On KECCAK and SHA-3

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Outline

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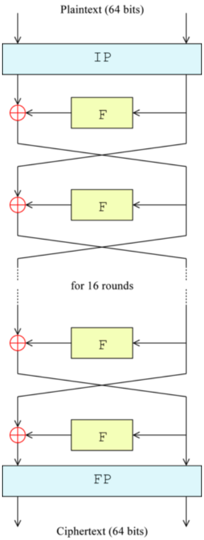
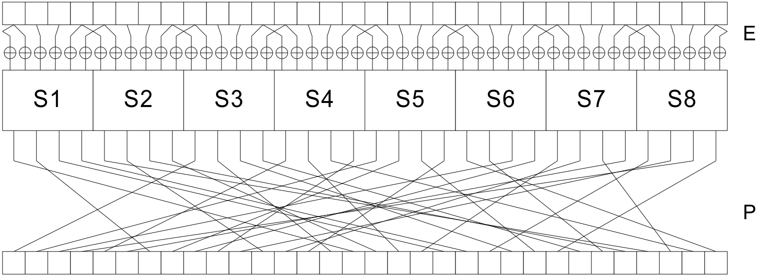
Symmetric crypto around ’89

- Stream ciphers: LFSR-based schemes
  - no actual design
  - many mathematical papers on linear complexity
- Block ciphers: DES
  - design criteria not published
  - DC [Biham-Shamir 1990]: “DES designers knew what they were doing”
  - LC [Matsui 1992]: “well, kind of”
- Popular paradigms, back then (but even now)
  - property-preservation: strong cipher requires strong S-boxes
  - confusion (nonlinearity): distance to linear functions
  - diffusion: (strict) avalanche criterion
  - you have to trade them off

Data encryption standard: datapath



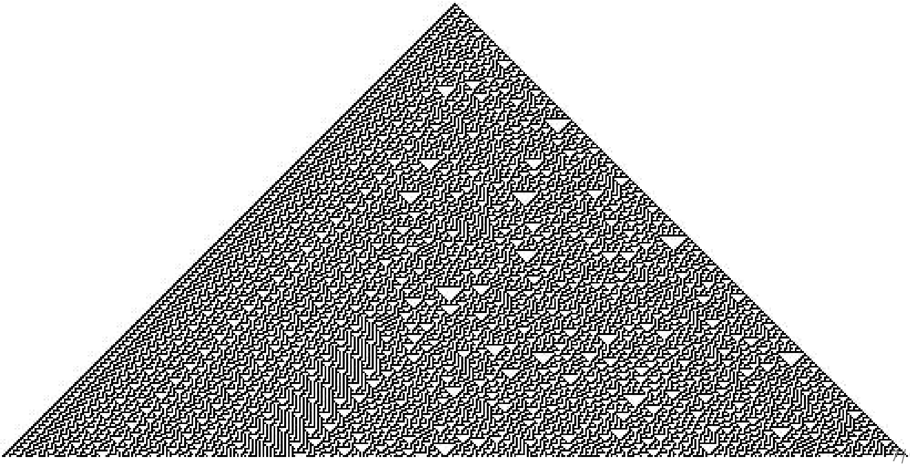
Data encryption standard: F-function



A different angle: cellular automata

- Simple local evolution rule, complex global behaviour
- Popular 3-bit neighborhood rule:

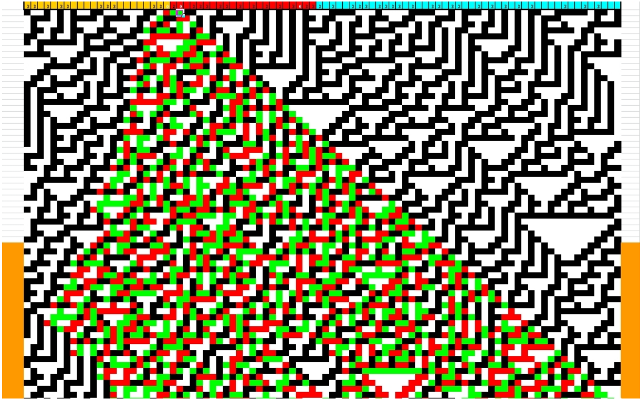
$$a_i \Leftarrow a_{i-1} \oplus (a_i \text{ OR } a_{i+1})$$



Crypto based on cellular automata

- CA guru Stephen Wolfram at Crypto '85:
  - looking for applications of CA
  - concrete stream cipher proposal
- Crypto guru Ivan Damgård at Crypto '89
  - hash function from compression function
  - proof of collision-resistance preservation
  - compression function with CA
- Both broken
  - stream cipher in [Meier-Staffelbach, Eurocrypt '91]
  - hash function in [Daemen et al., Asiacrypt '91]

