Permutation-based symmetric cryptography and KECCAK

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Joint work with
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Passwords^12, Oslo, 3 December 2012

Outline

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Symmetric crypto: what textbooks and intro's say

Symmetric cryptographic primitives:

- Block ciphers
- Stream ciphers
  - Synchronous
  - Self-synchronizing
- Hash functions
  - Non-keyed
  - Keyed: MAC functions

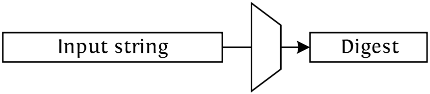
And their modes-of-use

The hash function cliché

Hash functions:

Cryptographic hash functions

- Function h
  - from any binary string $\{0,1\}^*$
  - to a fixed-size digest $\{0,1\}^n$
  - **One-way**: given $h(x)$ hard to find x…



- Applications in cryptography
  - *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*: $h(\text{what I know})$
  - *Message authentication*: $h(K\|M)$
  - …

A closer look at mainstream hash functions

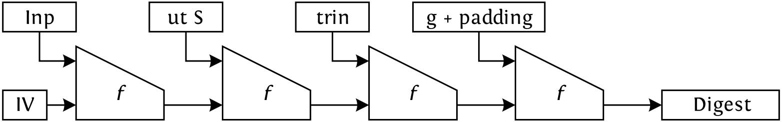
- Attempts at direct design of hash function are rare
- Mainstream hash functions have two layers:
  - Fixed-input-length compression function
  - Iterating mode: *domain extension*

Examples of popular hash functions

- MD5: $n = 128$
  - Published by Ron Rivest in 1992
  - Successor of MD4 (1990)
- SHA-1: $n = 160$
  - Designed by NSA, standardized by NIST in 1995
  - Successor of SHA-0 (1993)
- SHA-2: family supporting multiple lengths
  - Designed by NSA, standardized by NIST in 2001
  - 4 members named SHA-n
  - SHA-224, SHA-256, SHA-384 and SHA-512

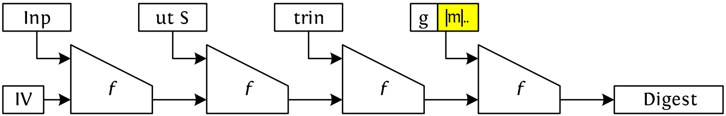
The chaining structure: Merkle-Damgård

- Simple iterative construction:
  - iterative application of compression function (CF)
- Proven collision-resistance preserving



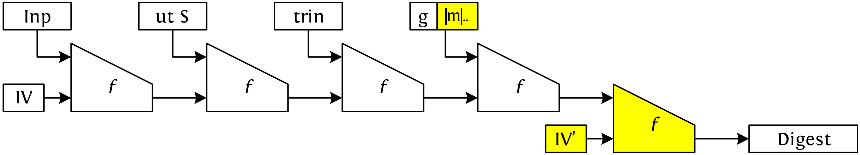
Merkle-Damgård strengthening

- Input length added to the input string



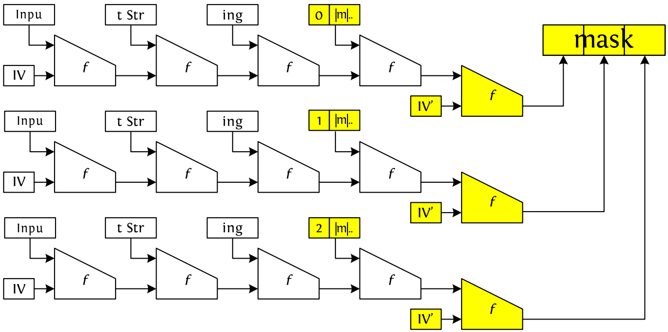
Enveloped Merkle-Damgård

- Special processing for last call

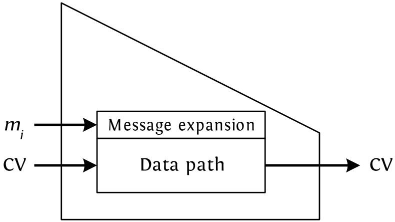


Variable-output-length Merkle-Damgård

- Mask generating function (MGF)



The compression function: Davies-Meyer (nearly)

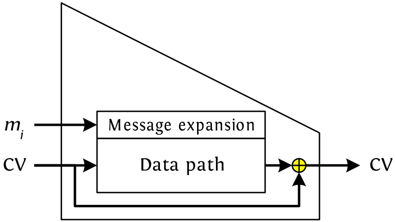


Uses a block cipher:

- Separated data path and message expansion

But not one-way!

