XPX: Generalized Tweakable Even-Mansour with Improved Security Guarantees

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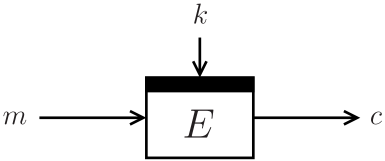
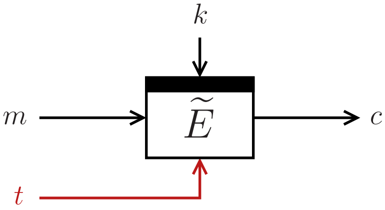
ASK 2015
October 2, 2015

Tweakable Blockciphers

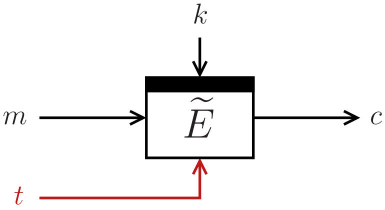


Tweakable Blockciphers



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

Tweakable Blockciphers



- Tweak: flexibility to the cipher
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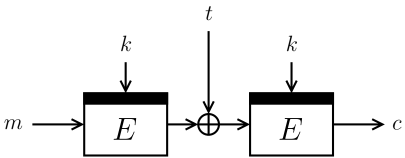
- Three approaches:
  - from scratch
  - from blockcipher
  - from permutation

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

Tweakable Blockciphers from Blockcipher

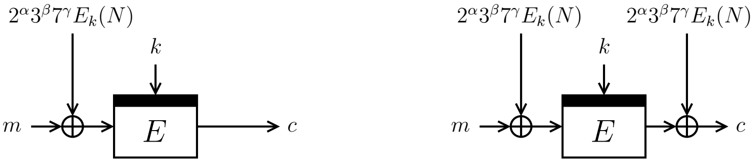
- LRW_1 and LRW_2 by Liskov et al. (2002):



- h is XOR-universal hash

Tweakable Blockciphers from Blockcipher

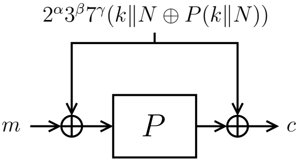
- XE and XEX by Rogaway (2004):



- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)

Tweakable Blockciphers from Permutation

- Minalpher's TEM [STA+14]:



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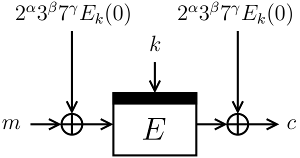
Tweakable Blockciphers from Permutation

- Prøst [KLL+14] uses XE(X) with Even-Mansour:



with $E_k(m) = P(m \oplus k) \oplus k$

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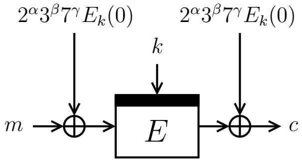

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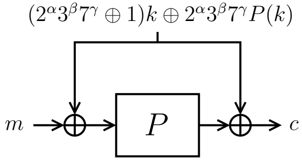
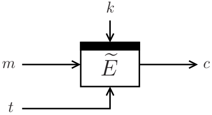
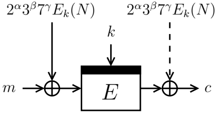


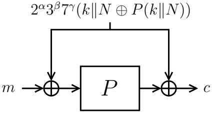
Tweakable Blockciphers in CAESAR



TWEAKEY



XE/XEX-inspired



TEM-inspired

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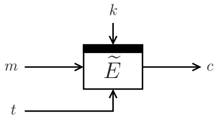

TWEAKEY

Deoxys,
Joltik,
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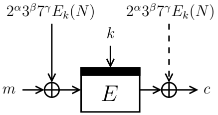

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AEZ, CBA, COBRA,
COPA, **ELmD**, iFeed,
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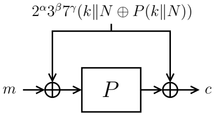
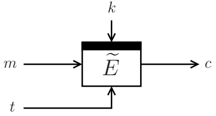


