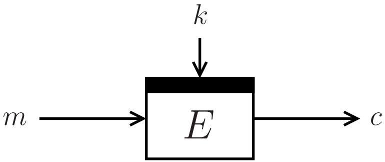
Tweakable Blockciphers: Theory and Application

Bart Mennink
KU Leuven (Belgium)

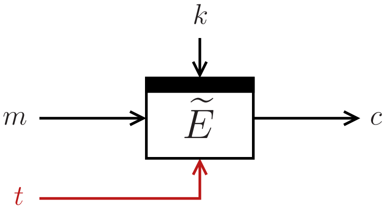
IACR School on Design and Security of Cryptographic Algorithms and Devices

October 21, 2015

Tweakable Blockciphers

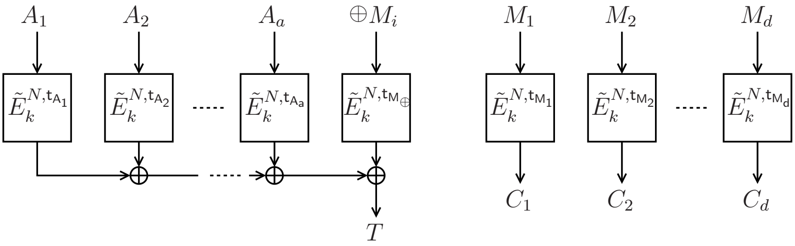


Tweakable Blockciphers



- Tweak: flexibility to the cipher
- Each tweak gives different permutation

Motivation: OCBx



- Generalized OCB by Rogaway et al. [RBBK01,Rog04,KR11]
- Internally based on tweakable blockcipher $\widetilde{E}$
  - Tweak (N, tweak) is unique for every evaluation

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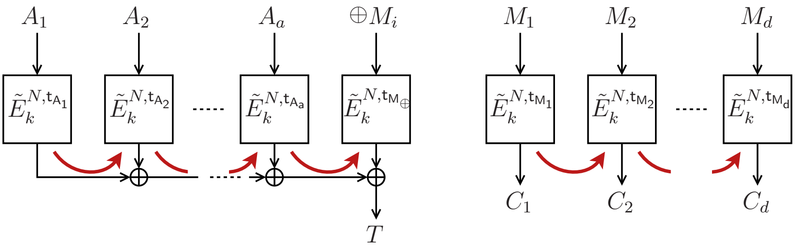

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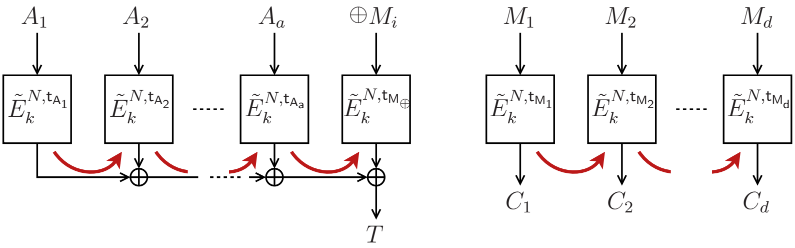

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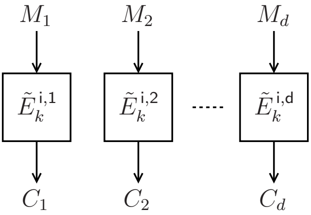
Tweakable blockcipher with efficient re-tweaking $\Longrightarrow$ efficient AE

Motivation: XTS



- XTS mode for disk encryption
- Tweak $(\mathsf{i}, \mathsf{j}) = (\mathsf{sector}, \mathsf{block})$ unique for every block

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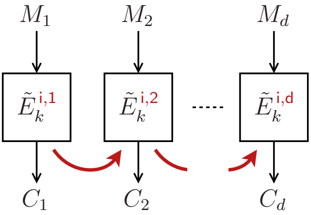

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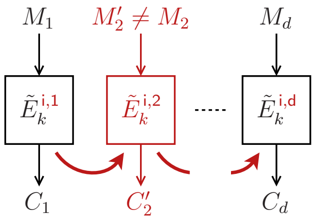

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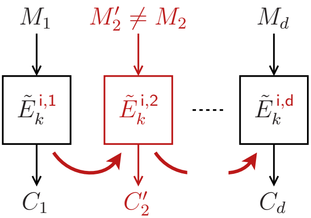

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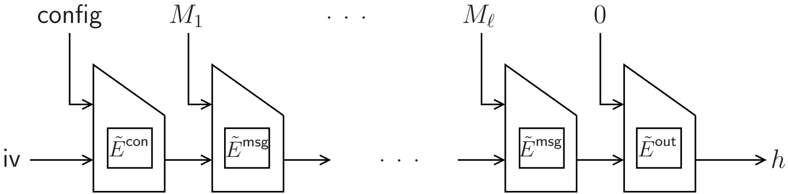
Tweakable blockcipher facilitates ECB-like modes $\Longrightarrow$ incrementality

Motivation: Skein



- Skein hash function by Ferguson et al. [FLS+07]
- Based on Threefish tweakable blockcipher
- Tweaks used for domain separation

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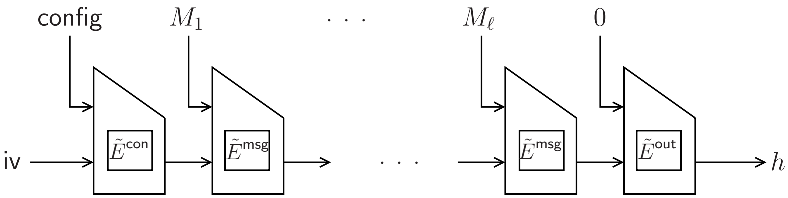

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Tweakable blockcipher $\Longrightarrow$ independent-looking blockciphers

Tweakable Blockciphers from Scratch

- Hasty Pudding Cipher [Sch98]
  - AES submission, "first tweakable cipher"
- Mercy [Cro01]
  - Disk encryption
- Threefish [FLS+07]
  - SHA-3 submission Skein
- TWEAKEY [JNP14]
  - CAESAR submissions Deoxys, Joltik, KIASU

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Our focus: generic tweakable blockcipher design

Outline

Birthday Bound TBCs

Improved Security for Birthday Bound TBCs

Improved Efficiency for Birthday Bound TBCs

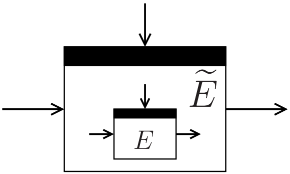
Beyond Birthday Bound TBCs

Conclusion

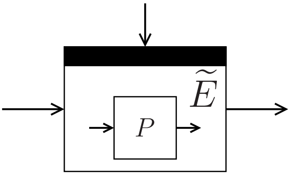
Outline

Tweakable Blockciphers from Blockciphers/Permutations

Blockcipher Based

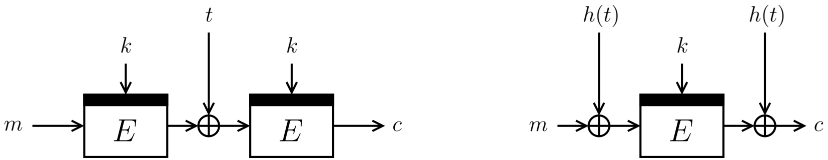


Permutation Based



Tweakable Blockciphers from Blockciphers

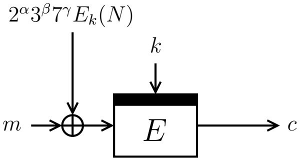
- LRW_1 and LRW_2 by Liskov et al. [LRW02]:

