot 4^{51} + w_{6,j+5} + w_{1,j+5} \cdot 4^3 + w_{2,j+5} \cdot 4^9 + w_{3,j+5} \cdot 2^{22} + w_{4,j+5} \cdot 4^{36} + w_{5,j+5} \cdot 4^{50} \\
&\quad 15 \text{ plookup constraints: } (w_{1,j+6}, w_{1,j+5}), (2^8 \cdot \\
w_{1,j+6}, w_{7,j+6}), (w_{2,j+6}, w_{2,j+5}), (w_{3,j+6}, w_{3,j+5}), (w_{4,j+6}, w_{4,j+5}), (w_{5,j+6}, w_{5,j+5}), (w_{6,j+6}, w_{6,j+5}), (2 \cdot \\
w_{6,j+6}, w_{8,j+6}), (w_{0,j+4}, w_{0,j+5}), (w_{1,j+4}, w_{7,j+5}), (w_{2,j+4}, w_{5,j+4}), (w_{3,j+4}, w_{6,j+4}), (w_{4,j+4}, w_{7,j+4}), (2^6 \cdot \\
&\quad w_{4,j+4}, w_{8,j+4})
\end{aligned}$$

**Compression** There are 80 rounds of compression. Each round of compression has the following table:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$e$	$e_0$	$e_1$	$e_2$	$e_3$	$e_4$	$e_5$	$\hat{e}_1$	$\hat{e}_3$
$j + 1$	$--$	$e'_0$	$e'_1$	$e'_2$	$e'_3$	$e'_4$	$e'_5$	$\hat{e}_5$	$--$
$j + 2$	$e'$	$f'$	$--$	$\hat{s}'_4$	$s'_0$	$s'_1$	$s'_2$	$s'_3$	$s'_4$
$j + 3$	$ch_{0,sparse}$	$ch_{1,sparse}$	$ch_{2,sparse}$	$ch_{3,sparse}$	$s_0$	$s_1$	$s_2$	$s_3$	$s_4$
$j + 4$	$g'$	$--$	$--$	$--$	$e_{new}$	$ch_0$	$ch_1$	$ch_2$	$ch_3$
$j + 5$	$c'$	$d$	$h$	$W_r$	$a_{new}$	$maj_3$	$maj_0$	$maj_1$	$maj_2$
$j + 6$	$maj_{0,sparse}$	$maj_{1,sparse}$	$maj_{2,sparse}$	$maj_{3,sparse}$	$s_0$	$s_1$	$s_2$	$s_3$	$s_4$
$j + 7$	$a'$	$b'$	$--$	$\hat{s}'_4$	$s'_0$	$s'_1$	$s'_2$	$s'_3$	$s'_4$
$j + 8$		$a'_0$	$a'_1$	$a'_2$	$a'_3$	$a'_4$	$a'_5$	$\hat{a}_5$	$--$
$j + 9$	$a$	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$	$\hat{a}_2$	$\hat{a}_3$

**The working variables**  $a, b, c, d, e, f, g, h$  equals to the fixed initial *SHA* – 512 values for the first chunk and to the sum of previous output and initial values for the rest of chunks. The variables with quotes are corresponded sparse representation. For each chunk, the following rows are used:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$a$	$a'$	$b$	$b'$	$d$	$--$	$--$	$--$	$--$
$j + 1$	$c$	$c'$	$e$	$e'$	$h$	$--$	$--$	$--$	$--$
$j + 2$	$f$	$f'$	$g$	$g'$	$--$	$--$	$--$	$--$	$--$

For the first round,  $a, a', b', c', d, e, e', f', g', h$  are copy constrained with corresponded values from the table above.

For the second round,  $b', c', d, f', g', h$  are copy constrained with  $a', b', c, e', f', g$  from the table. The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round.

For the third round,  $c', d, g', h$  are copy constrained with  $a', b, e', f$ . The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round. The values  $b', f'$  are copy constrained with  $a', e'$  from the previous round.

In the rest of the rounds the following ‘non-special’ copy constraints are used:

1. The values  $a, e$  are copy constrained with  $a_{new}, e_{new}$  from the previous round.

2. The values  $b', f'$  are copy constrained with  $a', e'$  from the previous round.
3. The values  $c', g'$  are copy constrained with  $b', c'$  from the previous round.
4. The values  $d, h$  are copy constrained with  $a', e'$  from the round  $r - 3$ , where  $r$  is current round.

**The  $\Sigma_0$  function** contains subcircuit with base 4. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3, a_4, a_5$  which equals to 14, 14, 6, 5, 14, 11 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3, a'_4, a'_5$  are in sparse form, and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE4** lookup table is used for mapping to sparse representation and range-constraining in the same way as for  $\sigma_0$ .