The trouble with Damgård's compression function

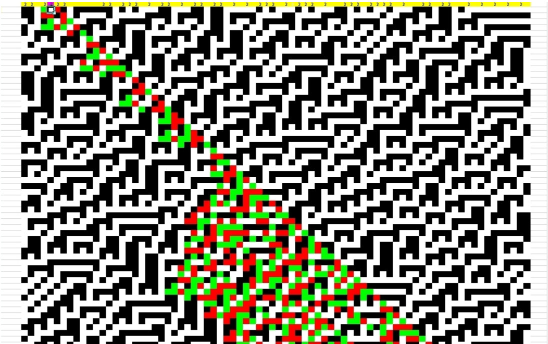


Salvaging CA-based crypto

- First experiments: investigate cycle distributions
- The following rule exhibited remarkable cycle lengths:
  γ: flip the bit iff 2 cells at the right are not 01

$$a_i \Leftarrow a_i + 1 + (a_{i+1} + 1)a_{i+2}$$

- Invertible if periodic boundary conditions and odd length
- nonlinear, but unfortunately, weak diffusion

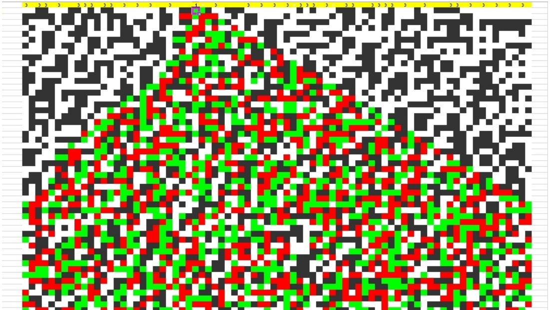


Salvaging CA-based crypto, second attempt

- Found invertible 5-bit neighborhood rules with good diffusion
- Turned out to be composition of γ and following rule
  - $\theta : a_i \Leftarrow a_i + a_{i+1} + a_{i+2}$
- Idea: alternate γ (nonlinearity) and variant of θ (mixing)
- Polynomial representation of θ variant:

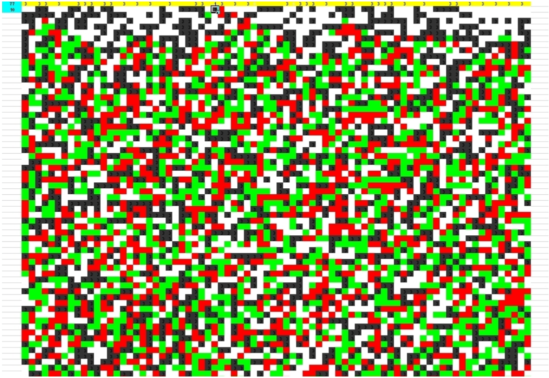
$$1 + x^3 + x^6$$

$$\text{mod } (1 + x^n)$$



Salvaging CA-based crypto, third attempt

- Abandon locality by adding in bit transpositions:
  - π: move bit in cell i to cell $9i$ modulo the length
- Round function: $R = \pi \circ \theta \circ \gamma$
- full diffusion after few rounds!



Resulting designs

- Round function composed of specialized steps
  - γ: non-linearity
  - θ: mixing
  - π: transposition
  - ι: addition of some constants for breaking symmetry
- Designs directly using this [PhD Thesis Daemen, 1995]
  - CELLHASH (1991): hash function
  - SUBTERRANEAN (1992), STEPRIGHTUP (1994) and PANAMA (1997): hash/stream cipher modules
  - 3-WAY and BASEKING (1993-94): block ciphers
- Theoretical basis: DC and LC
  - branch number
  - correlation matrices
  - wide trail strategy

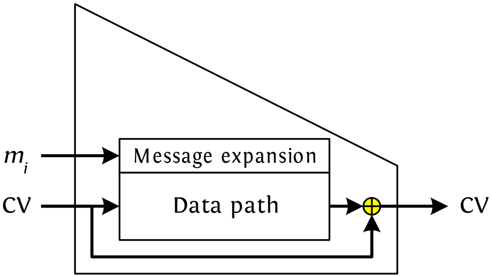
Outline

Our beginning: RadioGatún

- Initiative to design hash/stream function (late 2005)
  - rumours about NIST call for hash functions
  - forming of Keccak Team
  - starting point: fixing Panama [Daemen, Clapp, FSE 1998]
- RadioGatún [Keccak team, NIST 2nd hash workshop 2006]
  - more conservative than Panama
  - arbitrary output length primitive
  - **expressing security claim** for arbitrary output length primitive
- Sponge functions [Keccak team, Ecrypt hash, 2007]
  - … *closest thing to a random oracle with a finite state* …
  - Random sponge

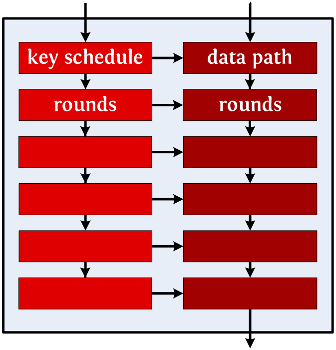
Intermezzo: block-cipher based compression function

Block cipher in Davies-Meyer mode



Is a block cipher appropriate?

- No diffusion from data path to key (and tweak) schedule
- Let's remove these artificial barriers...
- That's an iterative permutation!