The compression function: Davies-Meyer



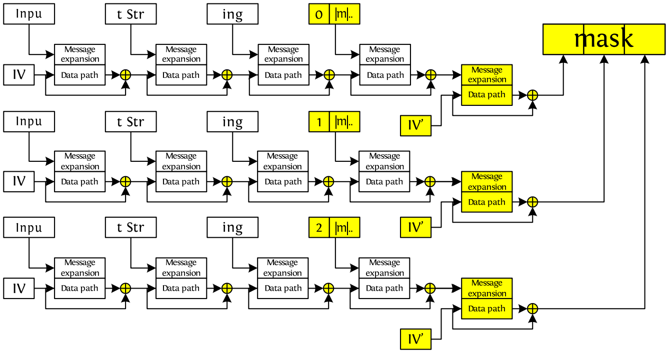
Uses a block cipher:

- Separated data path and message expansion

Some feedforward due to Merkle-Damgård

Combining them all

- A block cipher in a very complex mode of use...



Other uses of block ciphers

- Hashing (as discussed) 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 ...

The truth about symmetric crypto today

Block ciphers:

Back to mainstream hashing: the basic operations

- All popular hash functions were based on ARX
  - addition modulo 2^n with $n = 32$ (and $n = 64$)
  - bitwise addition: XOR
  - bitwise shift operations, cyclic shift
  - security: "algebraically incompatible operations"
- ARX would be elegant
  - ...but silently assumes a specific integer coding
- ARX would be efficient
  - ...but only in software on CPUs with n-bit words
- ARX would have good cryptographic properties
  - but is very hard to analyze
  - ...attacks have appeared after years

Trouble in paradise

- 1991-1993: Den Boer and Bosselaers attack MD4 and MD5
- 1996: Dobbertin improves attacks on MD4 and MD5
- 1998: Chabaud and Joux attack SHA-0
- 2004: Joux et al. break SHA-0
- 2004: Wang et al. break MD5
- 2004: Joux show multicollisions on Merkle-Damgård
- 2005: Lenstra et al., and Klima, make MD5 attack practical
- 2005: Wang et al. theoretically break SHA-1
- 2005: Kelsey and Schneier: 2nd pre-image attacks on MD
- 2006: De Cannière and Rechberger further break SHA-1
- 2006: Kohno and Kelsey: herding attacks on MD

Outline

A way out of the hash function crisis

- 2005-2006: trust in established hash functions was crumbling, due to
  - use of ARX
  - adoption of Merkle-Damgård
  - and SHA-2 were based on the same principles
- 2007: NIST calls for SHA-3
  - similar to AES contest
  - a case for the international cryptographic community!

SHA-3 contest

- Open competition organized by NIST
  - NIST provides forum
  - scientific community contributes: designs, attacks, implementations, comparisons
  - NIST draws conclusions and decides
- Goal: replacement for the SHA-2 family
  - 224, 256, 384 and 512-bit output sizes
  - other output sizes are optional
- Requirements
  - security levels specified for traditional attacks
  - each submission must have
    - complete documentation, including design rationale
    - reference and optimized implementations in C

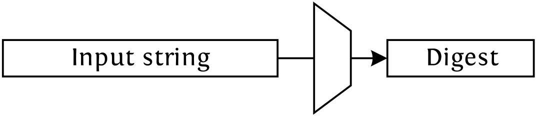
SHA-3 time schedule

- January 2007: initial call
- October 2008: submission deadline
- February 2009: first SHA-3 conference in Leuven
  - Presentation of 1st round candidates
- July 2009: NIST announces 2nd round candidates
- August 2010: second SHA-3 conference in Santa Barbara
  - cryptanalytic results
  - hardware and software implementation surveys
  - new applications
- Dec. 2010: finalists are Blake, Grøstl, JH, KECCAK and Skein
- March 2012: final SHA-3 conference
- October 2, 2012: and the winner is: KECCAK

Outline

Traditional security requirements of hash functions

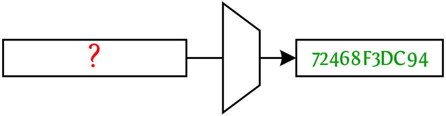
- Function h from $\mathbf{Z}_2^*$ to $\mathbf{Z}_2^n$



- Security requirements
  - pre-image resistance
  - 2nd pre-image resistance
  - collision resistance

Pre-image resistance

- Given $y \in \mathbf{Z}_2^n$, find $x \in \mathbf{Z}_2^*$ such that $h(x) = y$
- **Example**: given derived key $K_1 = h(K \| 1)$, find master key K



- There exists a generic attack requiring about ...?... calls to h
- Requirement: there is no attack more efficient

Pre-image resistance

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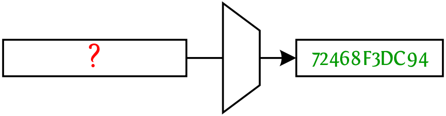
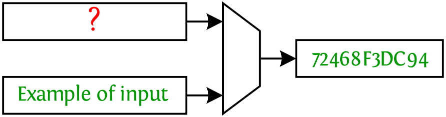


- There exists a generic attack requiring about 2^n calls to h
- Requirement: there is no attack more efficient

2nd pre-image resistance

- Given $x \in \mathbf{Z}_2^*$, find $x' \neq x$ such that $h(x') = h(x)$
- **Example**: signature forging
  - given M and sign$(h(M))$, find another M' with equal signature



