Squeezing the Most out of the Sponge

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Radboud University

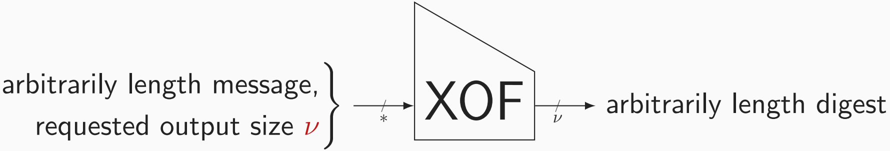
Nancy Seminar 2025

October 14, 2025

Overview i

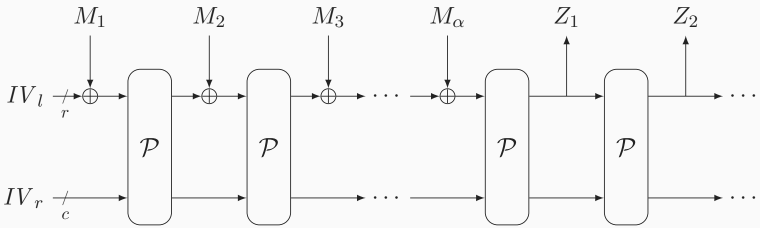
The Sponge Construction

Modern Definition of Hashing



- Function XOF from $\{0,1\}^*$ to $\{0,1\}^\infty$
  - Variable-length input
  - Variable-length output
  - User specifies output length ν when calling the function

The Sponge Construction [BDPV07]



- State of size $b = r + c$ bits:
  - rate r (efficiency parameter)
  - capacity c (security parameter)
- $M_1 \| \cdots \| M_\alpha$ is the message padded into r-bit blocks (e.g., 10^* padding)
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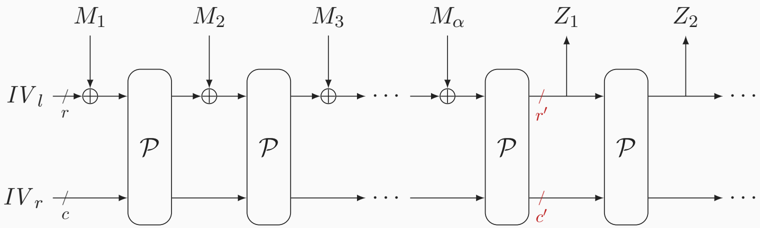

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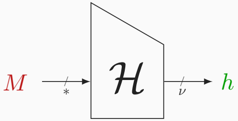
- Can squeeze at a larger rate [GPP11]

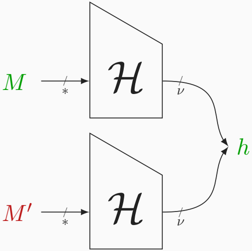
Classical security requirements

Preimage



Given h, find M

Second Preimage



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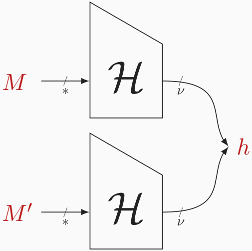
Collision



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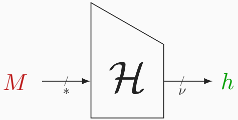

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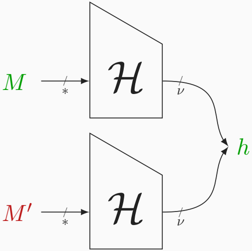

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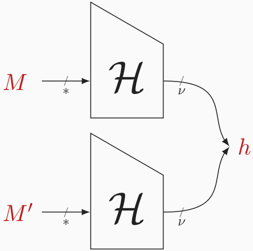

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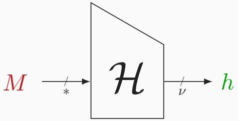

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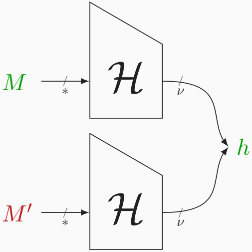

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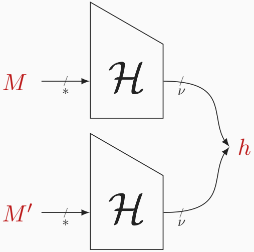

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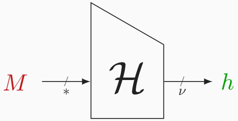

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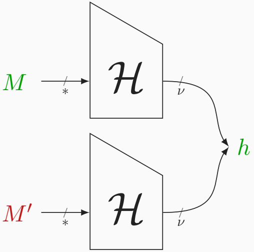

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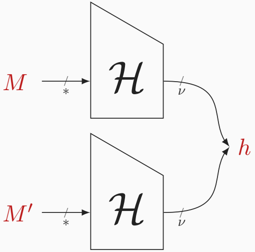

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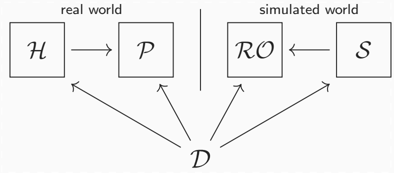
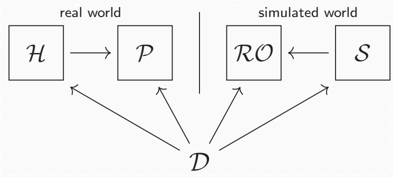
- Not always sufficient, e.g., $\mathrm{MAC}(k, m) = \mathcal{H}(k \| m)$ with $\mathcal{H} =$ plain MD
- Hash function should behave like a random oracle

Indifferentiability [MRH04, CDMP05]



