Security of Authenticated Encryption Modes

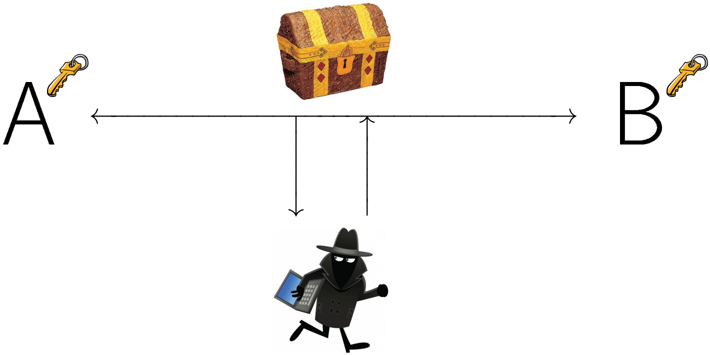
Bart Mennink
Radboud University (The Netherlands)

COST Training School on
Symmetric Cryptography and Blockchain

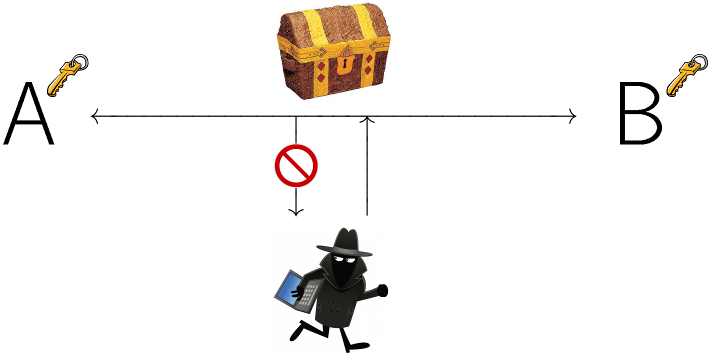
February 22, 2018

Authenticated Encryption

Authenticated Encryption



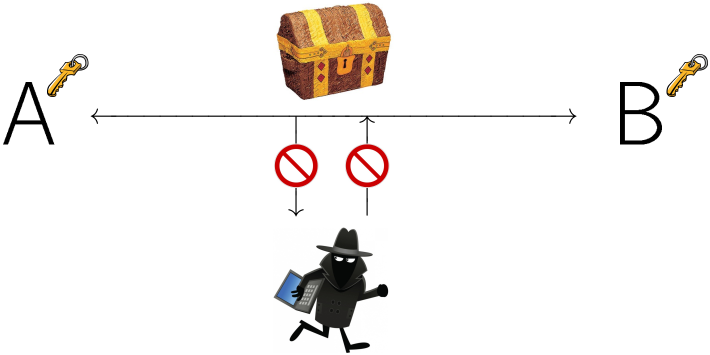
Authenticated Encryption



Encryption

- No outsider can learn anything about data

Authenticated Encryption



Encryption

- No outsider can learn anything about data

Authentication

- No outsider can manipulate data

CAESAR Competition

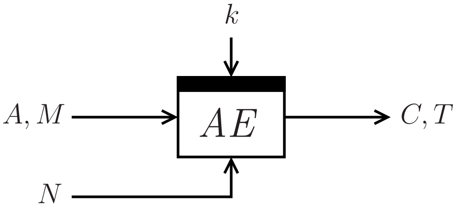
CAESAR Competition

Competition for Authenticated Encryption:
Security, Applicability, and Robustness

Goal: portfolio of authenticated encryption schemes

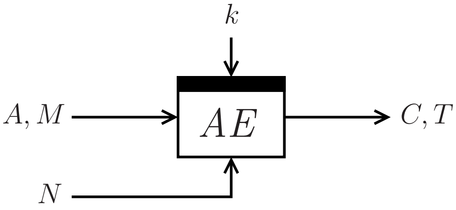
Mar 15, 2014: 57 first round candidates
Jul 7, 2015: 29.5 second round candidates
Aug 15, 2016: 16 third round candidates
??: announcement of finalists
??: announcement of final portfolio

Authenticated Encryption



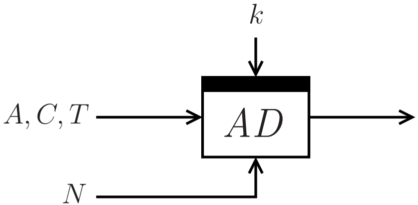
- Ciphertext C encryption of message M
- Tag T authenticates associated data A and message M

Authenticated Encryption



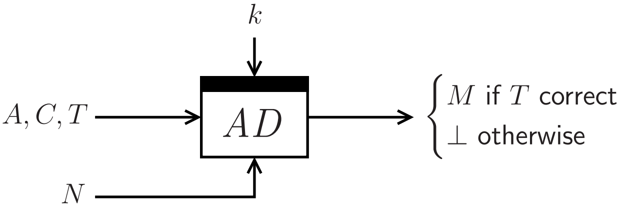
- Ciphertext C encryption of message M
- Tag T authenticates associated data A and message M
- Nonce N randomizes the scheme

Authenticated Decryption



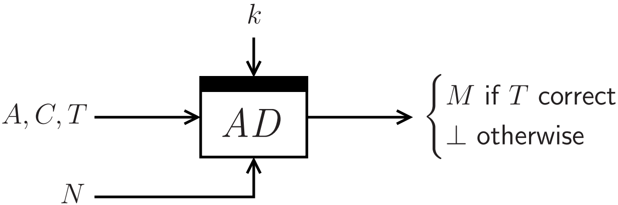
- Authenticated decryption needs to satisfy that
  - Message disclosed if tag is correct
  - Message is not leaked if tag is incorrect

Authenticated Decryption



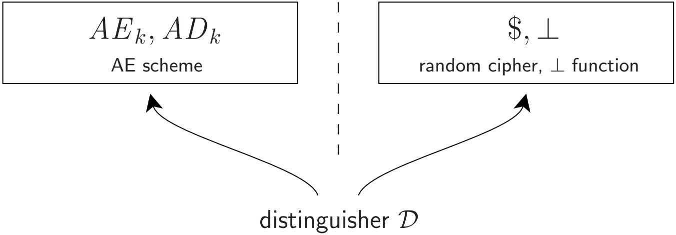
- Authenticated decryption needs to satisfy that
  - Message disclosed if tag is correct
  - Message is not leaked if tag is incorrect

Authenticated Decryption



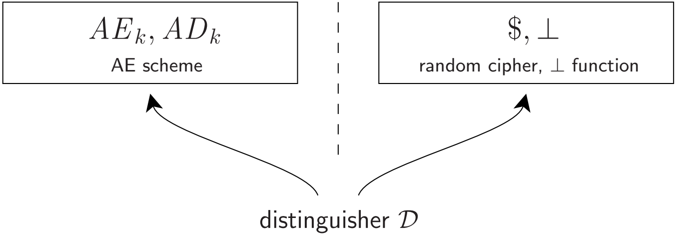
- Authenticated decryption needs to satisfy that
  - Message disclosed if tag is correct
  - Message is not leaked if tag is incorrect
- Correctness: $AD_k(N, A, AE_k(N, A, M)) = M$

Authenticated Encryption Security



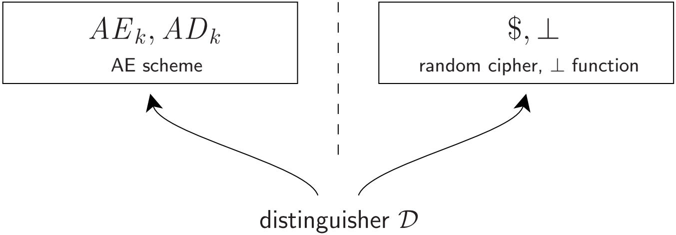
- Two oracles: (AE_k, AD_k) (for secret key k) and $(\$, \perp)$

Authenticated Encryption Security



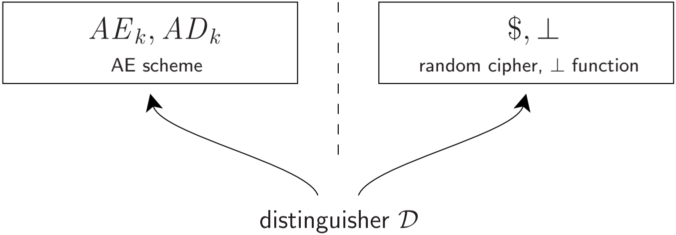
- Two oracles: (AE_k, AD_k) (for secret key k) and $(\$, \perp)$
- Distinguisher $\mathcal{D}$ has query access to one of these
  $\rightarrow$ unique nonce for each encryption query

Authenticated Encryption Security



- Two oracles: (AE_k, AD_k) (for secret key k) and $(\$, \perp)$
- Distinguisher $\mathcal{D}$ has query access to one of these
  $\rightarrow$ unique nonce for each encryption query
- $\mathcal{D}$ tries to determine which oracle it communicates with

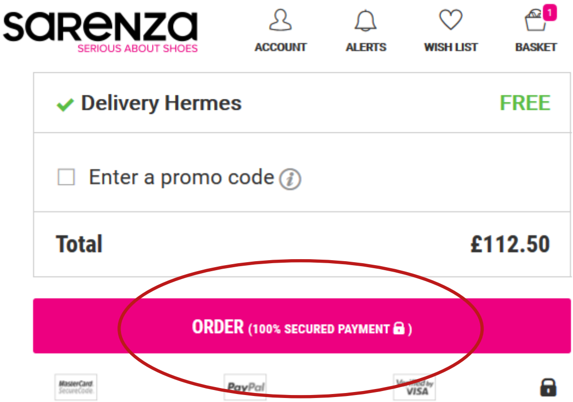
Authenticated Encryption Security



- Two oracles: (AE_k, AD_k) (for secret key k) and $(\$, \perp)$
- Distinguisher $\mathcal{D}$ has query access to one of these
  $\rightarrow$ unique nonce for each encryption query
- $\mathcal{D}$ tries to determine which oracle it communicates with

$$\mathbf{Adv}^{\mathrm{ae}}_{AE}(\mathcal{D}) = \left|\mathbf{Pr}\left[\mathcal{D}^{AE_k, AD_k} = 1\right] - \mathbf{Pr}\left[\mathcal{D}^{\$,\perp} = 1\right]\right|$$

100% Security is Impractical



Outline

Outline

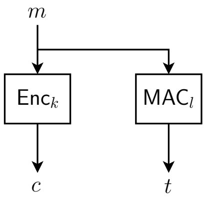
Generic Composition

- Generic constructions for AE:
  - Enc + MAC = AE

Generic Composition

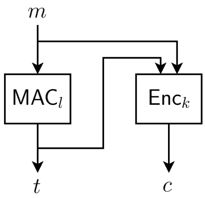
- Generic constructions for AE:
    - Enc + MAC = AE
- Bellare and Namprempre (2000): 3 basic approaches

E&M



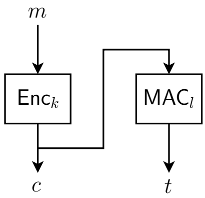
- Used in SSH

MtE



- Used in TLS

EtM

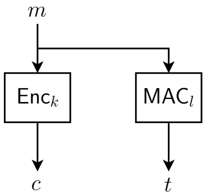


- Used in IPSec

Generic Composition

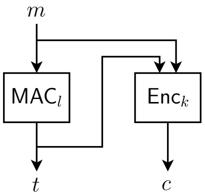
- Generic constructions for AE:
  - Enc + MAC = AE
- Bellare and Namprempre (2000): 3 basic approaches

E&M



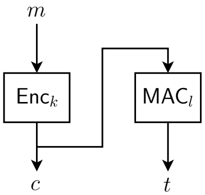
- Used in SSH
- Generically insecure
  - $\text{MAC}_L(m) = m \| t$

MtE



- Used in TLS

EtM

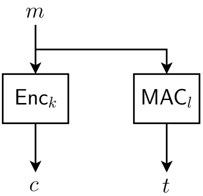


- Used in IPSec

Generic Composition

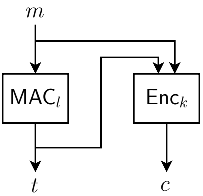
- Generic constructions for AE:
  - Enc + MAC = AE
- Bellare and Namprempre (2000): 3 basic approaches

E&M



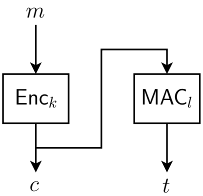
- Used in SSH
- Generically insecure
  - $\mathsf{MAC}_L(m) = m \| t$

