Permutation-based encryption, authentication and authenticated encryption

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Joint work with
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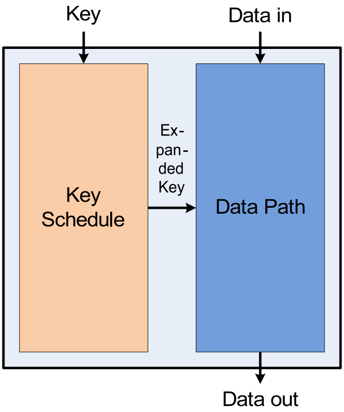
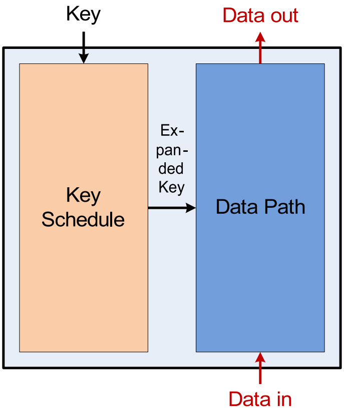
Modern-day cryptography is block-cipher centric

- (Standard) hash functions make use of block ciphers
  - SHA-1, SHA-256, SHA-512, Whirlpool, RIPEMD-160, ...
  - So HMAC, MGF1, etc. are in practice also block-cipher based
- Block encryption: ECB, CBC, ...
- Stream encryption:
  - synchronous: counter mode, OFB, ...
  - self-synchronizing: CFB
- MAC computation: CBC-MAC, C-MAC, ...
- Authenticated encryption: OCB, GCM, CCM ...

Structure of a block cipher



Structure of a block cipher (inverse operation)



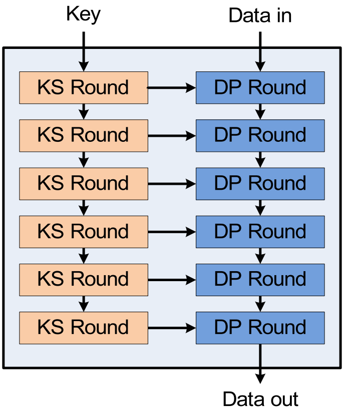
When is the inverse block cipher needed?

Indicated in red:

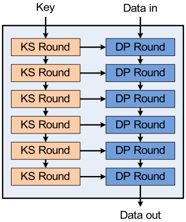
- Hashing and its modes HMAC, MGF1, ...
- Block encryption: ECB, CBC, ...
- Stream encryption:
  - synchronous: counter mode, OFB, ...
  - self-synchronizing: CFB
- MAC computation: CBC-MAC, C-MAC, ...
- Authenticated encryption: OCB, GCM, CCM ...

So a block cipher without inverse can do a lot!

Block cipher internals



Designer's view of a block cipher

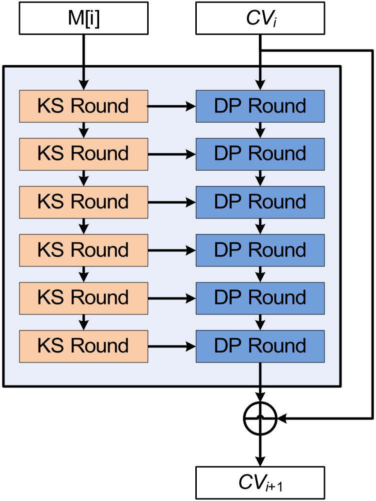


n-bit block cipher with $|K|$-bit key

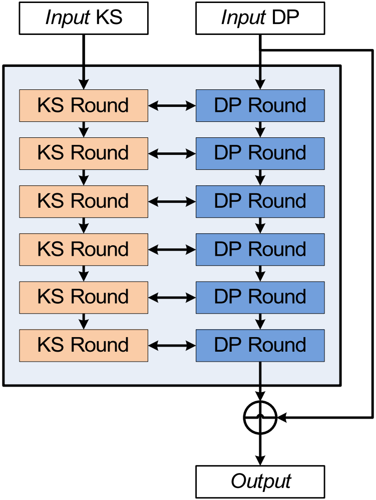
b-bit permutation with $b = n + |K|$

- obtained by repeating an invertible round function
- with an efficient inverse
- and no diffusion from data part to key part

