Security Proofs of Oribatida

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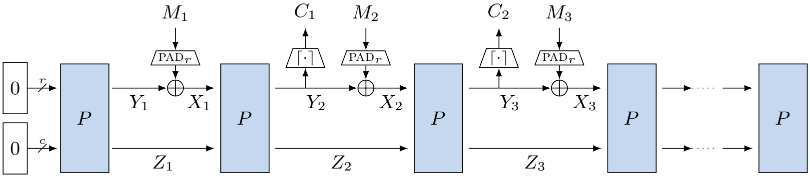
Section 1

Motivation

Permutation-based AE

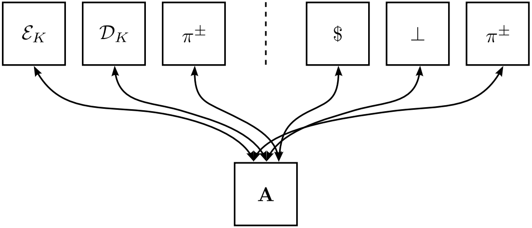
- Introduced by Bertoni et al. [BDPVA07]
- General constructions: Sponge [BDPVA07], Duplex [BDPA11]
- Many AE Schemes: Ascon [DEMS16], Keyak [BDP+16], Farfalle, NORX [AJN14], . . . ,



Security Model

nAE Security

- Ideal-permutation model
- $q_c/\sigma_c = \#$ Construction queries/blocks
- $q_e/\sigma_e = \#$ Construction encryption queries/blocks
- $q_d/\sigma_d = \#$ Construction decryption queries/blocks
- $q_p = \#$ Primitive queries



Bounds

Types:

- Inner-keyed, outer-keyed, full-keyed, suffix-keyed sponge
- SpongeWrap [BDPA11] and MonkeyDuplex [BDPVA12]

Large Corpus on Analysis:

- Keyed sponges [ADMA15, BDPA08, BDPA11, DMA17, GPT15, JLM14, MRV15, DM19, NY16]
- Bound by [DM19]:

$$\mathbf{Adv}_{\Pi}^{\mathsf{PRF}}(\mathbf{A}) = O\left(\frac{q_c^2 + q_c q_p}{2^c}\right) + \mathbf{Adv}_{\Pi}^{\mathsf{kp}}(\mathbf{A}')$$

- Improvements seem hard $\implies$ novel design approaches needed

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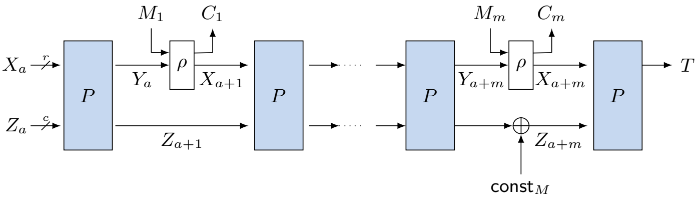
kp = key-prediction, $q_c = \#$construction queries (online), $q_p = \#$primitive queries (offline)

Beetle

[CDNY18a]

- Added transform ρ
- Permutation-input X_i and output block C_i differ



$$O\left(\frac{rq_p + r\sigma}{2^c} + \frac{q_v + q_p}{2^r} + \frac{\sigma^2 + q_p^2}{2^n}\right)$$

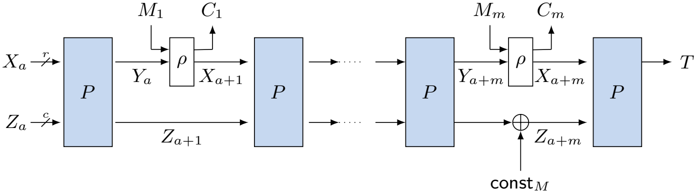
INT-RUP Security
[ABL+14]

- Correct authenticated decryption:
  Buffer entire plaintext until verification $\implies$ latency, storage
- Errors in resource-constrained environments $\implies$ Robustness desirable
- Andreeva et al. [ABL+14]:
  - PA1, PA2 notions for Privacy under release of unverified plaintext
  - INT-RUP for Integrity
  - PA2 unachievable for online schemes
  - INT-RUP achievable

