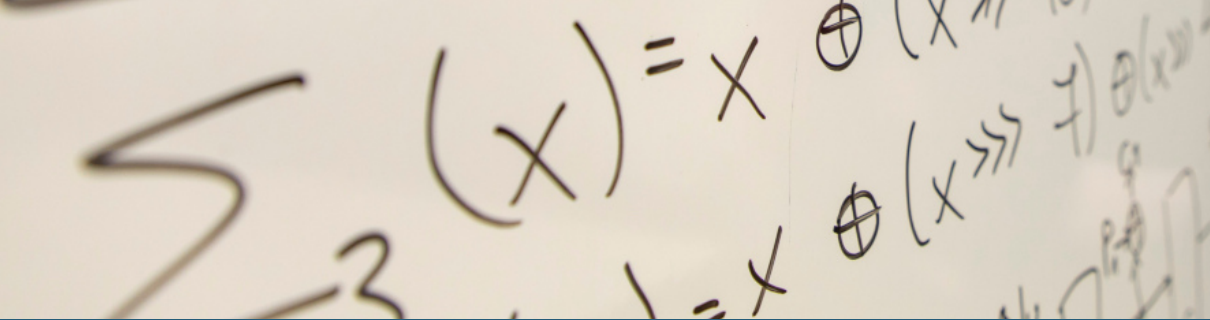


The Ascon Family for Lightweight Cryptography

Christoph Dobraunig · **Maria Eichlseder** · Florian Mendel · Martin Schläffer

- PBC 2023
- Lyon · 23 April 2023

TU Graz

› https://ascon.iaik.tugraz.at

Motivation

Lightweight Cryptography

Need lightweight authenticated encryption and hashing algorithms

Low **area** · Low **energy** · Low **power** · Low **latency**

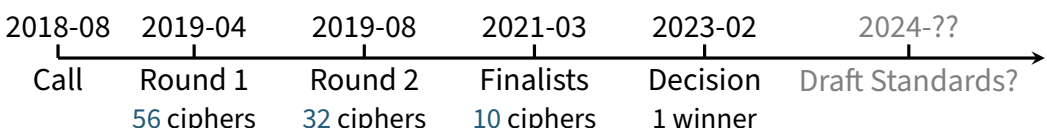
for efficient, secure, robust implementations on constrained devices

National Institute of Standards and Technology
U.S. Department of Commerce

LWC Competition – Standardizing LightWeight Crypto

- Standardize lightweight authenticated encryption and hashing algorithms
- Organized by NIST (US National Institute of Standards and Technology)

