Overview of the Sponge, Duplex and Farfalle constructions

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Based on joint work with Elena Andreeva, Guido Bertoni, Joan Daemen, Seth Hoffert, Bart Mennink, Michaël Peeters, Ronny Van Keer

Outline

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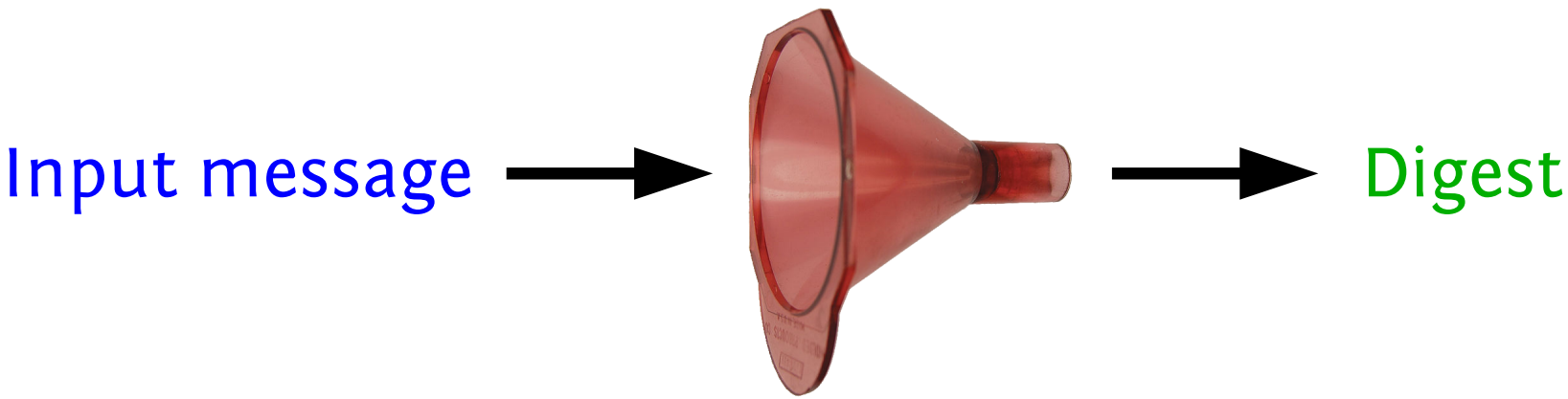
Cryptographic hash functions

$$h : \{0,1\}^* \to \{0,1\}^n$$



- Applications
  - *Signatures*: $\text{sign}_{\text{RSA}}(h(M))$ instead of $\text{sign}_{\text{RSA}}(M)$
  - *Key derivation*: master key K to derived keys ($K_i = h(K\|i)$)
  - *Bit commitment, predictions*: h(what I know)
  - *Message authentication*: $h(K\|M)$
  - ...

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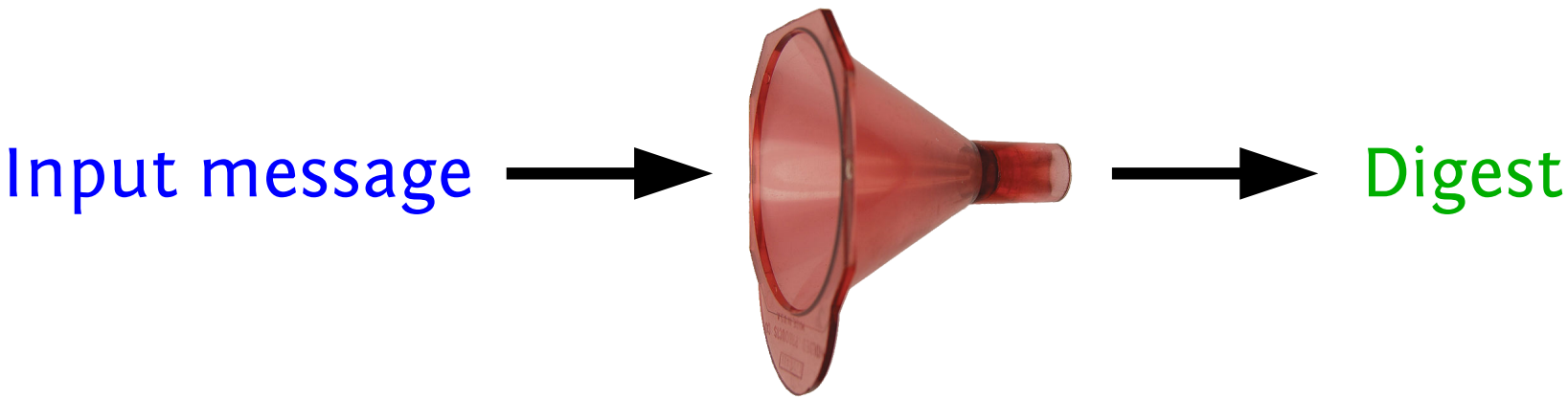

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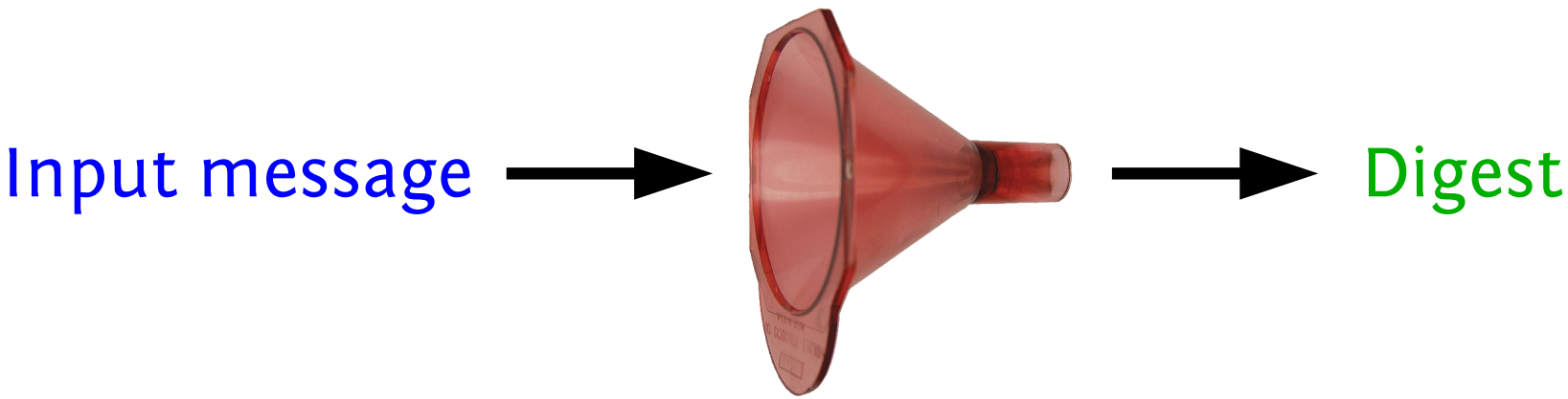

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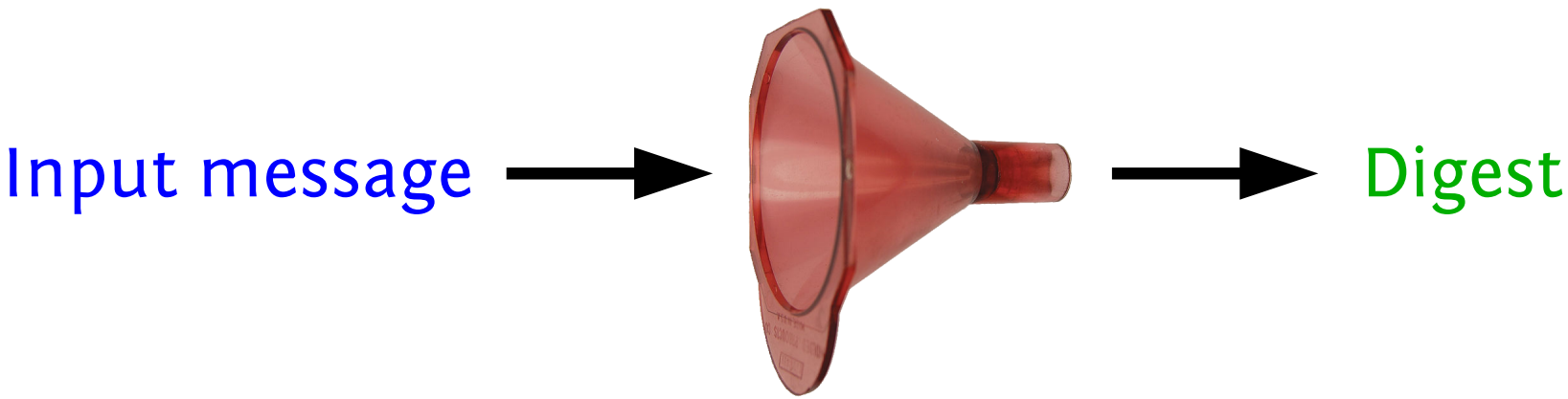

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Generalized: extendable output function (XOF)

$$h : \{0,1\}^* \to \{0,1\}^*$$

"XOF: a function in which the output can be extended to any length."

[Ray Perlner, SHA-3 workshop 2014]

- Applications
  - *Signatures*: full-domain hashing, mask generating function
  - *Key derivation*: as many/long derived keys as needed
  - *Stream cipher*: $C = P \oplus h(K \| \text{nonce})$

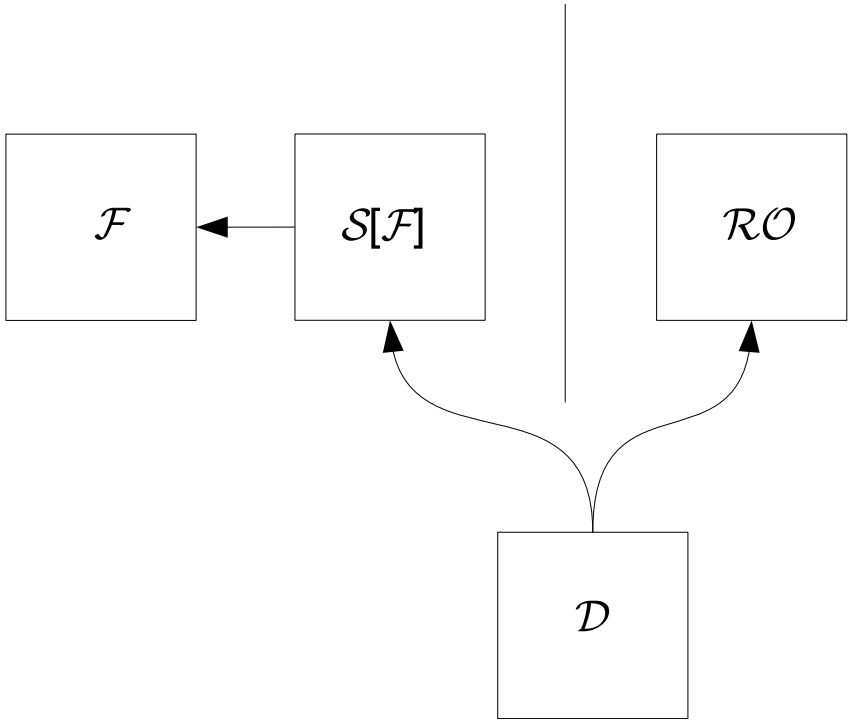
Modern security requirements

- Hash or XOF h with n-bit output
- Modern security requirements
  - h behaves like a random mapping
  - ... up to security strength s
- Classical security requirements, derived from it

Preimage resistance	$2^{\min(n,s)}$
Second-preimage resistance	$2^{\min(n,s)}$
Collision resistance	$2^{\min(n/2,s)}$

Outline

Generic security: indistinguishability



- Adversary $\mathcal{D}$ must tell apart
  - the ideal function: a monolithic random oracle $\mathcal{RO}$
  - construction $\mathcal{S}[\mathcal{F}]$ calling an ideal primitive $\mathcal{F}$
- Express $\Pr(\text{success}|\mathcal{D})$ as a function of total cost of queries N
- Problem: in real world, $\mathcal{F}$ is available to adversary

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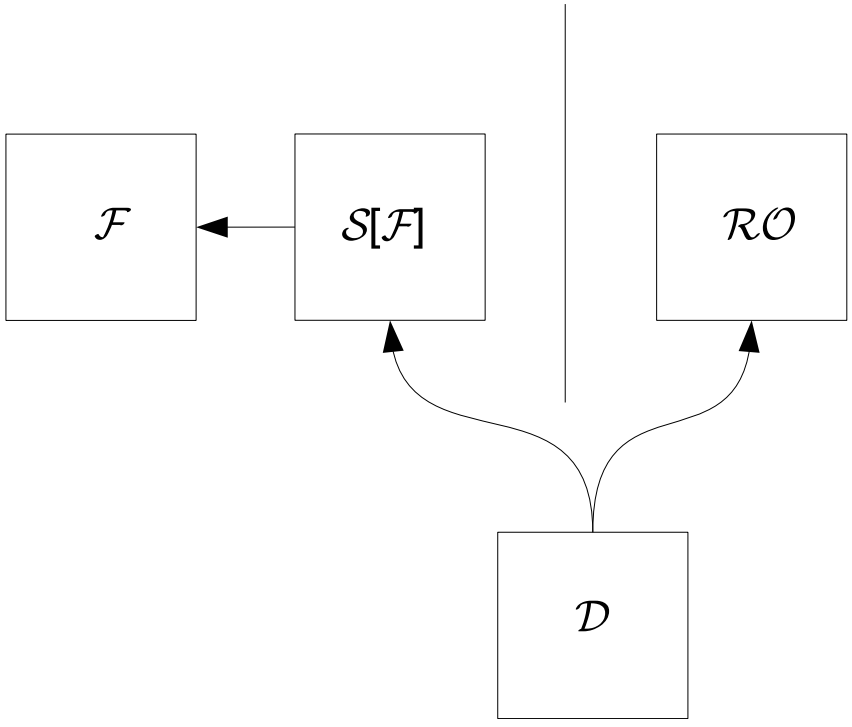