INT-RUP Security

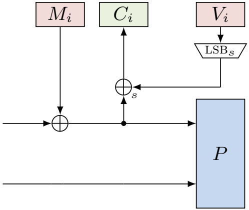
Beetle

- Bound of Beetle does not hold in INT-RUP
- Attack in $O(q_d q_p / 2^c)$
- Problem: #Offline primitive queries q_p



Idea: Ciphertext Masking

- Dynamic mask from earlier capacity (random permutation outputs)
- INT-RUP security: $O(q_d^2/2^c)$
- Only #Online construction queries q_d relevant

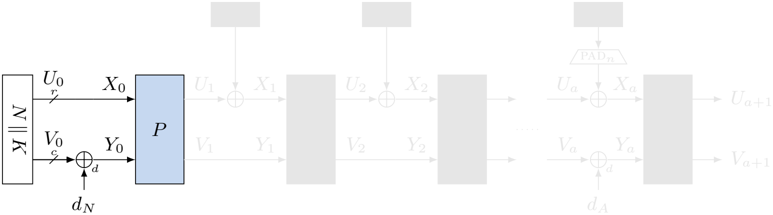


Section 2

Oribatida

- Nonce and key concatenated
- Domain separation

$$d_N = \begin{cases} 5 & \text{if } |A| + |M| > 0 \\ 9 & \text{otherwise.} \end{cases}$$

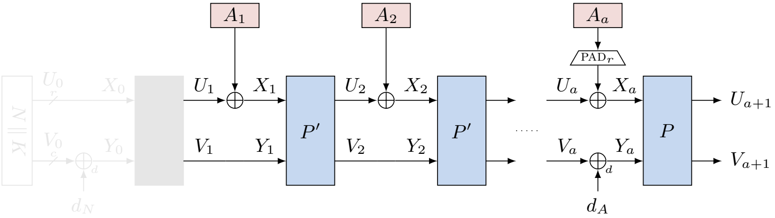


Oribatida

Associated-data Processing

- Absorbed in the rate
- Round-reduced permutation for intermediate blocks
- Always wrapped by full permutation calls
- Domain separation

$$d_A = \begin{cases} 4 & \text{if } |M| = 0 \wedge |A| \bmod r \equiv 0 \\ 6 & \text{if } |M| = 0 \wedge |A| \bmod r > 0 \\ 12 & \text{if } |M| > 0 \wedge |A| \bmod r \equiv 0 \\ 14 & \text{if } |M| > 0 \wedge |A| \bmod r > 0. \end{cases}$$

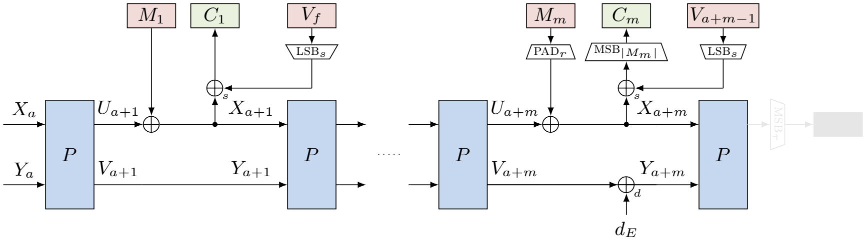


Oribatida

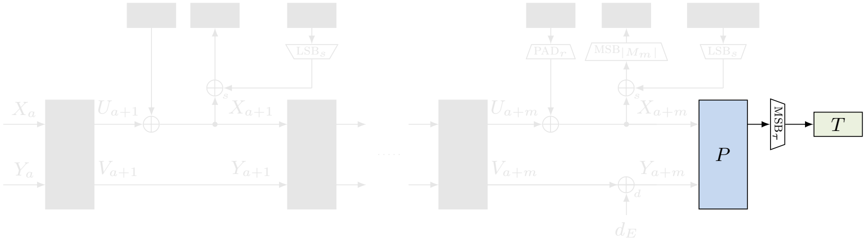
Encryption

- Absorbed in the rate
- Mask V_i: s lsb from previous capacity
- $V_f = V_0$ if no AD, and V_1 otherwise
- Domain separation

$$d_E = \begin{cases} 13 & \text{if } |M| \bmod r \equiv 0 \\ 15 & \text{if } |M| \bmod r \not\equiv 0 \end{cases}$$



