Cryptanalysis Results on Spook

Bringing Full Shadow-512 to the Light

Patrick Derbez[1], Paul Huynh[2], Virginie Lallemand[2], María Naya-Plasencia[3], Léo Perrin[3], André Schrottenloher[3]

[1] Université de Rennes, CNRS, Irisa - Rennes, France
[2] Université de Lorraine, INRIA, Loria, CNRS - Nancy, France
[3] INRIA - Paris, France

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Spook

Davide Bellizia, Francesco Berti, Olivier Bronchain, Gaëtan Cassiers, Sébastien Duval, Chun Guo, Gregor Leander, Gaëtan Leurent, Itamar Levi, Charles Momin, Olivier Pereira, Thomas Peters, François-Xavier Standaert, Balazs Udvarhelyi and Friedrich Wiemer

- 2nd round candidate to the NIST LWC standardization process
- Designed to achieve both resistance against side-channel analysis and low-energy implementations
- AEAD is provided using three sub-components
  - the Sponge One-Pass mode of operation (S1P)
  - the Clyde-128 tweakable block cipher
  - the Shadow permutation

Motivations

- Requirement for the permutation in the S1P mode of operation is that it provides **collision resistance** with respect to the 255 bits that generate the tag

  “Hence, a more specific requirement is to prevent truncated differentials with probability larger than 2^{-128} for those 255 bits. A conservative heuristic for this purpose is to require that no differential characteristic has probability better than 2^{-385}, which happens after twelve rounds (six steps).”

- Mathematical cryptanalysis challenge proposed by the designers on the permutation

Summary of our work

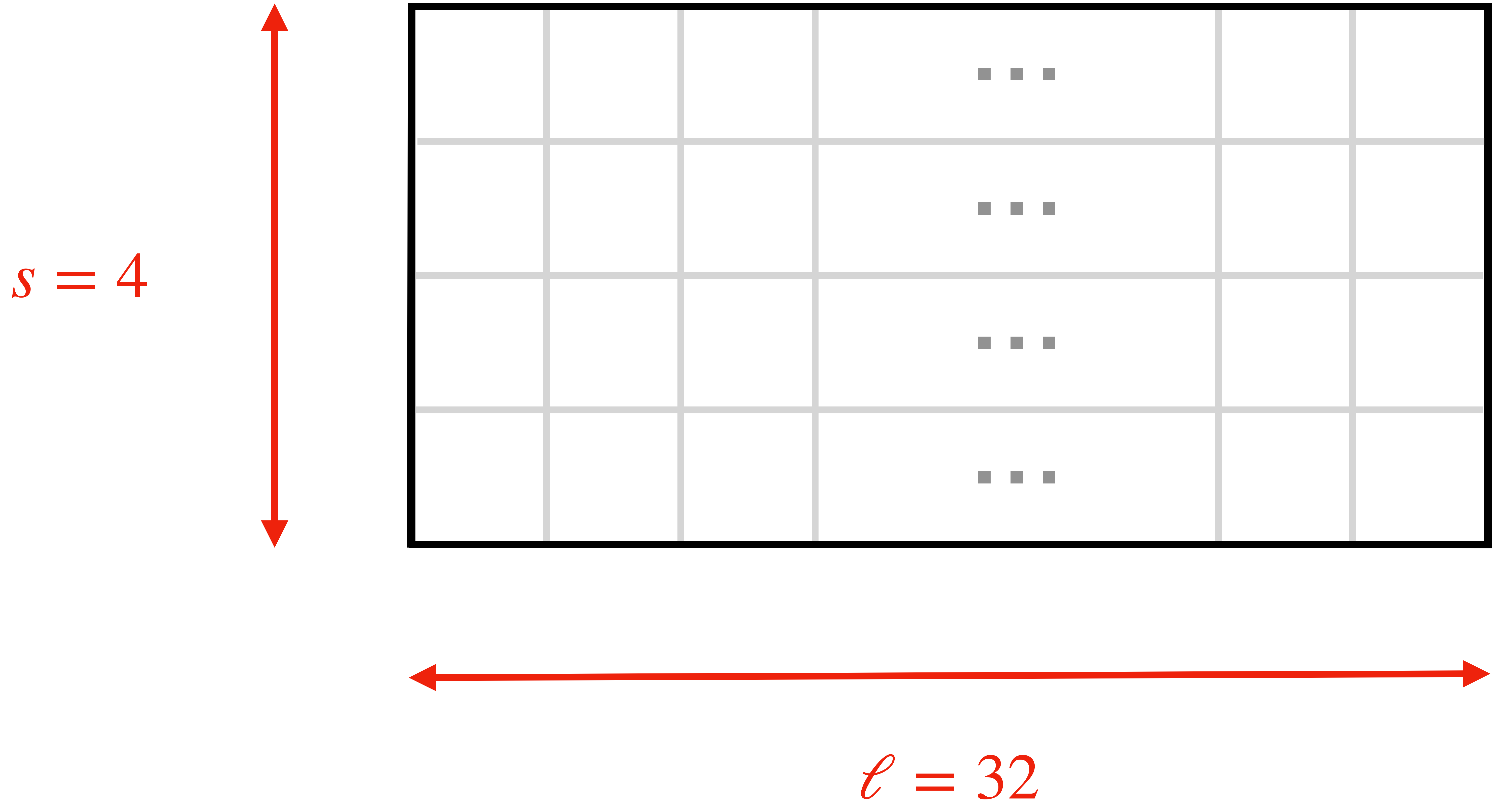
- **Practical distinguishers** of the full 6-step version of the Shadow-512 permutation and reduced 5-step version of Shadow-384
- **Practical forgeries** with 4-step Shadow for the S1P mode of operation (nonce misuse scenario)

All the analyses are practical and have been implemented and tested. Source code available at:

