Cryptanalysis of OCB2: Attacks on Authenticity and Confidentiality.

Based on

- Akiko Inoue, Tetsu Iwata, Kazuhiko Minematsu, and Bertram Poettering
- Cryptanalysis of OCB2: Attacks on Authenticity and Confidentiality, CRYPTO 2019
- Cryptology ePrint Archive: Report 2019/311

Penguin

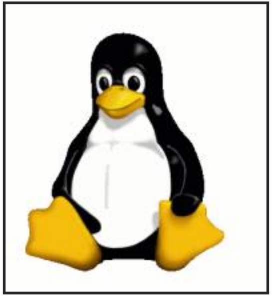
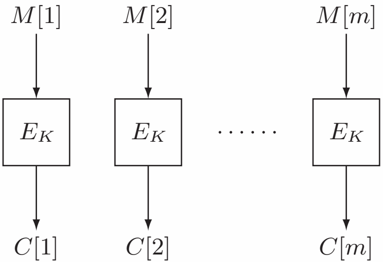


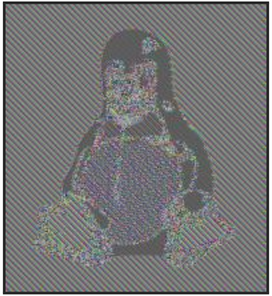
Image: Larry Ewing, lewing@isc.tamu.edu, created with the GIMP. https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation

ECB (Electronic Code Book)



- E_K: a block cipher with n-bit blocks
- $M = (M[1], \ldots, M[m])$
- $C = (C[1], \ldots, C[m])$

The ECB Penguin



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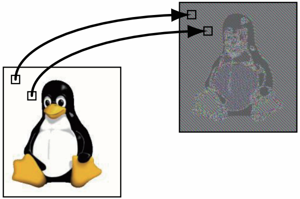
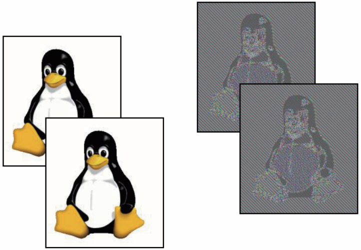
Issues with ECB

- $M[i] = M[j] \Rightarrow C[i] = C[j]$



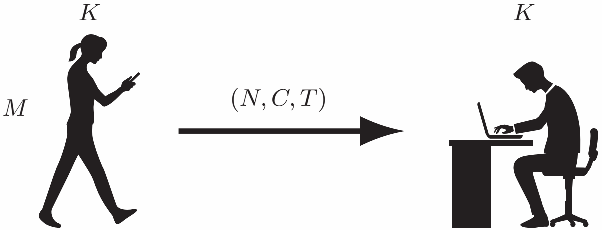
- $M = M' \Rightarrow C = C'$



- does not provide authenticity, “authenticated encryption”

AE (Authenticated Encryption)

- Symmetric-key primitive for privacy and authenticity
- Nonce-based AE [Rog02] (this talk will not consider associated data)
  - nonce: data that is changed for each encryption (counter)
- Encryption: $(K, N, M) \mapsto (C, T)$
- Decryption: $(K, N, C, T) \mapsto M$ or $(K, N, C, T) \mapsto \perp$ (authentication error, reject)



K: key
N: nonce
M: message
C: ciphertext
T: tag

$(C, T) \leftarrow \mathrm{Enc}_K(N, M)$

$M/\perp \leftarrow \mathrm{Dec}_K(N, C, T)$

[Rog02] Rogaway. Authenticated-encryption with associated-data. CCS 2002

Examples of AE

- GCM and CCM (NIST recommendations)
- 6 schemes in ISO/IEC 19772
- IETF RFC includes GCM, ChaCha20-Poly1305, ...
- 6 schemes in CAESAR final portfolio
- many schemes in the ongoing NIST lightweight cryptography standardization project

OCB (Offset Code Book)

