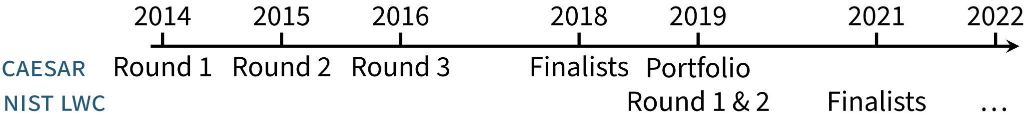
Update on the Security Analysis of Ascon

Christoph Dobraunig **Maria Eichlseder** Johannes Erlacher Florian Mendel Martin Schläffer

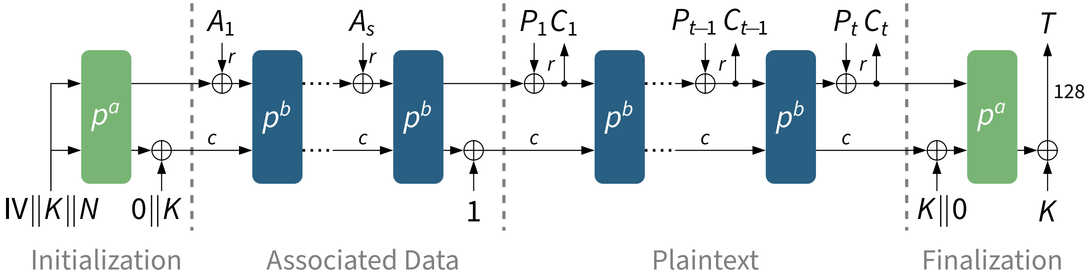
NIST LWC Workshop 2022 – 11 May 2022

The Ascon Family

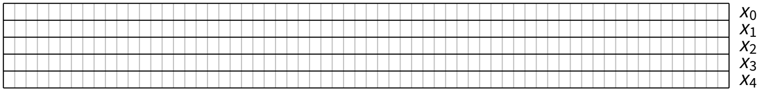
- Designed in 2014 [DEMS16]
- Selected in CAESAR portfolio as first choice for lightweight AEAD in 2019
- Published in Journal of Cryptology in 2021 [DEMS21c]
- Extensive published third-party cryptanalysis confirming its security margin
- **This talk**: Overview of recent third-party cryptanalysis results & our own work on new security bounds [EME22]



Ascon's Mode for Authenticated Encryption

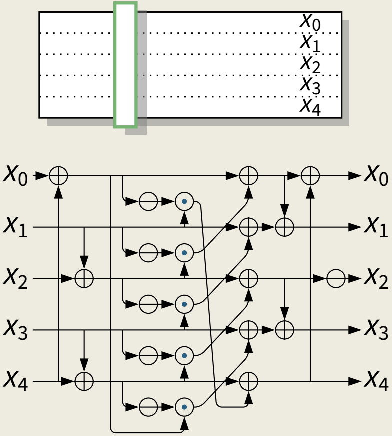


- **Doubly-keyed** initialization/finalization for higher robustness under misuse
- **Duplex sponge** mode using a $5 \times 64 = 320$-bit permutation

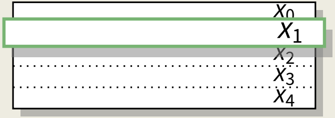


Ascon Permutation: $a = 12,\ b \in \{6, 8\}$ Rounds

S-box layer



Linear layer



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

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

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

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

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

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 Round-Reduced Ascon

Recent third-party analysis

Improvements to 7-Round Cube Attacks

Misuse-Free Key-Recovery and Distinguishing Attacks on 7-Round Ascon

Raghvendra Rohit[1], Kai Hu[2,5], Sumanta Sarkar[3] and Siwei Sun[4,6]

[1] Univ Rennes, Centre National de la Recherche Scientifique (CNRS), Institut de Recherche en

[RHSS21] slightly reduced the data complexity of 7-round attacks to stay **below the limit of 2^{64} blocks.**

Diving Deep into the Weak Keys of Round Reduced Ascon

Raghvendra Rohit[1] and Santanu Sarkar[2,3]

[1] Cryptography Research Centre, Technology Innovation Institute, Abu Dhabi, UAE

[RS21] investigated classes of "**weak keys**" which permit slightly better cube attacks for 7 rounds.

Refined Results for Differential Attacks

Exploring Differential-Based Distinguishers and Forgeries for ASCON

David Gerault[1,2], Thomas Peyrin[1] and Quan Quan Tan[1]

[1] Nanyang Technological University, Singapore, Singapore

[GPT21] investigate the applicability of **differential distinguishers for forgeries and collisions**.

