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The Missing Difference Problem, and its Applications to Counter Mode Encryption

Gaëtan Leurent, Ferdinand Sibleyras

Inria, équipe SECRET

Journées Codage & Cryptographie 2018



Introduction

- **Cryptography:** Alice encrypts then sends messages to Bob.
- **Symmetric:** Alice and Bob share the same key.
- **Public channel:** Eve (attacker) can see and/or manipulate what is being sent.



Introduction

Block Cipher

$$E_k : \{0, 1\}^n \rightarrow \{0, 1\}^n$$

A family of **permutations** indexed by a key (AES, 3DES, ...) where n is the bit size of the permutation or block's size.

Introduction

Block Cipher

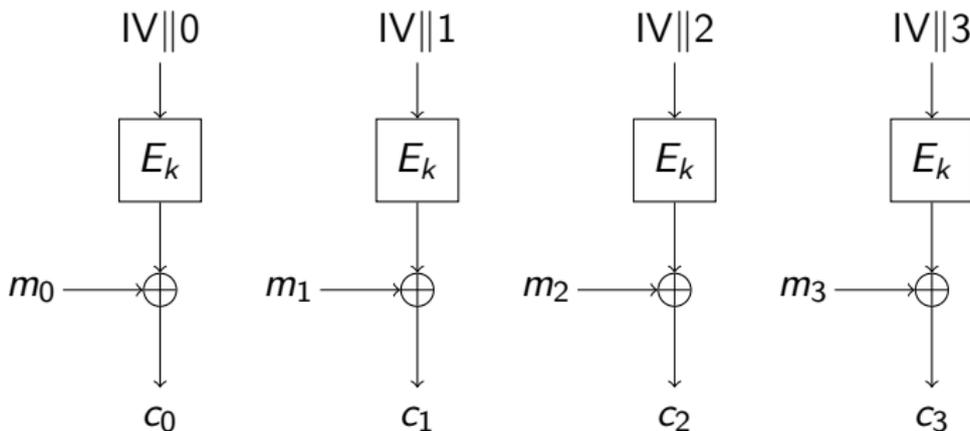
$$E_k : \{0, 1\}^n \rightarrow \{0, 1\}^n$$

A family of **permutations** indexed by a key (AES, 3DES, ...) where n is the bit size of the permutation or block's size.

Mode of operation

Describes how to use a **block cipher** along with a plaintext message of **arbitrary length** to achieve some concrete cryptographic goals.

The counter mode (CTR)



m_i : The plaintext.

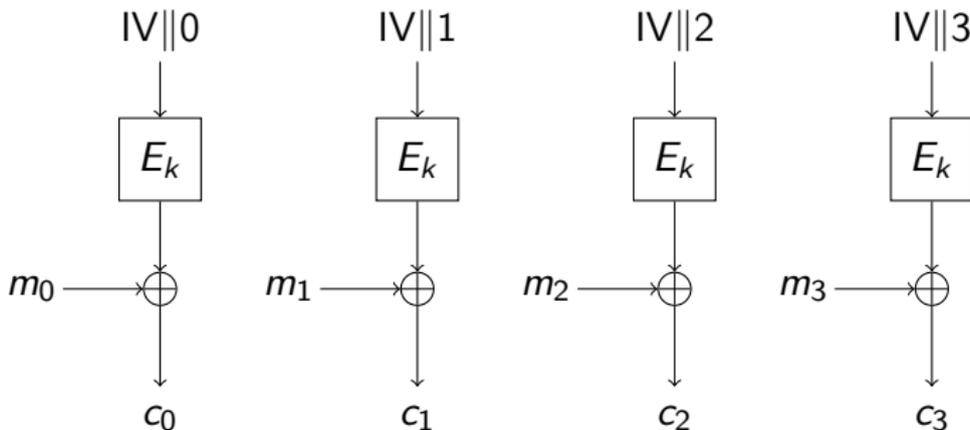
c_i : The ciphertext.

E_k : The block cipher.

IV : The Initialisation Value.

$$c_i = E_k(IV||i) \oplus m_i$$

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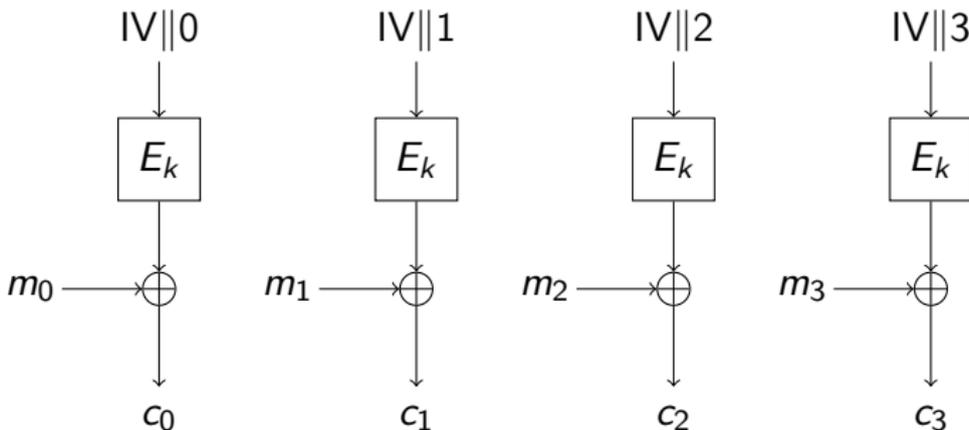
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Akin to a stream cipher: keystream XORed with the plaintext.