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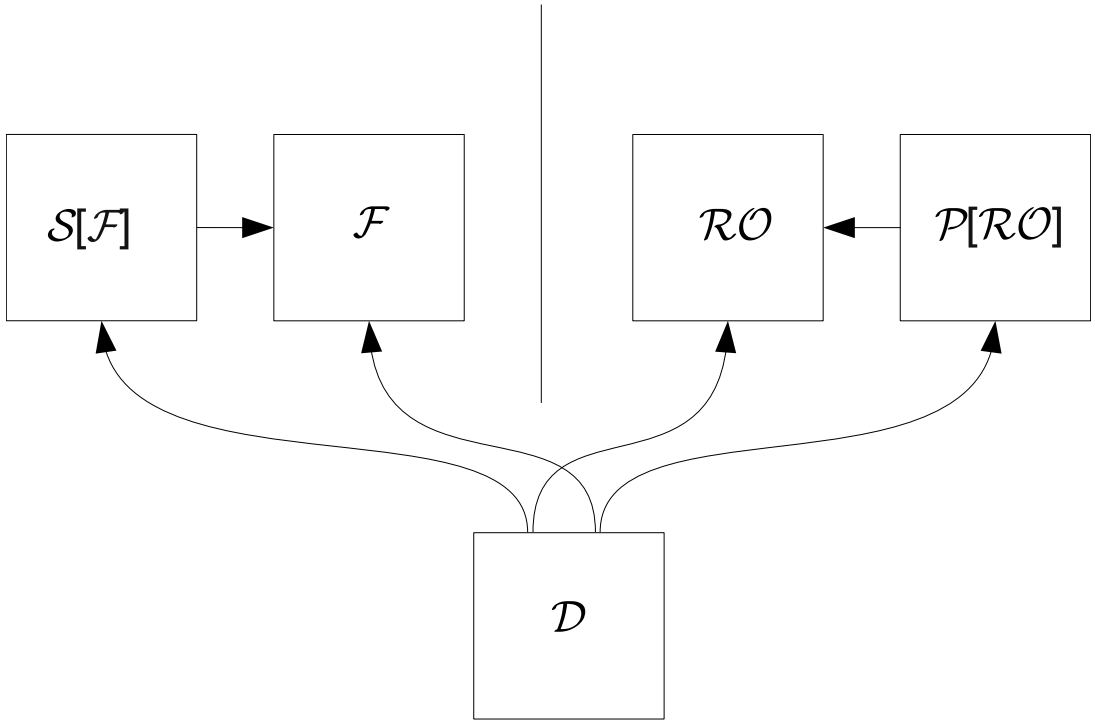
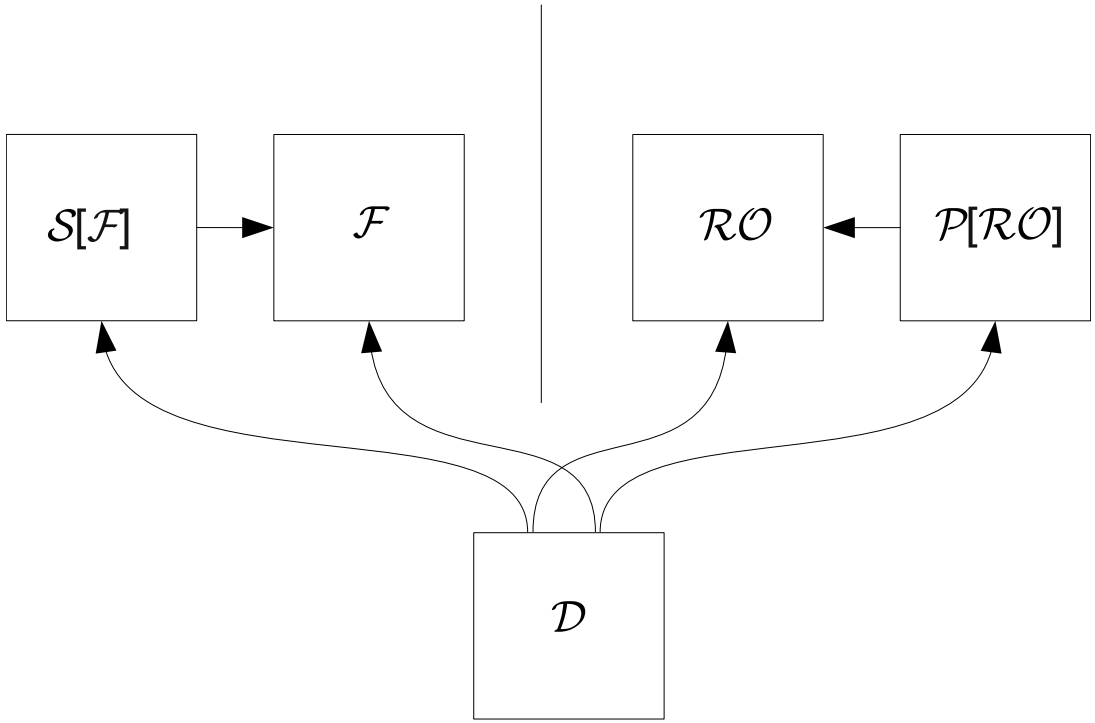
Generic security: indifferentiability [Maurer et al. (2004)]



Applied to hash functions in [Coron et al. (2005)]

- distinguishing mode-of-use from ideal function ($\mathcal{RO}$)
- covers adversary with access to primitive $\mathcal{F}$ at left
- additional interface, covered by a *simulator* at right

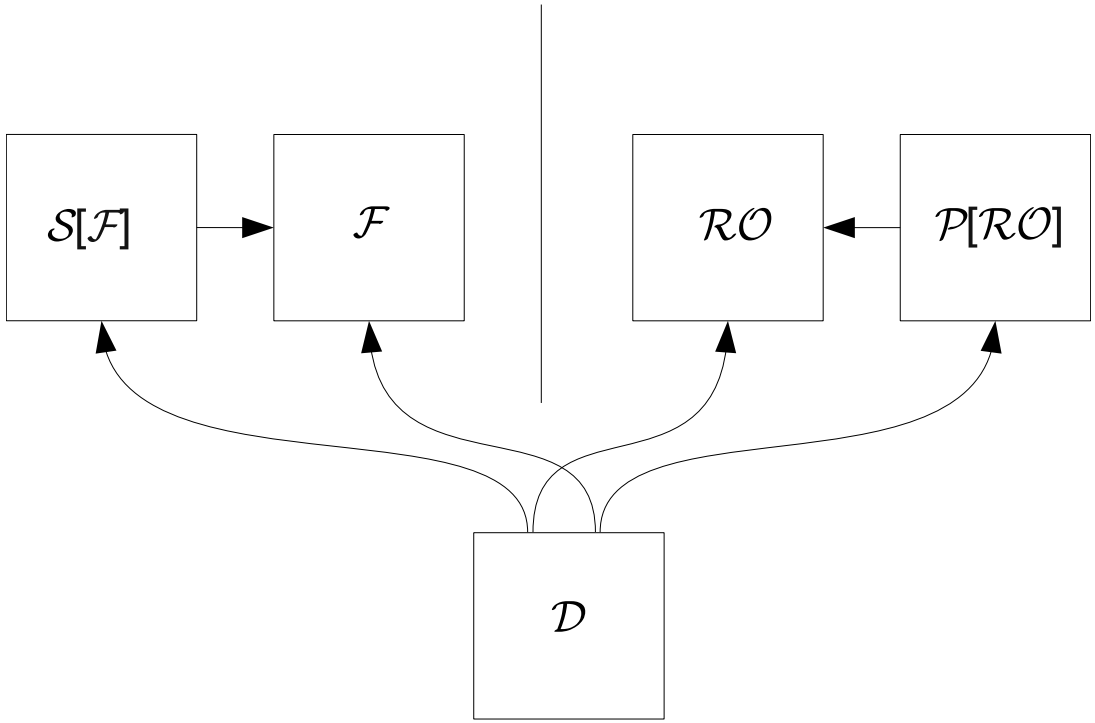
Generic security: indifferentiability [Maurer et al. (2004)]



Methodology:

- build $\mathcal{P}$ that makes left/right distinguishing difficult
- prove bound for advantage given this simulator $\mathcal{P}$
- $\mathcal{P}$ may query $\mathcal{RO}$ for acting $\mathcal{S}$-consistently: $\mathcal{P}[\mathcal{RO}]$

Generic security: indifferentiability [Maurer et al. (2004)]



$$\mathsf{Adv}(q) = \left|\Pr\left(\mathcal{D}^{\mathcal{S}[\mathcal{F}],\mathcal{F}}\right) - \Pr\left(\mathcal{D}^{\mathcal{RO},\mathcal{P}[\mathcal{RO}]}\right)\right| \leq \epsilon(q)$$

Consequences of indifferentiability

- Let $\mathcal{D}$: n-bit output pre-image attack. Success probability:
  - for random oracle: $P_{\text{pre}}(\mathcal{D}|\mathcal{RO}) = q2^{-n}$
  - for our construction: $P_{\text{pre}}(\mathcal{D}|\mathcal{S}[\mathcal{F}]) = ?$
- A distinguisher $\mathcal{D}$ with $\text{Adv}(q) = P_{\text{pre}}(\mathcal{D}|\mathcal{S}[\mathcal{F}]) - P_{\text{pre}}(\mathcal{D}|\mathcal{RO})$
  - do pre-image attack
  - if success, conclude our construction; otherwise, $\mathcal{RO}$
- But we have a proven bound $\text{Adv}(q) \leq \epsilon(q)$, so

$$P_{\text{pre}}(\mathcal{D}|\mathcal{S}[\mathcal{F}]) \leq P_{\text{pre}}(\mathcal{D}|\mathcal{RO}) + \epsilon(q)$$

- Can be generalized to any attack

Consequences of indifferentiability

Theorem 2. *Let $\mathcal{H}$ be a hash function, built on underlying primitive π, and RO be a random oracle, where $\mathcal{H}$ and RO have the same domain and range space. Denote by $\boldsymbol{Adv}^{\mathrm{pro}}_{\mathcal{H}}(q)$ the advantage of distinguishing $(\mathcal{H}, \pi)$ from (RO, S), for some simulator S, maximized over all distinguishers $\mathcal{D}$ making at most q queries. Let* atk *be a security property of $\mathcal{H}$. Denote by $\boldsymbol{Adv}^{\mathrm{atk}}_{\mathcal{H}}(q)$ the advantage of breaking $\mathcal{H}$ under* atk*, maximized over all adversaries $\mathcal{A}$ making at most q queries. Then:*

$$\boldsymbol{Adv}^{\mathrm{atk}}_{\mathcal{H}}(q) \leq \boldsymbol{Pr}^{\mathrm{atk}}_{RO}(q) + \boldsymbol{Adv}^{\mathrm{pro}}_{\mathcal{H}}(q), \tag{1}$$

where $\boldsymbol{Pr}^{\mathrm{atk}}_{RO}(q)$ denotes the success probability of a generic attack against $\mathcal{H}$ under atk*, after at most q queries.*

[Andreeva, Mennink, Preneel, ISC 2010]

Limitations of indifferentiability

- Only about the mode
  - No security proof with a concrete primitive
- Only about single-stage games [Ristenpart et al., Eurocrypt 2011]
  - Example: hash-based storage auditing

$$Z = h(\mathsf{File} \| C)$$

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$$Z = h(\mathsf{File} \| C)$$

Outline

Symmetric crypto: what textbooks and intro's say

Symmetric cryptography primitives:

- Block ciphers
- Key stream generators
- Hash functions

And their modes-of-use

Picture by GlasgowAmateur

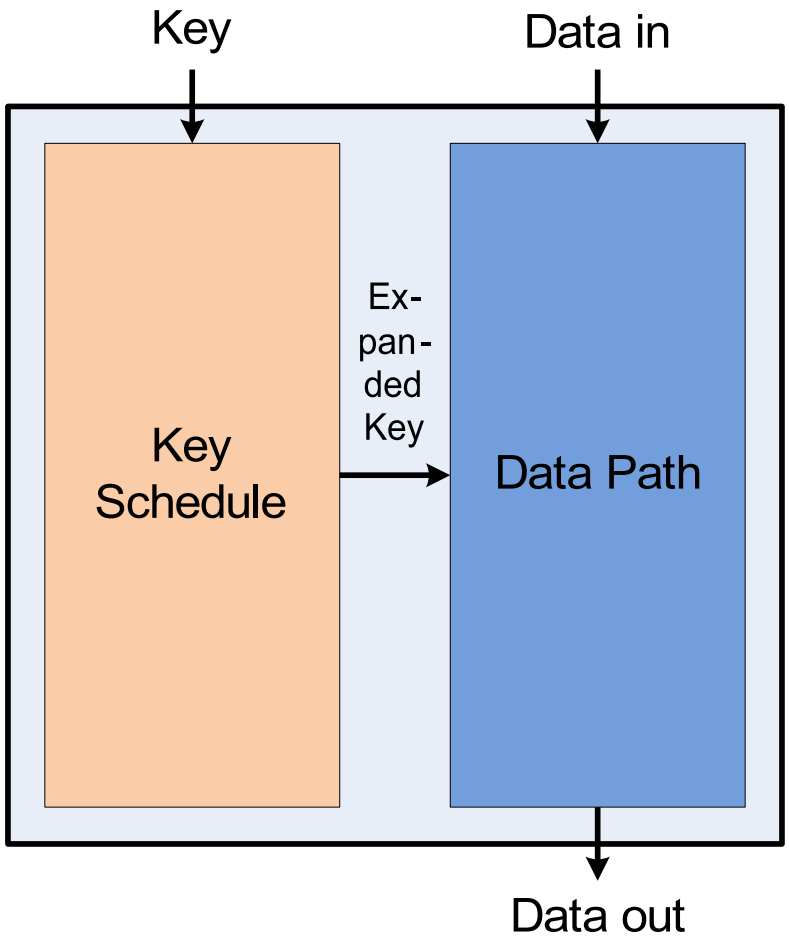
The truth about symmetric crypto today

Block ciphers:

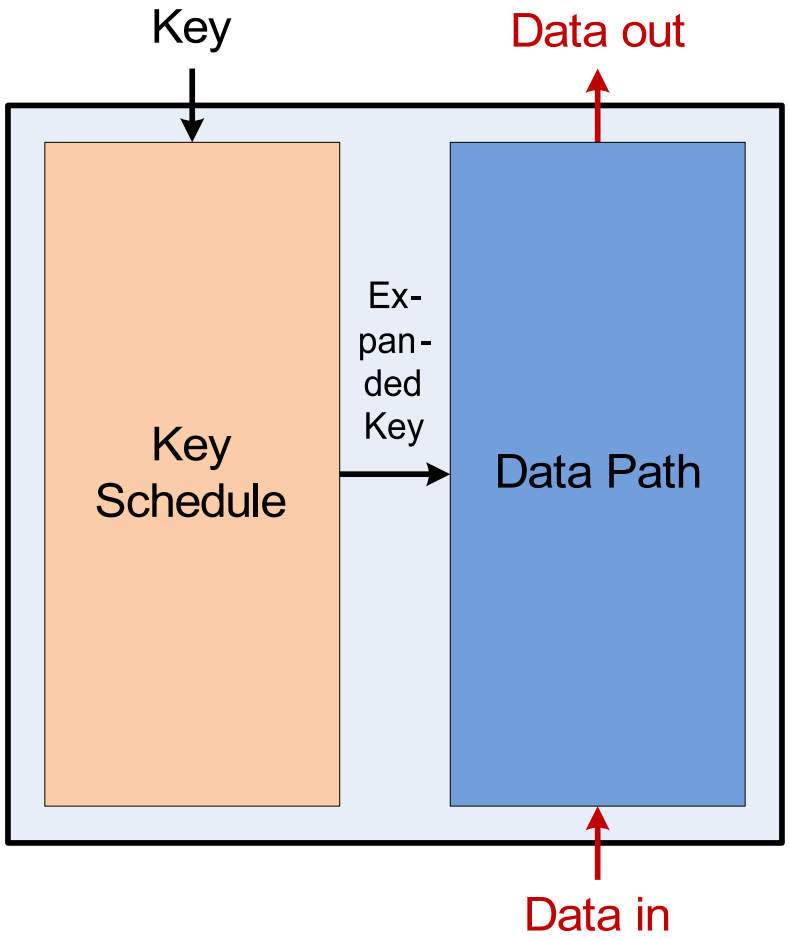
What block cipher are used for

- Hashing (Davies-Meyer) and its modes HMAC, MGF1, ...
- Block encryption: ECB, CBC, ...
- Stream encryption:
  - synchronous: counter mode, OFB, ...
  - self-synchronizing: CFB
- MAC computation: CBC-MAC, C-MAC, ...
- Authenticated encryption: OCB, GCM, CCM ...