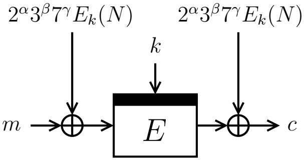


- h is XOR-universal hash
  - E.g., $h(t) = h \otimes t$ for n-bit "key" h

Tweakable Blockciphers from Blockciphers

- XE and XEX by Rogaway [Rog04]:





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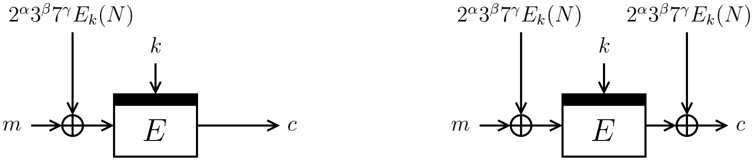
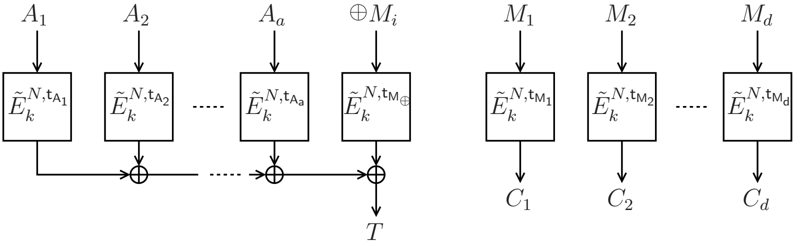


- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Used in OCB2 and XTS

Example: XEX in OCB2 and XTS

OCB2:



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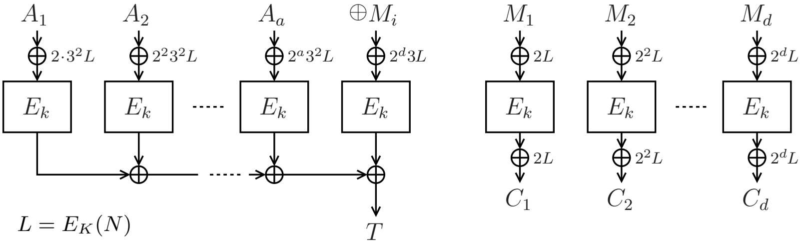

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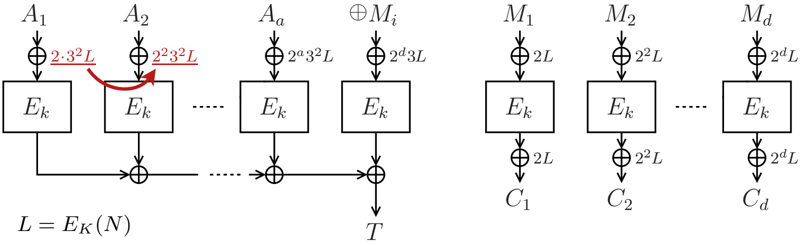

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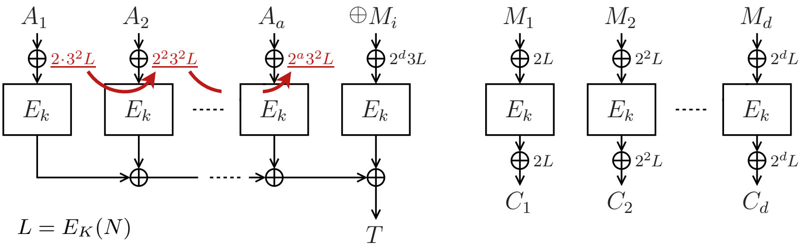

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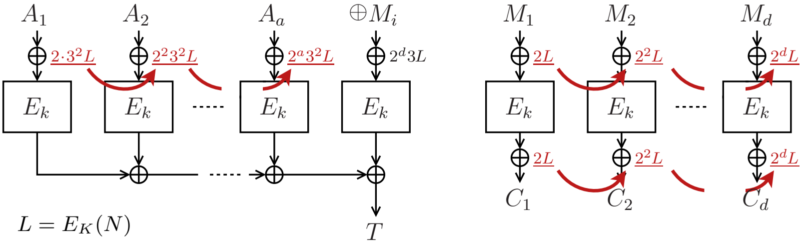

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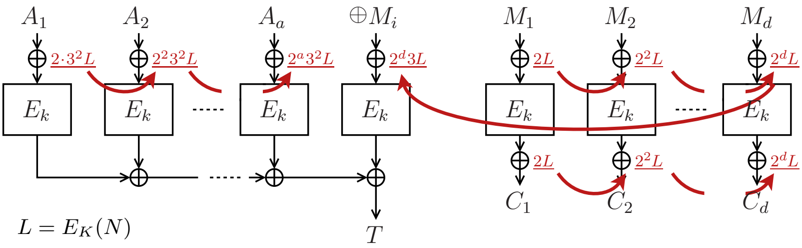

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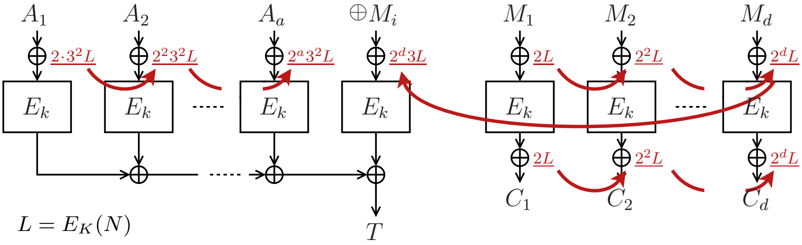
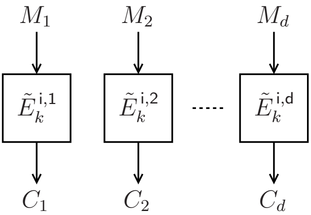


XTS:



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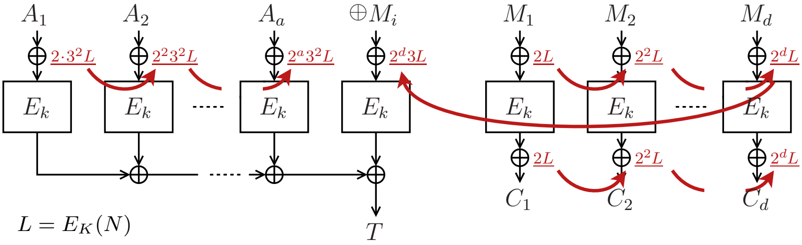

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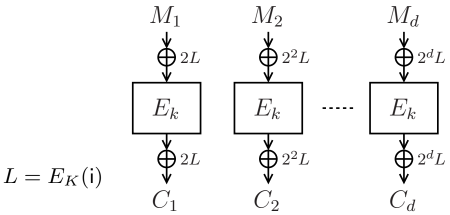

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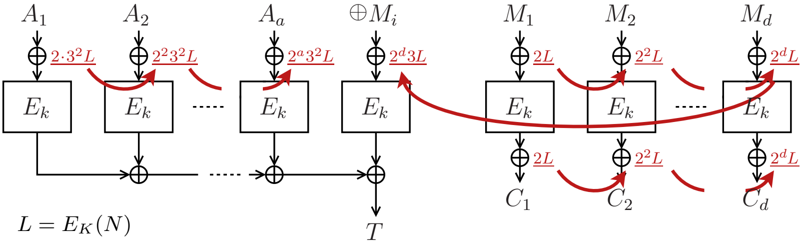

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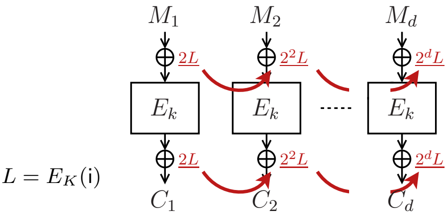

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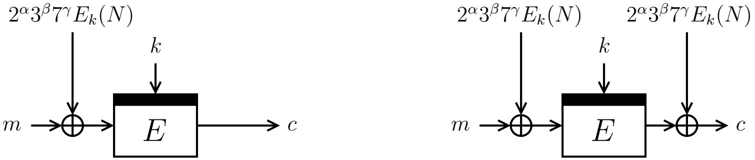