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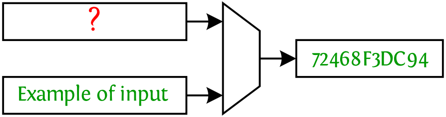

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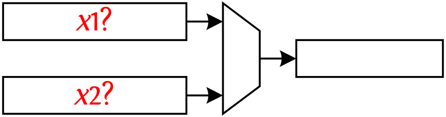

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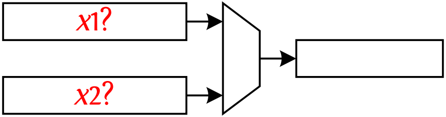


- There exists a generic attack requiring about $2^{n/2}$ calls to h
  - Birthday paradox: among 23 people, two have the same birthday (with 50% probability)
  - Scales as $\sqrt{|\text{range}|} = 2^{n/2}$

Other requirements

- What if we use a hash function in other applications?
- To build a MAC function, e.g., HMAC (FIPS 198)
- To destroy algebraic structure, e.g.,
  - encryption with RSA: OAEP (PKCS #1)
  - signing with RSA: PSS (PKCS #1)
- Problem:
  - additional requirements on top of traditional ones
  - how to know what a hash function is designed for?

Contract

- Security of a concrete hash function *h* cannot be proven
  - sometimes reductions are possible...
  - rely on public scrutiny!
- Security claim: contract between designer and user
  - security claims $\geq$ security requirements
  - attack that invalidates claim, breaks *h*!
- Claims often implicit
  - e.g., the traditional security requirements are implied

List of claimed properties

- Security claims by listing desired properties
  - collision resistant
  - (2nd) pre-image resistant
  - correlation-free
  - resistant against length-extension attacks
  - chosen-target forced-prefix pre-image resistance
  - ...
- But ever-growing list of desired properties
- Moving target as new applications appear over time

But hey, the ideal hash function exists!

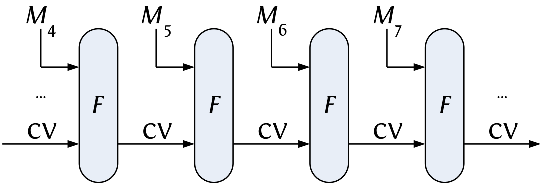
Random oracle $\mathcal{RO}$

- A random oracle [Bellare-Rogaway 1993] maps:
  - message of variable length
  - to an infinite output string
- Supports queries of following type: (M, ℓ)
  - M: message
  - ℓ: requested number of output bits
- Response Z
  - String of ℓ bits
  - Independently and identically distributed bits
  - Self-consistent: equal M give matching outputs

Compact security claim

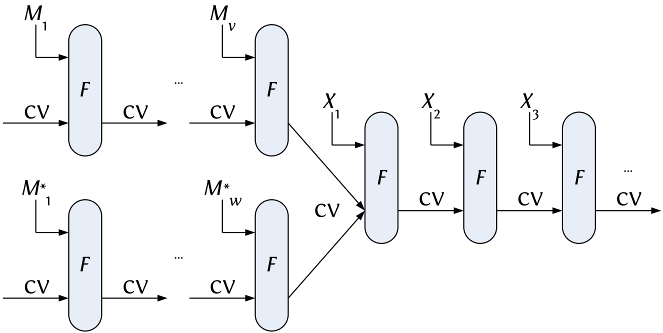
- Truncated to n bits, $\mathcal{RO}$ has all desired properties, e.g.,
  - Generating a collision: $2^{n/2}$
  - Finding a (2nd) pre-image: 2^n
  - And [my chosen requirement]: $f(n)$
- Proposal for a compact security claim:
  - "My function h behaves as a **random oracle**"
- Does not work, unfortunately

Iterated hash functions



- All practical hash functions are iterated
  - Message M cut into blocks $M_1, \ldots, M_l$
  - q-bit chaining value
- Output is function of final chaining value

Internal collisions!



- Difference inputs M and M' giving the same chaining value
- Messages $M||X$ and $M'||X$ always collide for any string X

Trouble in paradise

- 2004: Joux show multicollisions on Merkle-Damgård
- 2005: Kelsey and Schneier: 2nd pre-image attacks on MD
- 2006: Kohno and Kelsey: herding attacks on MD

- All due to internal collisions
- *Narrow pipe* means $q = n$

How to deal with internal collisions?

- $\mathcal{RO}$ has no internal collisions
  - If truncated to n bits, it does have collisions, say M and M'
  - But $M||X$ and $M'||X$ collide only with probability 2^{-n}
  - Random oracle has "infinite memory"
- Abandon *iterated modes* to meet the $\mathcal{RO}$ ideal?
  - In-memory hashing, non-streamable hash functions?
  - Model for finite memory, internal collisions!

Variable output-length functions

- Variable-length output:
  - Single function for different hash function lengths
  - Useful, e.g., for signatures, “mask generating functions”
  - Stream cipher
- Exponential scaling of the security requirements?!?