Block cipher operation



Block cipher operation: the inverse



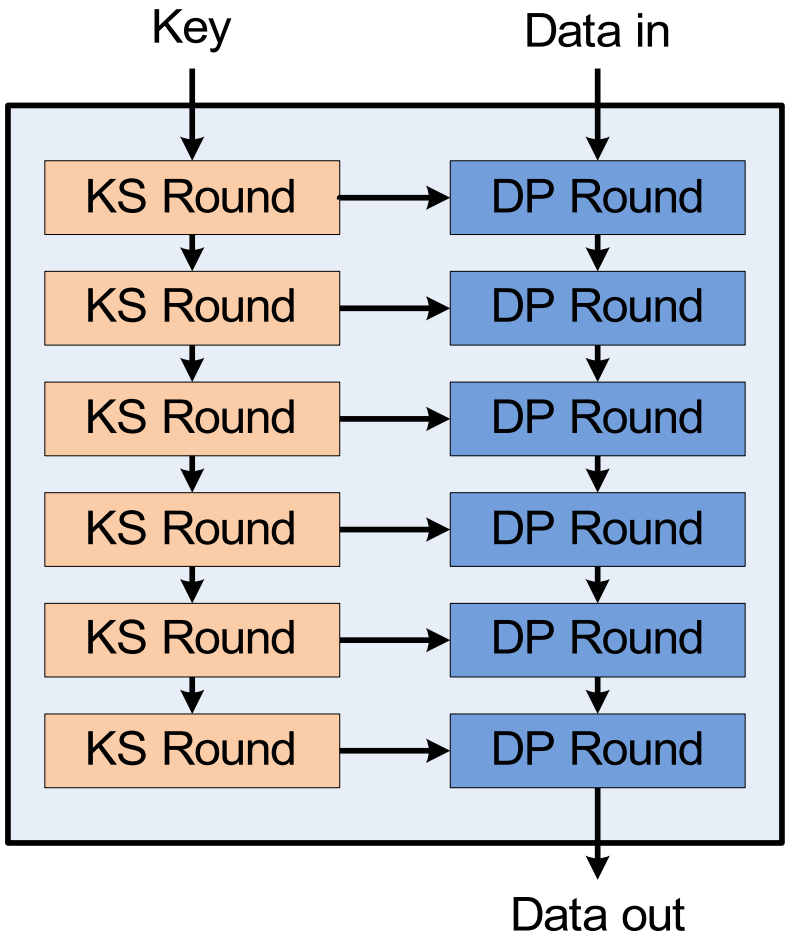
When do you need the inverse?

Indicated in red:

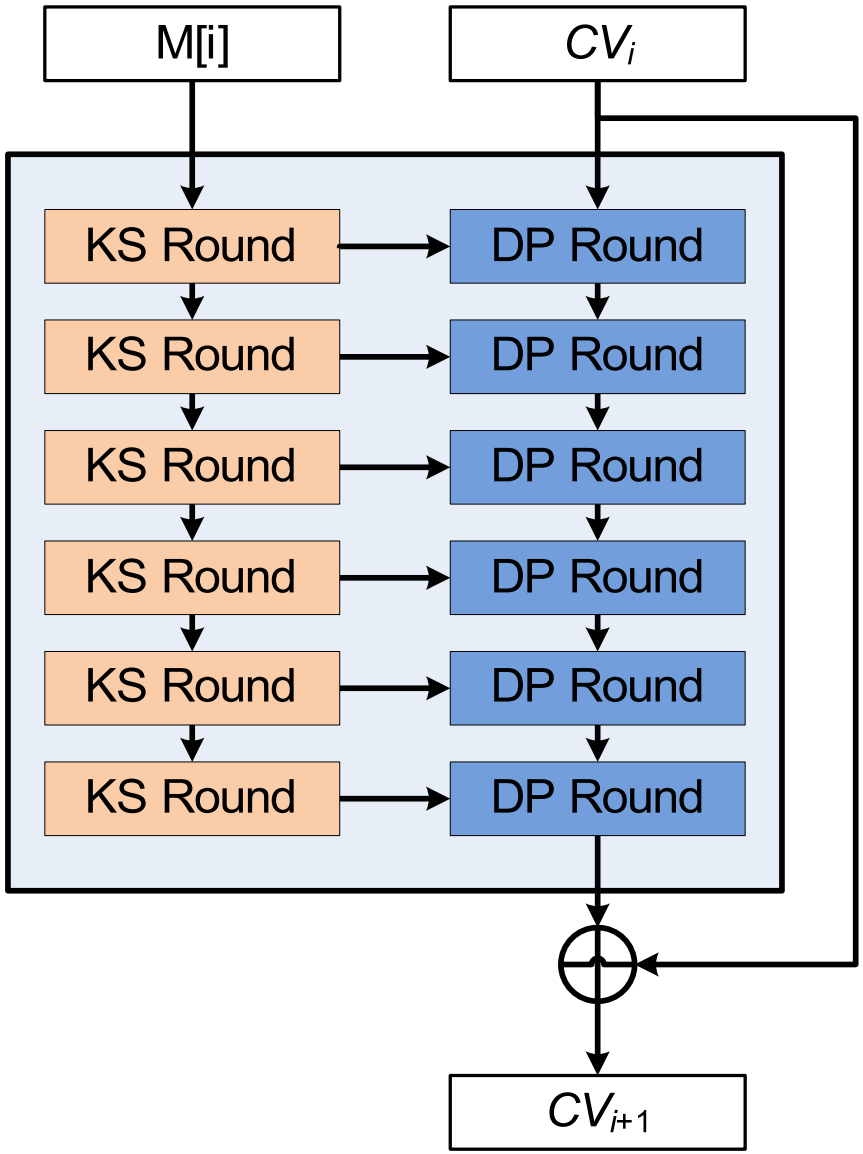
- Hashing and its modes HMAC, MGF1, ...
- Block encryption: ECB, CBC, ...
- Stream encryption:
  - synchronous: counter mode, OFB, ...
  - self-synchronizing: CFB
- MAC computation: CBC-MAC, C-MAC, ...
- Authenticated encryption: OCB, GCM, CCM ...
  - Most schemes with misuse-resistant claims

So for most uses you don't need the inverse!

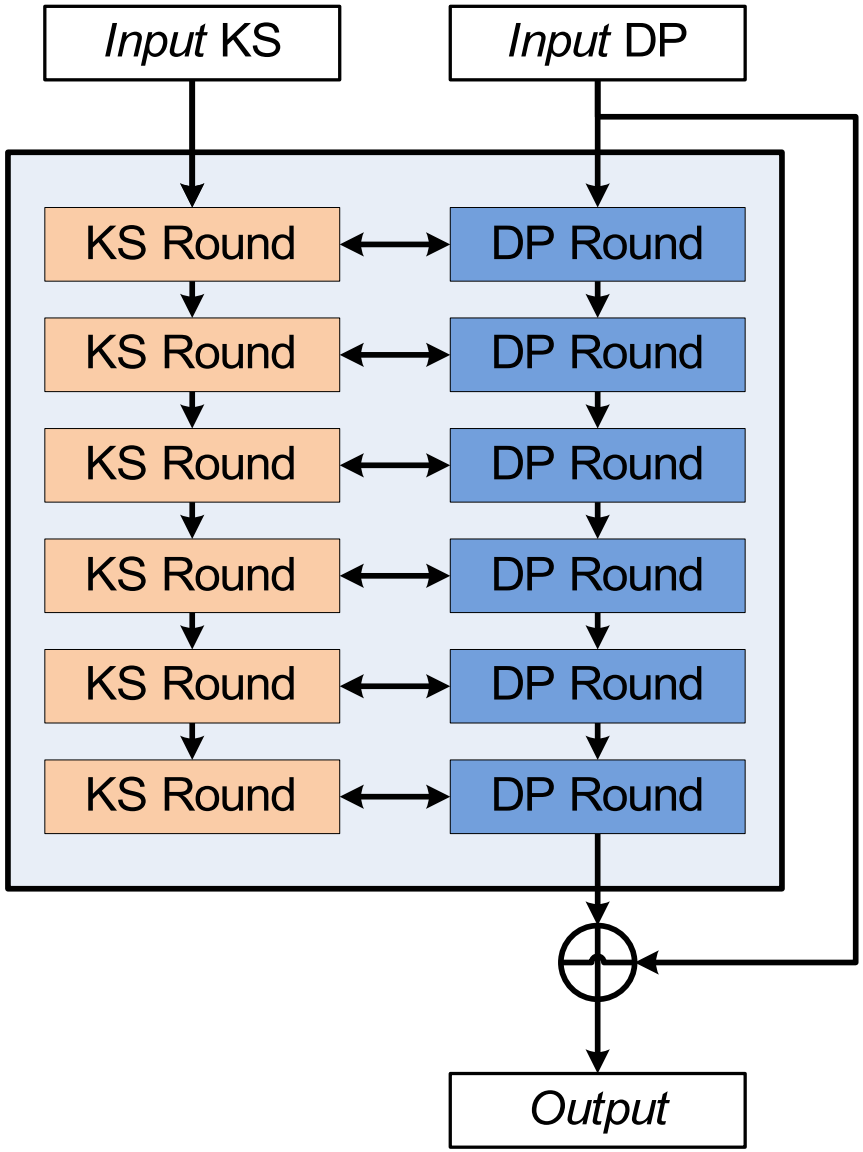
Block cipher internals



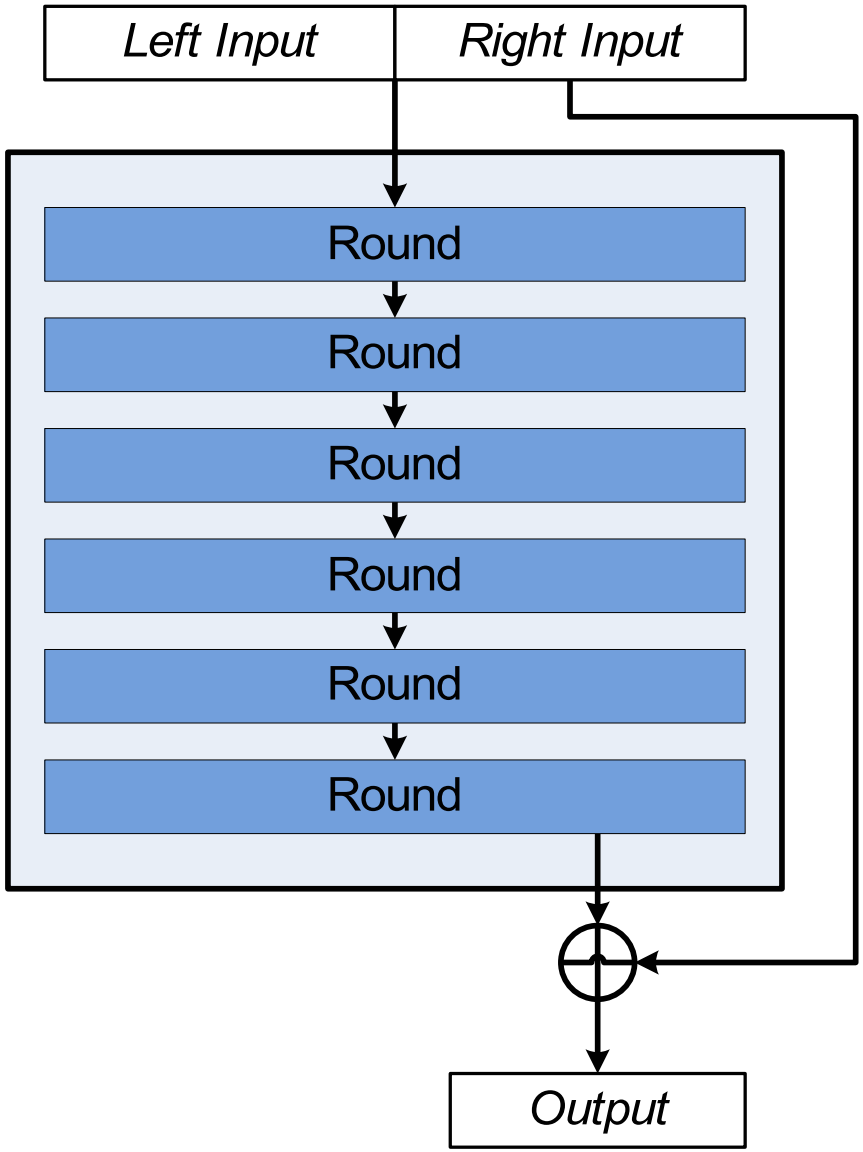
Davies-Meyer compression function



Removing restrictions not required in hashing



Simplifying the view: iterated permutation



Designing a permutation

- Remaining problem: design of iterated permutation
  - round function: good approaches known
  - asymmetry: round constants
- Advantages with respect to block ciphers:
  - less barriers $\Rightarrow$ more diffusion
  - no more need for efficient inverse
  - no more worries about key schedule

Examples of permutations

- In Salsa, Chacha, Spongent, Quark, Photon...
- In SHA-3 candidates: CubeHash, Grøstl, JH, MD6, ...
- In CAESAR candidates: Ascon, Icepole, Norx, π-cipher, Primates, Stribob, ...
- In recent proposals: Gimli, Xoodoo

And of course in KECCAK

What textbooks and intro's should say

Symmetric cryptography primitives:

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- Key stream generators
- **Permutations**