[MR22] find characteristics with **fewer active S-boxes** for 4 rounds ($44 \rightarrow 43$) and 5 rounds ($78 \rightarrow 72$).

(Higher-Order) Differential-Linear Distinguishers

Differential-linear Attacks on Permutation Ciphers Revisited: Experiments on Ascon and DryGASCON

Aslı Başak Civek[a] and Cihangir Tezcan[b]
…tics Institute, Department of Cyber Security, CyDeS Laboratory, Middle East Technical University, Ankara

Revisiting Higher-Order Differential(-Linear) Attacks from an Algebraic Perspective

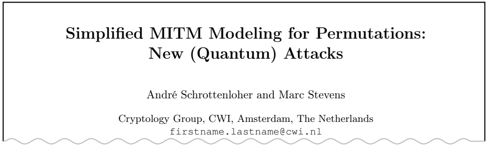
Applications to Ascon, Grain v1, Xoodoo, and ChaCha

Kai Hu and Thomas Peyrin

[CT22] provide experiments on **differential-linear cryptanalysis** to refine previous results on 7 rounds.

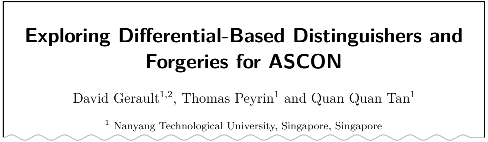
[HP22] investigate **higher-order DL distinguishers** and find 8-round permutation distinguishers in a dedicated setting and 6-round key-recovery attacks.

Other Distinguishers


Simplified MITM Modeling for Permutations: New (Quantum) Attacks

André Schrottenloher and Marc Stevens

Cryptology Group, CWI, Amsterdam, The Netherlands
firstname.lastname@cwi.nl


Exploring Differential-Based Distinguishers and Forgeries for ASCON

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[SS22a; SS22b] show that **structural MitM attacks** can find a fixpoint $x = P(x)$ for up to 2.5 rounds with complexity 2^{272}.

[GPT21] find **limited-birthday distinguishers** up to 7 rounds.

Misuse Analysis of Ascon

Recent third-party analysis

Analysis of Ascon in Misuse Settings

- Cryptanalysis in standard settings has only lead to small improvements in the last years
- Cryptanalysts increasingly consider misuse settings:
  - Nonce misuse
  - Decryption misuse
  - Implementation attacks

Analysis of Duplex Sponges in Misuse Settings

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:

Conditional Cube Attacks on Ascon in Misuse Settings

Practical cube-attack against nonce-misused Ascon†

Jules Baudrin, Anne Canteaut and Léo Perrin

Inria, France

[BCP22] find conditional cube attacks with nonce misuse for the full 6 encryption rounds of Ascon-128.

Ascon-80pq in a Nonce-misuse Setting

Donghoon Chang[1,2], Deukjo Hong[1,3], and Jinkeon Kang[1]

[CHK22] find similar results and KR attacks for Ascon-80pq ($> 2^{128}$).

A New Conditional Cube Attack on Reduced-Round Ascon-128a in a Nonce-misuse Setting

Donghoon Chang[1,2], Jinkeon Kang[1] and Meltem Sönmez Turan[1]

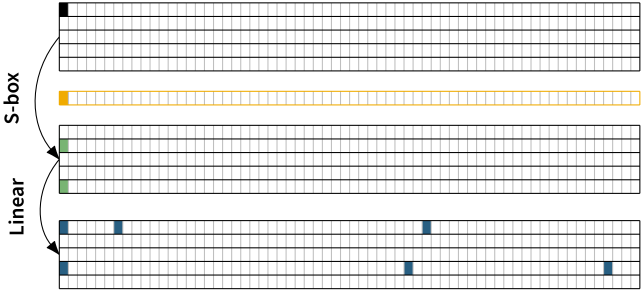
[CKT22] find conditional cube attacks with nonce misuse for 7 of 8 round in Ascon-128a and a key-recovery attack.

Differential & Linear Cryptanalysis: New Bounds

ToSC 2022/1

Differential and Linear Characteristics of Ascon

- **S-box** has max. differential probability 2^{-2}, max. squared correlation 2^{-2}
- Goal: Prove lower bound on number of **active S-boxes** of characteristics
- **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 (provable)	min #S-boxes (best known)	max Probability (provable)	max Probability (best known)	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`
	5	-	78	-	2^{-190}	CP
	6	-	-	-	-	

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	4	$\geq$ **36**	43	$\leq 2^{-\mathbf{72}}$	2^{-107}	`nldtool`, SAT
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	6	$\geq$ **54**	-	$\leq 2^{-\mathbf{108}}$	-	