- $(\mathcal{H}^{\mathcal{P}}, \mathcal{P})$ for a random primitive $\mathcal{P}$ should behave like a random oracle $\mathcal{RO}$ paired with a simulator $\mathcal{S}$ that maintains construction-primitive consistency
- $\mathcal{H}$ is indifferentiable from $\mathcal{RO}$ for some simulator $\mathcal{S}$ whenever any $\mathcal{D}$ can distinguish the two worlds only with a negligible probability



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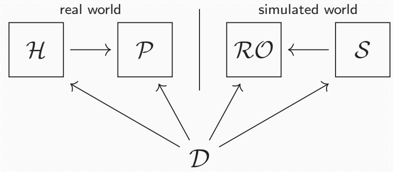

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$\Longrightarrow$ For $\mathsf{atk} \in \{\mathsf{col}, \mathsf{sec}, \mathsf{pre}\}$, we have [AMP10]

$$\mathbf{Adv}_{\mathcal{H}}^{\mathrm{atk}}(\mathcal{A}) \leq \mathbf{Adv}_{\mathcal{H}}^{\mathrm{iff}}(\mathcal{A}') + \mathbf{Adv}_{\mathcal{RO}}^{\mathrm{atk}}(\mathcal{A}'')$$

Indifferentiability of the Sponge Construction

- The sponge construction was proven indifferentiable with a tight bound [BDPV08]

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$$\mathbf{Adv}^{\mathrm{iff}}_{\mathrm{Sponge}}(\mathcal{N}) \leq \frac{\mathcal{N}(\mathcal{N}+1)}{2^c}$$

- The generalized sponge construction was proven indifferentiable with bound [NO14]

$$\tilde{\mathcal{O}}\left(\frac{\mathcal{N}}{2^{c'}} + \frac{\mathcal{N}(\mathcal{N}+1)}{2^c}\right)$$

$\implies$ c' may be set to $\approx c/2$ bits

Collision and (Second) Preimage Resistance of the Sponge

- Security of sponge truncated to ν bits against classical attacks [AMP10] (assuming $c' \geq c/2$):

Collision resistance:	$\mathcal{N}^2/2^c + \mathcal{N}^2/2^{\nu+1}$
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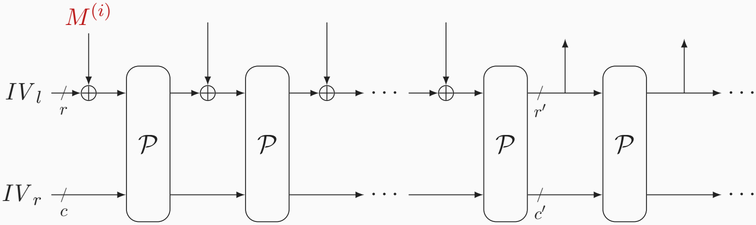
- In [LM22], this gap was closed

Collision Attack on the Sponge [BDPV11a]



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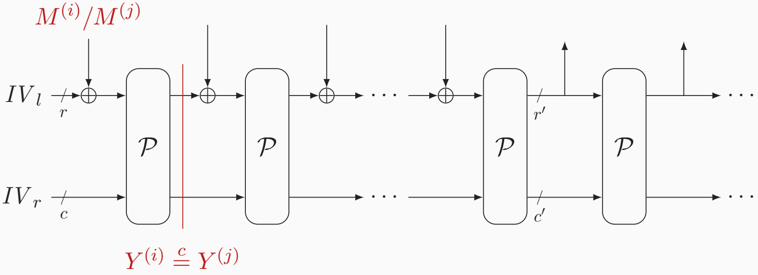

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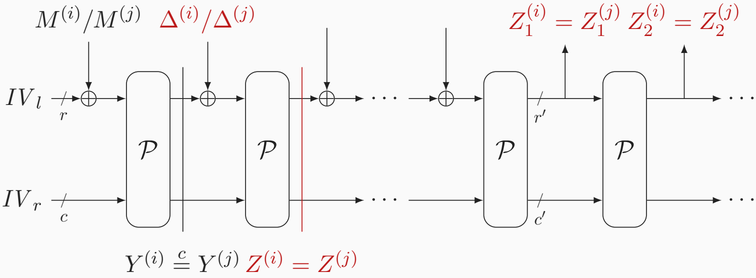

- Absorb $2^{c/2}$ different messages
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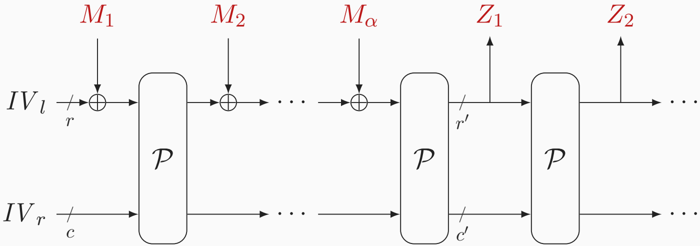
- Compensate the difference in next absorb call
- Triggers a full state collision $\implies$ collision in digests

Second Preimage Attack on the Sponge [BDPV11a]



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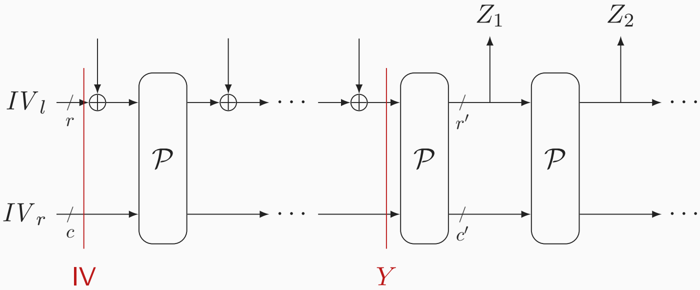

