Radboud University

Authenticated Encryption

Applied Cryptography – Spring 2024

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Last Lectures

Encryption

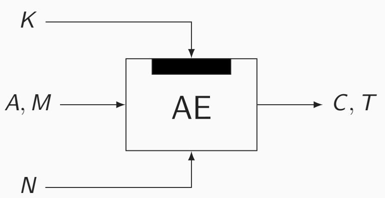
- Security goal: confidentiality
- Examples: ECB, counter mode

Authentication

- Security goal: data integrity
- Examples: CBC-MAC, Poly1305

Authenticated encryption combines both

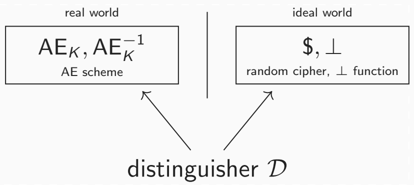
Authenticated Encryption



- Using key K:
  - Message M is encrypted in ciphertext C
  - Associated data A and message M are authenticated using T
- Nonce N randomizes the scheme

- Authenticated decryption discloses M if and only if T is correct

Authenticated Encryption Security



- Two oracles: $(\mathrm{AE}_K, \mathrm{AE}_K^{-1})$ (for secret key K) and $(\$, \perp)$ (secret)
- Distinguisher $\mathcal{D}$ has query access to one of these
  $\rightarrow$ unique nonce for each encryption query, and no trivial queries
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:

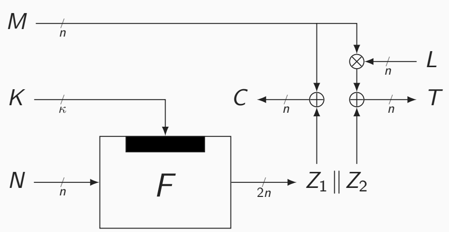
$$\mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathrm{AE}_K, \mathrm{AE}_K^{-1} \,;\, \$, \perp\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\mathrm{AE}_K, \mathrm{AE}_K^{-1}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\$,\perp} = 1\right)\right|$$

- $\mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}}(q_e, q_v)$: supremal advantage over any $\mathcal{D}$ with query complexity q_e, q_v

Outline

Authenticated Encryption Design

Simple Example



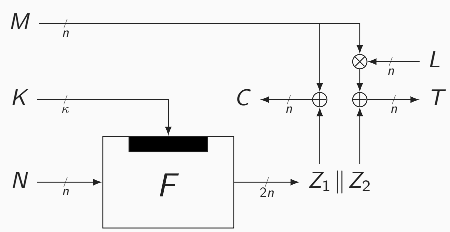
Encryption

- Input: (N, M)
- Compute keystream $Z_1 \parallel Z_2$
- Output:
  - $C = Z_1 \oplus M$
  - $T = Z_2 \oplus (M \otimes L)$

Decryption

- Input: (N, C, T)
- Compute keystream $Z_1 \parallel Z_2$
- Compute $M = Z_1 \oplus C$
- Compute $T^{\star} = Z_2 \oplus (M \otimes L)$
- Output: $\begin{cases} M \text{ if } T = T^{\star} \\ \perp \text{ otherwise} \end{cases}$

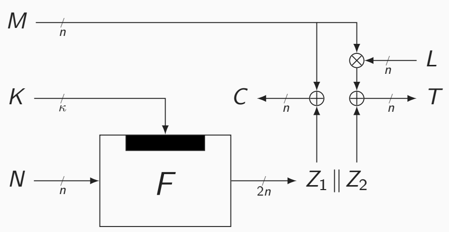
Simple Example: Confidentiality



Confidentiality

- Consider new query (N, M)
- N should be fresh
- Random $Z_1 \parallel Z_2$
  (if F is a good stream cipher)
- Random (C, T)