Constraints:

$$\begin{aligned}
w_{0,j+9} &= w_{1,j+9} + w_{2,j+9} \cdot 2^{14} + w_{3,j+9} \cdot 2^{28} + w_{4,j+9} \cdot 2^{34} + w_{5,j+9} \cdot 2^{39} + w_{6,j+9} \cdot 2^{53} \\
&\quad w_{4,j+7} + w_{5,j+7} \cdot 4^{14} + w_{6,j+7} \cdot 4^{28} + w_{7,j+7} \cdot 2^{42} + w_{8,j+7} \cdot 4^{56} = \\
&\quad w_{3,j+8} + w_{4,j+8} \cdot 4^6 + w_{5,j+8} \cdot 4^{11} + w_{6,j+8} \cdot 2^{25} + w_{1,j+8} \cdot 4^{36} + w_{2,j+8} \cdot 4^{50} + w_{4,j+8} + w_{5,j+8} \cdot 4^5 + w_{6,j+8} \cdot 4^{19} + \\
&\quad w_{1,j+8} \cdot 2^{30} + w_{2,j+8} \cdot 4^{44} + w_{3,j+8} \cdot 4^{58} + w_{5,j+8} + w_{6,j+8} \cdot 4^{14} + w_{1,j+8} \cdot 4^{25} + w_{2,j+8} \cdot 2^{39} + w_{3,j+8} \cdot 4^{53} + w_{4,j+8} \cdot 4^{59} \\
&\quad 15 \text{ plookup constraints: } (w_{1,j+9}, w_{1,j+8}), (w_{2,j+9}, w_{2,j+8}), (2^8 \cdot w_{3,j+9}, w_{7,j+9}), (w_{3,j+9}, w_{3,j+8}), (2^9 \cdot \\
&\quad w_{4,j+9}, w_{8,j+9}), (w_{4,j+9}, w_{4,j+8}), (w_{5,j+9}, w_{5,j+8}), (2^3 \cdot \\
&\quad w_{6,j+9}, w_{7,j+8}), (w_{6,j+9}, w_{6,j+8}), (w_{4,j+6}, w_{4,j+7}), (w_{5,j+6}, w_{5,j+7}), (w_{6,j+6}, w_{6,j+7}), (w_{7,j+6}, w_{7,j+7}), (w_{8,j+6}, w_{8,j+7}), (2^{10} \cdot \\
&\quad w_{8,j+7}, w_{3,j+7})
\end{aligned}$$

**The  $\Sigma_1$  function** contains subcircuit with base 7. Let  $a$  be divided to chunks  $a_0, a_1, a_2, a_3, a_4, a_5$  which equals to 14, 4, 14, 9, 14, 9 bits respectively. The values  $a'_0, a'_1, a'_2, a'_3, a'_4, a'_5$  are in sparse form, and  $a'$  is a sparse  $a$ . **SHA-256 NORMALIZE7** lookup table is used for mapping to sparse representation and range-constraining in the same way as for  $\sigma_0$ .

Constraints:

$$\begin{aligned}
w_{0,j+0} &= w_{1,j+0} + w_{2,j+0} \cdot 2^{14} + w_{3,j+0} \cdot 2^{18} + w_{4,j+0} \cdot 2^{32} + w_{5,j+0} \cdot 2^{41} + w_{6,j+0} \cdot 2^{55} \\
&\quad w_{4,j+2} + w_{5,j+2} \cdot 4^{14} + w_{6,j+2} \cdot 4^{28} + w_{7,j+2} \cdot 2^{42} + w_{8,j+2} \cdot 4^{56} = \\
&\quad w_{2,j+1} + w_{3,j+1} \cdot 4^4 + w_{4,j+1} \cdot 4^{18} + w_{5,j+1} \cdot 2^{27} + w_{6,j+1} \cdot 4^{41} + w_{1,j+1} \cdot 4^{50} + w_{3,j+1} + w_{4,j+1} \cdot 4^{14} + w_{5,j+1} \cdot 4^{23} + \\
&\quad w_{6,j+1} \cdot 2^{37} + w_{1,j+1} \cdot 4^{46} + w_{3,j+1} \cdot 4^{60} + w_{5,j+1} + w_{6,j+1} \cdot 4^{14} + w_{1,j+1} \cdot 4^{23} + w_{2,j+1} \cdot 2^{37} + w_{3,j+1} \cdot 4^{41} + w_{4,j+1} \cdot 4^{55} \\
&\quad 15 \text{ plookup constraints: } (w_{1,j+0}, w_{1,j+1}), (w_{2,j+0}, w_{2,j+1}), (2^{10} \cdot w_{2,j+0}, w_{7,j+0}), (w_{3,j+0}, w_{3,j+1}), (2^5 \cdot \\
&\quad w_{4,j+0}, w_{8,j+0}), (w_{4,j+0}, w_{4,j+1}), (w_{5,j+0}, w_{5,j+1}), (2^3 \cdot \\
&\quad w_{6,j+0}, w_{7,j+1}), (w_{6,j+0}, w_{6,j+1}), (w_{4,j+3}, w_{4,j+2}), (w_{5,j+3}, w_{5,j+2}), (w_{6,j+3}, w_{6,j+2}), (w_{7,j+3}, w_{7,j+2}), (w_{8,j+3}, w_{8,j+2}), (2^{10} \cdot \\
&\quad w_{8,j+3}, w_{3,j+2})
\end{aligned}$$