TEM-inspired

Minalpher,
Prøst

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

Tweakable Blockciphers in CAESAR



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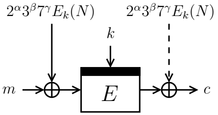

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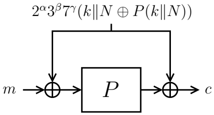


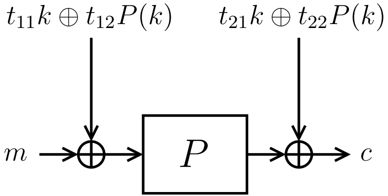
TEM-inspired

Minalpher, Prøst

We generalize this

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

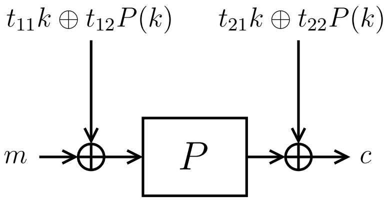
XPX



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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- Security of XPX strongly depends on choice of $\mathcal{T}$

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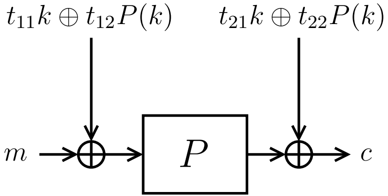

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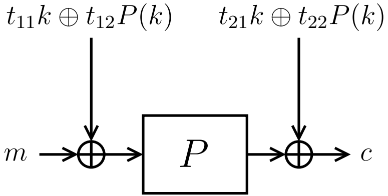
  1. "Stupid" $\mathcal{T}$ $\longrightarrow$ insecure

XPX



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

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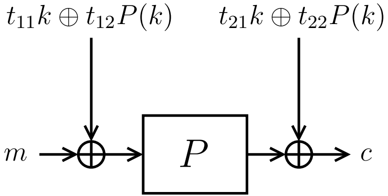

Tweak Set

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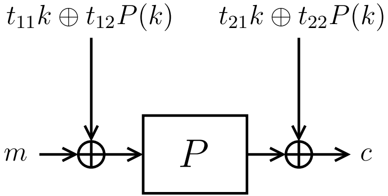
- $\mathcal{T}$ can (still) be any set

- 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: Valid Tweaks



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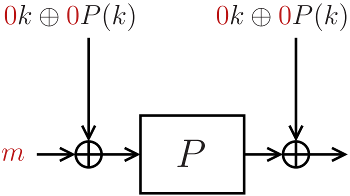
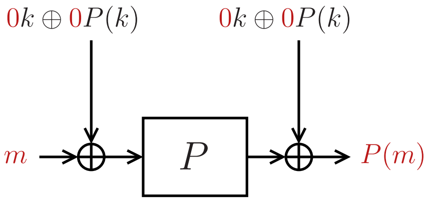


$(0, 0, 0, 0) \in \mathcal{T}$

XPX: Valid Tweaks



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

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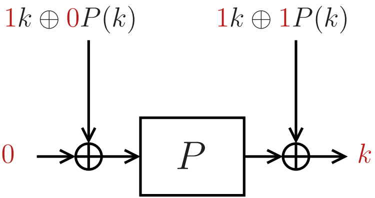

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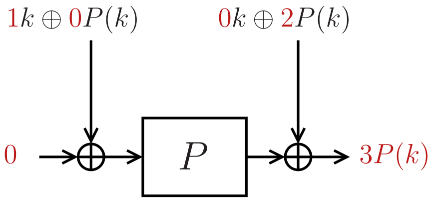

