CBEAM: Efficient Authenticated Encryption from Feebly One-Way ϕ Functions

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- Pseudorandom extractors (PRFs and PRNGs) [CHES 2010].
- **Authenticated Encryption** (AE,AEAD) [SAC 2011].
- Keyed Message Authentication Codes (MACs) [SKEW 2011].
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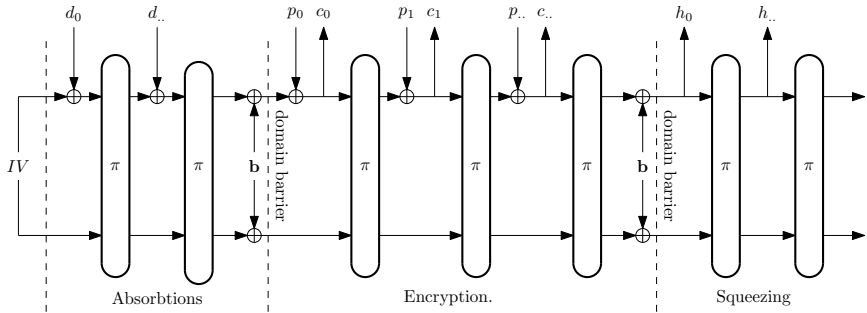
.. and **BLINKER two-party protocols** [Next talk: Saarinen CT-RSA 2014].

Sponge-based Authenticated Encryption



- First the key, nonce, sequence numbers, and associated data (all represented by d_i) are absorbed in state.
- Then plaintext p_i is used to produce ciphertext c_i (or vice versa).
- Finally a MAC or hash h_i is squeezed from the state.

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  - c is the **capacity** and determines an upper bound for **security**
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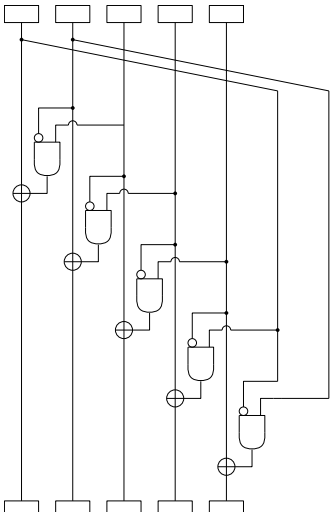
- For CBEAM, we have a $b = 256$-bit permutation with $r = 64$ **and** $c = 192$.
- We target Triple-DES security assuming at most 2^{40} invocations of π (8 TiB).

Background on ϕ Functions: Keccak's 5×5 - bit χ



χ is the only nonlinear component of Keccak

Usually implemented with 64× **bit-slicing** SIMD.

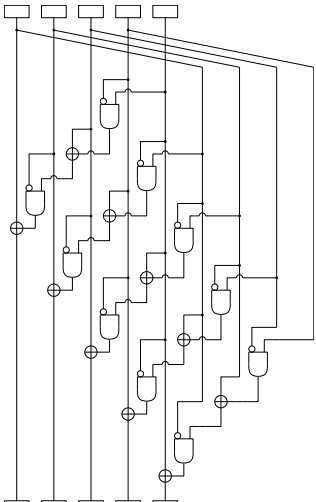
A **rotation-invariant** ϕ function:

$$\phi(x) = y \quad \Rightarrow \quad \phi(x \lll n) = y \lll n, \quad \forall\ n \in \mathbb{Z}.$$

Algebraic degree **2**.

Each output bit depends on **3** input bits.

Inverse of Keccak's 5×5 - bit χ



Inverse not required for implementing Keccak.

As an inverse of a ϕ function, χ^{-1} is also a ϕ function.

Higher circuit complexity. Algebraic degree **3**.

Each output bit depends **all** input bits.

Boura-Canteaut Inverse Algebraic Complexity Theorems

C. Boura and A. Canteaut: "On the Influence of the Algebraic Degree of F^{-1} on the Algebraic Degree of $G \circ F$." *IEEE Transactions on Information Theory* **59**(1), January 2013.

These theoretical results indicate that even if the inverse π^{-1} is **not** explicitly computed, an algebraically complex inverse makes the resulting iteration stronger.