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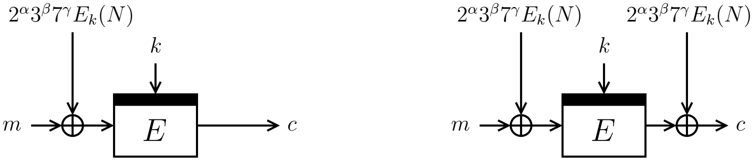

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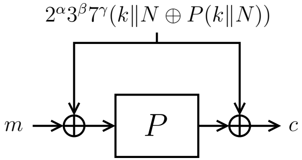
- Generalized masking:
  - Chakraborty and Sarkar [CS06]: $\varphi^\alpha(E_k(N))$ for LFSR φ
  - Gray codes (used in OCB1 and OCB3)

Tweakable Blockciphers from Permutations

- Minalpher's TEM [STA+14]:



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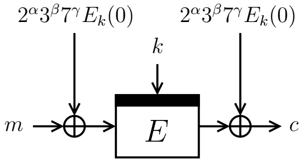

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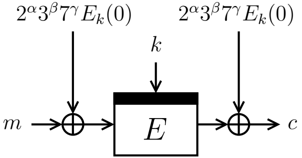

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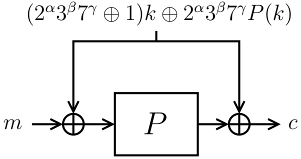
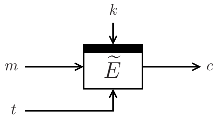
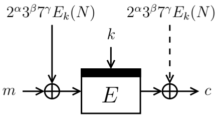


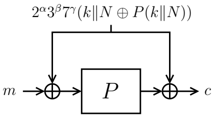
Tweakable Blockciphers in CAESAR



Dedicated



XE/XEX-inspired



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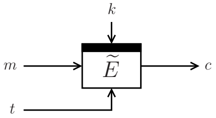

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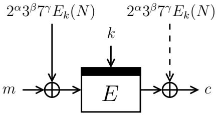
Deoxys,
Joltik,
KIASU,
SCREAM



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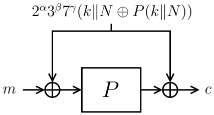

TEM-inspired

Minalpher,
Prøst

plain = first round, **bold = second round**

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Improved Security for Birthday Bound TBCs

Improved Efficiency for Birthday Bound TBCs

Beyond Birthday Bound TBCs

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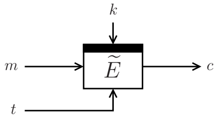

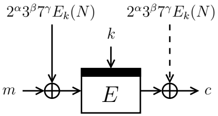

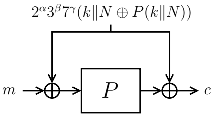

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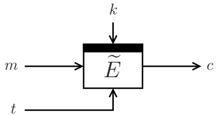

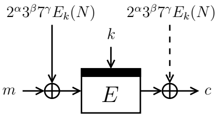

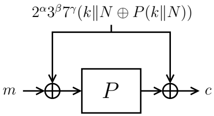

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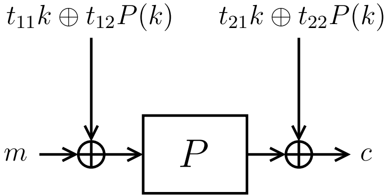
Minalpher, Prøst

XPX [Men15b], generalization of this

plain = first round, **bold = second round**

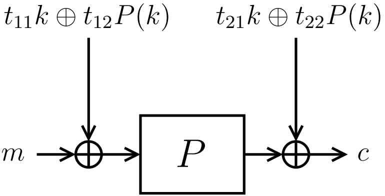
XPX



Tweak Set

- $(t_{11}, t_{12}, t_{21}, t_{22})$ from some tweak set $\mathcal{T} \subseteq (\{0,1\}^n)^4$
- $\mathcal{T}$ can (still) be any set

XPX



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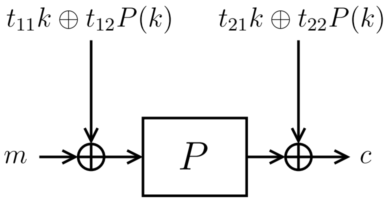

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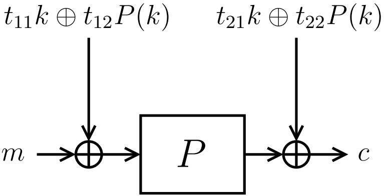

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  2. "Normal" $\mathcal{T}$ $\longrightarrow$ single-key secure

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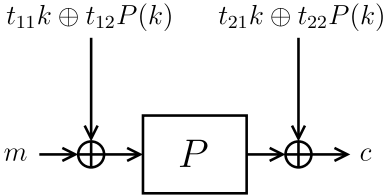

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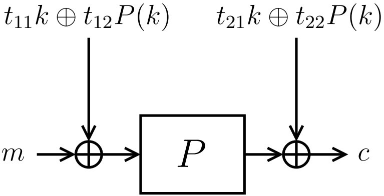
- Security of XPX strongly depends on choice of $\mathcal{T}$
  1. "Stupid" $\mathcal{T}$ $\longrightarrow$ insecure
  2. "Normal" $\mathcal{T}$ $\longrightarrow$ single-key secure
  3. "Strong" $\mathcal{T}$ $\longrightarrow$ related-key secure

XPX: Stupid Tweaks



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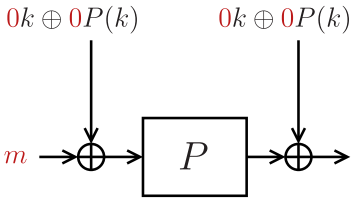

$(0, 0, 0, 0) \in \mathcal{T}$

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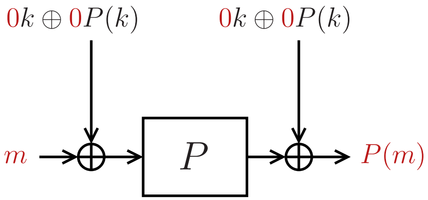

$$(0, 0, 0, 0) \in \mathcal{T} \quad \Longrightarrow \quad \mathsf{XPX}_k((0, 0, 0, 0), m) = P(m)$$

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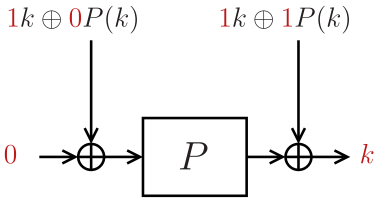

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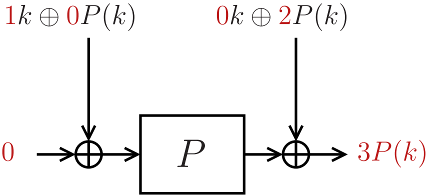

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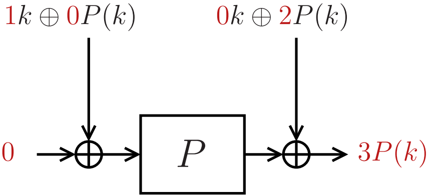
XPX: Stupid Tweaks



$$
\begin{array}{lcl}
(0,0,0,0) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((0,0,0,0),m) = P(m) \\
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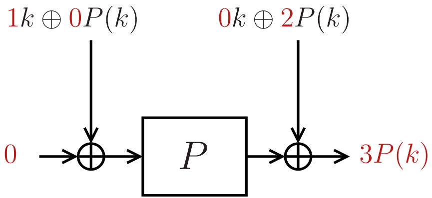
\cdots & \cdots & \cdots
\end{array}
$$