And their modes-of-use

Picture by Sébastien Wiertz

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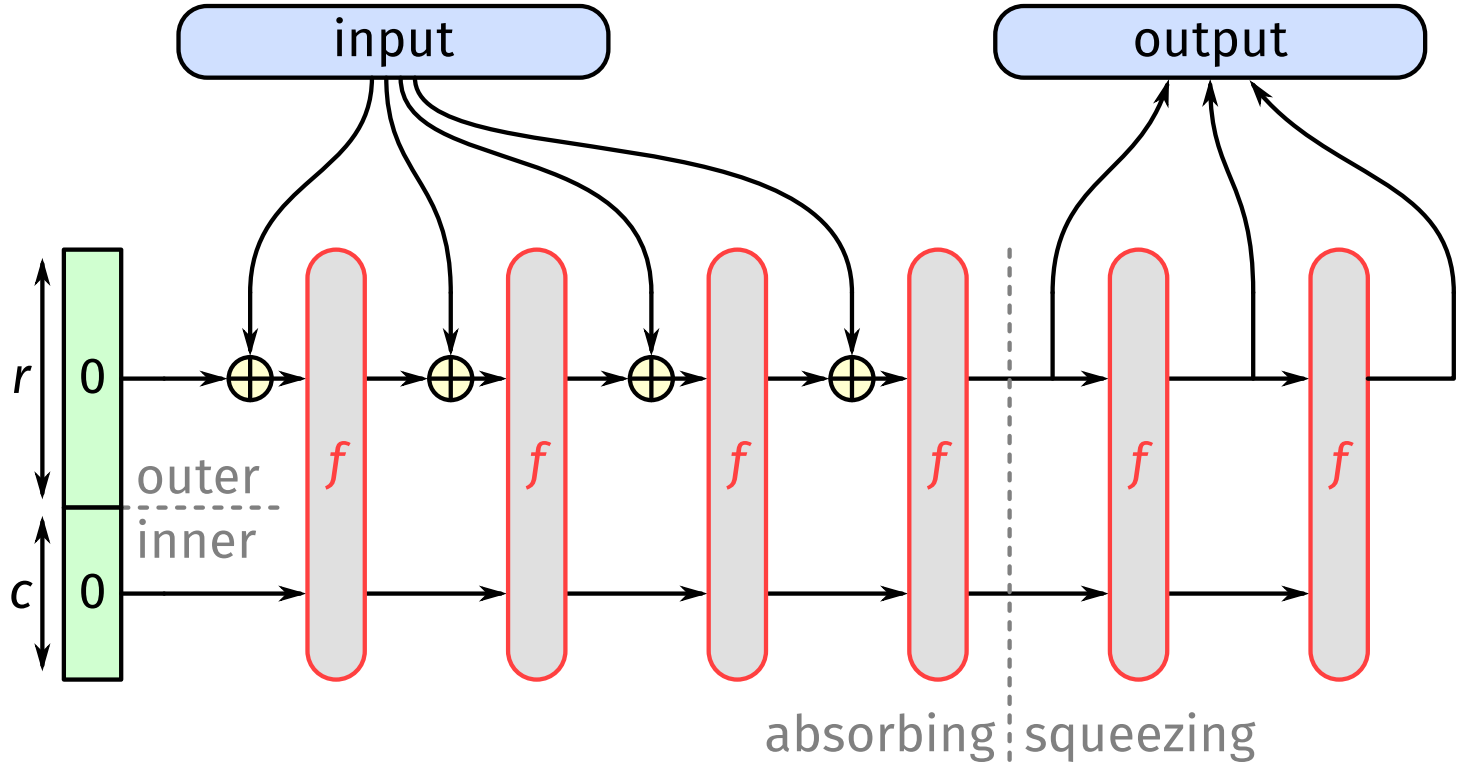
The sponge construction



- Calls a b-bit permutation f, with $b = r + c$
  - r bits of *rate*
  - c bits of *capacity* (security parameter)
- Natively implements a XOF

Generic security of the sponge construction

Theorem (Bound on the $\mathcal{RO}$-differentiating advantage of sponge)

$$A \leq \frac{N^2}{2^{c+1}}$$

A: differentiating advantage of random sponge from random oracle
N: total data complexity *c: capacity* *[Keccak Team, Eurocrypt 2008]*

Preimage resistance	$2^{\min(n,c/2)}$
Second-preimage resistance	$2^{\min(n,c/2)}$
Collision resistance	$2^{\min(n/2,c/2)}$
Any other attack	$2^{\min(\mathcal{RO},c/2)}$

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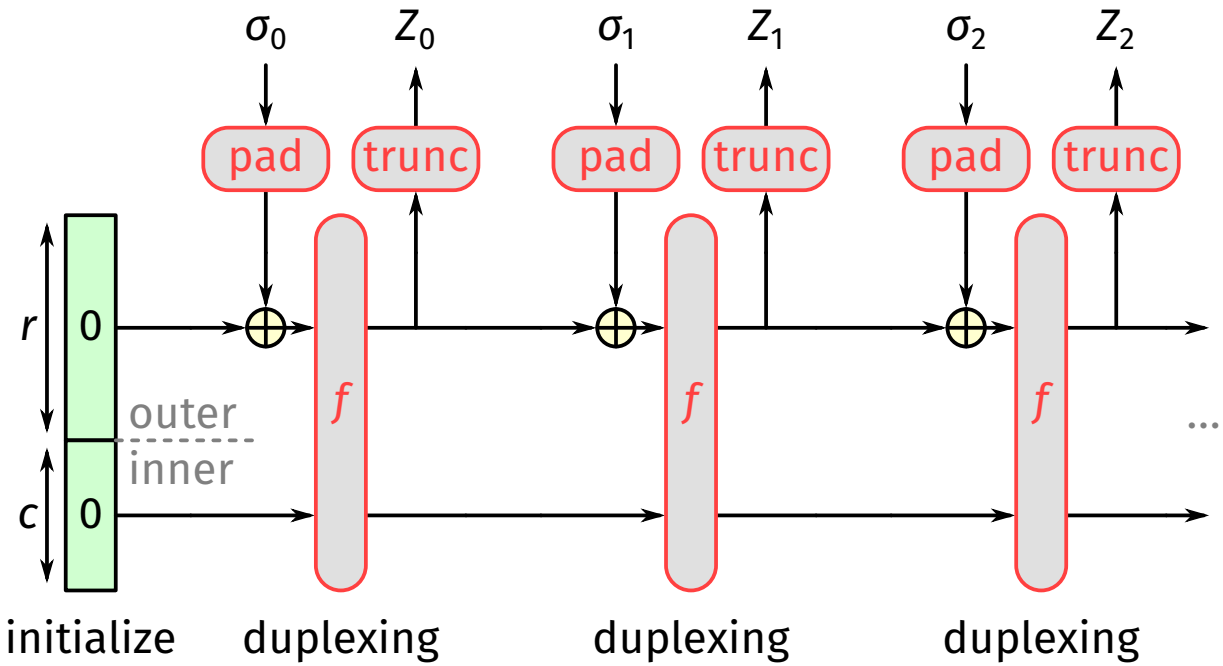
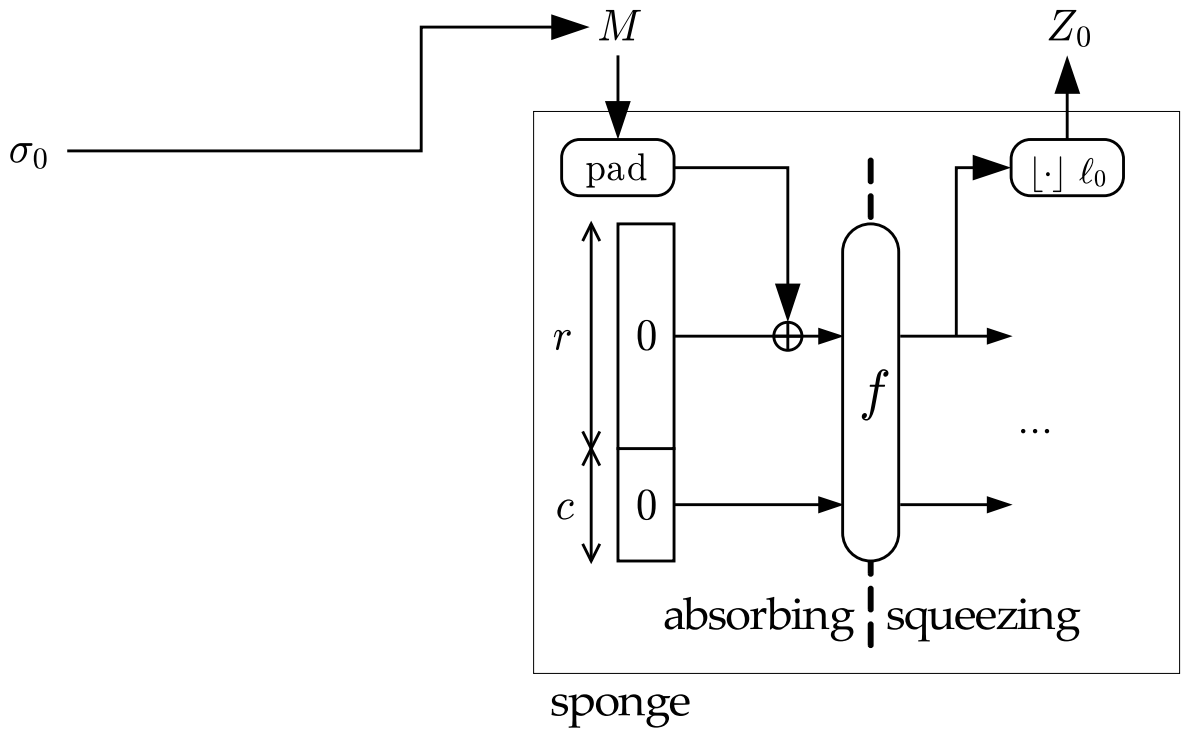
The duplex construction



- Object: $D = \text{DUPLEX}[f, \text{pad}, r]$
- Requesting ℓ-bit output $Z = D.\text{duplexing}(\sigma, \ell)$
  - input σ and output Z limited in length
  - Z depends on all previous inputs

Generating duplex responses with a sponge



$$Z_0 = \mathsf{sponge}(\sigma_0, \ell_0)$$

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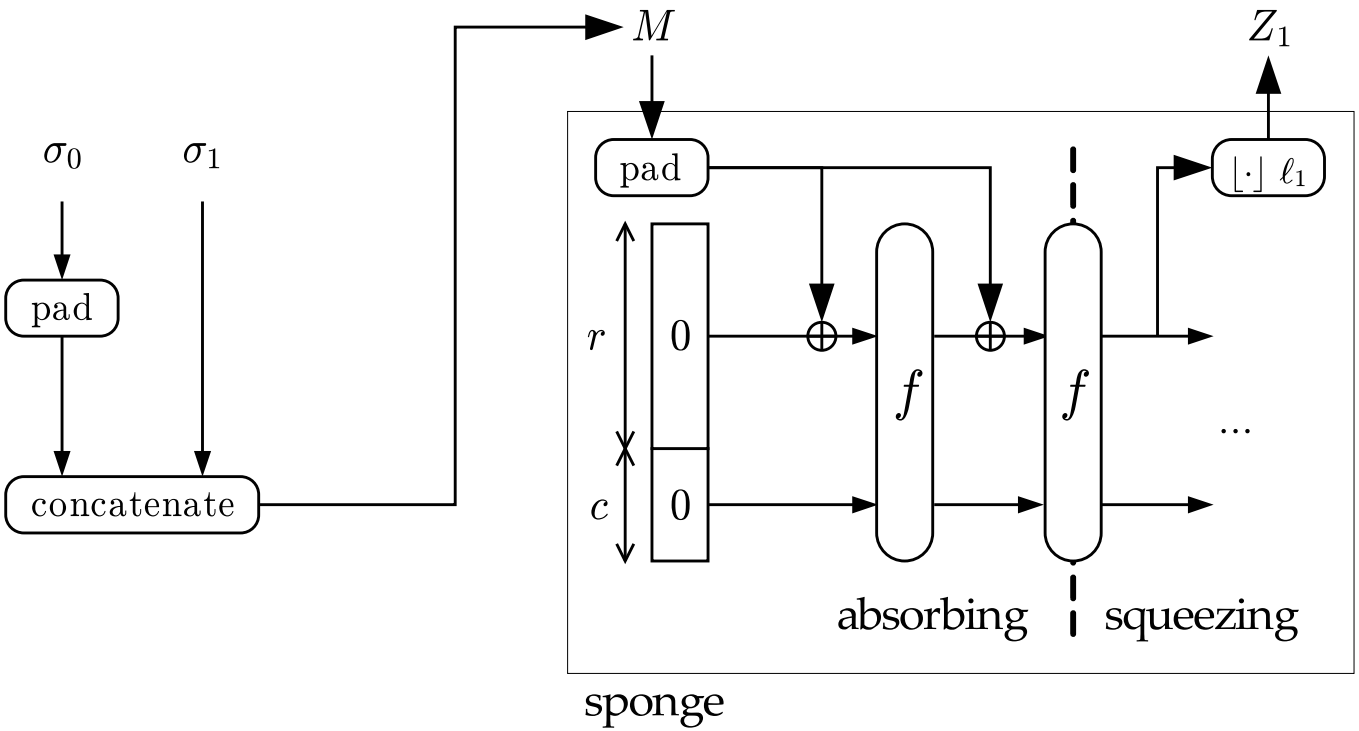
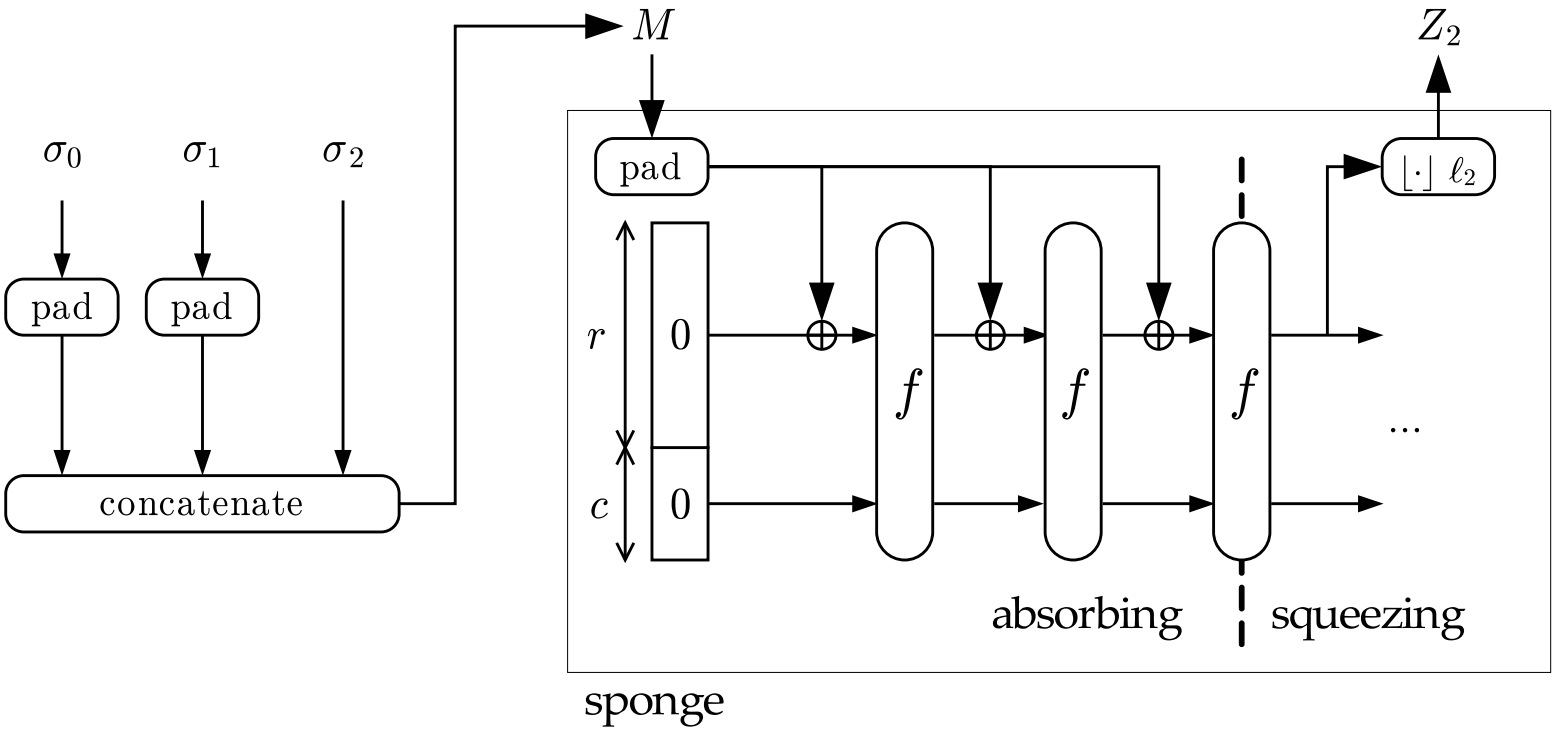


$$Z_1 = \mathsf{sponge}(\mathsf{pad}(\sigma_0)||\sigma_1, \ell_1)$$

Generating duplex responses with a sponge



$$Z_2 = \mathsf{sponge}(\mathsf{pad}(\sigma_0)||\mathsf{pad}(\sigma_1)||\sigma_2, \ell_2)$$