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Akin to a stream cipher: keystream XORed with the plaintext.

Inputs $IV||i$ to the block cipher **never repeat**.

The counter mode (CTR)

Let $K_i = E_k(\text{IV} \parallel i)$ the i th block of keystream.

- If E_k is a good Pseudo-Random Function (PRF) then all K_i are random and this is a one-time-pad.
- A block cipher is a Pseudo-Random **Permutation** (PRP) therefore K_i are all **distinct**: $K_i \neq K_j \forall i \neq j$.

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Security proof (σ the number of blocks)

$$\text{Adv}_{\text{CTR-}E_k}^{\text{IND}}(\sigma) \leq \text{Adv}_{E_k}^{\text{PRF}}(\sigma) \leq \text{Adv}_{E_k}^{\text{PRP}}(\sigma) + \sigma^2/2^{n+1}$$

Distinguisher

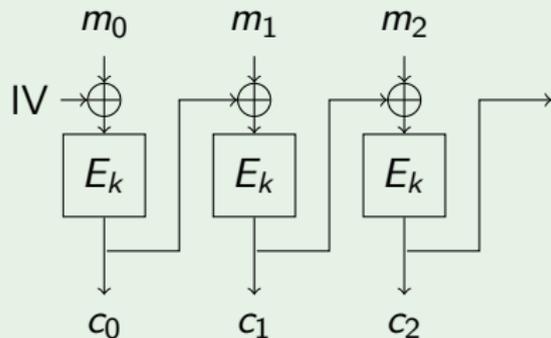
After $\sigma \simeq 2^{n/2}$ encrypted blocks we expect a collision on the K_i with high probability in the case of a random ciphertext.
That is the birthday bound coming from the birthday paradox.

CBC and CTR

Both modes are:

- widely deployed
- proven secure up to birthday bound ($2^{n/2}$)
- matching distinguishers at the proof's bound

CBC mode

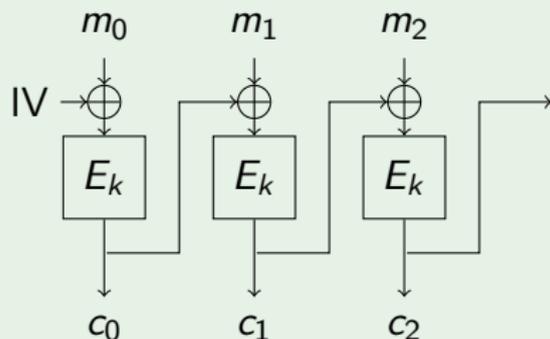


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CBC mode



Folklore assumptions

[Ferguson, Schneier, Kohno]

CTR leaks very little data. [...] It would be reasonable to limit the cipher mode to 2^{60} blocks, which allows you to encrypt 2^{64} bytes but restricts the leakage to a small fraction of a bit.

When using CBC mode you should be a bit more restrictive. [...]

We suggest limiting CBC encryption to 2^{32} blocks or so.

The counter mode (CTR)

From a **distinguishing** attack to a **plaintext recovery** attack ?

- If we know m_i , we recover $K_i = c_i \oplus m_i$.

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Main Idea

Collect many keystream blocks K_i and encryptions of secret block $c_j = K_j \oplus S$; then look for a value S such that $K_i \oplus c_j \neq S \forall i \neq j$.

Missing difference problem

The missing difference problem

- Given \mathcal{A} and \mathcal{B} , and a hint \mathcal{S} three sets of n -bit words
- Find $S \in \mathcal{S}$ such that:

$$\forall (a, b) \in \mathcal{A} \times \mathcal{B}, S \neq a \oplus b.$$

Missing difference problem

Main Idea

Collect many keystream blocks $K_j \in \mathcal{A}$ and encryptions of secret block $c_j = K_j \oplus S \in \mathcal{B}$; then look for a value $S \in \mathcal{S}$ such that $\forall (a, b) \in \mathcal{A} \times \mathcal{B}, S \neq a \oplus b$.

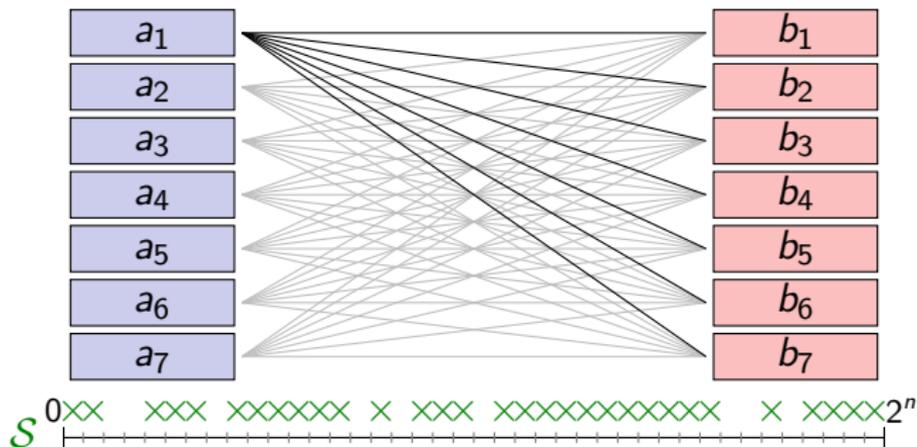
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Simple Sieving Algorithm