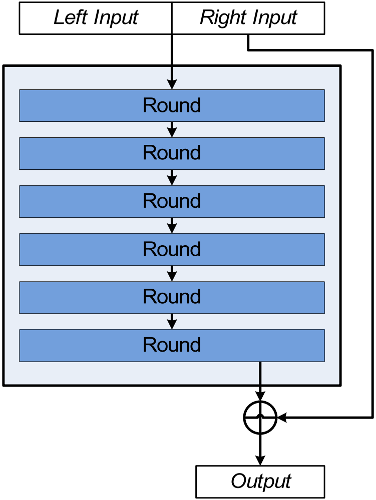
Hashing use case: Davies-Meyer compression function



Removing diffusion restriction not required in hashing



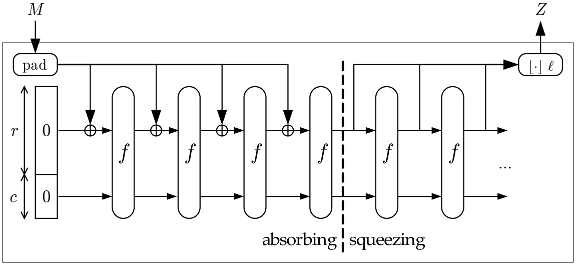
Simplifying the view: iterated permutation



Block cipher without inverse: wide permutation

- Previous applies to all modes where inverse is not needed
- Requirement of separate key schedule vanishes
- n-bit block cipher replaced by b-bit permutation with
  - $b = n + |K|$
- Permutation as a generalization of a block cipher
- Less is more!

Permutation-based construction: sponge



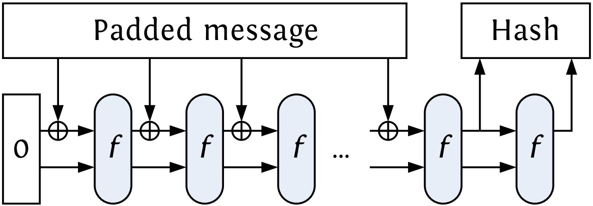
sponge

- f: a b-bit permutation with $b = r + c$
  - efficiency: processes r bits per call to f
  - security: provably resists generic attacks up to $2^{c/2}$
- Flexibility in trading rate r for capacity c or vice versa

What can we say about sponge security

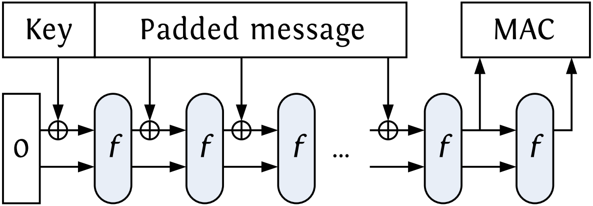
- Generic security:
  - assuming f has been chosen randomly
  - covers security against generic attacks
  - construction as sound as theoretically possible
- Security for a specific choice of f
  - security proof is infeasible
  - Hermetic Sponge Strategy
  - design with attacks in mind
  - security based on absence of attacks despite public scrutiny

Regular hashing



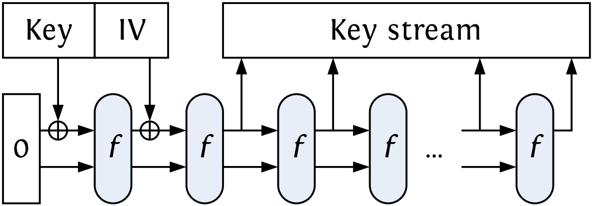
- Pre-sponge permutation-based hash functions
  - Truncated permutation as compression function: Snefru [Merkle '90], FFT-Hash [Schnorr '90], ...MD6 [Rivest et al. 2007]
  - Streaming-mode: SUBTERRANEAN, PANAMA, RADIOGATÚN, Grindahl [Knudsen, Rechberger, Thomsen, 2007], ...