- 3 versions, built on a block cipher (e.g., AES, with $n = 128$)
  - OCB1 by Rogaway et al. at CCS 2001 [RBBK01]
  - OCB2 by Rogaway at ASIACRYPT 2004 [Rog04]
  - OCB3 by Krovetz and Rogaway at FSE 2011 [KR11]
- Nonce-based AE (with AD) with strong features:
  - fully parallelizable
  - 1 block cipher call to process each n-bit block (rate-1, same as CTR and ECB modes)
  - provable security

[RBBK01] Rogaway, Bellare, Black, Krovetz. OCB: A block-cipher mode of operation for efficient authenticated encryption. CCS 2001

[Rog04] Rogaway. Efficient instantiations of tweakable blockciphers and refinements to modes OCB and PMAC. ASIACRYPT 2004

[KR11] Krovetz, Rogaway. The software performance of authenticated-encryption modes. FSE 2011

Security Evaluation of OCB

All versions have been extensively studied:

- Security proofs for all versions of OCB by Rogaway et al. [RBBK01, Rog04, KR11]
- Tightness of the security bounds: Ferguson [Fer02], Sun et al. [SWZ12]
- (Nonce) misuse attacks: Andreeva et al. [ABLMMY14], Ashur et al. [ADL17]
- Necessity of SPRP: Aoki and Yasuda [AY13]
- Bound improvement (for OCB3): Bhaumik and Nandi [BN17]

[Fer02] Ferguson. Collision attacks on OCB. Comments to NIST, 2002

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Our Results

Structural weakness of OCB2

- Independent of the underlying block cipher (and its block size)
- has been overlooked for about 15 years

Attacks

- Authenticity attacks (existential and universal forgeries)
- Privacy attacks (distinguishing attack and plaintext recovery)
- All attacks have very small complexity & the success probability is (almost) one

Practical Impacts

- OCB2 was one of the six algorithms in ISO/IEC 19772
  - ISO/IEC declared a plan for removal of OCB2 from the international standard
- SJCL Javascript crypto library implements OCB2
  - Users may be affected, though it is hard to see the real impact
  - Fixing crypto is not easy, time-consuming
- Joplin, a multi-platform application for taking notes
  - uses OCB2 through SJCL
  - decided to wait for the decision by SJCL team

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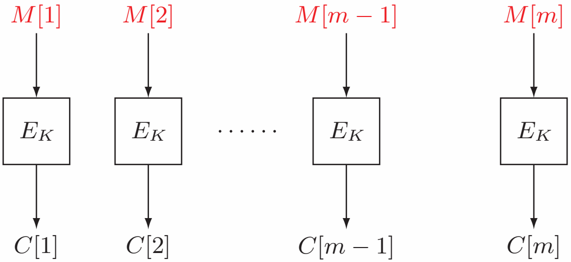
http://bitwiseshiftleft.github.io/sjcl/

https://joplinapp.org/

https://github.com/laurent22/joplin/issues/943

Technical Details of OCB2

- Encryption: $(N, M) \mapsto (C, T)$, ECB mode with masks generated from $L = E_K(N)$
  - $2a$ is doubling of a over $\mathrm{GF}(2^n)$, $3a = 2a \oplus a$
  - $M[m]$ is encrypted in CTR mode
  - $\texttt{len}(X)$ is an n-bit encoding of $|X|$
- The checksum is $\Sigma = M[1] \oplus \cdots \oplus M[m]$



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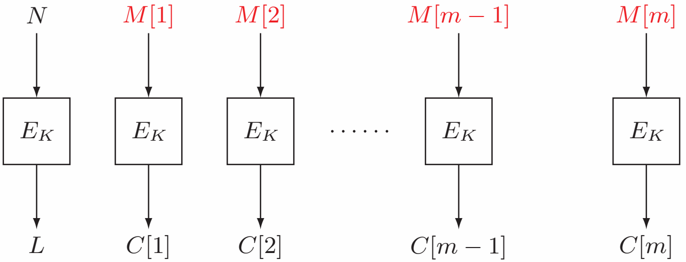