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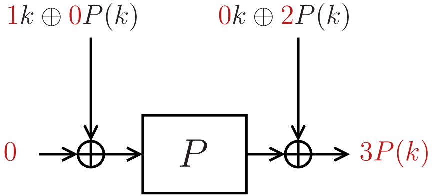
XPX: Valid Tweaks



$$
\begin{aligned}
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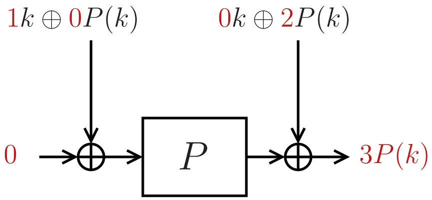
\dots \quad &\dots \quad \dots
\end{aligned}
$$

XPX: Valid Tweaks



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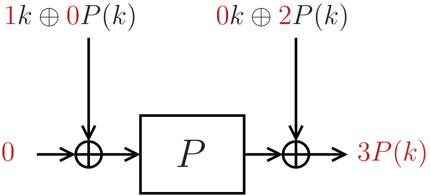
\end{aligned}$$

“Valid” Tweak Sets

- Technical definition to eliminate trivial cases

XPX: Valid Tweaks



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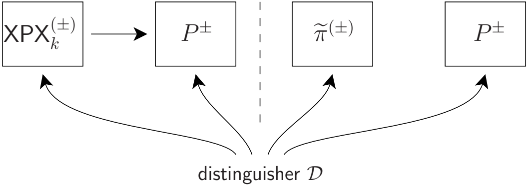
"Valid" Tweak Sets

- Technical definition to eliminate trivial cases
- Proven to be minimal: $\mathcal{T}$ invalid $\Rightarrow$ XPX insecure

XPX: Single-Key Security

(Strong) Tweakable PRP



- Information-theoretic indistinguishability
  - $\widetilde{\pi}$ ideal tweakable permutation
  - P ideal permutation
  - k secret key

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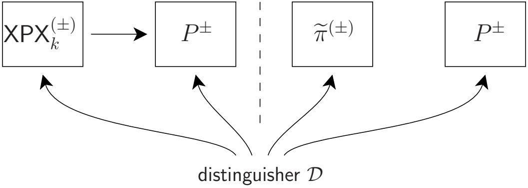

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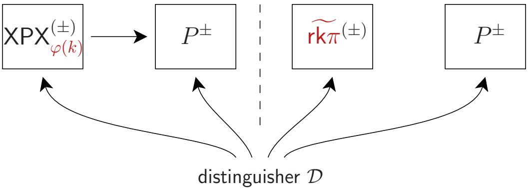
$$\mathcal{T} \text{ is valid} \quad \Longrightarrow \quad \text{XPX is (S)TPRP up to } \mathcal{O}\left(\frac{q^2+qr}{2^n}\right)$$

XPX: Related-Key Security

Related-Key (Strong) Tweakable PRP



- Information-theoretic indistinguishability
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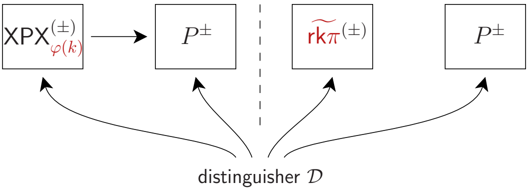
XPX: Related-Key Security

Related-Key (Strong) Tweakable PRP



- Information-theoretic indistinguishability
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- $\mathcal{D}$ restricted to some set of key-deriving functions Φ

XPX: Related-Key Security

Key-Deriving Functions (Informal)

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

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Results

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

XPX: Related-Key Security

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$t_{11}, t_{12} \neq 0$	TPRP	$\Phi_{P\oplus}$
$t_{11}, t_{12}, t_{21}, t_{22} \neq 0$	STPRP	$\Phi_{P\oplus}$

XPX: Security Proof Techniques

Patarin's H-coefficient Technique

- Each conversation defines a transcript
- Define good and bad transcripts

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$$\mathbf{Adv}_{\mathsf{XPX}}^{\text{rk-(s)prp}}(\mathcal{D}) \leq \varepsilon + \mathbf{Pr}\left[\text{bad transcript for } (\widetilde{\mathsf{rk}\pi}, P)\right]$$

↰ prob. ratio for good transcripts

XPX: Security Proof Techniques

Patarin's H-coefficient Technique

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↰ prob. ratio for good transcripts

- Trade-off: define bad transcripts smartly!