Simple Example: Authenticity

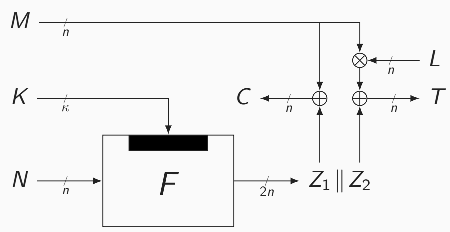


Authenticity

- Consider forgery attempt (N, C, T)
- N could be repeated nonce

- N fresh:
  - T^* is random, unpredictable
- N repeated:
  - Let (N, M', C', T') be old
  - $M = Z_1 \oplus C = M' \oplus C' \oplus C$
  - $T^* = Z_2 \oplus (M \otimes L)$
    $= T' \oplus ((M \oplus M') \otimes L)$
    $= T' \oplus ((C \oplus C') \otimes L)$
  - Forgery successful if
    $T \oplus T' = (C \oplus C') \otimes L$
  - Requires guessing L

Simple Example: How to Support Variable Length?



Suppose M is Variable-Length?

- Output F should be twice as large?
- $\otimes$ over arbitrary # of bits?
- $|M| + n$ bits turns out to suffice:
  - Use streaming mode for F
  - Replace $M \otimes L$ by $H_L(M)$

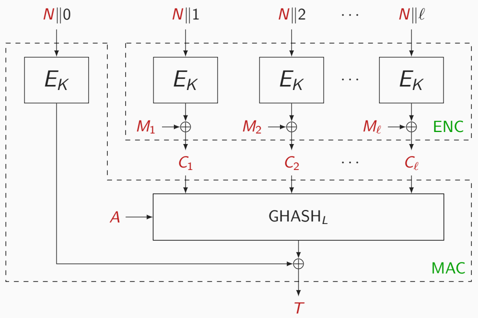
What about AD A?

- Can be processed by H_L as well:
  - $H_L(A, M)$

This is almost exactly GCM!

- Encrypt-*then*-MAC: $H_L(A, C)$
- Take CTR mode for F

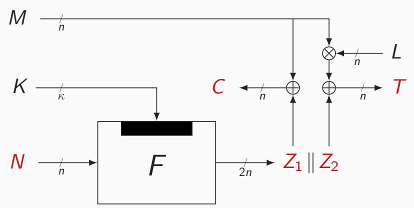
GCM for 96-bit Nonce N

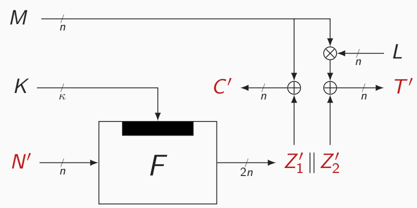


- McGrew and Viega (2004)
- EtM design
- Widely used (TLS!)
- Patent-free
- Parallelizable
- Evaluates E only (no E^{-1})
- Provably secure
  (if E is PRP)
- Very efficient in HW
- Reasonably efficient in SW
- Note: equally popular is
  ChaCha20-Poly1305!

What happens if nonce is re-used?

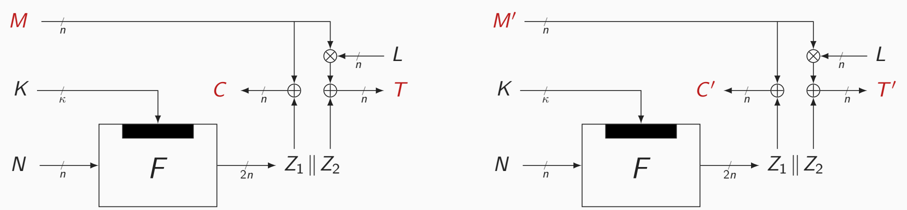
Nonce = "Number Used Once"





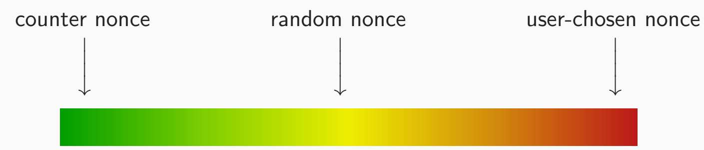
- Nonces N and N' should be distinct for two different evaluations
- What happens if a nonce would be repeated?