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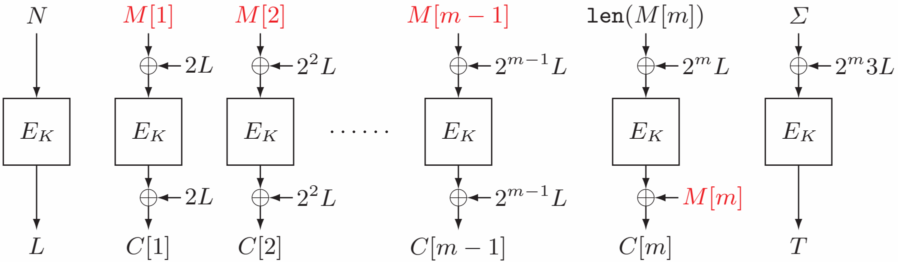
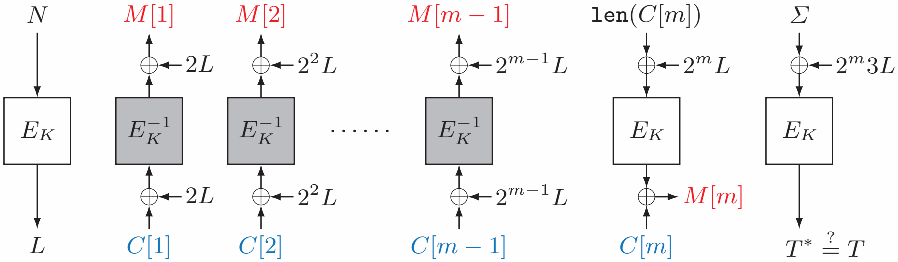


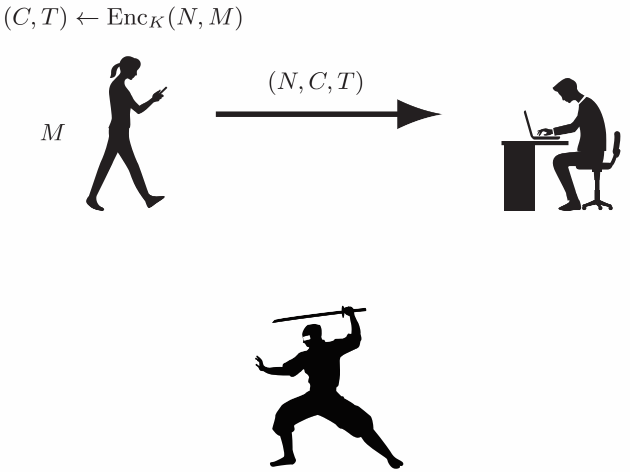
Technical Details of OCB2

- Decryption: $(N, C, T) \mapsto M/\perp$



- Theorem [Rog04]
  - $(C, T) \approx \text{random string}$ (privacy)
  - forgery is not possible (authenticity)

Minimal Forgery [IM18] (Existential Forgery)



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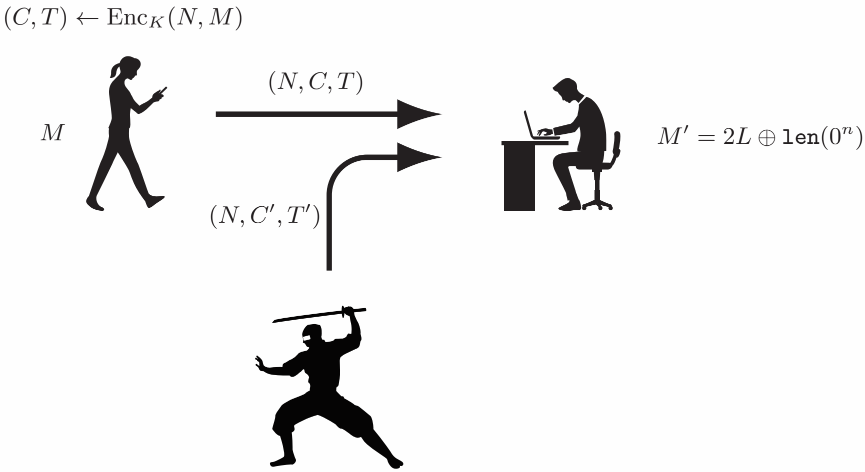

