# Column Parity Mixers

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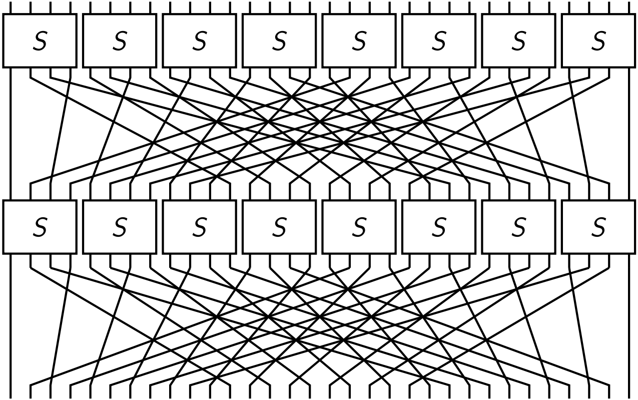
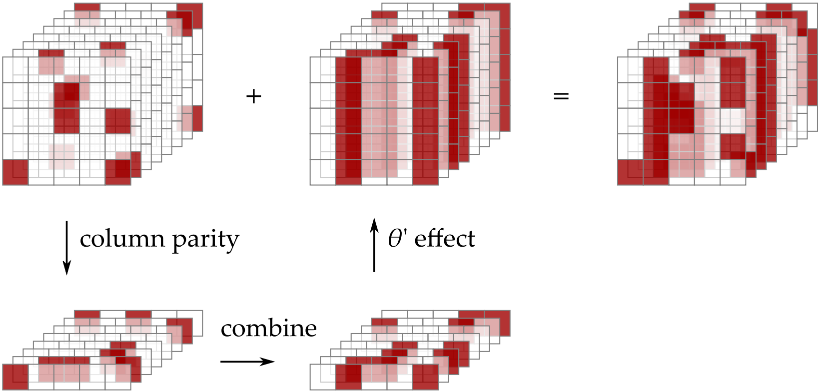
# Diffusion



# Diffusion in Keccak-$f$




Only 2 `XOR`s/bit + good bounds on differential trails [MDA17]

# Column parity mixers

For an $m \times n$ matrix $A$ over $\mathbb{F}_2^\ell$:

$$\theta(A) = A + \quad f(A)$$

$$\begin{pmatrix} a_{0,0} & a_{0,1} & a_{0,2} & a_{0,3} \\ a_{1,0} & a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,0} & a_{2,1} & a_{2,2} & a_{2,3} \end{pmatrix}$$

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$$\theta(A) = A + \quad \mathbf{1}_m^{\mathsf{T}} A$$

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$\theta$ fully defined by $m$, $n$ and $Z$

# Special case: circulant $Z$

$$\begin{pmatrix} z_0 & z_1 & z_2 & z_3 \\ z_1 & z_2 & z_3 & z_0 \\ z_2 & z_3 & z_0 & z_1 \\ z_3 & z_0 & z_1 & z_2 \end{pmatrix}$$

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$$\theta(a(x,y)) = a(x,y) + \frac{1+y^m}{1+y} z(x) a(x,y) \bmod (1+x^n)(1+y^m)$$

# Algebraic properties

$$\begin{aligned}\theta'(\theta(A)) &= \theta'(A + \mathbf{1}_m^m AZ)\\ &= A + \mathbf{1}_m^m AZ + \mathbf{1}_m^m AZ' + (\mathbf{1}_m^m)^2 AZZ'\end{aligned}$$

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  - $\theta'(\theta(A)) = A + \mathbf{1}_m^m A(Z + Z')$
  - Group isomorphic to $\left(\mathbb{Z}_2^{n^2}, +\right)$
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- If $m$ odd, $(\mathbf{1}_m^m)^2 = \mathbf{1}_m^m$:
  - $\theta'(\theta(A)) = A + \mathbf{1}_m^m A\left((Z + \mathbf{I})(Z' + \mathbf{I}) + \mathbf{I}\right)$
  - Group isomorphic to $GL(n, 2)$
  - CPM is invertible iff $Z + \mathbf{I}$ is, non-commutative

# Propagation properties

- Differences

  $A_\Delta = A + A'$ at the input

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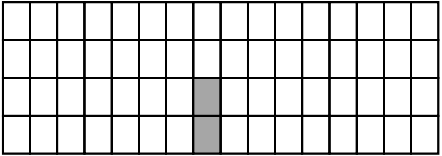
- Linear masks

  $V$ at the output

  $\Rightarrow U = V + \mathbf{1}_m^m V Z^\mathsf{T}$ at the input

# Diffusion with CPMs

- How about a state like this?