Security of the duplex construction

Duplexing-sponge lemma

Every output block of a duplex object $\textsc{duplex}[f, \text{pad}, r]$ is a valid output of $\textsc{sponge}[f, \text{pad}, r]$

Proof is trivial

Corollary

The security of $\textsc{duplex}[f, \text{pad}, r]$ can be reduced to that of $\textsc{sponge}[f, \text{pad}, r]$

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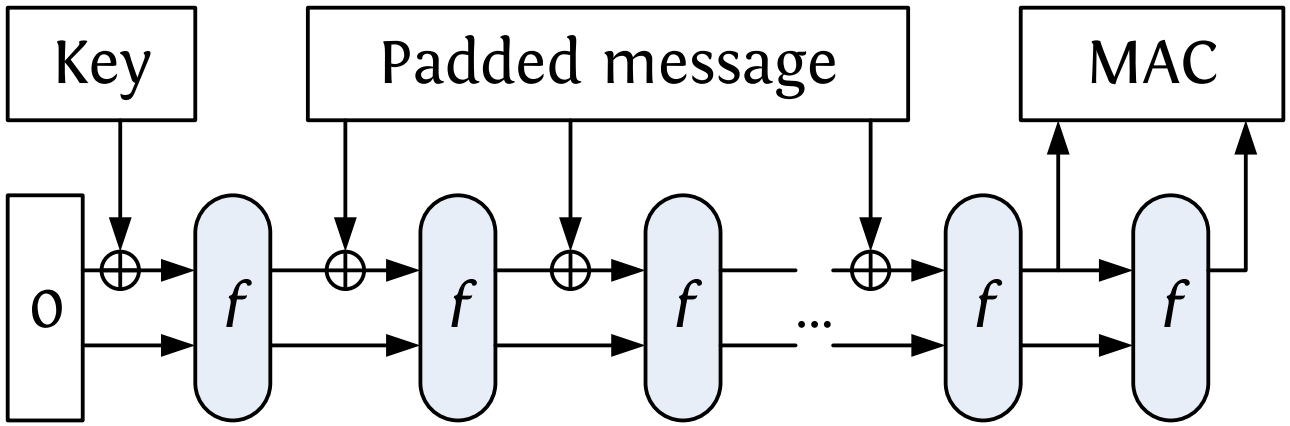
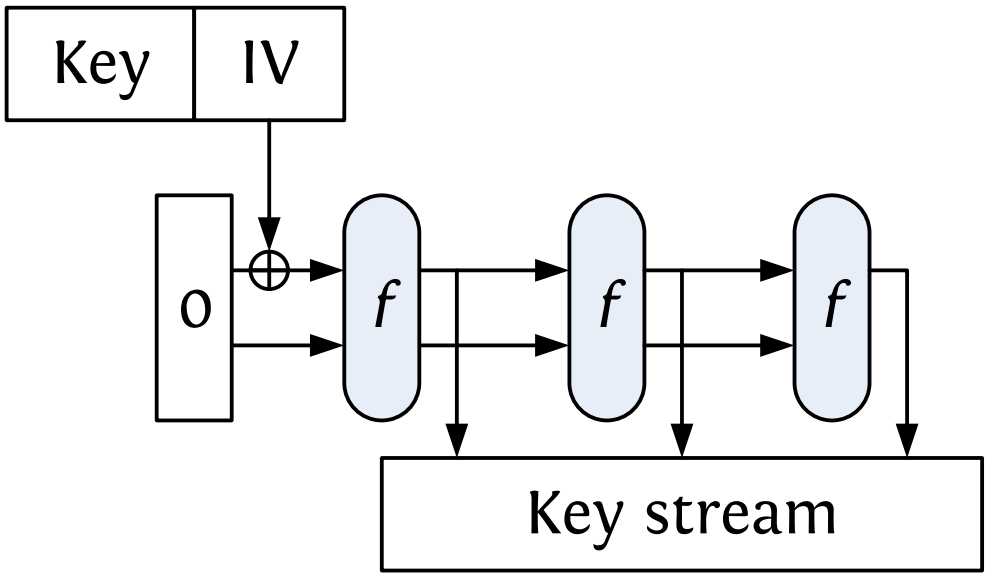
Message authentication codes



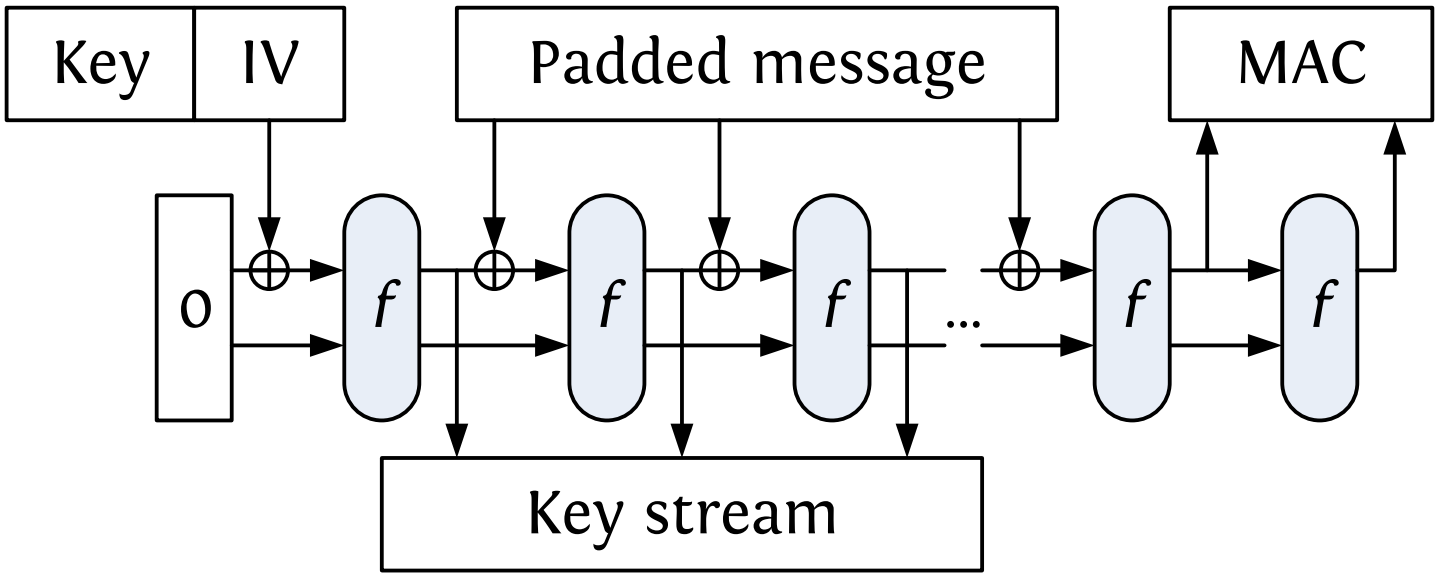
- Using sponge
- See also **KMAC** [NIST SP 800-185]

Stream encryption



- Using sponge
- Long output stream per IV: similar to OFB mode
- Short output stream per IV: similar to counter mode

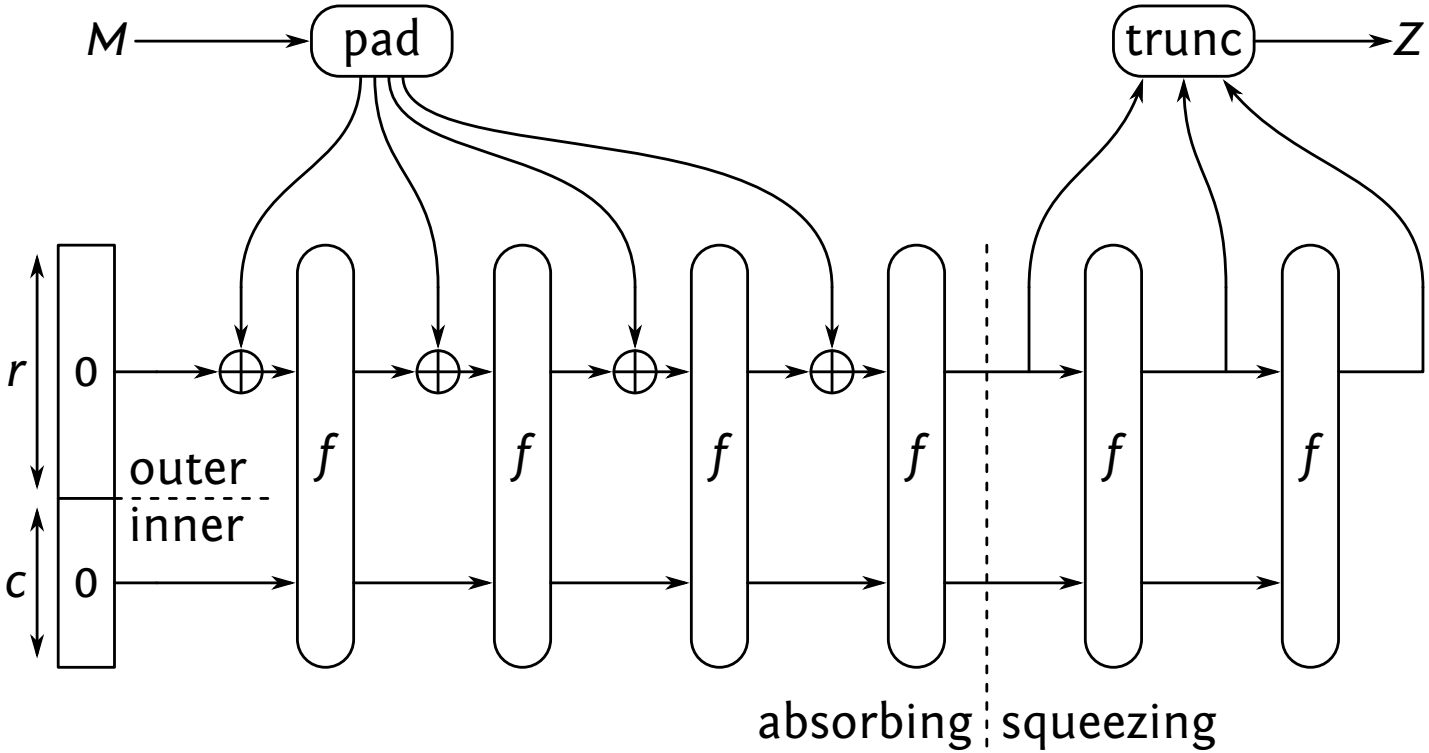
Authenticated encryption: spongeWrap



- Using duplex
- Adopted by several CAESAR and NIST LWC candidates

[Keccak Team, SAC 2011]

Outer keyed sponge



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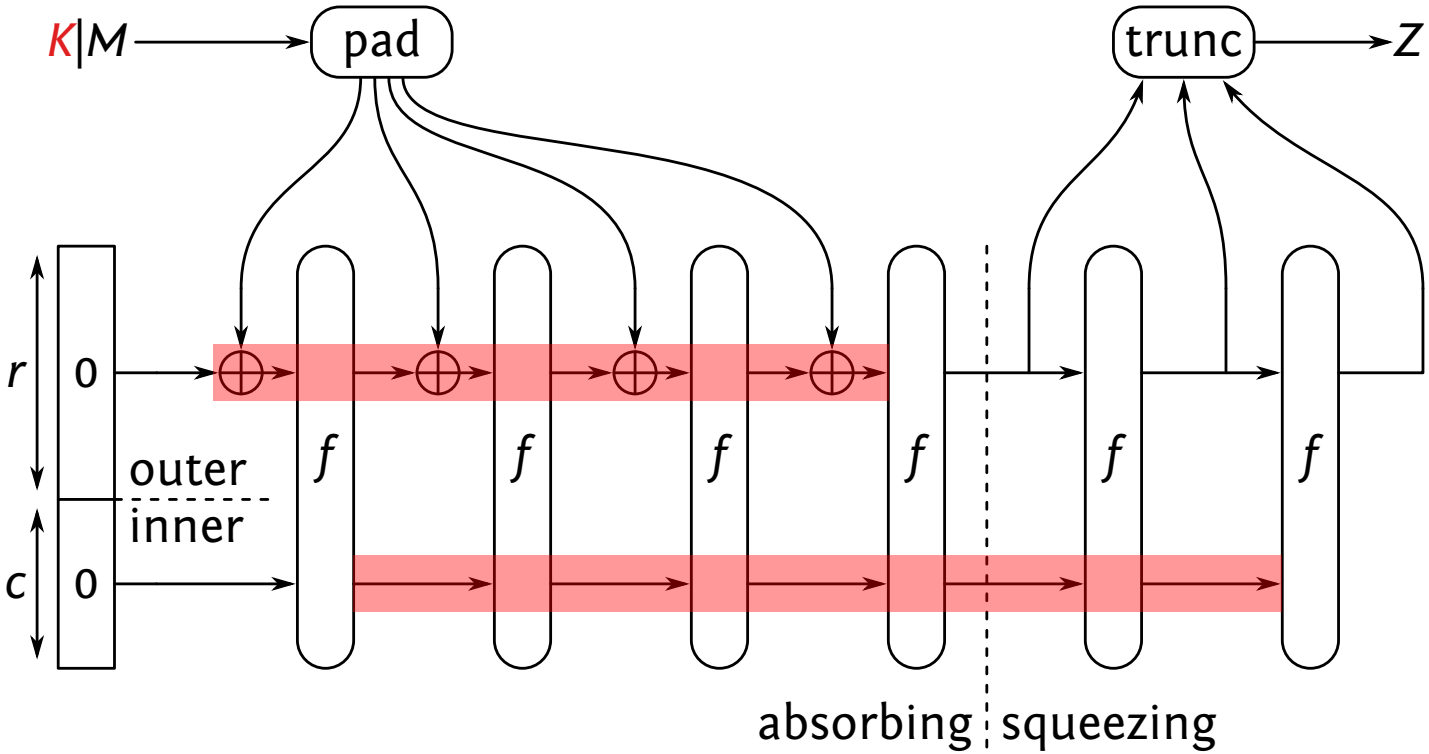
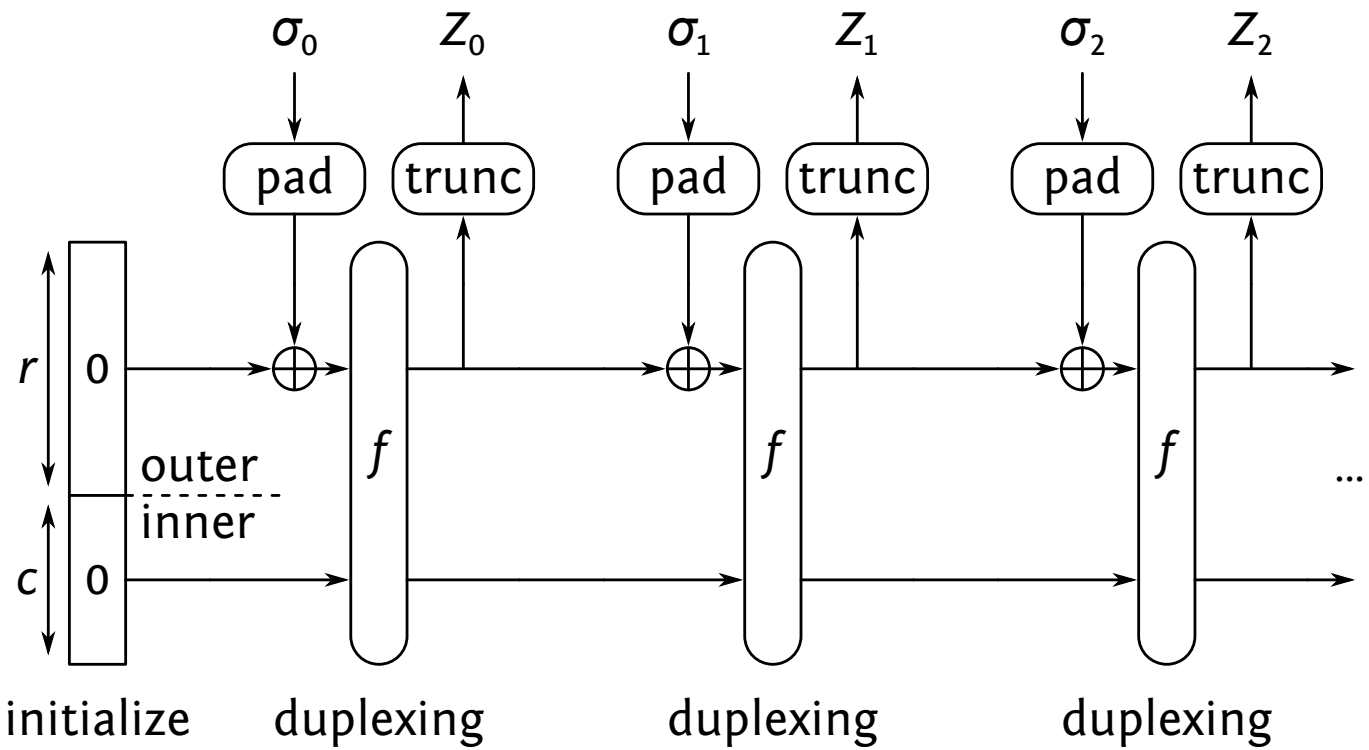