MtE



- Used in TLS
- Mildly insecure
- Padding oracle attack

EtM

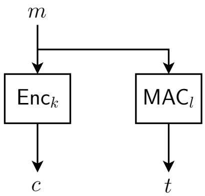


- Used in IPSec

Generic Composition

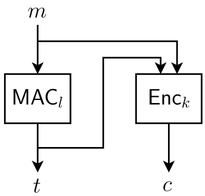
- Generic constructions for AE:
  - Enc + MAC = AE
- Bellare and Namprempre (2000): 3 basic approaches

E&M



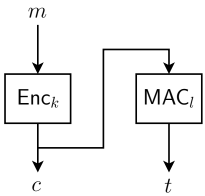
- Used in SSH
- Generically insecure
  - $\text{MAC}_L(m) = m \| t$

MtE



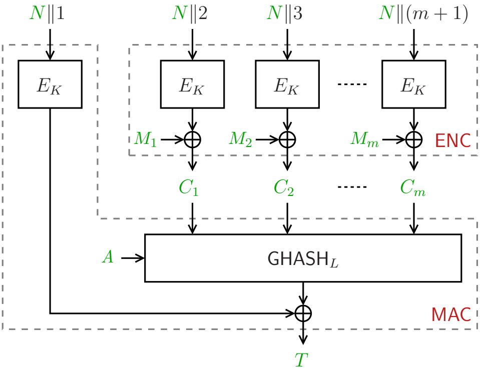
- Used in TLS
- Mildly insecure
- Padding oracle attack

EtM



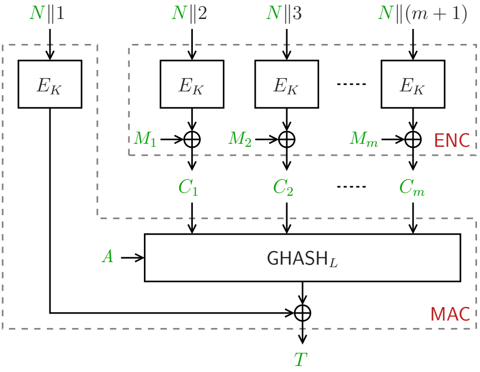
- Used in IPSec
- Most secure variant
- Ciphertext integrity

GCM for 96-bit nonce N



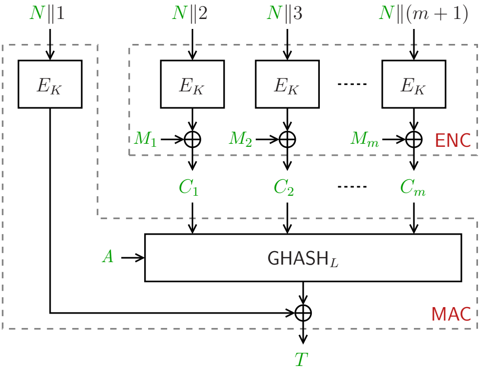
- McGrew and Viega (2004)
- EtM design
- Widely used (TLS!)
- Patent-free

GCM for 96-bit nonce N



- McGrew and Viega (2004)
- EtM design
- Widely used (TLS!)
- Patent-free
- Parallelizable
- Evaluates E only (no E^{-1})
- Provably secure (if E is PRP)
- Very efficient in HW
- Reasonably efficient in SW

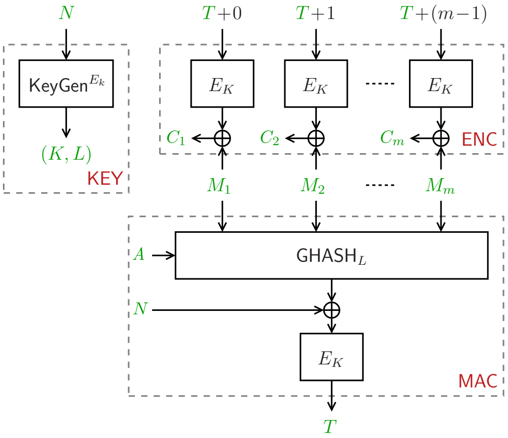
GCM for 96-bit nonce N



- McGrew and Viega (2004)
- EtM design
- Widely used (TLS!)
- Patent-free
- Parallelizable
- Evaluates E only (no E^{-1})
- Provably secure
  (if E is PRP)
- Very efficient in HW
- Reasonably efficient in SW

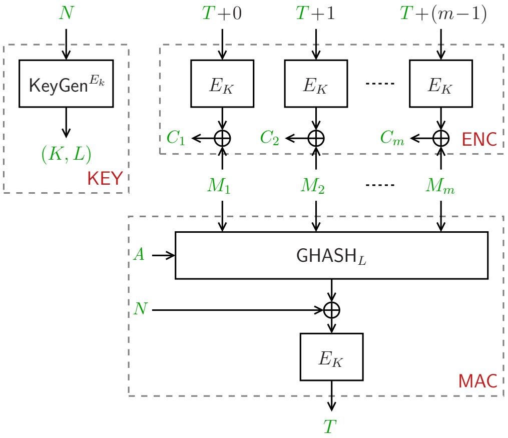
What happens if nonce is re-used?

GCM-SIV



- Gueron and Lindell (2015)
- MtE design
- Ongoing standardization (IETF RFC)
- Patent-free

GCM-SIV



- Gueron and Lindell (2015)
- MtE design
- Ongoing standardization (IETF RFC)
- Patent-free
- Inherits GCM features
- Secure against nonce-reuse
- Proof: Iwata and Seurin (2017)

Outline

Generic Composition

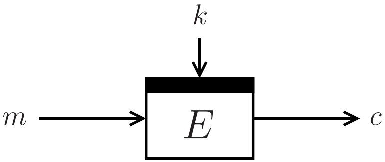
Link With Tweakable Blockciphers

Tweakable Blockciphers Based on Masking

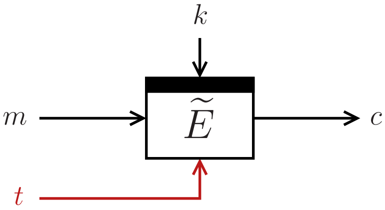
Nonce-Reuse

Conclusion

Tweakable Blockciphers

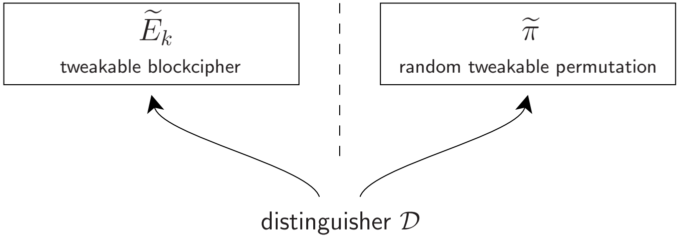


Tweakable Blockciphers



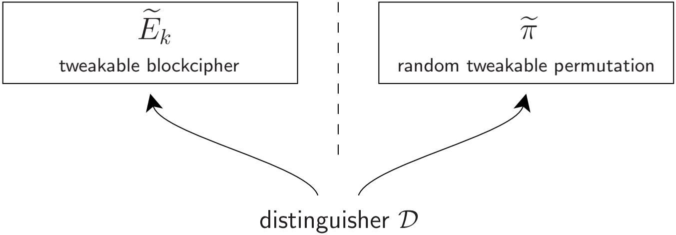
- Tweak: flexibility to the cipher
- Each tweak gives different permutation

Tweakable Blockcipher Security



- $\widetilde{E}_k$ should look like random permutation for every t
- Different tweaks $\longrightarrow$ pseudo-independent permutations

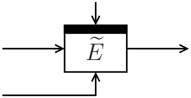
Tweakable Blockcipher Security



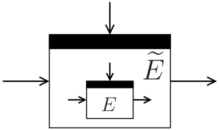
- $\widetilde{E}_k$ should look like random permutation for every t
- Different tweaks $\longrightarrow$ pseudo-independent permutations
- $\mathcal{D}$ tries to determine which oracle it communicates with

$$\mathbf{Adv}^{\text{stprp}}_{\widetilde{E}}(\mathcal{D}) = \left|\mathbf{Pr}\left[\mathcal{D}^{\widetilde{E}_k,\widetilde{E}_k^{-1}} = 1\right] - \mathbf{Pr}\left[\mathcal{D}^{\widetilde{\pi},\widetilde{\pi}^{-1}} = 1\right]\right|$$

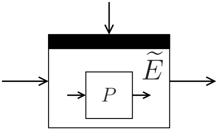
Tweakable Blockcipher Designs



Dedicated

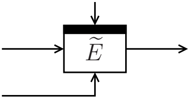


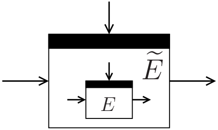
Blockcipher-Based

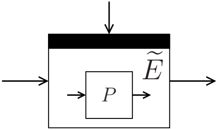


Permutation-Based

Tweakable Blockcipher Designs in CAESAR



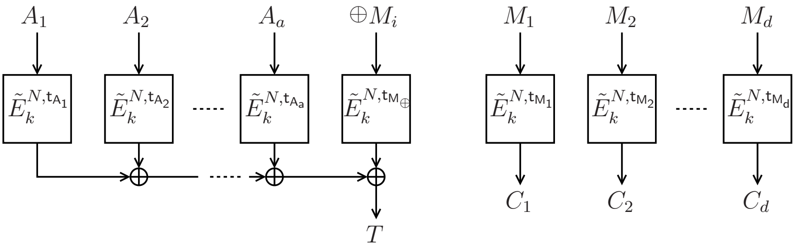




Dedicated	**Blockcipher-Based**	**Permutation-Based**
KIASU, **Joltik**, **SCREAM**, **Deoxys**	CBA, COBRA, iFeed, Marble, **OMD**, **POET**, **SHELL**, **AEZ**, **COPA/ELmD**, **OCB**, **OTR**	Prøst, **Minalpher**

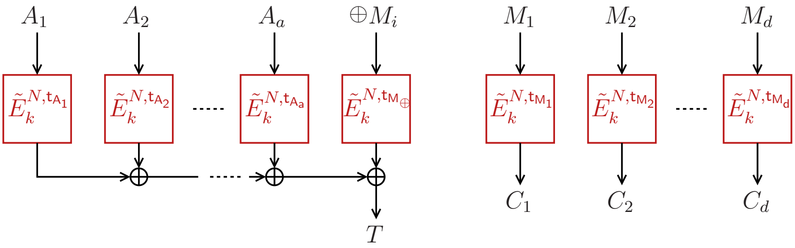
first round, **second round**, **third round**

Example Use in OCBx (1/2)



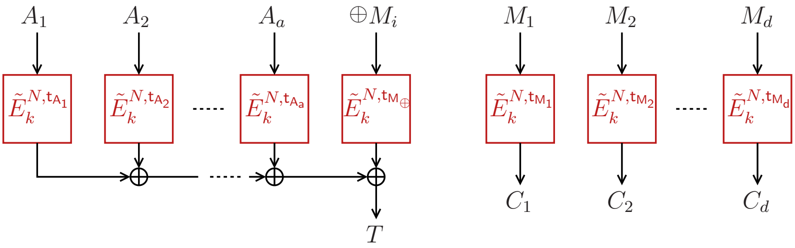
- Generalized OCB by Rogaway et al. [RBBK01,Rog04,KR11]

Example Use in OCBx (1/2)



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

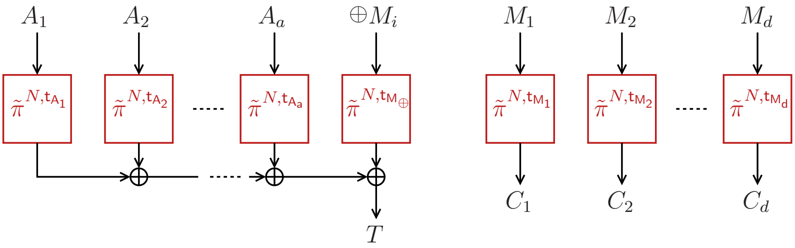
Example Use in OCBx (1/2)



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

$$\mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{E}_k]}(\sigma)$$

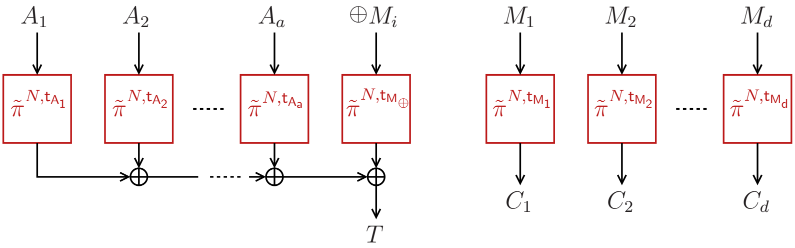
Example Use in OCBx (1/2)