- Outputs first τ bits
- Decryption analogously, only returns message if T valid



Oribatida

Variants

		Permutations					State size		
				Key	Nonce	Tag	Rate	Capacity	Mask
Rec.	Name	P	P'	(k)	(ν)	(τ)	(r)	(c)	(s)
1	Oribatida-256-64	SimP-256-4	SimP-256-2	128	128	128	128	128	64
2	Oribatida-192-96	SimP-192-4	SimP-192-2	128	64	96	96	96	96

Section 3

nAE Security

nAE Security

- H-coefficient technique [CS14, Pat08]
- Assumes: P, P' ideal (same) permutation

Bad events:

1. r-multi-collision on rate among encryption construction queries **or** in rate among primitive queries

$$\frac{\binom{\sigma}{r}}{2^{r(r-1)}} + \frac{\binom{q_p}{r}}{2^{r(r-1)}}$$

2. Collision of permutation in-/outputs in construction queries

$$2 \cdot \frac{\binom{\sigma}{2}}{2^n}$$

3. Collision of permutation in-/outputs between construction and primitive query

$$2 \cdot \left(\frac{\sigma_e \cdot q_p}{2^{c+s}} + \frac{r \cdot q_p}{2^{n-\tau}}\right)$$

4. Initial-state collision with primitive query

$$\frac{3q_p}{2^k} + \frac{q_c \cdot q_p}{2^{c+s}}$$

nAE Security (cont'd)

Interpolation probability of good transcripts:

$$\frac{\Pr[\Theta_{\mathsf{real}} = \tau]}{\Pr[\Theta_{\mathsf{ideal}} = \tau]} \leq 1 - \left(\frac{q_d}{2^{\tau}} + \frac{q_d(q_p + \sigma_e)}{2^{c+s}} + \frac{(\sigma_d + q_d) \cdot r}{2^{c+s}} \right)$$

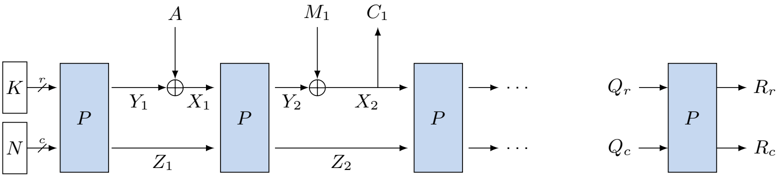
Bound:

$$\mathbf{Adv}^{\mathrm{NAE}}_{\Pi[\pi]_K}(\mathbf{A}) \leq \frac{\binom{\sigma}{r} + 2\binom{q_p}{r}}{2^{r(r-1)}} + \frac{\sigma^2}{2^n} + \frac{3q_p}{2^k} + \frac{r(q_d + \sigma_d) + 2\sigma_e q_p + q_p q_c + q_d(\sigma_e + q_p)}{2^{c+s}} + \frac{2rq_p}{2^{n-\tau}} + \frac{q_d}{2^{\tau}}$$

Section 4

INT-RUP Security

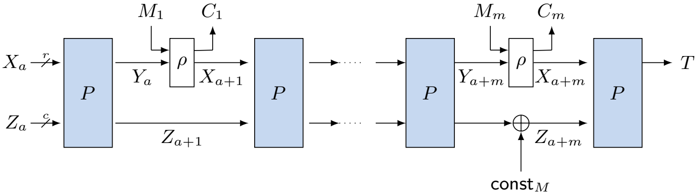
1. 1 encryption query $(N, A, M) \implies C$
2. q_d decryption queries $(N, A^i, C) \implies M^i$, with r bits fixed to constant
3. q_p primitive queries $Q^j \implies R^j$ with same r fixed bits
4. State collision when $q_d q_p \in O(2^n)$