**The Maj function** contains subcircuit with base 4 for  $a, b, c$ . **SHA-512 NORMALIZE MAJ** lookup table is used for mapping to sparse representation in the same way as for  $\sigma_0$ . The value of the *maj* function is stored in chunks of 16 bits. Constraints:

$$\begin{aligned}
w_{0,j+6} + w_{1,j+6} \cdot 4^{16} + w_{2,j+6} \cdot 4^{16 \cdot 2} + w_{3,j+6} \cdot 4^{16 \cdot 3} &= w_{0,j+7} + w_{1,j+7} + w_{0,j+5} \\
4 \text{ plookup constraints: } (w_{5,j+5}, w_{0,j+6}), (w_{6,j+5}, w_{1,j+6}), (w_{7,j+5}, w_{2,j+6}), (w_{8,j+5}, w_{3,j+6})
\end{aligned}$$

**The Ch function** contain sparse mapping subcircuit with base 7 for  $e, f, g$ . **SHA-512 NORMALIZE CH** lookup table is used for mapping to sparse representation in the same way as for  $\sigma_0$ . The value of the *ch* function is stored in chunks of 16 bits. Constraints:

$$\begin{aligned}
w_{0,j+3} + w_{1,j+3} \cdot 7^{16} + w_{2,j+3} \cdot 7^{16 \cdot 2} + w_{3,j+3} \cdot 7^{16 \cdot 3} &= w_{0,j+2} + 2 \cdot w_{1,j+2} + 3 \cdot w_{0,j+4} \\
4 \text{ plookup constraints: } (w_{5,j+4}, w_{0,j+3}), (w_{6,j+4}, w_{1,j+3}), (w_{7,j+4}, w_{2,j+3}), (w_{8,j+3}, w_{3,j+2})
\end{aligned}$$

**Update the values  $a$  and  $e$**  Constraints:

$$\begin{aligned}
w_{4,j+4} &= w_{1,j+5} + w_{2,j+5} + w_{5,j+3} \cdot 2^{14} + w_{6,j+3} \cdot 2^{28} + w_{7,j+3} \cdot 2^{42} + w_{8,j+3} \cdot 2^{56} + w_{5,j+4} + w_{6,j+4} \cdot 2^{16} + \\
&\quad w_{7,j+4} \cdot 2^{16 \cdot 2} + w_{8,j+4} \cdot 2^{16 \cdot 3} + k[r] + w_{3,j+5}, \text{ where } r \text{ is a number of round.} \\
w_{4,j+5} &= w_{4,j+4} - w_{1,j+5} + w_{4,j+6} + w_{5,j+6} \cdot 2^{14} + w_{6,j+6} \cdot 2^{28} + w_{7,j+6} \cdot 2^{42} + w_{8,j+6} \cdot 2^{56} + w_{5,j+5} + \\
&\quad w_{6,j+5} \cdot 2^{16} + w_{7,j+5} \cdot 2^{16 \cdot 2} + w_{8,j+5} \cdot 2^{16 \cdot 3}
\end{aligned}$$

**Cost** The total value of rows is  $64 \cdot 7 + 10 \cdot 80 + 3 = 1248$  per chunk.

### 2.5.4 Poseidon Circuit

Consider a poseidon permutation  $F : [0_{\mathbb{F}}, I[2], I[3]] \rightarrow [O[1], H, O[3]]$  of width 3 and  $\alpha = 5$ . The 1-call sponge function is used:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$0_{\mathbb{F}}$	$I[2]$	$I[3]$	$T_{1,0}$	$T_{1,1}$	$T_{1,2}$	$T_{2,0}$	$T_{2,1}$	$T_{2,2}$
$j + 1$	$T_{3,0}$	$T_{3,1}$	$T_{3,2}$	$T_{4,0}$	$T_{4,1}$	$T_{4,2}$	$T_{5,0}$	$T_{5,1}$	$T_{5,2}$
$\dots$									
$j + 21$	$T_{63,0}$	$T_{63,1}$	$T_{63,2}$	$T_{64,0}$	$T_{64,1}$	$T_{64,2}$	$O[1]$	$H$	$O[3]$

Constraints:

$$\begin{aligned}
& \text{For } j + 0: \\
& [w_{3,j+0}, w_{4,j+0}, w_{5,j+0}] = [w_{0,j+0}^5, w_{1,j+0}^5, w_{2,j+0}^5] \times M + RC \\
& [w_{6,j+0}, w_{7,j+0}, w_{8,j+0}] = [w_{2,j+0}^5, w_{3,j+0}^5, w_{4,j+0}^5] \times M + RC \\
& \text{For } j + 1: \\
& [w_{0,j+1}, w_{1,j+1}, w_{2,j+1}] = [w_{2,j+0}^5, w_{7,j+0}^5, w_{8,j+0}^5] \times M + RC \\
& [w_{3,j+1}, w_{4,j+1}, w_{5,j+1}] = [w_{0,j+1}^5, w_{1,j+1}^5, w_{2,j+1}^5] \times M + RC \\
& [w_{6,j+1}, w_{7,j+1}, w_{8,j+1}] = [w_{3,j+1}, w_{4,j+1}, w_{5,j+1}^5] \times M + RC \\
& \text{For } j + k, k \in \{2, 19\}: \\
& [w_{0,j+k}, w_{1,j+k}, w_{2,j+k}] = [w_{6,j+k-1}, w_{7,j+k-1}, w_{8,j+k-1}^5] \times M + RC \\
& [w_{3,j+k}, w_{4,j+k}, w_{5,j+k}] = [w_{0,j+k}, w_{1,j+k}, w_{2,j+k}^5] \times M + RC \\
& [w_{6,j+k}, w_{7,j+k}, w_{8,j+k}] = [w_{3,j+k}, w_{4,j+k}, w_{5,j+k}^5] \times M + RC \\
& \text{For } j + 20: \\
& [w_{0,j+20}, w_{1,j+20}, w_{2,j+20}] = [w_{6,j+19}, w_{7,j+19}, w_{8,j+19}^5] \times M + RC \\
& [w_{3,j+20}, w_{4,j+20}, w_{5,j+20}] = [w_{0,j+20}, w_{1,j+20}, w_{2,j+20}^5] \times M + RC \\
& [w_{6,j+20}, w_{7,j+20}, w_{8,j+20}] = [w_{2,j+20}^5, w_{3,j+20}^5, w_{4,j+20}^5] \times M + RC \\
& \text{For } j + 21: \\
& [w_{0,j+21}, w_{1,j+21}, w_{2,j+21}] = [w_{2,j+20}^5, w_{7,j+20}^5, w_{8,j+20}^5] \times M + RC \\
& [w_{3,j+21}, w_{4,j+21}, w_{5,j+21}] = [w_{0,j+21}^5, w_{1,j+21}^5, w_{2,j+21}^5] \times M + RC \\
& [w_{6,j+21}, w_{7,j+21}, w_{8,j+21}] = [w_{2,j+21}^5, w_{3,j+21}^5, w_{4,j+21}^5] \times M + RC
\end{aligned}$$

### 2.5.5 Merkle Tree Circuit

Merkle Tree generation for set  $\{H_{B_{n_1}}, \dots, H_{B_{n_2}}\}$ . Let  $k = \lceil \log(n_2 - n_1) \rceil$

1.  $n = n_2 - n_1$
2.  $2^k = n$
3. for  $i$  from 0 to  $n - 1$ :
  - 3.1  $T_i := H_i$  // just notation for simplicity, not a real part of the circuit
4. for  $i$  from 0 to  $k - 1$ :
  - 4.1 for  $j$  from 0 to  $(n - 1)/2$ :
    - 4.1.1  $T'_i = \text{hash}(T_{2 \cdot i}, T_{2 \cdot i + 1})$ . // see Section 2.5.4
  - 4.2  $n = \frac{n}{2}$
  - 4.3 for  $j$  from 0 to  $n - 1$ :
    - 4.3.1  $T_i := T'_i$ . // just notation for simplicity, not a real part of the circuit

### 2.5.6 Ed25519 Circuit

To verify a signature  $(R, s)$  on a message  $M$  using public key  $A$  and a generator  $B$  do:

1. Prove that  $s$  in the range  $L = 2^{252} + 277423177773723535851937790883648493$ .

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$s$	$z_0$	$z_1$	$z_2$	$z_3$	$z_4$	$z_5$	$z_6$	$z_7$
$j + 1$	$z_8$	$z_9$	$z_{10}$	$z_{11}$	$z_{12}$	$z_{13}$	$z_{14}$	$z_{15}$	$z_{16}$
$j + 2$	$z_{17}$	$z_{18}$	$z_{19}$	$z_{20}$	$z_{21}$	$z_{22}$	$z_{23}$	$z_{24}$	$z_{25}$



Evaluations:

$$z_0 = s + 2^{253} - L \text{ is decomposed into 10-bit windows } k_0 + 2^{10} \cdot k_1 + 2^{10 \cdot 2} \cdot k_2 + \dots + 2^{10 \cdot 25} \cdot k_{25}$$

$$z_i = (z_{i-1} - k_{i-1}) / 2^{10}$$

Constraints:

$$w_{1,j} = w_{0,j} + 2^{253} - L$$

Each  $w_{i,k} - 2^{10} \cdot w_{i+a,k+b}$ , where  $i = 1, \dots, 8$  for  $k = 0$ ,  $i = 0, \dots, 8$  for  $k = 1$  and  $i = 0, \dots, 7$  for  $k = 2$ ,  
 $(i+1) = b \cdot 9 + a$  is range-constrained by 10-bits plookup table.  
 $w_{8,j+2} \cdot 2^7$  is range-constrained by 10-bits plookup table.

It costs 3 rows.

2.  $k == \text{SHA-512}(data || R || A || M) //$  See section ?? It costs  $1248 \cdot 2 = 2496$  rows.

3.  $sB = R + kA$ :

3.1 Fixed-base scalar multiplication circuit is used for  $sB = S$ . The cell  $w_{0,j+84}$  is copy-constrained with  $w_{0,j+0}$  from the range circuit.