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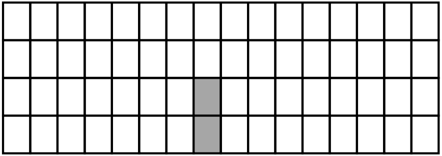

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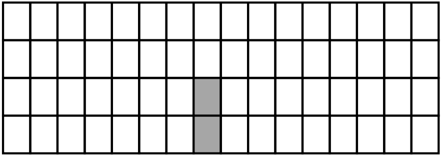

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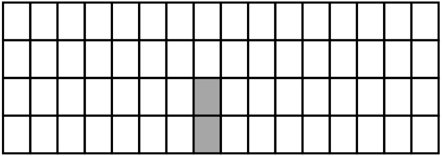

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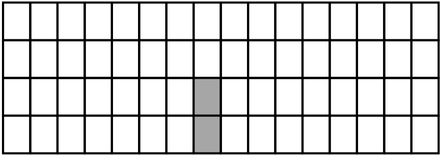

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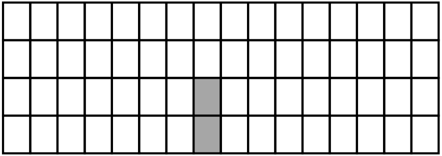

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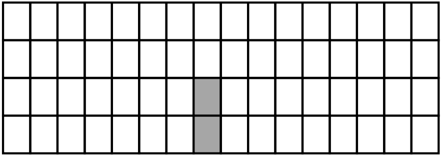

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- Single-bit difference propagates to $1 + |Z|\, m$ bits

# CPMs vs. (near-)MDS matrices

| Cipher | Type | XORs/bit | Branch no. |
|---|---|---|---|
| AES | MDS | 3.03 | 5 |
| Joltik | MDS | 3 | 5 |
| PHOTON | MDS | 5† | 7 |
| Prøst | MDS | 4.5† | 5 |
| Midori | Not MDS‡ | 1.5 | 4 |
| Minalpher | Not MDS‡ | 1.5 | 4 |
| Prince | Not MDS | 1.5 | 4 |
| SKINNY | Not MDS | 0.75 | 2 |
| Keccak-$f$ | CPM | 2 | 4 |
| Circulant CPM | CPM | $2 + \frac{\lvert z(x)\rvert - 2}{m}$ * | 4 |

* XORs/bit $\in [2 - 1/m, 2 + (n-2)/m]$

† Unknown whether it can be computed with less XORs

‡ Can also be considered to be a CPM!

# CPM example

$$\begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix}$$

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$$\begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{pmatrix}$$

$$\Leftrightarrow$$

$$m = 2, Z = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

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12. Give it a name

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- Dedicated software for CPM-based ciphers/permutations

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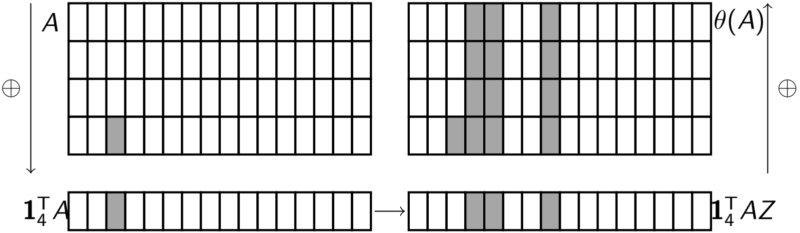

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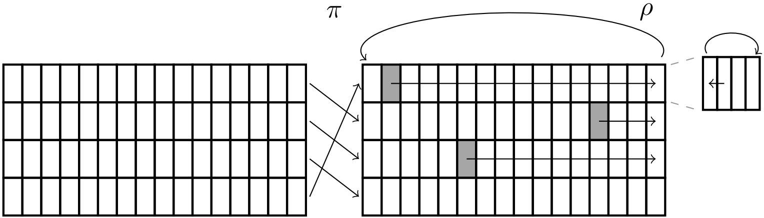