XPX: Stupid Tweaks



$$\begin{aligned}
(0,0,0,0) \in \mathcal{T} \quad &\Longrightarrow \quad \mathsf{XPX}_k((0,0,0,0),m) = P(m) \\
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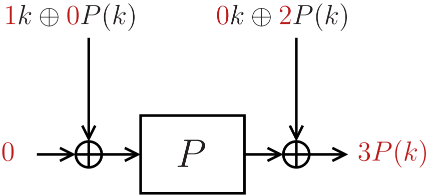
\cdots \qquad & \quad \cdots \qquad \cdots
\end{aligned}$$

"Valid" Tweak Sets

- Technical definition to eliminate trivial cases

XPX: Stupid Tweaks



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\dots & \dots & \dots
\end{array}
$$

"Valid" Tweak Sets

- Technical definition to eliminate trivial cases
- If $\mathcal{T}$ is invalid, then XPX is insecure

XPX: Normal and Strong Tweaks

Single-Key Security

- If $\mathcal{T}$ is valid, then XPX is STPRP

XPX: Normal and Strong Tweaks

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$\Phi_{\oplus}$-Related-Key Security (Simplified)

- $\mathcal{D}$ can influence key: $k \mapsto k \oplus \delta$

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- Note: maskings in XPX are $t_{i1}k \oplus t_{i2}P(k)$

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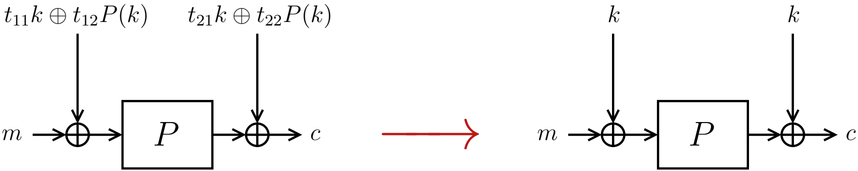
if $\mathcal{T}$ is valid, and for all tweaks:	security
$t_{12}, t_{22} \neq 0$ and $(t_{21}, t_{22}) \neq (0, 1)$	$\Phi_{\oplus}$-rk-STPRP
$t_{11}, t_{12}, t_{21}, t_{22} \neq 0$	$\Phi_{P\oplus}$-rk-STPRP

XPX Covers Even-Mansour

for $\mathcal{T} = \{(1,0,1,0)\}$

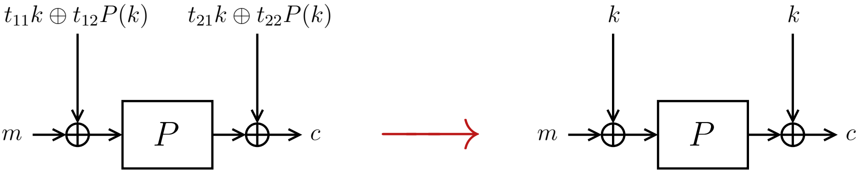
XPX Covers Even-Mansour



for $\mathcal{T} = \{(1,0,1,0)\}$

- Single-key STPRP secure (surprise?)

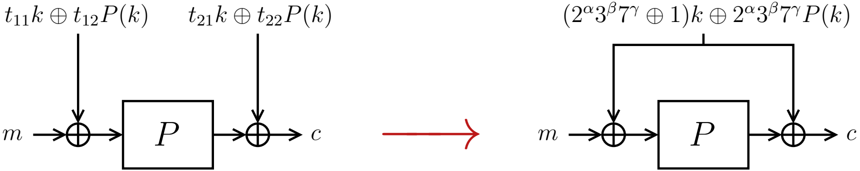
XPX Covers Even-Mansour



for $\mathcal{T} = \{(1,0,1,0)\}$

- Single-key STPRP secure (surprise?)
- Generally, if $|\mathcal{T}| = 1$, XPX is a normal blockcipher

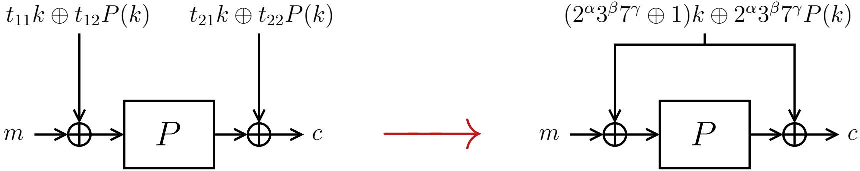
XPX Covers XEX With Even-Mansour



for $\mathcal{T} = \left\{ \begin{array}{l} (\,2^\alpha 3^\beta 7^\gamma \oplus 1\,,\, 2^\alpha 3^\beta 7^\gamma\,, \\ \;\; 2^\alpha 3^\beta 7^\gamma \oplus 1\,,\, 2^\alpha 3^\beta 7^\gamma\,) \end{array} \;\middle|\; (\alpha,\beta,\gamma) \in \{\text{XEX-tweaks}\} \right\}$

- (α, β, γ) is in fact the “real” tweak

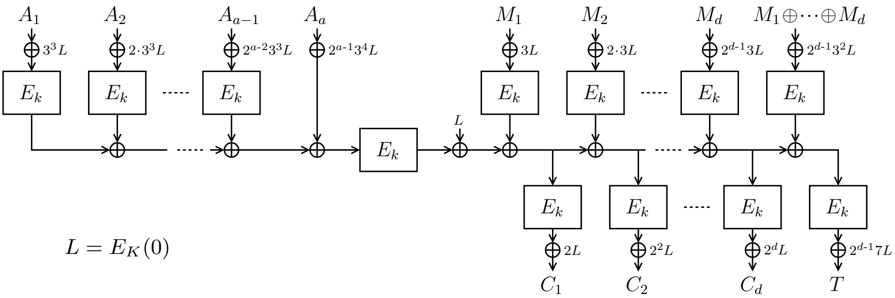
XPX Covers XEX With Even-Mansour



$$\text{for } \mathcal{T} = \left\{ \begin{array}{l} (\, 2^\alpha 3^\beta 7^\gamma \oplus 1 \,,\, 2^\alpha 3^\beta 7^\gamma \,, \\ \;\; 2^\alpha 3^\beta 7^\gamma \oplus 1 \,,\, 2^\alpha 3^\beta 7^\gamma \,) \end{array} \;\middle|\; (\alpha,\beta,\gamma) \in \{\text{XEX-tweaks}\} \right\}$$

- (α, β, γ) is in fact the "real" tweak
- $\Phi_{P\oplus}$-rk STPRP secure (if $2^\alpha 3^\beta 7^\gamma \neq 1$)

Application of XPX to AE: COPA



- By Andreeva et al. [ABL+14]
- Implicitly based on XEX based on AES

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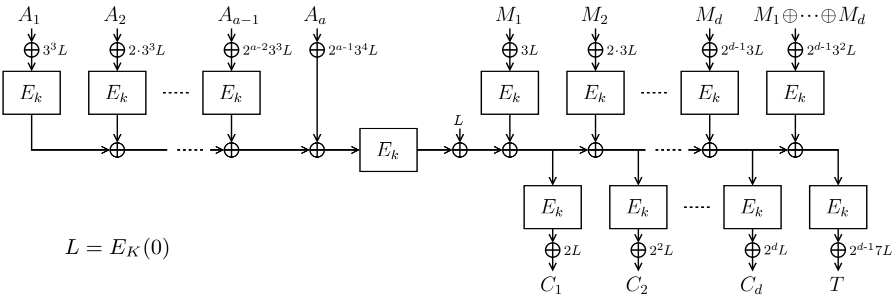

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- Prøst-COPA by Kavun et al. [KLL+14]:
  COPA based on XEX based on Even-Mansour