3.2 One addition is used for  $S + (-R)$ . The coordinates of  $R$  and  $T = S + (-R)$  are placed on the last row of fixed-base scalar multiplication circuit.

$$j + 0 \mid x_s \mid x_r \mid y_r \mid x_t \mid y_t \mid y_s \mid -- \mid -- \mid --$$

In total, three constraints are used for addition:

$$w_{3,j+0} \cdot (1 + dw_{0,j+0} \cdot (-w_{1,j+0}) \cdot w_{5,j+0} \cdot w_{2,j+0}) = w_{0,j+0} \cdot w_{2,j+0} + (-w_{1,j+0}) \cdot w_{5,j+0}$$

$$w_{4,j+0} \cdot (1 - dw_{0,j+0} \cdot (-w_{1,j+0}) \cdot w_{5,j+0} \cdot w_{2,j+0}) = w_{0,j+0} \cdot (-w_{1,j+0}) + w_{2,j+0} \cdot w_{5,j+0}$$

$$(-w_{1,j+0})^2 + w_{2,j+0}^2 = 1 - d \cdot w_{1,j+0}^2 \cdot w_{2,j+0}^2 \quad w_{1,j+0}, w_{5,j+0} \text{ are copy-constrained with } w_{6,j+84}, w_{7,j+84} \text{ from fixed-base multiplication circuit.}$$

3.3 Variable-base scalar multiplication circuit for  $T = k \cdot A$ , where cells  $w_{1,j+254}, w_{2,j+254}$  are copy constrained with  $w_{3,j+0}, w_{5,j+0}$ .

It costs  $3 + 2496 + 85 + 255 + 1 = 2840$  rows.

## 2.5.7 Elliptic Curves Arithmetics

### WIP

This section instantiates the arithmetic of edwards25519 curve:

$$-x^2 + y^2 = 1 - (121665/121666) \cdot x^2 \cdot y^2$$

Affine coordinates are used for points. Let  $d$  be equal to  $121665/121666$ .

**Fixed-base scalar multiplication circuit** : We precompute all values  $w(B, s', k) = k_i \cdot 8^{s'} B$ , where  $k_i \in \{0, \dots, 7\}$ ,  $s' \in \{0, \dots, 84\}$ .

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$acc$	$b_{252}$	$b_{251}$	$b_{250}$	$u_1$	$v_1$	$x_{acc}$	$y_{acc}$	--
$j + 1$	$acc$	$b_{249}$	$b_{248}$	$b_{247}$	$u_1$	$v_1$	$x_{acc}$	$y_{acc}$	--
...									
$j + 84$	$s$	--	--	--	--	$b_0$	$x_{acc}$	$y_{acc}$	--

Evaluations:

The values  $b_i$ ,  $i = 0, \dots, 252$  are binary representation of the scalar  $s$  and  $acc$  in each row is an accumulator for these bits.

$$(u_1, v_1) = (b_{i+2} \cdot 2^2 + b_{i+1} \cdot 2 + b_i) \cdot B \text{ for each row.}$$

$$(x_{acc_{j+0}}, y_{acc_{j+0}}) = (u_{1_{j+0}}, v_{1_{j+0}})$$

$$(x_{acc_{j+k}}, y_{acc_{j+k}}) = (u_{1_{j+k}}, v_{1_{j+k}}) + (x_{acc_{j+k-1}}, y_{acc_{j+k-1}})$$

Define the following functions:

1.  $\phi_1 : (x_1, x_2, x_3, x_4) \mapsto$   
 $x_3 \cdot (-u'_0 \cdot x_2 \cdot x_1 + u'_0 \cdot x_1 + u'_0 \cdot x_2 - u'_0 + u'_2 \cdot x_1 \cdot x_2 - u'_2 \cdot x_2 + u'_4 \cdot x_1 \cdot x_2 - u'_4 \cdot x_2 - u'_6 \cdot x_1 \cdot x_2 +$   
 $u'_1 \cdot x_2 \cdot x_1 - u'_1 \cdot x_1 - u'_1 \cdot x_2 + u'_1 - u'_3 \cdot x_1 \cdot x_2 + u'_3 \cdot x_2 - u'_5 \cdot x_1 \cdot x_2 + u'_5 \cdot x_2 + u'_7 \cdot x_1 \cdot x_2) - (x_4 -$   
 $u'_0 \cdot x_2 \cdot x_1 + u'_0 \cdot x_1 + u'_0 \cdot x_2 - u'_0 + u'_2 \cdot x_1 \cdot x_2 - u'_2 \cdot x_2 + u'_4 \cdot x_1 \cdot x_2 - u'_4 \cdot x_2 - u'_6 \cdot x_1 \cdot x_2)$
2.  $\phi_2 : (x_1, x_2, x_3, x_4) \mapsto$   
 $x_3 \cdot (-v'_0 \cdot x_2 \cdot x_1 + v'_0 \cdot x_1 + v'_0 \cdot x_2 - v'_0 + v'_2 \cdot x_1 \cdot x_2 - v'_2 \cdot x_2 + v'_4 \cdot x_1 \cdot x_2 - v'_4 \cdot x_2 - v'_6 \cdot x_1 \cdot x_2 + v'_1 \cdot$   
 $x_2 \cdot x_1 - v'_1 \cdot x_1 - v'_1 \cdot x_2 + v'_1 - v'_3 \cdot x_1 \cdot x_2 + v'_3 \cdot x_2 - v'_5 \cdot x_1 \cdot x_2 + v'_5 \cdot x_2 + v'_7 \cdot x_1 \cdot x_2) - (x_4 - v'_0 \cdot$   
 $x_2 \cdot x_1 + v'_0 \cdot x_1 + v'_0 \cdot x_2 - v'_0 + v'_2 \cdot x_1 \cdot x_2 - v'_2 \cdot x_2 + v'_4 \cdot x_1 \cdot x_2 - v'_4 \cdot x_2 - v'_6 \cdot x_1 \cdot x_2)$
3.  $\phi_3 : (x_1, x_3, x_4, x_5, x_6) \mapsto$   
 $x_1 \cdot (1 + d \cdot x_3 \cdot x_4 \cdot x_5 \cdot x_6) - (x_3 \cdot x_6 + x_4 \cdot x_5)$
4.  $\phi_4 : (x_2, x_3, x_4, x_5, x_6) \mapsto$   
 $x_2 \cdot (1 - d \cdot x_3 \cdot x_4 \cdot x_5 \cdot x_6) - (x_3 \cdot x_5 + x_4 \cdot x_6)$