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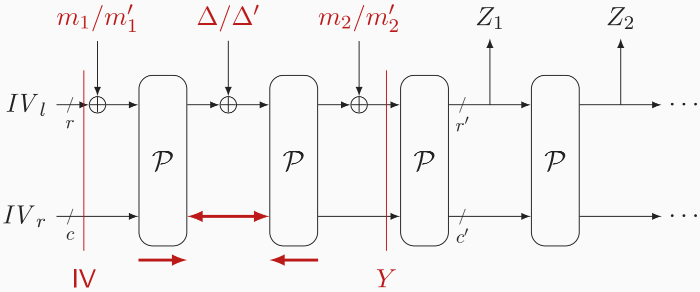

- Let $M_1 \| M_2 \| \cdots \| M_\alpha$ be the first preimage blocks
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- Connect the Y and IV with an inner collision
- Cost: $\approx 2^{c/2}$

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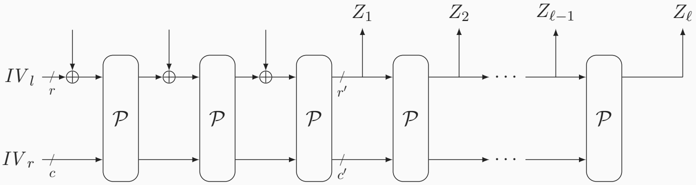

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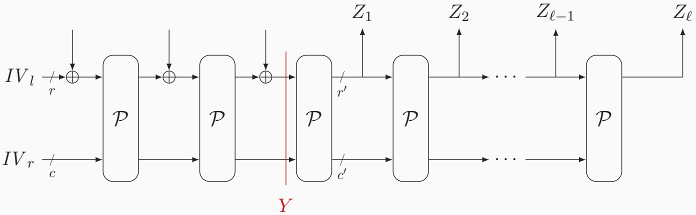

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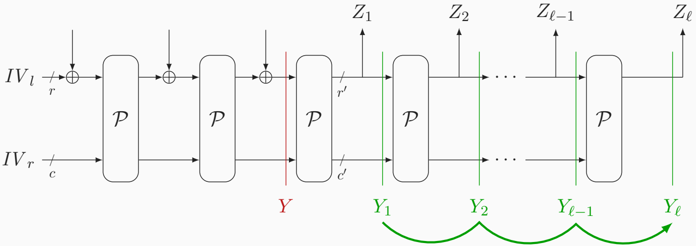

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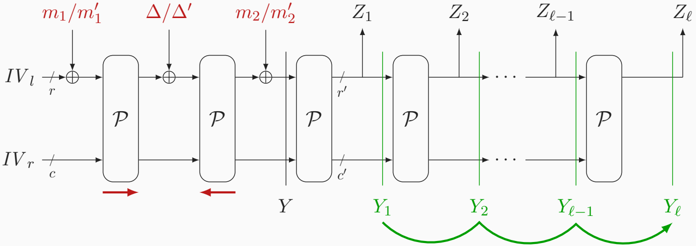

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- Total attack costs $\approx 2^{\nu - r'} + 2^{c/2}$ queries

Improved First Preimage Resistance

- Best known attack has cost $\approx \min\left\{2^{\nu}, 2^{\nu-r'} + 2^{c/2}\right\}$
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- [LM22]: preimage resistance proven with bound

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- The proof relies on decomposing the bad events triggered by adversary by following the aforementioned attack

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- Ascon-Hash parameters:
  - $(b, c, r, \nu) = (320, 256, 64, 256)$
  - Generic preimage resistance improved from 128 to 192 bits of security
- Other lightweight sponges may also benefit (e.g., NIST LWC finalists, Spongent, Photon)

Permutation-Based Hashing with Stronger (Second) Preimage Resistance

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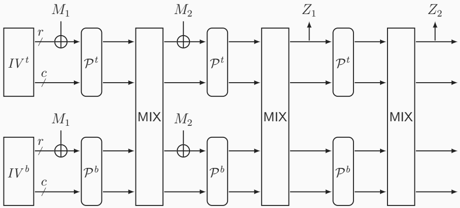
Stronger (Second) Preimage Resistance

- Some applications require strong security guarantees, such as hash-based post-quantum signature schemes
- Example: the National Institute of Commercial Cryptography Standards (NICCS) of China calls for hash functions with 1024-bit preimage and second-preimage resistance
  - To achieve this with a sponge, the capacity must be at least 2048 bits
  - As a result, Keccak-p[1600,24] is not suitable for this scenario

Double Sponge

- One possibility: use the double sponge construction [LM24]



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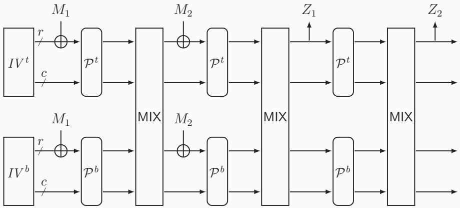

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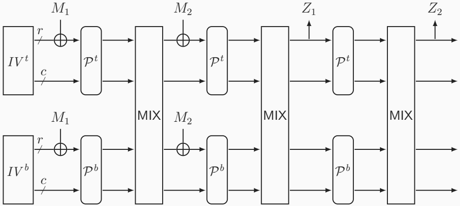