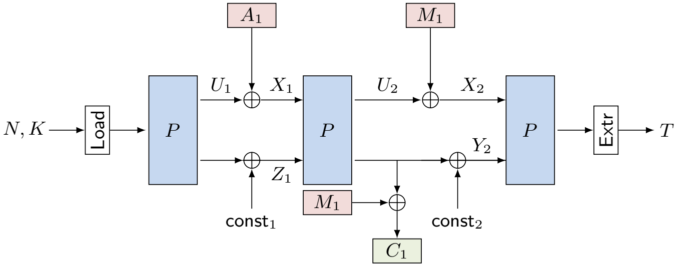
INT-RUP-Security

Attack on Beetle [CDNY18b]

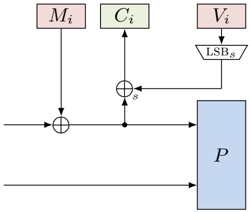
1. q_d encryption queries $(N, A^i, M) \implies C^i$, with r bits fixed to constant
2. q_d decryption queries $(N, A^i, {C'}^i) \implies {M'}^i$, with ${C'}^i = Y_2^i \oplus \text{shuffle}(Y_2^i)$ fixes first r bits
3. Again, q_p primitive queries with r bits fixed
4. State collision when $q_d q_p \in O(2^n)$



1. Encryption queries $(N, A, M_1) \implies (C_1, T)$
2. q_d decryption queries $(N, A, C_1^i) \implies M_1^i$
   capacity value Y_2 is fixed and known
3. Again, q_p primitive queries with Y_2 fixed
4. State collision when $q_d q_p \in O(2^n)$



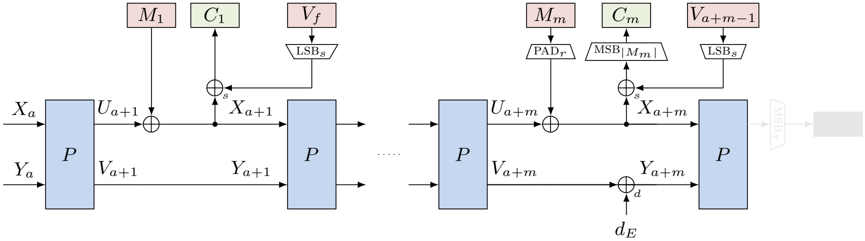
- $\mathbf{A}$ cannot fix the rate to a known constant
- Input to primitive oracle unknown



INT-RUP-Security

Best Attack

1. q_d encryption queries $(N^i, A^i, M) \implies C^i$
2. q_d decryption queries $(N, A^i, C'^i) \implies M'^i$
3. State collision in $V_2^i = V_2^j$ in $q_d^2 \in O(2^n)$



INT-RUP-Security

Bound

- H-coefficient technique [CS14, Pat08]
- Assumes: P, P' ideal (same) permutation

Bad events:

1. Non-trivial collision of permutation in/outputs in construction queries
2. Multi-collision between r tags
3. Non-trivial collision of permutation in/outputs between construction and primitive query
4. Initial-state collision with a primitive query
5. Multi-collision in the rate part of r primitive queries
6. Forgery in decryption queries if all blocks are old