Constraints:

- For  $j + 0$ :
  - $(w_{1,j+0} - 1) \cdot w_{1,j+0} = 0$
  - $(w_{2,j+0} - 1) \cdot w_{2,j+0} = 0$
  - $(w_{3,j+0} - 1) \cdot w_{3,j+0} = 0$
  - $w_{0,j+0} = w_{1,j+0} \cdot 2^2 + w_{2,j+0} \cdot 2 + w_{3,j+0}$
  - $\phi_1(w_{1,j+0}, w_{2,j+0}, w_{3,j+0}, w_{4,j+0}) = 0$ , where  $(u'_i, v'_i) = w(B, j + 0, i)$
  - $\phi_2(w_{1,j+0}, w_{2,j+0}, w_{3,j+0}, w_{5,j+0}) = 0$ , where  $(u'_i, v'_i) = w(B, j + 0, i)$
  - $w_{6,j+0} = w_{4,j+0}$
  - $w_{7,j+0} = w_{5,j+0}$
- For  $j + z, z \neq 0, z \neq 84$ :
  - $(w_{1,j+z} - 1) \cdot w_{1,j+z} = 0$
  - $(w_{2,j+z} - 1) \cdot w_{2,j+z} = 0$
  - $(w_{3,j+z} - 1) \cdot w_{3,j+z} = 0$
  - $w_{0,j+z} = w_{0,j+z-1} \cdot 2^3 + w_{1,j+z} \cdot 2^2 + w_{2,j+z} \cdot 2 + w_{3,j+z}$
  - $\phi_1(w_{1,j+z}, w_{2,j+z}, w_{3,j+z}, w_{4,j+z}) = 0$ , where  $(u'_i, v'_i) = w(B, j + z, i)$
  - $\phi_2(w_{1,j+z}, w_{2,j+z}, w_{3,j+z}, w_{5,j+z}) = 0$ , where  $(u'_i, v'_i) = w(B, j + z, i)$
  - $\phi_3(w_{6,j+z}, w_{6,j+z-1}, w_{7,j+z-1}, w_{4,j+z}, w_{5,j+z}) = 0$
  - $\phi_4(w_{7,j+z}, w_{6,j+z-1}, w_{7,j+z-1}, w_{4,j+z}, w_{5,j+z}) = 0$
- For  $j + 84$ :
  - $(w_{5,j+84} - 1) \cdot w_{5,j+84} = 0$
  - $w_{0,j+84} = w_{0,j+83} \cdot 2 + w_{5,j+84}$
  - $\phi_3(w_{6,j+z}, w_{6,j+z-1}, w_{7,j+z-1}, w_{5,j+84} \cdot x_B, w_{5,j+84} \cdot y_B + (1 - w_{5,j+84})) = 0$
  - $\phi_4(w_{7,j+z}, w_{6,j+z-1}, w_{7,j+z-1}, w_{5,j+84} \cdot x_B, w_{5,j+84} \cdot y_B + (1 - w_{5,j+84})) = 0$ , where  $B = (x_B, y_B)$ .