What if a Nonce is Repeated?



- Consider evaluations for identical nonce but distinct M, M'
- Key streams will be identical
- Ciphertexts satisfy $C \oplus C' = M \oplus M'$ $\longrightarrow$ attacker knew C' in advance
- Tags satisfy $T \oplus T' = M \otimes L \oplus M' \otimes L = (M \oplus M') \otimes L$ $\longrightarrow$ key recovery

Guaranteeing Uniqueness of Nonce



- Issues with nonce generation:
  - Counter needs storage
  - Need synchronization or transmission
  - Efficiency cost
  - Laziness or mistake of implementor
  - ...
- Sometimes, attacker can use same nonce multiple times

Nonce-Reuse in Practice

Nonce-Disrespecting Adversaries: Practical Forgery Attacks on GCM in TLS

Böck et al., USENIX WOOT 2016

- GCM is widely used authenticated encryption scheme
- Used in TLS ("https")

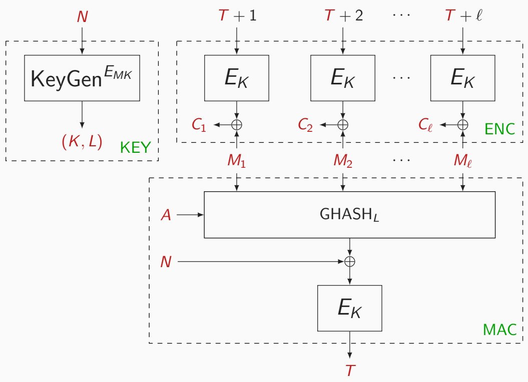
- Internet-wide scan for GCM implementations
- 184 devices with duplicated nonces
  - VISA, Polish bank, German stock exchange, ...
- $\approx$ 70.000 devices with random nonce

Resistance Against Nonce-Reuse

Intuition

- All input should be cryptographically transformed
- Any change in (N, A, M) $\longrightarrow$ unpredictable (C, T)
- Often comes at a price:
  - Efficiency
  - Security
  - Parallelizability
  - ...

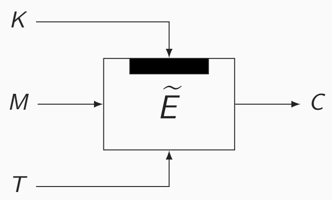
GCM-SIV



- Gueron and Lindell (2015)
- MtE design
- Ongoing standardization (IETF RFC)
- Patent-free
- Inherits GCM features
- Secure against nonce-reuse
- Proof: Iwata and Seurin (2017)

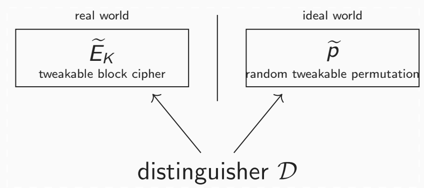
Tweakable Block Ciphers

Tweakable Block Ciphers



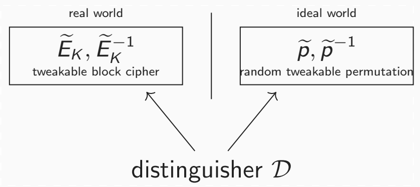
- Using key K, message M is bijectively transformed to ciphertext C
- Tweak T: flexibility to the cipher
- Each tweak gives different permutation
- A good tweakable block cipher should behave like a random tweakable permutation

Tweakable Block Cipher Security



- Two oracles: $\widetilde{E}_K$ (for secret key K) and $\widetilde{p}$ (secret)
- Distinguisher $\mathcal{D}$ has query access to one of these
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:
$$\mathbf{Adv}^{\mathrm{tprp}}_{\widetilde{E}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\widetilde{E}_K \,;\, \widetilde{p}\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\widetilde{E}_K} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\widetilde{p}} = 1\right)\right|$$
- $\mathbf{Adv}^{\mathrm{tprp}}_{\widetilde{E}}(q)$: supremal advantage over any $\mathcal{D}$ with query complexity q