We have discovered new ϕ functions with more radical computational "asymmetry" than the χ of Keccak**.**

CBEAM's "S-Box" ϕ_{16}: A 16×16 - Bit ϕ Function

First define a 5×1 - bit nonlinear function ϕ_5:

$$\phi_5(x_0, x_1, x_2, x_3, x_4) = x_0x_1x_3x_4 + x_0x_2x_3 + x_0x_1x_4 + x_1x_2x_3 + x_2x_3x_4 + x_0x_3 + x_1x_3 + x_2x_3 + x_2x_4 + x_3x_4 + x_1 + x_3 + x_4.$$

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This is turned into a 16×16 - bit function ϕ_{16} defined on $V[\,0 \cdots 15\,] \mapsto V'[\,0 \cdots 15\,]$ via convolution:

$$V'[\,i\,] = \phi_5\big(V[\,i\,],\ V[\,(i-1) \bmod 16\,],\ V[\,(i-2) \bmod 16\,],\ V[\,(i-3) \bmod 16\,],\ V[\,(i-4) \bmod 16\,]\big).$$

Degree is of both ϕ_5 and ϕ_{16} is clearly **4**. The Algebraic Normal Form (ANF) polynomial has **13 monomials**.

What about it's inverse ϕ_{16}^{-1} ?

- First of all, there is an inverse, which is by no means obvious.
- We tested all 2^{32} 5-input Boolean functions to find ϕ_5.
- ϕ_{16}^{-1} **has degree 11 for each output bit and 13465 monomials in its ANF**

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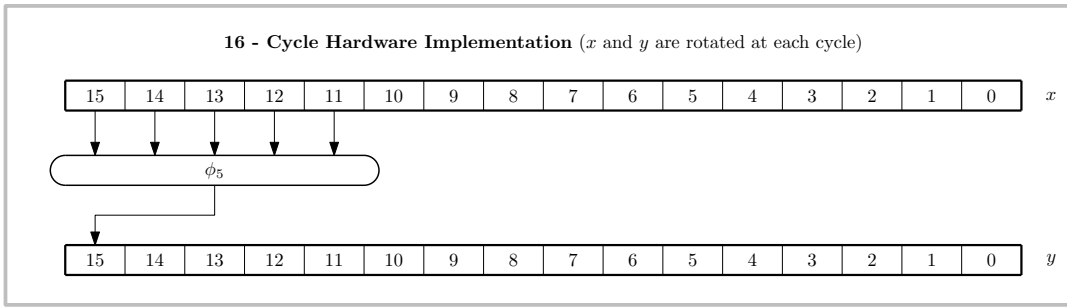
- ϕ_{16}^{-1} **has degree 11 for each output bit and 13465 monomials in its ANF**
- Each output bit depends on all input bits (only $\frac{5}{n}$ in case of ϕ_n.)
- The degree of ϕ_n^{-1} grows **linearly** with n and the number of ANF monomials **exponentially**.

Implementation Technique 1: 16-Cycle Hardware



Two cyclic shift registers x and y and a single nonlinear ϕ_5 function.
The direction of shift does not matter.

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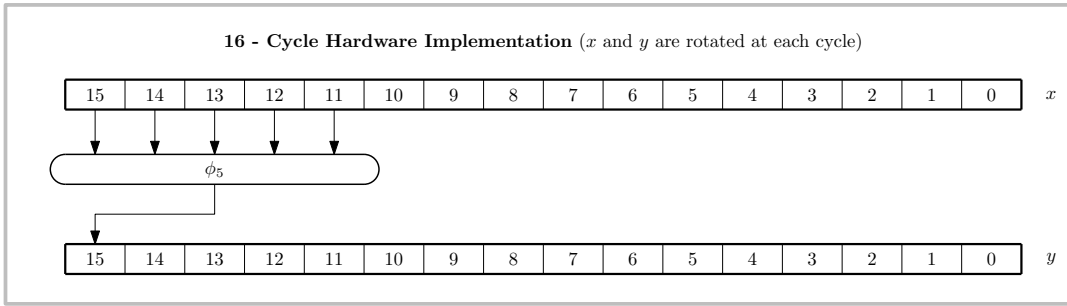
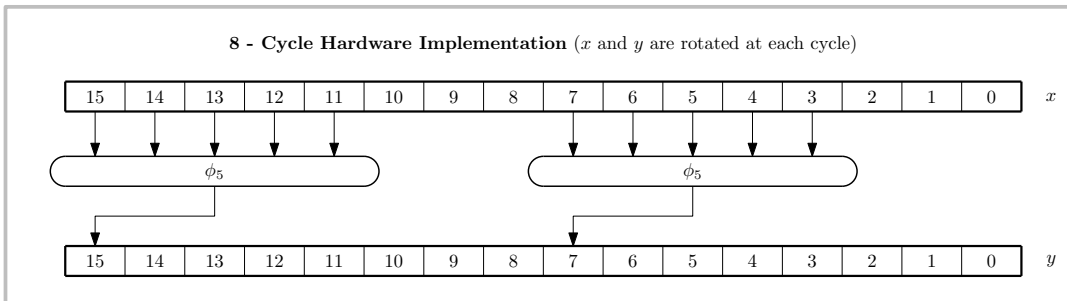