$$\mathrm{OKS}^f_K(M) = \mathrm{SPONGE}^f(K||M)$$

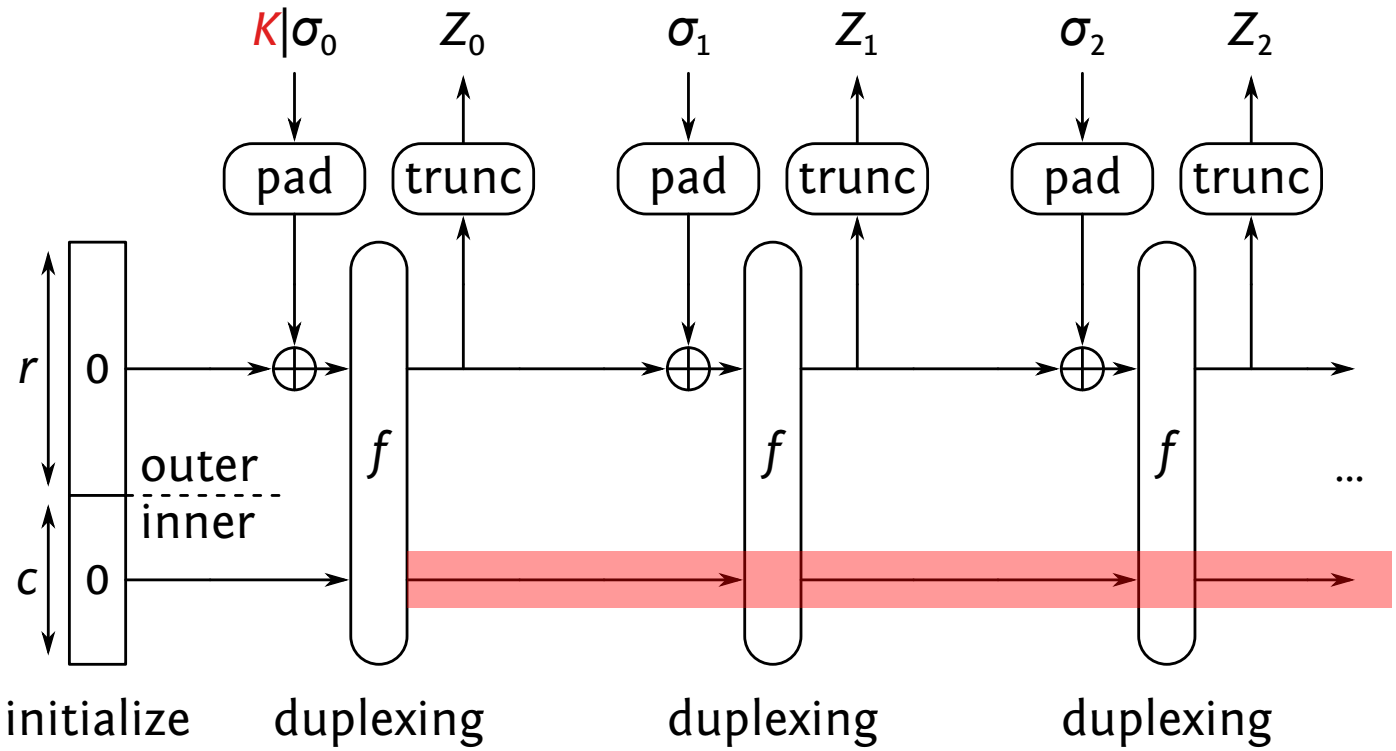
Outer keyed duplex



Duplexing-sponge lemma

$Z_i = \text{SPONGE}(\sigma_0||\text{pad}||\ldots||\sigma_i)$

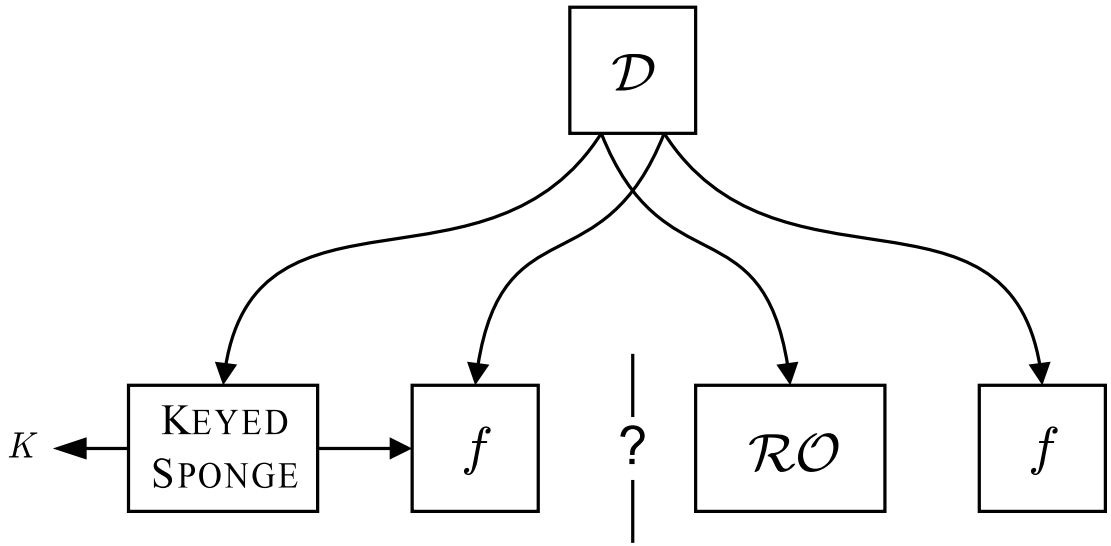
Outer keyed duplex



Duplexing-sponge lemma

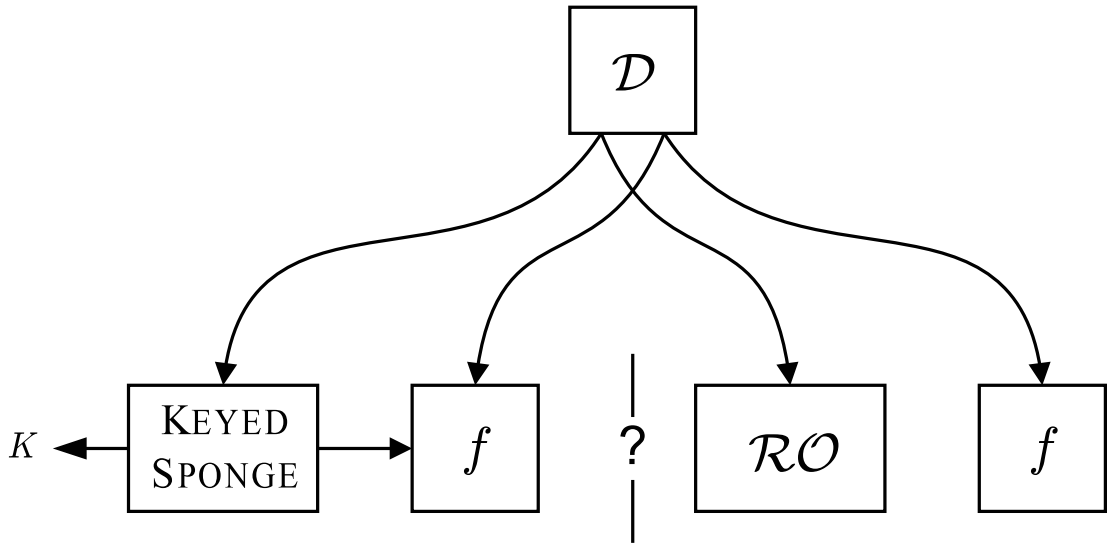
$Z_i = \text{SPONGE}(K||\sigma_0||\text{pad}||\ldots||\sigma_i) \Rightarrow$ equivalent to OKS_K

Keyed sponge: distinguishing setting



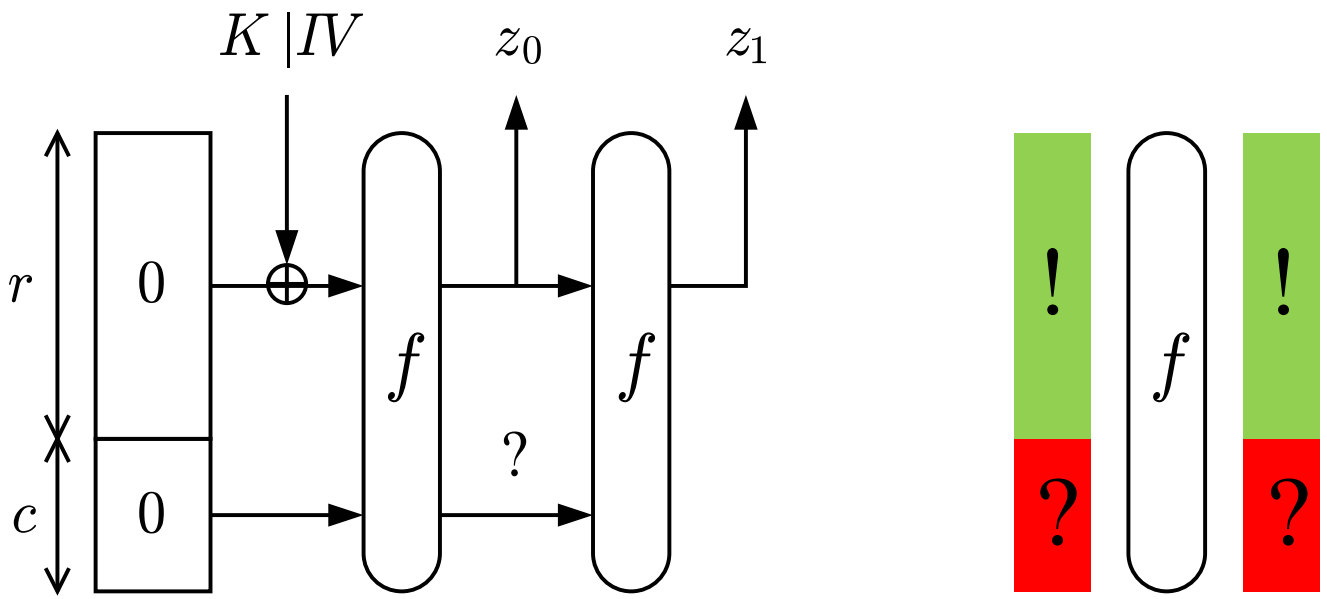
- Straightforward bound: $M^2/2^{c+1} + M/2^k$
- Security strength s: expected complexity of succesful attack
  - strength s means attack complexity 2^s
  - bounds can be converted to security strength statements
- Here: $s \leq \min(c/2, k)$
  - e.g., $s = 128$ requires $c = 256$ and $k = 128$
  - $c/2$: birthday bound