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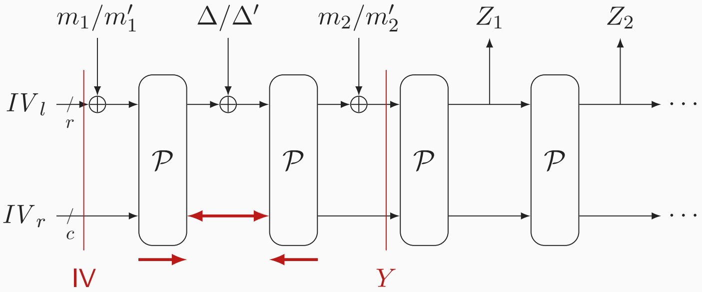
- Not the most efficient approach
- Instead, aim to achieve λ-bit security for both preimage and second preimage using a sponge with λ-bit capacity



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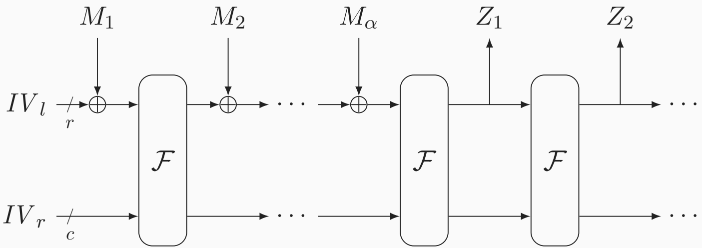

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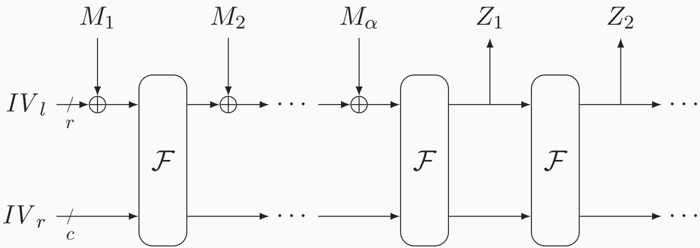
- Foekens [Foe23] proved that sponge with a random transformation has:
  - Preimage resistance up to $\approx 2^{\nu}$ queries
  - Second preimage resistance up to $\approx \min\{2^{\nu}, 2^{c}/\alpha\}$ queries (α: size of first preimage)

Sponge with a Random Transformation



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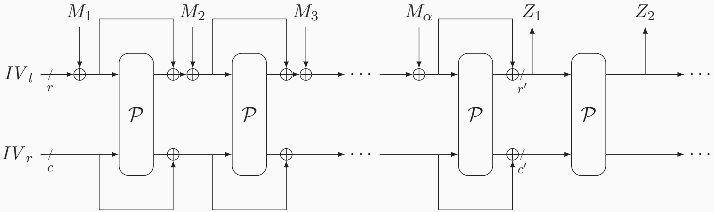
- But non-invertible functions more scarce than permutations

Sponge with a Feed-Forward: SPONGE-DM



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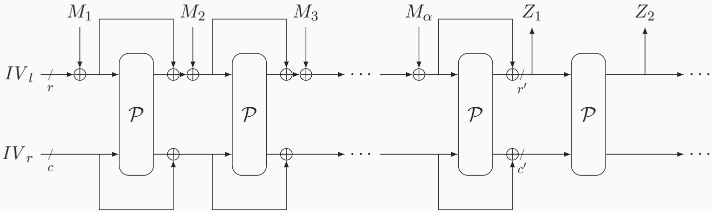

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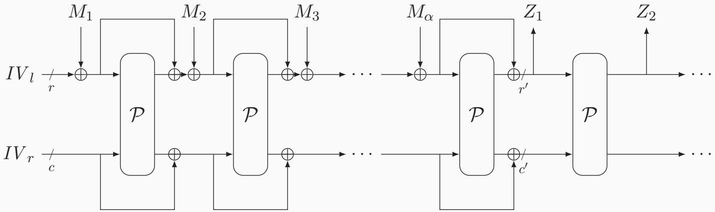
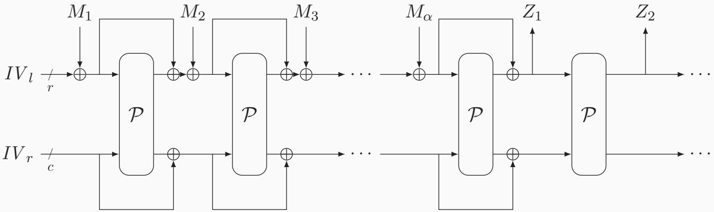
- This construction, named SPONGE-DM, achieves
  - Preimage resistance up to $\approx 2^\nu$ queries
  - Second preimage resistance up to $\min\{2^\nu, 2^c/\alpha\}$ queries
  - Indifferentiability up to sponge's bound

Sponge with a Feed-Forward: SPONGE-DM



- **Alternative**: add a feed-forward only during absorption (independent related work: [GHF+25])
- This construction, named SPONGE-DM, achieves
  - Preimage resistance up to $\approx 2^\nu$ queries
  - Second preimage resistance up to $\min\{2^\nu, 2^c/\alpha\}$ queries
  - Indifferentiability up to sponge's bound
- **Cost**: adds a extra b-bit state $\implies$ can we lower the size of the feed-forward?