XPX: Security Proof Techniques

Before the Interaction

- Reveal dedicated construction queries

After the Interaction

- Reveal key information
  - Single-key: k and $P(k)$
  - $\Phi_{\oplus}$-related-key: k and $P(k \oplus \delta)$
  - $\Phi_{P\oplus}$-related-key: k and $P(k \oplus \delta)$ and $P^{-1}(P(k) \oplus \varepsilon)$

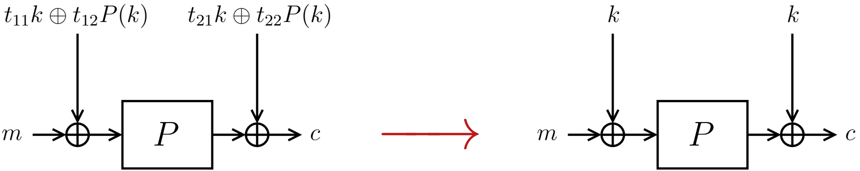
Bounding the Advantage

- Smart definition of bad transcripts

XPX Covers Even-Mansour

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

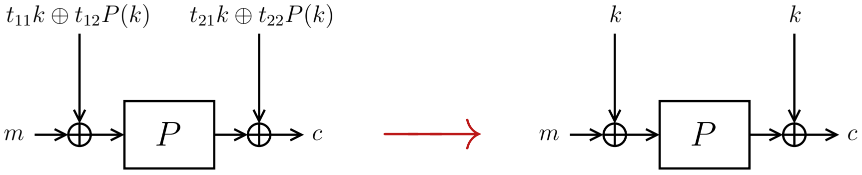
XPX Covers Even-Mansour



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

- Single-key STPRP secure (surprise?)

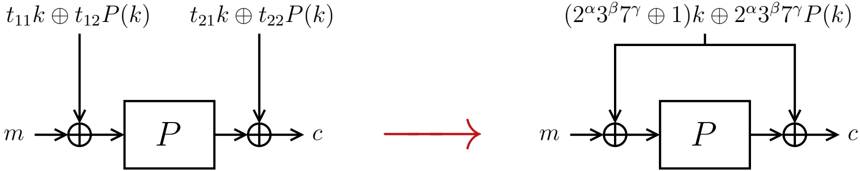
XPX Covers Even-Mansour



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

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

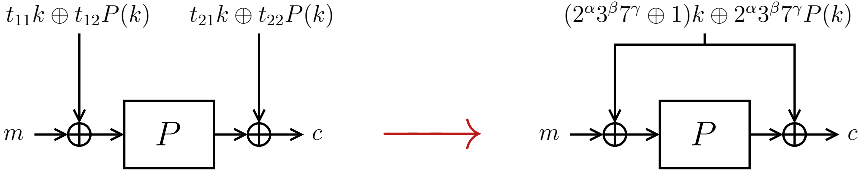
XPX Covers XEX With Even-Mansour



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

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

XPX Covers XEX With Even-Mansour



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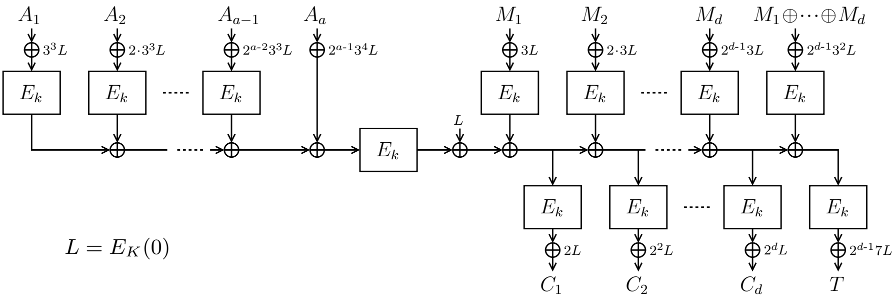
- (α, β, γ) is in fact the "real" tweak
- $\Phi_{P\oplus}$-related-key STPRP secure (if $2^\alpha 3^\beta 7^\gamma \neq 1$)