https://who.paris.inria.fr/Leo.Perrin/code/spook/index.html

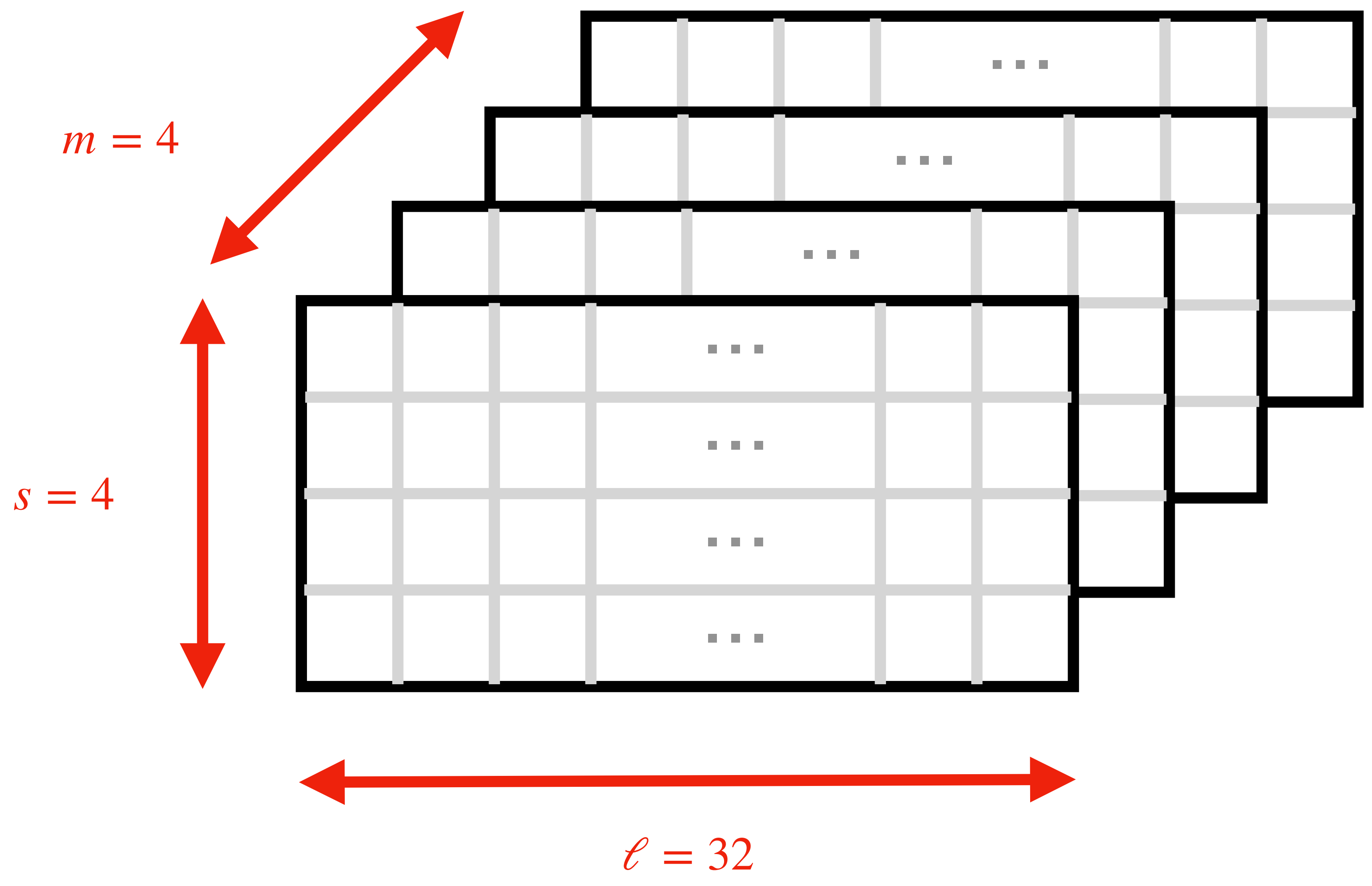
Description of Shadow

A Shadow bundle

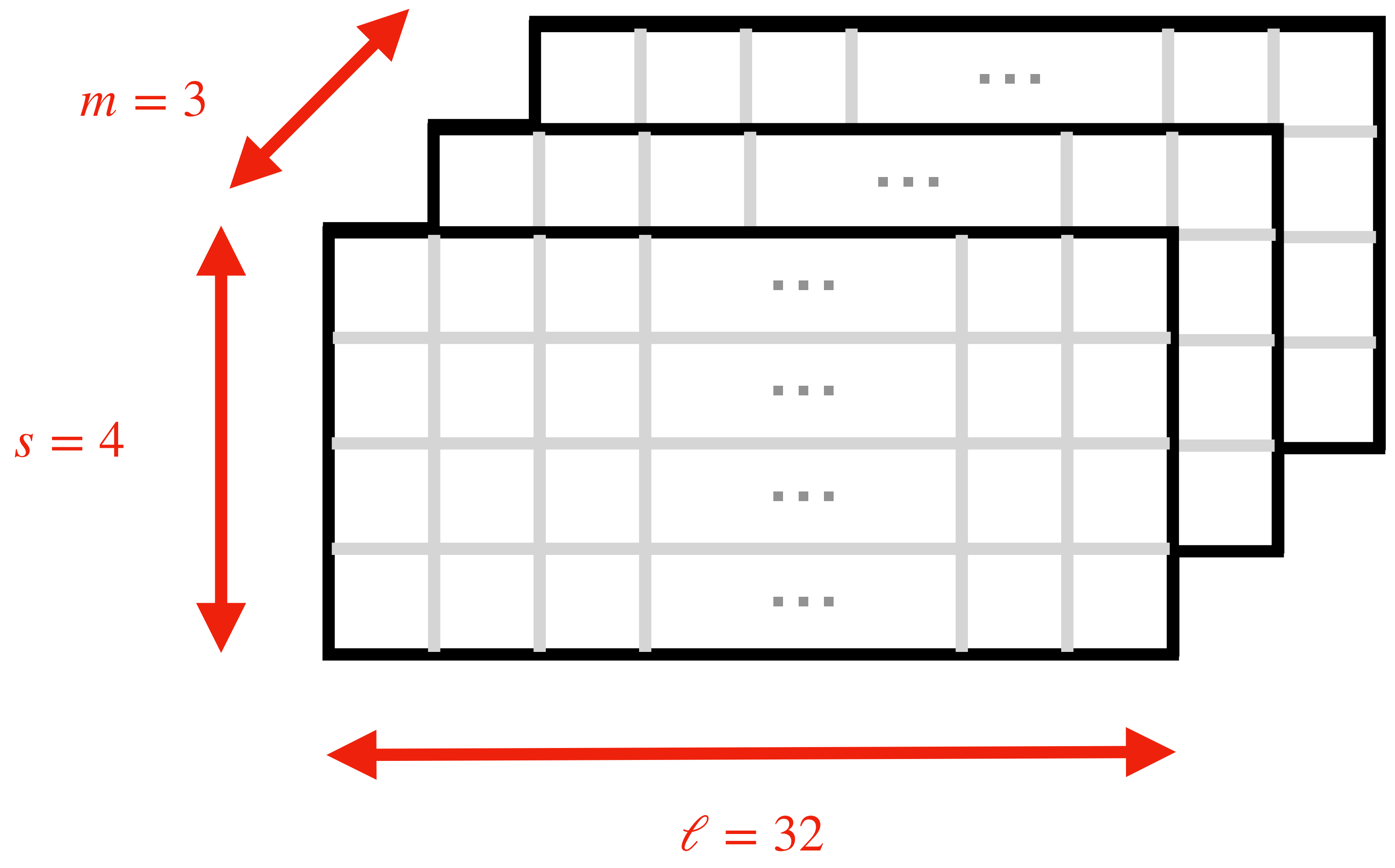


128 bits

A Shadow state

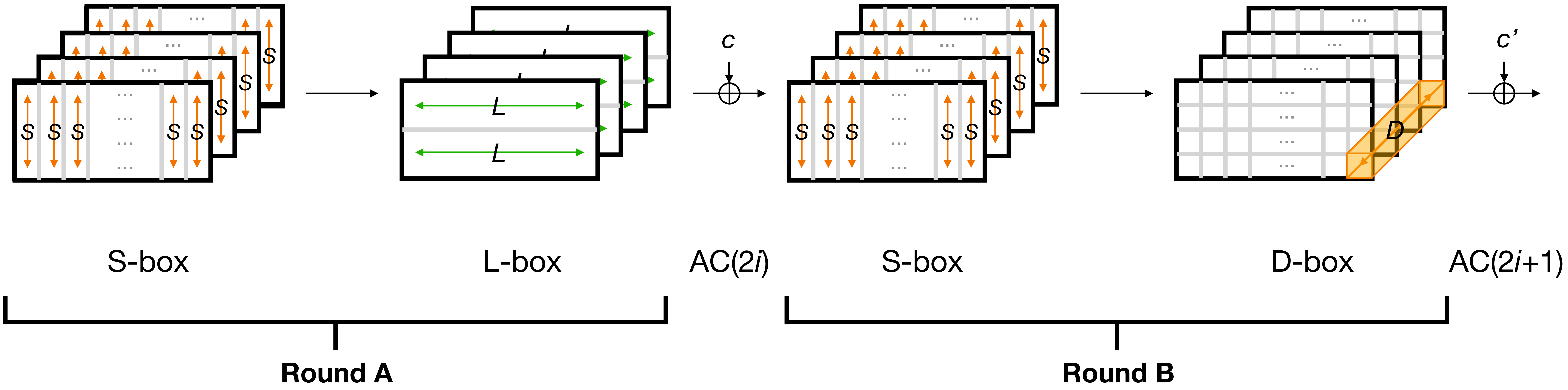


Shadow-512



Shadow-384

A Shadow **encryption step**

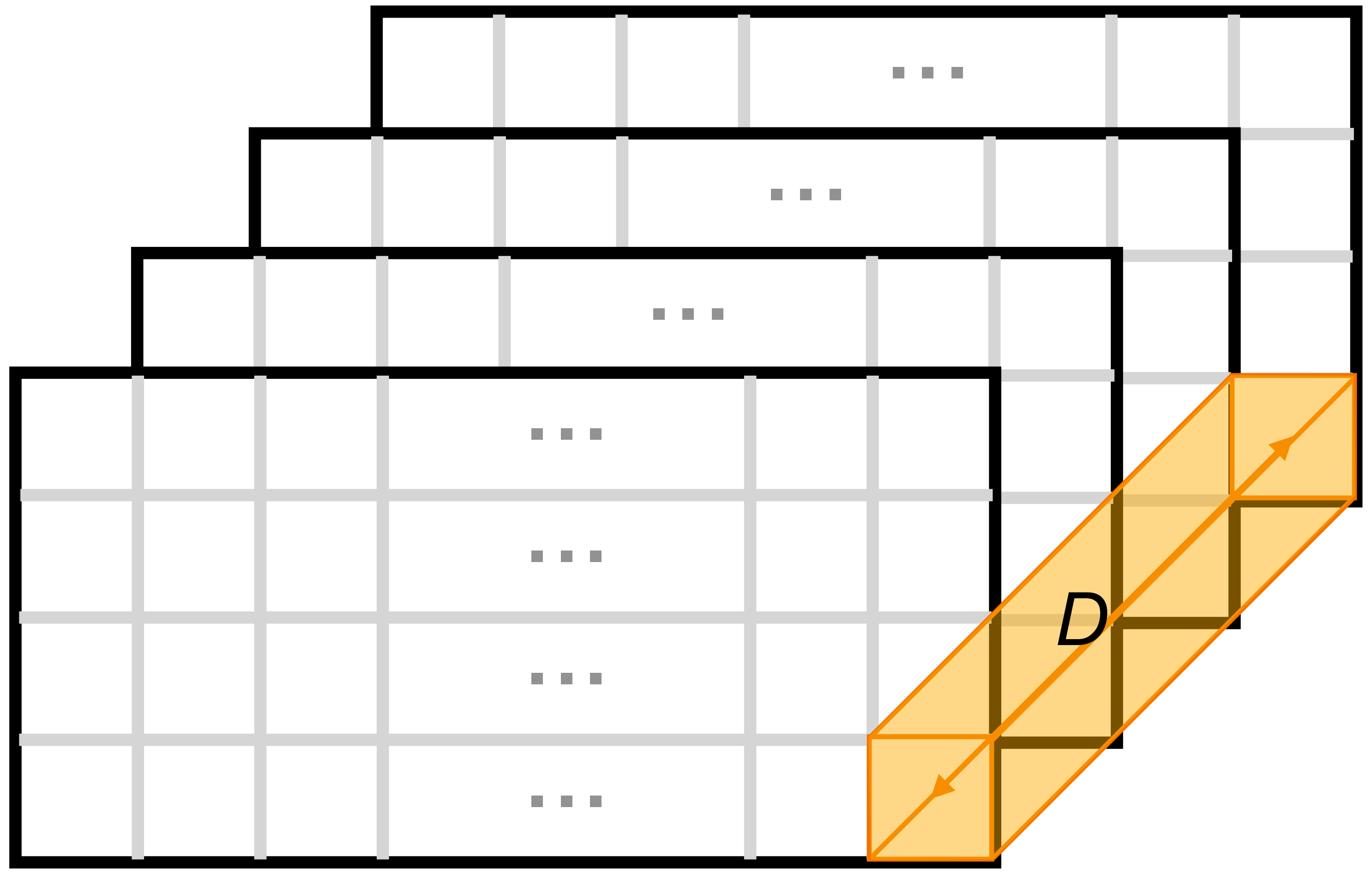


4-bit LFSR-generated constants added to **column *i* of bundle *i***

6 steps to complete encryption

The D-layer

D is the only diffusion layer between the m bundles



- Shadow-512:

$$D(a,b,c,d) = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \times \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix}$$

- Shadow-384:

$$D(a,b,c) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \times \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$

Main ideas

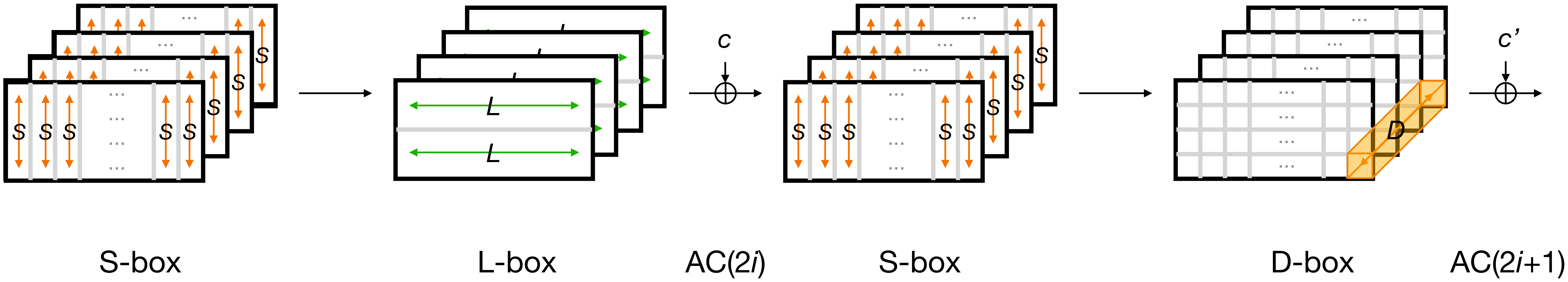
- Exploit the **similarity between the functions applied in parallel** on each bundle.

- Truncated differential distinguisher: variant of differentials in which only a portion of the difference is fixed while the remaining part is undetermined.

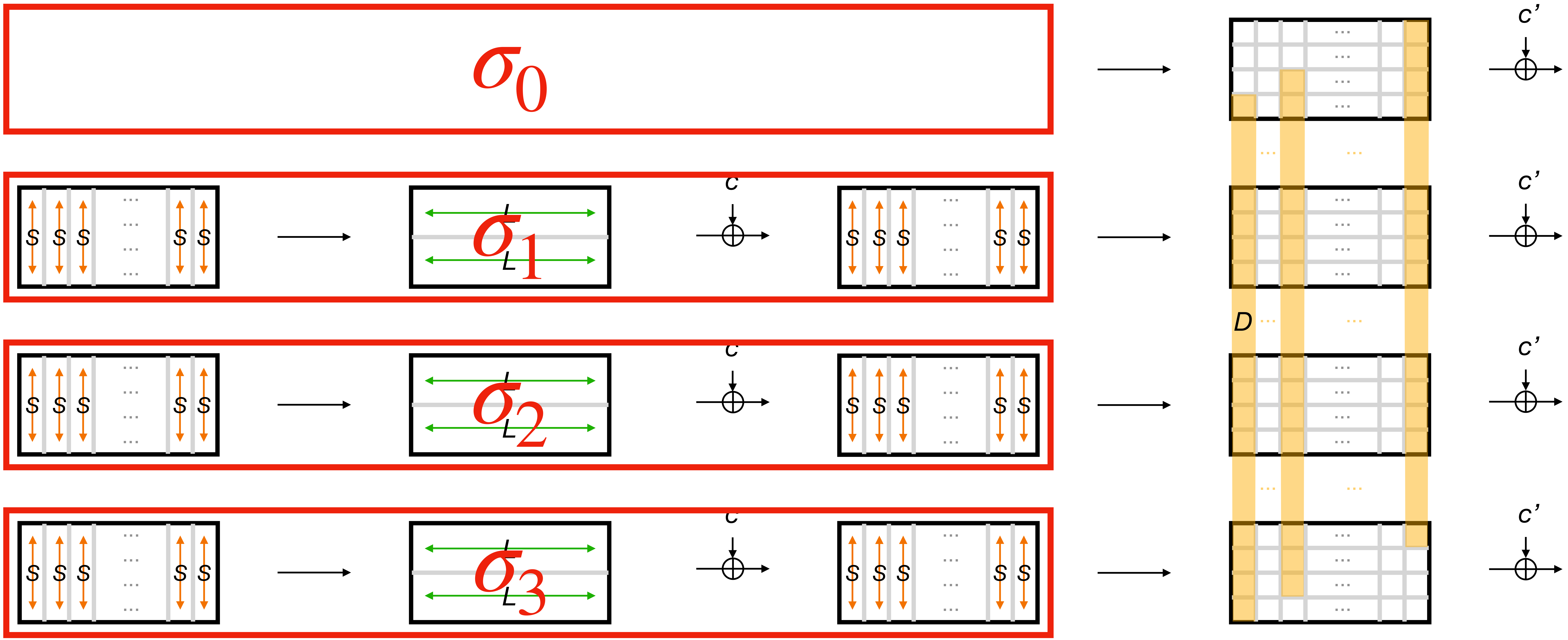
  $x \oplus x' = (*, *, *, 0)$ and shadow(x) $\oplus$ shadow(x') = D(0, 0, 0, *)

  ‘**0**’ the two bundles are identical
  ‘*****’ the difference between the bundles is not determined