Sponge with a Feed-Forward: Attempt to Reduce Size of Feed-Forward



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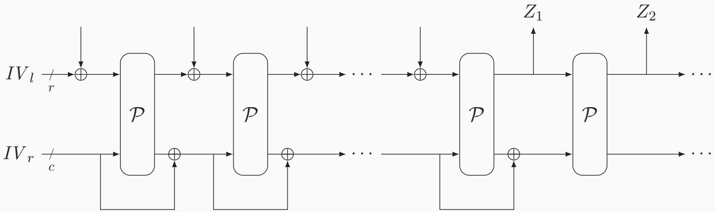

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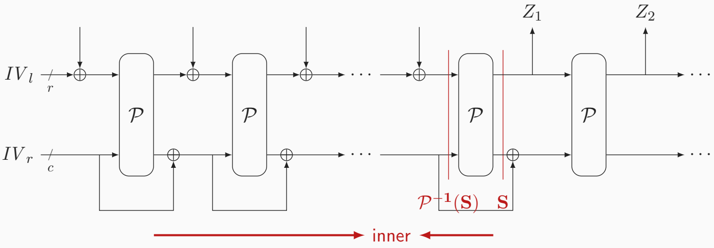
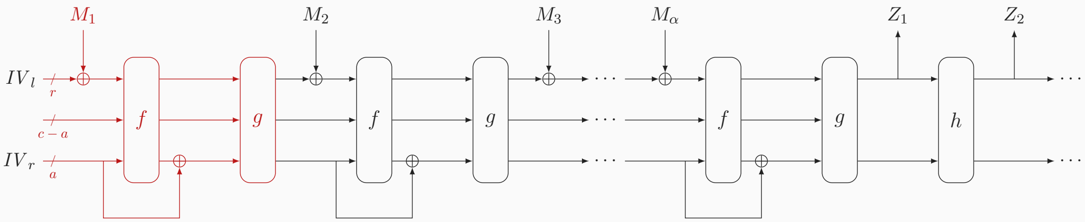


- Intuition: the adversary has control on the outer part of the state, so feeding it forward seems unnecessary
- This intuition is incorrect: can mount to attack in $\approx 2^{c/2}$ queries when $n \leq r$

SPONGE-EDM^a for $a = \{0, \ldots, b\}$



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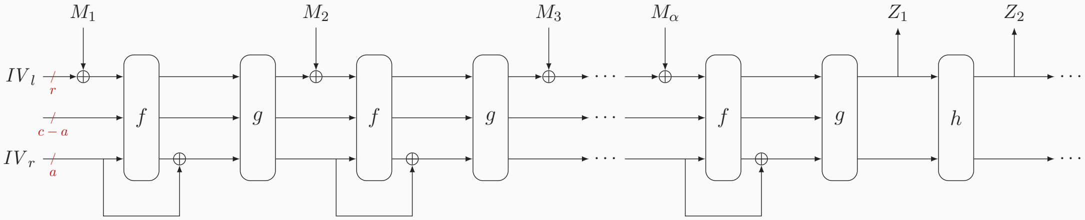
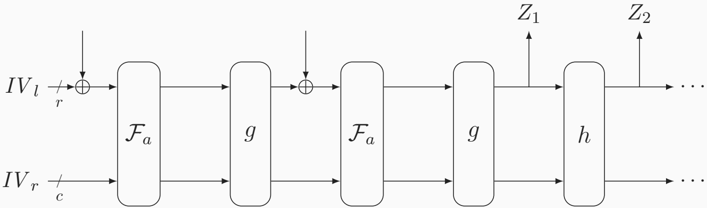


- Idea: augment absorbing phase by one extra permutation call (may have $a \geq c$)
- May use round-reduced permutations
- We proved:
  - $\approx \min\{\nu, \max\{\nu - r', a, \min\{\frac{a+c}{2}, \frac{b+c}{3}\}\}\}$ bits of preimage security
  - $\approx \min\{\nu, c - \log_2(\alpha), \max\{a, \min\{\frac{a+c}{2}, \frac{b+c}{3}\}\}\}$ bits of second preimage security

$\mathcal{F}_a(x) = f(x) \oplus 0^{b-a} \| \lfloor x \rfloor_a$

security: $\min\{\nu, \max\{\nu - r', a, \min\{\frac{a+c}{2}, \frac{b+c}{3}\}\}\}$



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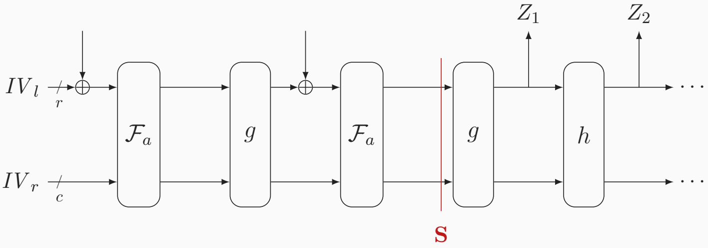

❶ Find a squeezing state $\mathbf{S}$ (cost: $2^{\nu - r'}$)

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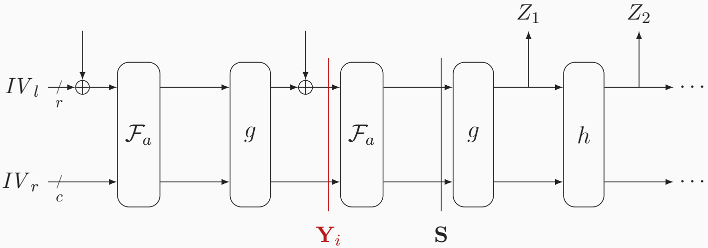

1. Find a squeezing state $\mathbf{S}$ (cost: $2^{\nu-r'}$)
2. Invert $\mathcal{F}_a$ several times (costs 2^a per inversion, do $2^{\min\{0,\frac{c-a}{2}\}}$ inversions)

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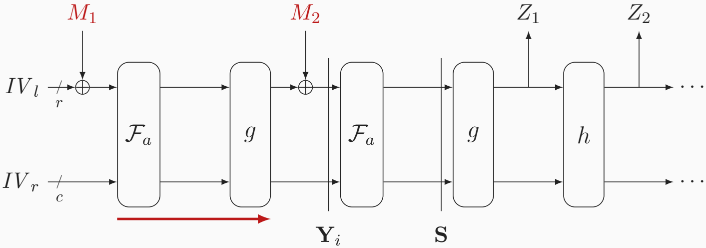