**Variable-base scalar multiplication circuit** :

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
j + 0	acc	$b_{511}$	$b_{510}$	$x_2$	$y_2$	$b_{509}$	$x_3$	$y_3$	$b_{508}$
j + 1	acc	$x_1$	$y_1$	$x_4$	$y_4$	$b_{507}$	$x_5$	$y_5$	$b_{506}$
j + 2	acc	$x_1$	$y_1$	$x_6$	$y_6$	$b_{505}$	$x_7$	$y_7$	$b_{504}$
...									
j + 253	acc	$x_1$	$y_1$	$x_{508}$	$y_{508}$	$b_3$	$x_{509}$	$y_{509}$	$b_2$
j + 254	$k$	$x_{512}$	$y_{512}$	$x_{510}$	$y_{510}$	$b_1$	$x_{511}$	$y_{511}$	$b_0$

Evaluations:

The values  $b_i, i = 0, \dots, 511$  are binary representation of the scalar  $k$  and  $acc$  in each row is an accumulator for these bits.

The values  $(x_1, y_1) = A$ .

$$(x_2, y_2) = 2(b_{511} \cdot (x_1, y_1)) + b_{510} \cdot (x_1, y_1)$$

$$(x_i, y_i) = 2(x_{i-1}, y_{i-1}) + b_{512-i} \cdot (x_1, y_1)$$

Define the following functions:

1.  $\phi_1 : (b, x_1, y_1, x_2, y_2, x_3) \mapsto$   
 $x_3 \cdot ((y_1^2 - x_1^2) \cdot (2 - y_1^2 + x_1^2) + 2dx_1y_1(y_1^2 + x_1^2) \cdot x_2y_2b) - (2x_1y_1 \cdot (2 - y_1^2 + x_1^2) \cdot (y_2b + (1 - b)) + (y_1^2 + x_1^2) \cdot (y_1^2 - x_1^2) \cdot x_2b)$
2.  $\phi_2 : (b, x_1, y_1, x_2, y_2, y_3) \mapsto$   
 $y_3 \cdot ((y_1^2 - x_1^2) \cdot (2 - y_1^2 + x_1^2) - 2dx_1y_1(y_1^2 + x_1^2) \cdot x_2y_2b) - (2x_1y_1 \cdot (2 - y_1^2 + x_1^2) \cdot x_2b + (y_1^2 + x_1^2) \cdot (y_1^2 - x_1^2) \cdot (y_2b + (1 - b)))$

Constraints:

- For  $j + 0$ :
  - $(w_{1,j+0} - 1) \cdot w_{1,j+0} = 0$
  - $(w_{2,j+0} - 1) \cdot w_{2,j+0} = 0$
  - $(w_{5,j+0} - 1) \cdot w_{5,j+0} = 0$
  - $(w_{8,j+0} - 1) \cdot w_{8,j+0} = 0$
  - $w_{0,j+0} = w_{1,j} \cdot 2^3 + w_{2,j+0} \cdot 2^2 + w_{5,j+0} \cdot 2 + w_{8,j+0}$
  - $\phi_1(w_{2,j+0}, w_{1,j+1} \cdot w_{1,j+0}, (w_{2,j+1} \cdot w_{1,j+0} + (1 - w_{1,j+0})), w_{1,j+1}, w_{2,j+1}, w_{3,j+0})$
  - $\phi_2(w_{2,j+0}, w_{1,j+1} \cdot w_{1,j+0}, (w_{2,j+1} \cdot w_{1,j+0} + (1 - w_{1,j+0})), w_{1,j+1}, w_{2,j+1}, w_{4,j+0})$
  - $\phi_1(w_{5,j+0}, w_{3,j+0}, (w_{4,j+0}, w_{1,j+1}, w_{2,j+1}, w_{6,j+0}))$
  - $\phi_2(w_{5,j+0}, w_{3,j+0}, (w_{4,j+0}, w_{1,j+1}, w_{2,j+1}, w_{7,j+0}))$
- For  $j + z, z \equiv 1 \pmod{2}$ :
  - $w_{1,j+z} = w_{1,j+z-1}$
  - $w_{2,j+z} = w_{2,j+z-1}$
  - $(w_{5,j+z} - 1) \cdot w_{5,j+z} = 0$
  - $(w_{8,j+z} - 1) \cdot w_{8,j+z} = 0$
  - $w_{0,j+z} = w_{0,j+z-1} \cdot 2^2 + w_{5,j+z} \cdot 2 + w_{8,j+z}$
  - $\phi_1(w_{8,j+z-1}, w_{6,j+z-1}, w_{7,j+z-1}, w_{1,j+z}, w_{2,j+z}, w_{3,j+z})$
  - $\phi_2(w_{8,j+z-1}, w_{6,j+z-1}, w_{7,j+z-1}, w_{1,j+z}, w_{2,j+z}, w_{4,j+z})$
  - $\phi_1(w_{5,j+z}, w_{3,j+z}, w_{4,j+z}, w_{1,j+z}, w_{2,j+z}, w_{6,j+z})$
  - $\phi_2(w_{5,j+z}, w_{3,j+z}, w_{4,j+z}, w_{1,j+z}, w_{2,j+z}, w_{7,j+z})$
- For  $j + z, z \equiv 0 \pmod{2}, z \neq 0$ :
  - $w_{1,j+z} = w_{1,j+z-1}$
  - $w_{2,j+z} = w_{2,j+z-1}$
  - $(w_{5,j+z} - 1) \cdot w_{5,j+z} = 0$
  - $(w_{8,j+z} - 1) \cdot w_{8,j+z} = 0$
  - $w_{0,j+z} = w_{0,j+z-1} \cdot 2^2 + w_{5,j+z} \cdot 2 + w_{8,j+z}$
  - $\phi_1(w_{8,j+z-1}, w_{6,j+z-1}, w_{7,j+z-1}, w_{1,j+z-1}, w_{2,j+z-1}, w_{3,j+z})$
  - $\phi_2(w_{8,j+z-1}, w_{6,j+z-1}, w_{7,j+z-1}, w_{1,j+z-1}, w_{2,j+z-1}, w_{4,j+z})$
  - $\phi_1(w_{5,j+z}, w_{3,j+z}, w_{4,j+z}, w_{1,j+z-1}, w_{2,j+z-1}, w_{6,j+z})$
  - $\phi_2(w_{5,j+z}, w_{3,j+z}, w_{4,j+z}, w_{1,j+z-1}, w_{2,j+z-1}, w_{7,j+z})$
- For  $j + 254$ :
  - $(w_{5,j+z} - 1) \cdot w_{5,j+z} = 0$
  - $(w_{8,j+z} - 1) \cdot w_{8,j+z} = 0$
  - $w_{0,j+254} = w_{0,j+253} \cdot 2^2 + w_{5,j+254} \cdot 2 + w_{8,j+254}$
  - $\phi_1(w_{8,j+253}, w_{6,j+253}, w_{7,j+253}, w_{1,j+253}, w_{2,j+253}, w_{1,j+254})$
  - $\phi_2(w_{8,j+253}, w_{6,j+253}, w_{7,j+253}, w_{1,j+253}, w_{2,j+253}, w_{4,j+254})$
  - $\phi_1(w_{5,j+254}, w_{3,j+254}, w_{4,j+254}, w_{1,j+253}, w_{2,j+253}, w_{6,j+254})$
  - $\phi_2(w_{5,j+254}, w_{3,j+254}, w_{4,j+254}, w_{1,j+253}, w_{2,j+253}, w_{7,j+254})$
  - $\phi_1(w_{8,j+254}, w_{6,j+254}, w_{7,j+254}, w_{1,j+253}, w_{2,j+253}, w_{1,j+254})$
  - $\phi_2(w_{8,j+254}, w_{6,j+254}, w_{7,j+254}, w_{1,j+253}, w_{2,j+253}, w_{2,j+254})$