Application of XPX to AE: COPA

Single-Key Security of COPA

$$\boxed{\text{COPA}} \xrightarrow[\text{sk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XEX}} \xrightarrow[\text{sk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{E}$$

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Related-Key Security of COPA

- Approach generalizes for any Φ (proof in [Men15b])

$$\boxed{\text{COPA}} \xrightarrow[\Phi\text{-rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XEX}} \xrightarrow[\Phi\text{-rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{E}$$

Application of XPX to AE: Prøst-COPA

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Application of XPX to AE: Prøst-COPA

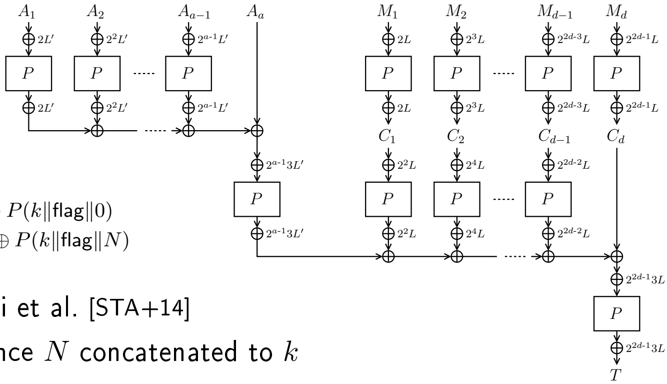
Single-Key Security of Prøst-COPA

$$\begin{tikzcd} \boxed{\text{COPA}} \arrow[r, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\text{sk}"'] & \boxed{\text{XEX}} \arrow[r, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\text{sk}"'] & \boxed{E} \arrow[r, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\text{sk}"'] & \boxed{P} \end{tikzcd}$$

Related-Key Security of Prøst-COPA

$$\begin{tikzcd} \boxed{\text{COPA}} \arrow[r, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\Phi\text{-rk}"'] & \boxed{\text{XEX}} \arrow[r, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\Phi\text{-rk}"'] \arrow[rr, bend right, "\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)", "\Phi_{P\oplus}\text{-rk}"'] & \boxed{E} \arrow[r, "\Omega\left(1\right)", "\Phi\text{-rk}"'] & \boxed{P} \end{tikzcd}$$

Application of XPX to AE: Minalpher



$$L' = k \| \mathsf{flag} \| 0 \oplus P(k \| \mathsf{flag} \| 0)$$
$$L = k \| \mathsf{flag} \| N \oplus P(k \| \mathsf{flag} \| N)$$

- By Sasaki et al. [STA+14]
- Extra nonce N concatenated to k

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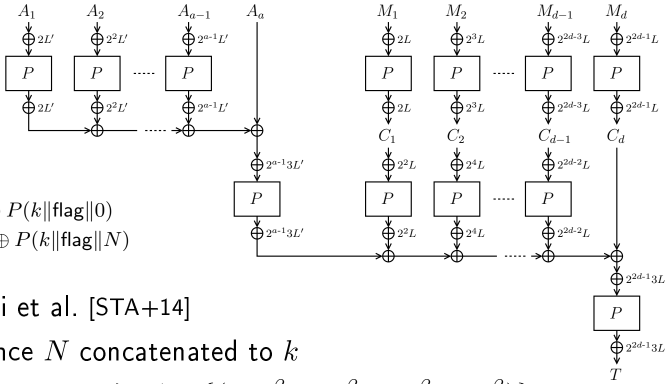

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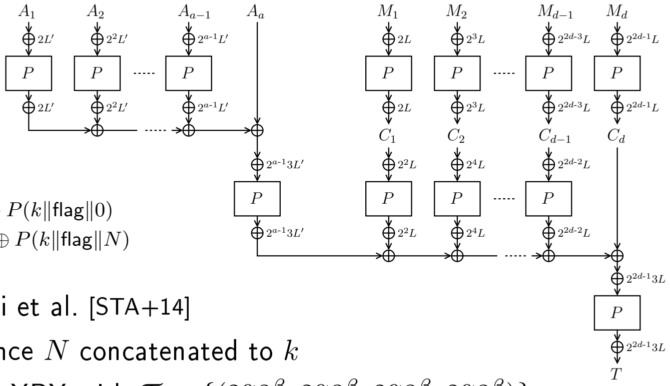

$L' = k\|\text{flag}\|0 \oplus P(k\|\text{flag}\|0)$
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$$\boxed{\text{Minalph.}} \xrightarrow[\Phi\text{-rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XPX}} \qquad \boxed{P}$$

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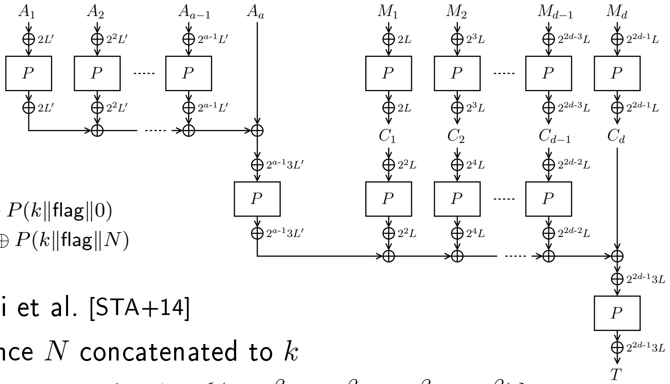

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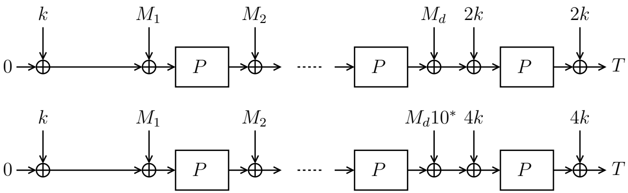
Application of XPX to MAC: Chaskey



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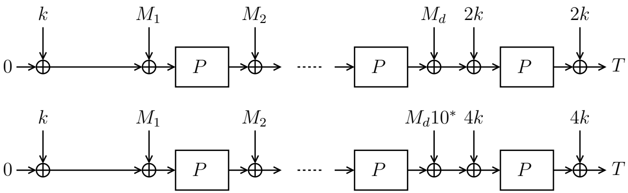

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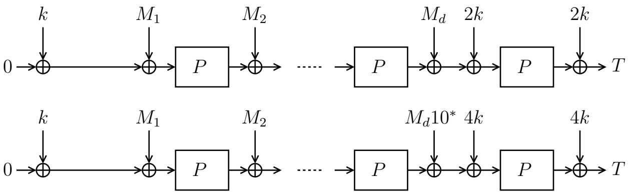

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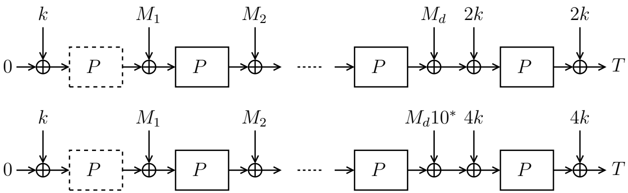
Application to MAC: Adjusted Chaskey



- Extra P-call
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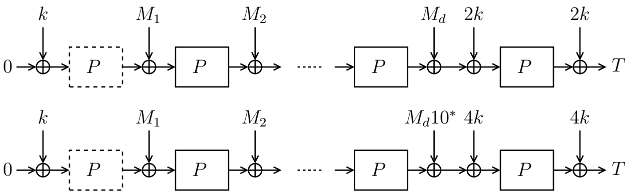
Application to MAC: Adjusted Chaskey



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$$\boxed{\text{Chaskey}} \xrightarrow[\Phi\text{-rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XPX}} \xrightarrow[\Phi_{\oplus}\text{-rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{P}$$