- Generalized OCB by Rogaway et al. [RBBK01,Rog04,KR11]
- Internally based on tweakable blockcipher $\widetilde{E}$
  - Tweak (N, tweak) is unique for every evaluation
  - Different blocks always transformed under different tweak
- Triangle inequality:

$$\mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{E}_k]}(\sigma) \leq \mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{\pi}]}(\sigma)$$

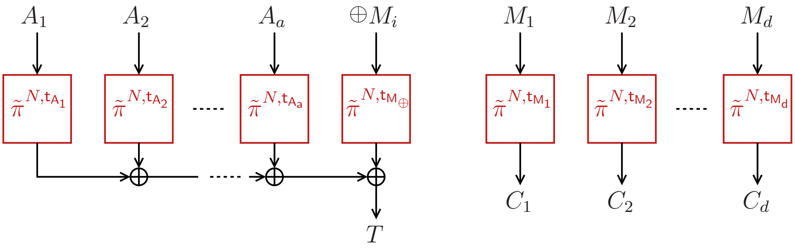
Example Use in OCBx (1/2)



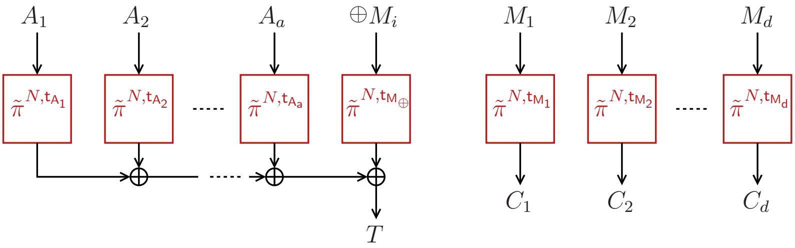
- Generalized OCB by Rogaway et al. [RBBK01,Rog04,KR11]
- Internally based on tweakable blockcipher $\widetilde{E}$
  - Tweak (N, tweak) is unique for every evaluation
  - Different blocks always transformed under different tweak
- Triangle inequality:

$$\mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{E}_k]}(\sigma) \leq \mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{\pi}]}(\sigma) + \mathbf{Adv}^{\mathrm{stprp}}_{\widetilde{E}}(\sigma)$$

Example Use in OCBx (2/2)

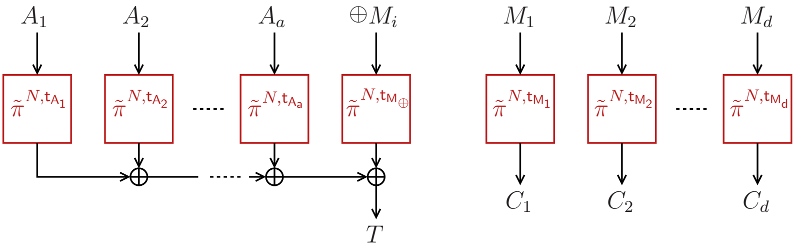


Example Use in OCBx (2/2)



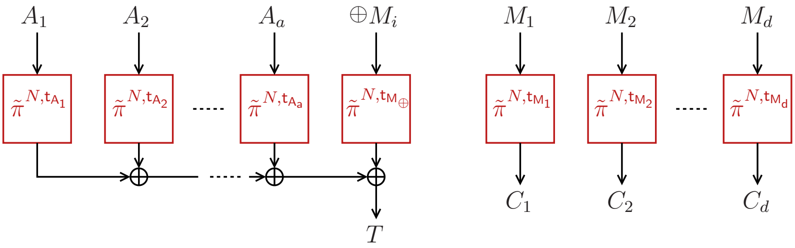
- Nonce uniqueness $\Rightarrow$ tweak uniqueness

Example Use in OCBx (2/2)



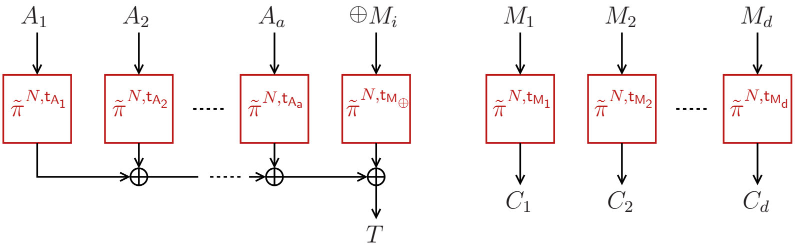
- Nonce uniqueness $\Rightarrow$ tweak uniqueness
- Encryption calls behave like random functions: $AE[\widetilde{\pi}] = \$$

Example Use in OCBx (2/2)



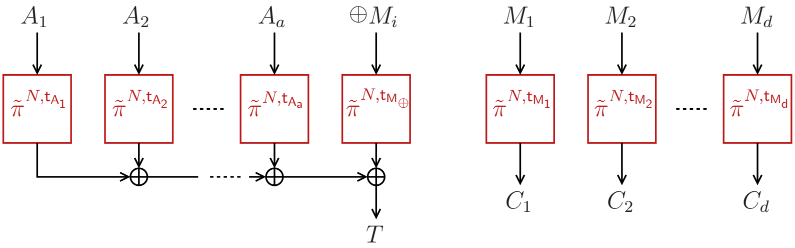
- Nonce uniqueness $\Rightarrow$ tweak uniqueness
- Encryption calls behave like random functions: $AE[\widetilde{\pi}] = \$$
- Authentication behaves like random function

Example Use in OCBx (2/2)



- Nonce uniqueness $\Rightarrow$ tweak uniqueness
- Encryption calls behave like random functions: $AE[\widetilde{\pi}] = \$$
- Authentication behaves like random function
    - Tag forged with probability at most $1/(2^n - 1)$

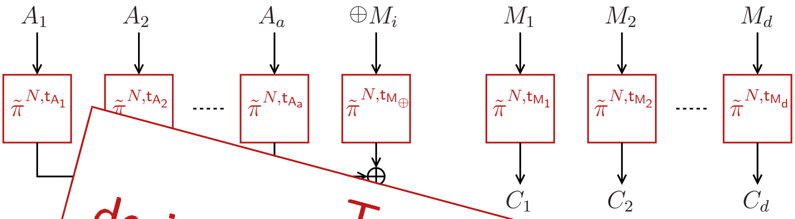
Example Use in OCBx (2/2)



- Nonce uniqueness $\Rightarrow$ tweak uniqueness
- Encryption calls behave like random functions: $AE[\widetilde{\pi}] = \$$
- Authentication behaves like random function
  - Tag forged with probability at most $1/(2^n - 1)$

$$\mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{\pi}]}(\sigma) \leq 1/(2^n - 1)$$

Example Use in OCBx (2/2)



To do:
design tweakable blockcipher

- Nonce uniquene...
- Encryption calls behave like ra... $= \$$
- Authentication behaves like random functio...
  - Tag forged with probability at most $1/(2^n - 1)$

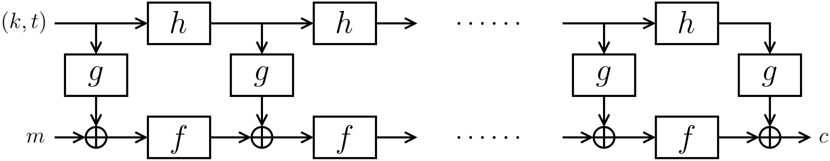
$$\mathbf{Adv}^{\mathrm{ae}}_{AE[\widetilde{\pi}]}(\sigma) \leq 1/(2^n - 1)$$

Dedicated Tweakable Blockciphers

- Hasty Pudding Cipher [Sch98]
    - AES submission, “first tweakable cipher”
- Mercy [Cro01]
    - Disk encryption
- Threefish [FLS+07]
    - SHA-3 submission Skein
- TWEAKEY framework [JNP14]
    - Four CAESAR submissions
    - SKINNY & MANTIS

TWEAKEY Framework

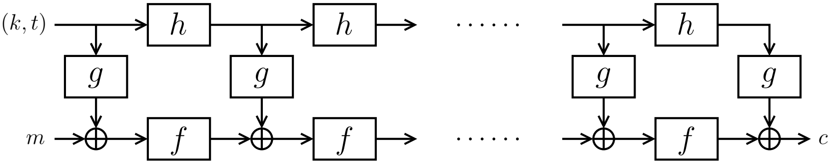
- TWEAKEY by Jean et al. [JNP14]:



- f: round function
- g: subkey computation
- h: transformation of (k,t)

TWEAKEY Framework

- TWEAKEY by Jean et al. [JNP14]:



- f: round function
- g: subkey computation
- h: transformation of (k,t)

- Security measured through cryptanalysis
- Our focus: modular design

Outline

Generic Composition

Link With Tweakable Blockciphers

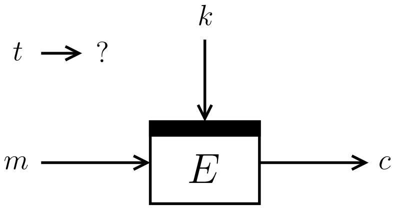
Tweakable Blockciphers Based on Masking

- Intuition
- State of the Art
- Improved Efficiency
- Improved Security

Nonce-Reuse

Conclusion

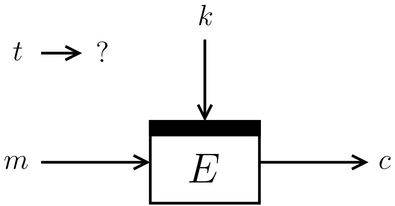
Intuition: Design



- Consider a blockcipher E with κ-bit key and n-bit state

How to mingle the tweak into the evaluation?

Intuition: Design



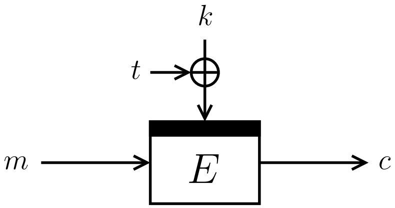
- Consider a blockcipher E with κ-bit key and n-bit state

How to mingle the tweak into the evaluation?

blend it with the key

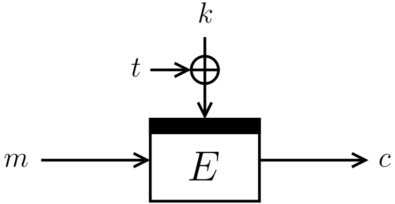
blend it with the state

Intuition: Design



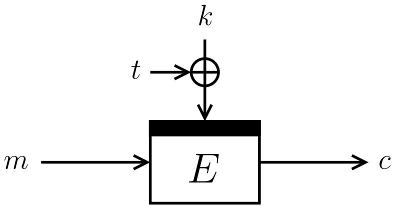
- Blending tweak and key works. . .
- . . . but: careful with related-key attacks!

Intuition: Design



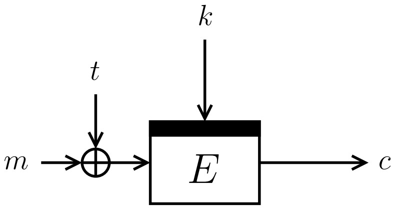
- Blending tweak and key works...
- ... but: careful with related-key attacks!
- For $\oplus$-mixing, key can be recovered in $2^{\kappa/2}$ evaluations
- Scheme is insecure if E is Even-Mansour

Intuition: Design



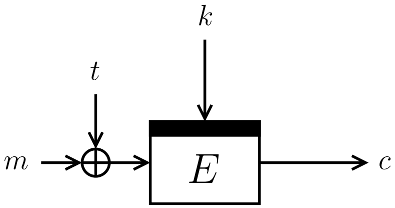
- Blending tweak and key works...
- ... but: careful with related-key attacks!
- For $\oplus$-mixing, key can be recovered in $2^{\kappa/2}$ evaluations
- Scheme is insecure if E is Even-Mansour
- TWEAKEY blending [JNP14] is more advanced

Intuition: Design



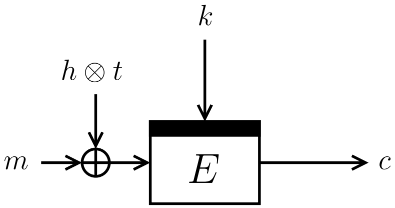
- Simple blending of tweak and state does not work

Intuition: Design



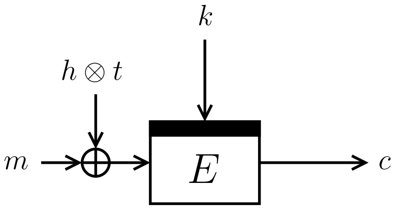
- Simple blending of tweak and state does not work
  - $\widetilde{E}_k(t, m) = \widetilde{E}_k(t \oplus C, m \oplus C)$