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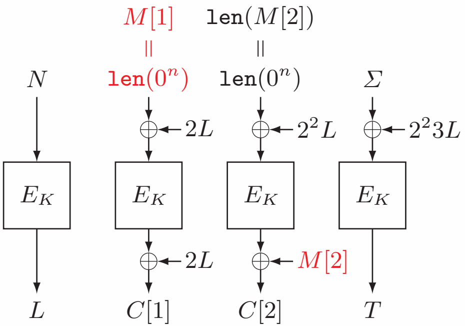
Minimal Forgery [IM18] (For Experts)

- Encrypt (N, M) to obtain $(C[1], C[2], T)$, where $M = (\texttt{len}(0^n), M[2])$ and $|M[2]| = n$



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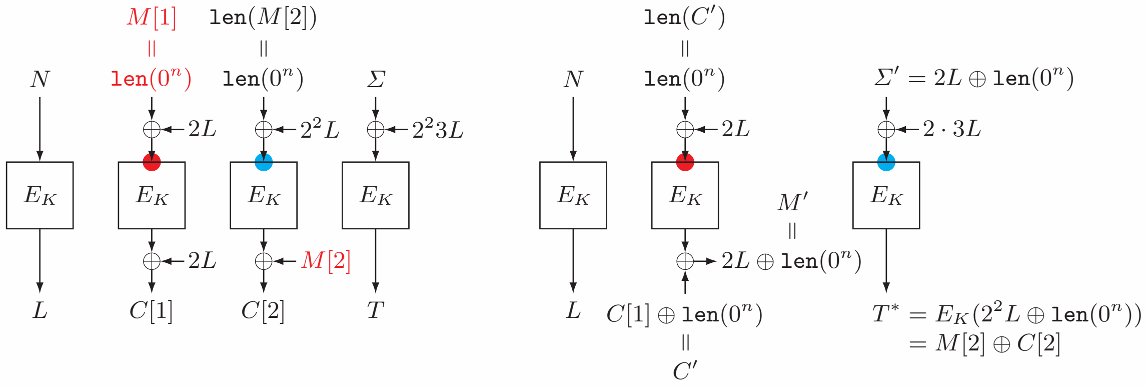
- Encrypt (N, M) to obtain $(C[1], C[2], T)$, where $M = (\texttt{len}(0^n), M[2])$ and $|M[2]| = n$
- Decrypt (N, C', T'), where $C' = C[1] \oplus \texttt{len}(0^n)$ and $T' = M[2] \oplus C[2]$
  - Note: $2L \oplus 2 \cdot 3L = 2L \oplus 2(2+1)L = 2^2 L$
  - $M' = 2L \oplus \texttt{len}(0^n)$ is returned, L can be used for powerful attacks



Attacks

Quickly triggered other attacks [IIMP19] (all under CCA):

- forgery of longer messages
- universal forgery
- distinguishing attack
- plaintext recovery
- simulation of block cipher encryption
- simulation of block cipher decryption

[IIMP19] Inoue, Iwata, Minematsu, Poettering. Cryptanalysis of OCB2: Attacks on Authenticity and Confidentiality. CRYPTO 2019

Universal Forgery [IIMP19]

- "Minimal forgery" forges $M' = 2L \oplus \texttt{len}(0^n)$
- Universal forgery: for any (N, M), the adversary can compute (C, T)