[McGrew, FSE'13]



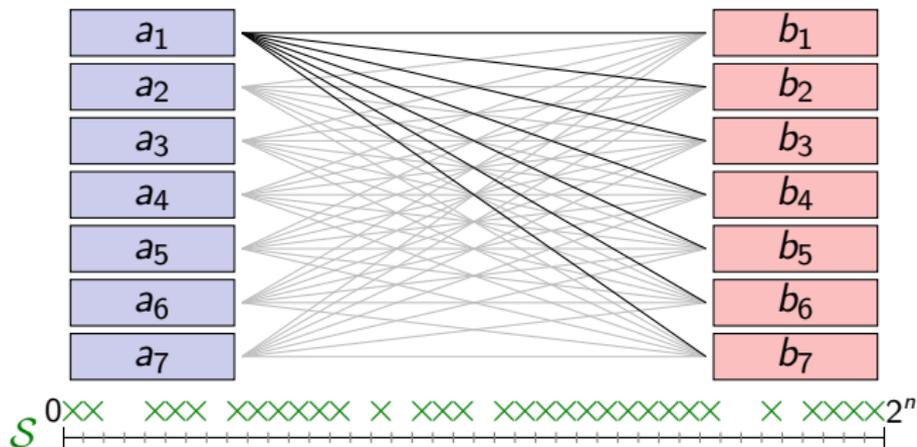
Compute all $a_i \oplus b_j$, remove results from a sieve \mathcal{S} .

Analysis: case $|\mathcal{S}| = 2^n$ via coupon collector problem

- To exclude 2^n candidates of \mathcal{S} , we need $n \cdot 2^n$ values $a_i \oplus b_j$
 - Lists \mathcal{A} and \mathcal{B} of size $\sqrt{n} \cdot 2^{n/2}$. **Complexity:** $\tilde{O}(2^n)$

Simple Sieving Algorithm

[McGrew, FSE'13]



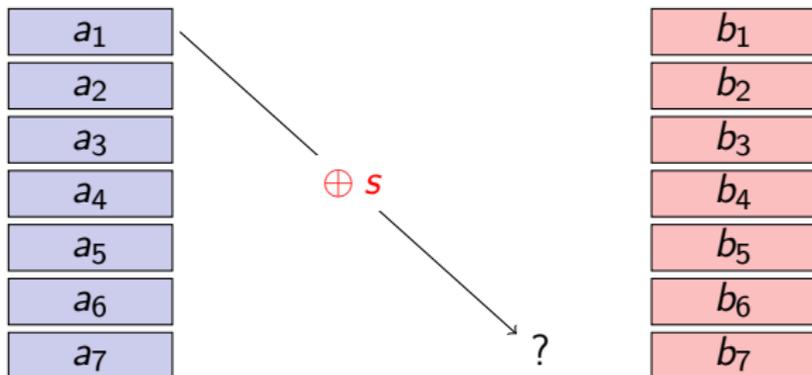
Compute all $a_i \oplus b_j$, remove results from a sieve S .

Analysis: case $|\mathcal{S}| = 2$

- To exclude **1 candidate** of S , we need 2^n values $a_i \oplus b_j$
 - Lists \mathcal{A} and \mathcal{B} of size $2^{n/2}$. **Complexity:** $\tilde{O}(2^n)$

Searching Algorithm

[McGrew, FSE'13]



- Make a guess and verify.

Try Guess (s)

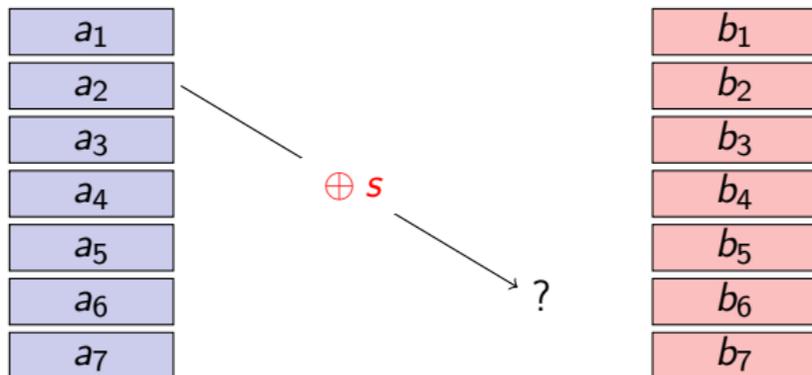
```

for  $a$  in  $\mathcal{A}$  do
  if  $(s \oplus a) \in \mathcal{B}$  then
    return 0
return 1

```

Searching Algorithm

[McGrew, FSE'13]