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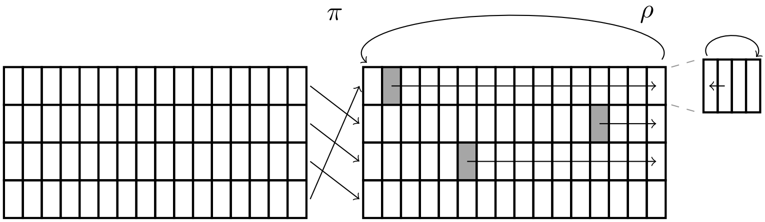

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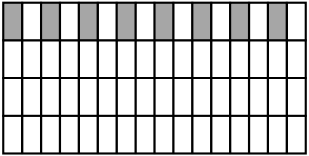
- $\iota$: add $\texttt{0xF3485763} \gg i$ in round $i$ to every other cell of top row



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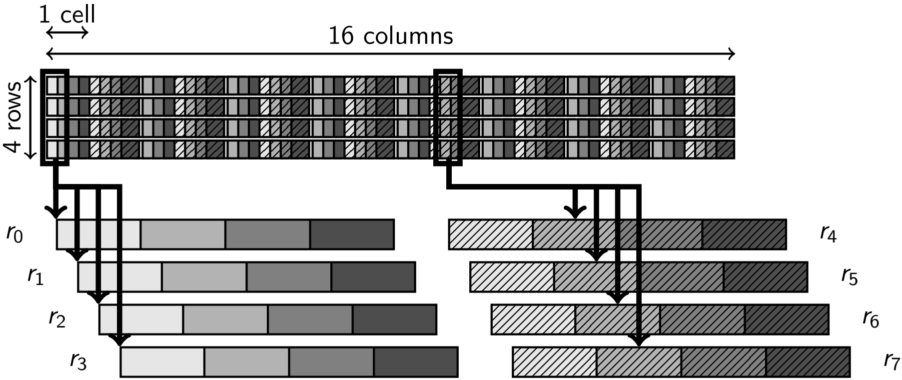
- Preliminary study makes us believe trail clustering, impossible differentials, invariant attacks are not a concern

# Mixifer implementation



# Mixifer comparison (ARM Cortex-M4)

| Cipher | Width (bits) | $r$ | Speed (cpb) Full | Speed (cpb) $/r$ | Bound trails $r$ | Bound trails W | Bound trails $/r$ |
|---|---|---|---|---|---|---|---|
| AES bitsliced | 128 | 10 | 50.52 | 5.05 | 4 | 150 | 37.5 |
| AES tables | | | 39.97 | 4.00 | | | |
| Gimli | 384 | 24 | 21.81 | 0.91 | 8 | 52 | 6.5 |
| Keccak-$f$[400] | 400 | 20 | 106 | 5.3 | 6 | 92 | 15.3 |
| Keccak-$f$[800] | 800 | 22 | 48.02 | 2.18 | 6 | 92 | 15.3 |
| Salsa20/20 | 512 | 20 | 13.88 | 0.69 | 3 | 18 | 6 |
| Mixifer | 256 | 16 | 36.69 | 2.33 | 4 | 92 | 23 |

# Thanks...

...for your attention

Questions?

# References I


Christof Beierle, Anne Canteaut, Gregor Leander, and Yann Rotella.
Proving resistance against invariant attacks: How to choose the round constants.
In Jonathan Katz and Hovav Shacham, editors, *Advances in Cryptology – CRYPTO 2017, Part II*, volume 10402 of *Lecture Notes in Computer Science*, pages 647–678, Santa Barbara, CA, USA, August 20–24, 2017. Springer, Heidelberg, Germany.

Silvia Mella, Joan Daemen, and Gilles Van Assche.
New techniques for trail bounds and application to differential trails in Keccak.
*IACR Transactions on Symmetric Cryptology*, 2017(1):329–357, 2017.