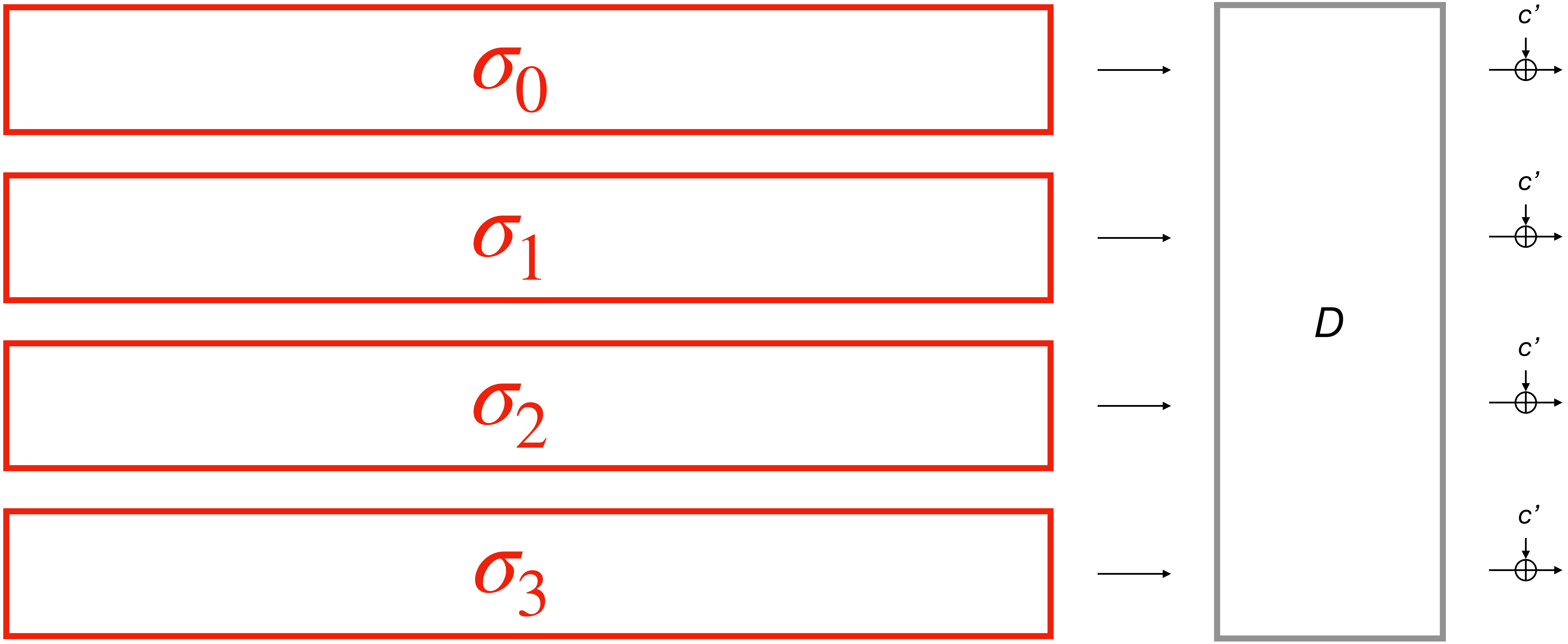
A Shadow step



A Shadow step rewritten

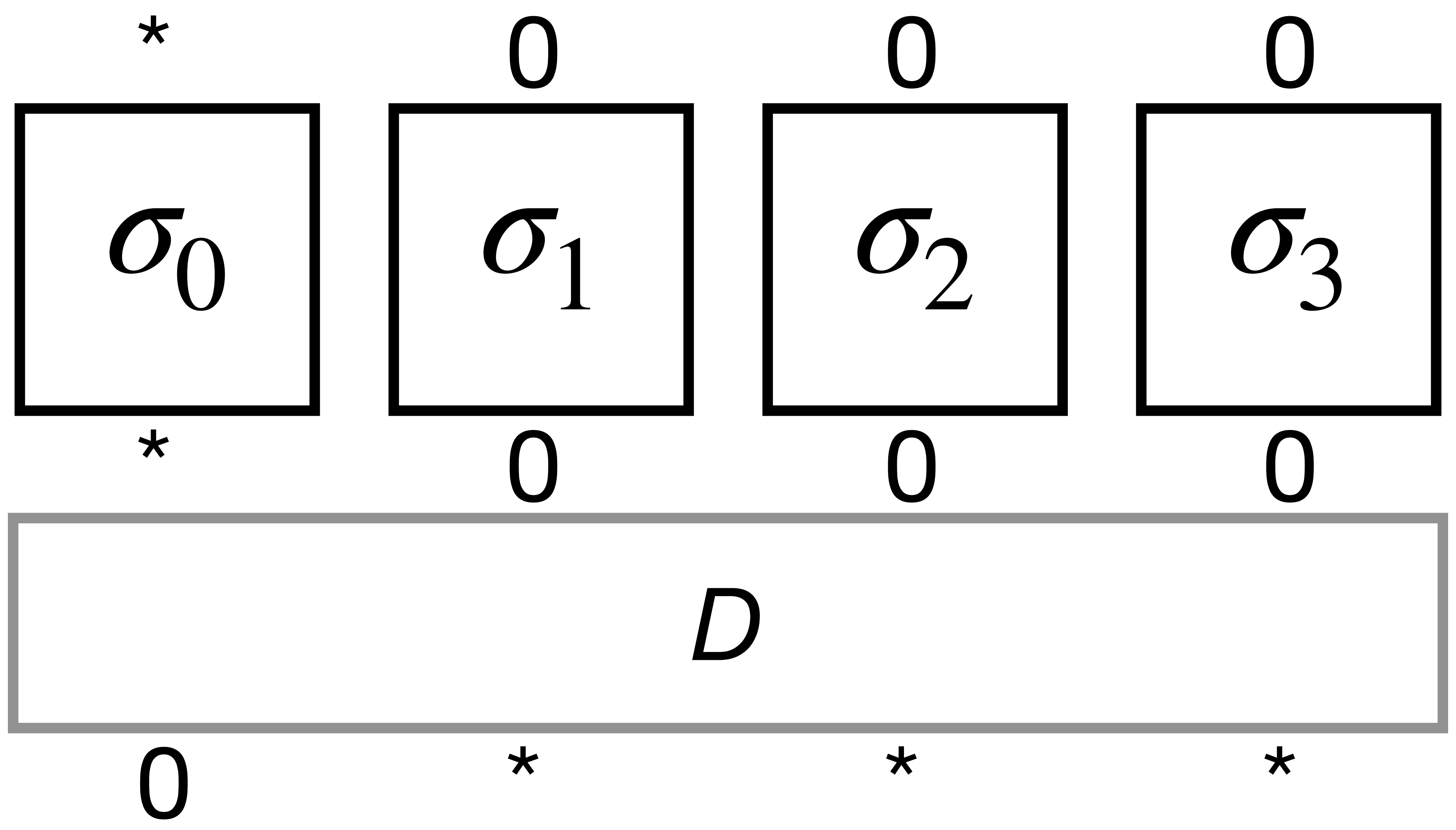


A Shadow step rewritten



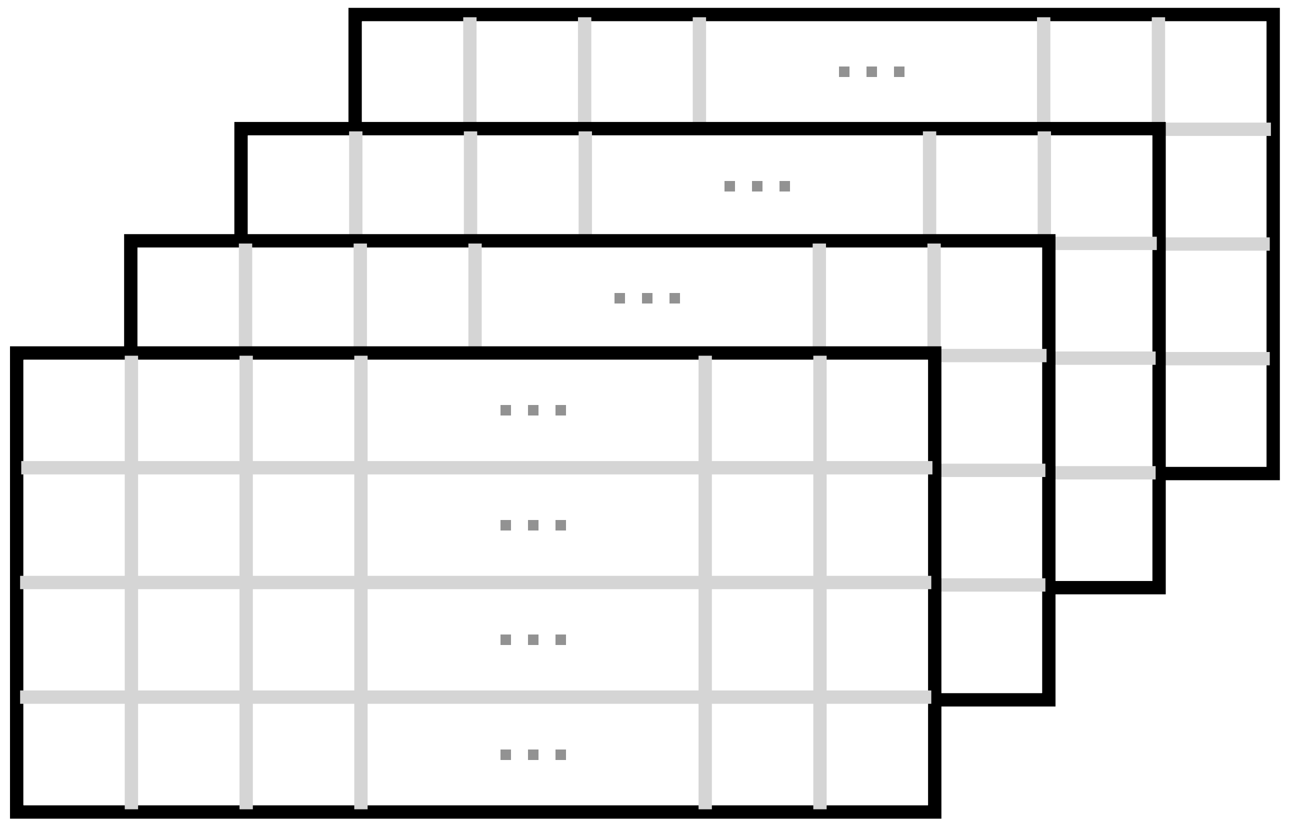
A Shadow step rewritten

Seen as an SPN, using four 128-bit **Super S-boxes σ_i** interleaved with a linear permutation D operating on the full state.



Structural observations

We call ***i*-identical** an internal state of Shadow in which i bundles are equal.



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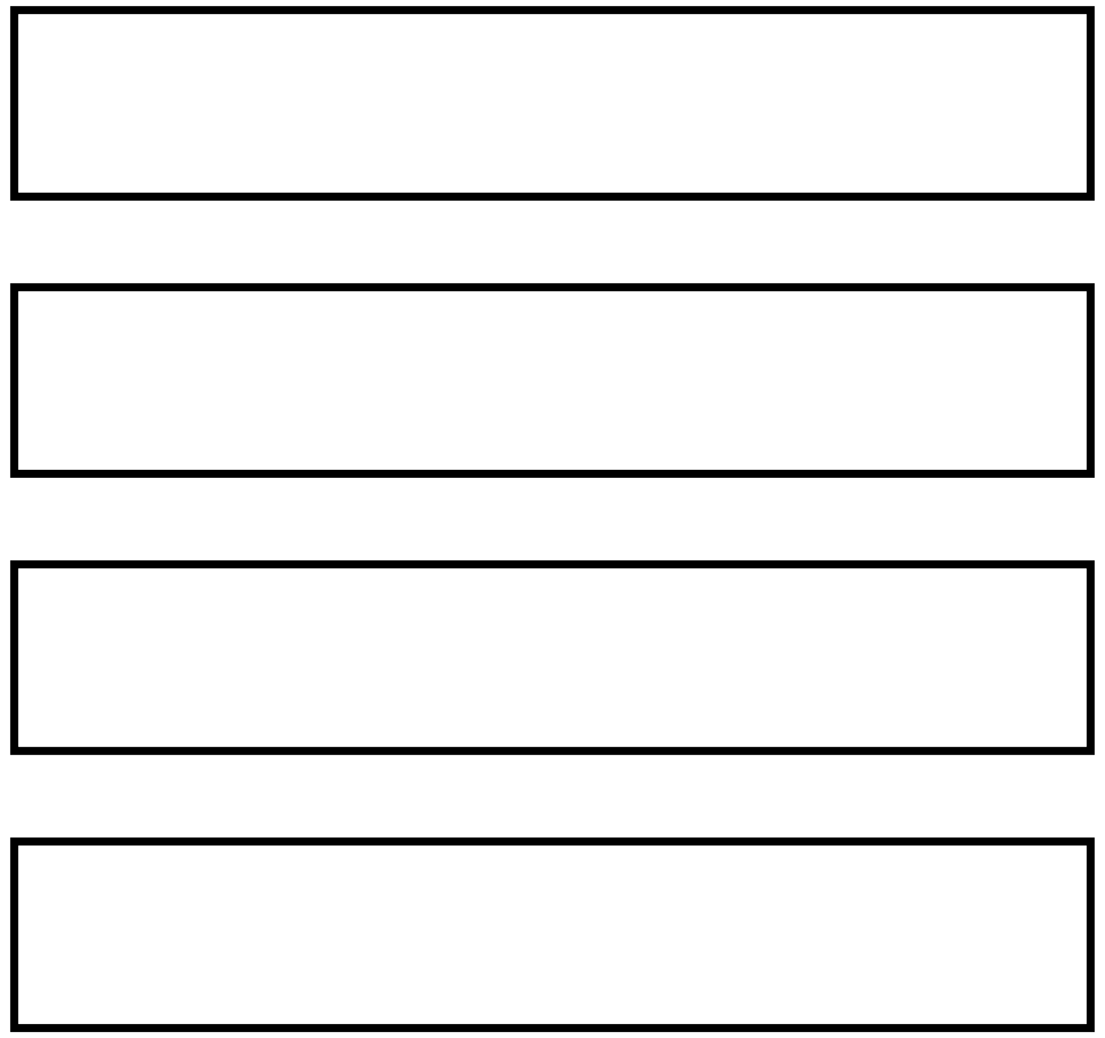
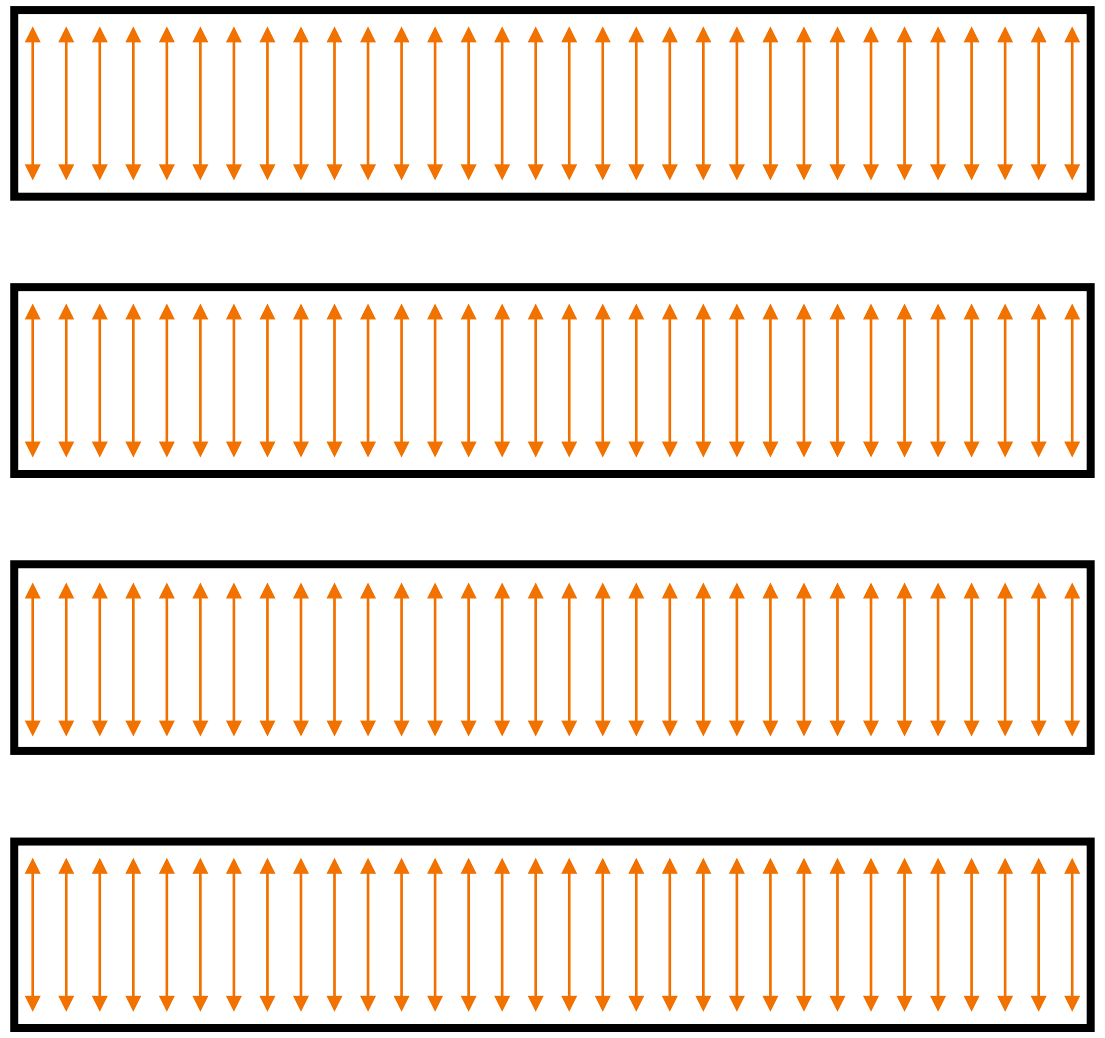


Initial state

Structural observations

We call ***i*-identical** an internal state of Shadow in which i bundles are equal.