Message authentication codes



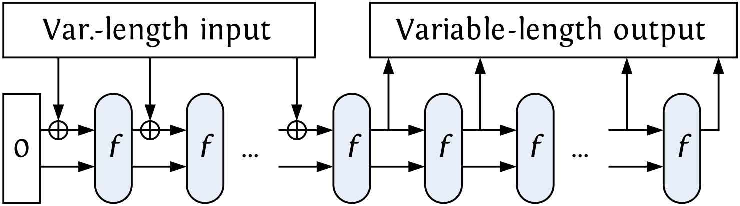
- Pre-sponge (partially) permutation-based MAC function: Pelican-MAC [Daemen, Rijmen 2005]

Stream encryption

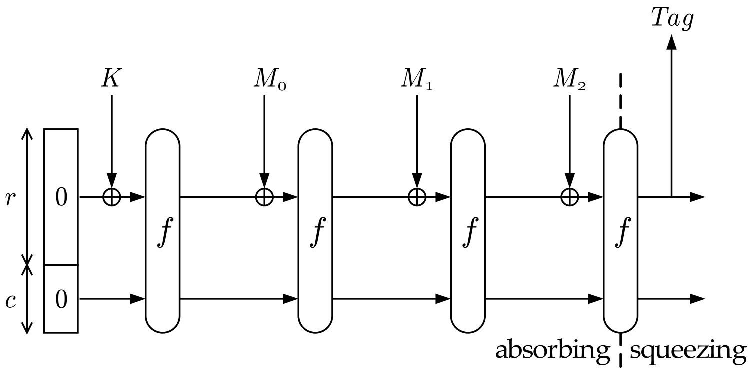


- Similar to block cipher modes:
  - Long keystream per IV: like OFB
  - Short keystream per IV: like counter mode
- Independent permutation-based stream ciphers: Salsa and ChaCha [Bernstein 2007]

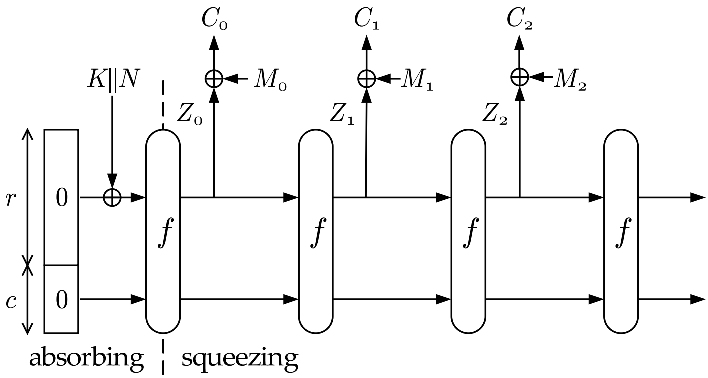
Mask generating function



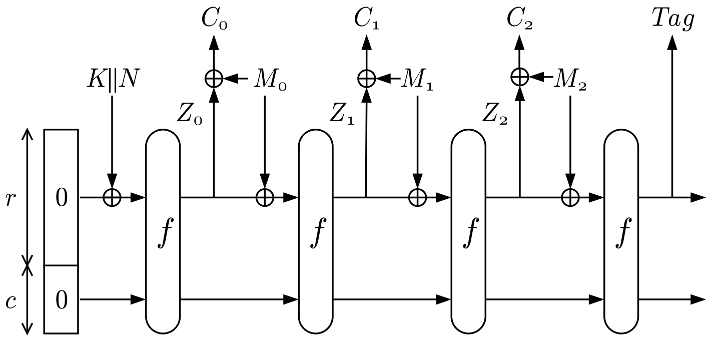
Authenticated encryption: MAC generation



Authenticated encryption: encryption

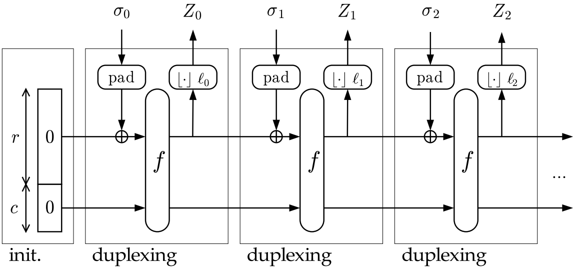


Authenticated encryption: just do them both?