Intuition: Design



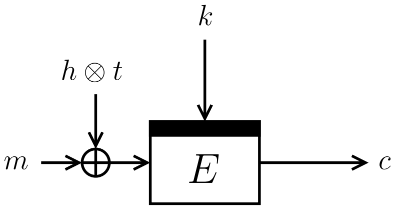
- Simple blending of tweak and state does not work
  - $\widetilde{E}_k(t, m) = \widetilde{E}_k(t \oplus C, m \oplus C)$
- Some secrecy required: h

Intuition: Design



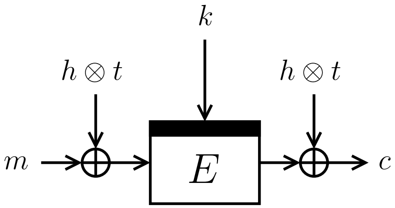
- Simple blending of tweak and state does not work
  - $\widetilde{E}_k(t, m) = \widetilde{E}_k(t \oplus C, m \oplus C)$
- Some secrecy required: h
- Still does not work if adversary has access to $\widetilde{E}_k^{-1}$

Intuition: Design



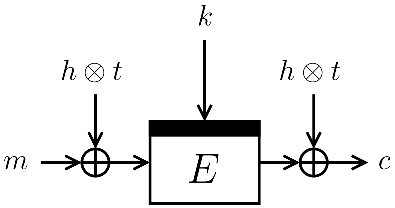
- Simple blending of tweak and state does not work
  - $\widetilde{E}_k(t, m) = \widetilde{E}_k(t \oplus C, m \oplus C)$
- Some secrecy required: h
- Still does not work if adversary has access to $\widetilde{E}_k^{-1}$
  - $\widetilde{E}_k^{-1}(t, c) \oplus \widetilde{E}_k^{-1}(t \oplus C, c) = h \otimes C$

Intuition: Design



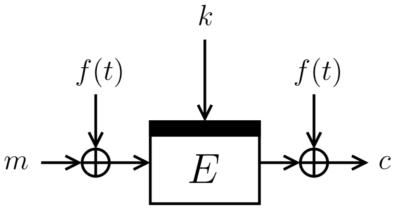
- Simple blending of tweak and state does not work
  - $\widetilde{E}_k(t, m) = \widetilde{E}_k(t \oplus C, m \oplus C)$
- Some secrecy required: h
- Still does not work if adversary has access to $\widetilde{E}_k^{-1}$
  - $\widetilde{E}_k^{-1}(t, c) \oplus \widetilde{E}_k^{-1}(t \oplus C, c) = h \otimes C$
  - Two-sided masking necessary

Intuition: Design



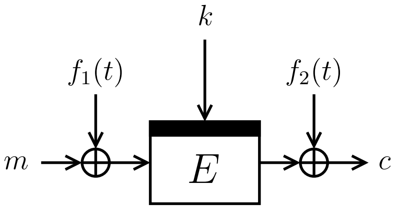
- Two-sided secret masking seems to work
- Can we generalize?

Intuition: Design



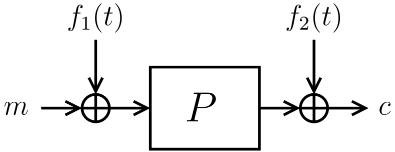
- Two-sided secret masking seems to work
- Can we generalize?
- Generalizing masking? Depends on function f

Intuition: Design



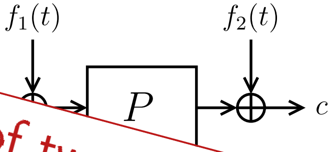
- Two-sided secret masking seems to work
- Can we generalize?
- Generalizing masking? Depends on function f
- Variation in masking? Depends on functions f_1, f_2

Intuition: Design



- Two-sided secret masking seems to work
- Can we generalize?
- Generalizing masking? Depends on function f
- Variation in masking? Depends on functions f_1, f_2
- Releasing secrecy in E? Usually no problem

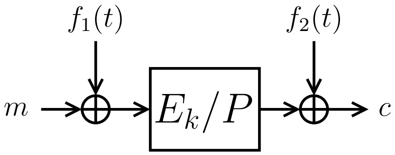
Intuition: Design



Majority of tweakable blockciphers follow mask-E_k/P-mask principle

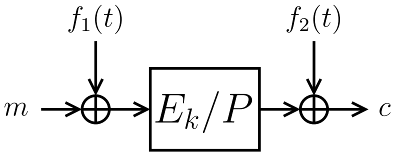
- Two-sided sec
- Can we generalize?
- Generalizing masking? Depends on func
- Variation in masking? Depends on functions f_1, f_2
- Releasing secrecy in E? Usually no problem

Intuition: Analysis



- $\widetilde{E}_k$ should "look like" random permutation for every t
- Consider adversary $\mathcal{D}$ that makes q evaluations of $\widetilde{E}_k$

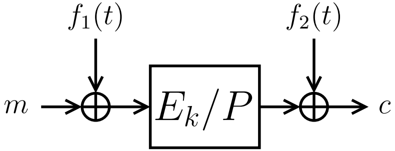
Intuition: Analysis



- $\widetilde{E}_k$ should "look like" random permutation for every t
- Consider adversary $\mathcal{D}$ that makes q evaluations of $\widetilde{E}_k$

- Step 1:
  - How many evaluations does $\mathcal{D}$ need at most?
  - Boils down to finding generic attacks

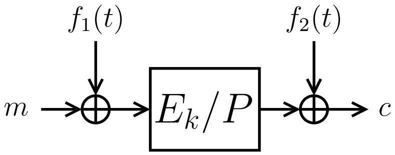
Intuition: Analysis



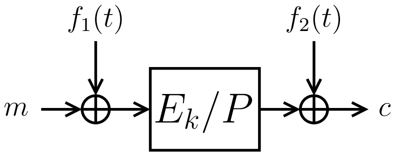
- $\widetilde{E}_k$ should "look like" random permutation for every t
- Consider adversary $\mathcal{D}$ that makes q evaluations of $\widetilde{E}_k$

- Step 1:
  - How many evaluations does $\mathcal{D}$ need at most?
  - Boils down to finding generic attacks
- Step 2:
  - How many evaluations does $\mathcal{D}$ need at least?
  - Boils down to provable security

Intuition: Analysis



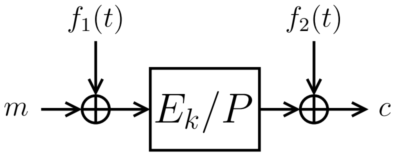
Intuition: Analysis



- For any two queries (t, m, c), (t', m', c'):

$$m \oplus f_1(t) = m' \oplus f_1(t') \Longrightarrow c \oplus f_2(t) = c' \oplus f_2(t')$$

Intuition: Analysis

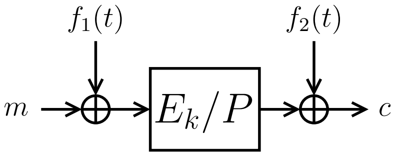


- For any two queries (t, m, c), (t', m', c'):

$$m \oplus f_1(t) = m' \oplus f_1(t') \Longrightarrow c \oplus f_2(t) = c' \oplus f_2(t')$$

- Unlikely to happen for random family of permutations

Intuition: Analysis

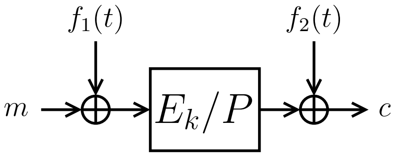


- For any two queries (t, m, c), (t', m', c'):

$$m \oplus f_1(t) = m' \oplus f_1(t') \Longrightarrow c \oplus f_2(t) = c' \oplus f_2(t')$$

- Unlikely to happen for random family of permutations
- Implication still holds with difference C xored to m, m'

Intuition: Analysis



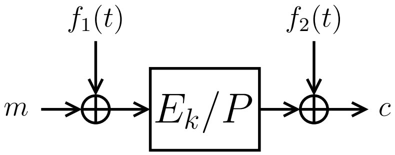
- For any two queries (t, m, c), (t', m', c'):

$$m \oplus f_1(t) = m' \oplus f_1(t') \Longrightarrow c \oplus f_2(t) = c' \oplus f_2(t')$$

- Unlikely to happen for random family of permutations
- Implication still holds with difference C xored to m, m'

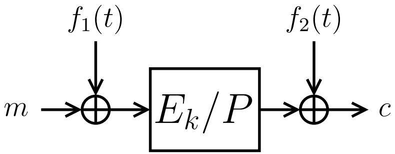
Scheme can be broken in $\approx 2^{n/2}$ evaluations

Intuition: Analysis



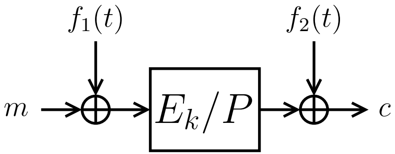
- The fun starts here!
- More technical and often more involved

Intuition: Analysis



- The fun starts here!
- More technical and often more involved
- Typical approach:
  - Consider any transcript τ an adversary may see
  - Most τ's should be equally likely in both worlds
  - Odd ones should happen with very small probability

Intuition: Analysis



- The fun starts here!
- More technical and often more involved
- Typical approach:
  - Consider any transcript τ an adversary may see
  - Most τ's should be equally likely in both worlds
  - Odd ones should happen with very small probability

All constructions in this presentation: secure up to $\approx 2^{n/2}$ evaluations

Outline

Generic Composition

Link With Tweakable Blockciphers

Tweakable Blockciphers Based on Masking

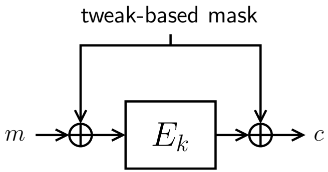
- Intuition
- State of the Art
- Improved Efficiency
- Improved Security

Nonce-Reuse

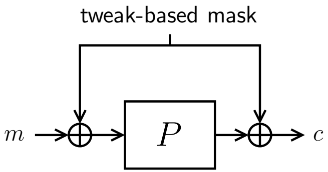
Conclusion

Tweakable Blockciphers Based on Masking

Blockcipher-Based

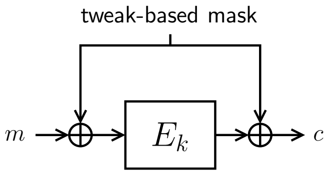


Permutation-Based



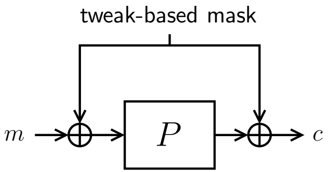
Tweakable Blockciphers Based on Masking

Blockcipher-Based



typically 128 bits

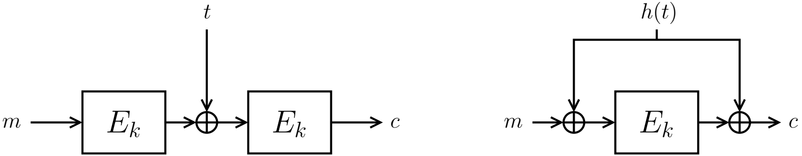
Permutation-Based



much larger: 256-1600 bits

Original Constructions

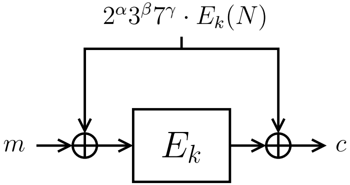
- LRW_1 and LRW_2 by Liskov et al. [LRW02]:



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

Powering-Up Masking (XEX)

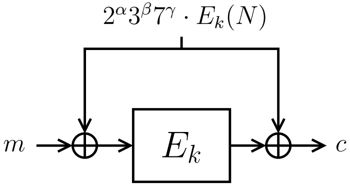
- XEX by Rogaway [Rog04]:



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

Powering-Up Masking (XEX)

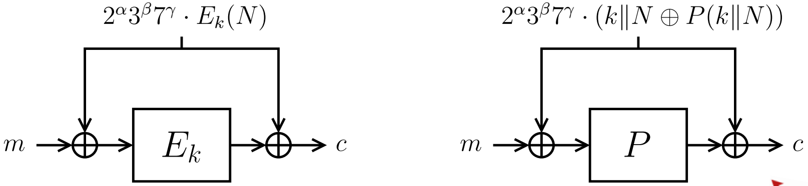
- XEX by Rogaway [Rog04]:



- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Used in OCB2 and $\pm$14 CAESAR candidates

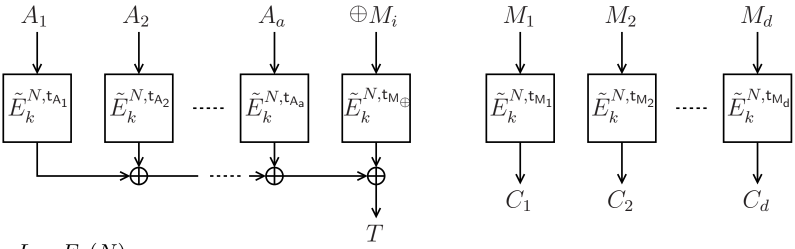
Powering-Up Masking (XEX)