S-Box layer

Structural observations

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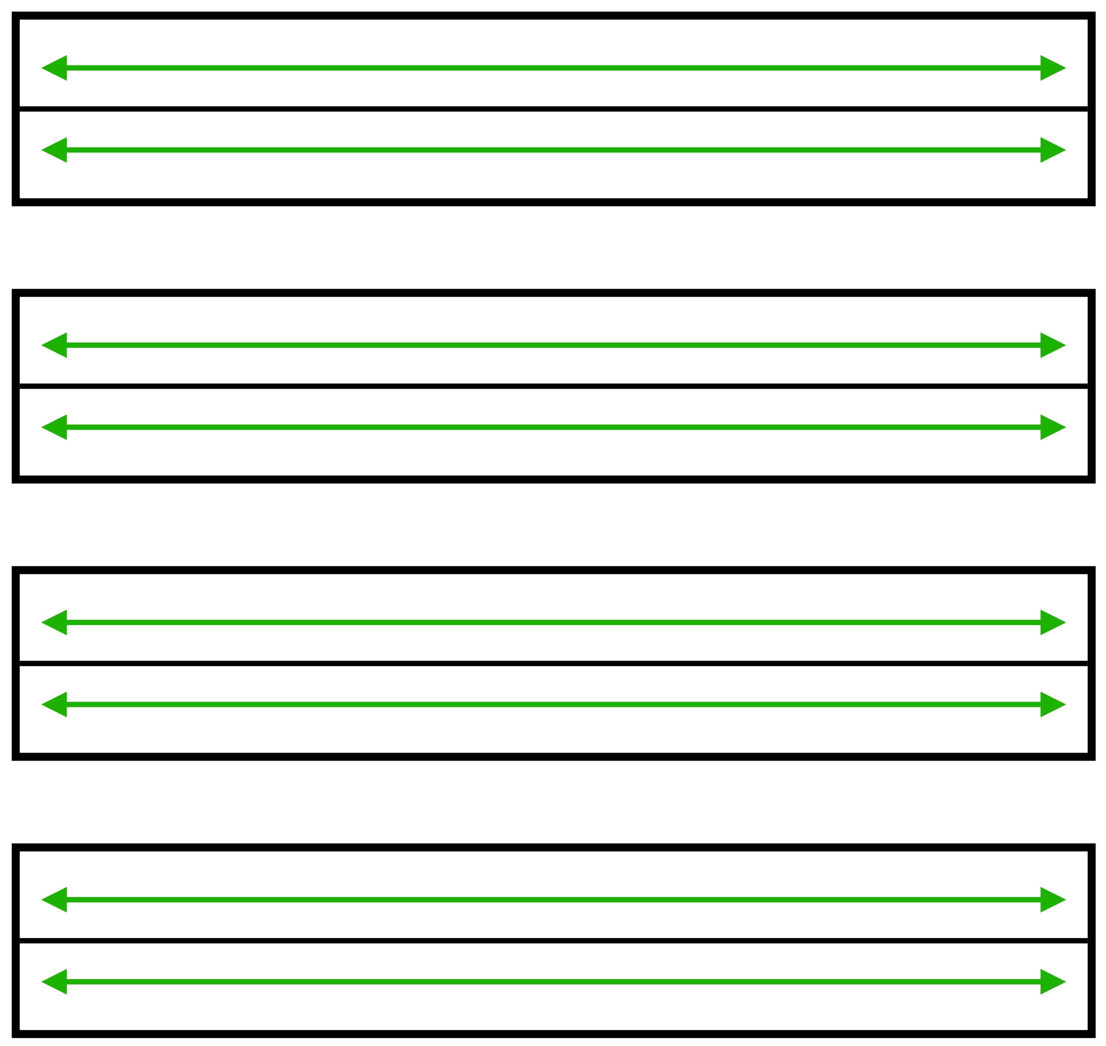
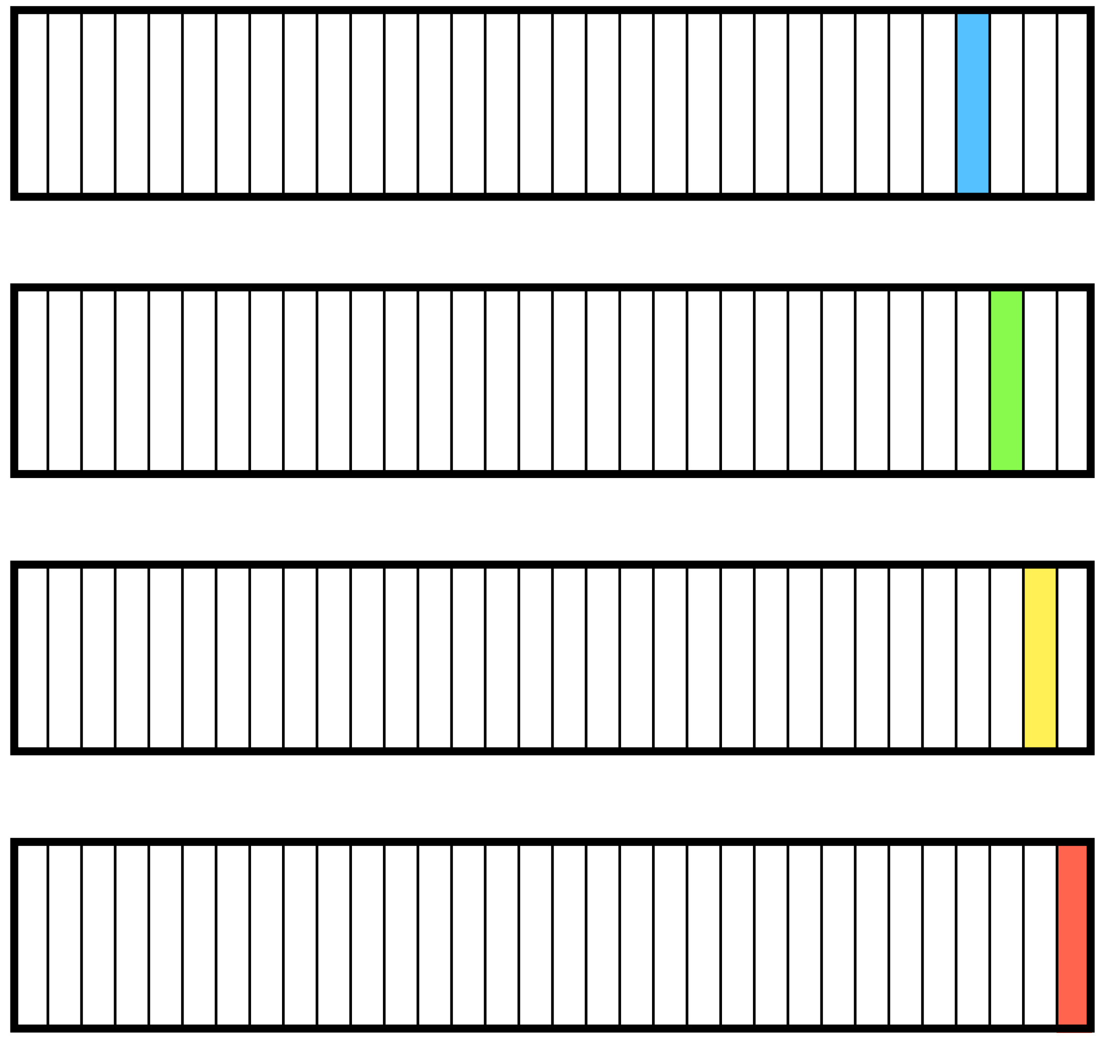


L-Box layer

Structural observations

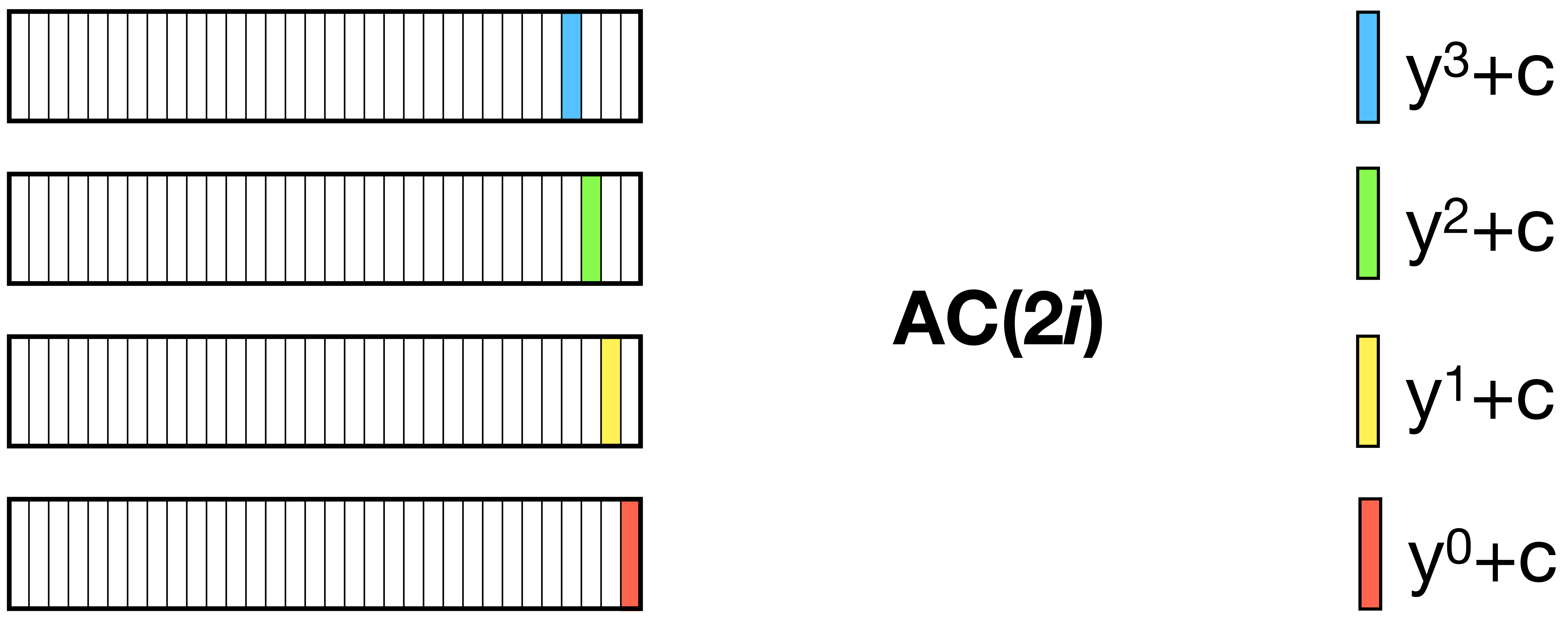
We call ***i*-identical** an internal state of Shadow in which i bundles are equal.



AC(2*i*)

Structural observations

We call ***i*-identical** an internal state of Shadow in which i bundles are equal.



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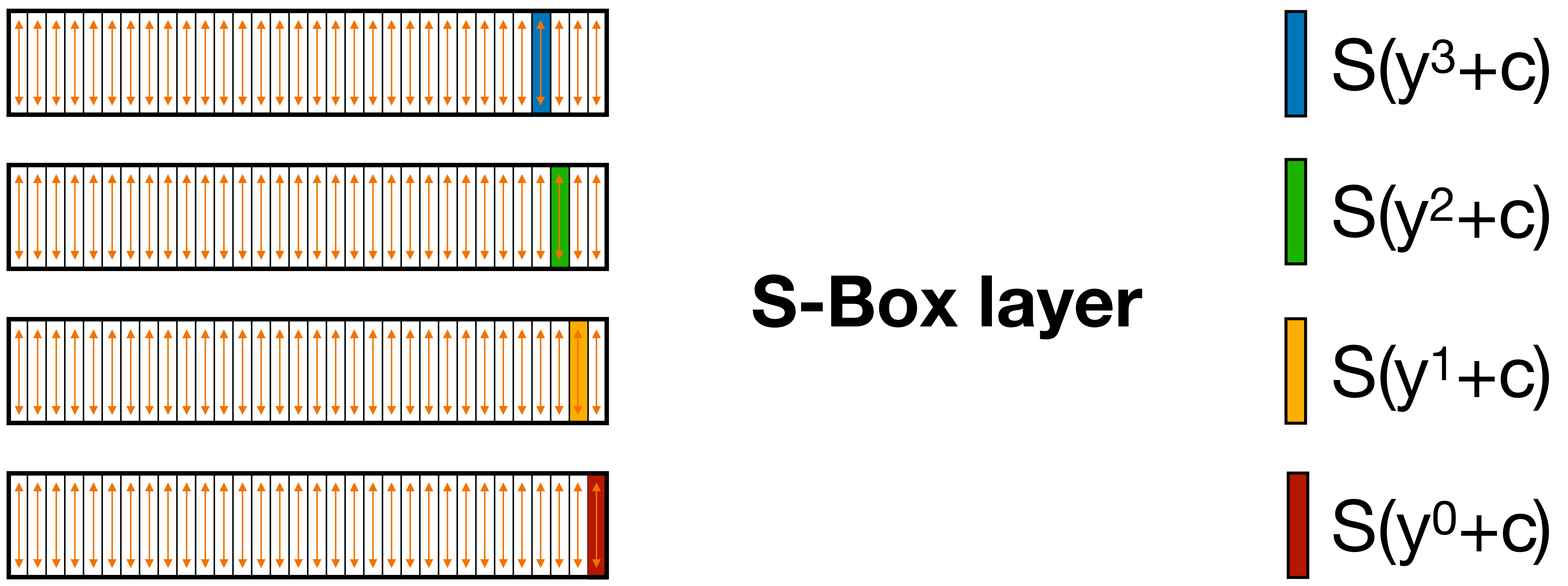

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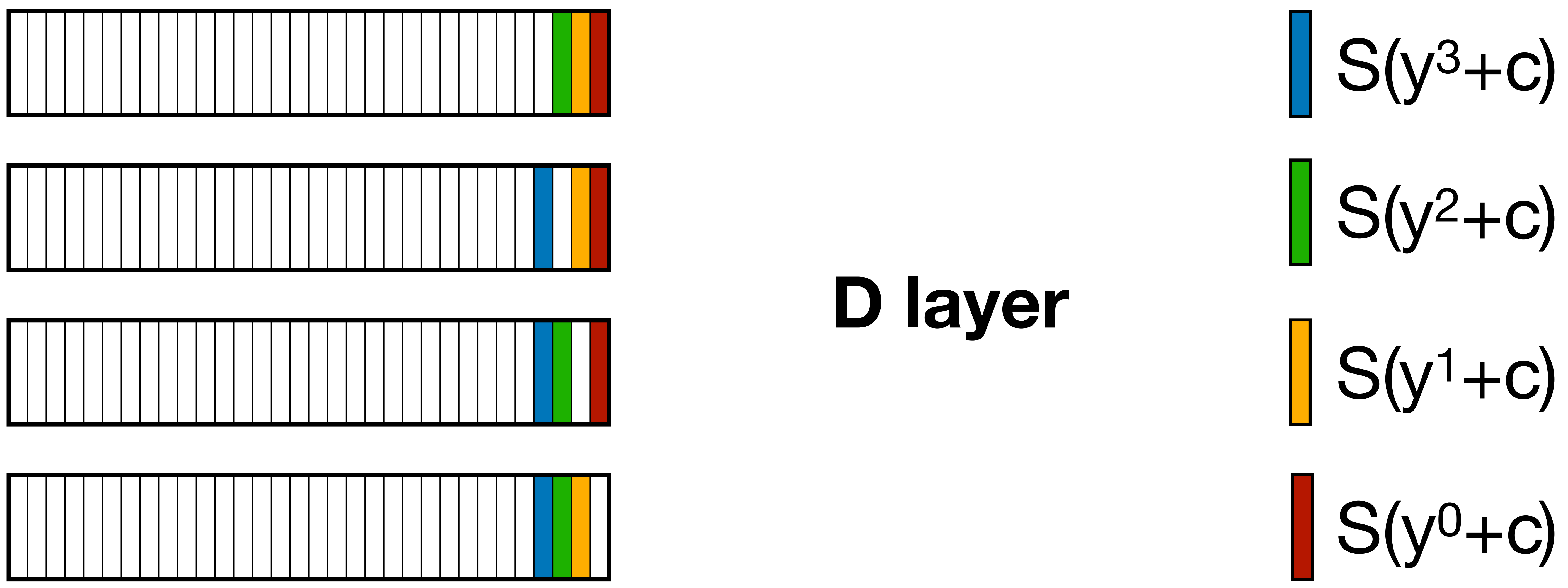