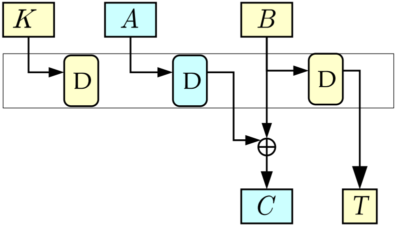
Absorbing and squeezing

The duplex construction



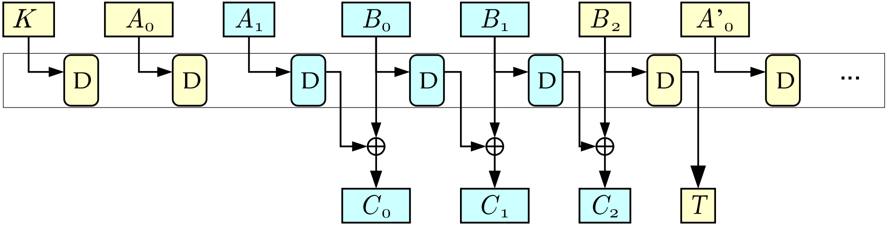
- Object: $D = \text{DUPLEX}[f, \text{pad}, r]$
- Requesting ℓ-bit output $Z = D.\text{duplexing}(\sigma, \ell)$
- Generic security equivalent to that of sponge

SpongeWrap authenticated encryption



- Single-pass authenticated encryption
- Processes up to r bits per call to f
- Functionally similar to (P)helix [Lucks, Muller, Schneier, Whiting, 2004]

The SpongeWrap mode



- Key K, data header A and data body B of arbitrary length
- Confidentiality assumes unicity of data header
- Supports intermediate tags

Sponge functions: existing proposals to date

KECCAK	Bertoni, Daemen, Peeters, Van Assche	SHA-3 2008	25, 50, 100, 200 400, 800, 1600
Quark	Aumasson, Henzen, Meier, Naya-Plasencia	CHES 2010	136, 176 256
Photon	Guo, Peyrin, Poschmann	Crypto 2011	100, 144, 196, 256, 288
Spongent	Bogdanov, Knezevic, Leander, Toz, Varici, Verbauwhede	CHES 2011	88, 136, 176 248, 320

The current perception

- Quark, Photon, Spongent: *lightweight hash functions*
- Lightweight is synonymous with low-area here
- Easy to see why. Let us target security strength $c/2$
  - Davies-Meyer block cipher based hash ("narrow pipe")
    - chaining value (block size): $n \geq c$
    - input block size (*key* length): typically $k \geq n$
    - feedforward (block size): n
    - total state $\geq 3c$
  - Sponge ("huge state")
    - permutation width: $c + r$
    - r can be made arbitrarily small, e.g. 1 byte
    - total state $\geq c + 8$

The current perception (continued)

One cryptographic expert's opinion:

"The sponge construction is a pretty poor way to encrypt. One either gets high-speed but low security or low-speed and high security."

- KECCAK showed that sponge can be secure *and* fast
- Keyed sponge still perceived as *possible* but *inefficient*
  - higher speed expected from MAC and stream encryption
  - competing proposals in keyed applications are faster

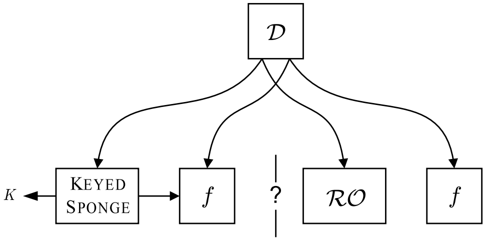
Permutations vs block ciphers

- Unique block cipher features
  - pre-computation of key schedule
    - storing expanded key costs memory
    - may be prohibitive in resource-constrained devices
  - misuse resistance
    - issue: keystream re-use in stream encryption
    - not required if nonces are affordable or available
    - address it with decent nonce management
- Unique permutation features
  - diffusion across full state
  - flexibility in choice of rate/capacity