Strong Tweakable Block Cipher Security

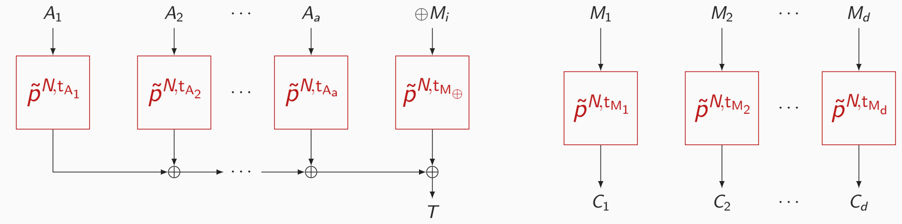


- Two oracles: $(\widetilde{E}_K, \widetilde{E}_K^{-1})$ (for secret key K) and $(\widetilde{p}, \widetilde{p}^{-1})$ (secret)
- Distinguisher $\mathcal{D}$ has query access to one of these
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:

$$\mathbf{Adv}^{\mathrm{stprp}}_{\widetilde{E}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\widetilde{E}_K, \widetilde{E}_K^{-1}\ ;\ \widetilde{p}, \widetilde{p}^{-1}\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\widetilde{E}_K, \widetilde{E}_K^{-1}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\widetilde{p}, \widetilde{p}^{-1}} = 1\right)\right|$$

- $\mathbf{Adv}^{\mathrm{stprp}}_{\widetilde{E}}(q)$: supremal advantage over any $\mathcal{D}$ with query complexity q

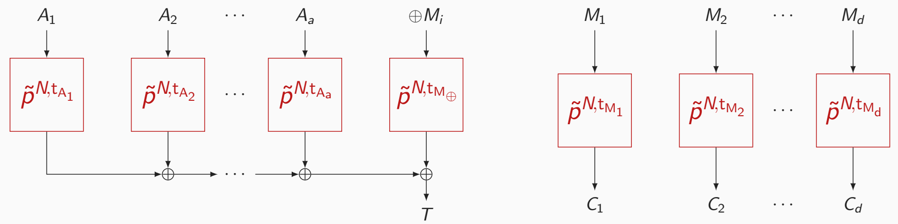
Example Use in ΘCB (1/2)



- Generalized OCB by Rogaway et al. [RBBK01,Rog04,KR11]
- Internally based on tweakable block cipher $\widetilde{E}$
  - Tweak (N, tweak) is unique for every evaluation
  - Different blocks always transformed under different tweak
- Triangle inequality:

$$\mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}[\widetilde{E}_k]}(q) \le \mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}[\widetilde{p}]}(q) + \mathbf{Adv}^{\mathrm{stprp}}_{\widetilde{E}}(q)$$

Example Use in ΘCB (2/2)



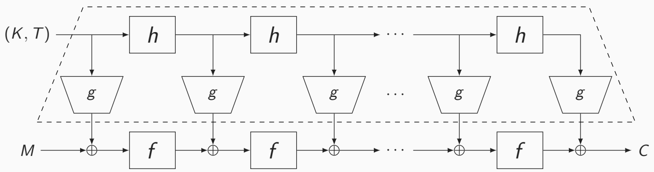
- Nonce uniqueness $\Rightarrow$ tweak uniqueness
- Encryption calls behave like random functions: $\mathrm{AE}[\widetilde{p}] = \$$
- Authentication almost behaves like random function (but nonces may repeat)
  - Tag forged with probability at most $1/(2^n - 1)$

$$\mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}[\widetilde{p}]}(q) \le 1/(2^n - 1)$$

Building Tweakable Block Ciphers

TWEAKEY Framework

- TWEAKEY by Jean et al. [JNP14]:

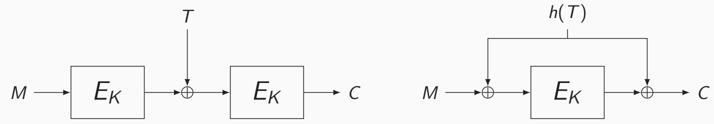


- f: round function
- g: subkey computation
- h: transformation of (K, T)