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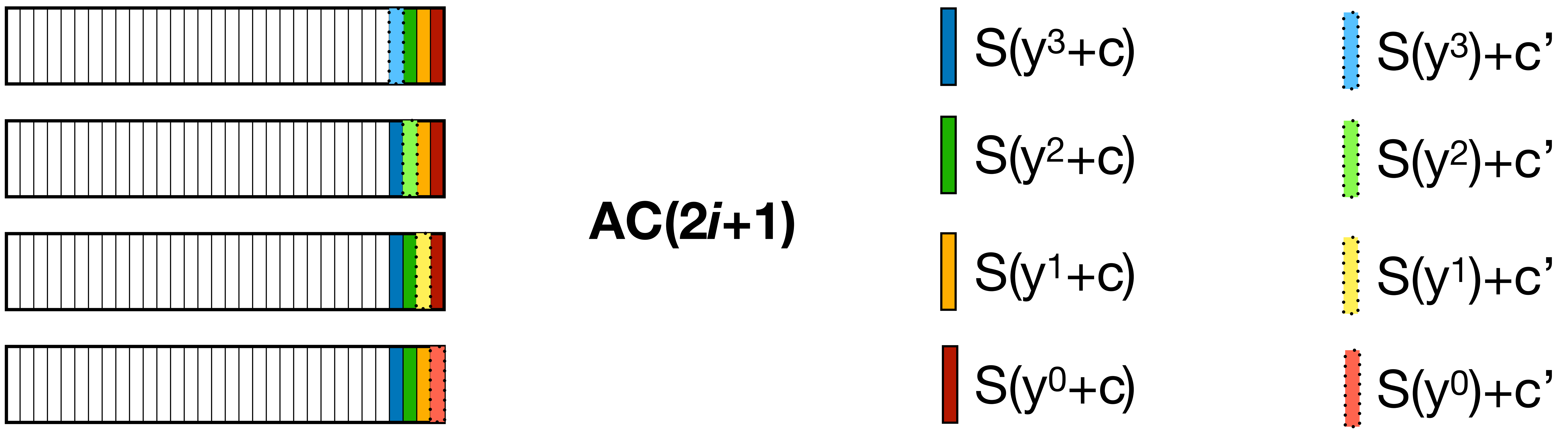

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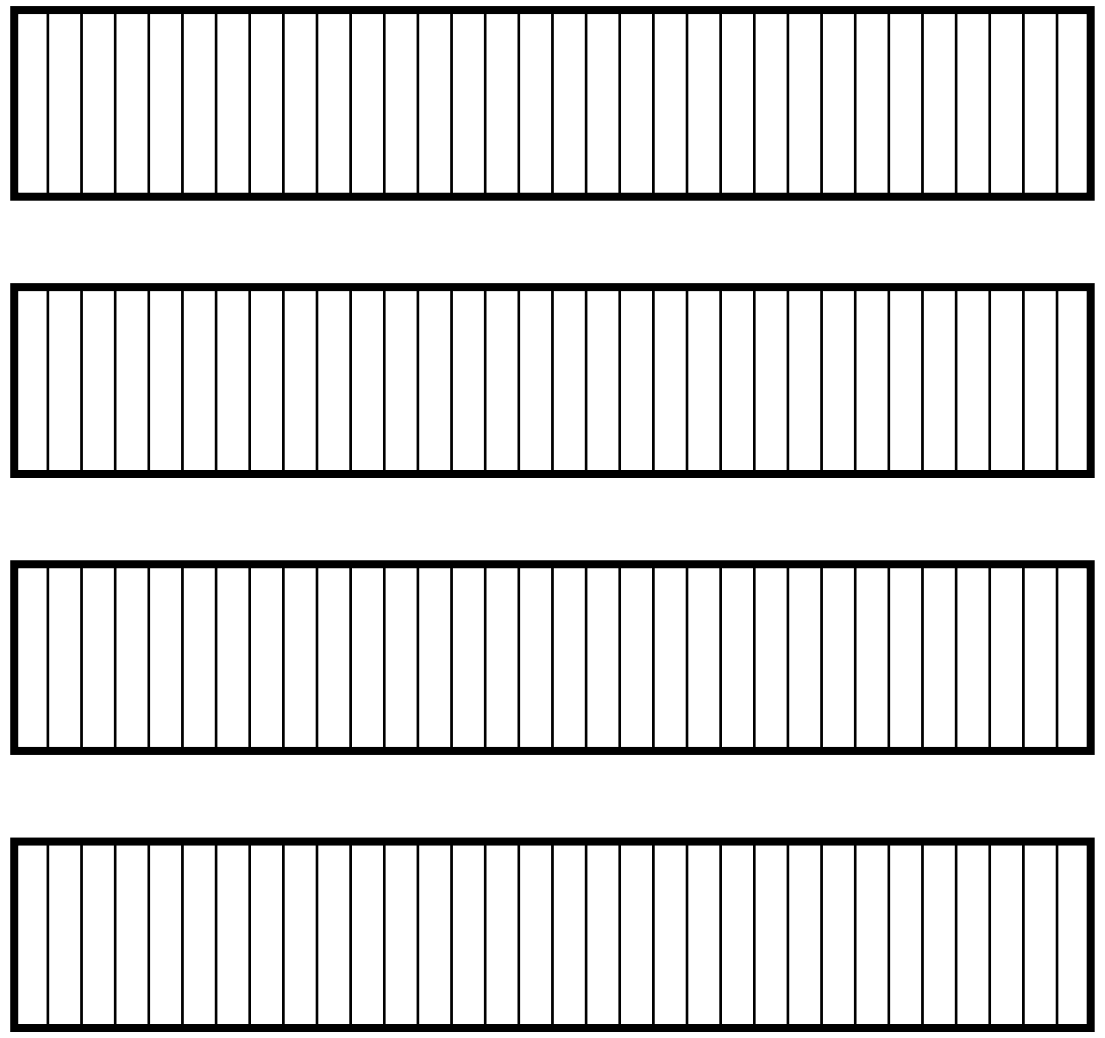


$S(y^3+c) = S(y^3)+c'$

$S(y^2+c) = S(y^2)+c'$

$S(y^1+c) = S(y^1)+c'$

$S(y^0+c) = S(y^0)+c'$

Structural observations

We call ***i*-identical** an internal state of Shadow in which i bundles are equal.

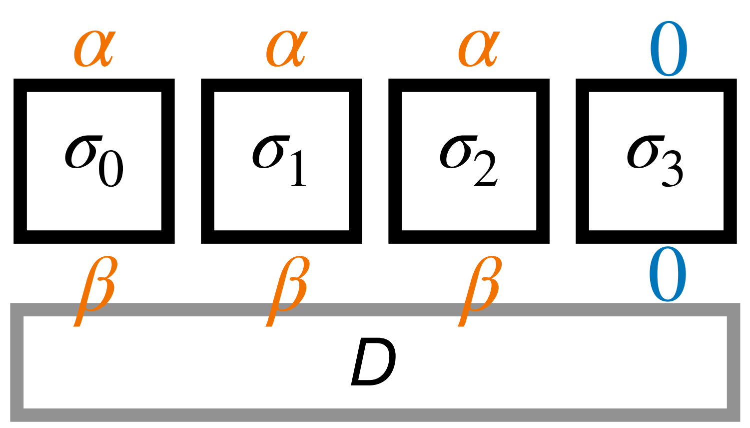
probabilities of an i-identical state at step s

s	0	1	2	3	4	5
i=4	0	0	0	2^{-12}	2^{-8}	0
i=3	0	0	0	2^{-9}	2^{-6}	0
i=2	0	0	0	2^{-6}	2^{-4}	0

Distinguisher

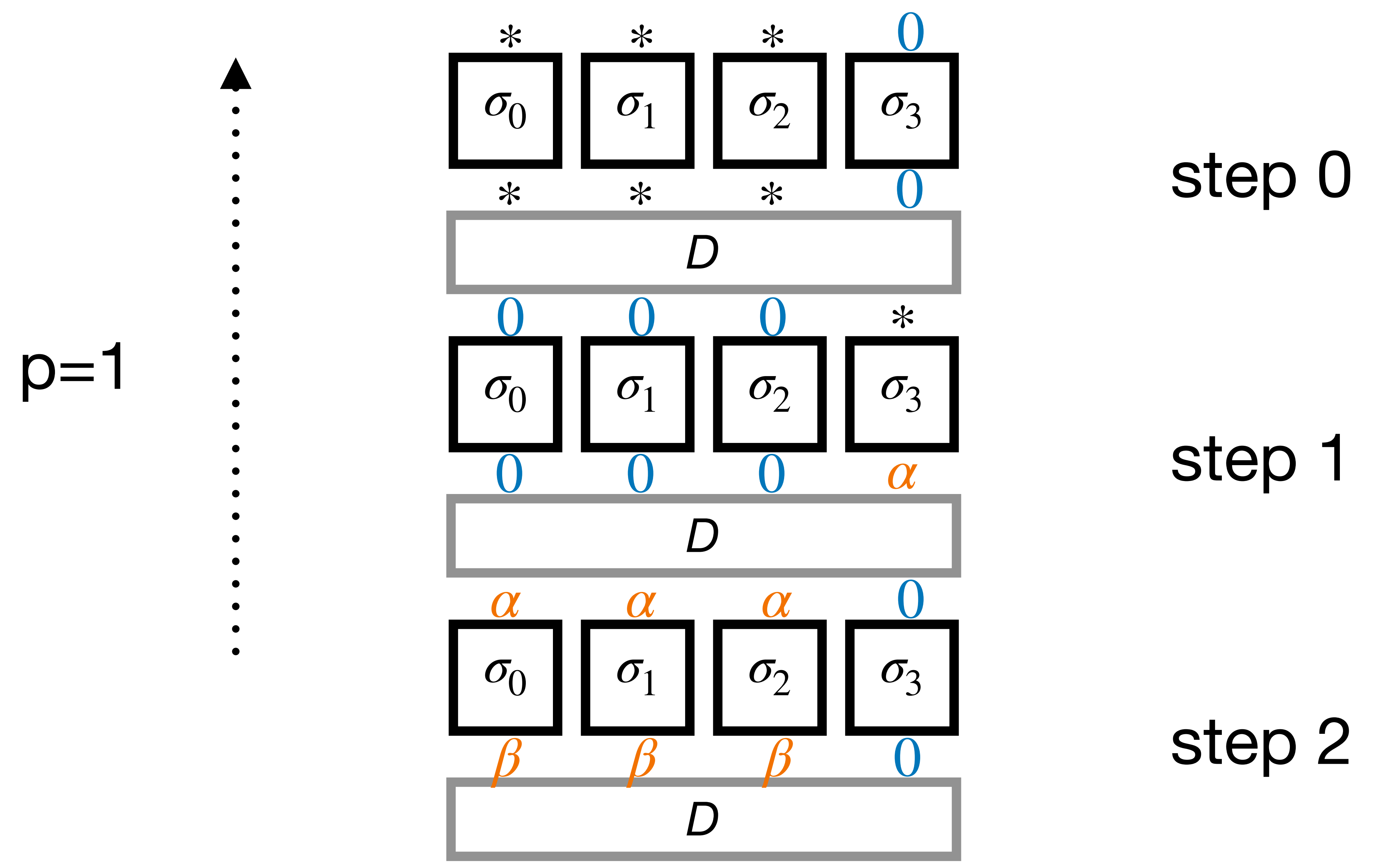
Distinguisher on 6 steps of Shadow-512

- x ⊕ x' = (*, *, *, 0) and shadow(x) ⊕ shadow(x') = D(0, 0, 0, *)
- Generic cost 2^{-64} vs $2^{-16.245}$ here