Boosting keyed permutation modes

- Taking a closer look at rate/capacity trade-off
  - keyed generic security is $c - a$ instead of $c/2$
  - with 2^a ranging from data complexity down to 1
  - allows increasing the rate
- Distinguishing vulnerability in keyed vs unkeyed modes
  - in keyed modes attacker has less power
  - allows decreasing number of rounds in permutation
- Introducing dedicated variants
  - MAC computation
  - authenticated encryption strongly relying on nonces

Distinguishing attack setup

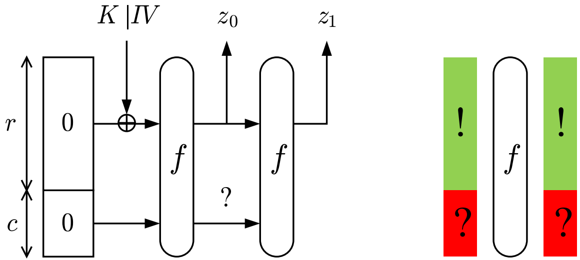


- M: online **data** complexity (r-bit blocks)
- N: offline **time** complexity (calls to f)

If $M = 2^a \ll 2^{c/2}$

Expected time complexity is about $\min\left(2^{c-a-1}, 2^{|K|}\right)$

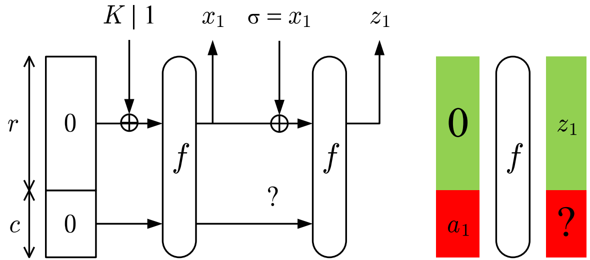
Intuition behind 2^{c-a-1}



CICO problem:

- given r input and r output to f, determine remaining c bits
- expected workload: 2^c computations of f

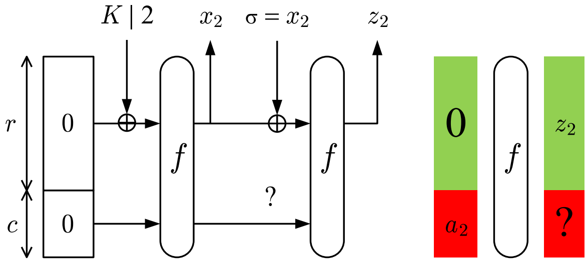
Intuition behind 2^{c-a-1}



Multi-target CICO problem (with multiplicity μ):

- μ instances with same partial r-bit input
- expected workload: $2^c/\mu$ computations of f

Intuition behind 2^{c-a-1}



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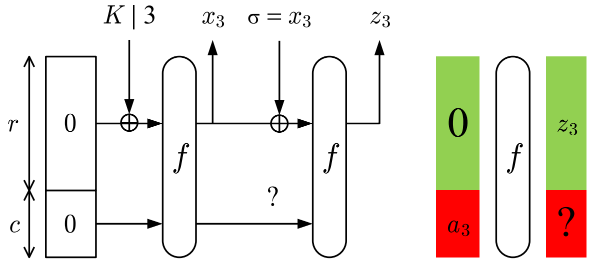

Multi-target CICO problem (with multiplicity μ):

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Intuition behind 2^{c-a-1}: multiplicity

- Multiplicity μ:
  - # CICO instances with same r-bit part
  - Upper bound: $\mu \leq 2^a$
- In most modes attacker cannot force high multiplicity
  - MAC computation: absolute input unknown
  - keystream generation: each r-bit input different
  - authenticated encryption, passive attacker
- Counting on collisions in r-bit (input or output) part
  - If $a \lll r$, multiplicity μ small
  - if $a > r$, multiplicity μ of order 2^{a-r}

Numeric example

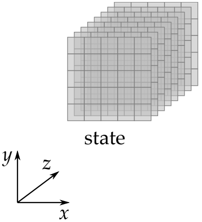
- Say we have the following requirements:
  - we have a permutation with width 200 bits
  - we want to realize different functions
  - desired security strength: 80 bits
  - we assume active adversary, limited to 2^{48} data complexity
- Collision-resistant hashing: $c = 2 \times 80 \Rightarrow r = 40$
- SpongeWrap: $c = 80 + 48 + 1 \Rightarrow r = 71$
- MAC computation: $c = 80 \Rightarrow r = 120$

Unkeyed modes weaker than keyed modes?