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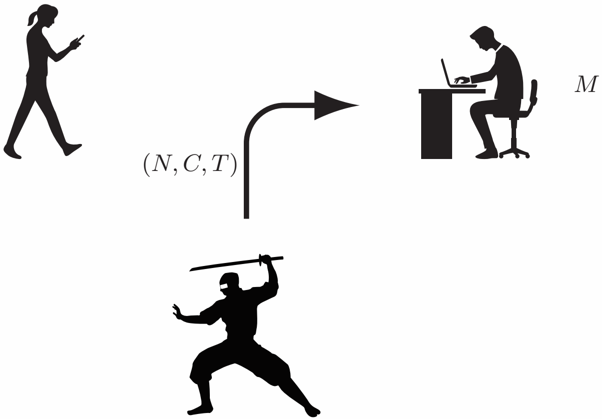
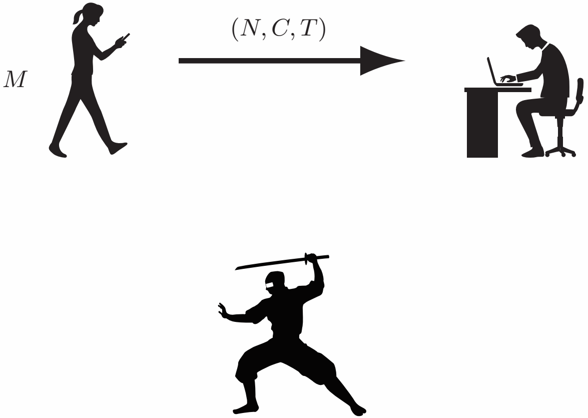
- Universal forgery: for any (N, M), the adversary can compute (C, T)
  - uses the minimal forgery as a subroutine, the most powerful authenticity attack



Plaintext Recovery [IIMP19]

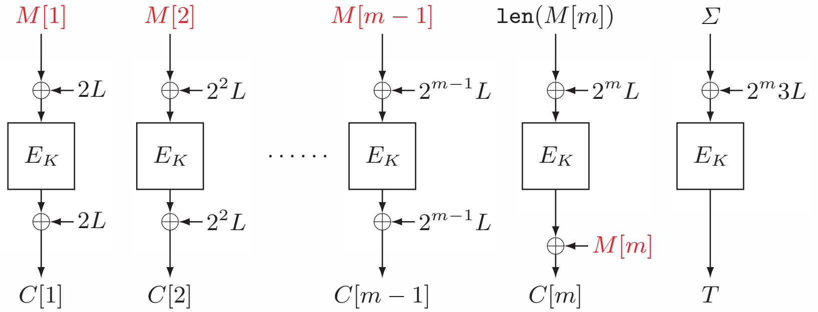
- The most powerful privacy attack: for any (N, C, T) (for unknown M), the adversary can compute M
  - uses the minimal forgery as a subroutine

$$(C, T) \leftarrow \mathrm{Enc}_K(N, M)$$



What Went Wrong?

- OCB2 has a proof of security [Rog04]
- The technical specification of OCB2 is too complex for a direct security proof
- To prove the security, [Rog04] uses "abstraction" of OCB2



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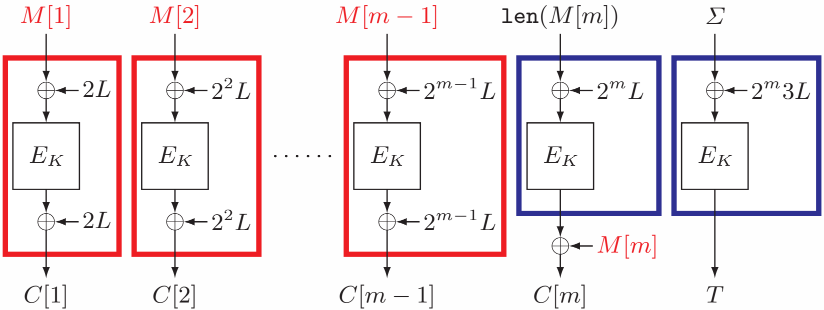

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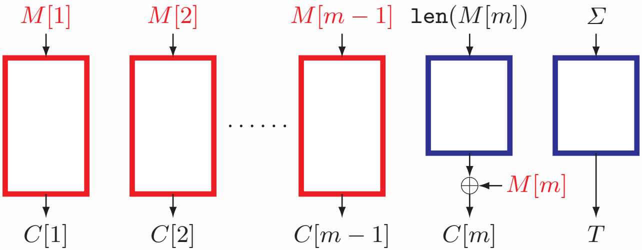
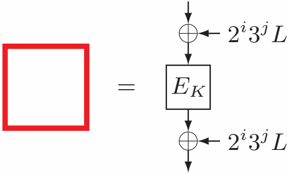
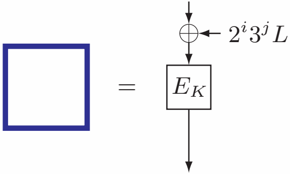