Application to AE: COPA



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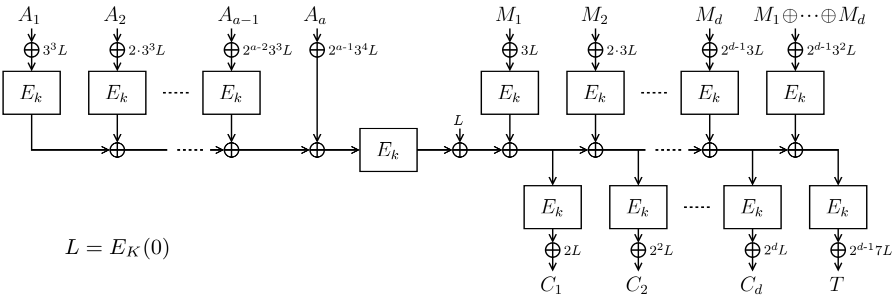

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Single-Key Security of COPA

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

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Related-Key Security of COPA

- Approach generalizes for any Φ (proof in paper)

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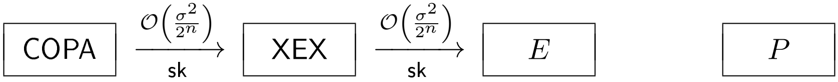

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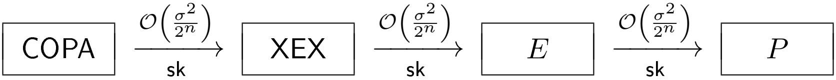

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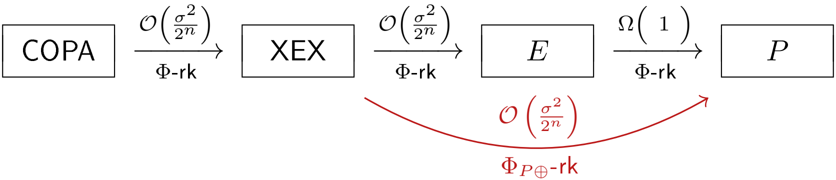
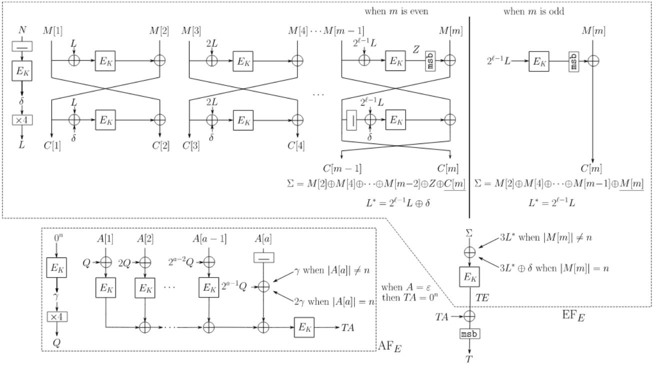


Application to AE: Prøst-OTR



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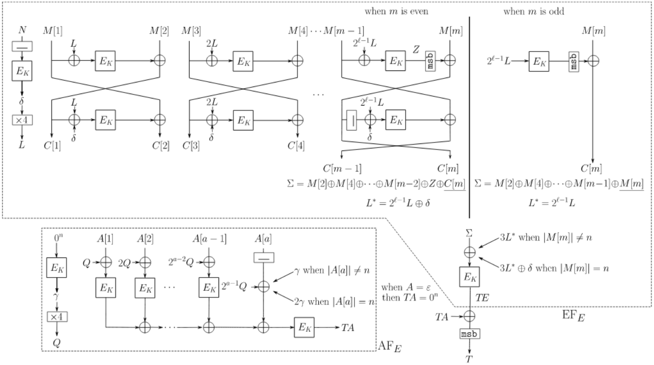