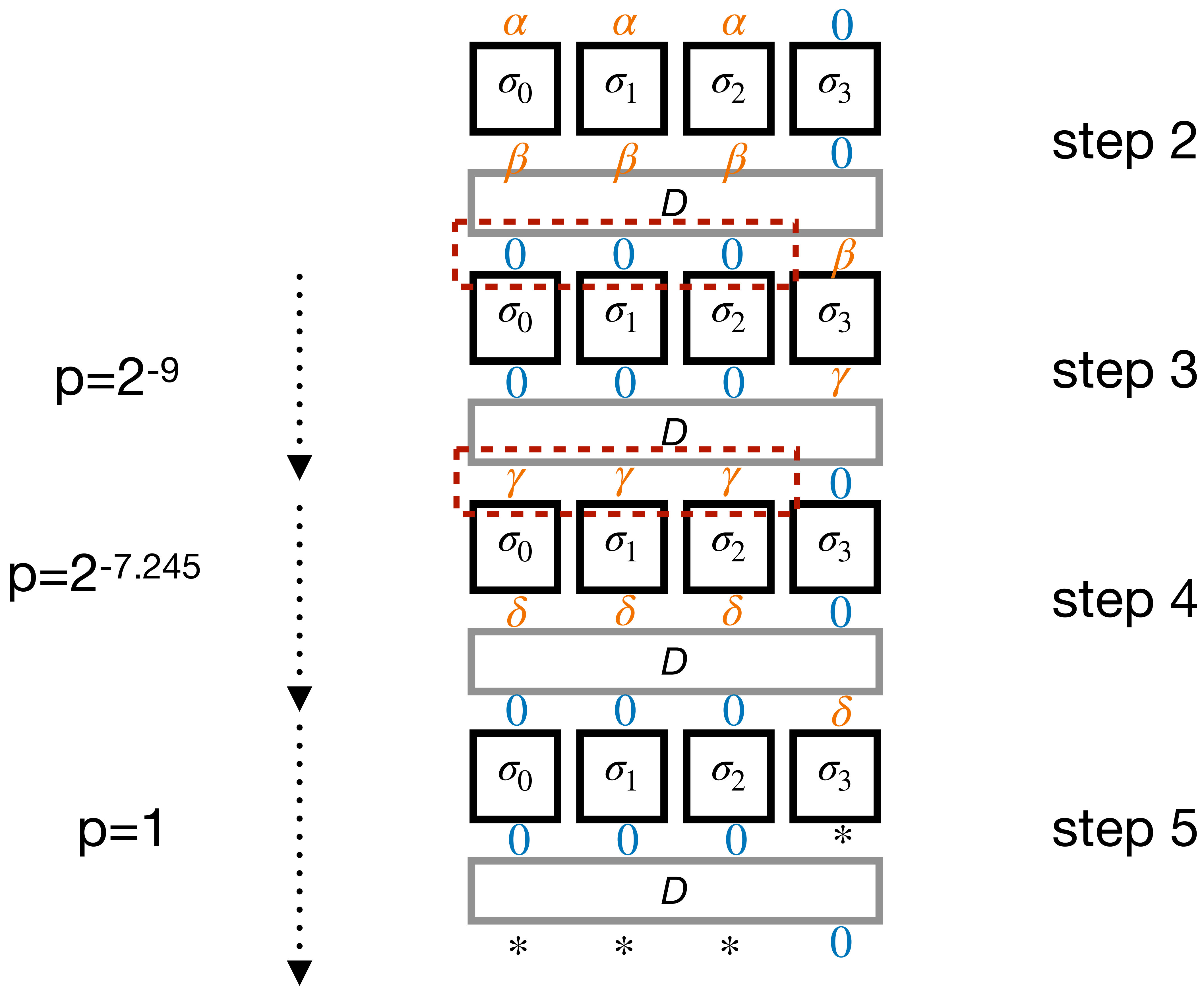


step 2

Distinguisher on 6 steps of Shadow-512



Distinguisher on 6 steps of Shadow-512



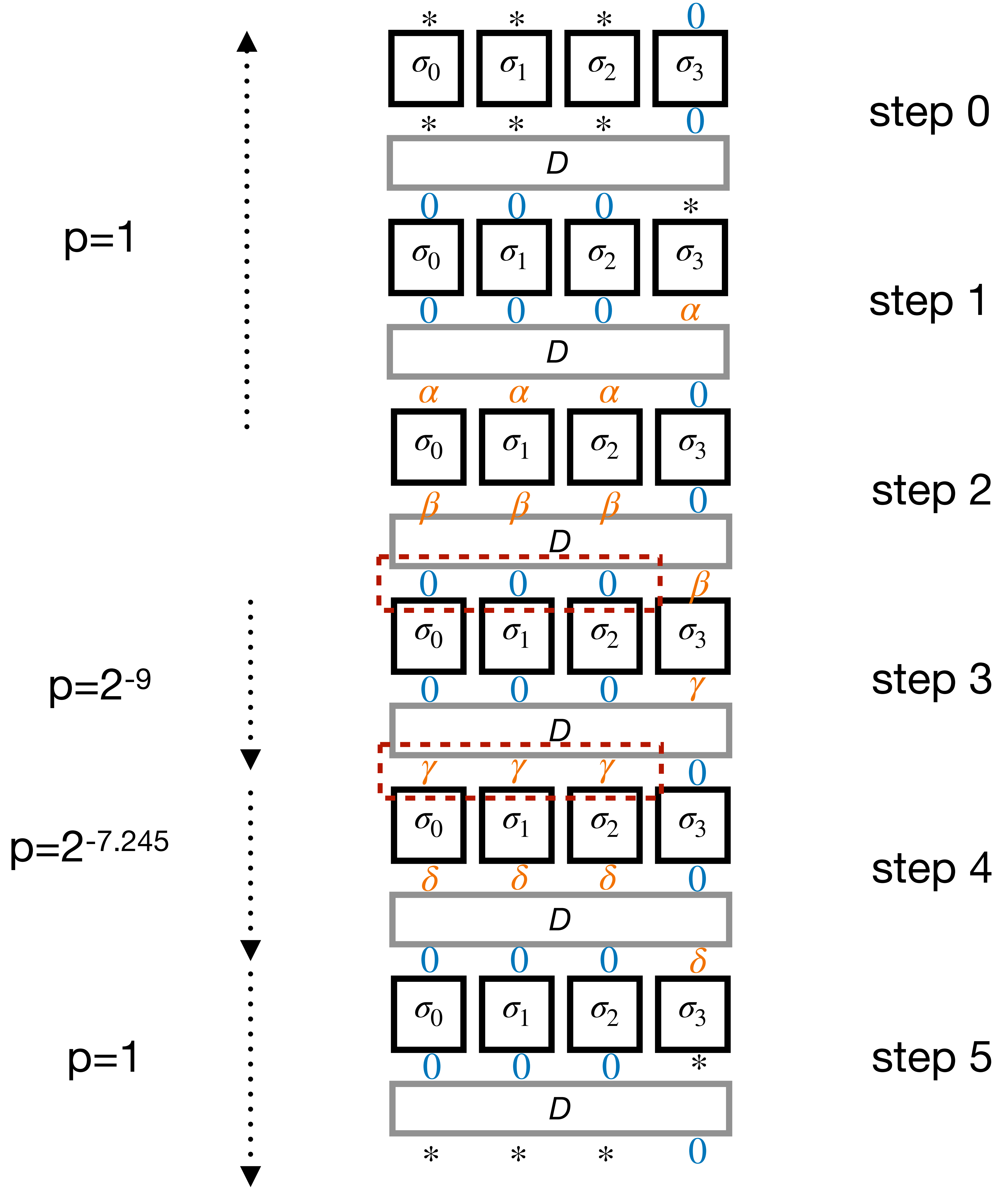
Some details

- Constructing a pair for **step 2**:
  - $\sigma_0(x) + \sigma_0(x + \alpha) = \beta$
    $\sigma_1(x + \epsilon) + \sigma_1(x + \epsilon + \alpha) = \beta$
    $\sigma_2(x + \epsilon') + \sigma_2(x + \epsilon' + \alpha) = \beta$

    and **3-identical state at the end of step 2**
  - Impact of the constant additions limited to the S-boxes with indices in {0,1,2,3}
  - Bits with indices **22** and **23** in each of the 4 input words of a Super S-box have **no influence** on the output bits with indices in {0,1,2,3}

    $$\nabla = \{a \times e_{22} + b \times e_{23}, a \in \mathbb{F}_2^4, b \in \mathbb{F}_2^4\}$$

    For all $\alpha \in \nabla$, all steps and all bundle index i,
    $\sigma_i(x) + \sigma_i(x + \alpha) = (*, *, \ldots, *, 0,0,0,0)$



Some details

- **Step 3**: probability of a **3-identical state** = **2^{-9}**
- **Step 4: difference of the form $(0,0,0,\delta)$ at the end of the step**

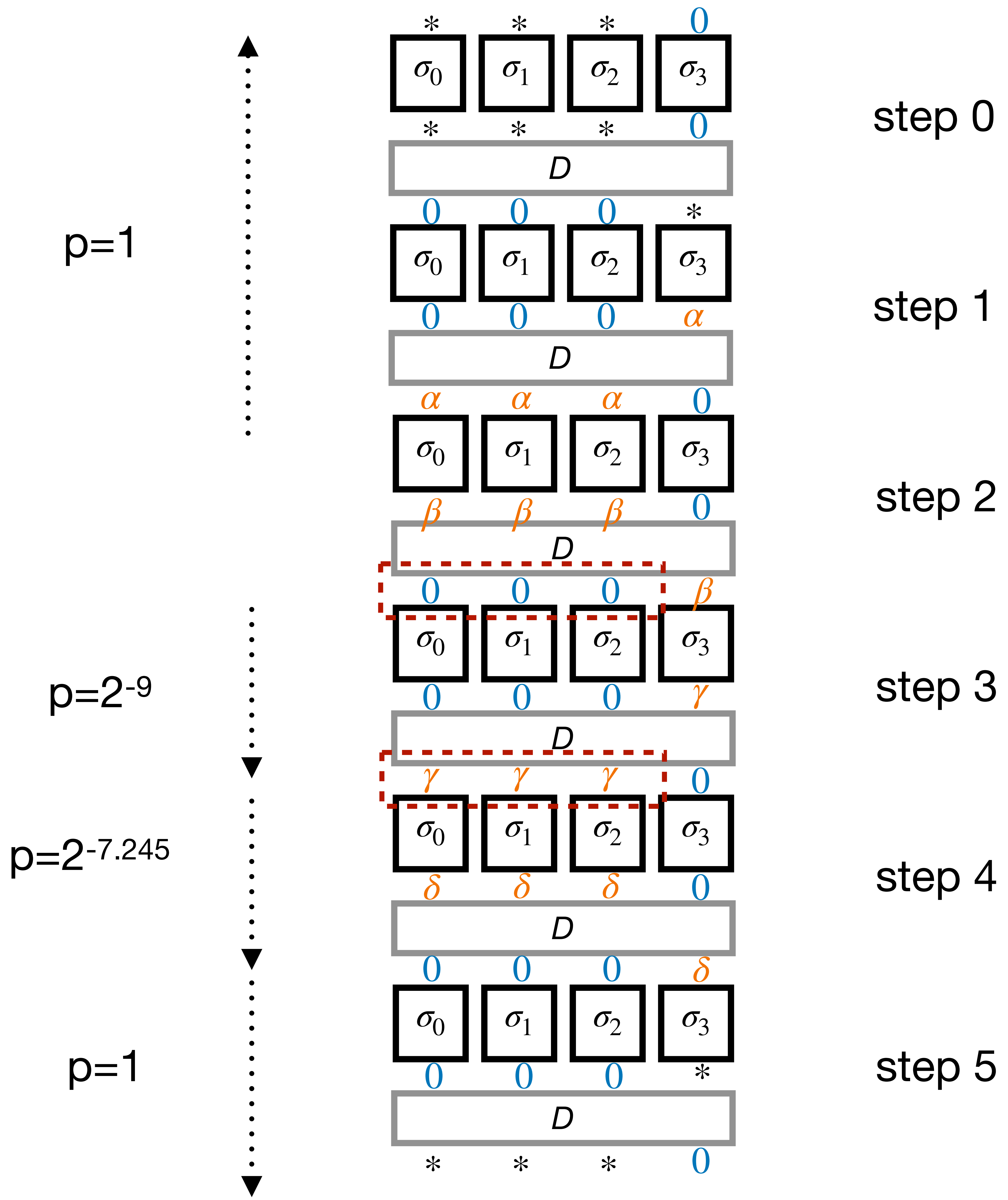
  Let (y, y, y, w) and (y', y', y', w) denote two messages after the application of S and L of step 4 then:

  $$S(y'^2) \oplus S(y'^2 \oplus c) = S(y^2) \oplus S(y^2 \oplus c)$$
  $$S(y'^1) \oplus S(y'^1 \oplus c) = S(y^1) \oplus S(y^1 \oplus c)$$
  $$S(y'^0) \oplus S(y'^0 \oplus c) = S(y^0) \oplus S(y^0 \oplus c)$$