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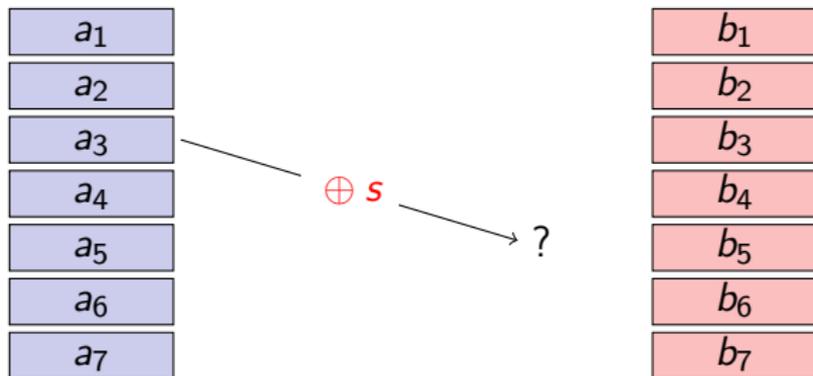
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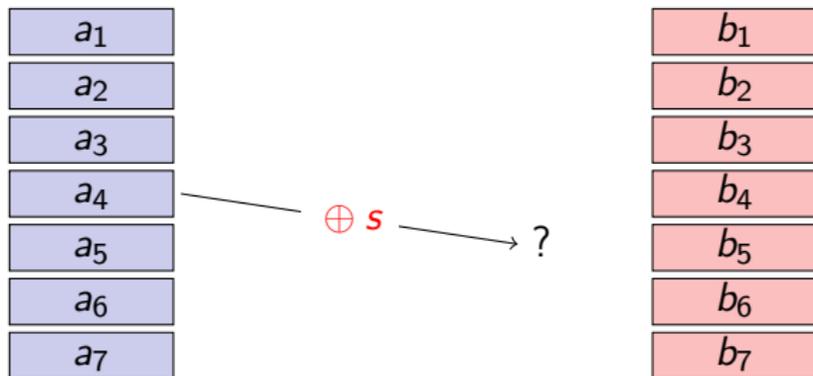
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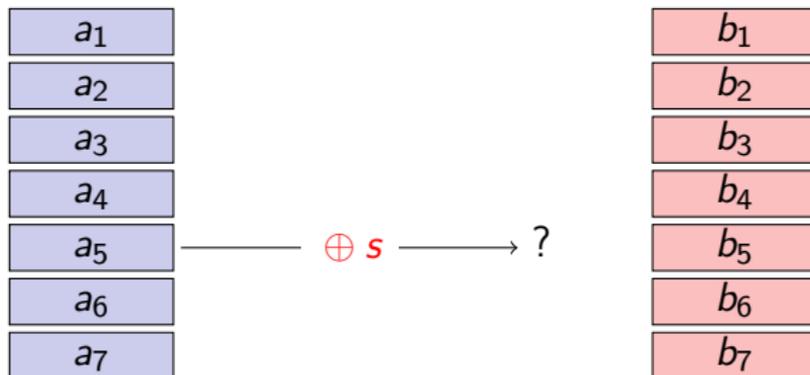
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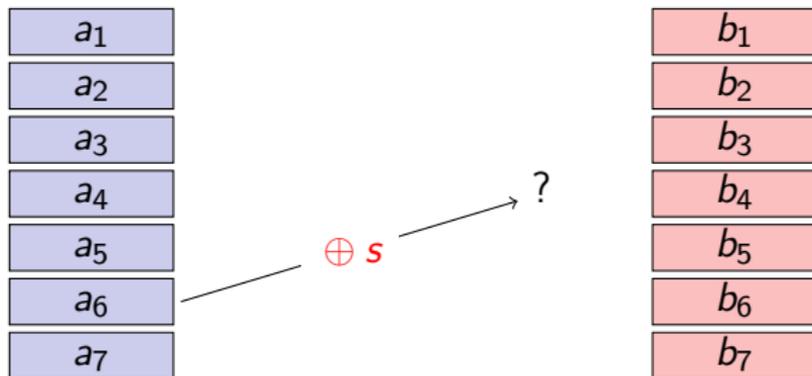
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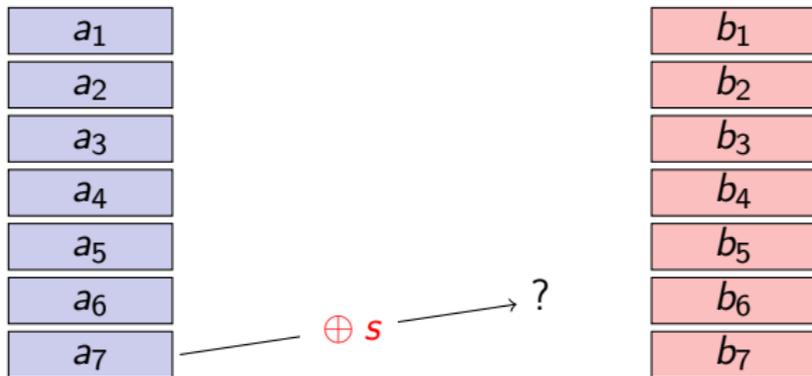
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return 1

```

Searching Algorithm

[McGrew, FSE'13]



- Make a guess and verify.
- Complexity $\tilde{O}(2^{n/2} \sqrt{|S|})$ with unbalanced \mathcal{A}, \mathcal{B} .

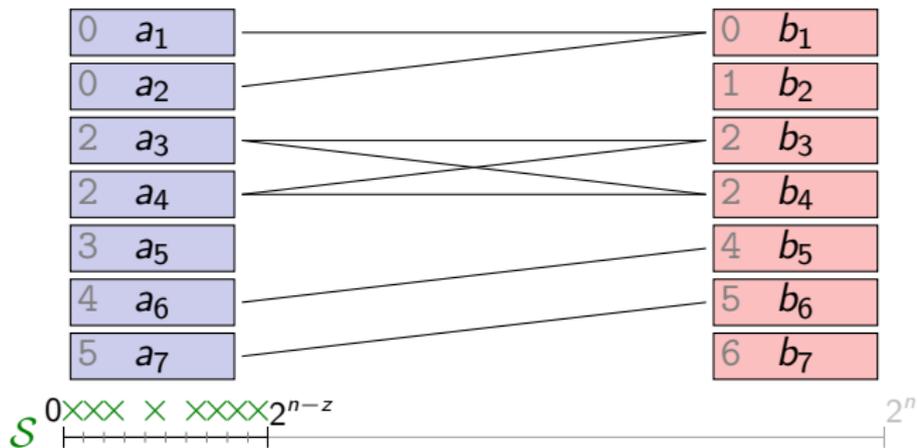
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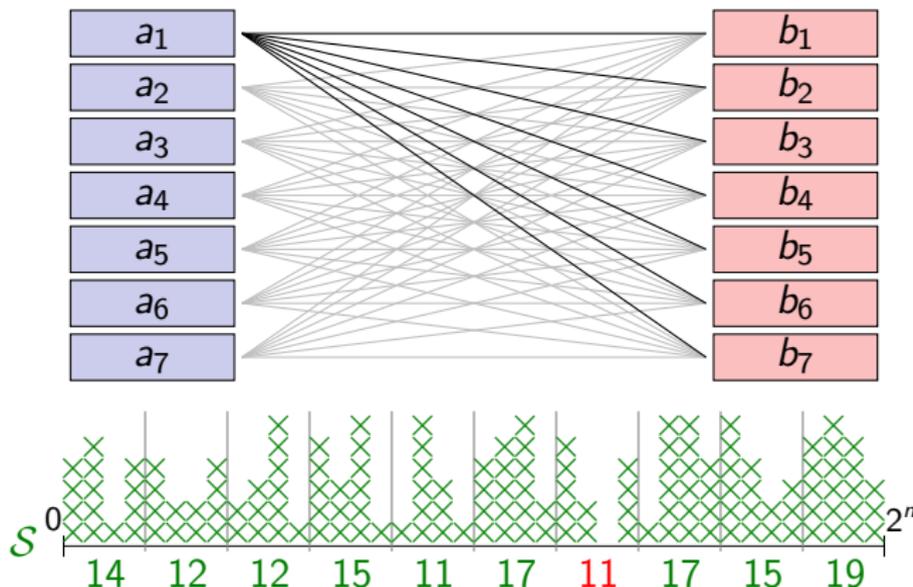
```