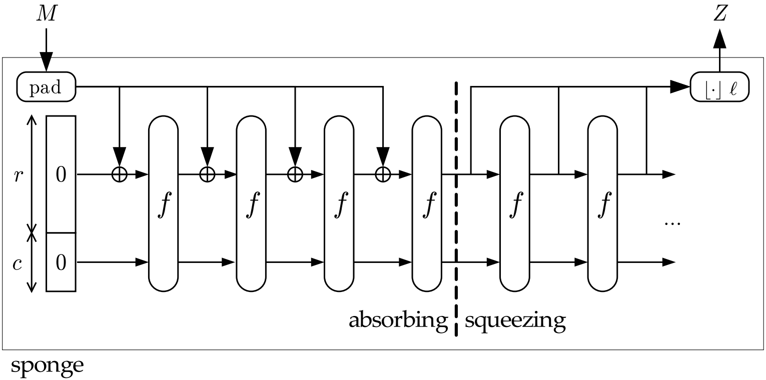
Pre-image resistance	2^n ?
2nd pre-image resistance	2^n ?
Collision resistance	$2^{n/2}$?

How to have a compact security claim?

- Try to define some *thing* Π that
  - has the same interface as $\mathcal{RO}$
  - behaves like $\mathcal{RO}$ ...
  - ...modulo internal collisions
- Strength of Π depends on some (size) parameters
- Compact security claim would then be:
  - "My function h behaves as a Π with given size parameters"
- Output length no longer appears in security claim
- What could Π be?

Outline

The sponge construction



- r bits of *rate*
- c bits of *capacity*

Random sponges

- Random T-sponge
  - f chosen randomly from $(2^{r+c})^{2^{r+c}}$ transformations
- Random P-sponge
  - f chosen randomly from $(2^{r+c})!$ permutations
- Random sponges become our reference Π

Like a random oracle below $2^{c/2}$

Random sponge functions are secure against attacks with $< 2^{c/2}$ calls to f

Flat sponge claim

Simplifying the claim to a single parameter

Flat sponge claim with claimed capacity c

The success probability of any attack on h satisfies:

$$\Pr_{h}(\text{success}) \leq \Pr_{\mathcal{RO}}(\text{success}) + \frac{N^2}{2^{c+1}} ,$$

with

- $\Pr_{\mathcal{RO}}(\text{success})$: of that attack on a random oracle
- N: attack workload expressed as number of calls to f.

What does a flat sponge claim state?

- Example: $c = 256$
- $N^2 / 2^{257}$ becomes significant when $N \approx 2^{128}$
- Collision-resistance:
  - Similar to that of random oracle up to $n = 256$
  - Maximum achievable security level: 2^{128}
- (2nd) pre-image resistance:
  - Similar to that of random oracle up to $n = 128$
  - Maximum achievable security level: 2^{128}
- Flat sponge claim forms a ceiling to the security claim

The NIST SHA-3 security requirements

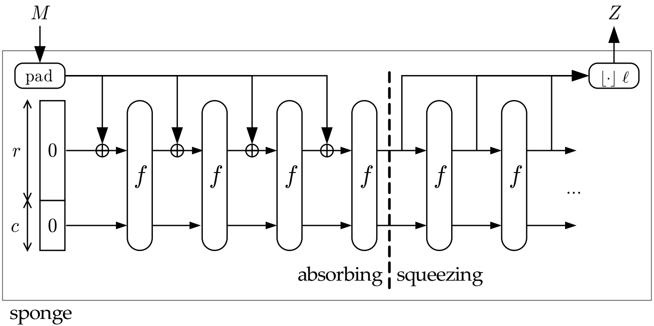
Output length	224	256	384	512
Collision resistance	2^{112}	2^{128}	2^{192}	2^{256}
Pre-image resistance	2^{224}	2^{256}	2^{384}	2^{512}
2nd pre-image resistance	$2^{224}/\ell$	$2^{256}/\ell$	$2^{384}/\ell$	$2^{512}/\ell$

$\ell =$ message length

Designing a hash function

- What about using the sponge construction as mode of operation?

The hermetic sponge strategy



Hermetic sponge strategy

Adopting the sponge construction and building an permutation f that should not have any structural distinguishers.

Outline

The beginning

- SUBTERRANEAN: Daemen (1991)
    - variable-length input and output
    - hashing and stream cipher
    - round function interleaved with input/output
- STEPRIGHTUP: Daemen (1994)
- PANAMA: Daemen and Clapp (1998)
- RADIOGATÚN: KECCAK team (2006)
    - experiments did not inspire confidence in RADIOGATÚN
    - NIST SHA-3 deadline approaching ...
    - U-turn: design a sponge with strong permutation f
- KECCAK (2008)

Designing the permutation KECCAK-f

Our mission

To design a permutation called KECCAK-f that cannot be distinguished from a random permutation.

- Classical LC/DC criteria
  - absence of large differential propagation probabilities
  - absence of large input-output correlations
- Immunity to
  - integral cryptanalysis
  - algebraic attacks
  - slide and symmetry-exploiting attacks
  - ...