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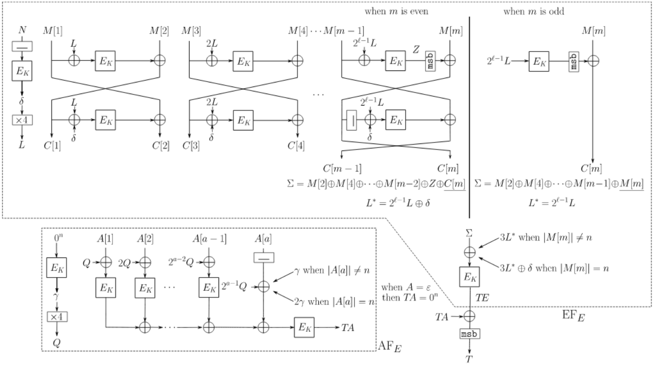

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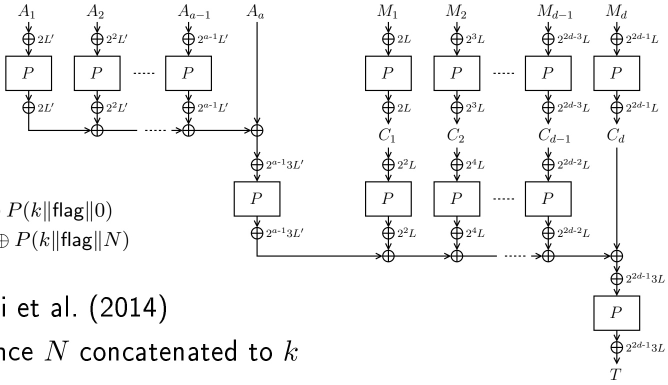
- Nonce-based masking: $t_{11}k \oplus t_{11}P(k \oplus N)$

Application to AE: Minalpher



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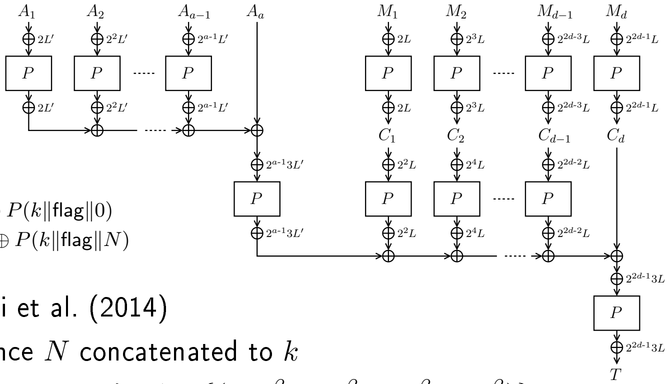

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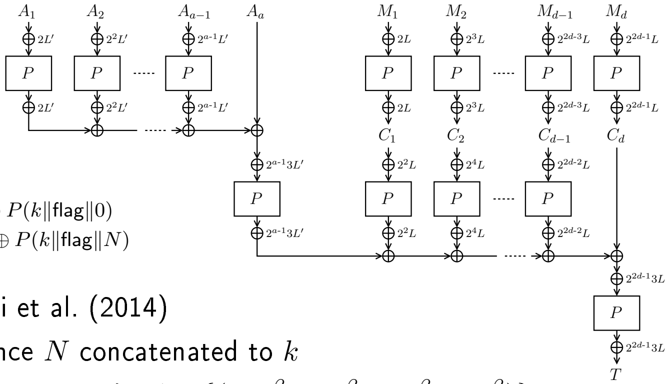