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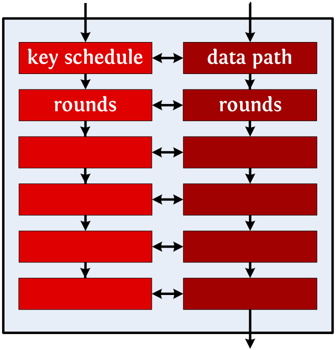

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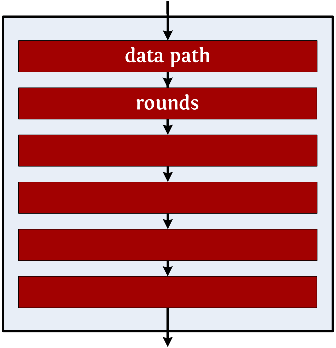
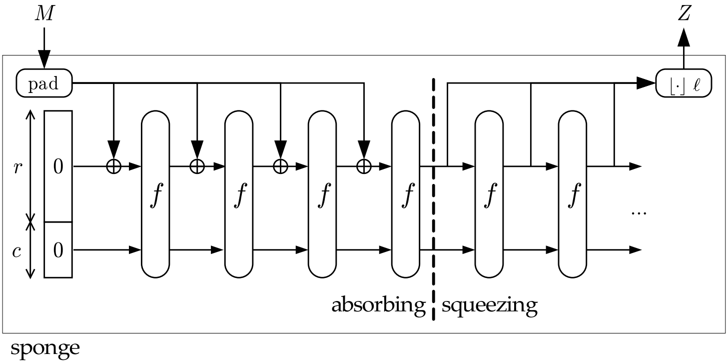


The sponge construction



- More general than a hash function: arbitrary-length output
- Calls a b-bit permutation f, with $b = r + c$
  - r bits of *rate*
  - c bits of *capacity* (security parameter)

Generic security of the sponge construction

Theorem (Indifferentiability of the sponge construction)

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

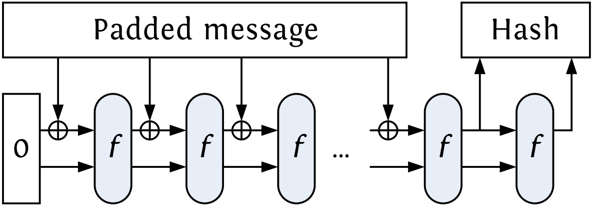
A: differentiating advantage of random sponge from a random oracle
N: total data complexity in r-bit blocks
c: capacity

[Keccak team, Eurocrypt 2008]

Informally, a random sponge is like a random oracle when $N < 2^{c/2}$.

- Collision-, preimage-resistance, etc., up to security strength $c/2$
- Assumes f is a random permutation
  - provably secure against generic attacks
  - ...but not against attacks that exploit specific properties of f

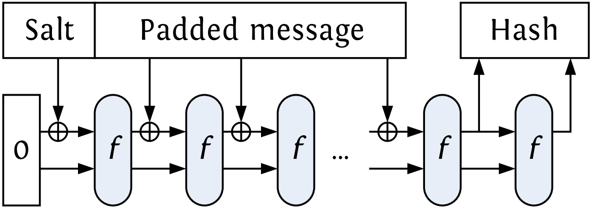
Regular hashing



- Electronic signatures
- Data integrity (*shaXsum* ...)
- Data identifier (*Git, online anti-virus, peer-2-peer* ...)

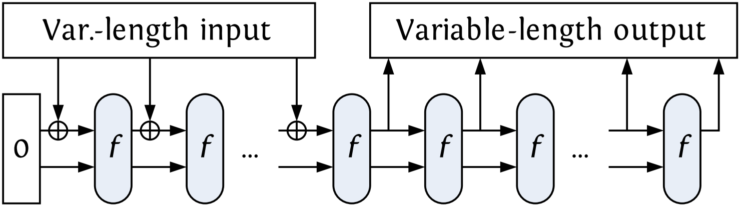
See [Cryptographic sponge functions] for more details

Salted hashing



- Randomized hashing (RSASSA-PSS)
- Password storage and verification (*Kerberos*, `/etc/shadow`)

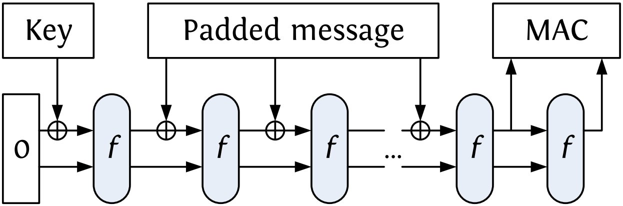
Mask generation function



output length often dictated by application …
… rather than by security strength level

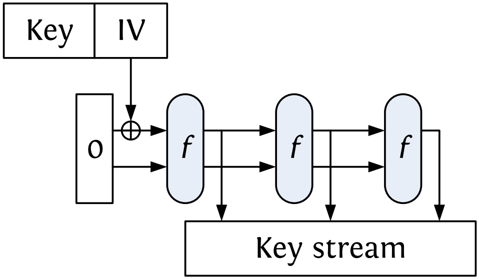
- Key derivation function in SSL, TLS
- Full-domain hashing in public key cryptography
  - electronic signatures RSASSA-PSS [PKCS#1]
  - encryption RSAES-OAEP [PKCS#1]
  - key encapsulation methods (KEM)