Known-prefix Sieving



- Assume S starts with z zero bits (more generally, linear subspace with $\dim\langle S \rangle = n - z$)
- Sort lists, consider a_i 's and b_j 's with matching z -bit prefix
- Complexity: $\tilde{O}(2^{n/2} + 2^{\dim\langle S \rangle})$
 - Looking for collision + needed number of collisions
- Complexity: $\tilde{O}(2^{n/2})$ when $\dim\langle S \rangle \leq n/2$

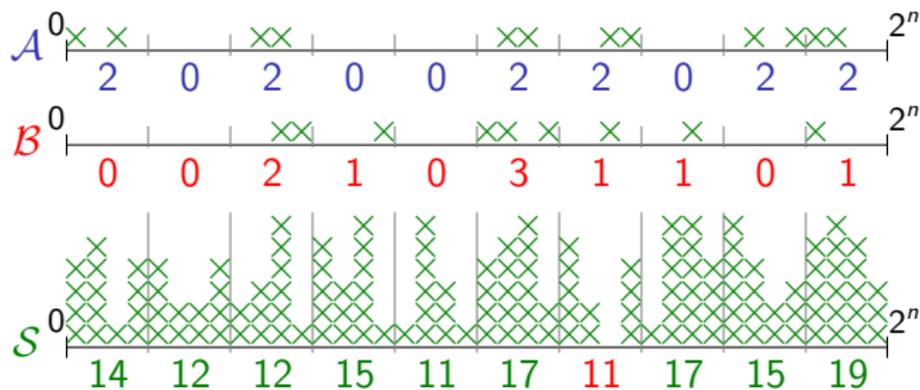
Fast Convolution Sieving



- Instead of computing full sieve, use **buckets** (ie. truncate)
- With enough data, missing difference has **smallest bucket** with high probability

Computing the sieve

- Count buckets for \mathcal{A} and \mathcal{B}
 - $C_x[i] = |\{x \in \mathcal{X} \mid T(x) = i\}|$



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$$= \sum_{a \in \mathcal{A}} |\{b \in \mathcal{B} \mid T(a \oplus b) = i\}|$$

$$= \sum_{a \in \mathcal{A}} C_{\mathcal{B}}[i \oplus T(a)]$$

$$= \sum_{j \in \{0,1\}^{n-t}} C_{\mathcal{A}}[j] \cdot C_{\mathcal{B}}[i \oplus j]$$