- MD5 hash function [Rivest 1992]
  - unkeyed: collisions usable in constructing fake certificates [Stevens et al. 2009]
  - keyed: very little progress in 1st pre-image generation
- PANAMA hash and stream cipher [Clapp, Daemen 1998]
  - unkeyed: instantaneous collisions [Daemen, Van Assche 2007]
  - keyed: stream cipher unbroken till this day
- KECCAK crypto contest with reduced-round challenges
  - unkeyed: collision challenges up to 4 rounds broken [Dinur, Dunkelman, Shamir 2012]
  - keyed: 1st pre-image challenges up to 2 rounds broken [Morawiecki 2011]

KECCAK-f: the permutations in KECCAK

Operates on 3D state:



- (5×5)-bit slices
- 2^ℓ-bit lanes
- param. $0 \leq \ell < 7$

- Round function with 5 steps:
  - θ: mixing layer
  - ρ: inter-slice bit transposition
  - π: intra-slice bit transposition
  - χ: non-linear layer
  - ι: round constants
- Lightweight, but high diffusion
- $\#$ rounds: $12 + 2\ell$ for $b = 2^\ell 25$
  - 12 rounds in KECCAK-$f[25]$
  - 24 rounds in KECCAK-$f[1600]$
- High safety margin, even if unkeyed

KECCAK: reference versions

- KECCAK with default parameters: KECCAK[]
  - width $b = 1600$: largest version
  - rate $r = 1024$: a round number
  - gives generic security strength $c/2 = 288$ bits
  - roughly 7 % slower than the KECCAK SHA-3 256-bit candidate
  - For performance see eBash, Athena, XBX, etc.
- KECCAK[r=40, c=160]
  - width $b = 200$: small state
  - $c = 160$, generic security strength 80 bits
  - gives rate of $r = 40$
  - roughly 2.4 more work per input/output bit than KECCAK

KECCUP: reduced-round versions of KECCAK

- For keyed modes use reduced-round versions of KECCAK-f
  - called KECCUP$[r, c, n]$ and KECCUP-$f[b, n]$
  - we assume that the multiplicity is below 2^{64}
- Same can be done for any iterated permutation
  - Quark, Photon, Spongent
  - JH's E8
  - Gröstl's P512, Q512, P1024, Q1024
  - ECHO, Cubehash, etc.
  - block cipher with fixed key: e.g., Rijndael

Keyed sponge and duplex with KECCUP

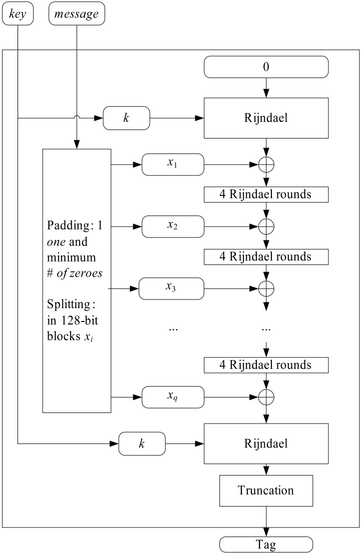
Some KECCUP varieties that we think are reasonable:

width b	strength $\|K\|$	capacity c	rate r	# rounds	speedup
1600	128	192	1408	10	3.3
1600	256	320	1280	11	2.7
200	80	144	56	9	2.8
200	128	192	8	6	0.6

Introducing dedicated variants

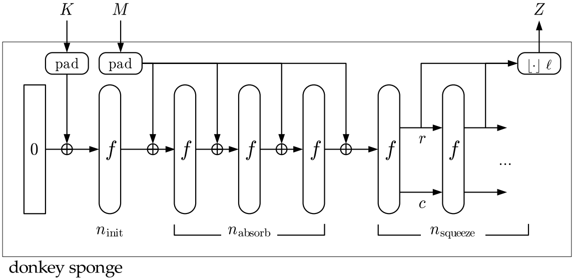
- Sponge and duplex are generic constructions
  - flexible and multi-purpose
  - do not exploit mode-specific adversary limitations
- MAC computation
  - before squeezing adversary has no information about state
  - relaxes requirements on f during absorbing
- Authenticated encryption in presence of nonces
  - nonce can be used to *decorrelate* computations