https://csrc.nist.gov/projects/lightweight-cryptography



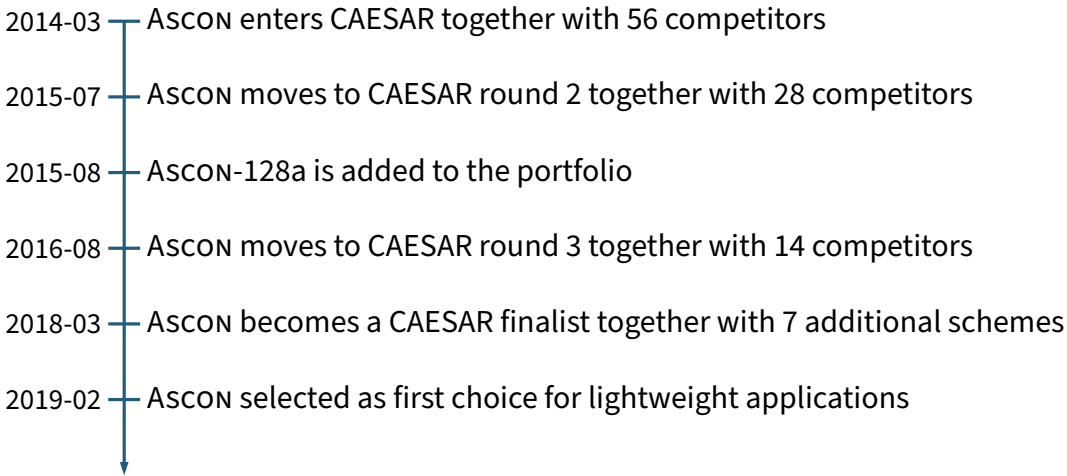
Designing the Ascon Family

The Ascon Team

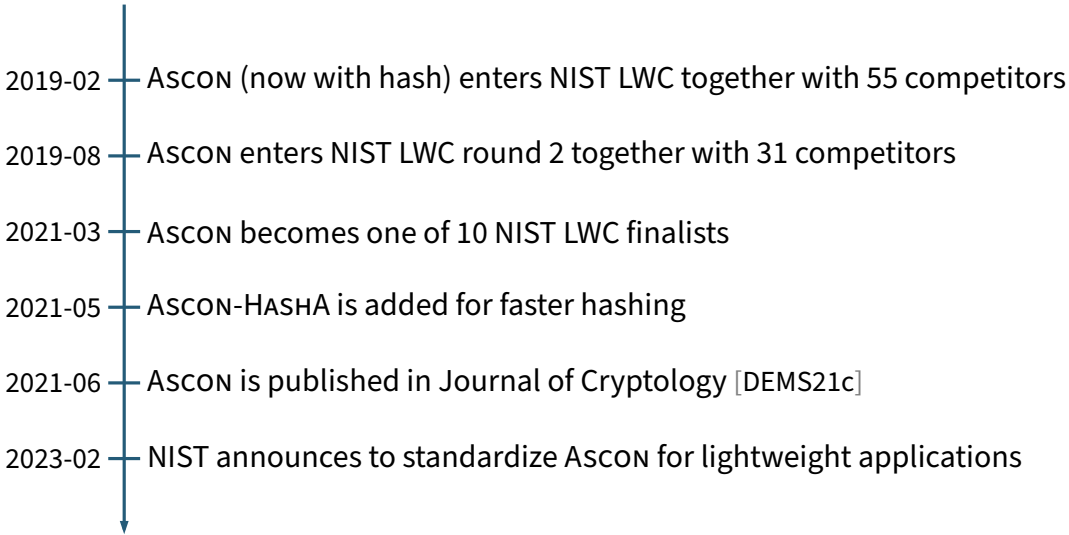
- Martin Schläffer
- Florian Mendel
- Christoph Dobraunig
- Maria Eichlseder

(c) Lunghammer, TU Graz

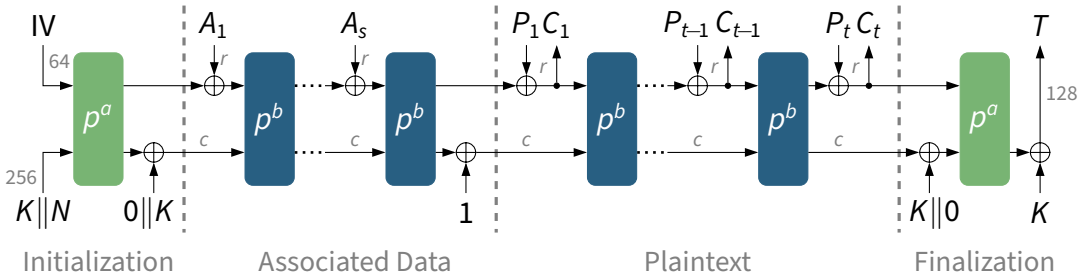
History I


2014-03
Ascon enters CAESAR together with 56 competitors
2015-07
Ascon moves to CAESAR round 2 together with 28 competitors
2015-08
Ascon-128a is added to the portfolio
2016-08
Ascon moves to CAESAR round 3 together with 14 competitors
2018-03
Ascon becomes a CAESAR finalist together with 7 additional schemes
2019-02
Ascon selected as first choice for lightweight applications

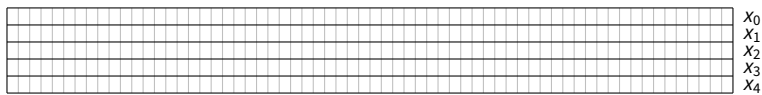
History II


2019-02
Ascon (now with hash) enters NIST LWC together with 55 competitors
2019-08
Ascon enters NIST LWC round 2 together with 31 competitors
2021-03
Ascon becomes one of 10 NIST LWC finalists
2021-05
Ascon-Hasha is added for faster hashing
2021-06
Ascon is published in Journal of Cryptology [DEMS21c]
2023-02
NIST announces to standardize Ascon for lightweight applications