More fine-grained attack complexity



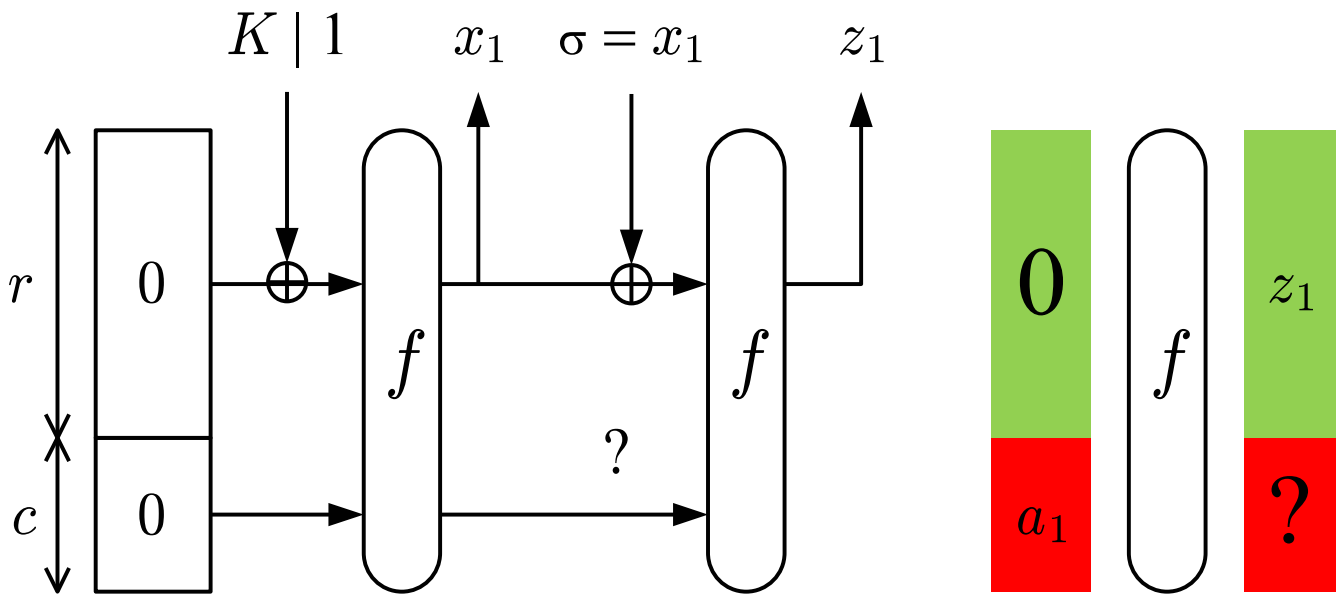
- Splitting attack complexity:
  - queries to construction: data complexity M
  - queries to f or f^{-1}: computational complexity N
- Our ambition around 2010: $M^2/2^{c+1} + NM/2^c + N/2^k$
- If we limit data complexity $M \leq 2^a \lll 2^{c/2}$:
  - $s \leq \min(c - a, k)$
  - e.g., $s = 128$ and $a = 64$ require $c = 192$ and $k = 128$

Intuition behind $NM/2^c$



- Typically just one instance with the same partial r-bit input
- Success probability per guess: $1/2^c$

Intuition behind $NM/2^c$



- Multiple instances ($\mu \leq M$) with same partial r-bit input
- Success probability per guess: $\mu/2^c$

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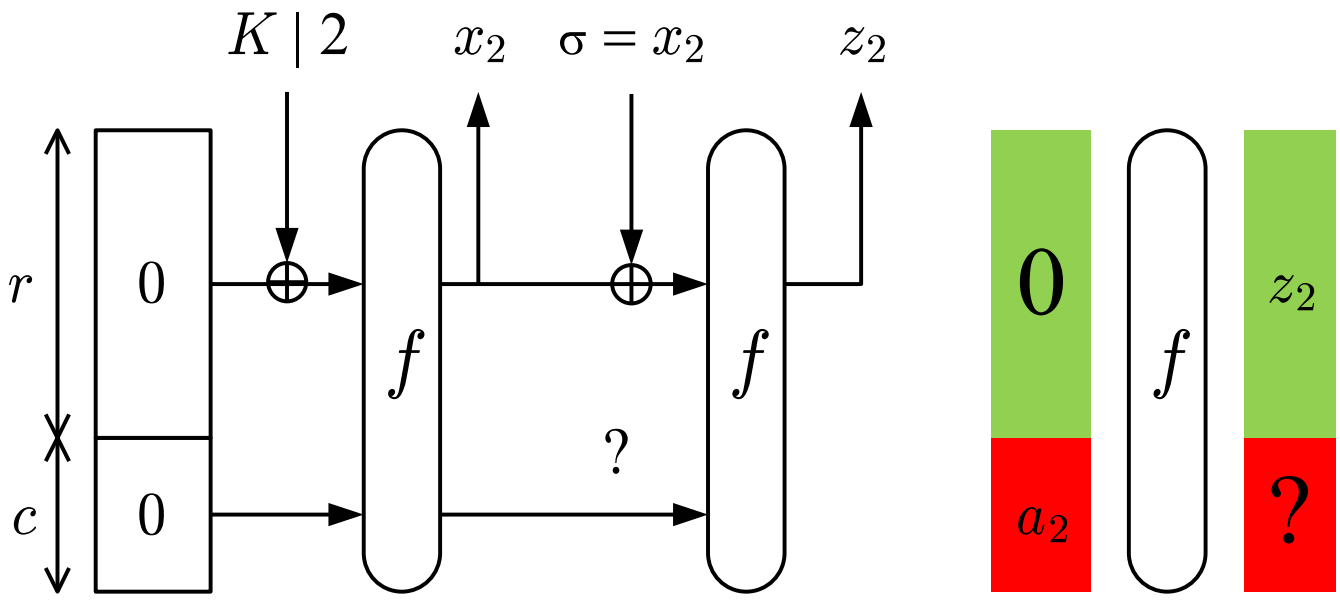

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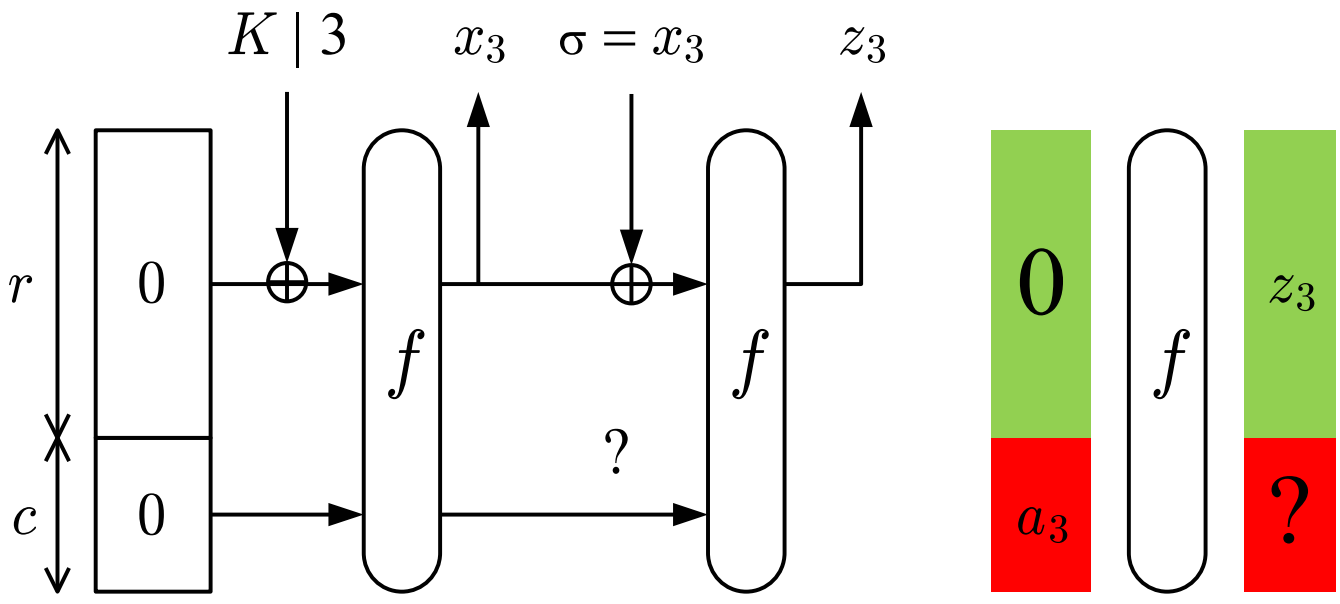
- Success probability per guess: $\mu/2^c$

Intuition behind $NM/2^c$

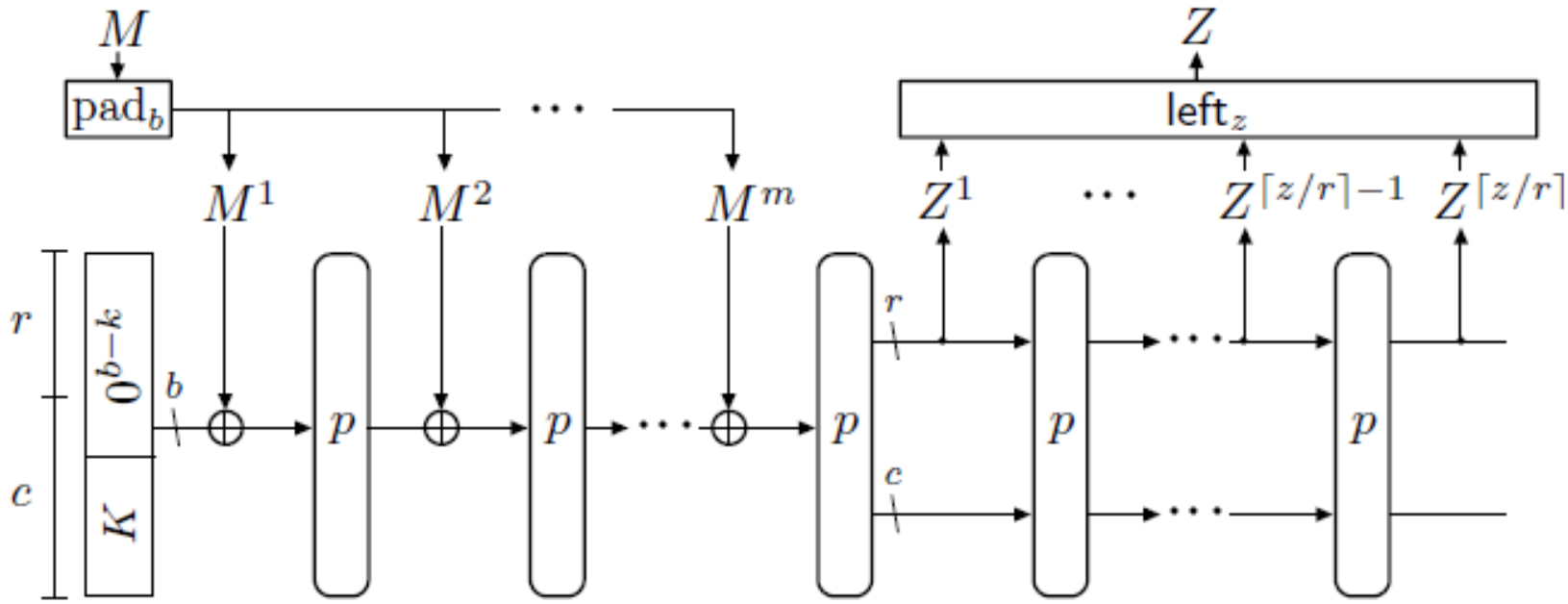


- Multiple instances ($\mu \leq M$) with same partial r-bit input
- Success probability per guess: $\mu/2^c$

Proof evolution

- Outer keyed sponge
  [Keccak Team, SKEW 2011]
- Inner keyed sponge
  [Chang, Dworkin, Hong, Kelsey, Nandi, 2012]
- Security beyond $2^{c/2}$
  [Jovanovic, Luykx, Mennink, Asiacrypt 2014]
- Inner and outer keyed sponges, multi-target
  [Andreeva, Daemen, Mennink, Van Assche, FSE 2015]
- Partially full-state sponge-based AE
  [Sasaki, Yasuda, CT-RSA 2015]
- Full-state keyed sponge (but fixed output size)
  [Gaži, Pietrzak, Tessaro, Crypto 2015]
- Full-state keyed sponge and duplex
  [Mennink, Reyhanitabar, Vizár, Asiacrypt 2015]
- Improved security of the outer keyed sponge
  [Naito, Yasuda, FSE 2016]

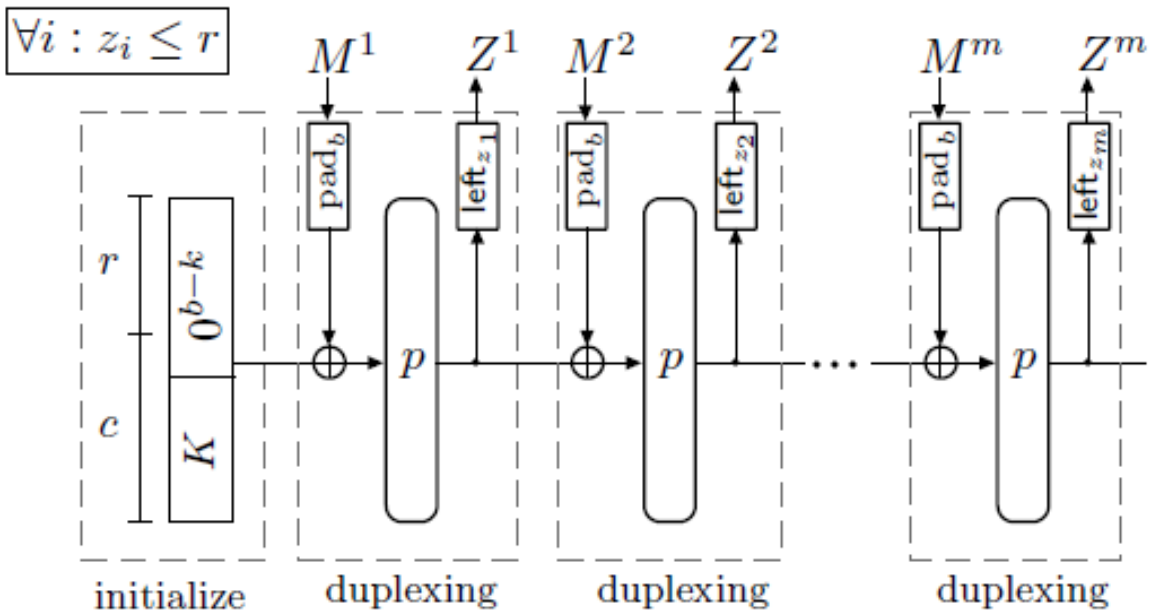
Full-state absorbing!



Absorbing on full permutation width does not degrade bounds

[Mennink, Reyhanitabar, Vizár, Asiacrypt 2015]

Full-state absorbing!