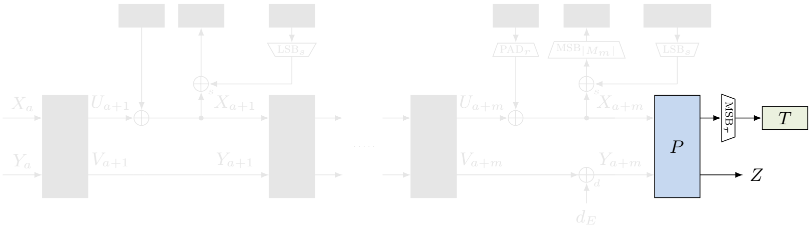
$$\mathbf{Adv}^{\text{INT-RUP}}_{\Pi[\pi]_K}(\mathbf{A}) \leq \frac{\sigma_e^2}{2^n} + \frac{4\sigma_e\sigma_d + 4\sigma q_p + q_c q_p + q_p + r(\sigma_d + q_d)}{2^{c+s}} + \frac{q_d^2 + \binom{q_d+q_v}{2}}{2^c} + \frac{\binom{q_e}{r}}{2^{\tau(r-1)}} + \frac{3rq_p}{2^{n-\tau}} + \frac{3q_p}{2^k} + \frac{2\binom{q_p}{r}}{2^{r(r-1)}} + \frac{2q_v}{2^\tau}.$$

Section 5

Tweaks

Observation by Rohit and Sarkar

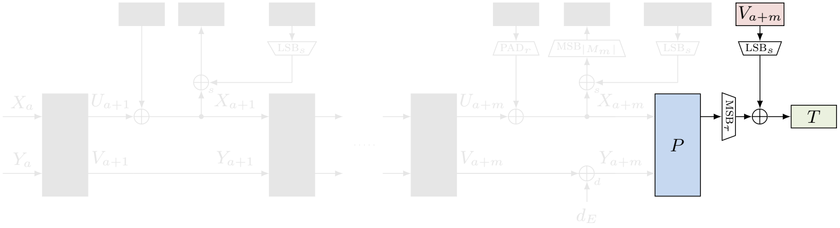
- Guess final permutation output $Z \implies$ recover state
- Only effective for our secondary proposal Oribatida-192
  Not for our primary proposal Oribatida-256
- nAE analysis used to have one incorrect denominator: $q_p/2^{c+s}$ $\implies q_p/2^{n-\tau}$
- Covered in final workshop submission



Possible Tweaks

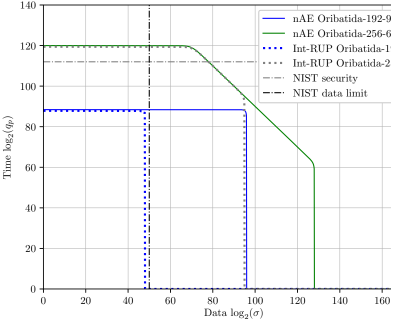
- Simple: Restrict tags to 64 bits for Oribatida-192
- Better: Mask the tag like ciphertext outputs before.
- Increases the relevant term from

$$\frac{3rq_p}{2^{n-\tau}} \quad \text{to} \quad \frac{3rq_p}{2^{n-\tau+s}}$$

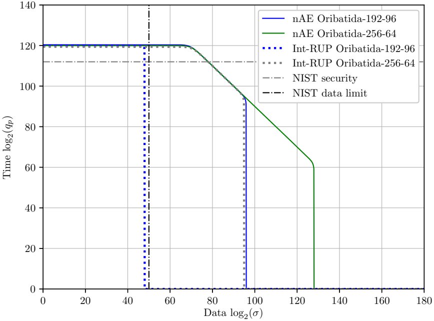


Possible Tweaks

Current Security



With Tag Masking



For $q_c = 2^{50}$

Section 6

Features

Implementation

Hardware Implementation on *Virtex 7 FPGA*

Table: LUTs = lookup tables; AD = associated data; Enc. = encryption; Dec. = decryption.

	LUTs	FF	#Slices	Frequency (MHz)	Cycles		Throughput (Mbps)	
					AD	Message	AD	Message
SimP								
SimP-256	495	340	148	580.51	69	137	1 076.88	542.37
SimP-192	383	259	122	581.98	53	105	1 054.15	532.10
Oribatida-256-64								
Enc. and Dec.	940	599	298	554.16	68	138	1 043.12	514.00
Enc. only	805	595	253	560.71	68	138	1 055.45	520.08

Oribatida– Features

- **Lightweight:** Permutation-based, no additional subkeys
- **Cross-platform:** SimP permutation only AND, rotation, XOR, no S-boxes
  State can be split according to platform needs
- **Well-known Components:** Duplex, Simon in SimP
- **High nAE-Security** as for Beetle:

$$\frac{r\sigma}{2^c} + \frac{\sigma^2 + q_p^2}{2^n} + \frac{q_p}{2^c}$$

- **Int-RUP-robust:** Limits damage if messages may leak

Questions?