- If 

(XEX) and 

(XE), then OCB2

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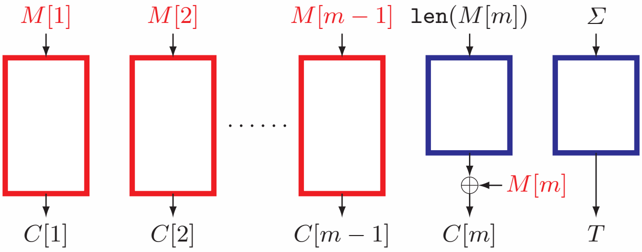
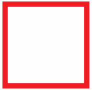
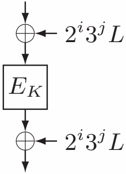
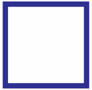
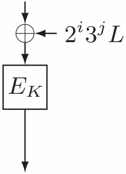


- If  $=$ 

(XEX) and  $=$ 

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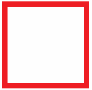
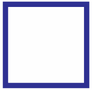
- If  is Π_1 (ideally secure XEX) and  is Π_0 (ideally secure XE), then $\Theta\mathrm{CB2}$

What Went Wrong?

- Three steps to prove the security of OCB2
  - Prove that $\Theta\mathrm{CB2}$ is secure (privacy and authenticity)
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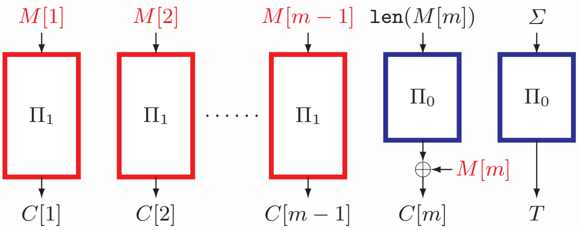
  - Conclude that OCB2 is secure, "hybrid argument"



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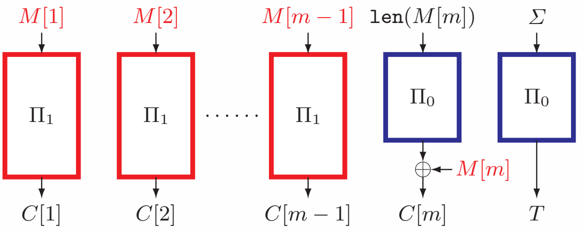

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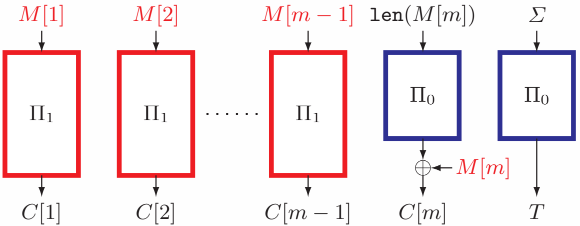

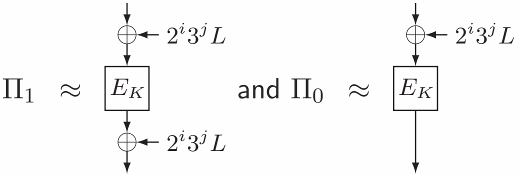

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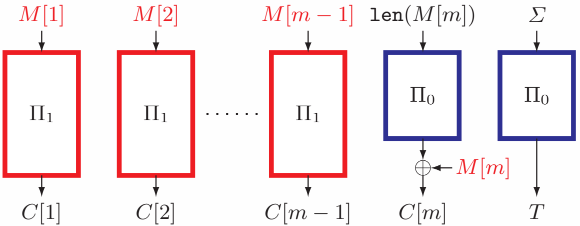
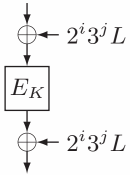
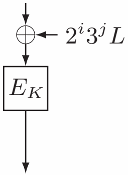