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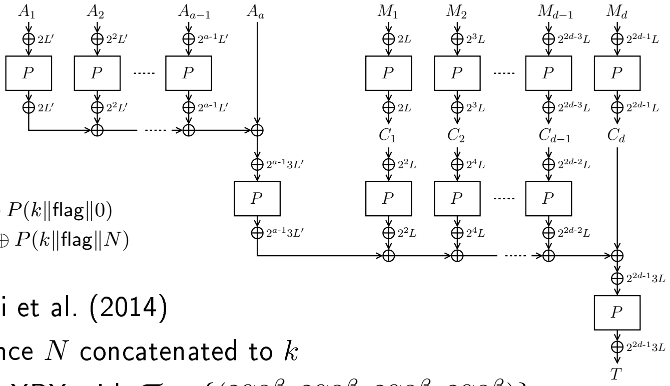

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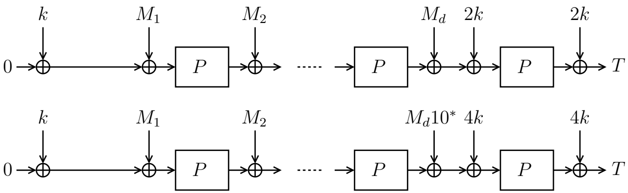
Application to MAC: Chaskey



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- Original proof based on 3 EM's: $\begin{cases} E_k(m) = P(m \oplus k) \oplus k \\ E_k(m) = P(m \oplus 3k) \oplus 2k \\ E_k(m) = P(m \oplus 5k) \oplus 4k \end{cases}$

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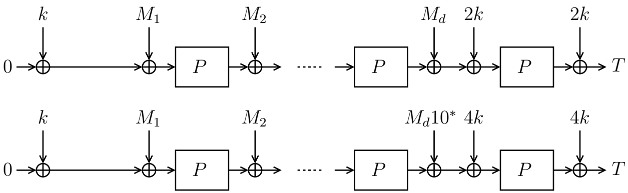

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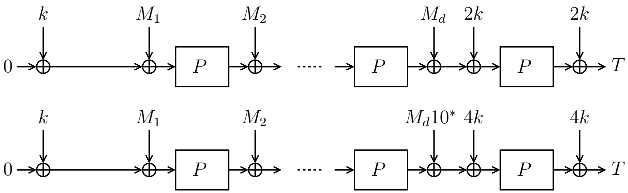

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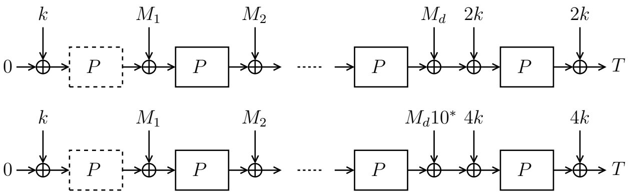

- Extra P-call

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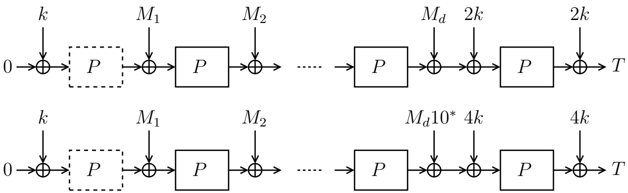

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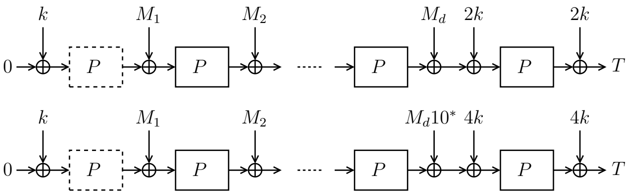

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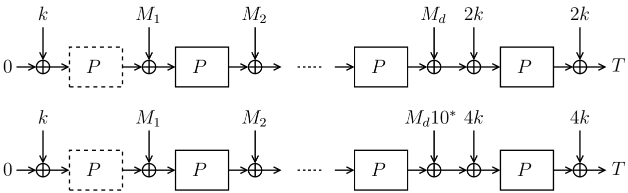