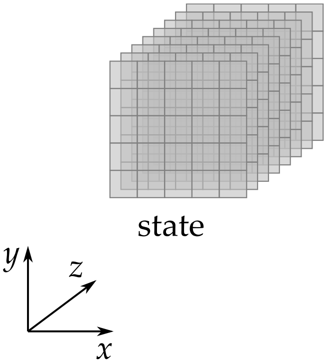
Designing the permutation KECCAK-f

- Permutation width b?
  - long term: *security strength* up to 256 bits
  - capacity up to 512 bits
  - rate: $r = b - 512$ bits
  - width ranges from 600 to 2400 bits
- Like a block cipher
  - sequence of identical rounds
  - round function that is nonlinear and has good diffusion
- ...but not quite
  - no need for key schedule
  - round constants instead of round keys
  - inverse permutation need not be efficient

KECCAK

- Instantiation of a *sponge function*
- KECCAK uses a permutation KECCAK-*f*
    - 7 permutations: $b \in \{25, 50, 100, 200, 400, 800, 1600\}$
- Security-speed trade-offs using the same permutation
- Examples
    - SHA-3: $r = 1024$ and $c = 576$ for $2^{c/2} = 2^{288}$ security
    - lightweight: $r = 40$ and $c = 160$ for $2^{c/2} = 2^{80}$ security

The state: an array of $5 \times 5 \times 2^\ell$ bits



- 5×5 lanes, each containing 2^ℓ bits (1, 2, 4, 8, 16, 32 or 64)
- (5×5)-bit slices, 2^ℓ of them

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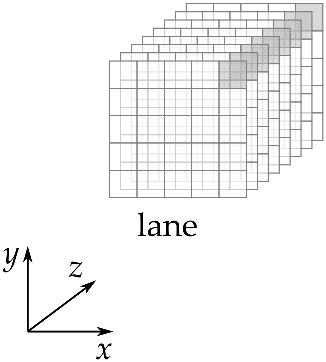

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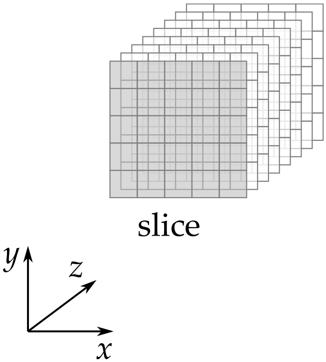

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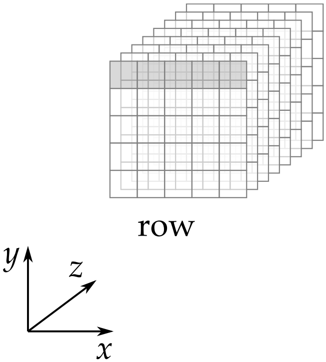

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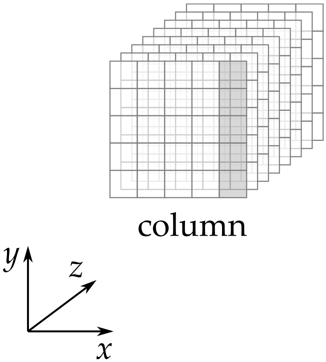

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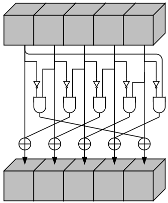
χ, the nonlinear mapping in KECCAK-f

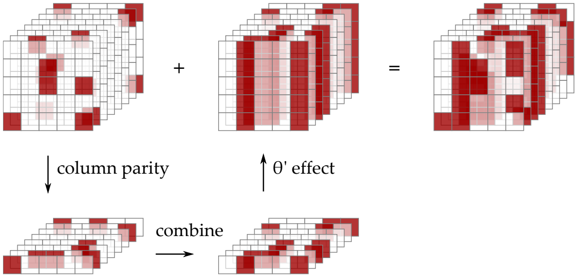


- “Flip bit if neighbors exhibit 01 pattern”
- Operates independently and in parallel on 5-bit rows
- Algebraic degree 2, inverse has degree 3
- LC/DC propagation properties easy to describe and analyze

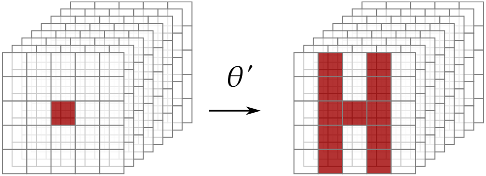
θ', a first attempt at mixing bits

- Compute parity $c_{x,z}$ of each column
- Add to each cell parity of neighboring columns:

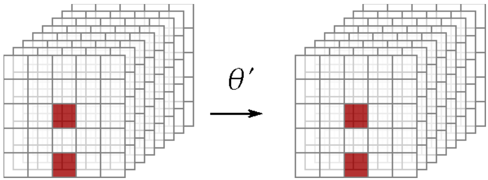
$$b_{x,y,z} = a_{x,y,z} \oplus c_{x-1,z} \oplus c_{x+1,z}$$



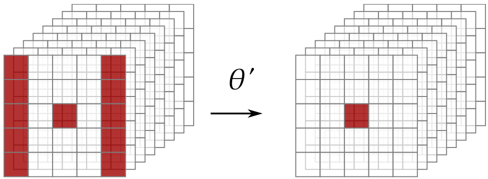
Diffusion of θ'