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

Bounds and Best Known Characteristics

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

	R	min #S-boxes (provable)	min #S-boxes (best known)	max Square Corr. (provable)	max Square Corr. (best known)	Methods
Linear	1	1	1	2^{-2}	2^{-2}	LAT
	2	4	4	2^{-8}	2^{-8}	LAT
	3	13	13	$\leq 2^{-26}$	2^{-28}	SMT, `lineartrails`
	4	-	43	-	2^{-98}	`lineartrails`
	5	-	67	-	2^{-186}	`lineartrails`
	6	-	-	-	-	

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Approach for SAT Model to Prove Bounds

- **Optimized** SAT model
  - **SAT encoding** for **characteristics** by Sun et al. [SWW21; SWW18]
  - Different **counter encodings**

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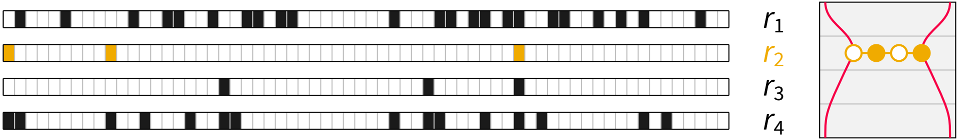
  - Different **counter encodings**
- **Parallelization**
  - Solver-based [HKWB11; HFB20; BSS15; SS21]
  - Manual partitioning

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**



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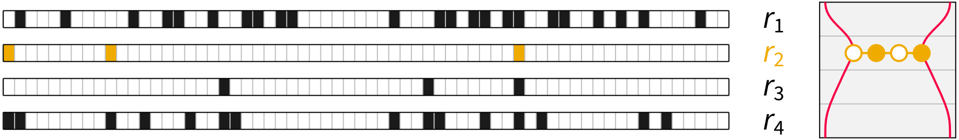
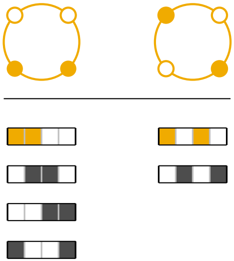


- **Reduce** the number of subproblems to be solved
- **Optimize** the individual SAT models

Manual parallelization approach

Consider **rotational symmetries**

- Use **necklace theory** to eliminate redundant checks [Mor72]



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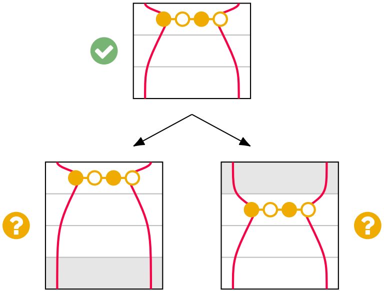
  - Reduces model complexity



Manual parallelization approach

- Consider **rotational symmetries**
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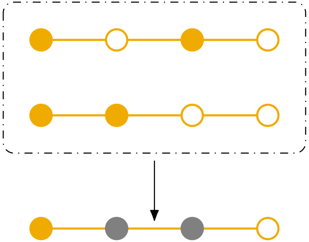
- **Prefilter** individual problems
  - Reduces model complexity
- **Pooling** individual problems
  - Reduces overhead



New Bounds

- Single characteristic for **4-round Ascon**
  - $\geq$ **36 active S-boxes**
  - Runtime $\approx$ 600 CPU days

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  - $\geq$ **54 active S-boxes**
  - Runtime $\approx$ 60 CPU days
  - Utilizing intermediate results from our 4 round bound

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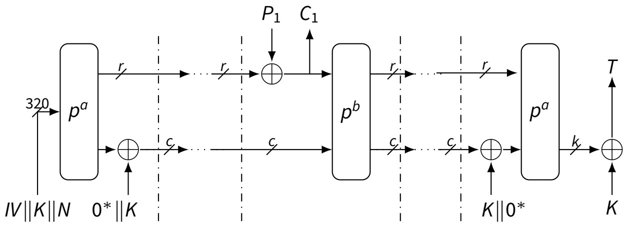
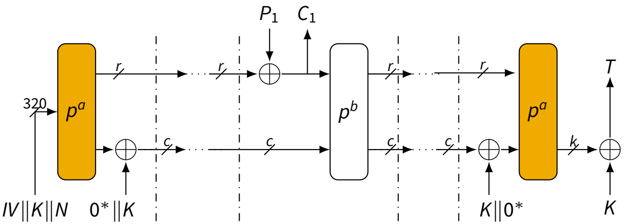
- Single characteristic for **6-round Ascon**
  - $\geq$ **54 active S-boxes**
  - Runtime $\approx$ 60 CPU days
  - Utilizing intermediate results from our 4 round bound
- Almost certainly not tight, but good enough to support trust in the permutation