Ascon's Mode for Authenticated Encryption



- **Doubly-keyed** initialization/finalization for higher robustness under misuse
- **Duplex sponge** mode using a $5 \times 64 = 320$-bit permutation

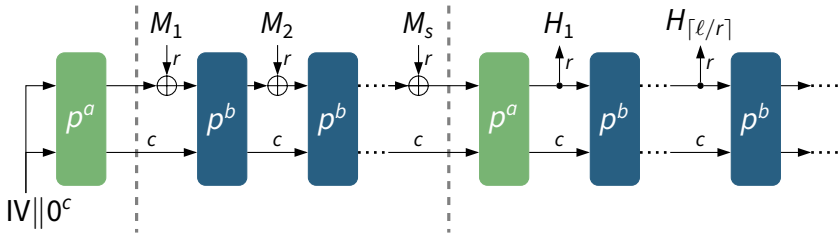


AEAD Family

Name	Algorithms	Bit size of				Rounds	
		key	nonce	tag	data block	p^a	p^b
Ascon-128	$\mathcal{E}, \mathcal{D}_{128,64,12,6}$	128	128	128	64	12	6
Ascon-128a	$\mathcal{E}, \mathcal{D}_{128,128,12,8}$	128	128	128	128	12	8
Ascon-80pq	$\mathcal{E}, \mathcal{D}_{160,64,12,6}$	160	128	128	64	12	6

- **Ascon-128**: Primary recommendation
- **Ascon-128a**: Same security, 33 % faster (more rounds but larger rate)
- **Ascon-80pq**: Same classical security, higher PQ security

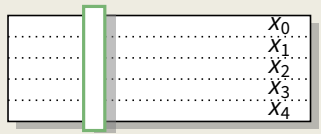
Ascon Hashing

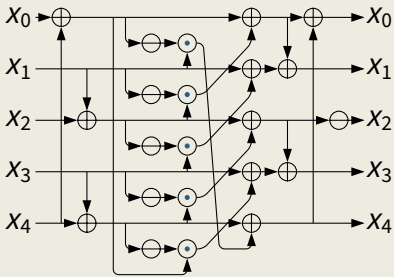


Name	Algorithm	Bit size of		Rounds	
		hash	data block	p^a	p^b
Ascon-Hash	$\mathcal{X}_{256,64,12,12}$ with $\ell = 256$	256	64	12	12
Ascon-Hasha	$\mathcal{X}_{256,64,12,8}$ with $\ell = 256$	256	64	12	8

Ascon Permutation: $a = 12,\ b \in \{6, 8\}$ Rounds

S-box layer





Linear layer

$$x_0 := x_0 \oplus (x_0 \ggg 19) \oplus (x_0 \ggg 28)$$

$$x_1 := x_1 \oplus (x_1 \ggg 61) \oplus (x_1 \ggg 39)$$

$$x_2 := x_2 \oplus (x_2 \ggg 1) \oplus (x_2 \ggg 6)$$

$$x_3 := x_3 \oplus (x_3 \ggg 10) \oplus (x_3 \ggg 17)$$

$$x_4 := x_4 \oplus (x_4 \ggg 7) \oplus (x_4 \ggg 41)$$

Security

When used correctly (nonce-respecting, etc.):

Requirement	Security in bits			
	Ascon-128 Ascon-128a	Ascon-80pq	Ascon-Hash Ascon-Hasha	Ascon-Xof Ascon-Xofa
Confidentiality of M	128	128		
Integrity of M, A, N	128	128		
Collision resistance			128	$\min(128, \ell/2)$
Pre-image resistance			128	$\min(128, \ell)$

In case of nonce misuse or other misuse (side-channels, …):
Aim to keep damage “local” to misused setting (resilience)