Message authentication codes



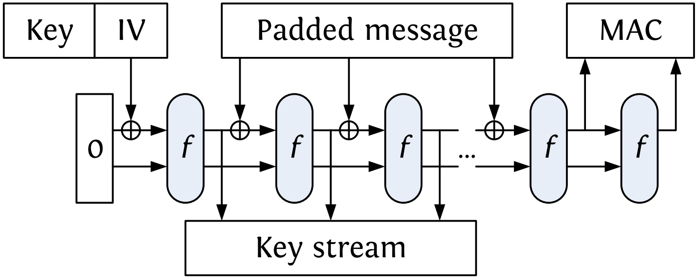
- As a message authentication code
- Simpler than HMAC [FIPS 198]
    - Required for SHA-1, SHA-2 due to length extension property
    - HMAC is **no longer needed** for sponge!

Stream encryption



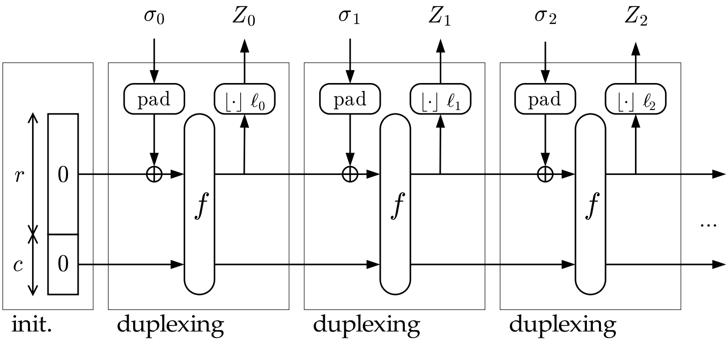
- As a stream cipher
  - Long output stream per IV: similar to OFB mode
  - Short output stream per IV: similar to counter mode

Single pass authenticated encryption



- Authentication and encryption in a single pass!
- Secure messaging (*SSL/TLS, SSH, IPSEC* ...)

The duplex construction



- Generic security equivalent to Sponge [Keccak team, SAC 2011]
- Applications include:
  - Authenticated encryption: spongeWrap
  - Reseedable pseudorandom sequence generator

A new branch of symmetric crypto

- Primitive: (iterative) permutation
- Modes can be made for quasi all functions
- Simpler than block ciphers: no key input
- More flexible: $r - c$ trade-off

Permutation-based cryptography!

Outline

Design approach

Hermetic sponge strategy

- Instantiate a sponge function
- Claim a security level of $2^{c/2}$

Our mission

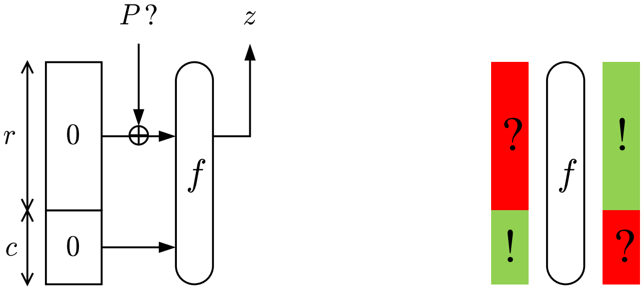
Design permutation f without exploitable properties

Criteria for a strong permutation

- Classical LC/DC criteria
  - absence of large differential propagation probabilities
  - absence of large input-output correlations
  - ...differential and linear trails and clustering
- Infeasibility of the CICO problem
- Resistance against
  - Slide and symmetry-exploiting attacks
  - Algebraic attacks
  - ...
- Keeping efficiency in mind

The CICO problem

- Given partial input and output, determine remaining parts
- Important in many attacks



Pre-image generation in hashing

The CICO problem

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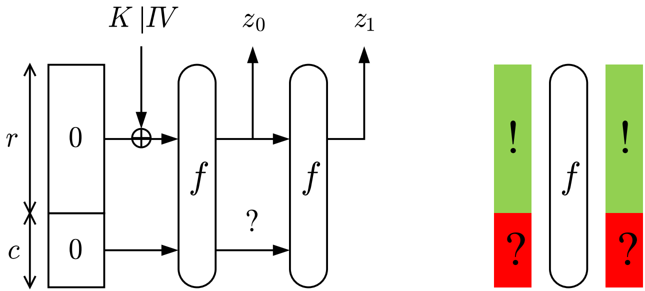

State recovery in stream encryption

How to build a strong permutation

- Like a block cipher
  - Sequence of identical rounds
  - Round consists of sequence of simple step mappings
- …but not quite
  - No key schedule
  - Round constants instead of round keys
  - Inverse permutation need not be efficient

KECCAK

- Instantiation of a *sponge function*
- Using the permutation KECCAK-f
  - 7 permutations: $b \in \{25, 50, 100, 200, 400, 800, 1600\}$
    … from toy over lightweight to high-speed …
- SHA-3 instance: $r = 1088$ and $c = 512$
  - permutation width: 1600
  - security strength 256: post-quantum sufficient
- Lightweight instance: $r = 40$ and $c = 160$
  - permutation width: 200
  - security strength 80: same as (initially expected from) SHA-1