- XEX by Rogaway [Rog04]:



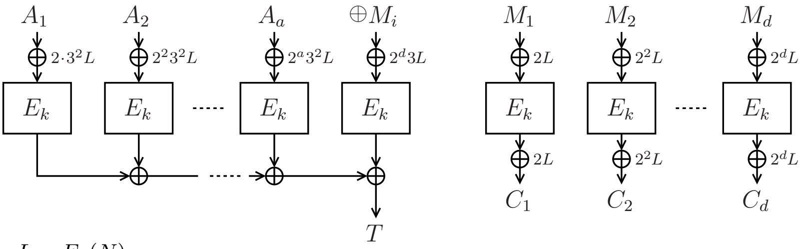
- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Used in OCB2 and $\pm$14 CAESAR candidates
- Permutation-based variants in Minalpher and Prøst (generalized by Cogliati et al. [CLS15])

Powering-Up Masking in OCB2



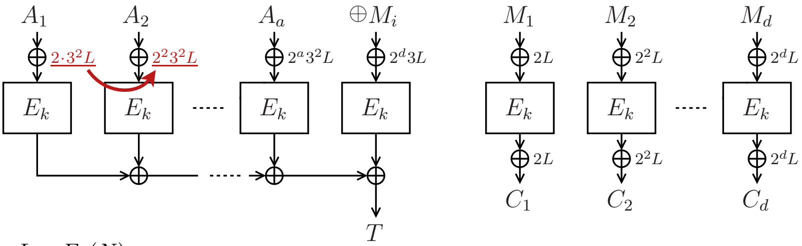
$L = E_k(N)$

Powering-Up Masking in OCB2



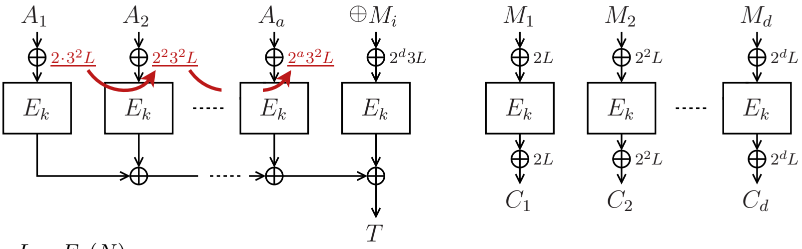
$L = E_k(N)$

Powering-Up Masking in OCB2



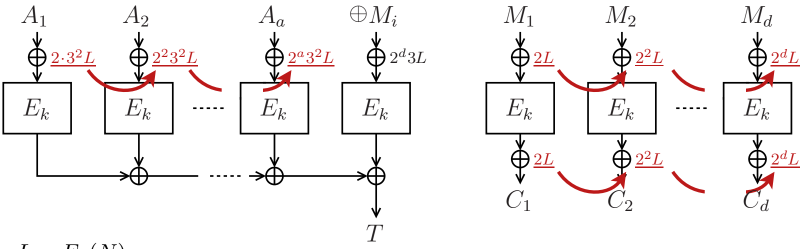
$L = E_k(N)$

Powering-Up Masking in OCB2



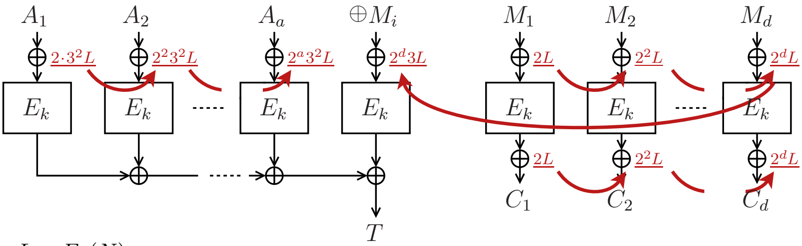
$L = E_k(N)$

Powering-Up Masking in OCB2



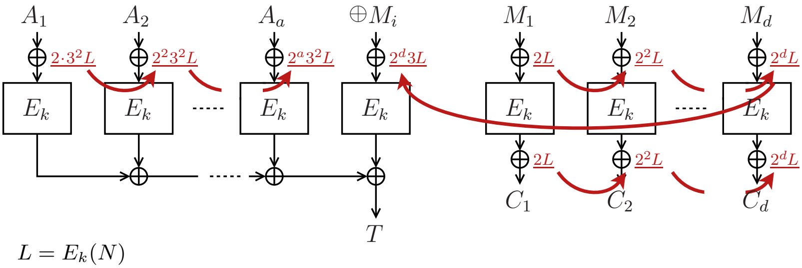
$L = E_k(N)$

Powering-Up Masking in OCB2



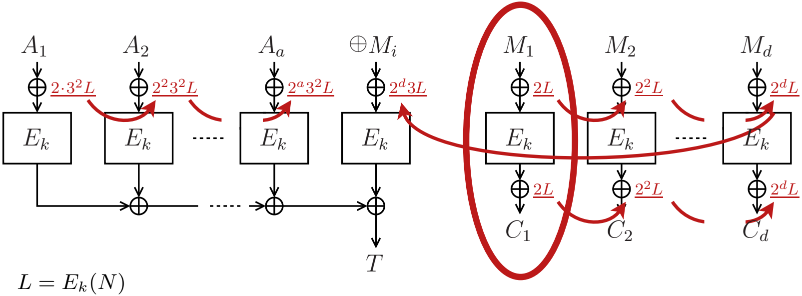
$L = E_k(N)$

Powering-Up Masking in OCB2



- Update of mask:
    - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

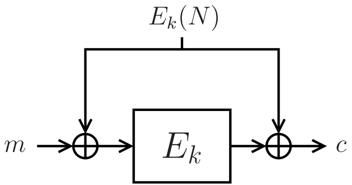
Intermezzo: Why Start at $2 \cdot E_k(N)$?



- Update of mask:
    - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

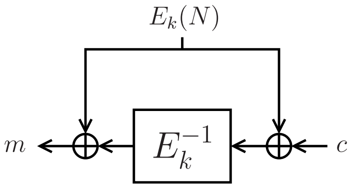
Intermezzo: Why Start at $2 \cdot E_k(N)$?

- Suppose we would mask with $E_k(N)$:



Intermezzo: Why Start at $2 \cdot E_k(N)$?

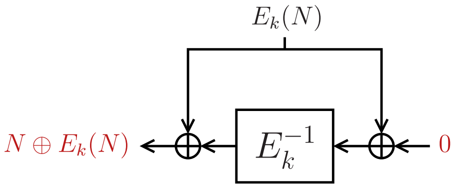
- Suppose we would mask with $E_k(N)$:



- Distinguisher can make inverse queries

Intermezzo: Why Start at $2 \cdot E_k(N)$?

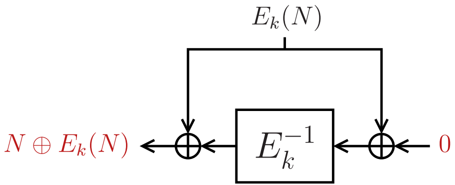
- Suppose we would mask with $E_k(N)$:



- Distinguisher can make inverse queries
- Putting $c = 0$ gives $m = N \oplus E_k(N)$

Intermezzo: Why Start at $2 \cdot E_k(N)$?

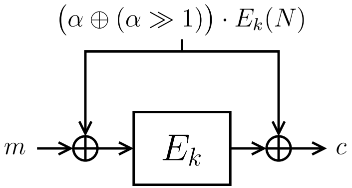
- Suppose we would mask with $E_k(N)$:



- Distinguisher can make inverse queries
- Putting $c = 0$ gives $m = N \oplus E_k(N)$
- Distinguisher knows N so learns "subkey" $E_k(N)$

Gray Code Masking

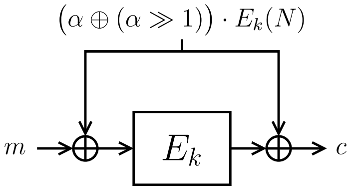
- OCB1 and OCB3 use Gray Codes:



- (α, N) is tweak
- Updating: $G(\alpha) = G(\alpha - 1) \oplus 2^{\mathsf{ntz}(\alpha)}$

Gray Code Masking

- OCB1 and OCB3 use Gray Codes:

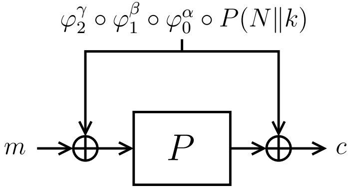


- (α, N) is tweak
- Updating: $G(\alpha) = G(\alpha - 1) \oplus 2^{\mathsf{ntz}(\alpha)}$
    - Single XOR
    - Logarithmic amount of field doublings (precomputed)
- More efficient than powering-up [KR11]

Outline

Masked Even-Mansour (MEM)

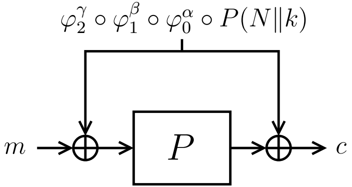
- MEM by Granger et al. [GJMN16]:



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

Masked Even-Mansour (MEM)

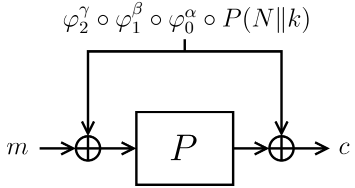
- MEM by Granger et al. [GJMN16]:



- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Combines advantages of:
  - Powering-up masking
  - Word-based LFSRs

Masked Even-Mansour (MEM)

- MEM by Granger et al. [GJMN16]:



- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Combines advantages of:
  - Powering-up masking
  - Word-based LFSRs
- Simpler, constant-time (by default), more efficient

MEM: Design Considerations

- Particularly suited for large states (permutations)
- Low operation counts by clever choice of LFSR

MEM: Design Considerations

- Particularly suited for large states (permutations)
- Low operation counts by clever choice of LFSR
- Sample LFSRs (state size b as n words of w bits):

b	w	n	φ
128	8	16	$(x_1, \ldots, x_{15}, (x_0 \lll 1) \oplus (x_9 \gg 1) \oplus (x_{10} \ll 1))$
128	32	4	$(x_1, \ldots, x_3, (x_0 \lll 5) \oplus x_1 \oplus (x_1 \ll 13))$
128	64	2	$(x_1, (x_0 \lll 11) \oplus x_1 \oplus (x_1 \ll 13))$
256	64	4	$(x_1, \ldots, x_3, (x_0 \lll 3) \oplus (x_3 \gg 5))$
512	32	16	$(x_1, \ldots, x_{15}, (x_0 \lll 5) \oplus (x_3 \gg 7))$
512	64	8	$(x_1, \ldots, x_7, (x_0 \lll 29) \oplus (x_1 \ll 9))$
1024	64	16	$(x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$
1600	32	50	$(x_1, \ldots, x_{49}, (x_0 \lll 3) \oplus (x_{23} \gg 3))$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

MEM: Design Considerations

- Particularly suited for large states (permutations)
- Low operation counts by clever choice of LFSR
- Sample LFSRs (state size b as n words of w bits):

b	w	n	φ
128	8	16	$(x_1, \ldots, x_{15}, (x_0 \lll 1) \oplus (x_9 \gg 1) \oplus (x_{10} \ll 1))$
128	32	4	$(x_1, \ldots, x_3, (x_0 \lll 5) \oplus x_1 \oplus (x_1 \ll 13))$
128	64	2	$(x_1, (x_0 \lll 11) \oplus x_1 \oplus (x_1 \ll 13))$
256	64	4	$(x_1, \ldots, x_3, (x_0 \lll 3) \oplus (x_3 \gg 5))$
512	32	16	$(x_1, \ldots, x_{15}, (x_0 \lll 5) \oplus (x_3 \gg 7))$
512	64	8	$(x_1, \ldots, x_7, (x_0 \lll 29) \oplus (x_1 \ll 9))$
1024	64	16	$(x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$
1600	32	50	$(x_1, \ldots, x_{49}, (x_0 \lll 3) \oplus (x_{23} \gg 3))$
⋮	⋮	⋮	⋮

- Work exceptionally well for ARX primitives

MEM: Uniqueness of Masking

- Intuitively, masking goes well as long as

$$\varphi_2^{\gamma} \circ \varphi_1^{\beta} \circ \varphi_0^{\alpha} \neq \varphi_2^{\gamma'} \circ \varphi_1^{\beta'} \circ \varphi_0^{\alpha'}$$