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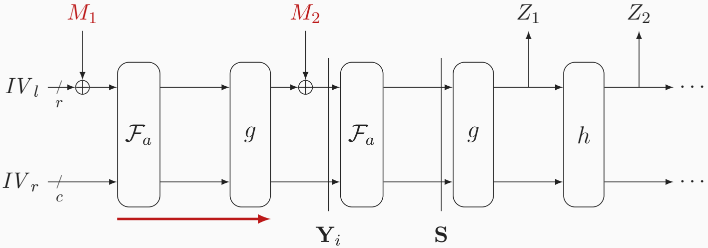

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4. Overall cost: $2^{\nu-r'} + \max\{2^a, 2^{\frac{a+c}{2}}\}$

Application

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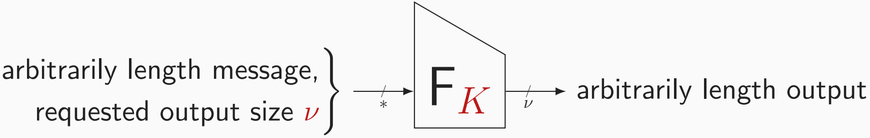
- Future work: what about the setting of a quantum adversary?

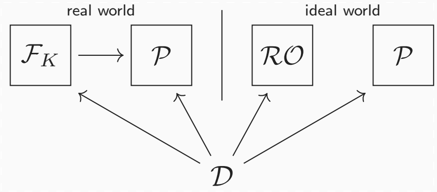
Sponge-Based PRFs

Pseudorandom Function (PRF)



- Keyed function F_K from $\{0,1\}^*$ to $\{0,1\}^\infty$
  - Variable-length input
  - Ideally: variable-length output, where user specifies output length ν when calling the function

Indistinguishability in the Ideal Model



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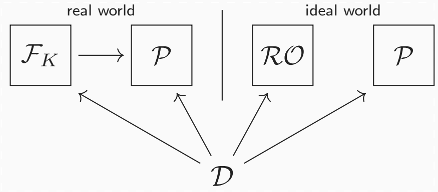
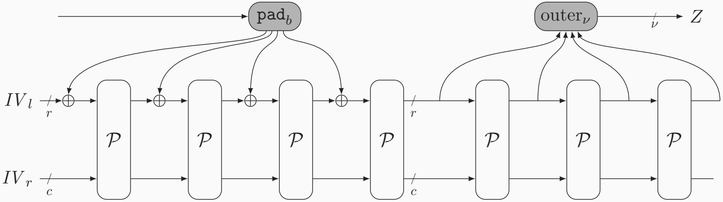


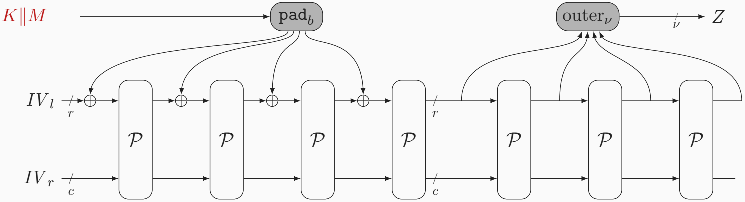
- $\mathcal{F}_K^{\mathcal{P}}$ for a random primitive $\mathcal{P}$ and key K should behave like a random oracle $\mathcal{RO}$
- In our case: $\mathcal{P}$ is a random permutation, and let:
  - $\mathcal{N}$ number of $\mathcal{P}$-queries,
  - $\mathcal{M}$ online complexity (number of blocks),
  - μ number of users

Turning a Sponge into a PRF



- Black-box approaches to keying a sponge:

Turning a Sponge into a PRF



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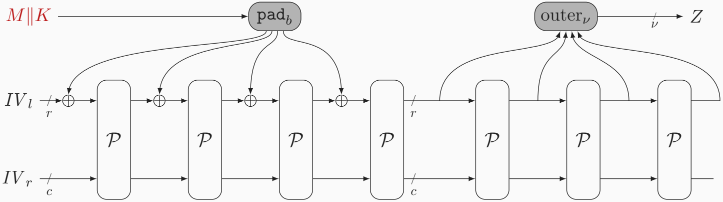

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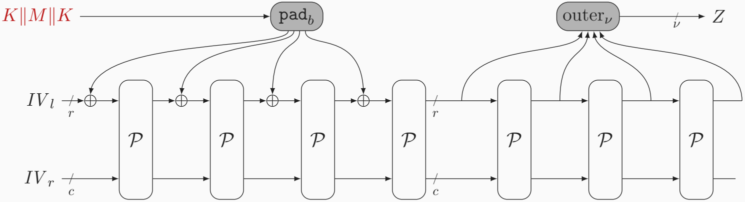

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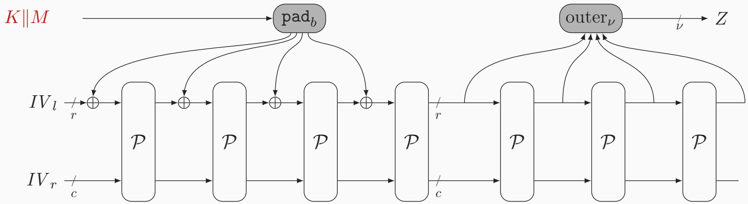