See [The KECCAK reference] for more details

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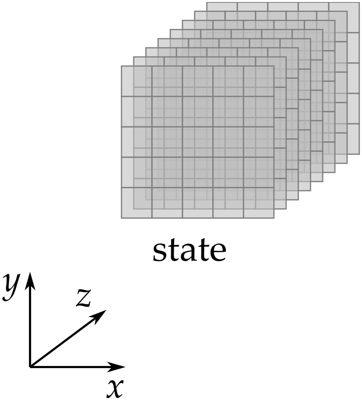
KECCAK-f state: an array of $5 \times 5 \times 2^\ell$ bits



- 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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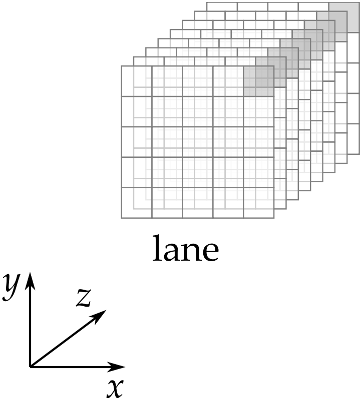

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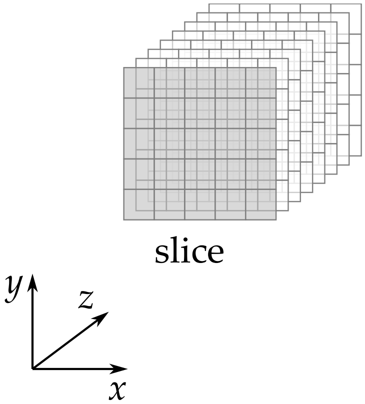

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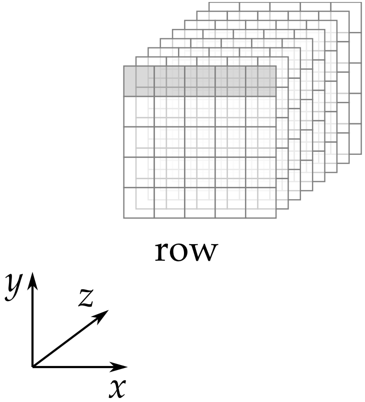

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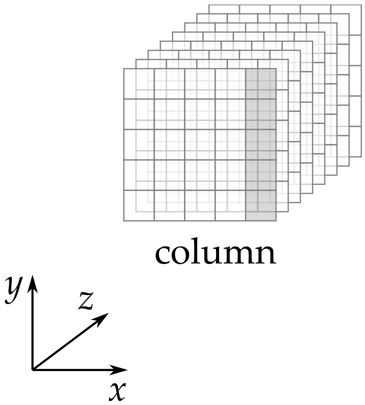

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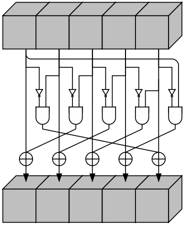
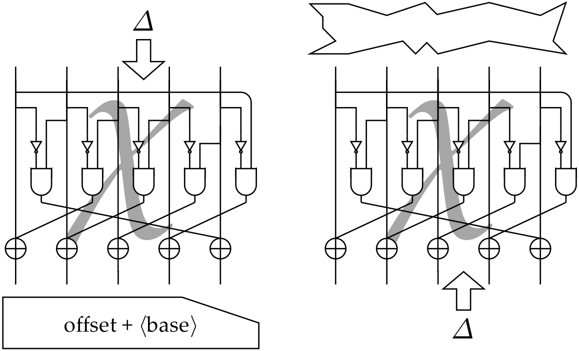
χ, the nonlinear mapping in KECCAK-f



- "Flip bit if neighbors exhibit 01 pattern"
- Operates independently and in parallel on 5-bit rows
- Cheap: small number of operations per bit
- Algebraic degree 2, inverse has degree 3
- LC/DC propagation properties easy to describe and analyze

Propagating differences through χ



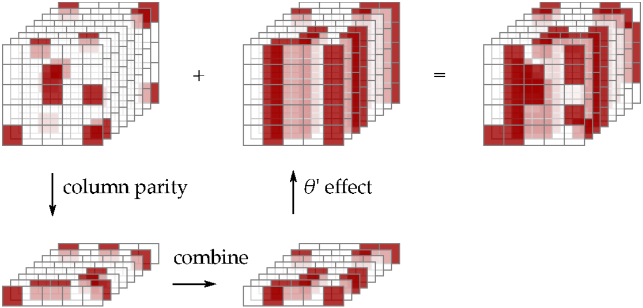
- The propagation weight…
  - … is equal to $-\log_2$(fraction of pairs);
  - … is determined by input difference only;
  - … is the size of the affine base;
  - … is the number of affine conditions.