MAC: take a look at Pelican-MAC [Daemen, Rijmen, 2005]



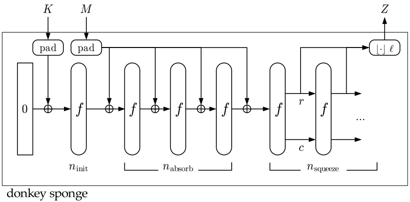
- Block cipher based MAC
  - application of Alred
  - based on Rijndael (AES)
  - permutation-based absorbing
- Speed: for long messages:
  - 4 rounds per 128 bits
  - 2.5 times faster than AES
- Security rationale
  - key recovery: block cipher
  - secret state recovery:
    - block cipher at the end
    - hardness of inner collisions
    - relies on low MDP of AES 4R
    - security claims with $2^a \leq 2^{60}$

The donkeySponge MAC construction



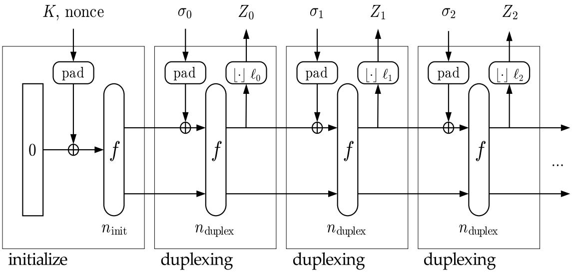
- Usage of full state width *b* during absorbing
- Reduced number of rounds during init and absorbing
- Truncated permutation instead of final block cipher

Applying donkeySponge to KECCUP



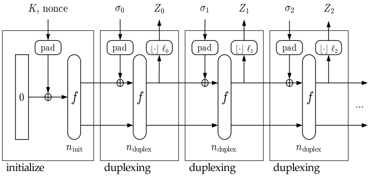
- KECCUP proposed values:
  - $n_{\text{init}} = 3$: sufficient to make all state bits depend on the key
  - $n_{\text{absorb}} = 6$: dictated by MDP estimation
  - $n_{\text{squeeze}} = 12$: dictated by chosen-input-difference attacks
- $b = 1600$ and $|K| = 256$: gains factor 6.25
- $b = 200$ and $|K| = 128$: gains factor 15

The monkeyDuplex construction



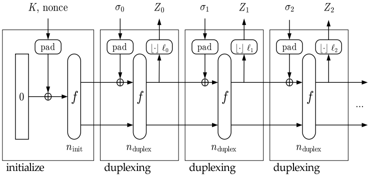
- For authenticated encryption and keystream generation
- Initialization: key, nonce and strong permutation
- reduced number of rounds in duplex calls

monkeyDuplex rationale



- Initialization
  - decorrelates states for different nonces
  - is assumed to rule out differential attacks
- Remaining attack: state reconstruction
  - high rate: solving CICO problem
  - low rate: multiple iterations of f must be considered
  - Number of rounds to span: n_{unicity}

Some monkeyDuplex KECCAK varieties



- $n_{\text{init}} = 12$: dictated by chosen-input-difference attacks
- For $b = 200$ we propose $n_{\text{duplex}} = 1$: streaming mode
- For $b = 1600$ we propose $2r > b$: blockwise mode

b	$\|K\|$	c	r	n_{duplex}	n_{unicity}	speedup
1600	256	320	1280	8	8	3.75
200	80	184	16	1	12	7.2

Conclusions

- Iterated permutations
  - versatile cryptographic primitives
  - more flexible modes than with block ciphers
- Permutation-based keyed modes can be boosted
  - generic security: reducing capacity from $2|K|$ to $|K| + a$
  - permutation-specific security: reducing $\#$ rounds
  - mode-specific security: dedicated constructions

Questions?

Thanks for your attention!

Q?

More information on
http://keccak.noekeon.org/
http://sponge.noekeon.org/