- Security measured through cryptanalysis
- Our focus: modular design

Original Constructions

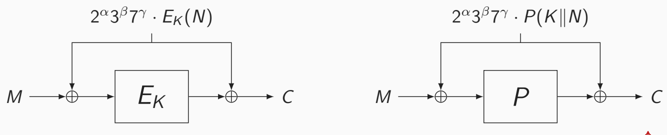
- LRW_1 and LRW_2 by Liskov et al. [LRW02]:



- h is XOR-universal hash
  - E.g., $h(T) = h \otimes T$ for n-bit "key" h

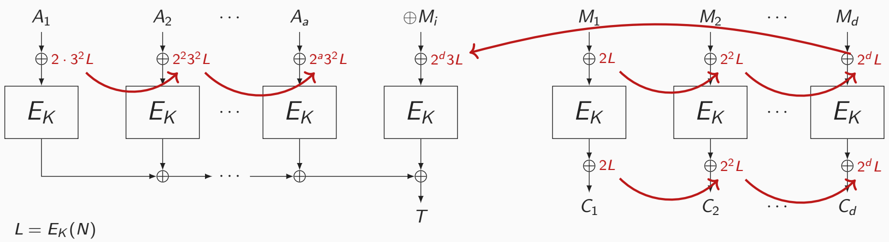
Powering-Up Masking (XEX)

- XEX by Rogaway [Rog04]:



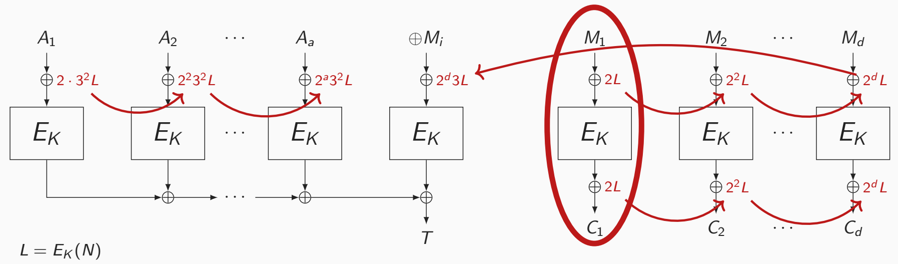
- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Used in OCB2 and ± 14 CAESAR candidates
- Permutation-based variants in Minalpher and Prøst (generalized by Cogliati et al. [CLS15])
- STPRP up to $2^{n/2}$ queries provided masks are all distinct

Powering-Up Masking in OCB2-Like Construction



- Update of mask:
  - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

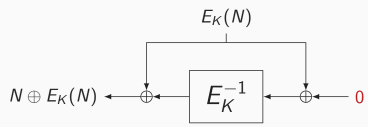
Intermezzo: Why Start at $2 \cdot E_K(N)$? (1/2)



- Update of mask:
  - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

Intermezzo: Why Start at $2 \cdot E_K(N)$? (2/2)

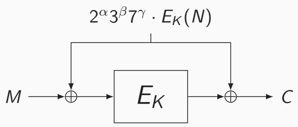
- Suppose we would mask with $E_K(N)$:



- Distinguisher can make inverse queries
- Putting $C = 0$ gives $M = N \oplus E_K(N)$
- Distinguisher knows N so learns "subkey" $E_K(N)$

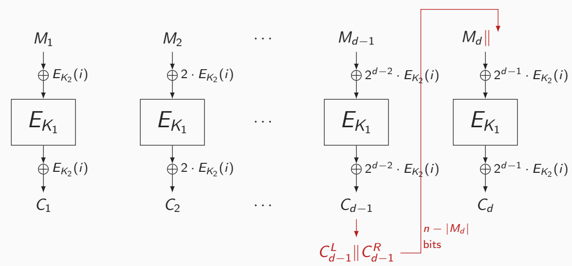
Powering-Up Masking (XEX): Setting Admissible Domain