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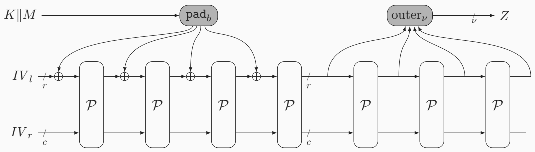
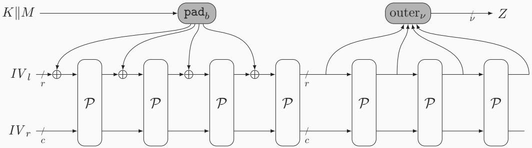
- These variants give different security guarantees; here we focus on OKS



- Indifferentiability is overkill, dedicated proofs give tighter security bounds: assuming that $\lceil k/r \rceil$ is a small constant, we have [GPT15, ADMV15, NY16, Men18]

$$\mathbf{Adv}_{\text{OKS}}^{\mu\text{-PRF}} = \tilde{\mathcal{O}}\left(\frac{\mu\mathcal{N}}{2^k} + \frac{\mathcal{M}\mathcal{N}}{2^c}\right)$$

OKS: Security



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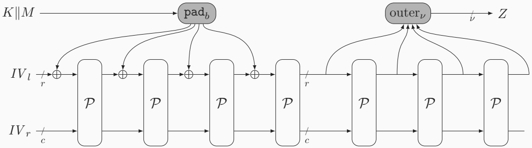

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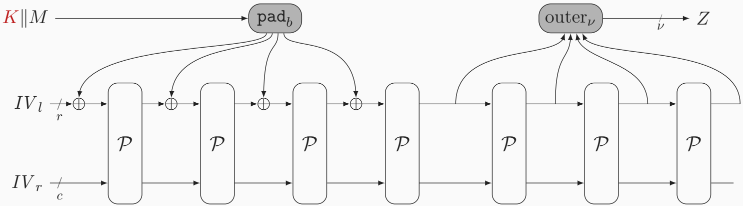
- The bound is tight
- **Concrete example:** with $b = 320$, $r = 128$, $c = 192$, $k = 128$, $\mu = 1$, and assuming $\mathcal{M} \ll 2^{64}$, this gives 128 bits of security

OKS: Improvements [BDPV11b, BDPV12, CDH+12, ADMV15]



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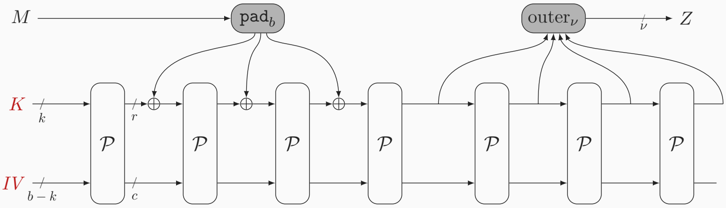
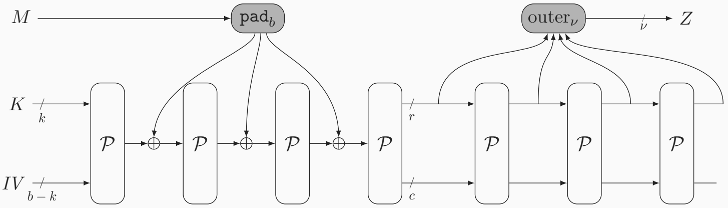


- V2: Key into the initial state $\implies$ more efficient, no security loss



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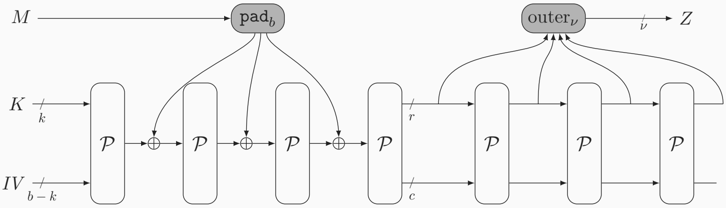
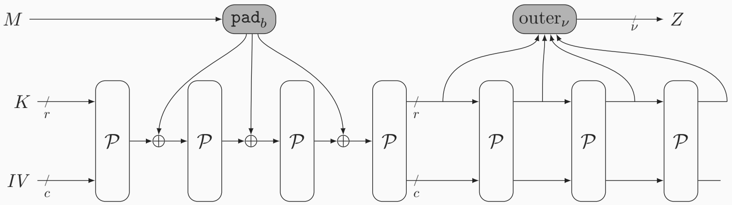
- V3: absorb over the entire state $\implies$ Full-State Keyed Sponge (FSKS) [MRV15]



- V2: Key into the initial state $\implies$ more efficient, no security loss
- V3: absorb over the entire state $\implies$ Full-State Keyed Sponge (FSKS) [MRV15]
- With some optimizations (e.g., unique IV per user, domain separation), security can be pushed as far as [DM24, DMV17, Men23]

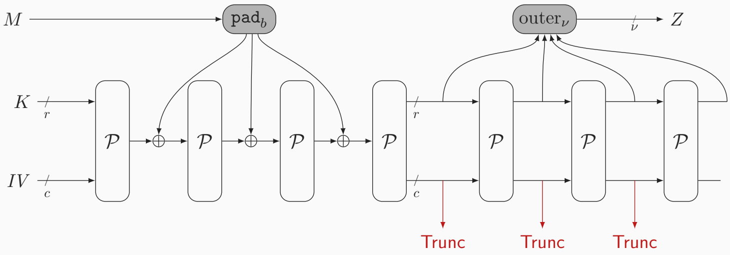
$$\mathbf{Adv}^{\mu\text{-PRF}}_{\mathsf{FSKS}^*} = \tilde{\mathcal{O}}\left(\frac{\mathcal{N}}{2^k} + \frac{\mathcal{M}\mathcal{N}}{2^b} + \frac{\mathcal{N}}{2^c}\right)$$

MacaKey



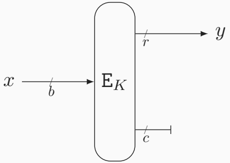
- We have: full-state absorption, multi-user security optimized, tight security bounds

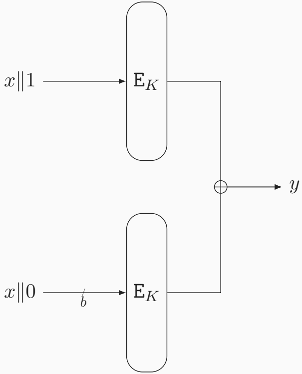
The Full-State Keyed Sponge



- We have: full-state absorption, multi-user security optimized, tight security bounds
- Can we get full-state squeezing? Those inner parts seem wasted..