## 2.5.8 Redshift Verification

WIP

Redshift circuit repeats all steps from Section 2.4.2. The verification circuit is a part of bridge design, and it is supposed that any output of the basic proof is an input to the verification circuit. Thus, we do not suppose any decoding for the proof because it can be represented directly in the desirable form.

In the previous sections, we described circuits for most of the steps of the verifier algorithm. However, steps 15-16 require additional clarification.

We consider step 16 firstly as a simpler one. It contains basic arithmetic operations over finite field elements. These operations can be done with standard generic PLONK gate:

$$\mathbf{q}_L \cdot w_0 + \mathbf{q}_R \cdot w_1 + \mathbf{q}_M \cdot w_0 \cdot w_1 + \mathbf{q}_O \cdot w_2 + \mathbf{q}_C$$

There are more optimal ways to perform these calculations. However, the number of arithmetic operations is much less than in Step 15. It means that any optimizations do not decrease prover or verifier complexities in any noticeable way.

**FRI Verification** is the main part of Step 15. It contains two operations: Merkle tree path check and polynomial interpolation. The circuit version of Merkle path check algorithm does not differ from the original one. The circuit from Section 2.5.4 is used to check hash operations correctness.

To check polynomial interpolation, the following circuit is used:

	$w_0$	$w_1$	$w_2$	$w_3$	$w_4$	$w_5$	$w_6$	$w_7$	$w_8$
$j + 0$	$a_0$	$a_1$	$s_0$	$s_1$	$x$	$y$	$\alpha$	$\beta$	$\dots$

Constraints (**max degree** = 2):

1.  $w_6 \cdot w_0 + w_7 = w_2 \iff \alpha \cdot a_0 + \beta = s_0$
2.  $w_6 \cdot w_0 + w_7 = w_2 \iff \alpha \cdot a_1 + \beta = s_1$
3.  $w_6 \cdot w_0 + w_7 = w_2 \iff \alpha \cdot x + \beta = y$

Copy constraints:

1.  $a_0, a_1, s_0, s_1, y$  are constrained by public input.

The gate uses the line equation to check that all three points are on the same line. This means, it checks  $f(a_0) = s_0$ ,  $f(a_1) = s_1$ ,  $f(x) = y$  for  $f(X) = \alpha \cdot X + \beta$ .

### 2.5.9 Validator Set Proof Circuit

WIP

## Chapter 3

# In-EVM State Proof Verifier

This introduces a description for Solana's 'Light-Client' state proof in-EVM verifier. Crucial components which define this part design are:

1. Verification architecture description.
2. Verification logic API reference.
3. Input data structures description.

### 3.1 Verification Logic Architecture

### 3.2 Verification Logic API Reference

### 3.3 Input Data Structures

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