Diffusion of θ' (kernel)



Diffusion of the inverse of θ'

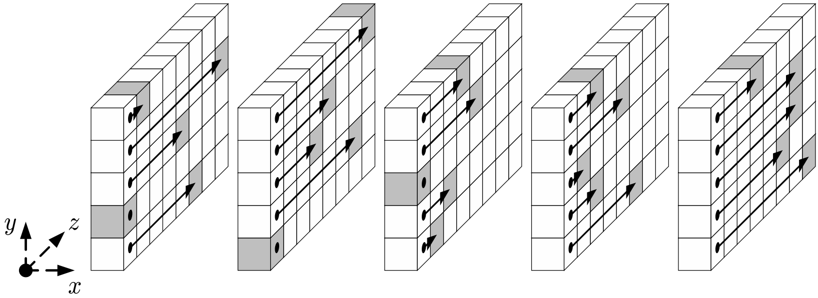


ρ for inter-slice dispersion

- We need diffusion between the slices …
- ρ: cyclic shifts of lanes with offsets

$$i(i+1)/2 \bmod 2^{\ell}$$

- Offsets cycle through all values below 2^{ℓ}

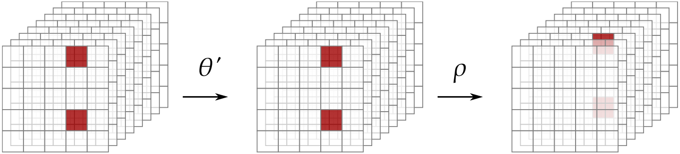


ι to break symmetry

- XOR of round-dependent constant to lane in origin
- Without ι, the round mapping would be symmetric
  - invariant to translation in the z-direction
- Without ι, all rounds would be the same
  - susceptibility to *slide* attacks
  - defective cycle structure
- Without ι, we get simple fixed points (000 and 111)

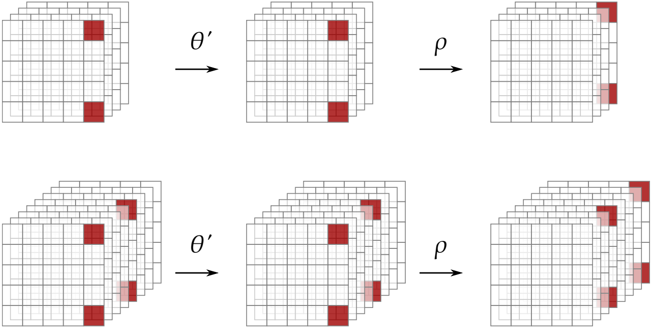
A first attempt at KECCAK-f

- Round function: $\mathrm{R} = \iota \circ \rho \circ \theta' \circ \chi$
- Problem: low-weight periodic trails by chaining:



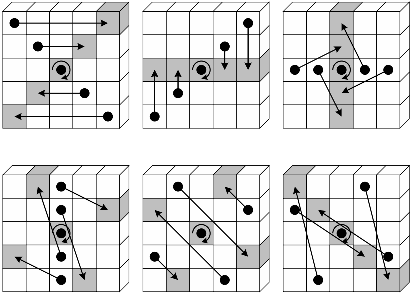
- χ: may propagate unchanged
- θ': propagates unchanged, because all column parities are 0
- ρ: in general moves active bits to different slices ...
- ...but not always

The Matryoshka property



- Patterns in Q' are z-periodic versions of patterns in Q

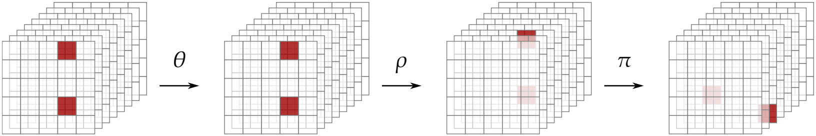
π for disturbing horizontal/vertical alignment



$$a_{x,y} \leftarrow a_{x',y'} \text{ with } \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 2 & 3 \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix}$$

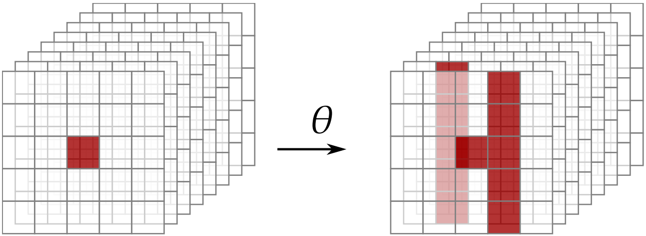
A second attempt at KECCAK-f

- Round function: $\mathrm{R} = \iota \circ \pi \circ \rho \circ \theta' \circ \chi$
- Solves problem encountered before:

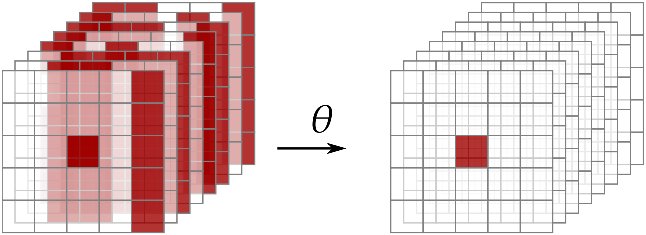


- π moves bits in same column to different columns!