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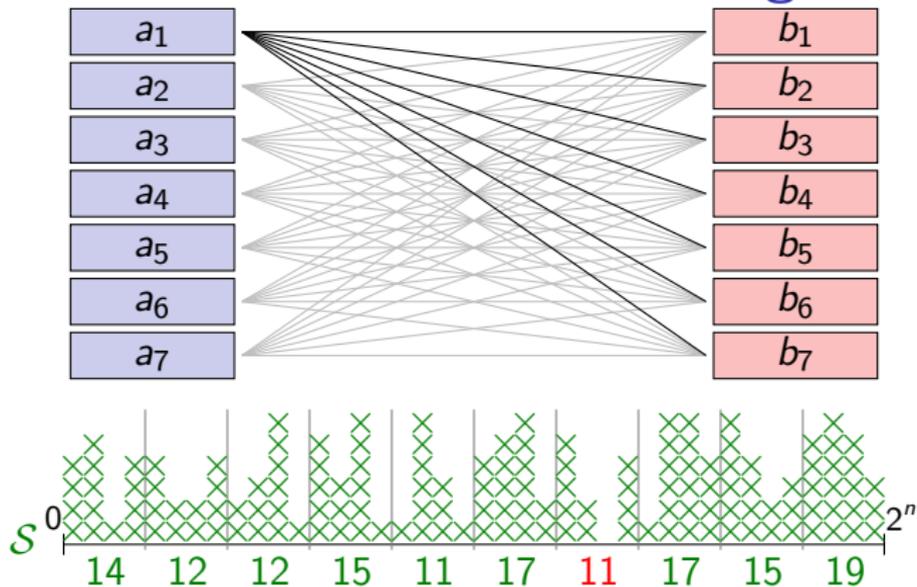
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$$= \sum_{j \in \{0,1\}^{n-t}} C_{\mathcal{A}}[j] \cdot C_{\mathcal{B}}[i \oplus j]$$
- Discrete convolution can be computed efficiently with the Fast Walsh-Hadamard transform!
 - Complexity:** $\tilde{O}(|C_{\mathcal{S}}|)$ for arbitrary \mathcal{S}

Fast Convolution Sieving



$$T(S) \stackrel{?}{=} \operatorname{argmin} C_S[i]$$

And we can finish with Known-prefix Sieving to recover the rest.

- $2^{2n/3}$ queries, sieving with $2^{2n/3}$ buckets of $2^{n/3}$ elements

Missing difference problem algorithms

Algorithms for the missing difference problem

Simple Sieving Complexity $\tilde{O}(2^n)$ [McGrew]

Searching Complexity $\tilde{O}(2^{n/2} \sqrt{|S|})$ [McGrew]

Known-prefix Sieving Complexity $\tilde{O}(2^{n/2} + 2^{\dim\langle S \rangle})$

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Known-prefix Sieving Complexity $\tilde{O}(2^{n/2} + 2^{\dim\langle \mathcal{S} \rangle})$

Fast Convolution Sieving Complexity $\tilde{O}(2^{2n/3})$

- Improved algorithm if \mathcal{S} is a linear subspace
 - In particular still near optimal when $\dim\langle \mathcal{S} \rangle = n/2$
- Improved algorithm for arbitrary \mathcal{S} at the cost of data
 - First algorithm with complexity below 2^n in that case

Back to Cryptanalysis

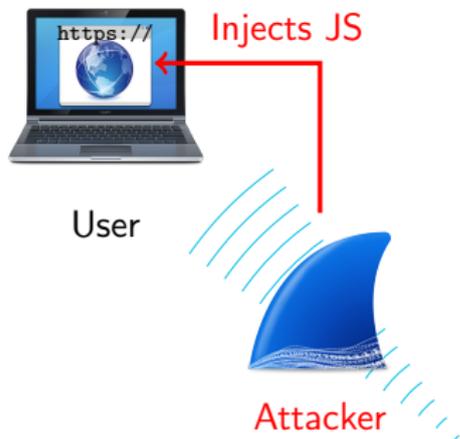
New Tools, New Attacks

Known-prefix → plaintext recovery on CTR mode

Fast Convolution → forgery on GMAC and Poly1305

BEAST Attack Setting

[Duong & Rizzo 2011]

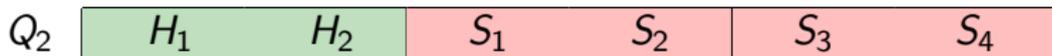


- Attacker has access to the network (eg. public WiFi)
1. Attacker uses JS to generate traffic
 - Tricks victim to malicious site
 - JS makes *cross-origin* requests
 2. Attacker captures encrypted data
 - Chosen plaintext attack
 - Chosen-Prefix Secret-Suffix model
 $M \rightarrow \mathcal{E}(M||S)$

[Hoang & al., Crypto'15]

Application to CTR (CPSS queries)

- **Plaintext recovery** using the known-prefix sieving algorithm
- Two kind of queries; half-block and full-block headers:



1. **Recover S_1** using the first block of each query:

$$\left. \begin{array}{l} \mathcal{A} = \{\mathcal{E}(H_1 \| H_2)\} \\ \mathcal{B} = \{\mathcal{E}(H_1 \| S_1)\} \end{array} \right\} \rightarrow \text{Missing difference: } 0 \| (S_1 \oplus H_2).$$

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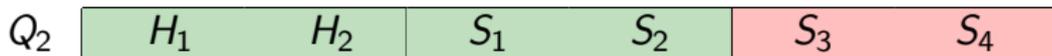
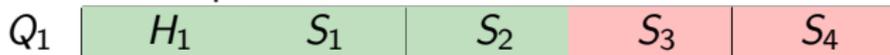
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2. When S_1 is known, **recover S_2** , with Q_2 queries:

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- When S_2 is known, recover S_3 :

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- ...

Application to CTR (CPSS queries)

Full Asymptotic Complexity

Queries $\mathcal{O}(\sqrt{n} \cdot 2^{n/2})$

Memory $\mathcal{O}(\sqrt{n} \cdot 2^{n/2})$

Time $\mathcal{O}(n \cdot 2^{n/2})$

Impacts

How practical can be the plaintext recovery attack on CTR ?