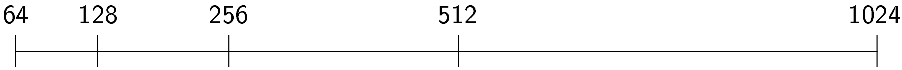
  for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
- Challenge: set proper domain for (α, β, γ)
- Requires computation of discrete logarithms

MEM: Uniqueness of Masking

- Intuitively, masking goes well as long as

$$\varphi_2^{\gamma} \circ \varphi_1^{\beta} \circ \varphi_0^{\alpha} \neq \varphi_2^{\gamma'} \circ \varphi_1^{\beta'} \circ \varphi_0^{\alpha'}$$

  for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
- Challenge: set proper domain for (α, β, γ)
- Requires computation of discrete logarithms

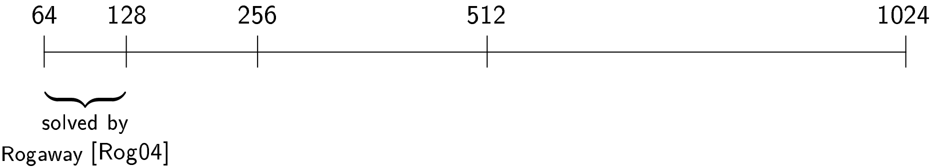


MEM: Uniqueness of Masking

- Intuitively, masking goes well as long as

$$\varphi_2^{\gamma} \circ \varphi_1^{\beta} \circ \varphi_0^{\alpha} \neq \varphi_2^{\gamma'} \circ \varphi_1^{\beta'} \circ \varphi_0^{\alpha'}$$

  for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
- Challenge: set proper domain for (α, β, γ)
- Requires computation of discrete logarithms

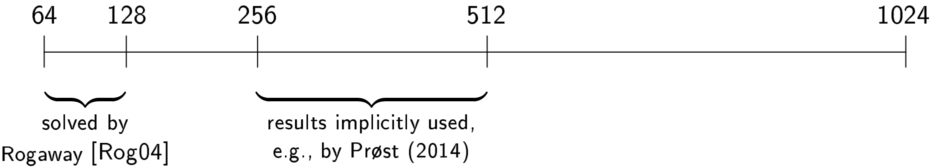


MEM: Uniqueness of Masking

- Intuitively, masking goes well as long as

$$\varphi_2^{\gamma} \circ \varphi_1^{\beta} \circ \varphi_0^{\alpha} \neq \varphi_2^{\gamma'} \circ \varphi_1^{\beta'} \circ \varphi_0^{\alpha'}$$

  for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
- Challenge: set proper domain for (α, β, γ)
- Requires computation of discrete logarithms

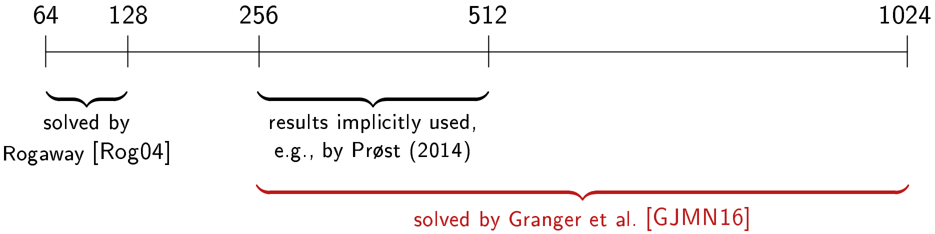


MEM: Uniqueness of Masking

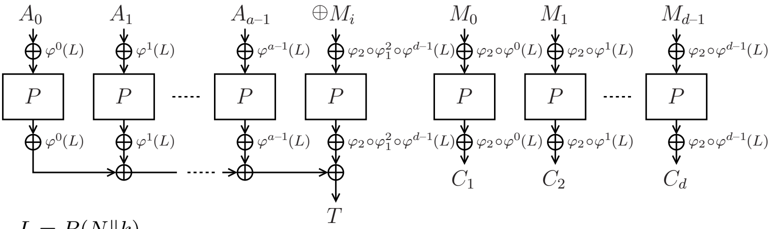
- Intuitively, masking goes well as long as

$$\varphi_2^{\gamma} \circ \varphi_1^{\beta} \circ \varphi_0^{\alpha} \neq \varphi_2^{\gamma'} \circ \varphi_1^{\beta'} \circ \varphi_0^{\alpha'}$$

  for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
- Challenge: set proper domain for (α, β, γ)
- Requires computation of discrete logarithms



Application to AE: OPP

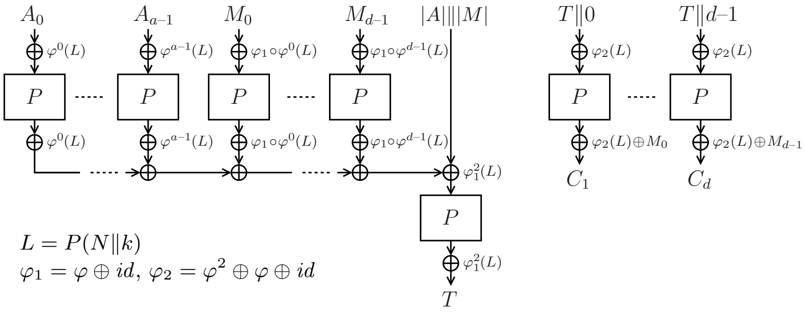


$L = P(N \| k)$

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

- Offset Public Permutation (OPP)
- Generalization of OCB3:
  - Permutation-based
  - More efficient MEM masking
- Security against nonce-respecting adversaries
- 0.55 cpb with reduced-round BLAKE2b

Application to AE: MRO

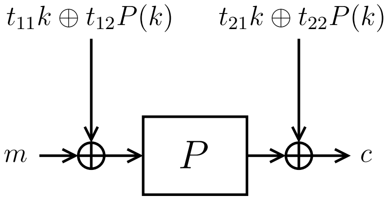


- Misuse-Resistant OPP (MRO)
- Fully nonce-misuse resistant version of OPP
- 1.06 cpb with reduced-round BLAKE2b

Outline

XPX

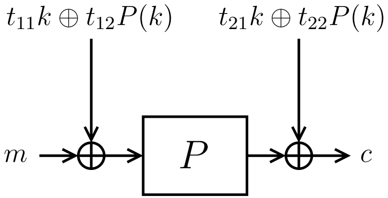
- XPX by Mennink [Men16]:



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

XPX

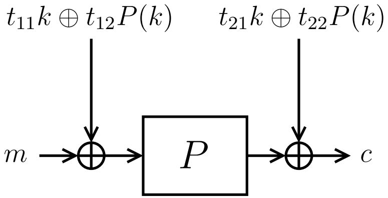
- XPX by Mennink [Men16]:



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

XPX

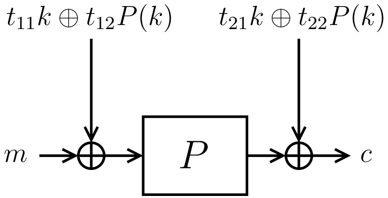
- XPX by Mennink [Men16]:



- $(t_{11}, t_{12}, t_{21}, t_{22})$ from some tweak set $\mathcal{T} \subseteq (\{0,1\}^n)^4$
- $\mathcal{T}$ can (still) be any set
- Security of XPX strongly depends on choice of $\mathcal{T}$
  1. "Weak" $\mathcal{T}$ $\longrightarrow$ insecure

XPX

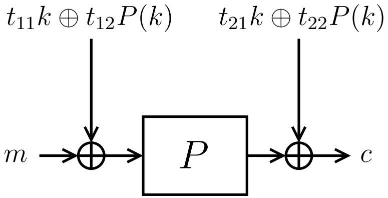
- XPX by Mennink [Men16]:



- $(t_{11}, t_{12}, t_{21}, t_{22})$ from some tweak set $\mathcal{T} \subseteq (\{0,1\}^n)^4$
- $\mathcal{T}$ can (still) be any set
- Security of XPX strongly depends on choice of $\mathcal{T}$
  1. "Weak" $\mathcal{T}$ $\longrightarrow$ insecure
  2. "Normal" $\mathcal{T}$ $\longrightarrow$ single-key secure

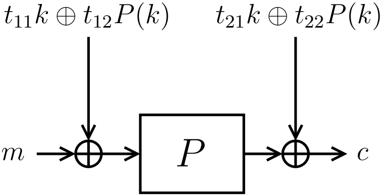
XPX

- XPX by Mennink [Men16]:

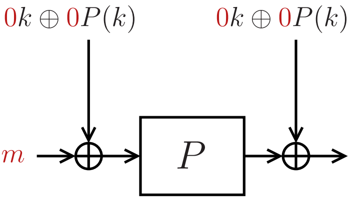


- $(t_{11}, t_{12}, t_{21}, t_{22})$ from some tweak set $\mathcal{T} \subseteq (\{0,1\}^n)^4$
- $\mathcal{T}$ can (still) be any set
- Security of XPX strongly depends on choice of $\mathcal{T}$
  1. "Weak" $\mathcal{T}$ $\longrightarrow$ insecure
  2. "Normal" $\mathcal{T}$ $\longrightarrow$ single-key secure
  3. "Strong" $\mathcal{T}$ $\longrightarrow$ related-key secure

XPX: Weak Tweaks

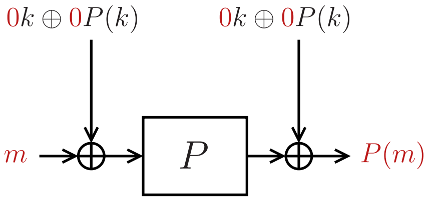


XPX: Weak Tweaks



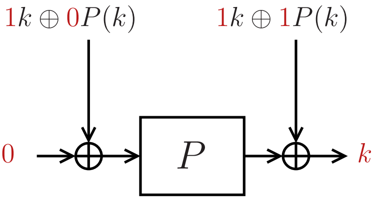
$(0, 0, 0, 0) \in \mathcal{T}$

XPX: Weak Tweaks



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

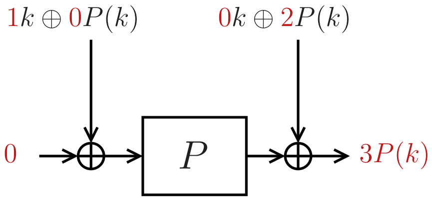
XPX: Weak Tweaks



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

$$(1,0,1,1) \in \mathcal{T} \implies \mathsf{XPX}_k((1,0,1,1),0) = k$$

XPX: Weak Tweaks

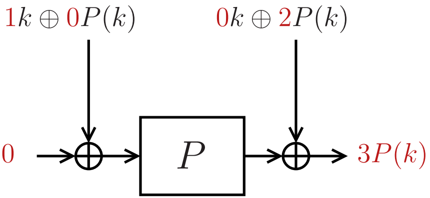


$$(0,0,0,0) \in \mathcal{T} \implies \mathsf{XPX}_k((0,0,0,0),m) = P(m)$$

$$(1,0,1,1) \in \mathcal{T} \implies \mathsf{XPX}_k((1,0,1,1),0) = k$$

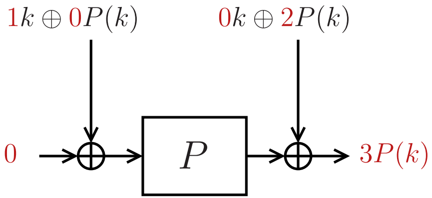
$$(1,0,0,2) \in \mathcal{T} \implies \mathsf{XPX}_k((1,0,0,2),0) = 3P(k)$$

XPX: Weak Tweaks



$$
\begin{array}{lcl}
(0,0,0,0) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((0,0,0,0),m) = P(m) \\
(1,0,1,1) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,1,1),0) = k \\
(1,0,0,2) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,0,2),0) = 3P(k) \\
\cdots & \cdots & \cdots
\end{array}
$$

XPX: Weak Tweaks

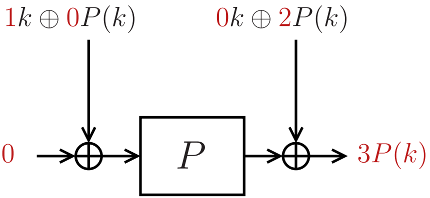


$$
\begin{array}{lcl}
(0,0,0,0) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((0,0,0,0),m) = P(m) \\
(1,0,1,1) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,1,1),0) = k \\
(1,0,0,2) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,0,2),0) = 3P(k) \\
\dots & \dots & \dots
\end{array}
$$

"Valid" Tweak Sets

- Technical definition to eliminate weak cases

XPX: Weak Tweaks

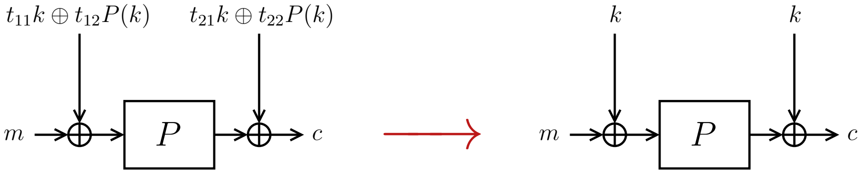


$$
\begin{array}{lcl}
(0,0,0,0) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((0,0,0,0),m) = P(m) \\
(1,0,1,1) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,1,1),0) = k \\
(1,0,0,2) \in \mathcal{T} & \Longrightarrow & \mathsf{XPX}_k((1,0,0,2),0) = 3P(k) \\
\dots & \dots & \dots
\end{array}
$$

“Valid” Tweak Sets

- Technical definition to eliminate weak cases
- $\mathcal{T}$ invalid $\Longleftrightarrow$ XPX insecure
- $\mathcal{T}$ valid $\Longleftrightarrow$ XPX single- or related-key secure

XPX Covers Even-Mansour



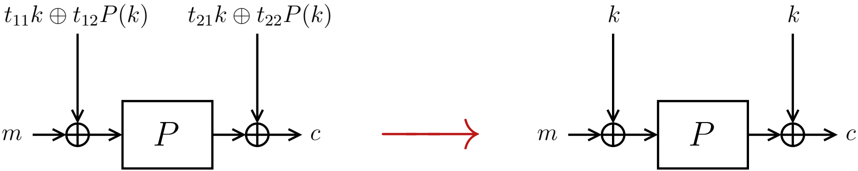
for $\mathcal{T} = \{(1,0,1,0)\}$

XPX Covers Even-Mansour

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

- Single-key STPRP secure (surprise?)