  with $c = 0x5$, probability of **$2^{-2.415}$** for each equality

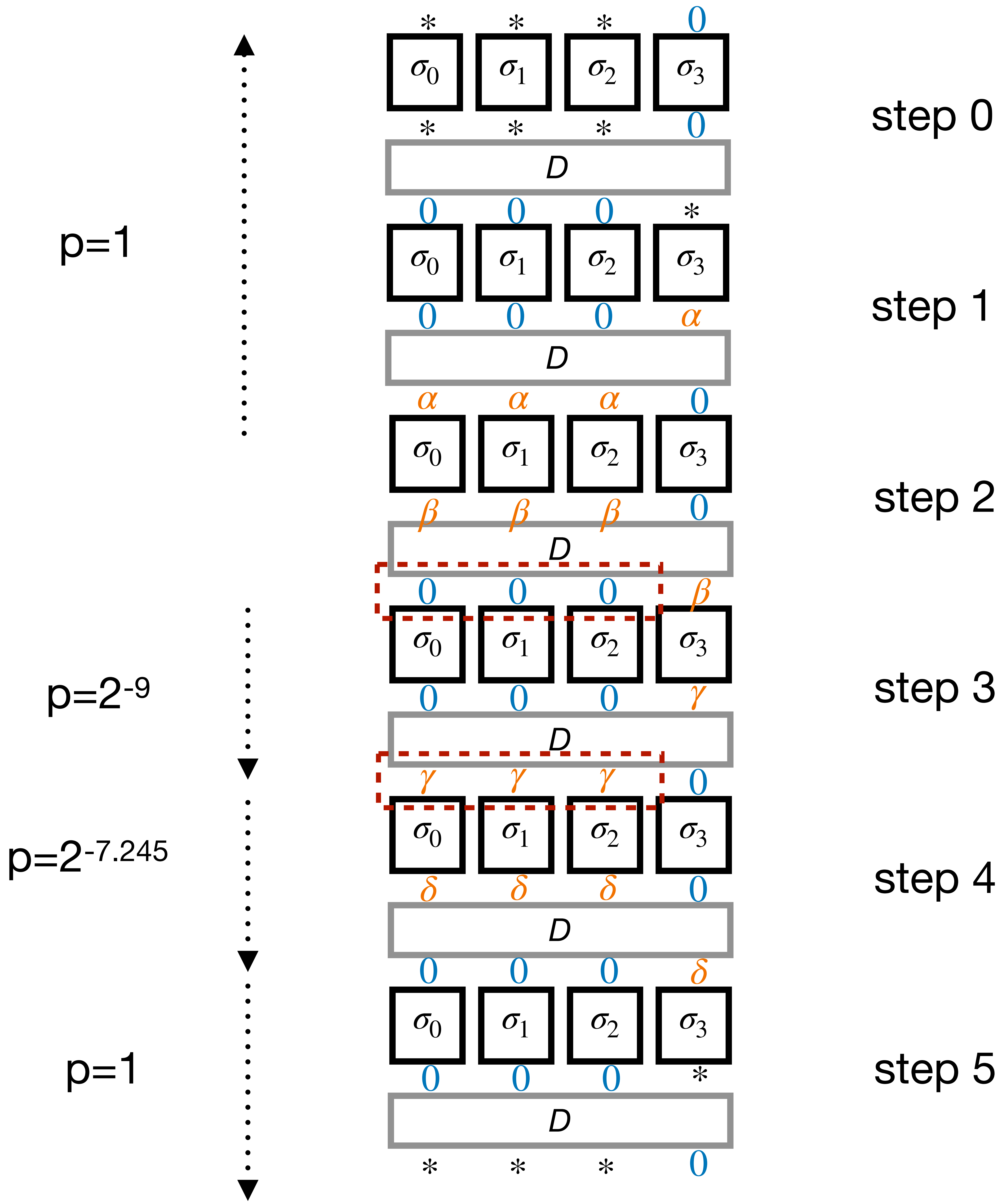
- **Step 5** has probability **1**

Total probability: $(2^{-2.415})^3 \times 2^{-9} = 2^{-16.245}$



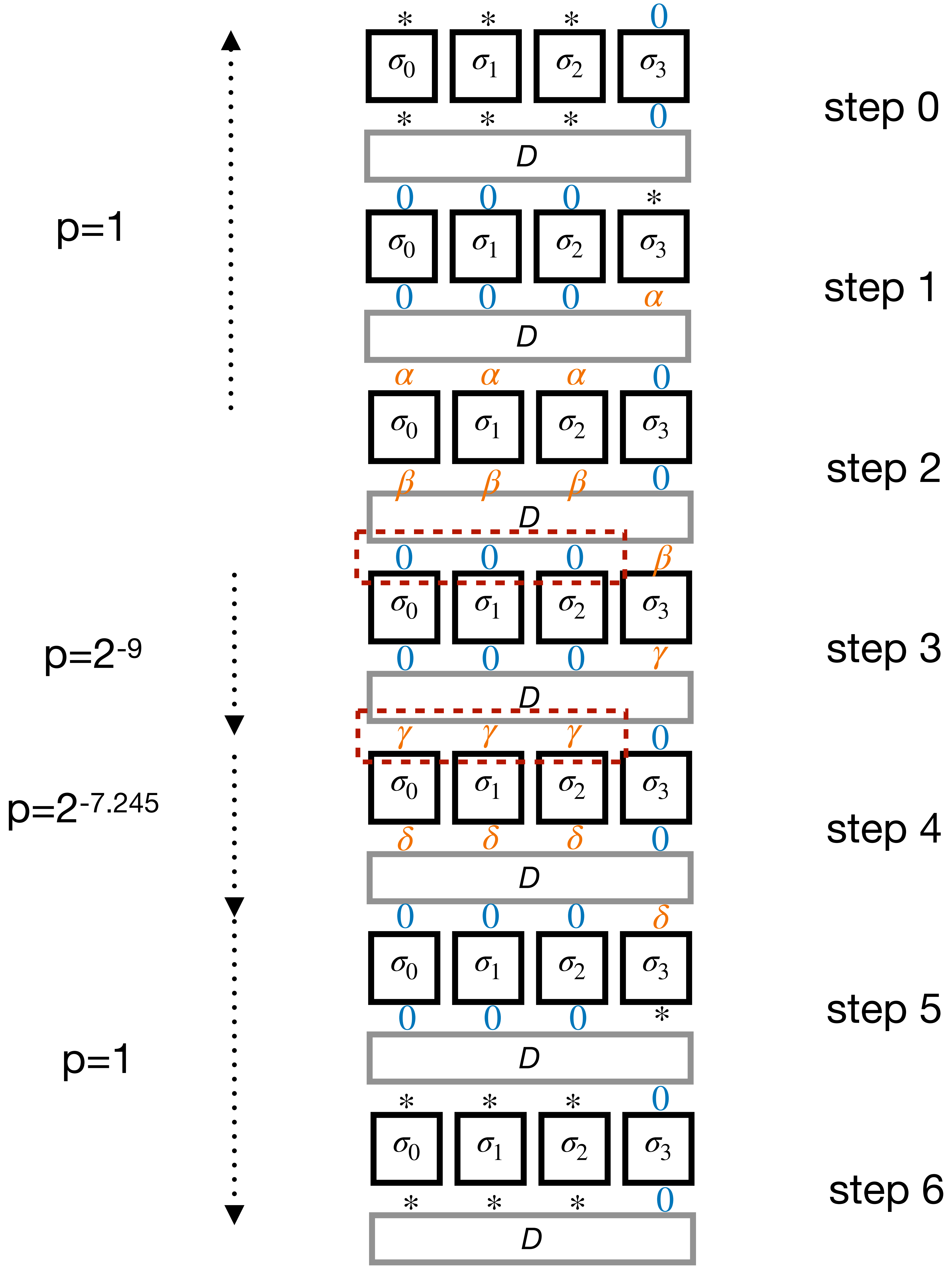
Summary

1. Select a difference $\alpha \in \nabla$.
2. Select a state (y_2, y_2, y_2, z_2) that will be a state after step 2.
3. Invert step 2 on (y_2, y_2, y_2, z_2), obtaining (x_1, y_1, z_1, t_1).
4. Invert step 1 on (x_1, y_1, z_1, t_1) and $(x_1 \oplus \alpha, y_1 \oplus \alpha, z_1 \oplus \alpha, t_1)$, obtaining (x_0, y_0, z_0, t_0) and (x_0, y_0, z_0, t_0').
5. Invert step 0, obtaining a pair of Shadow-512 states with a zero-difference in the last bundle.
6. Return this pair of state. With high probability $\geq 2^{-16.245}$, it satisfies the truncated trail.



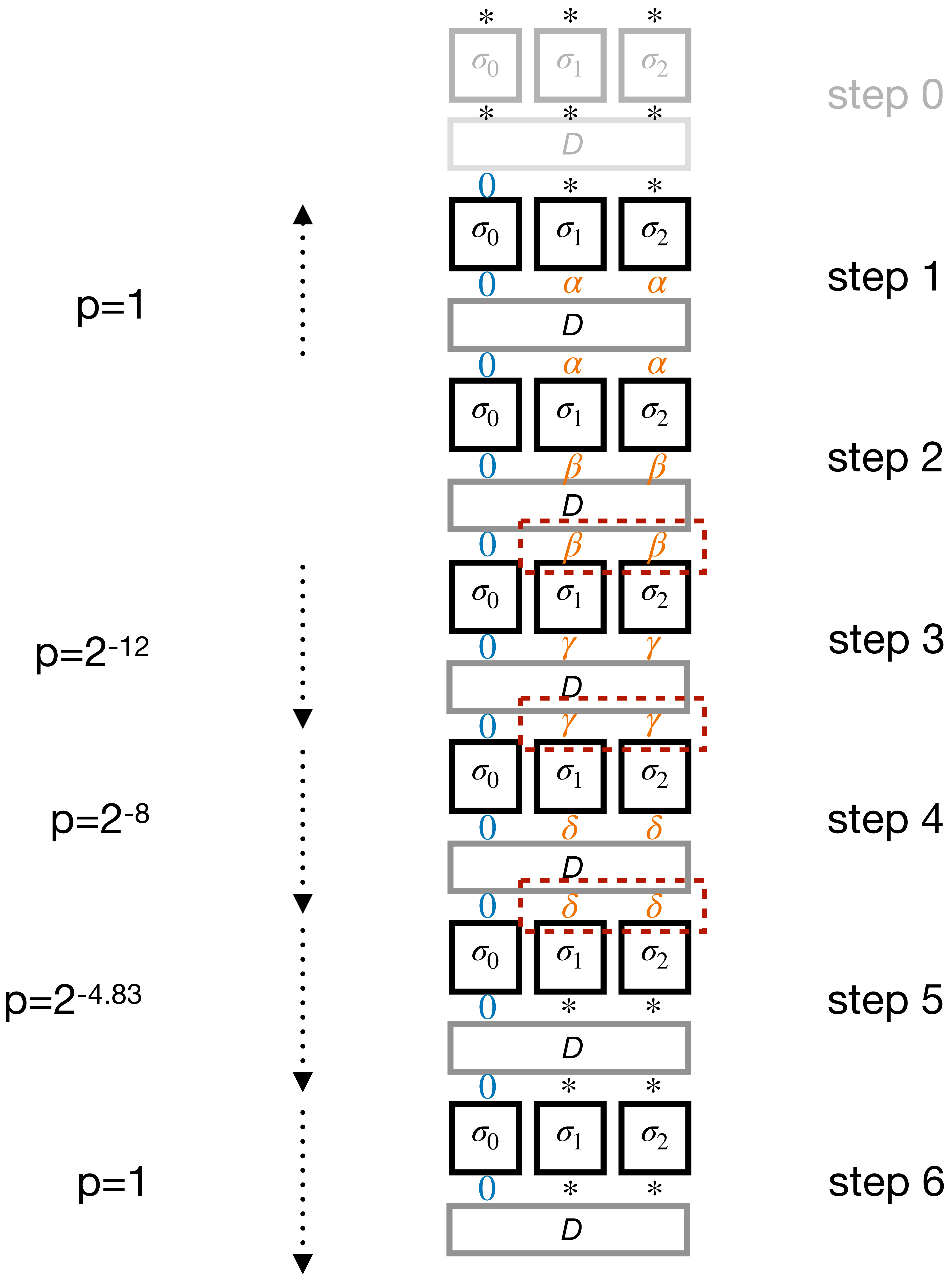
Extension to 7 steps

No extra cost.



The Shadow-384 case

$$D(a,b,c) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \times \begin{pmatrix} a \\ b \\ c \end{pmatrix}$$



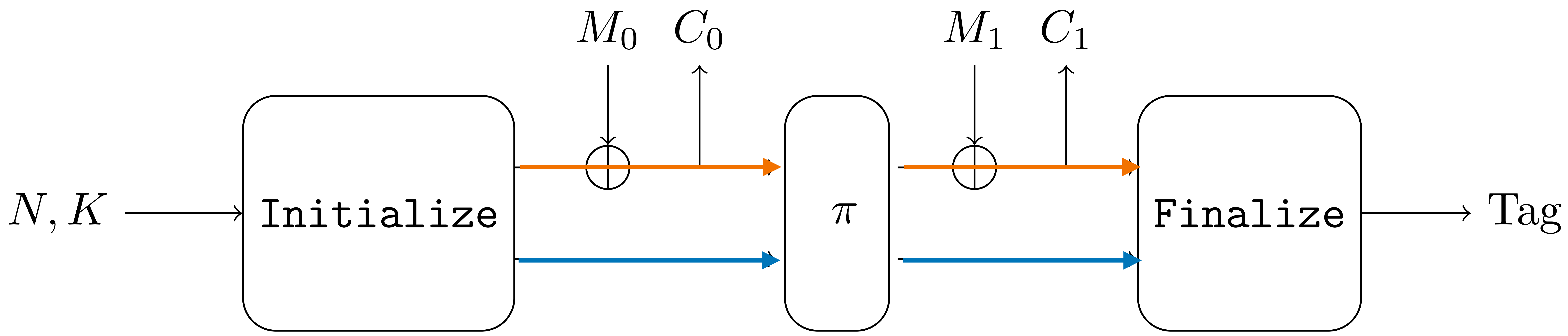
Forgery

Forgery

- “Aggressive parameters”: 8 rounds for Shadow-512
- Shifted version (step 2 to step 5)
- Same nonce used 3 times (nonce misuse scenario) to build collisions: **2 different plaintexts** that yield the **same tag**