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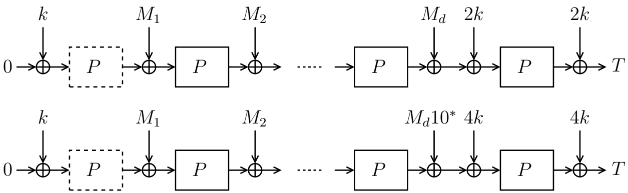

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- Approach also applies to Keyed Sponges

Outline

Birthday Bound TBCs

Improved Security for Birthday Bound TBCs

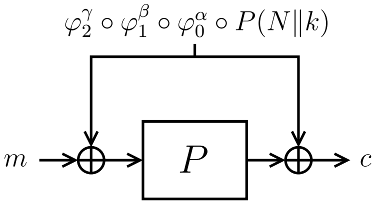
Improved Efficiency for Birthday Bound TBCs

Beyond Birthday Bound TBCs

Conclusion

MEM

- MEM by Granger et al. [GJMN15]:



- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)

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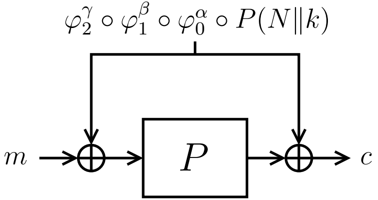

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- Masking combines advantages of:
  - Powering-up masking
  - LFSR masking

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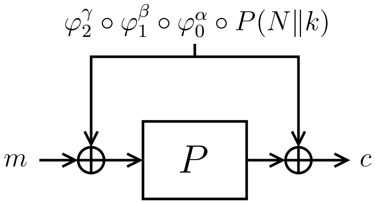
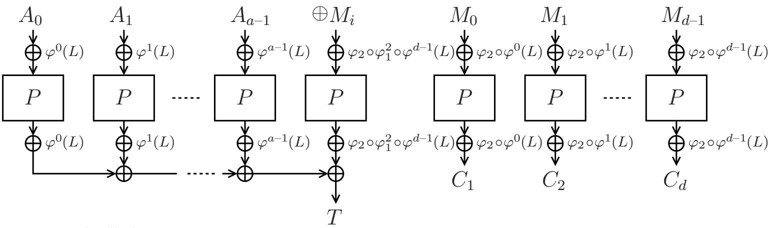


- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Masking combines advantages of:
  - Powering-up masking
  - LFSR masking

New masking is simpler, constant-time (by default), more efficient

Application of MEM to AE: OPP

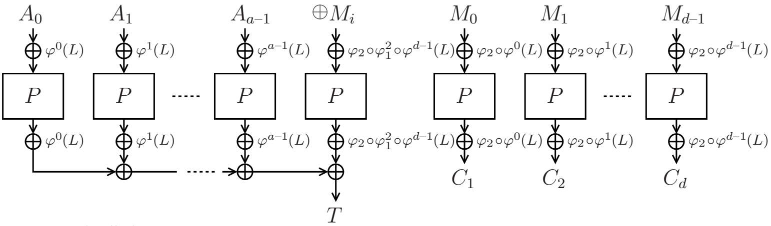


$L = P(N \| k)$

$\varphi_1 = \varphi \oplus id$, $\varphi_2 = \varphi^2 \oplus \varphi \oplus id$

- Offset Public Permutation (OPP) [GJMN15]
- Generalization of OCB3:
  - Permutation-based
  - More efficient MEM-masking
- Security against nonce-respecting adversaries

Application of MEM to AE: OPP



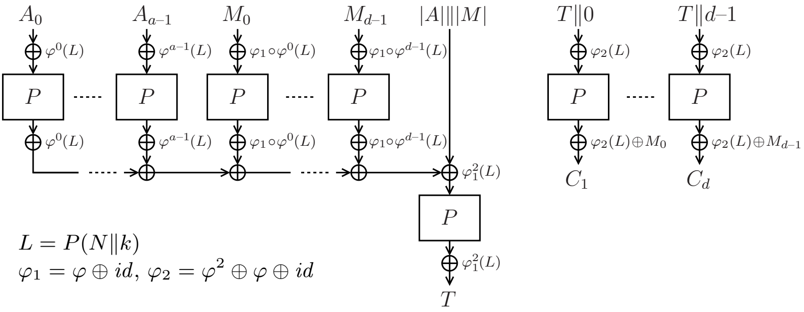
$L = P(N \| k)$

$\varphi_1 = \varphi \oplus id$, $\varphi_2 = \varphi^2 \oplus \varphi \oplus id$

- Offset Public Permutation (OPP) [GJMN15]
- Generalization of OCB3:
  - Permutation-based
  - More efficient MEM-masking
- Security against nonce-respecting adversaries

0.55 cpb with reduced-round BLAKE2b

Application of MEM to AE: MRO



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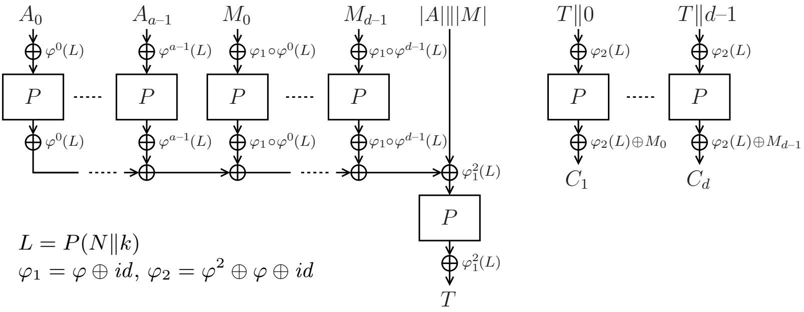

- Misuse-Resistant OPP (MRO) [GJMN15]
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1.06 cpb with reduced-round BLAKE2b

Outline

Security Beyond Birthday Bound?

- All results so far: up to birthday bound

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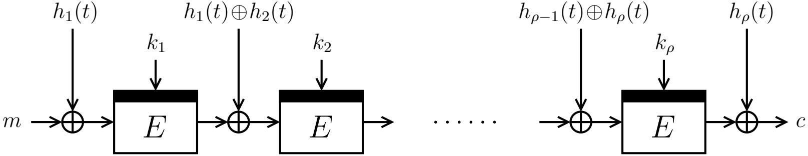
Can we improve this?

BBB Tweakable Blockciphers from Blockciphers



- $\mathsf{LRW}_2[\rho]$: concatenation of ρ LRW_2's
- $k_1, \ldots, k_\rho$ and $h_1, \ldots, h_\rho$ independent

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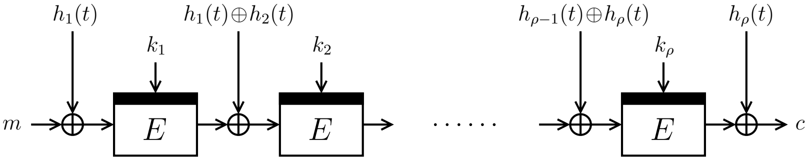

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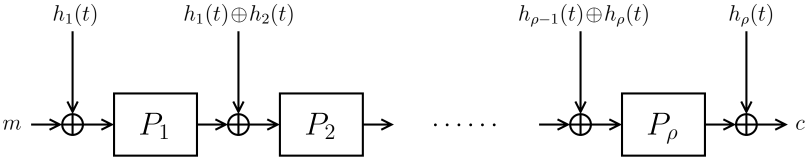
- $\rho = 2$: secure up to $2^{2n/3}$ queries [LST12,Pro14]
- $\rho \geq 2$ even: secure up to $2^{\rho n/(\rho+2)}$ queries [LS13]
- Conjecture: optimal $2^{\rho n/(\rho+1)}$ security

BBB Tweakable Blockciphers from Permutations



- TEM[ρ]: concatenation of ρ TEM-like's
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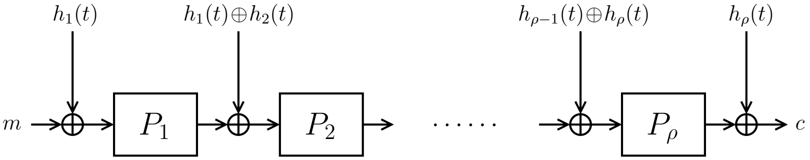

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State of the Art (Blockcipher Based)

scheme	security ($\log_2$)	key length	cost	
			E	$\otimes/h$
LRW_1	$n/2$	n	2	0
LRW_2	$n/2$	$2n$	1	1
XEX	$n/2$	n	2	0
$\text{LRW}_2[2]$	$2n/3$	$4n$	2	2
$\text{LRW}_2[\rho]$	$\rho n/(\rho+2)$	$2\rho n$	ρ	ρ

Optimal 2^n security only if key length and cost $\rightarrow \infty$?