- Mostly used with AES, famous 128-bit block cipher, as part of GCM. 90% of Firefox HTTPS traffic uses **AES-GCM**.
 - Requires 128×2^{64} bits = 256 exbibytes over **one session**
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Sweet32 attack by Bhargavan and Leurent

Attack in the **BEAST** setting with birthday bound complexity already shown to be a threat over the web in recent work.

This is the **Sweet32** attack on CBC mode, more commonly used with 64-bit block ciphers.

Wegman-Carter Authentication Modes

- Wegman-Carter: build a MAC from a universal hash function and a PRF

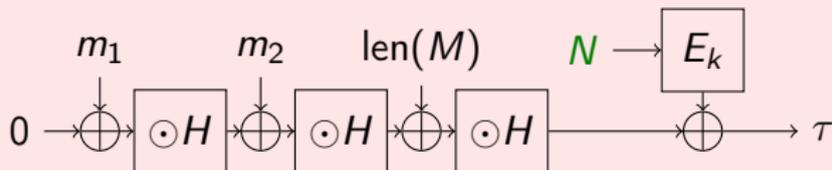
$$WC(N, M) = H_{k_1}(M) \oplus F_{k_2}(N).$$

$$\mathbf{Adv}_{WC[H,F]}^{\text{MAC}} \leq \mathbf{Adv}_F^{\text{PRF}} + \varepsilon + 2^{-n}$$

- Wegman-Carter-Shoup: use a block cipher as a PRF

$$WCS(N, M) = H_{k_1}(M) \oplus E_{k_2}(N),$$

Example: Polynomial-based hashing (GMAC, Poly1305-AES)



Key recovery as a missing difference problem

- Fix two messages $M \neq M'$, capture MACs
 - $a_i = \text{MAC}(i, M) = H_{K_1}(M) \oplus K_i$
 - $b_j = \text{MAC}(j, M') = H_{K_1}(M') \oplus K_j$
 - $a_i \oplus b_j \neq H_{K_1}(M) \oplus H_{K_1}(M')$
- For polynomial hashing, easy to recover universal hash key from $H_{K_1}(M) \oplus H_{K_1}(M')$

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- **Sieving** algorithm recovers $H(M) \oplus H(M')$ with $\tilde{O}(2^{n/2})$ queries and $\tilde{O}(2^n)$ computations
 - Independently done in another Eurocrypt paper!



Optimal Forgeries Against Polynomial-Based MACs and GCM

Atul Luykx, Bart Preneel

[Eurocrypt '18]

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 - $a_i \oplus b_j \neq H_{K_1}(M) \oplus H_{K_1}(M')$
- For polynomial hashing, easy to recover universal hash key from $H_{K_1}(M) \oplus H_{K_1}(M')$
- **Sieving** algorithm recovers $H(M) \oplus H(M')$ with $\tilde{O}(2^{n/2})$ queries and $\tilde{O}(2^n)$ computations
 - Independently done in another Eurocrypt paper!
 -  **Optimal Forgeries Against Polynomial-Based MACs and GCM**
Atul Luykx, Bart Preneel [Eurocrypt '18]
- **Fast convolution sieving** recovers $H(M) \oplus H(M')$ with $\tilde{O}(2^{2n/3})$ queries and computations
 - First universal forgery attack with less than 2^n operations

Bonus algorithm

Citation

[Luykx & Preneel, Eurocrypt'18]

... implementing the attacks seems to require a **large amount of storage** to achieve significant success probability. It is unclear whether there is a compact way of representing the set of false keys.

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Optimal queries and memory complete sieving

Guess first half of difference.

Run Known-prefix sieving over second half.

Repeat until found.

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Time is still $\tilde{O}(2^n)$ but **memory reduced to $\mathcal{O}(2^{n/2})$** in the nonce-respecting CPA model.

Conclusion

We defined the **missing difference problem** and **improved** the algorithms to solve it in particular for some cases:

Case	Previous	This work	Improved attacks
S affine subspace of dim $n/2$	$\tilde{O}(2^{3n/4})$	$\tilde{O}(2^{n/2})$	CTR plaintext recovery
No prior info <i>ie.</i> $ \mathcal{S} = 2^n$	$\tilde{O}(2^n)$	$\tilde{O}(2^{2n/3})$	GMAC, Poly1305 universal forgery

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Main take away :

- CTR mode **not more secure** than CBC (Sweet32).
- **Frequent rekeying** away from birthday bound will prevent these attacks.

Known-prefix Sieving Simulation

We challenge the **heuristic assumptions** we made (independence of the XORs $\{a \oplus b\}$). Approximations seem good enough.

Ran simulations with $n = 64$ bits and $z = n/2 = 32$ zeros.

- Each round we compare two lists of $2^{n/2}$ elements.
- Each round we expect $2^{n/2}$ **partial collisions**.
- Coupon collector predicts $n/2 \cdot \ln(2) \cdot 2^{n/2}$ partial collisions to recover S , that is **23 rounds on expectation**.
- Simulation gives an idea of what is hidden in the \mathcal{O} notations.

Consistent speed of leaking

In every runs, after **16 rounds** the sieve was left **between 419 and 560** candidates of S only.