$\Pi_1 \approx$ 

and $\Pi_0 \approx$ 

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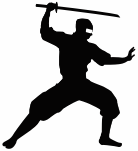

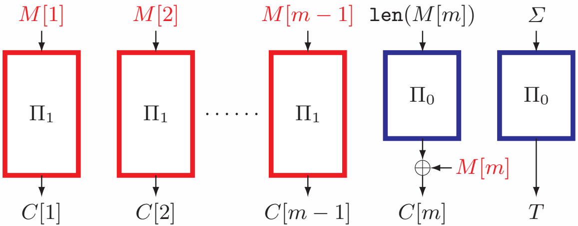

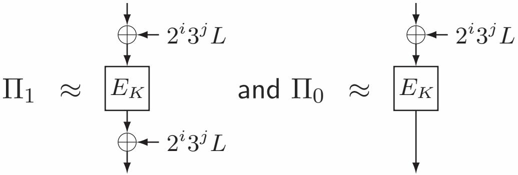

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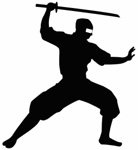

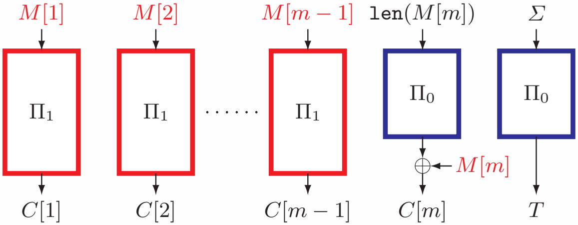

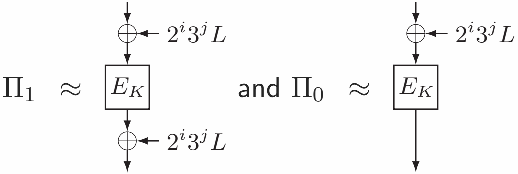

What Went Wrong?

- Three steps to prove the security of OCB2
  - Prove that $\Theta\mathrm{CB2}$ is secure (privacy and authenticity) ✓
  - Prove that for any tag-respecting adversary, $(\mathsf{XEX}, \mathsf{XE}) \approx (\Pi_1, \Pi_0)$ ✓
  - Conclude that OCB2 is secure, "hybrid argument" — XEX/XE misused, does not work!
- Lesson learned: prove all the statements PLUS carefully check they fit together

Fixes

Some ways to fix OCB2

- Use XEX for the last message block (OCB2f, provably secure)
- Change the definition of the mask (OCB2ff, provably secure, will be included in [ePrint 2019/311])
- Other potential (unproven) options
  - Always-nonempty-AD, always-PMAC
  - Rejecting harmful inputs to OCB2 (Counter-cryptanalysis)

Some ways to avoid OCB2

- GCM
- OCB3

Timeline

2001	OCB1 proposed at CCS 2001
2004	OCB2 proposed at ASIACRYPT 2004
2009	OCB2 included in ISO/IEC 19772:2009
2011	OCB3 proposed at FSE 2011
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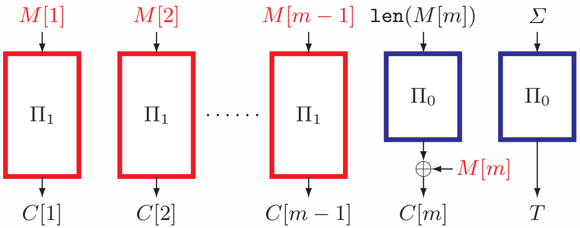
2018 Nov 11 10:00	[Iwa18] sent to ePrint, full plaintext recovery (posted on Nov 12, 02:00)
2018 Nov 11 14:00	[IM18] updated, universal forgery
2018 Nov 11 22:00	[Poe18] updated, BC simulation, universal forgery, partial plaintext recovery
2018 Nov 12 16:00	[Poe18] updated, full plaintext recovery
2018 Nov 16	[Iwa18] updated, BC decryption simulation