Tweak-Dependent Keys

Efficiency

tweak schedule lighter
than key schedule

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Efficiency	**Security**
tweak schedule lighter than key schedule	tweak schedule stronger than key schedule

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Tweak and key change approximately equally expensive

Tweak-Dependent Keys

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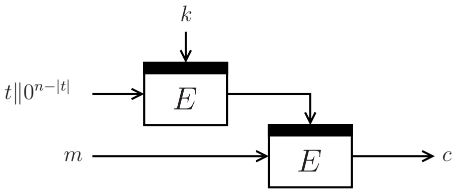
Tweak and key change approximately equally expensive

- TWEAKEY [JNP14] key scheduling blends key and tweak

Tweak-Dependent Keys

- Minematsu [Min09]:



- Secure up to $\max\{2^{n/2}, 2^{n-|t|}\}$ queries
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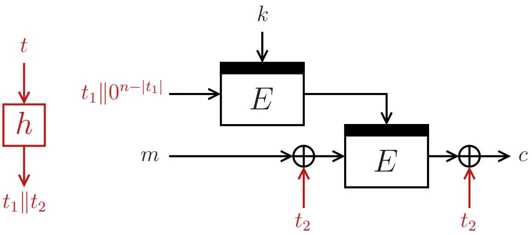


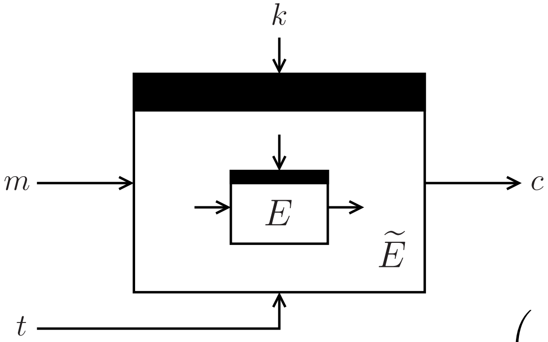
- Secure up to $\max\{2^{n/2}, 2^{n-|t|}\}$ queries
- Beyond birthday bound for $|t| < n/2$
- Tweak-length extension possible by XTX [MI15]

State of the Art (Blockcipher Based)

scheme	security ($\log_2$)	key length	cost		
			E	$\otimes/h$	tdk
LRW_1	$n/2$	n	2	0	0
LRW_2	$n/2$	$2n$	1	1	0
XEX	$n/2$	n	2	0	0
$\text{LRW}_2[2]$	$2n/3$	$4n$	2	2	0
$\text{LRW}_2[\rho]$	$\rho n/(\rho+2)$	$2\rho n$	ρ	ρ	0
Min	$\max\{n/2, n-\lvert t\rvert\}$	n	2	0	1
Min-XTX	$2n/3$	$7n/3$	2	1	1

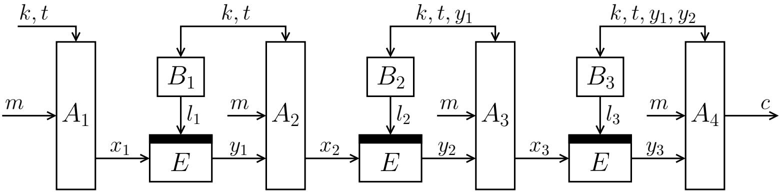
Goal

Given a blockcipher E,
construct optimally secure tweakable blockcipher $\widetilde{E}$



$\left(\begin{array}{c}\text{all wires}\\ \text{carry } n \text{ bits}\end{array}\right)$

Generic Design



$\widetilde{E}[\rho]$ (for $\rho \geq 1$)

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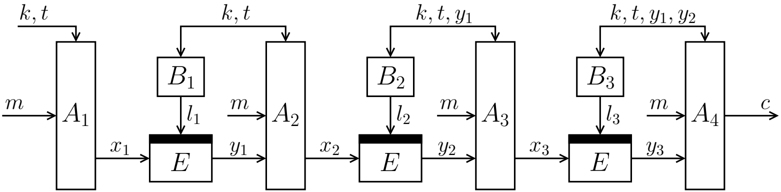
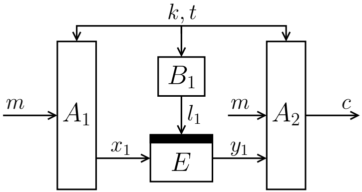


$\widetilde{E}[\rho]$ (for $\rho \geq 1$)

- Mixing functions A_i, B_i
  - should be such that $\widetilde{E}[\rho]$ is invertible
  - but can be anything otherwise

One E-Call with Linear Mixing



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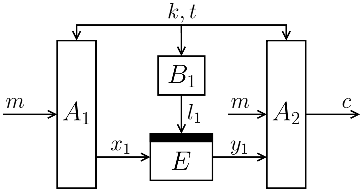
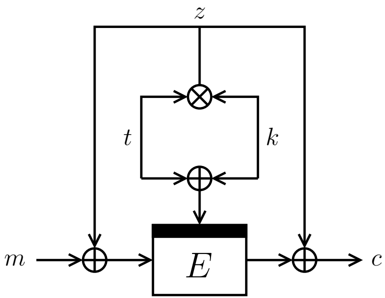


Theorem [Men15a]

- If A_1, B_1, A_2 are linear, $\widetilde{E}[1]$ can be attacked in at most about $2^{n/2}$ queries

One E-Call with Polynomial Mixing



$\text{Men}_1(k, t, m) = c$ [Men15a]

Idea

- Subkey $k \oplus t$
- Masking $k \otimes t$

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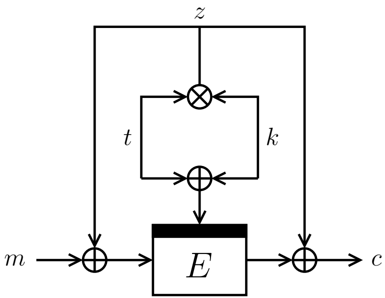

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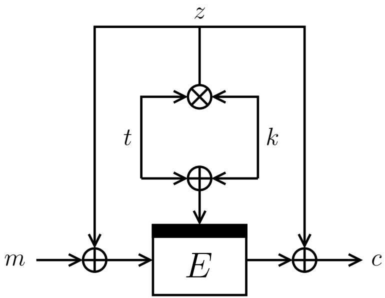

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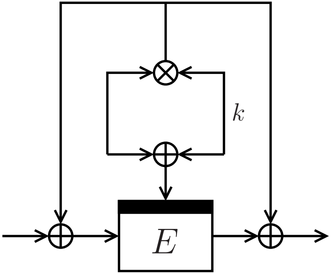
One E-Call with Polynomial Mixing: Proof Idea