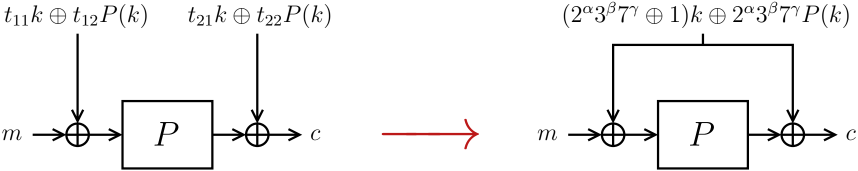
XPX Covers Even-Mansour



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

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

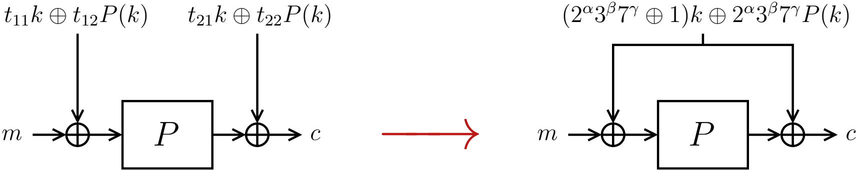
XPX Covers XEX With Even-Mansour



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

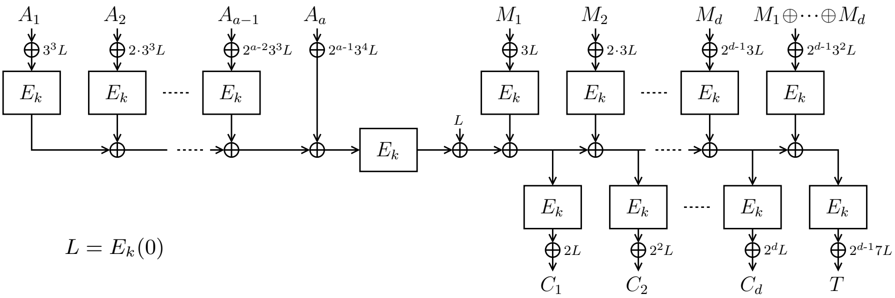
XPX Covers XEX With Even-Mansour



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

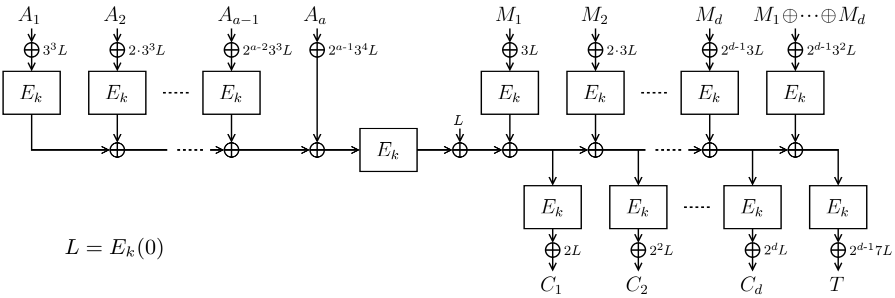
- (α, β, γ) is in fact the "real" tweak
- Related-key STPRP secure (if $2^\alpha 3^\beta 7^\gamma \neq 1$)

Application to AE: COPA and Prøst-COPA



- By Andreeva et al. (2014)
- Implicitly based on XEX based on AES

Application to AE: COPA and Prøst-COPA



- By Andreeva et al. (2014)
- Implicitly based on XEX based on AES

- Prøst-COPA by Kavun et al. (2014):
  COPA based on XEX based on Even-Mansour

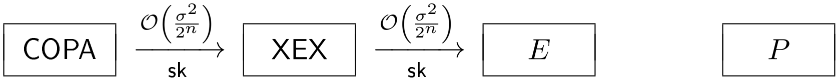
Application to AE: COPA and Prøst-COPA

Single-Key Security of COPA

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

Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA



Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA

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

Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA

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

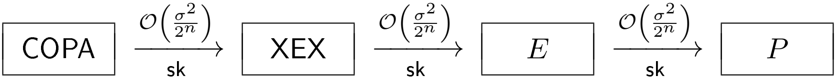
Related-Key Security of COPA

- Existing proof generalizes

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

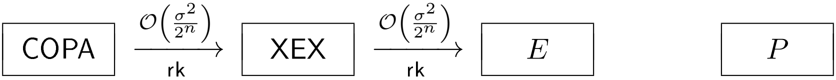
Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA



Related-Key Security of Prøst-COPA

- Existing proof generalizes



Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA

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

Related-Key Security of Prøst-COPA

- Existing proof generalizes

$$\boxed{\text{COPA}} \xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XEX}} \xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{E} \xrightarrow[\text{rk}]{\Omega\left(\,1\,\right)} \boxed{P}$$

Application to AE: COPA and Prøst-COPA

Single-Key Security of Prøst-COPA

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

Related-Key Security of Prøst-COPA

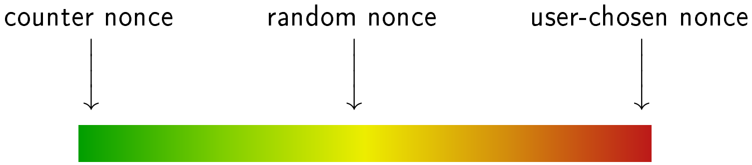
- Existing proof generalizes

$$\boxed{\text{COPA}} \xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{\text{XEX}} \xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{E} \xrightarrow[\text{rk}]{\Omega\left(1\right)} \boxed{P}$$

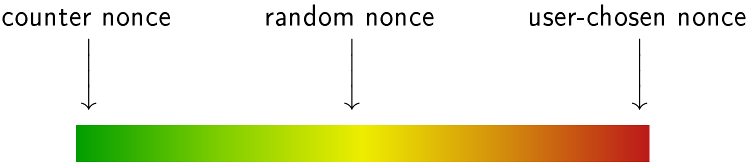
$$\boxed{\text{XEX}} \xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)} \boxed{P}$$

Outline

Guaranteeing Uniqueness of Nonce

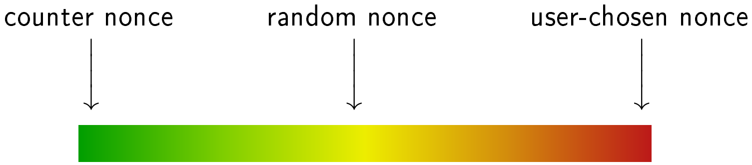


Guaranteeing Uniqueness of Nonce



- Issues with nonce generation:
  - Counter needs storage
  - Need synchronization or transmission
  - Efficiency cost
  - Laziness or mistake of implementor
  - ...

Guaranteeing Uniqueness of Nonce



- Issues with nonce generation:
  - Counter needs storage
  - Need synchronization or transmission
  - Efficiency cost
  - Laziness or mistake of implementor
  - ...
- Sometimes, attacker can use same nonce multiple times

Nonce-Reuse in Practice

> **Nonce-Disrespecting Adversaries: Practical Forgery Attacks on GCM in TLS**
>
> Böck et al., USENIX WOOT 2016

- GCM is widely used authenticated encryption scheme
- Used in TLS (“https”)

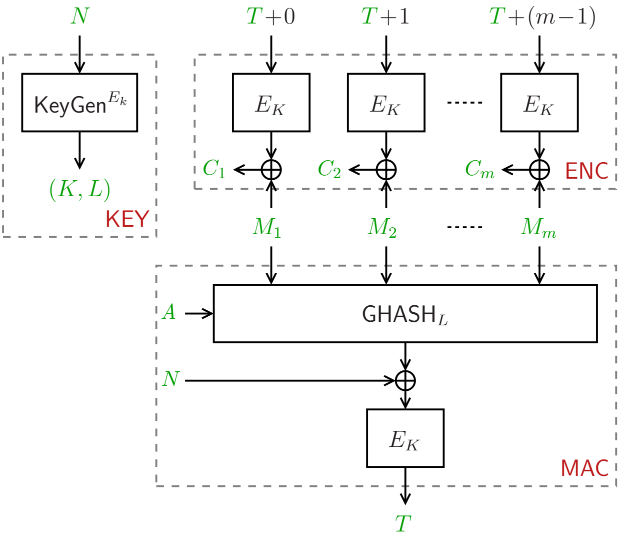
- Internet-wide scan for GCM implementations
- 184 devices with duplicated nonces
  - VISA, Polish bank, German stock exchange, ...
- $\approx$ 70.000 devices with random nonce

Resistance Against Nonce-Reuse

Intuition

- All input should be cryptographically transformed
- Any change in $(N, A, M) \longrightarrow$ unpredictable (C, T)
- Often comes at a price:
  - Efficiency
  - Security
  - Parallelizability
  - ...

Back to GCM-SIV



Outline

Conclusion

Authenticated Encryption

- Nonce-based AE: currently the norm
  - CCM, GCM, OCB3, ...
- Nonce-reuse comes at efficiency penalty
  - GCM-SIV, MRO, AEZ, ...
- CAESAR competition

Conclusion

Authenticated Encryption

- Nonce-based AE: currently the norm
  - CCM, GCM, OCB3, ...
- Nonce-reuse comes at efficiency penalty
  - GCM-SIV, MRO, AEZ, ...
- CAESAR competition

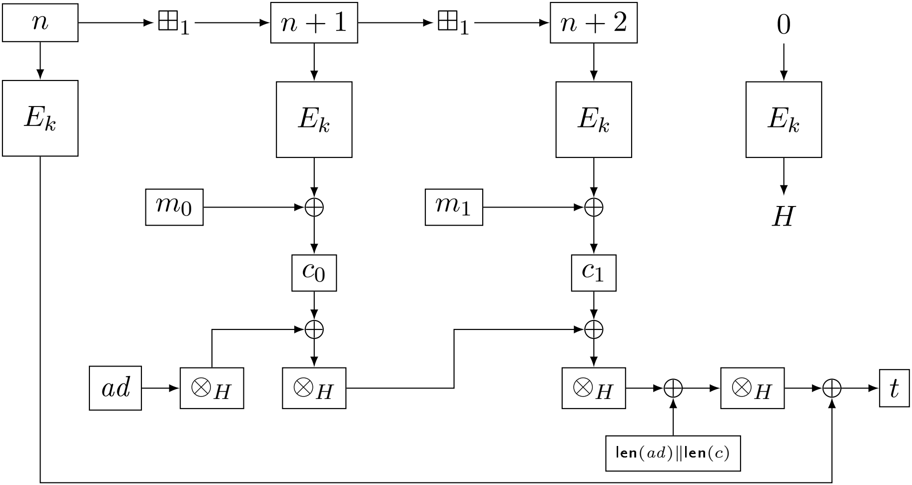
Tweakable Blockciphers

- Allow for modular and compact proofs
- Birthday-bound secure TBCs: simple and efficient
- Security beyond the birthday bound?