Implications for Ascon



R	min #S	Probability
6	$\geq$ 54	$\leq 2^{-108}$
8	$\geq$ 72	$\leq 2^{-144}$
12	$\geq$ 108	$\leq 2^{-216}$

Implications for ASCON



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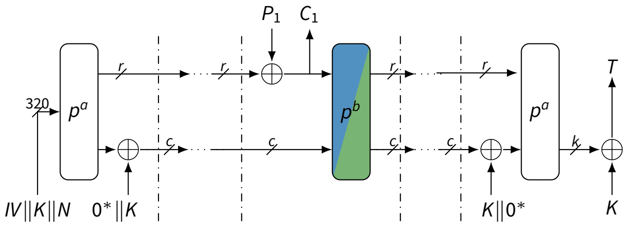
Authenticated Encryption: Initialization and Finalization

- 12 round configuration
- Ample security margin for **128-bit security**

Implications for Ascon



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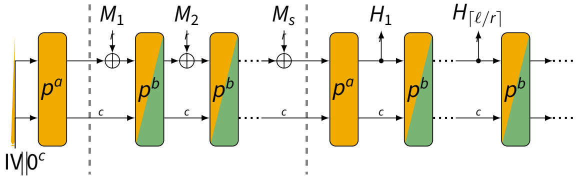
Authenticated Encryption: Data processing

- Ascon-128: **6 rounds**
- Ascon-128a: **8 rounds**
- Data limit of 2^{64} encrypted blocks
- Goal: Find better (tighter) 6-round bound

Implications for Ascon



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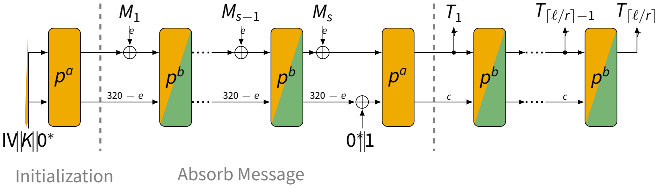
Ascon-Hash and Ascon-Xof

- Difficult to evaluate unkeyed modes based on probability
- Assumption: 2^{-128} (attempts) $\times$ 2^{-64} (degrees of freedom)

➔ 12 round bound $< 2^{-192}$

Implications for Ascon



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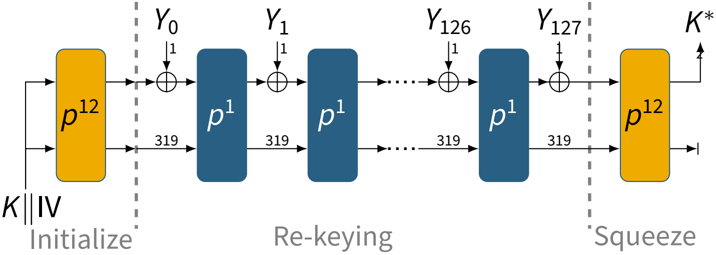
Ascon-Mac and Ascon-Prf [DEMS21b]

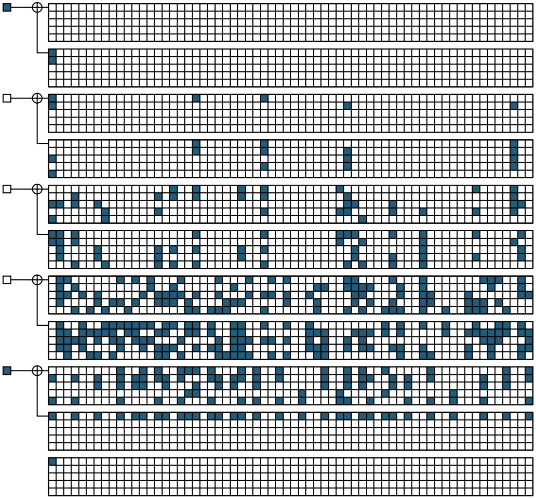
- Ascon-Mac, Ascon-Prf: **12 rounds**
- Ascon-MacA, Ascon-PrfA: **8 rounds**

Bounds for ISAP



- **Scenario**: Create collision based on 1-bit absorption
- For **1 to 4** rounds (consecutive bits), **no solution exists**
- For **5** rounds, collision-producing characteristic with **105** active S-boxes exists
- General bound: For **3+** final rounds in any collision-producing characteristic with 1-bit rate, there are at least **64** active S-boxes

Bounds for ISAP – 5-round characteristic



Conclusion

- Ascon has received a lot of attention by cryptanalysts
  - during CAESAR and during NIST LWC
- Main results: Optimizations of 7-round cube attack; Misuse attacks
- No cryptanalytic breakthroughs
- Improved bounds

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