- XEX by Rogaway [Rog04]:



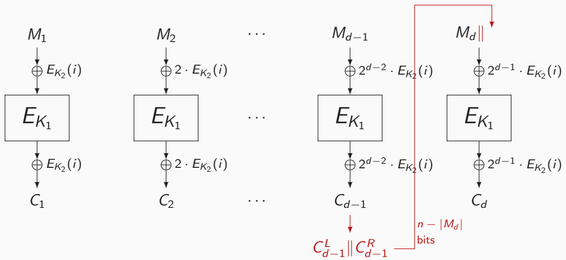
- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- (α, β, γ) must be from a certain admissible domain
- We need that $2^\alpha 3^\beta 7^\gamma \neq 2^{\alpha'} 3^{\beta'} 7^{\gamma'}$ for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
  - Otherwise, attacker can obviously break the scheme
- Typical: $\alpha \in \{1, \ldots, \text{large}\}$, and $\beta, \gamma \in \{0, 1, 2\}$

Intermezzo: XTS Disk Encryption Mode (1/2)



- XTS = XEX-based Tweaked-codebook mode with ciphertext Stealing
  - Electronic CodeBook (ECB) ...
  - ... with XEX as primitive (i is sector, j is block within sector) ...
  - ... and doing a fancy thing called "ciphertext stealing"
- One sector consists of 512 bytes, or 32 blocks

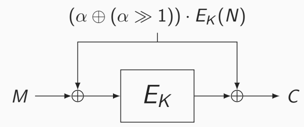
Intermezzo: XTS Disk Encryption Mode (2/2)



- Features:
  - Tweak unique for every block, changing tweak is efficient
  - Incrementality: change in one (or few) blocks
- XTS-AES is standardized as IEEE P1619
- Supported by myriad disk encryption tools: BestCrypt, dm-crypt, TrueCrypt, VeraCrypt, DiskCryptor, FileVault 2 (MacOS), BitLocker (Windows 10)

Gray Code Masking

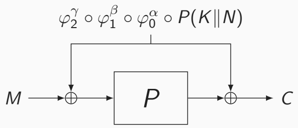
- OCB1 and OCB3 use Gray Codes:



- (α, N) is tweak
- Updating: $G(\alpha) = G(\alpha - 1) \oplus 2^{\mathrm{ntz}(\alpha)}$
  - Single XOR
  - Logarithmic amount of field doublings (precomputed)
- More efficient than powering-up [KR11]

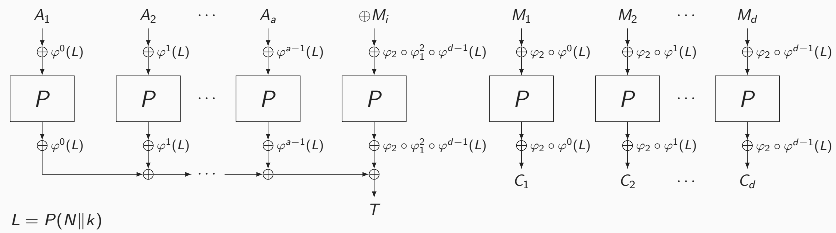
Masked Even-Mansour (MEM)

- MEM by Granger et al. [GJMN16]:



- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Combines advantages of:
  - Powering-up masking
  - Word-based LFSRs
- Simpler, constant-time (by default), more efficient

Application to AE: OPP



$L = P(N \| k)$

$\varphi_1 = \varphi \oplus id$, $\varphi_2 = \varphi^2 \oplus \varphi \oplus id$

- Offset Public Permutation (OPP)
- Generalization of OCB3:
  - Permutation-based
  - More efficient MEM masking
- Security against nonce-respecting adversaries

NIST Competition

- US NIST recently currently ran competition for lightweight cryptography
- Round 1: 56 submissions in February 2019
- Round 2: 32 submissions in August 2019
- Final round: 10 submissions in March 2021
- Winner Ascon announced February 2023

- Some submissions were sponge-based (like Ascon)
- Some submissions used techniques from this lecture