Two cyclic shift registers x and y and a single nonlinear ϕ_5 function.
The direction of shift does not matter.

After 16 cycles, $y = \phi_{16}(x)$. The hardware area is very small ($\approx$ 100 GE).

Implementation Technique 2: 8-Cycle Hardware

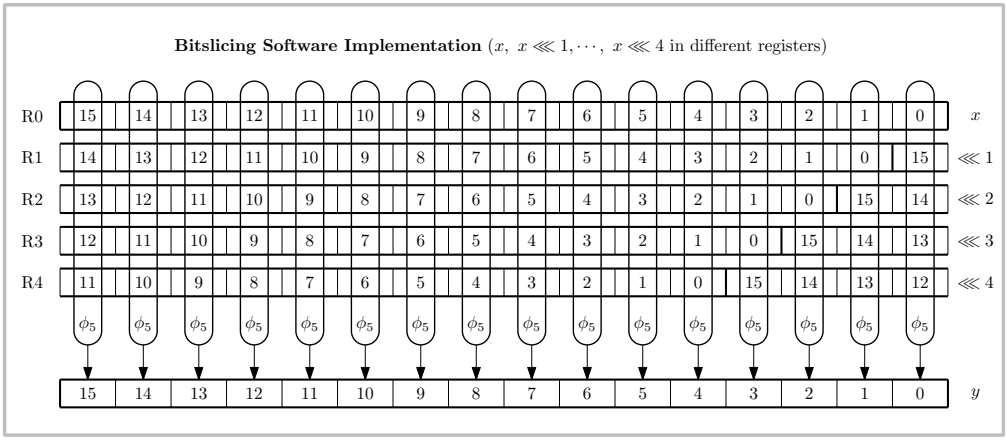


Again two cyclic shift registers x and y but two nonlinear ϕ_5 functions.

After 8 cycles, $y = \phi_{16}(x)$. The number of GE is is increased somewhat.

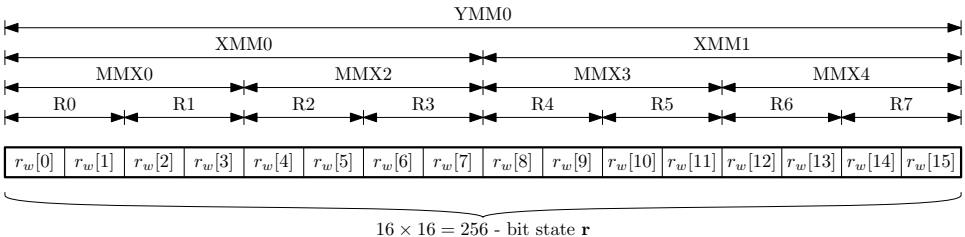
This way we can have speed/area trade-offs for $1, 2, 4, 8, 16$ cycles.

Implementation Technique 3: Rotational Bit-Slicing



Get cyclic rotations of input word $x_i = x \lll i$ for $0 \leq i \leq 4$ into five 16-bit registers Ri: R0, R1, R2, R3, R4. Then compute $16\times$ ϕ_5 in parallel using bitwise logic.