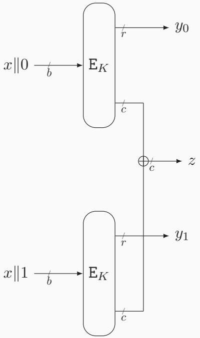
Truncation and Summation





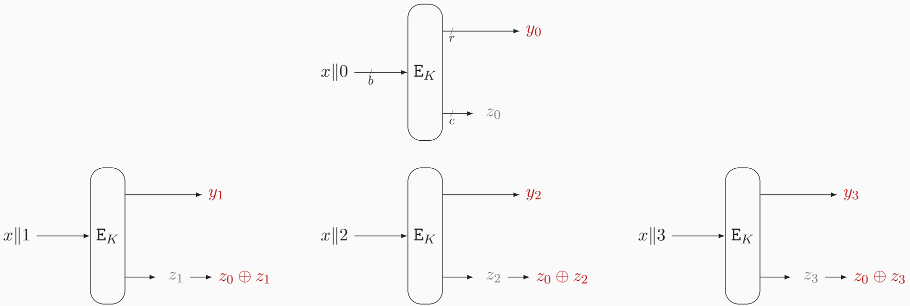
- Holds in the secret permutation setting (i.e., block cipher-based)
- Truncation and Summation: common PRP-to-PRF conversions

The Summation Truncation Hybrid (STH) [GM20] (1/2)



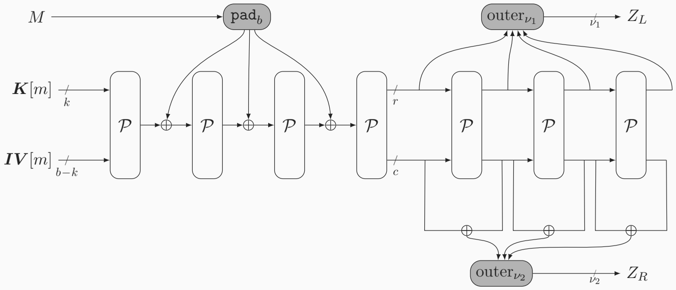
- With truncation, discarding truncated parts is wasteful
- Can group the evaluations two by two, sum them together $\implies$ get c bits for free, *without sacrificing security*

The Summation Truncation Hybrid (STH) [GM20] (2/12)



- Can be generalized to larger groups (in a CENC [Iwa06] fashion)
- Group of w evaluations: output of $r + b(w-1)$ bits $\implies$ approaches b bit per permutation call when w is large

Incorporating the STH into the FSKS: MacaKey



- V1: First call during squeezing phase: r bits of output

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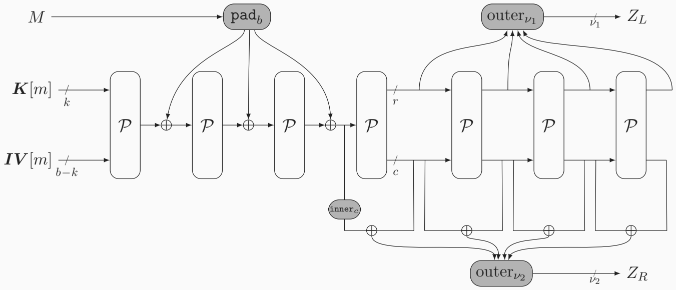

- V1: First call during squeezing phase: r bits of output

  After the first call: b bits of output per permutation call
- V2: b bits squeezed per permutation call

- We prove

$$\mathbf{Adv}^{\mathrm{PRF}}_{\mathsf{MacaKey}}(\mathcal{A}) = \tilde{\mathcal{O}}\left(\frac{\mathcal{N} \cdot u^{\boldsymbol{IV}}_{\max}}{2^k} + \frac{\mathcal{M}\mathcal{N}}{2^b} + \frac{\mathcal{M}^2}{2^c} + \frac{(\mathcal{L}+1)\mathcal{N}}{2^c}\right)$$

- $u^{\boldsymbol{IV}}_{\max}$ depends on the choice of the IVs $(1 \leq u^{\boldsymbol{IV}}_{\max} \leq \mu)$
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- $\mathcal{L}$ denotes the number of states where the adversary has control on the outer part
- **Concrete example:** with $b = 320,\ r = 128,\ c = 192,\ k = 128, \mu \ll 2^{20}$, one IV per user, $\mathcal{L} = 0$ and assuming $\mathcal{M} \ll 2^{64}\mu$, this gives 128 bits of security

Conclusions

- **Hashing improvements:** feed-forward mechanisms enhance (second) preimage security:
  - SPONGE-DM with ideal preimage resistance ($\approx 2^{\nu}$) and significantly improved second preimage bound,
  - SPONGE-EDM^{a} that gives a tunable trade-off
- **PRF improvements:** STH into FSKS allows full-state squeezing without sacrificing generic security
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Thank you for your attention!

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