- Key k is secret

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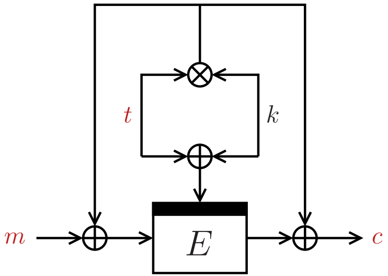

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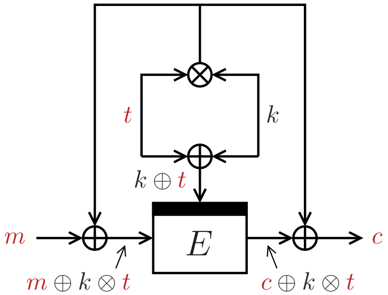

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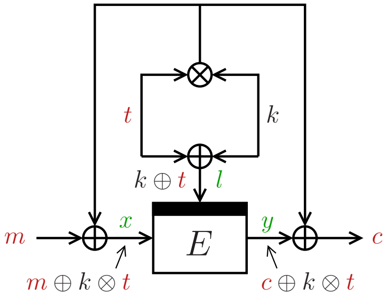

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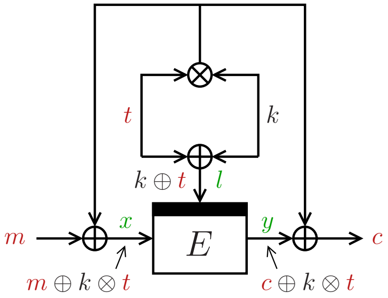

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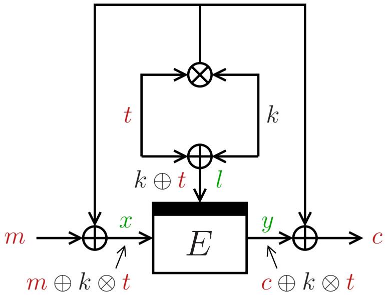

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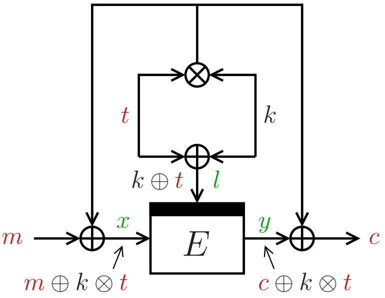

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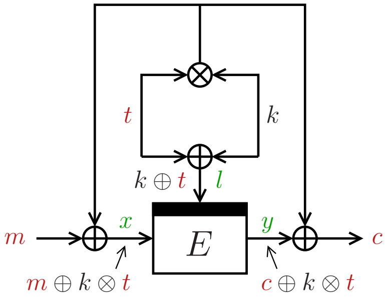

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Szemerédi-Trotter theorem [ST83]

Consider a finite field $\mathbb{F}$. Let

- $L \subseteq \mathbb{F}^2$ be a set of lines
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\# point-line incidences $\leq \min\{|L|^{1/2}|P| + |L|, |L||P|^{1/2} + |P|\}$

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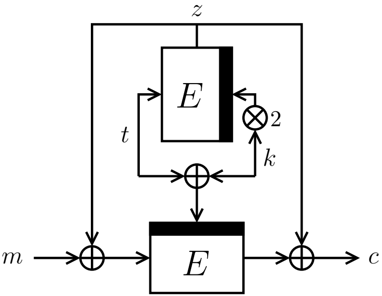
- k is random n-bit key

Two E-Calls with Linear Mixing



$\mathsf{Men}_2(k, t, m) = c$

Idea

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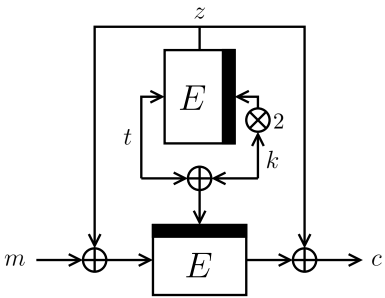
- Masking $E(2k, t)$

Two E-Calls with Linear Mixing



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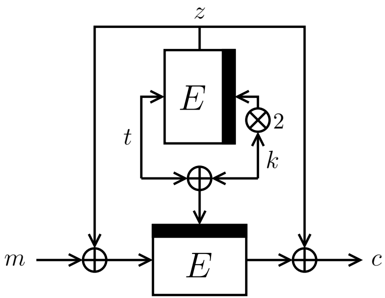

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Cost

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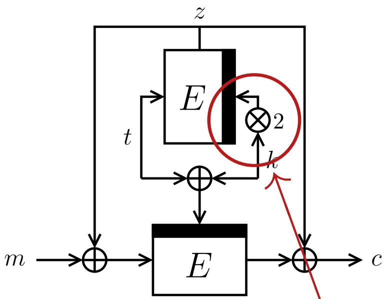
- Zero $\otimes$-evaluations
- One re-key

Two E-Calls with Linear Mixing



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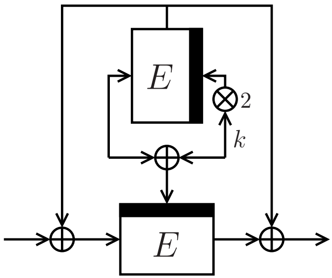
New after observation by Guo et al.
(original proof only for $t \neq 0$)

Two E-Calls with Linear Mixing: Proof Idea



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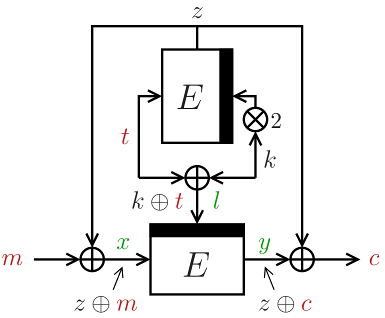

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or

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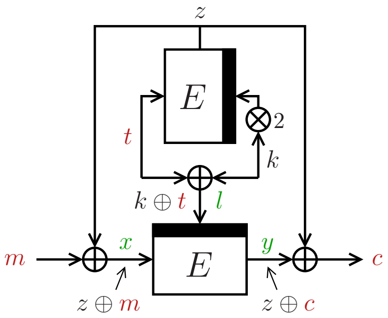
Two E-Calls with Linear Mixing: Proof Idea



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- k is random key, z is almost-random subkey

Comparison

scheme	security ($\log_2$)	key length	cost E	$\otimes/h$	tdk
LRW_1	$n/2$	n	2	0	0
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Men_1	$2n/3$ *	n	1	1	1
Men_2	n *	n	2	0	1

* Information-theoretic model

Outline

Birthday Bound TBCs

Improved Security for Birthday Bound TBCs

Improved Efficiency for Birthday Bound TBCs

Beyond Birthday Bound TBCs

Conclusion

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Birthday Bound Tweakable Blockciphers

- Myriad applications to AE, MAC, encryption, ...
- Various solutions for different problems:
    - Efficiency
    - Related-key security
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Beyond Birthday Bound Tweakable Blockciphers

- Allow for beyond birthday bound secure AE
- Efficient scheme without re-keying?
- One-call tweakable cipher with improved security?
- Optimal security in standard model?

Conclusion

Birthday Bound Tweakable Blockciphers

- Myriad applications to AE, MAC, encryption, ...
- Various solutions for different problems:
  - Efficiency
  - Related-key security
  - ...

Beyond Birthday Bound Tweakable Blockciphers

- Allow for beyond birthday bound secure AE
- Efficient scheme without re-keying?
- One-call tweakable cipher with improved security?
- Optimal security in standard model?

Thank you for your attention!

SUPPORTING SLIDES

Generic Design: Inverse

Valid Mixing Functions (informal)

A_i, B_i are valid if there is one A_{i^*} that processes m, s.t.

- first $i^* - 1$ rounds computable in forward direction
- last $\rho - (i^* - 1)$ rounds computable in inverse direction

both without usage of m

Example for $i^* = 2$