Tweaking θ' to θ



Inverse of θ



- Diffusion from single-bit output to input very high
- Increases resistance against LC/DC and algebraic attacks

KECCAK-*f* summary

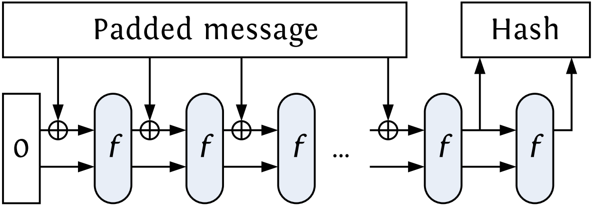
- Round function:

$$\mathrm{R} = \iota \circ \chi \circ \pi \circ \rho \circ \theta$$

- Number of rounds: $12 + 2\ell$
  - KECCAK-$f[25]$ has 12 rounds
  - KECCAK-$f[1600]$ has 24 rounds
- Efficiency
  - high level of parallellism
  - flexibility: bit-interleaving
  - software: competitive on wide range of CPU
  - dedicated hardware: very competitive
  - suited for protection against side-channel attack

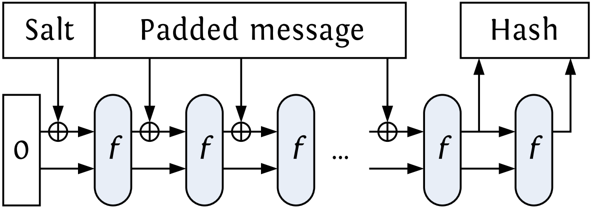
Outline

How to use a sponge function?



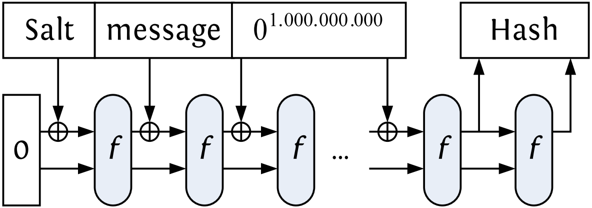
- For regular hashing

How to use a sponge function?



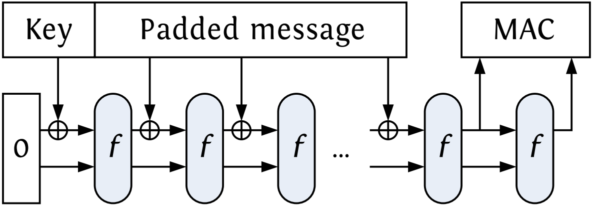
- For salted hashing

How to use a sponge function?



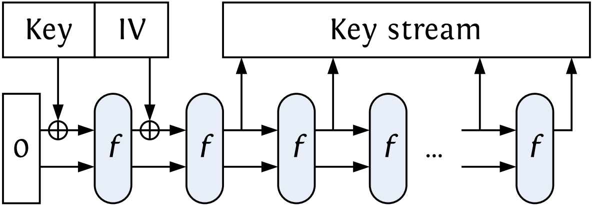
- For salted hashing, as slow as you like it

How to use a sponge function?



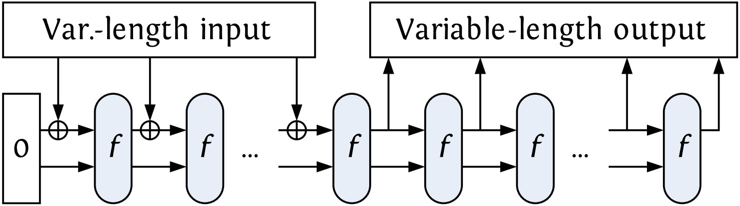
- As a message authentication code

How to use a sponge function?



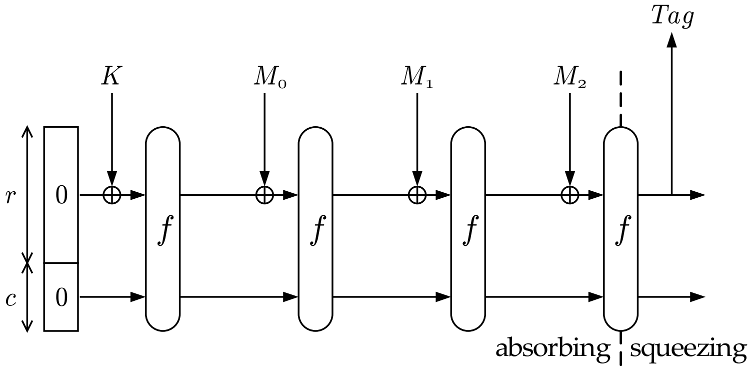
- As a stream cipher

How to use a sponge function?