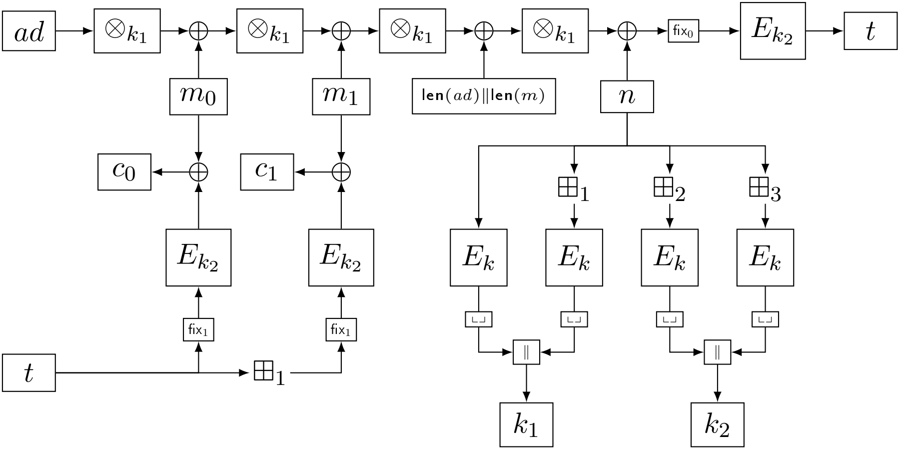
Thank you for your attention!

SUPPORTING SLIDES

Detailed Picture of GCM



Detailed Picture of GCM-SIV



MEM: Implementation

- State size $b = 1024$
- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- P: BLAKE2b permutation with 4 or 6 rounds

MEM: Implementation

- State size $b = 1024$
- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- P: BLAKE2b permutation with 4 or 6 rounds

- Main implementation results:

	nonce-respecting					misuse-resistant
Platform	AES-GCM	OCB3	Deoxys$^{\neq}$	OPP$_4$	OPP$_6$	
Cortex-A8	38.6	28.9	-	4.26	5.91	
Sandy Bridge	2.55	0.98	1.29	1.24	1.91	
Haswell	1.03	0.69	0.96	0.55	0.75	

MEM: Implementation

- State size $b = 1024$
- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- P: BLAKE2b permutation with 4 or 6 rounds

- Main implementation results:

	nonce-respecting					misuse-resistant			
Platform	AES-GCM	OCB3	Deoxys$^{\neq}$	OPP_4	OPP_6	GCM-SIV	Deoxys$^{=}$	MRO_4	MRO_6
Cortex-A8	38.6	28.9	-	4.26	5.91	-	-	8.07	11.32
Sandy Bridge	2.55	0.98	1.29	1.24	1.91	-	$\approx$ 2.58	2.41	3.58
Haswell	1.03	0.69	0.96	0.55	0.75	1.17	$\approx$ 1.92	1.06	1.39

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

$$\begin{matrix} x_0 & x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 & x_7 \\ x_8 & x_9 & x_{10} & x_{11} \\ x_{12} & x_{13} & x_{14} & x_{15} \end{matrix}$$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

$$\begin{array}{cccc} x_0 & x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 & x_7 \\ x_8 & x_9 & x_{10} & x_{11} \\ x_{12} & x_{13} & x_{14} & x_{15} \\ x_{16} & & & \end{array}$$

- $x_{16} = (x_0 \lll 53) \oplus (x_5 \ll 13)$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

$$\begin{matrix} x_0 & x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 & x_7 \\ x_8 & x_9 & x_{10} & x_{11} \\ x_{12} & x_{13} & x_{14} & x_{15} \\ x_{16} & x_{17} & & \end{matrix}$$

- $x_{16} = (x_0 \lll 53) \oplus (x_5 \ll 13)$
- $x_{17} = (x_1 \lll 53) \oplus (x_6 \ll 13)$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

$$\begin{array}{cccc} x_0 & x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 & x_7 \\ x_8 & x_9 & x_{10} & x_{11} \\ x_{12} & x_{13} & x_{14} & x_{15} \\ x_{16} & x_{17} & x_{18} & \end{array}$$

- $x_{16} = (x_0 \lll 53) \oplus (x_5 \ll 13)$
- $x_{17} = (x_1 \lll 53) \oplus (x_6 \ll 13)$
- $x_{18} = (x_2 \lll 53) \oplus (x_7 \ll 13)$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

$$\begin{array}{cccc} x_0 & x_1 & x_2 & x_3 \\ x_4 & x_5 & x_6 & x_7 \\ x_8 & x_9 & x_{10} & x_{11} \\ x_{12} & x_{13} & x_{14} & x_{15} \\ x_{16} & x_{17} & x_{18} & x_{19} \end{array}$$

- $x_{16} = (x_0 \lll 53) \oplus (x_5 \ll 13)$
- $x_{17} = (x_1 \lll 53) \oplus (x_6 \ll 13)$
- $x_{18} = (x_2 \lll 53) \oplus (x_7 \ll 13)$
- $x_{19} = (x_3 \lll 53) \oplus (x_8 \ll 13)$

MEM: Parallelizability

- LFSR on 16 words of 64 bits:

$$\varphi(x_0, \ldots, x_{15}) = (x_1, \ldots, x_{15}, (x_0 \lll 53) \oplus (x_5 \ll 13))$$

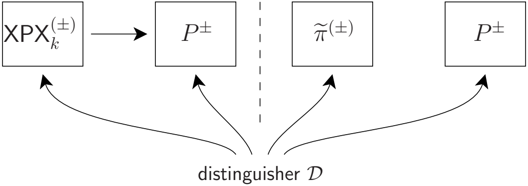
- Begin with state $L_i = [x_0, \ldots, x_{15}]$ of 64-bit words

x_0	x_1	x_2	x_3
x_4	x_5	x_6	x_7
x_8	x_9	x_{10}	x_{11}
x_{12}	x_{13}	x_{14}	x_{15}
x_{16}	x_{17}	x_{18}	x_{19}

- $x_{16} = (x_0 \lll 53) \oplus (x_5 \ll 13)$
- $x_{17} = (x_1 \lll 53) \oplus (x_6 \ll 13)$
- $x_{18} = (x_2 \lll 53) \oplus (x_7 \ll 13)$
- $x_{19} = (x_3 \lll 53) \oplus (x_8 \ll 13)$
- Parallelizable (AVX2) and word-sliceable

XPX: Single-Key Security

(Strong) Tweakable PRP

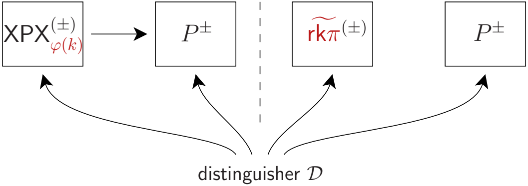


- Information-theoretic indistinguishability
  - $\widetilde{\pi}$ ideal tweakable permutation
  - P ideal permutation
  - k secret key

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

XPX: Related-Key Security

Related-Key (Strong) Tweakable PRP



- Information-theoretic indistinguishability
  - $\widetilde{\mathsf{rk}\pi}$ ideal tweakable related-key permutation
  - P ideal permutation
  - k secret key
- $\mathcal{D}$ restricted to some set of key-deriving functions Φ

XPX: Related-Key Security

Key-Deriving Functions

- $\Phi_{\oplus}$: all functions $k \mapsto k \oplus \delta$

XPX: Related-Key Security

Key-Deriving Functions

- $\Phi_{\oplus}$: all functions $k \mapsto k \oplus \delta$
- $\Phi_{P\oplus}$: all functions $k \mapsto k \oplus \delta$ or $P(k) \mapsto P(k) \oplus \epsilon$

XPX: Related-Key Security

Key-Deriving Functions

- $\Phi_{\oplus}$: all functions $k \mapsto k \oplus \delta$
- $\Phi_{P\oplus}$: all functions $k \mapsto k \oplus \delta$ or $P(k) \mapsto P(k) \oplus \epsilon$
- Note: maskings in XPX are $t_{i1}k \oplus t_{i2}P(k)$

XPX: Related-Key Security

Key-Deriving Functions

- $\Phi_\oplus$: all functions $k \mapsto k \oplus \delta$
- $\Phi_{P\oplus}$: all functions $k \mapsto k \oplus \delta$ or $P(k) \mapsto P(k) \oplus \epsilon$
- Note: maskings in XPX are $t_{i1}k \oplus t_{i2}P(k)$

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

Key-Deriving Functions

- $\Phi_{\oplus}$: all functions $k \mapsto k \oplus \delta$
- $\Phi_{P\oplus}$: all functions $k \mapsto k \oplus \delta$ or $P(k) \mapsto P(k) \oplus \epsilon$
- Note: maskings in XPX are $t_{i1}k \oplus t_{i2}P(k)$

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	$\Phi_{\oplus}$
$t_{11}, t_{12} \neq 0$	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

XPX: Security Proof Techniques

Patarin's H-coefficient Technique

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

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

↰ prob. ratio for good transcripts

XPX: Security Proof Techniques

Patarin's H-coefficient Technique

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

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

↰ prob. ratio for good transcripts

- Trade-off: define bad transcripts smartly!

XPX: Security Proof Techniques

Before the Interaction

- Reveal "dedicated" oracle queries

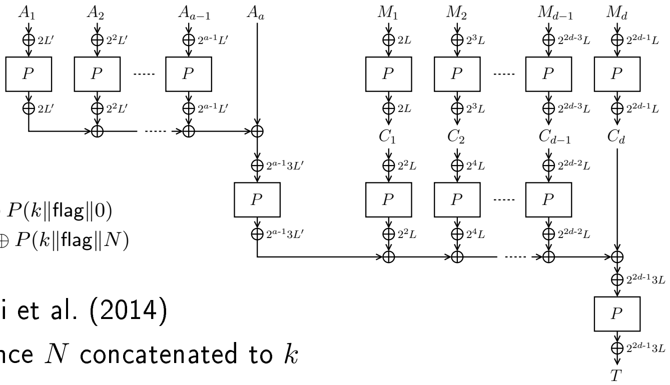
After the Interaction

- 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: Application to AE: Minalpher

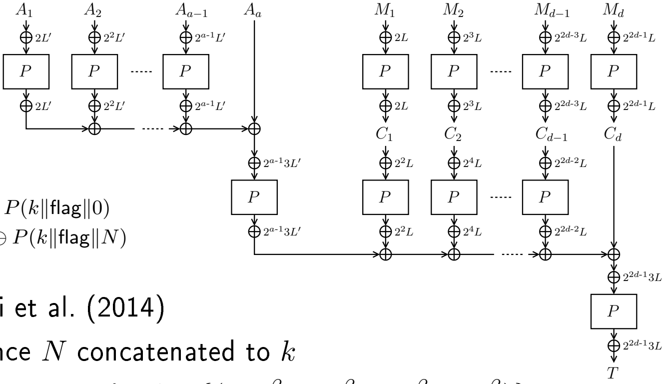


$L' = k\|\text{flag}\|0 \oplus P(k\|\text{flag}\|0)$

$L \ = k\|\text{flag}\|N \oplus P(k\|\text{flag}\|N)$

- By Sasaki et al. (2014)
- Extra nonce N concatenated to k

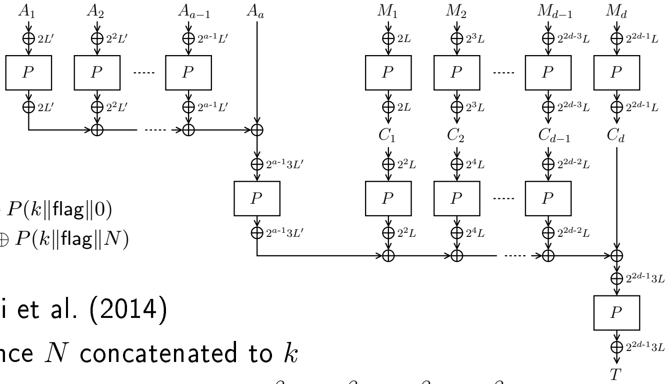
XPX: Application to AE: Minalpher



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

- By Sasaki et al. (2014)
- Extra nonce N concatenated to k
- Based on XPX with $\mathcal{T} = \{(2^\alpha 3^\beta, 2^\alpha 3^\beta, 2^\alpha 3^\beta, 2^\alpha 3^\beta)\}$

XPX: Application 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. (2014)
- Extra nonce N concatenated to k
- Based on XPX with $\mathcal{T} = \{(2^\alpha 3^\beta, 2^\alpha 3^\beta, 2^\alpha 3^\beta, 2^\alpha 3^\beta)\}$

Minalph. $\xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)}$ XPX $\xrightarrow[\text{rk}]{\mathcal{O}\left(\frac{\sigma^2}{2^n}\right)}$ P