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Section 7

Supporting Slides

Int-RUP Security

- H-coefficient technique [CS14, Pat08]
- Assumes: P, P' ideal (same) permutation

Bad events:

1. r-multi-collision on rate among encryption construction queries **or** in rate among primitive queries

$$\frac{\binom{\sigma}{r}}{2^{r(r-1)}} + \frac{\binom{q_p}{r}}{2^{r(r-1)}}$$

2. Collision of permutation in-/outputs in construction queries

$$2 \cdot \frac{\binom{\sigma}{2}}{2^n}$$

3. Collision of permutation in-/outputs between construction and primitive query

$$2 \cdot \left(\frac{\sigma_e \cdot q_p}{2^{c+s}} + \frac{r \cdot q_p}{2^{n-\tau}} \right)$$

4. Initial-state collision with primitive query

$$\frac{3q_p}{2^k} + \frac{q_c \cdot q_p}{2^{c+s}}$$

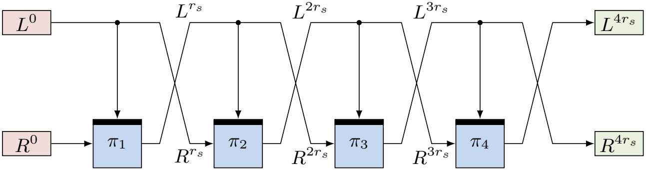
Section 8

Permutation

SimP

Ψ_r Domain extender [CDMS10]:

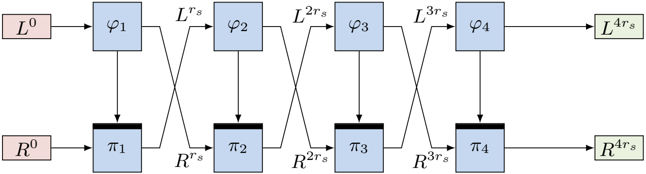
- Swap halves after each step
- Indifferentiable $O(q^2/2^n)$



SimP

Φ_r:

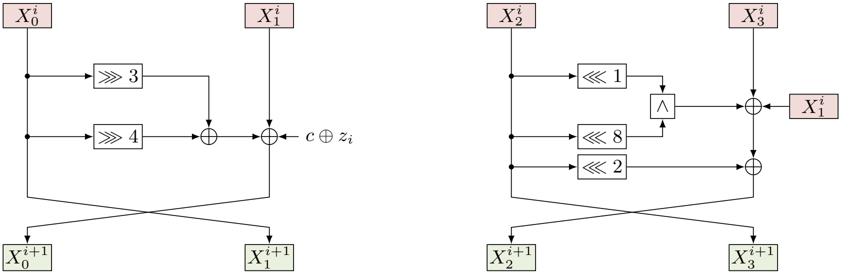
- Key-update permutation φ_i for other branch



SimP

Instantiation of Φ:

- Simon [BSS$^+$13]
- Lightweight: only 3 rotations, 3 XORs, 1 AND
- Intense analysis [ALLW14, CW16, LLW17, Rad15, XZBL16]
- Original round and rotation constants



- 4-word state: Simon round-function + Simon key-update function
- Half #rounds of full Simon-96-96/-128-128 per step
- Each bit passes full Simon

Variant	Word size (w)	#Steps (θ)	#Rounds/Step (r_s)
SimP-192-2	48	2	26
SimP-192-4	48	4	26
SimP-256-2	64	2	34
SimP-256-4	64	4	34

SimP

Analysis

- Round-reduced for intermediate blocks of AD
- Need only differentials
- Always wrapped by full steps