θ', a first attempt at mixing bits

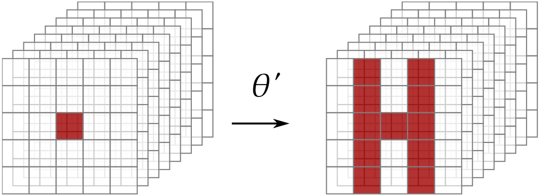
- Compute parity $c_{x,z}$ of each column
- Add to each cell parity of neighboring columns:

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

- Cheap: two XORs per bit

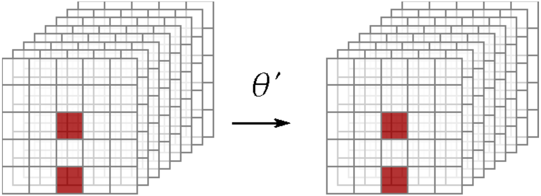


Diffusion of θ'



$$1 + \left(1 + y + y^2 + y^3 + y^4\right)\left(x + x^4\right)$$
$$\left(\bmod \left\langle 1 + x^5, 1 + y^5, 1 + z^w \right\rangle\right)$$

Diffusion of θ' (kernel)



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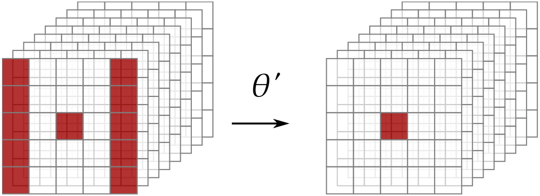
Diffusion of the inverse of θ'



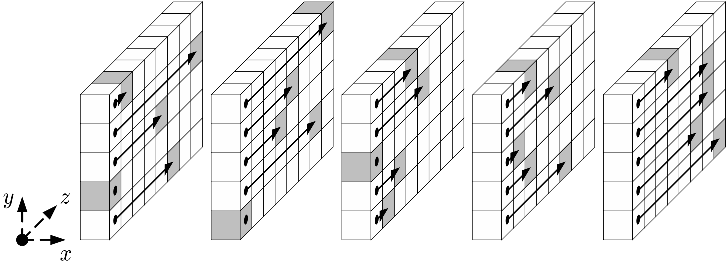
$$1 + \left(1 + y + y^2 + y^3 + y^4\right)\left(x^2 + x^3\right)$$
$$\left(\bmod \left\langle 1 + x^5, 1 + y^5, 1 + z^w \right\rangle\right)$$

ρ for inter-slice dispersion

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

$$i(i+1)/2 \bmod 2^{\ell}, \text{ with } \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 2 & 3 \end{pmatrix}^{i-1} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

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

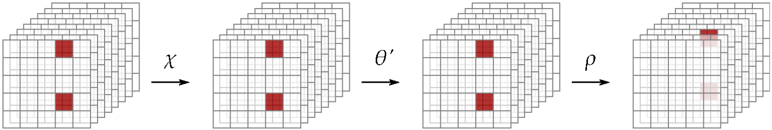


ι to break symmetry

- XOR of round-dependent constant to lane in origin
- Without ι, the round mapping would be symmetric
  - invariant to translation in the z-direction
  - susceptible to *rotational* cryptanalysis
- 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)

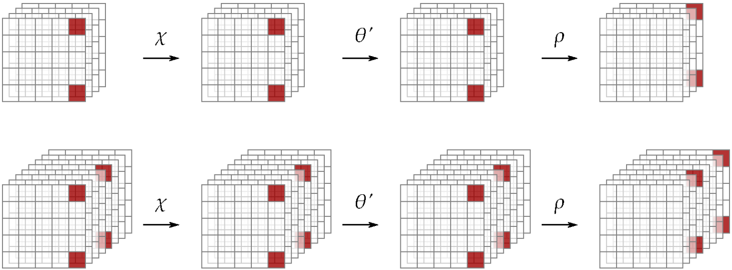
A first attempt at KECCAK-f

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



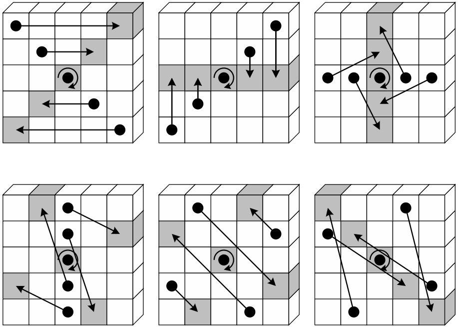
  - χ: propagates unchanged with weight 4
  - θ': propagates unchanged, because all column parities are 0
  - ρ: in general moves active bits to different slices ...
    ...but not always

The Matryoshka property



- Patterns in Q' are z-periodic versions of patterns in Q
- Weight of trail Q' is twice that of trail Q (or 2^n times in general)

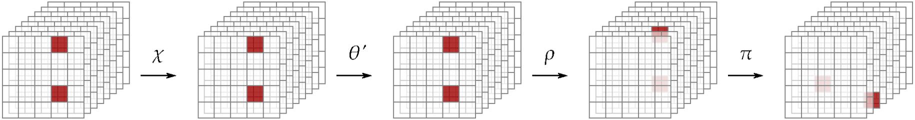
π for disturbing horizontal/vertical alignment