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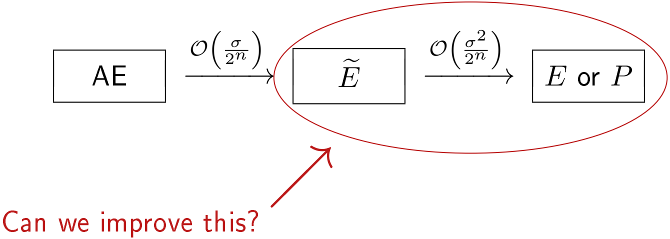
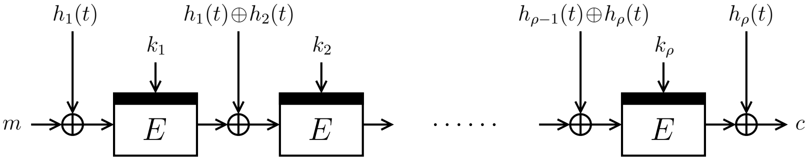


BBB Tweakable Blockciphers from Blockcipher



- $\text{LRW}_2[\rho]$: concatenation of ρ LRW_2's
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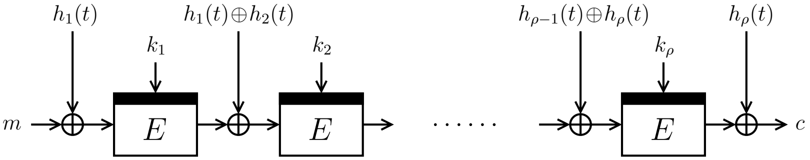

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- $\rho = 2$: secure up to $2^{2n/3}$ queries [LST12,Pro14]
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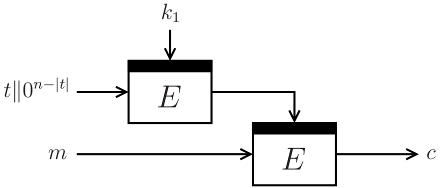

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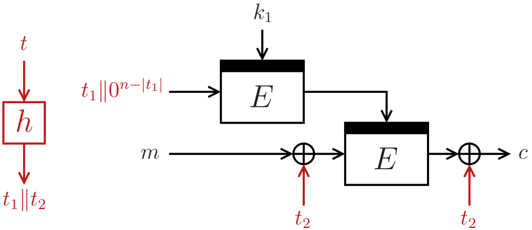

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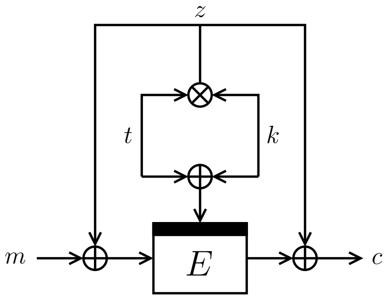


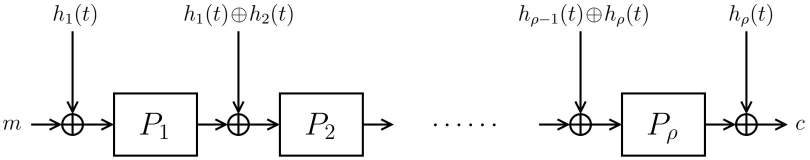
Secure up to $2^{2n/3}$ queries

(one $\otimes$, one E)

Secure up to 2^n queries

(two E's)

BBB Tweakable Blockciphers from Permutation



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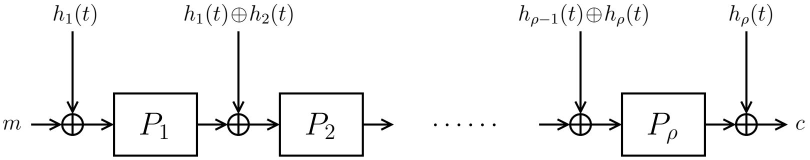

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Conclusions

XPX

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- Various levels of security
  - Single-key to related-key
- Many applications to AE and MAC

Optimal Secure AE?

- AE with cascaded LRW_2 or TEM: $2^{\rho n/(\rho+2)}$ security,
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Thank you for your attention!