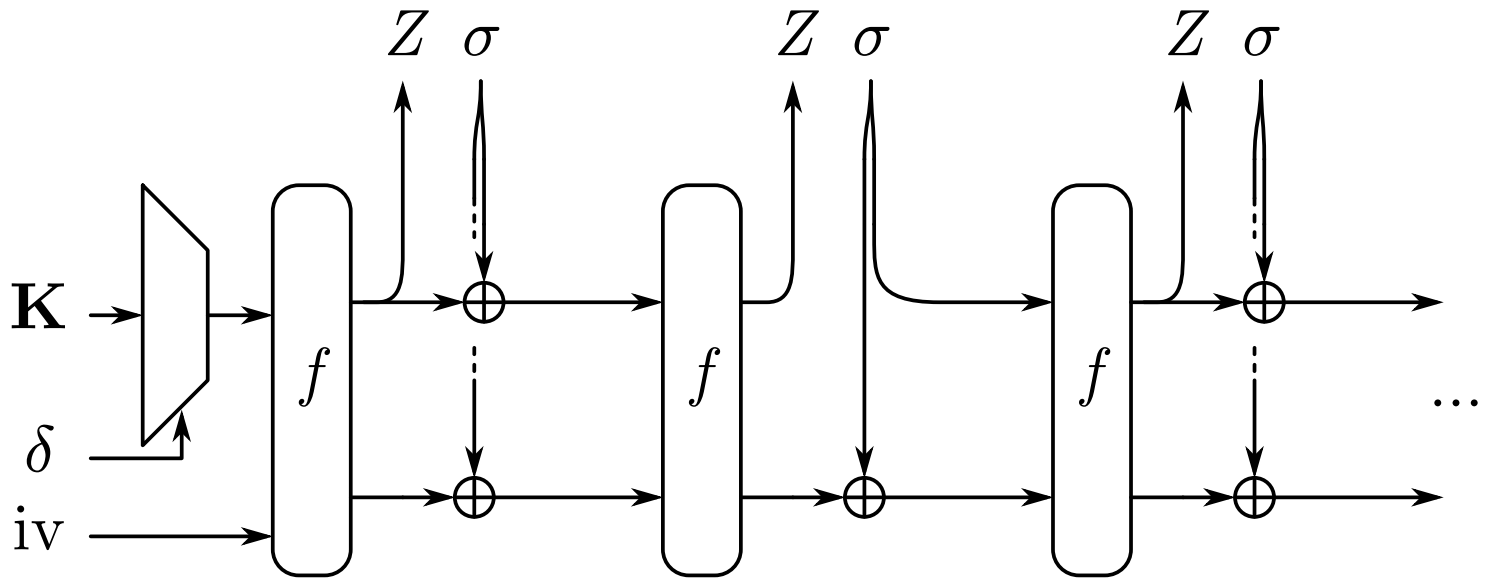


Absorbing on full permutation width does not degrade bounds

[Mennink, Reyhanitabar, Vizár, Asiacrypt 2015]

Outline

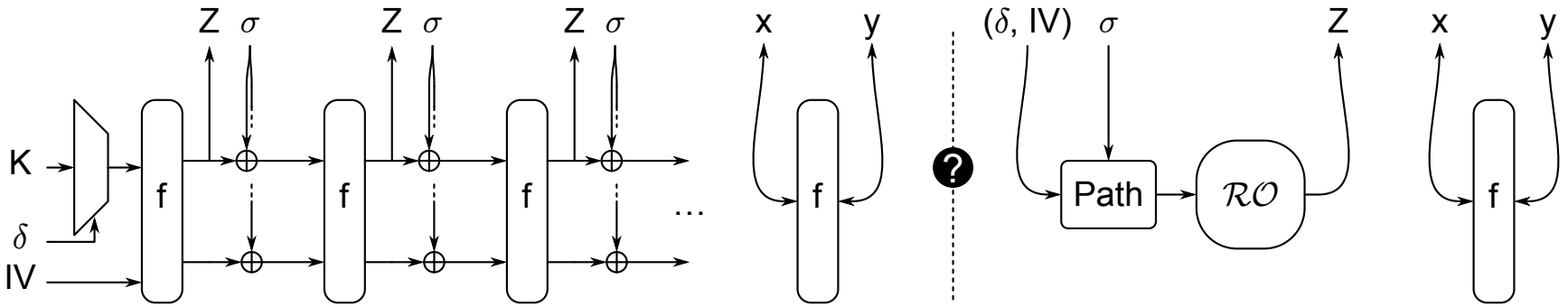
Keyed duplex



- Initial state: concatenation of key $k = \mathbf{K}[\delta]$ and IV
- Full-state absorbing, no padding: $|\sigma| = b$
- Re-phased: f, Z, σ instead of σ, f, Z

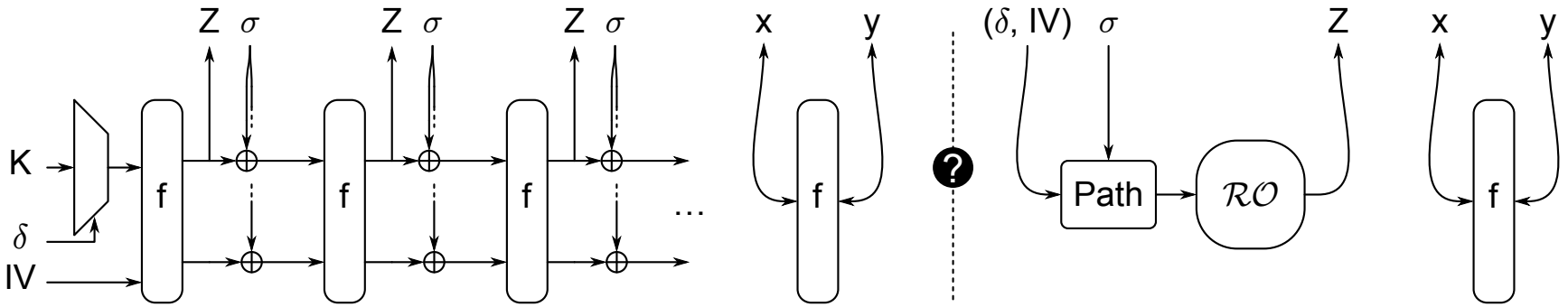
$\approx$ all keyed sponge functions are modes of this

Generic security of keyed duplex: the setup



- Ideal function: Ideal eXtendable Input Function (IXIF)
  - $\mathcal{RO}$-based object with duplex interface
  - Independent outputs Z for different paths
- Further refine adversary's capability
  - L: # queries to keyed duplex/$\mathcal{RO}$ with repeated path
  - q_{IV} : $\max_{IV}$ # init queries with different keys

Generic security of keyed duplex: the bound



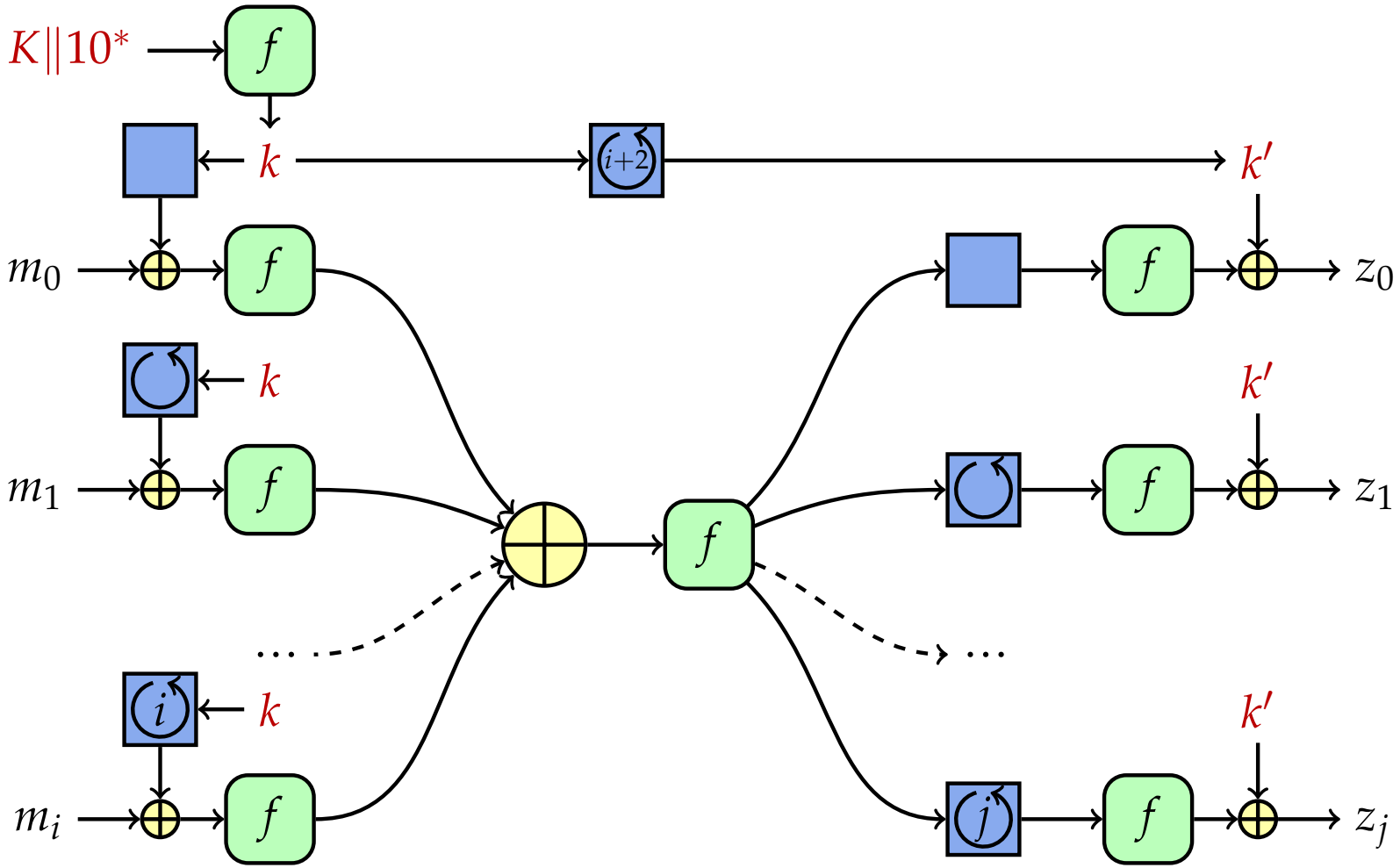
$$L^2/2^{c+1} + (L + 2\nu)N/2^c + q_{\mathsf{IV}}N/2^k + M^2/2^b + \ldots$$

with ν: chosen such that probability of ν-wise multi-collision in set of M r-bit values is negligible

[Daemen, Mennink, VA, Asiacrypt 2017]

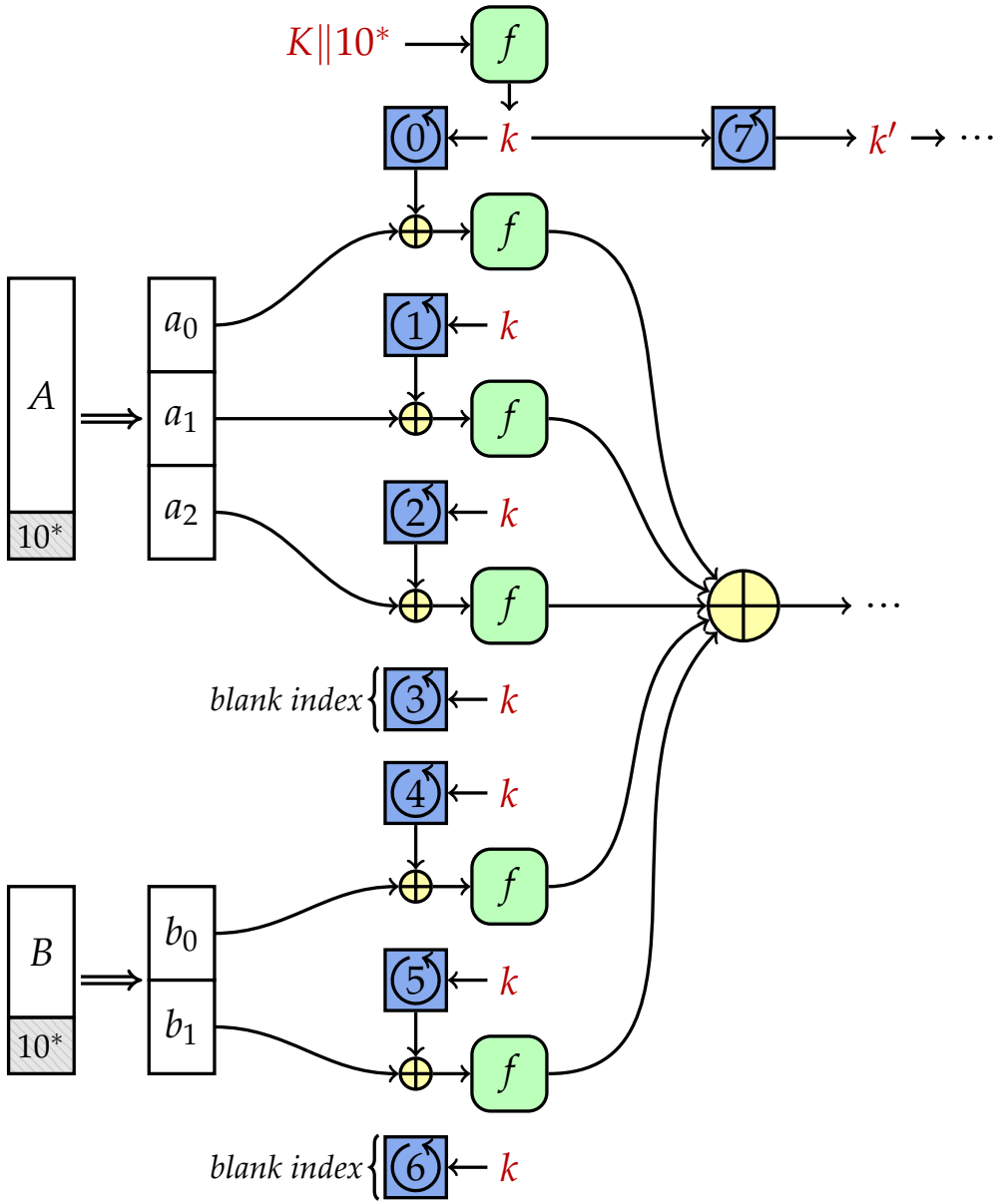
Outline

Farfalle



[FSE 2018]

Multi-string input and incrementality



Outline

Definition of a deck function

A deck function F_K

$$Z = 0^n + F_K\left(X^{(m)} \circ \cdots \circ X^{(1)}\right) \ll q$$

doubly extendable cryptographic keyed function

Definition of a deck function

A deck function F_K

$$Z = 0^n + F_K\left(X^{(m)} \circ \cdots \circ X^{(1)}\right) \ll q$$

- Input: sequence of strings $X^{(m)} \circ \cdots \circ X^{(1)}$

Definition of a deck function

A deck function F_K

$$Z = 0^n + F_K\left(X^{(m)} \circ \cdots \circ X^{(1)}\right) \ll q$$

- Input: sequence of strings $X^{(m)} \circ \cdots \circ X^{(1)}$
- Output: potentially infinite output
  - **pseudo-random function of the input**
  - taking n bits starting from offset q

Definition of a deck function

A deck function F_K

$$Z = 0^n + F_K\left(X^{(m)} \circ \cdots \circ X^{(1)}\right) \ll q$$

Efficient incrementality

- Extendable input
  1. Compute $F_K(X)$
  2. Compute $F_K(Y \circ X)$: cost independent of X

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Efficient incrementality

- Extendable input
  1. Compute $F_K(X)$
  2. Compute $F_K(Y \circ X)$: cost independent of X
- Extendable output
  1. Request n_1 bits from offset 0
  2. Request n_2 bits from offset n_1: cost independent of n_1

Deck-SANE: session-supporting and nonce-based

Initialization taking nonce $N \in \mathbb{Z}_2^*$
$e \leftarrow 0^1$
history $\leftarrow N$
return optional setup tag $T = 0^t + F_K(\text{history})$

Wrap taking metadata $A \in \mathbb{Z}_2^*$ and plaintext $P \in \mathbb{Z}_2^*$
$C \leftarrow P + F_K(\text{history}) \ll t$
history $\leftarrow A||0||e \circ$ history
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Other applications

Using a deck function:

- Deck-SANE: session AE relying on user nonce
- Deck-SANSE: session AE using SIV technique
- Deck-WBC: tweakable wide block cipher

Any questions?

Thanks for your attention!

`https://keccak.team/`