Forgery

S1P mode in our attack setting

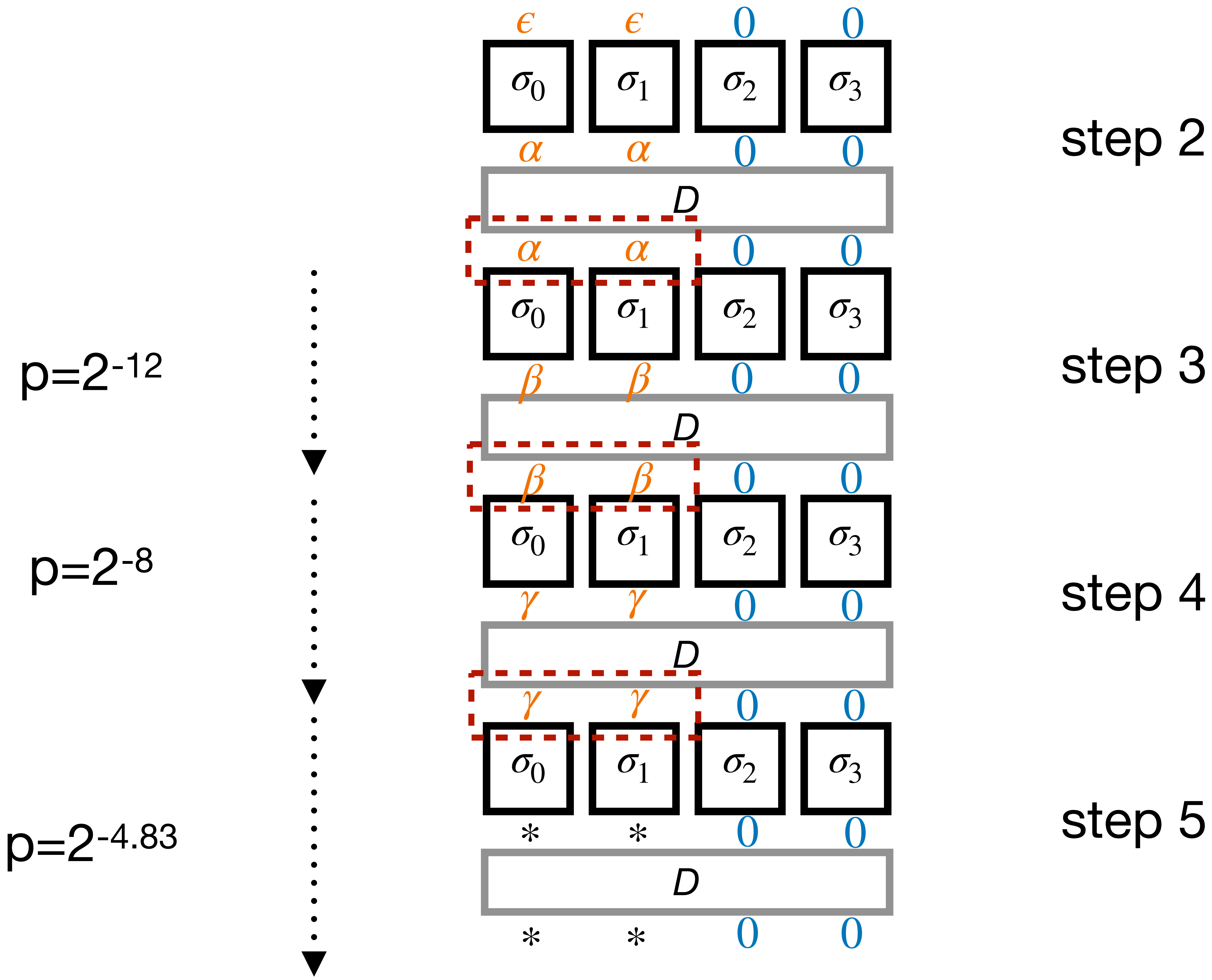


rate: bundle 0, 1

capacity: bundle 2, 3, **not visible**

Forgery

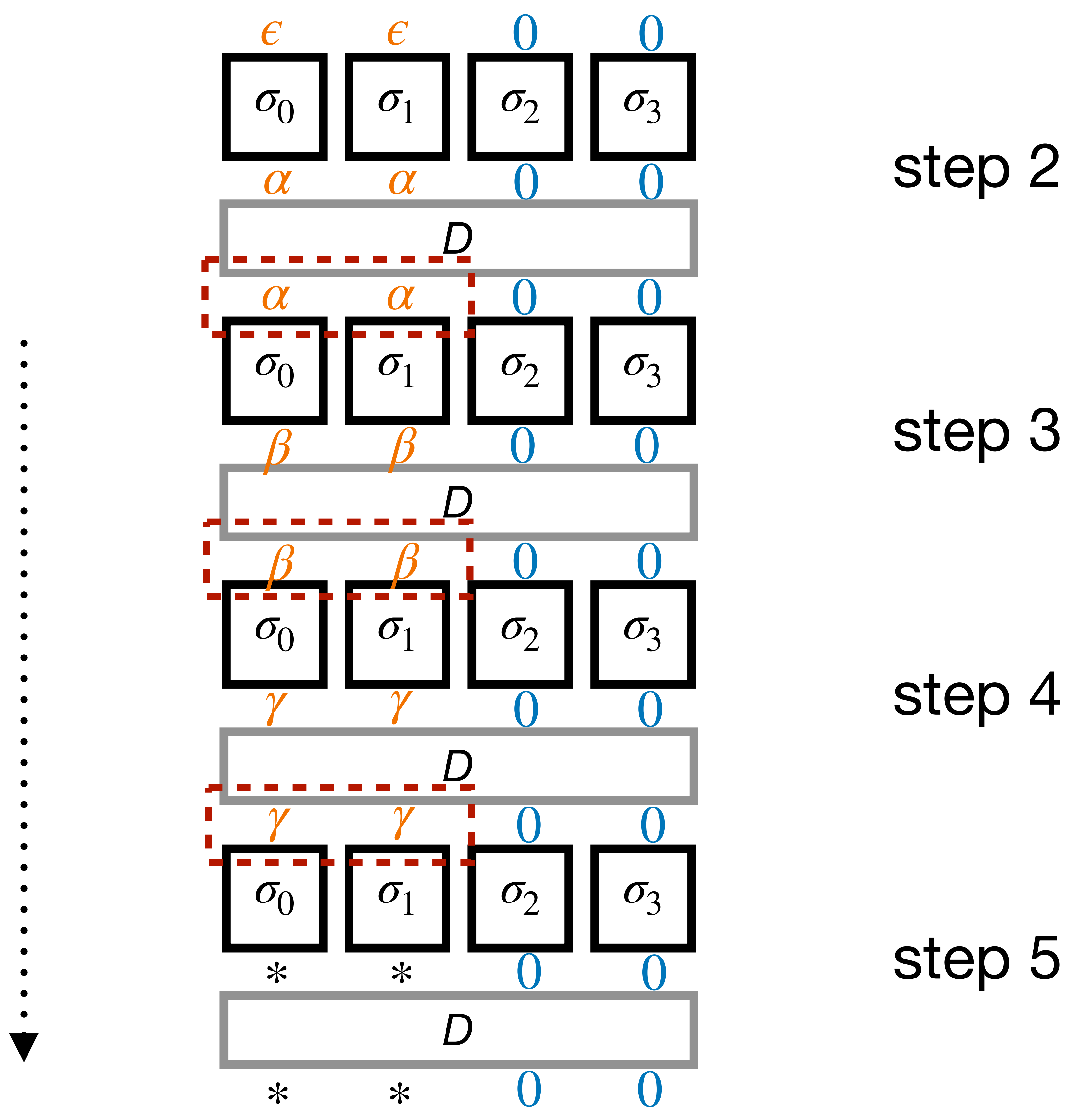
Differential trail



Forgery

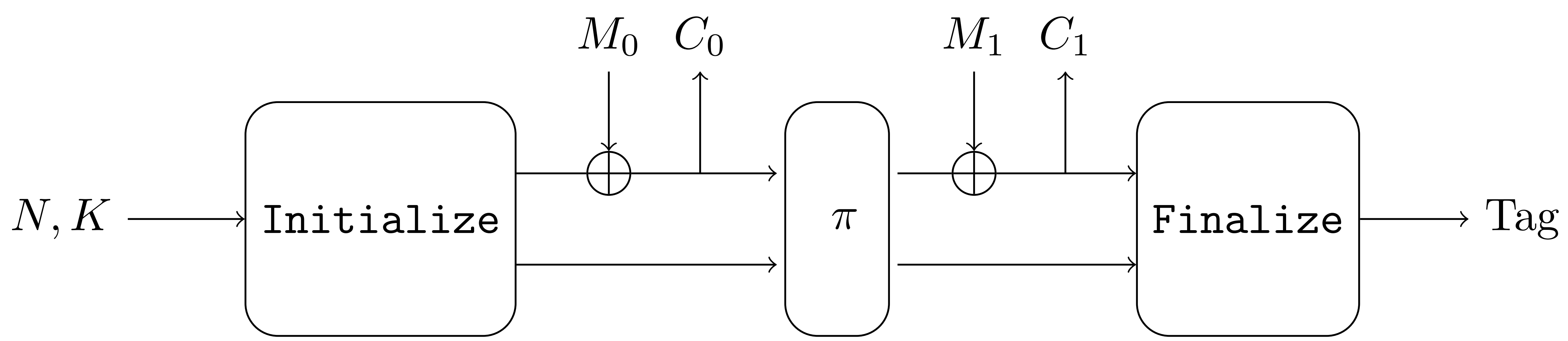
Differential trail

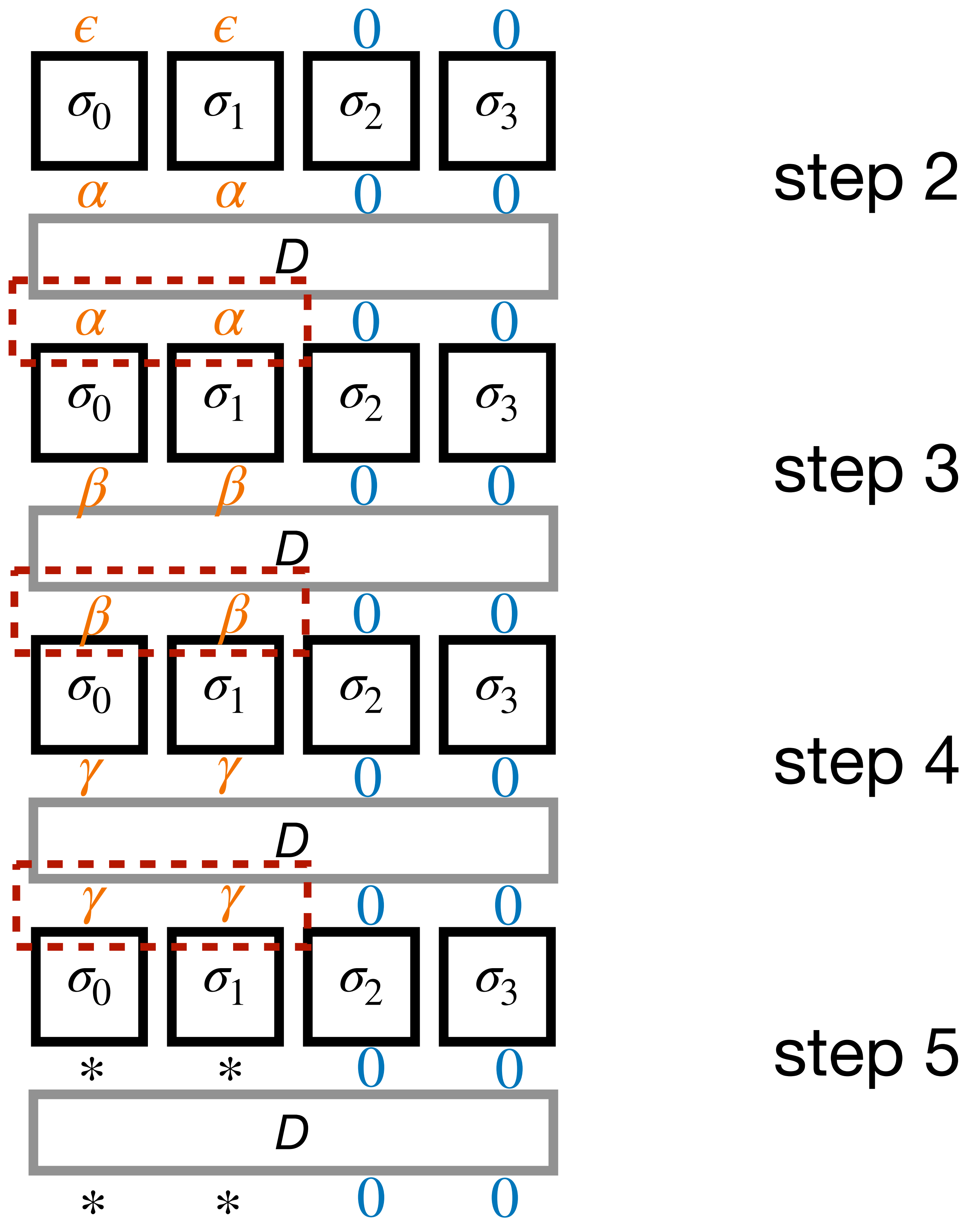
Total probability: $2^{-24.83}$



Forgery

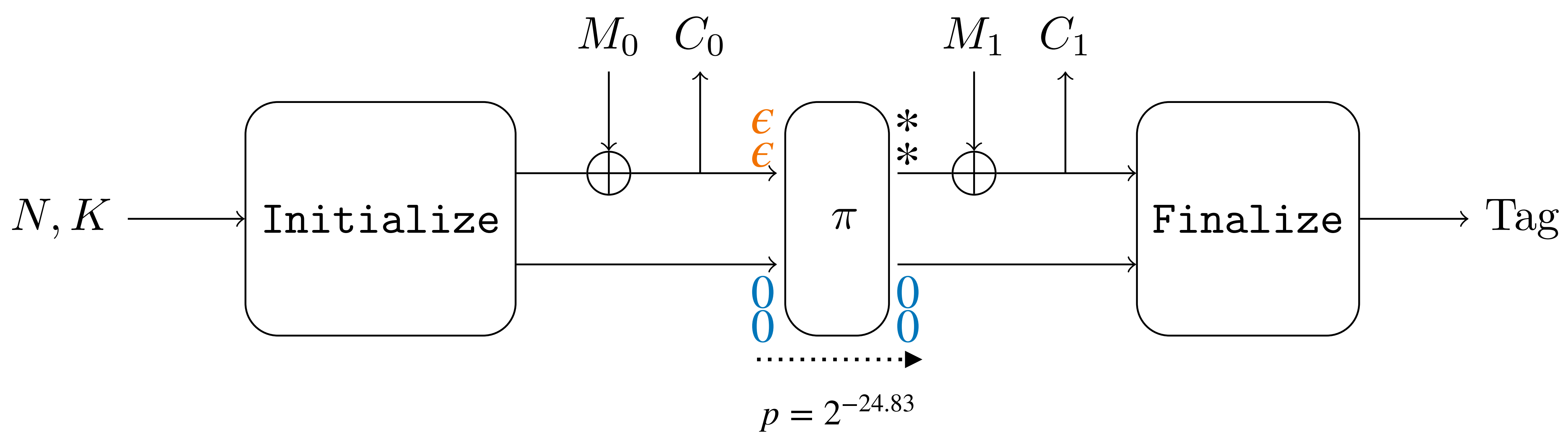
Outline





Forgery

Attack Outline



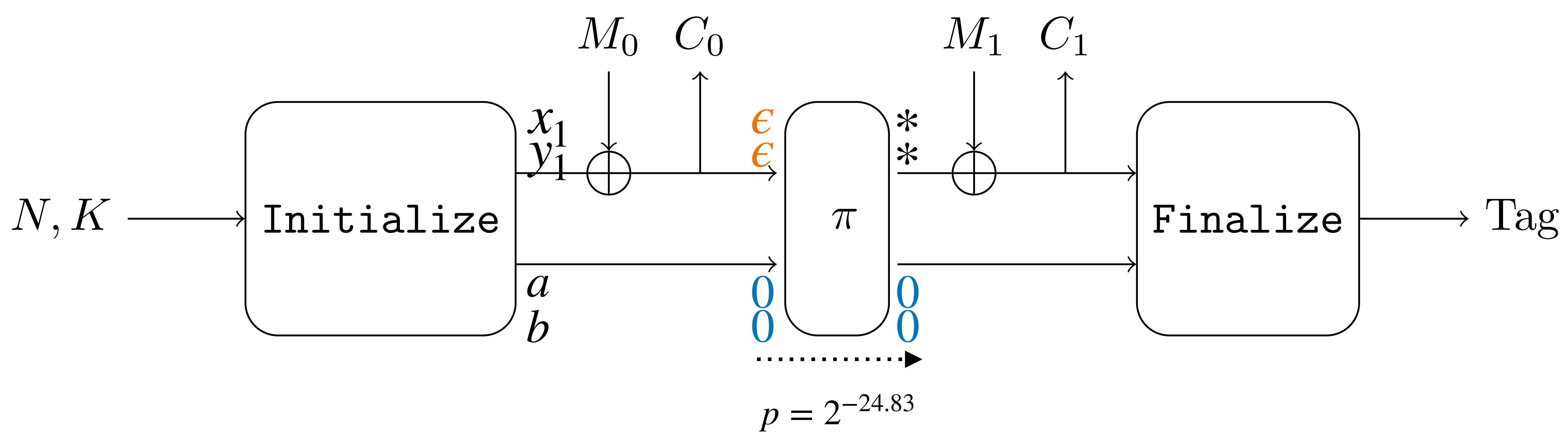
2 different plaintexts that yield the **same tag**

↓

(M_0, M_1) and **(M'_0, M'_1)** that yield a **(0,0,0,0) difference after π**

Forgery

Attack Outline



1. **Query 1**: encrypt a two-block (4 bundles) message (0,0)(0,0) to recover the 2-bundle rate value after `Initialize` (x_1, y_1) **(C_0)**.

2. Generate two pairs of **rate bundles** $(x_1', y_1'), (x_1'', y_1'')$ that satisfy the truncated trail with probability p.

3. **Query 2 and 3**: get the difference after π.

   - Encrypt $(x_1 \oplus x_1', y_1 \oplus y_1'), (0,0)$ to obtain the **value of the rate after π on** (x_1', y_1', a, b), denoted by (c_2', c_3') **(C_1)**.

   - Encrypt $(x_1 \oplus x_1'', y_1 \oplus y_1''), (0,0)$ to obtain the **value of the rate after π on** (x_1'', y_1'', a, b), denoted by (c_2'', c_3'') **(C_1)**.

4. Cancel out the difference after π.

   - $(x_1 \oplus x_1', y_1 \oplus y_1'), (c_2', c_3')$ and $(x_1 \oplus x_1'', y_1 \oplus y_1''), (c_2'', c_3'')$ yield the same internal state before `Finalize` with probability $p \simeq 2^{-24.83}$.

Conclusion

- Summary of our work:
  - **Practical distinguishers** of the full 6-step version of Shadow-512 and Shadow-384 (shifted)
  - **Practical forgeries** with 4-step Shadow for the S1P mode of operation (nonce misuse scenario)
- After our results, the authors proposed **Spook v2** [ToSC special Issue] :
  - *D* matrix replaced with an efficient MDS matrix
  - modification of the round constants of Shadow for more efficiency
  - 2nd mathematical challenge ongoing: https://www.spook.dev/challenges
- New criterion for choosing round constants: prevent more than invariant subspaces attacks

Thank you!