Implementing Ascon

Ascon Permutation Properties

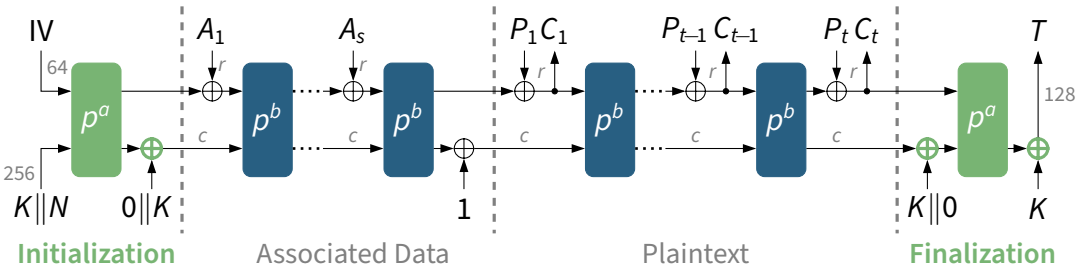
- **Simplicity**
  - Low 320-bit state size
  - Bitwise Boolean functions defined on 64-bit words
- **Bitsliced in Software**
  - 64-bit words
  - Up to 5 instructions in parallel
  - Minimal temporary registers
- **Flexible in Hardware**
  - Small area
  - High speed
- **Easy to integrate side-channel countermeasures**
  - No look-up tables
  - Low-degree S-boxes
  - Easy to mask

Ascon Performance Characteristics

- Often much more efficient than AES-GCM
  - Up to **3x to 5x speed on microcontrollers** (from `https://lwc.las3.de`)
  - Up to **2x throughput** with **0.5x energy** in hardware (from `https://ia.cr/2021/049`)
- Designed for ease of protection against physical attacks

Protecting against Implementation Attacks

- Robustness: Limited damage if state recovered through some misuse
- **Mode**: **Levelled Implementation** [BBC+20]: only **Init/Final** need full protection



- **Primitive**: Efficient masking (e.g., using Toffoli gate [DDE+20])

Analyzing Ascon

Analysis of Ascon

Key recovery	Ascon initialization	7 / 12	2^{97} ⊘	Cube-like	[LZWW17]
	Ascon initialization	7 / 12	2^{104}	Cube-like	[LDW17]
	Ascon initialization	7 / 12	2^{123} ✓	Cube	[RHSS21]
	Ascon initialization	6 / 12	2^{74}	Cond. HDL	[HP22]
	Ascon initialization	5 / 12	2^{31} ✓	Diff.-linear	[Tez20]
	Ascon-128a iteration	7 / 8	2^{118} ⊘	Cond. cube	[CKT22]
	Ascon-80pq iteration	6 / 6	2^{130} ⊘ ⌛	Cond. cube	[CHK22]
Forgery	Ascon-128 finalization	6 / 12	2^{33} ⊘	Cube tester	[LZWW17]
	Ascon-128 finalization	4 / 12	2^{102}	Differential	[DEMS15]
	Ascon-128 finalization	4 / 12	2^{97}	Differential	[GPT21]
	Ascon-128a finalization	3 / 12	2^{20} ✓	Differential	[GPT21]

⊘ = nonce misuse = exceeds data limit of 2^{64} blocks ⌛ = time exceeds 2^{128}

weak-key variants omitted

Analysis of Ascon: (Partial*) state recovery

State recovery	Ascon-128 iteration	6 / 6	2^{40}	⊘	Cond. cube	[BCP22]
	Ascon-128 iteration*	6 / 6	2^{45}	⊘	Cond. cube	[CHK22]
	Ascon-128 iteration	5 / 6	2^{66}	⊘	Cube-like	[LZWW17]
	Ascon-128a iteration	7 / 8	2^{118}	⊘ 🔕	Cond. cube	[CKT22]
	Ascon-128a iteration	3 / 8	2^{117}	✔	Differential	[GPT21]
	Ascon-128a iteration	2 / 8	–	✔	Sat-Solver	[DKM+17]

⊘ = nonce misuse 🔕 = exceeds data limit of 2^{64} blocks
weak-key variants omitted