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

A second attempt at KECCAK-f

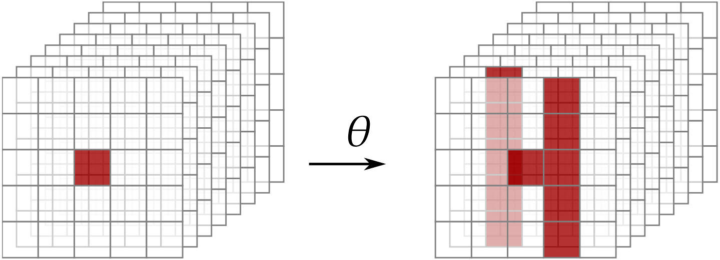
- Round function: $\mathrm{R} = \iota \circ \pi \circ \rho \circ \theta' \circ \chi$
- Solves problem encountered before:



- π moves bits in same column to different columns!

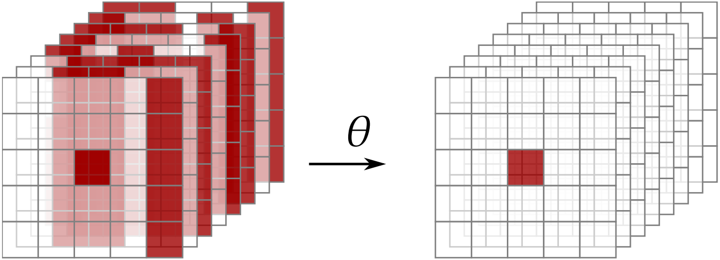
Almost there, still a final tweak ...

Tweaking θ' to θ



$$1 + \left(1 + y + y^2 + y^3 + y^4\right)\left(x + x^4 z\right)$$
$$\left(\bmod \left\langle 1 + x^5, 1 + y^5, 1 + z^w \right\rangle\right)$$

Inverse of θ



$$1 + \left(1 + y + y^2 + y^3 + y^4\right) \mathbf{Q},$$

$$\text{with } \mathbf{Q} = 1 + \left(1 + x + x^4 z\right)^{-1} \bmod \left\langle 1 + x^5, 1 + z^w \right\rangle$$

- **Q** is dense, so:
  - Diffusion from single-bit output to input very high
  - Increases resistance against LC/DC and algebraic attacks

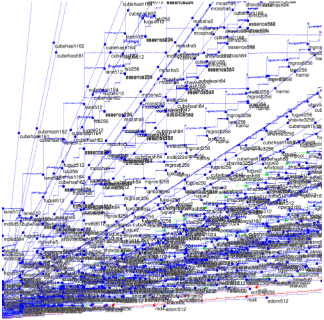
KECCAK-f summary

- Round function:

$$R = \iota \circ \chi \circ \pi \circ \rho \circ \theta$$

- Number of rounds: $12 + 2\ell$
  - KECCAK-$f[25]$ has 12 rounds
  - KECCAK-$f[1600]$ has 24 rounds
- Some features
  - weak alignment
  - high level of parallellism and symmetry
  - efficient and flexible in hard- and software
  - suited for protection against side-channel attack
    [Debande, Le and Keccak team, HASP 2012 + ePrint 2013/067]

Performance in software



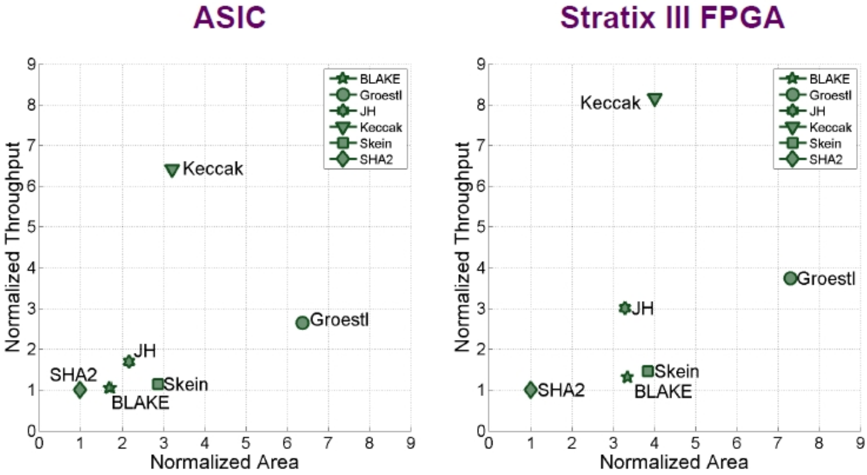
- Faster than SHA-2 on all modern PCs
- KECCAKTREE faster than MD5 on some platforms

C/b	Algo		Strength
4.79	keccakc256treed2		128
4.98	md5	**broken!**	64
5.89	keccakc512treed2		256
6.09	sha1	**broken!**	80
8.25	keccakc256		128
10.02	keccakc512		256
13.73	sha512		256
21.66	sha256		128

[eBASH, hydra6 (AMD Bulldozer), http://bench.cr.yp.to/]

Efficient and flexible in hardware

From Kris Gaj's presentation at SHA-3, Washington 2012:



Outline

Output length oriented approach

Output length	Collision resistance	Pre-image resistance	Required capacity	Relative perf.	SHA-3 instance
$n = 224$	$s \leq 112$	$s \leq 224$	$c = 448$	$\times 1.125$	**SHA3n224**
$n = 256$	$s \leq 128$	$s \leq 256$	$c = 512$	$\times 1.063$	**SHA3n256**
$n = 384$	$s \leq 192$	$s \leq 384$	$c = 768$	$\div 1.231$	**SHA3n384**
$n = 512$	$s \leq 256$	$s \leq 512$	$c = 1024$	$\div 1.778$	**SHA3n512**
n	$s \leq n/2$	$s \leq n$	$c = 2n$	$\times \frac{1600-c}{1024}$	

s: security strength level [NIST SP 800-57]

- These instances address the SHA-3 requirements, but:
  - multiple security strengths each
  - levels outside of [NIST SP 800-57] range
- Performance penalty!

Security strength oriented approach

Security strength	Collision resistance	Pre-image resistance	Required capacity	Relative perf.	SHA-3 instance
$s = 112$	$n \geq 224$	$n \geq 112$	$c = 224$	$\times 1.343$	**SHA3c224**
$s = 128$	$n \geq 256$	$n \geq 128$	$c = 256$	$\times 1.312$	**SHA3c256**
$s = 192$	$n \geq 384$	$n \geq 192$	$c = 384$	$\times 1.188$	**SHA3c384**
$s = 256$	$n \geq 512$	$n \geq 256$	$c = 512$	$\times 1.063$	**SHA3c512**
s	$n \geq 2s$	$n \geq s$	$c = 2s$	$\times \frac{1600-c}{1024}$	**SHA3[c=2s]**

s: security strength level [NIST SP 800-57]

- These SHA-3 instances
  - are consistent with philosophy of [NIST SP 800-57]
  - provide a one-to-one mapping to security strength levels
- Higher efficiency

NIST SHA-3 standardization plans

- A new FIPS number (not 180-n)
- Two capacities: 256 and 512
- 6 instances with domain separation between them
- Tree-hashing ready: SAKURA coding

Sponge instances	SHA-2 drop-in replacements
$\text{KECCAK}[c = 256](M\|\|11\|\|11)$	$\lfloor \text{KECCAK}[c = 256](M\|\|11\|\|001) \rfloor_{224}$ $\lfloor \text{KECCAK}[c = 256](M\|\|11\|\|101) \rfloor_{256}$
$\text{KECCAK}[c = 512](M\|\|11\|\|11)$	$\lfloor \text{KECCAK}[c = 512](M\|\|11\|\|001) \rfloor_{384}$ $\lfloor \text{KECCAK}[c = 512](M\|\|11\|\|101) \rfloor_{512}$

SAKURA and tree hashing

- Sound tree hashing is relatively easy to achieve
  - Sufficient conditions for indifferentiability from RO
    [Keccak team, ePrint 2009/210 – **updated April 2013**]
- Defining tree hash modes addressing all future use cases is hard
  - A chosen number of leaves for a chosen amount of parallelism?
  - Or a binary tree with the option of saving intermediate hash results?
- Defining future-proof tree hash coding is easy

SAKURA, a flexible coding for tree hashing

- Automatically satisfying the sufficient conditions of [ePrint 2009/210]
- For any underlying hash function (not just KECCAK)
- For any tree topology

$\Rightarrow$ no conflicts adding future tree structures

See [Keccak team, ePrint 2013/231] for more details

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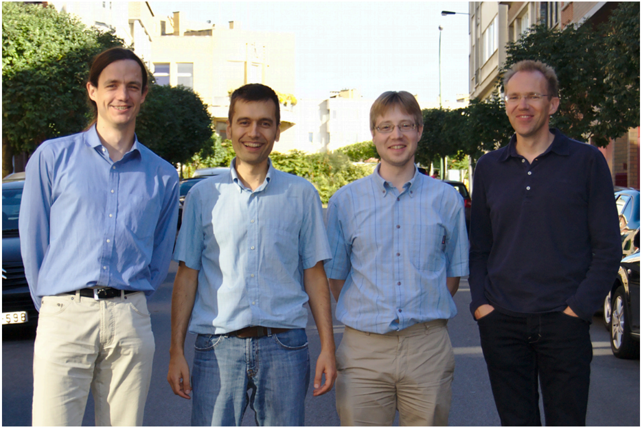
Ongoing work

- Boosting performance of keyed modes
    - usage: MAC, stream cipher, CAESAR
    - better generic security bound in keyed mode
    - reduced-round KECCAK-f instances
    - bounding differential and linear trail weights
    - dedicated keyed modes
- Protection against side-channel attacks
- ...

Conclusions

- Trying to do things right pays off in the long run
  - re-factoring over patching
  - simplicity over complexity
  - result-focused over publication-driven
- Team up with critical minds
  - overlapping competences rather than complementary
  - keep good ideas and abandon mistakes
  - not too much ego please
- Great to work with Guido, Michaël and Gilles!

Thanks for your attention!



http://sponge.noekeon.org/
http://keccak.noekeon.org/

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