Timeline

- An exciting competition!
  - multiple teams from industry and academia (NEC, Nagoya U, and IBM & RHUL), across different corners in the world
- After the first finding of the potential gap, everything happened in a very short period of time
- Attacks only get better, for the case of OCB2, attacks got better very quickly

Concluding Remarks

- OCB2 is broken.
  - should not be used
- A (seemingly) small flaw in the proof led to surprisingly powerful attacks
- Not applicable to OCB1 and OCB3
  - They do not misuse XEX/XE
  - The general structure of OCB is sound



Lessons learned

- Even the most promising scheme can fail
- Active third-party verification of security proofs is important

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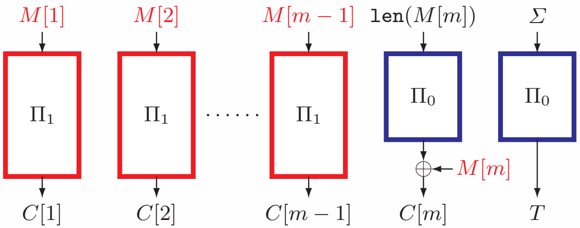

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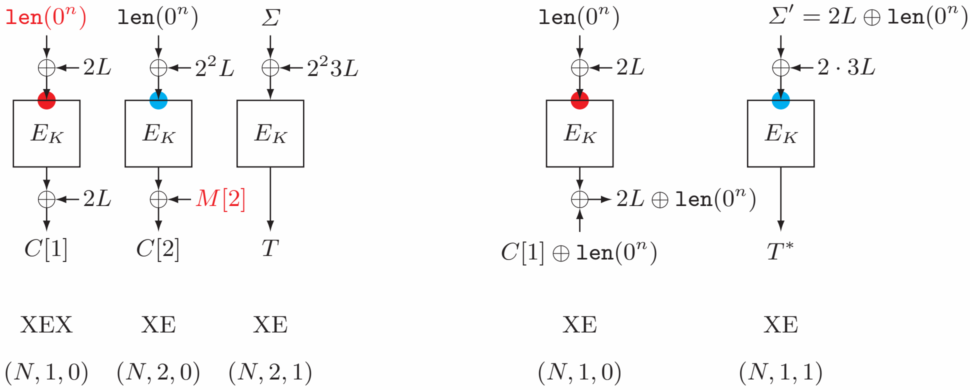
Thanks!

The Hybrid (For Experts, Backup Slide)

- If there is an adversary against OCB2, then there is an adversary against XEX/XE



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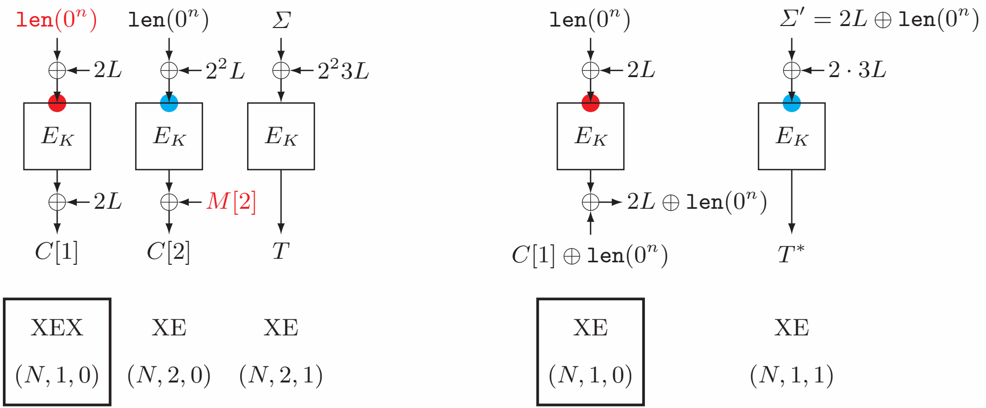

- Without violating the tag-respecting condition, the simulation is impossible. The hybrid does not work