Analysis of Ascon-Hash and Ascon-Xof

Type	Target	Output size	Rounds	Time	Method	Reference
Preimage	Ascon-Xof	64	6 / 12	$2^{63.3}$	Algebraic	[DEMS19]
	Ascon-Xof	64	2 / 12	2^{39}	Cube-like	[DEMS19]
Collision	Ascon-Xof	all	4 / 12	– ⊘	Differential	[DEMS19]
	Ascon-Xof	64	2 / 12	2^{15}	Differential	[ZDW19]
	Ascon-Hash	256	2 / 12	2^{125}	Differential	[ZDW19]
	Ascon-Hash	256	2 / 12	2^{103}	Differential	[GPT21]

(⊘ = chosen IV)

Analysis of Ascon's Permutation

Distinguisher	Permutation	12 / 12	2^{55} 👁	Zero-sum	[HP22]
	Permutation	11 / 12	2^{85} 👁	Zero-sum	[DEMS21a]
	Permutation	8 / 12	2^{46} 👁	Integral	[HP22]
	Permutation	7 / 12	2^{65}	Integral	[Tod15]
	Permutation	7 / 12	2^{60}	Integral	[RHSS21]
	Permutation	7 / 12	2^{34} 👁	Limited-Birthday	[GPT21]
	Permutation	5 / 12	2^{109}	Truncated Differential	[Tez16]
	Permutation	5 / 12	2^{80}	Rectangle	[GPT21]
	Permutation	5 / 12	–	Zero-Correlation	[DEMS21a]
	Permutation	5 / 12	–	Impossible Differential	[DEMS21a]
	Permutation	4 / 12	2^{107}	Differential	[DEMS21a]
	Permutation	4 / 12	2^{101}	Linear	[DEM15a]
	Permutation	3 / 12	–	Subspace Trails	[LTW18]

(👁 = non-black-box distinguisher)

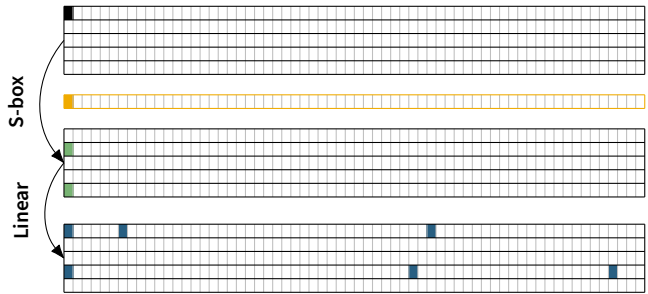
Analysis of Ascon in Misuse Settings

- Cryptanalysts increasingly consider misuse settings:
  Nonce misuse · Decryption misuse · Implementation attacks
- Generic nonce-misuse attacks on duplex designs include
  - Confidentiality break
    with $1 + 1$ misuse query per block of the challenge message.
  - State recovery
    with D misuse queries, $T \cdot D = 2^c$.
    Does not lead to trivial key recovery in Ascon

With more massive nonce misuse, some dedicated attacks are possible

Differential and Linear Characteristics of Ascon

- Goal: Prove lower bound on number of **active S-boxes** of characteristics
- **S-box** has max. differential probability 2^{-2}, max. squared correlation 2^{-2}
- **Weak alignment** $\rightarrow$ proving bounds is challenging, need bitwise model



Bounds and Best Known Characteristics

Gap of **provable bounds** vs. **best known characteristics** [DEMS15; DEM15b; GPT21]:

	R	min #S-boxes		max Probability		Methods
Differential	1	1	1	2^{-2}	2^{-2}	DDT
	2	4	4	2^{-8}	2^{-8}	DDT
	3	15	15	$\leq 2^{-30}$	2^{-40}	SMT, `nldtool`
	4	-	44	-	2^{-107}	`nldtool`, SAT
	5	-	78	-	2^{-190}	CP, SAT
	6	-	-	-	-	

- New lower bounds for **4** and **6** rounds [EME22; HMMD22]
- Slightly better characteristics [MR22]

Bounds and Best Known Characteristics

Gap of **provable bounds** vs. **best known characteristics** [DEMS15; DEM15b; GPT21]:

	R	min #S-boxes		max Probability		Methods
Differential	1	1	1	2^{-2}	2^{-2}	DDT
	2	4	4	2^{-8}	2^{-8}	DDT
	3	15	15	$\leq 2^{-30}$	2^{-40}	SMT, `nldtool`
	4	≥ 36	43	$\leq 2^{-86}$	2^{-107}	`nldtool`, [HMMD22]
	5	-	72	$\leq 2^{-100}$	2^{-190}	CP, [HMMD22]
	6	≥ 54	-	$\leq 2^{-129}$	-	

- New lower bounds for **4** and **6** rounds [EME22; HMMD22]
- Slightly better characteristics [MR22]

Bounds and Best Known Characteristics

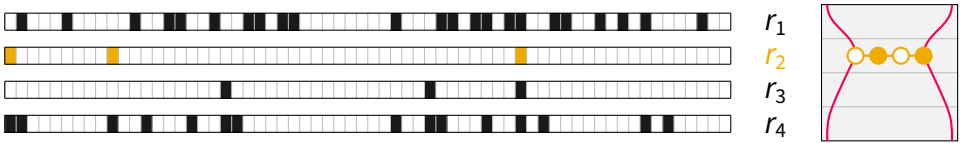
Gap of **provable bounds** vs. **best known characteristics** [DEMS15; DEM15b; GPT21]:

	R	min #S-boxes		max Square Corr.		Methods
Linear	1	1	1	2^{-2}	2^{-2}	LAT
	2	4	4	2^{-8}	2^{-8}	LAT
	3	13	13	2^{-28}	2^{-28}	SMT, `lineartrails`, [HMMD22]
	4	≥ 36	43	$\leq 2^{-88}$	2^{-98}	`lineartrails`, [HMMD22]
	5	-	67	$\leq 2^{-96}$	2^{-186}	`lineartrails`, [HMMD22]
	6	≥ 54	-	$\leq 2^{-132}$	-	[HMMD22]

- New lower bounds for **4** and **6** rounds [EME22; HMMD22]
- Slightly better characteristics [MR22]

Manual parallelization approach

- **Partition** the search space into **many independent problems**
- Categorize characteristics based on "**girdle patterns**"
  - S-box activity within the **round with fewest active S-boxes**



- **Reduce** the number of subproblems to be solved
- **Optimize** the individual SAT models

Shaping & Extending the Ascon Family

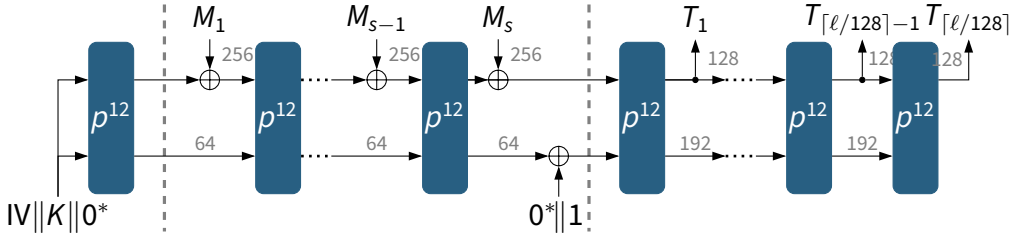
What's Next?

NIST will …

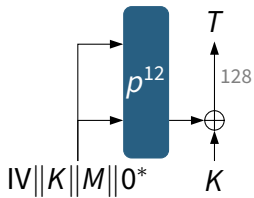
- publish a report (NIST IR 8454) with details on the competition process
- work with the Ascon team to draft the new standard for public comments
- host a workshop (June 21–22) to discuss various aspects of the process

Open discussion: Potential extensions based on requests from community (MAC/PRF, key/tag sizes, sessions, …)

Potential Extensions for MAC/PRF/KDF: Ascon-PRF [DEMS21b]



Ascon-PRFshort:



Conclusion

- NIST announced selection of Ascon as new lightweight cryptography standard
- Ascon has received a lot of attention by cryptanalysts (CAESAR, LWC)
- Many implementations for different platforms available

- Many decisions to be made for final standard (variants, extensions)
- Now is the perfect time for comments and suggestions

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