Implementation Technique 4: Massive Parallelism



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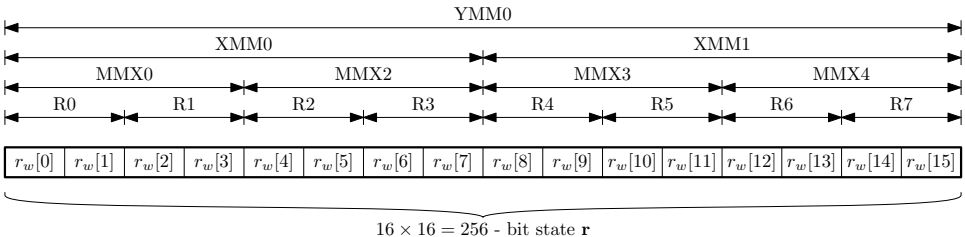

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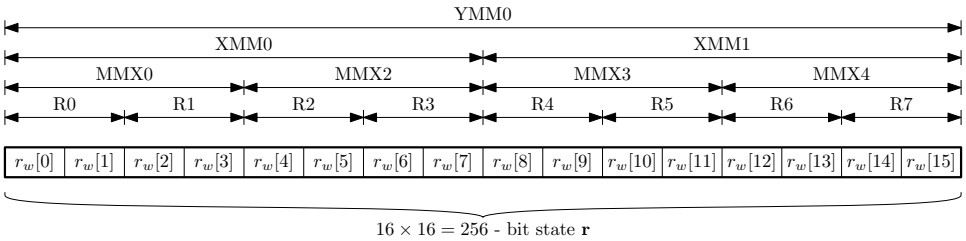

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Massive improvement over traditional S-Box lookups of similar size in both low-end and high-end software and hardware.

TI MSP430 (16-bit) and Intel AVX2 (256-bit)

TI MSP430 assembly for $16 \times \phi_5$
with 9 instructions on 16-bit regs:

```
// r14 = Phi5(r15, .. ,r11)
bic     r12, r11
inv     r13
and     r13, r12
and     r11, r13
xor     r12, r11
and     r11, r15
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AVX2 C intrinsics for $256 \times \phi_5$ with 8 instructions on 256-bit regs:

```
// t0 = Phi5(x0,x1,x2,x3,x4)
t0 = _mm256_andnot_si256(x3,x4);
t1 = _mm256_andnot_si256(x2,x3);
t2 = _mm256_andnot_si256(x2,t0);
t3 = _mm256_or_si256(x1,t1);
t0 = _mm256_xor_si256(t0,t1);
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This is optimal: Eight instructions required in 3-operand architectures (x86 SIMD, ARM, PPC, MIPS) and nine in sensible 2-operand architectures (MSP430).

Putting it together: Mixing Function mx

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- $.^T$ Transpose of the 16×16 - bit state makes mixing efficient.
- λ Parity operation on 4-bit nibbles.
- ϕ Is just 16 independent invocations of nonlinear ϕ_{16}.

Due to transpose, mx is usually implemented as double rounds mx^2 ("vertical" and "horizontal" round) in software.

Speed on 64-bit x86

We compare to OpenSSL 1.0.1e AES implementation, which is the de facto standard AES implementation. Generic assembler optimizations were enabled but we disabled the full hardware AES for fairness.

Implementation	Throughput	Cycles/Byte
CBEAM-GCC	58.5 MB/s	32.5
CBEAM-AVX2	117.5 MB/s	16.1
OpenSSL AES-128	106.5 MB/s	17.8
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CBEAM implementation is much more compact and is not vulnerable to cache timing attacks as it is only straight-line code.

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AES-128 [1]	2536	?	5432	8802	550.1
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The IAIK [1] implementation is commercial and written in hand-optimized assembly.
The Texas Instruments [2] AES core is recommended by the SoC vendor themselves.

Security Theorems

For MonkeyWrap and BLINKER modes with t-bit authentication tags, N invocations of π, k-bit key, and max q queries:

$$\mathrm{Adv}^{\mathsf{priv}}_{\mathsf{enc}}(\mathcal{A}) < q2^{-k} + \frac{N(N+1)}{2^{c+1}} \tag{1}$$

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We claim security equivalent or better than Triple-DES with $t = 128$, $k \geq 128$, $q \leq 2^{32}$ and $N \leq 2^{40}$.

Security against Differential, Linear, and especially Algebraic cryptanalysis. We recommend the MonkeDuplex-like single-use nonce modes for additional security.

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- **Compact straight-line** code, hence no cache timing attacks as in AES. Highly flexible implementations in high- and low-performance platforms.
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- **Further research**: discovery of surprising features of ϕ functions, refined quantification of security from feedble one-wayness.