Known-prefix Sieving Simulation

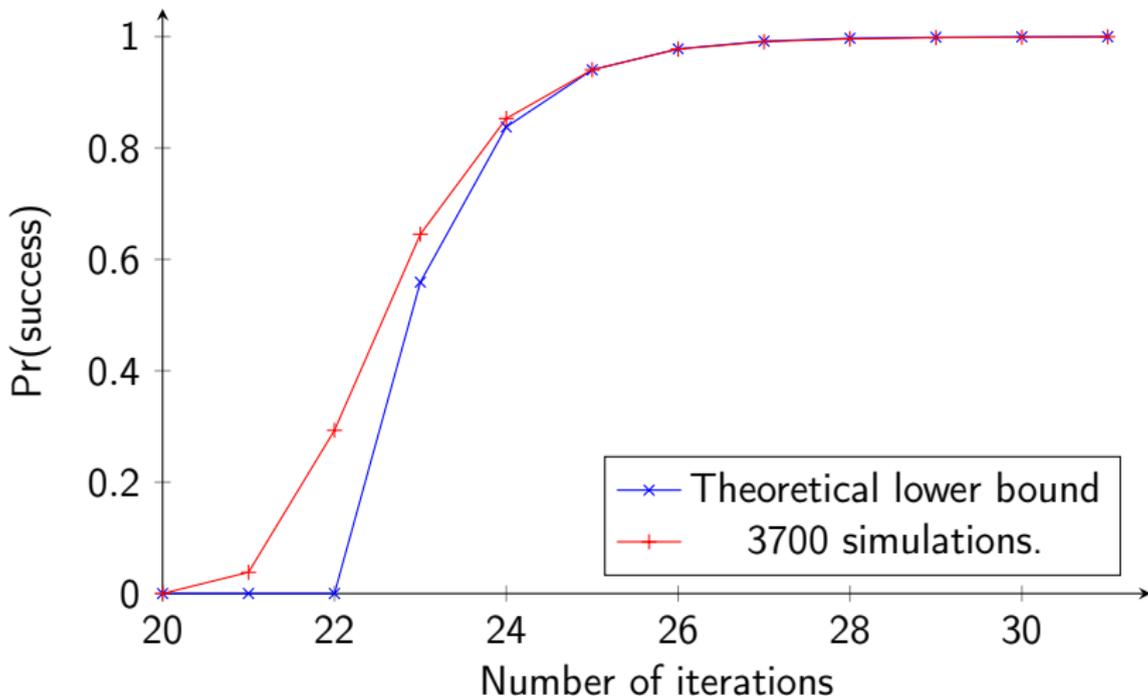
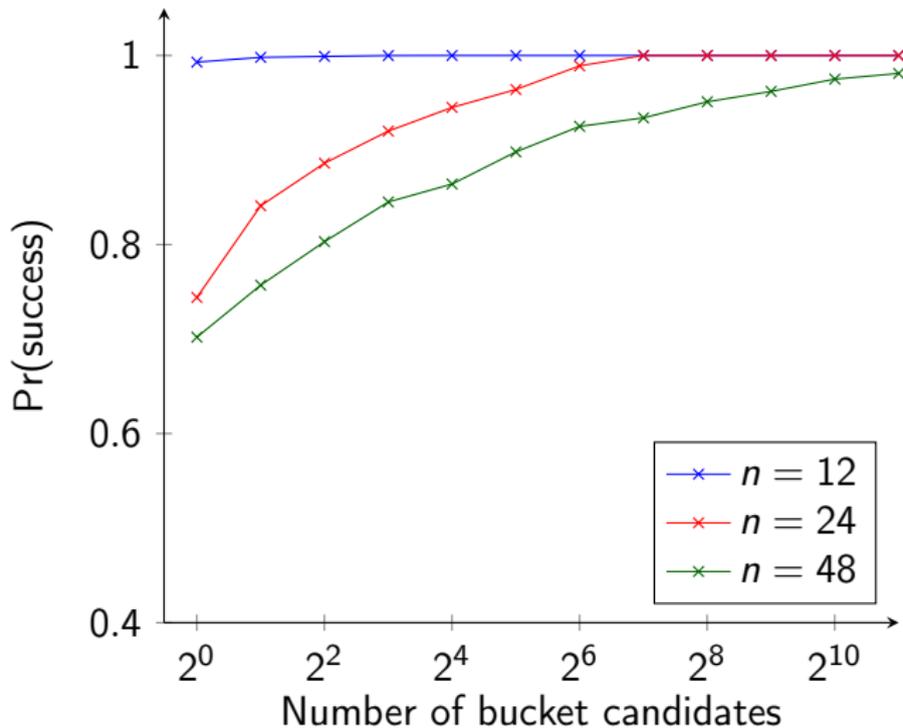


Figure: Probability of success of the known prefix sieving knowing 2^{32} encryptions of a 32-bit secret against the number of chunks of 2^{32} keystream blocks of size $n = 64$ bits used.

Fast Convolution Simulation

Figure: Results for $\sqrt{n}2^{2n/3}$ data; counting over $2n/3$ bits.



Works comparison

We independently described roughly the same attack on GCM, yet luckily our works complete each others:

Leurent & Sibleyras, EC'18

- Computational model
- Focus on **algorithms**
- Run simulations
- Provide a range of novel techniques and trade-offs
- Approach extendable to forgery on CWC mode

Luykx & Preneel, EC'18

- Information theoretic model
- Focus on **proofs**
- More rigorous analysis
- Show optimality w.r.t the best proofs
- Approach extendable to the KPA setting