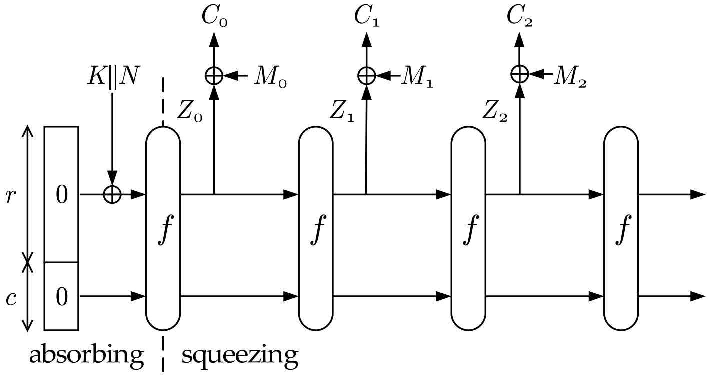


- As a mask generating function [PKCS#1, IEEE Std 1363a]

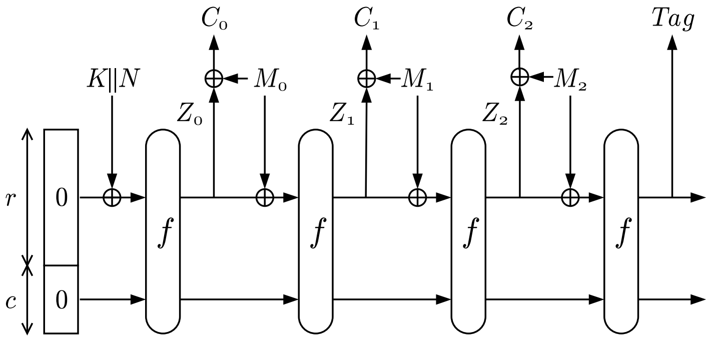
MAC generation with a sponge



Encryption with a sponge

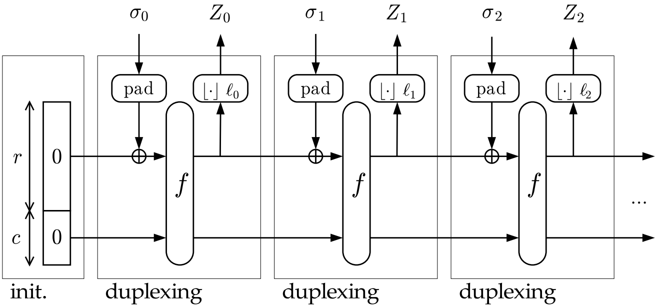


Both encryption and MAC?



Absorbing and squeezing

The duplex construction

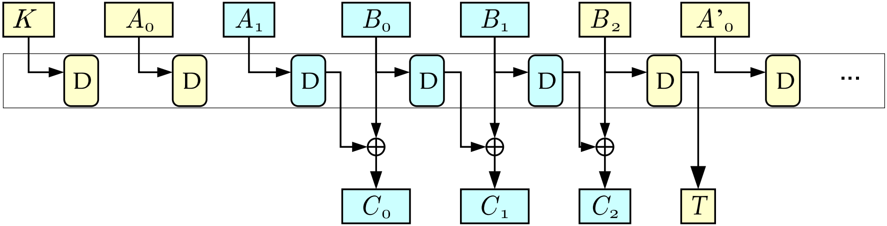


- Object: $D = \textsc{duplex}[f, \text{pad}, r]$
- Requesting ℓ-bit output $Z = D.\text{duplexing}(\sigma, \ell)$
  - input σ and output Z limited in length
  - Z depends on all previous inputs

Authenticated encryption

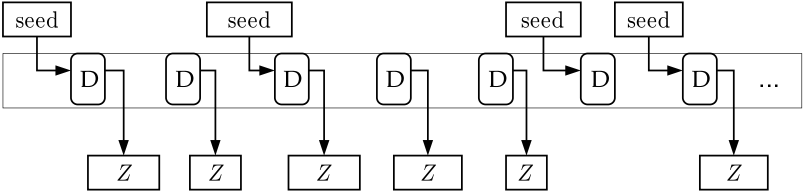
- Functionality:
  - Tag computation over data header and data body
  - Encryption of body into cryptogram, *diversified by* header
- Wrapping:
  - Input: key, data header and body
  - Output: tag and cryptogram
- Unwrapping
  - Input: key, data header and cryptogram, tag
  - Output: cryptogram or error message if tag is invalid
- Security requirements
  - Tag forgery infeasibility
  - Plaintext recovery infeasibility

The SpongeWrap mode



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

Reseedable pseudorandom bit generator



Requirements:

- Seeding and reseeding
- Pseudo-random output depends on all past seeds
- Forward secrecy

What textbooks and intro's should say from now on:-)

Symmetric cryptographic primitives:

- Permutations
- Block ciphers
- Stream ciphers
- Hash functions
    - Non-keyed
    - Keyed: MAC functions

And their modes-of-use

Questions?

Thanks for your attention!

Q?

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